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# Was Haiti in 2010 the next Tangshan in 1976:

## Heritage Structures Reveal the Hidden Truth about Risk and Resilience during the Haiti Earthquake

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1. Like a scene from Dante's Inferno, central Port-au-Prince, 4 months after the earthquake. *Photo © Randolph Langenbach*

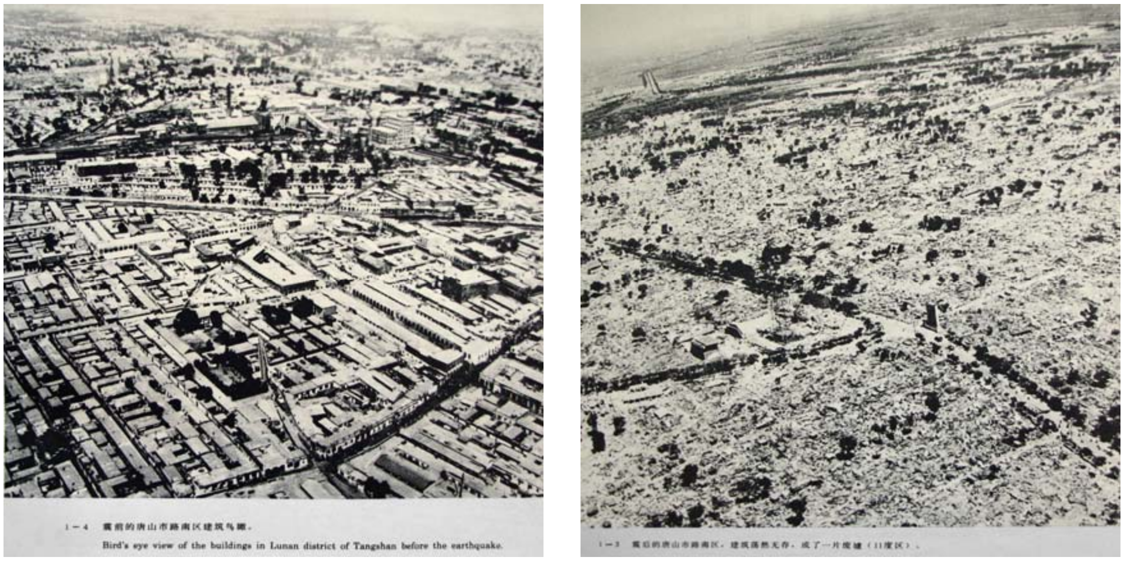
## Introduction: Tangshan 1976

On the 27th of July, 1976, the ground shook in Tanghan, only 150 kilometers from Beijing. When the shaking stopped less than 15 seconds later, the city was veritably destroyed, and the official estimates report that almost a quarter of a million people died. Unofficial casualty estimates were as high as 655,000. Using either number made this at the time it happened, the largest loss of life in an earthquake in exactly 420 years, and the second largest in all of documented human history. The record setter is reported to have also been in China – an earthquake on the 1st of June, 1556 near Huaxian, Shaanxi (formerly Shensi) that is reported in the literature to have killed 830,000 at a time when the human population of the planet was far less than in the 20th century [USGS.GOV].

Now it is 38 years after the Tangshan earthquake, and on the US Geological Survey (USGS) web page referenced above, the *second* item under “Earthquakes with 50,000 or More Deaths” is the 2010 Haiti earthquake, with Tangshan 1976 listed *third*! Haiti? Bigger than the 1976 Tangshan earthquake? With the Government of Haiti’s publication of the “official” death toll of 316,000, its official number exceeds that of Tangshan, bumping it into second position, while the earthquake magnitude of 7.0 places it as the lowest magnitude for any earthquake with over 50,000 fatalities.

This paper is not intended to verify this number or refute it. That is a task for others – and a controversial and thankless task it is. Earthquake causualty data cuts both ways in international the political spectrum – with international aid contributions coming often in response to the outpouring of concern and support in response to such vast body counts, while at the same time, it cannot help by shine a sharp light onto the obvious and apparent failure to oversee and regulate the building delivery process in the public interest.

In the case of Haiti, with a range of casualty estimates that range from as low as 50,000 to as high as the over 300,000, whatever the actual casualties were, the unrefutable evidence is that it was the collapse of vast numbers of formal, contractor-built downtown commercial and residential buildings that was both most widespread and most inexcusable. Then it may be asked: *What about the many published images of large areas of destruction of the informal housing in the hillside and coastal slum settlements*? This paper will explore that issue – and the answer is not what is most commonly believed to have been the case.



2. Tangshan before and after 1976 earthquake. Source: The Mammoth Tangshan Earthquake of 1976 Building Damage Photo Album "China Academy Of Building Research"

**Haiti on January 12, 2010:** The Haiti earthquake was, and continues to be, a seminal event in terms of fatalities. It is believed that close to 100,000 to well over a quarter of a million people died in buildings – almost all of which are of recent origin. The most severely affected buildings utilize a construction system – reinforced concrete – which has rapidly become almost the universal choice for new buildings in urban, and even many rural areas.[1]

My recent research on Haiti stems from access to an unusual source of data – the oblique aerial photography of the damage district in and around Port-au-Prince, Haiti done by Pictometry International Corp. in the weeks following the 2010 earthquake that devastated that area. For the first time, it was possible to survey the damage patterns with very clear data over a much larger area than would be possible to do from the ground.

3. A detail from a Pictometry oblique aerial view of central Port-au-Prince one week after the earthquake. The collapsed unfinished building in Figure 1 is visible in the upper left. *Photo © Pictometry International Corp.*

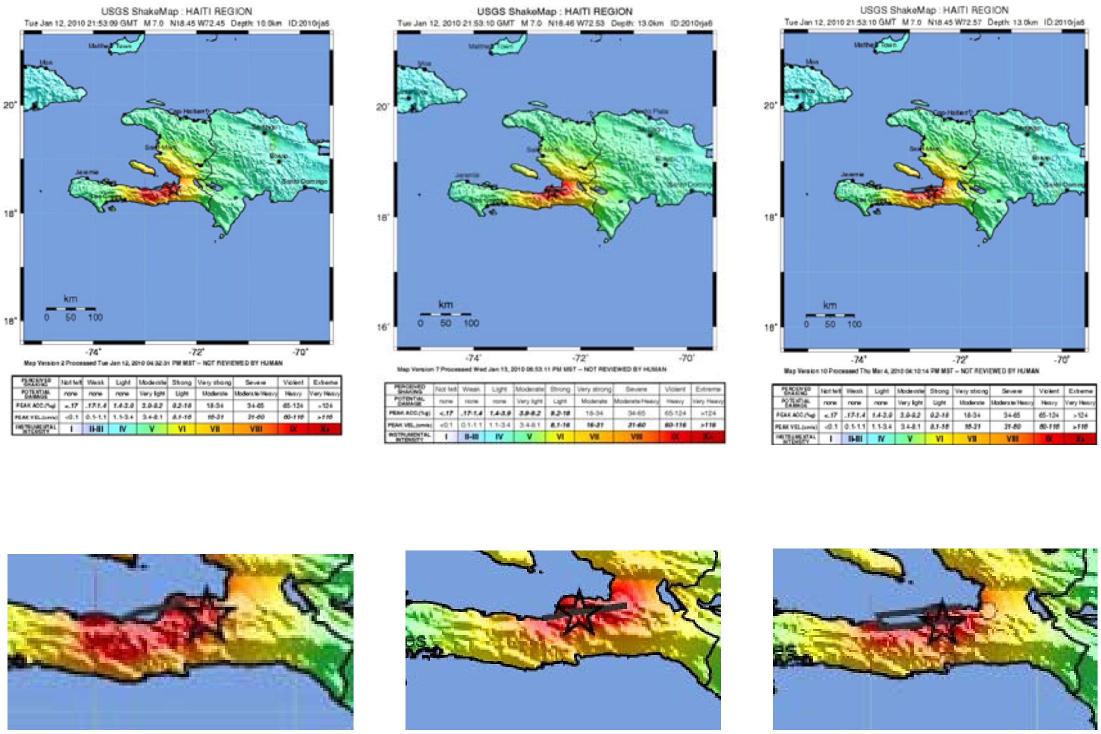
RMS FAQ: 2010 Haiti Earthquake and Caribbean Earthquake Risk

4. The RMS report showing shakemap based on USGS shakemap dated 13 January. See Endnotes (2) for link to a copy of the report.

After most disasters, government inspectors and engineers as well as the news photographers head for the most evocative and extensive damage, blanketing the information pathways with poignent images of devastation and distress. All of this is important to do – but such view from the ground can fail to also notice or fully recognize those areas with fewer collapses and thus fewer deaths.

The World Bank sponsored an extensive preliminary damage survey from high resolution straight-down aerial imagery using Google Earth as a platform, and this has been published on the web and used extensively in the post-disaster planning work. [2] However, the Pictometry oblique imagery provides a chance to glean more complete information of the architecture and structural systems of the still standing buildings. The oblique views of the framework and still standing walls of those that are partially and totally collapsed are more clearly visible, and thus provide an opportunity to see better the nature of their failures. Together, this allows for the classification and rough dating of the affected building types, as well as a more accurate assessment of whether or not partial or total collapses have occurred when a straight-down view of the roof would be more obscure.

Before exploring what this Pictometry imagery revealed, first it is worth moving back to the the several days following the earthquake when the first technical data was issued by seismologists from around the world including the USGS (United States Geological Survey). Ten days after the earthquake, the California-based risk and loss estimation firm Risk Management Solutions (RMS) published a report in which they estimated that the earthquake had caused 250,000 fatalities. This number is uncannily close to the 222,570 reported by the United Nations Office for Coordination of Humanitarian Affairs (UNOCHA), cited a USGS “Newsroom” page released on February 22, 2011, thirteen months after the earthquake.”[3] On the first anniversary of the quake, Prime Minister Jean-Max Bellerive said that the death toll from the quake was more than 316,000, a figure that is almost 100,000 higher than that cited by the UNOCHA, and higher even than the 300,000 reported by the USGS as the number who suffered injuries.[4]



5. USGS Shakemaps with details of each map below: Version 2 (January 12-Day of earthquake): *left,* Version 7 (January 13): *middle.* Version 10 (March 4): *right.*

What makes this interesting is that the RMS estimate was stated in the report as based on a “USGS Shakemap published on January 13, 2010,” one day after the earthquake. The USGS shakemaps customarily go through a number of revisions as more data is processed and interpreted, but only the latest (in this case Version 10, dated March 4, 2010) is now available on the USGS site. The earlier versions are no longer available from USGS, so to find them one has to search the internet for copies that managed to be reproduced into reports and posted on other websites. From that research, I was able to locate USGS Shakemap versions 2, 3, 7, as well as #10. If one compares these versions for the Haiti earthquake it appears that both the precise location of the fault and also the rupture zone on that fault were shifted on the map as the later versions were published.

Versions 2 and 3 were produced immediately after the earthquake on January 12 at 4:30PM and 6:30PM respectively. As luck had it, the one found most resembling the map in the January 22 RMS report and of the date cited by RMS, was found on Wikipedia linked to their page on the "Mercali Intensity Scale." This shakemap is marked as version 7 published at 7PM on the 13th. This was probably the most up-to-date shakemap available at the time that RMS prepared their report.

This January 13 version 7 shakemap shows the city of Port-au-Prince as having been subjected to a shaking equivalent to an Modified Mercalli Scale (MMI) IX while the March 4 version 10 shows this reduced to an MMI-VII or VIII. (The transition from the yellow for VII, to orange for VIII extends over part of the area). An undated UN/European Commission shakemap has all of Port-au-Prince as a VII. Interestingly, USGS versions 2 and 3, published on the day of the earthquake also show Port-au-Prince subjected to a MMI-VI to MMI-VII, considerably lower than version 7 a day later, but not as different from the latest and final map version 10 of March 4.[5]


6. Bodies in outside a Port-au-Prince hospital. What little actual counting of fatalities was by measuring the body count in squares such as this and reporting on how often they were refilled after bodies were cleared for burial. It was also done by counting truckloads of dead bodies. *AP*

To put this all in perspective, a quarter of a million fatalities places this earthquake side-by-side with the Tangshan earthquake of 1976, which, as described above, caused more fatalities than any other in the 20th century by an order of magnitude. With the poverty and bad construction known to exist in Haiti, combined with an intensity calibrated to be an MMI-IX in Port-au-Prince, it is plausible, but what if the actual shaking is correctly classified as an MMI-VII?

At the time of the earthquake, it was the widespread collapse of the more formally constructed buildings in Port-au-Prince that undoubtedly fed the perception that a classification of the intensity as an MMI-IX and even an MMI-X (as is still reported in Wikipedia) was correct – not just in the epicentral area near Léogâne, but also extending through Port-au-Prince and including Pétionville. In fact, two buildings in particular that may have influenced this are the five start Hotel Montana, and the former five star hotel used by the UN to house its staff in Haiti (figures 7 & 8). The Hotel Montana was the hotel heavily used by visiting governmental officials from the USA. Both of these hotels pancake collapsed, killing most of their occupants – and knowledge of this spread fast, including to USGS. Since it would seem inconceivable that these considerably more formal buildings would be less structurally sound than the shanty-town houses, early knowledge of their collapse may have influenced the steep rise in the intensity shown in the January 13 version 7 shakemap over that in those published the day of the earthquake. Later, with more technical data, the subsequent USGS shakemaps show a return to a lower MMI for Port-au-Prince.

7. Five star collapses in Petionville: *left:* Hotel Montana before, and *center* after the earthquake

8. UN Headquarters after the earthquake. *Google images.*

Patricia Grossi, the lead author of the RMS document, reported in a phone conversation on April 14, 2011 that since there were no seismographs in Haiti at the time of the earthquake the interpretation of data from the more remote instruments is all that anyone had to generate the shakemaps. Grossi confirmed that the casualty estimates in the RMS report were based on the MMI-IX, not MMI-VII or VIII. Grossi also reported that, had USGS published the lower MMI on the 13th of January, the RMS estimate of casualties would have been lower.

To try to calibrate how much lower, one can look at how the Modified Mercalli scale calibrates damage. This intensity scale was updated from the late 19th century Rossi–Forel scale by Italian volcanologist Giuseppe Mercalli and given his name in 1902, and was later re-written slightly by Charles Francis Richter in 1958. It is based on an extrapolation of intensity based on peoples' perceptions of motion, and then in the higher intensities based upon damage to buildings – primarily buildings of unreinforced masonry (which were ubiquitous in nineteenth century Italy at the time of Mercalli).

As a source for the estimate of 250,000 fatalities, the RMS report on page 7 says:

> *The initial casualty estimates were developed using publically available information including population data, ground shaking intensities, and the Haitian construction materials and practices, as previously summarized…The building vulnerability was assumed to map on average to unreinforced masonry construction, which is extremely susceptible to collapses and heavy enough to cause significant casualties to occupants. This is consistent with the prevalent construction type in the urban regions of Haiti (i.e., blocks/concrete), but actual construction practices vary and include reinforced concrete, reinforced masonry, and unreinforced self-constructed buildings.*

As mentioned above, this is predicated on a finding that an MMI of IX is correct for central Port-au-Prince including the shanty-towns, known as *bidonvilles*, or "tin can cities," on the surrounding hilllsides. An MMI-IX is described in part as *"Violent: …Damage to masonry buildings ranges from collapse to serious damage unless modern [ca. 1958] design. Wood frame structures, if not bolted, shifted off foundations. Frames racked."* If instead it were only an MMI-VII, then the calibrating description is thus: *"Strong:…damage to some poorly built unreinforced masonry buildings. … Some cracks even in better built masonry buildings if not reinforced"*

9. The unreinforced brick masonry Hotel Oloffson, Port-au-Prince after the earthquake. © *Randolph Langenbach*

In addition to the later USGS shakemap, there are other indicators on the ground that MMI-VII may actually be the more correct estimate. The Oloffson Hotel, a building which is contemporaneous with Mercalli's publication of the scale and is of URM construction with good quality brickwork (which in the MMI scale would be termed "*better built*") came through with only minor cracks, as specified for a VII (Figure 9). Other historic masonry buildings from the same period with poorly maintained rubble stone making up parts of the walls suffered damage from medium to heavy, but with very few collapses (Figure 10). This is also consistent with the MMI-VII classification. As evidence that the Oloffson was not on a site subjected to less shaking, a nine story RC hotel structure immediately behind the Oloffson pancake collapsed. All the affected buildings were within the central Port-au-Prince damage district, making it difficult to explain these phenomena as only a consequence of extreme differences in local site effects.**[6]**

10. Brick and empanelled rubble stone construction, as is typically found in many of the Port-au-Prince "Gingerbread" Houses from the late 19th century, showing different levels of damage from onset, to collapse of the rubble panels. Surprisingly few houses with this construction collapsed overall, despite the weakness and vulnerability to earthquake shaking of this construction – a further verification that the intensity did not exceed MMI-VII at these Port-au-Prince sites. © *Randolph Langenbach*

This then leads to the question of how did the RMS casualty estimate and other initial estimates immediately after the earthquake before any actual body counts could have been undertaken end up being uncannily close to the casualty totals now reported more than a year after the earthquake if the source used for these estimates was off by one or two intensity levels.**[7]** There are three possible answers to this question: (1) after the early large estimates of fatalities from RMS and other sources based on the January 13 versions of the USGS shakemap, the numbers have stuck because of a true lack of knowledge of what the numbers really are, (2) the actual shaking in and near Port-au-Prince was greater than the remote instruments could show, leading to more fatalities than a VII would indicate, or (3) the structural resilience of the building stock in which people were at the time of the earthquake was far worse than even the "*…map to unreinforced masonry construction…*" could represent when RMS did its estimate.

It is possibly a combination of all three. On (1), the fatalities, while many sources cite casualties in the 225,000 to 300,000 range, most are simply quoting impressionistic comments and many make it clear that because of a lack of quantitative data on the populations even from before the disaster, the true number of deaths will never be known. With no real census or listing of the citizenry living in Port-au-Prince prior to the disaster, speculation on the numbers of dead after the earthquake is just that. A paragraph from Wikipedia says it best:

> *In the weeks following the earthquake …the Red Cross stated that 40,000-50,000 may have died, while Haitian Interior Minister Paul Antoine Bien-Aimé estimated that the dead were between 100,000-200,000. On 12 January Haitian Prime Minister Jean-Max Bellerive stated that the death toll could be "well over 100,000." Later Red Cross officials issued a death toll estimate of 50,000 killed, while Haitian Interior Minister Paul Antoine Bien-Aimé stated that … "there will be between 100,000 and 200,000 dead in total, although we will never know the exact number." Prime Minister Bellerive then announced that over 70,000 bodies have been buried in mass graves. … Haitian President Rene Preval reported on 27 January that "nearly 170,000" bodies had been counted. On 10 February the Haitian government reported the death toll to have reached 230,000…. Edmond Mulet, who was appointed head of the United Nations after the quake, stated that "I don't think we will ever know what the death toll is from this earthquake." And the director of the Haitian Red Cross, Guiteau Jean-Pierre, noted that his organization didn't "have time to count" bodies…*[8]

Even so, Engineer Kit Miyamoto, who has led teams of inspectors for more than a year since the earthquake, believes that the current range of estimates of fatalities are plausible, however, on June 2nd, a draft of a USAID report by PhD anthropologist Timothy Schwartz was obtained by Associated Press which estimated that between "46,000 to 85,000 people" were killed in the earthquake, contrary to all other much higher estimates. Despite their large discrepancy with the higher estimates, these numbers do show a more rational relationship between the numbers of deaths vs number of injured, and also with the population still living at their original addresses.

In terms of (2), the shaking, the lack of local instrumentation makes representations of enhanced shaking because of site effects plausible, but only speculative. Subsequent research of the geology of the Port-au-Prince area does show subsoil and geological strata that could have resulted in shaking differences, but because of the range of damage within each of these strata subdivisions, the differences cannot explain the discrepancy between the overall bad performance of the reinforced concrete moment frame buildings when compared with either the masonry buildings or the non-engineered self-built houses in the *bidonvilles*of all construction types.

That then leaves (3) the collapsed buildings as the third variable – and it is this is the one variable that can be best inspected and calibrated. Even before this comparative research, it is hard not to acknowledge that the performance of buildings of recent origin in this earthquake in central Port-au-Prince was particularly abysmal. Here is where the Pictometry imagery provides insight into where it was that most of the people probably died, whether it be 80,000 or 300,000.

Unlike most recent earthquakes that have stricken developing countries where the affected buildings are largely rural, this one struck a capital city with mostly a modern building stock constructed of a mixture of reinforced concrete (RC) and concrete block masonry. The RMS report anticipated that the preponderance of damage would consist of the owner-built houses in the informal squatter settlements.

11. A downtown commercial building in a near state of collapse – illustrating the brittle vulnerable nature of many of the formal, contractor-built reinforced concrete buildings in Port-au-Prince. Many buildings of this type did pancake collapse, but, as demonstrated by the buildings on either side that are still intact, everything did not fall down. Approximately 40% of the buildings in the central city were partially or totally collapsed, but of the remaining 60%, many suffered little damage. *©Randolph Langenbach*

However, the Pictometry images have revealed that the preponderance of the building collapses were not, as anticipated by RMS, in the *bidonvilles*, but in the more formal, contractor-built multistory reinforced concrete buildings in and around the city center, including the 5 star Hotel Montana well to the east. Shockingly, almost every Haitian government building, including the 1916 National Palace and the much more recently constructed Legislative complex collapsed. In addition, the principle focus of the devastation was the hundreds of offices and shop buildings in the city center. Thus the worst building performance was with the more formal “engineeered” and contractor-built buildings of reinforced concrete with concrete block masonry infill, particularly in the commercial downtown area of the city and in some of the more permanent and formal parts of the outlying areas to the north and east.

The collapse of these buildings may in fact require the setting of a new lower limit for damage in the MMI scale definitions – collapse risks at levels of shaking not anticipated by either Guiseppi Mercalli or Charles Francis Richter. The calibration of that scale was based on an earlier category of unreinforced masonry buildings perhaps not unlike the quality of the 1890’s Oloffson Hotel (originally constructed as a private home) at the high quality end, and the brick and rubble stone houses in the Gingerbread District at the lower quality end.

12. Views of *bidonville* near central Port-au-Prince showing (*left*) view of area with extensive collapses, and (*right*) area with very few collapses. A careful review of the Pictometry of the Port-au-Prince damage district as a whole has shown that views with minimal evidence of collapses was significantly more prevalent than those with heavy collapses. *left –UNDP Global (from RMS Report), right © Pictometry*

The more recent single-wythe low-strength cement block masonry buildings with (and sometimes without) poorly designed and built non-ductile concrete frames would not have existed at the time the Modified Mercalli Scale was created. They may best be classified as falling into a lower standard of resilience than even what is described for MMI-VII as "*damage to some poorly built unreinforced masonry buildings.*" The description of MMI-VI includes "*Weak plaster, adobe buildings, and some poorly built unreinforced masonry buildings cracked.*" It is hard to imagine that this category should now contain a phrase such as: '*pancake collapse of a portion of a building stock of multi-story reinforced concrete frame with infill construction buildings, particularly in areas low on the socio-economic scale*' but how else can one explain the situation?

13. *left:* Pancake collapse of a reinforced concrete building on east (away from epicenter) side of Port-au-Prince. Pancake collapses of the heavy floors of multi-story RC buildings are particularly lethal and make it hard to extract the survivors. © *Randolph Langenbach. Right:* Reinforce concrete building in Rikuzentakata, Japan swept onto its side and carried upstream by the March 10, 2011 earthquake and tsunami. *AFP/Getty*

This situation in Haiti contrasts sharply with that which followed it in Chile and then, a year later, in Japan. Ironically, it is only the buildings of reinforced concrete and steel that remained standing after the remarkable onslaught of the Tsunami in Japan. Some smaller RC buildings were even found to have been turned on their side by the tidal wave and perhaps even moved some distance, remaining after the sea retreated with their superstructures intact, as shown in figure 10 (right) of one in Rikuzen. In Haiti, which is quite frequently subject to hurricanes, the resistance from weight of even poorly constructed concrete buildings makes that system favored over wood and lighter materials – but as can be seen, an earthquake of only moderately large surface shaking has made the choice to use concrete and cement blocks for almost 100% of the new houses in recent years unfortunate.

Sadly and ironically, the introduction of modern materials and systems such as reinforced concrete, concrete block and even light weight steel (as demonstrated by the Bam earthquake where the use of steel and masonry jack-arch roofs on adobe walled buildings caused countless fatalities) may have led to an increase rather than a decrease in risk when those new materials and systems have been adopted for practically all of the new buildings in a construction environment in which quality control inspection does not exist, and which lacks training of the workers in the necessary skills. Reinforced concrete buildings can be exceedingly strong if well designed and constructed, but they are more subject to faults which can dramatically reduce their inelastic capacity and ductility if the work deviates from good practice in any one of a myriad of different ways – faults which can easily lead to collapse in earthquakes specifically because it is with design level or greater earthquakes for which inelastic response is presumed to occur.

14. *left:* National Palace in Port-au-Prince after the earthquake and partial demolition, revealing the reinforced concrete frame infilled with rubble stone. The steel reinforcing bars in the exterior portions of the frame and poured concrete walls (visible on left side of left photo) were heavily corroded in this over 90 year old structure. *Left: © Randolph Langenbach.*

Concrete construction came to Haiti relatively early. The iconic view of this particular earthquake is the image of the collapsed National Palace, with its heavy white square domes scrunched down over the ruins of the building below. This building dates from 1916-18 and it is reported that it was finished by the U.S. Navy when the United States occupied Haiti.[9] It has a reinforced concrete frame infilled with masonry – a masonry partially composed of rubble stone!

The Catholic Cathedral was also of reinforced concrete, with a steel truss roof. The upper level walls and towers collapsed, bringing down the roof. The steel reinforcing was minimal to begin with and the century of exposure to the tropical elements had caused corrosion in the reinforcing in many of the older concrete structures. The Cathedral collapsed very much as if it were a single wythe of unreinforced masonry as the rebars in it and the National Palace had in places almost disappeared from corrosion.

Of course, most of the collapsed buildings where people died were of much more recent vintage, repeating on a grand scale what has been observed as an increasing problem with each successive earthquake – collapses of modern buildings with moment frames of reinforced concrete infilled with masonry. But rather than further discussing the fate of these buildings in the city center – the back story that needs to be explored is what happened with what one would expect would be the weakest and most dangerous of buildings – the illegal and unregulated owner-built squatter housing in the vast mountainside and water's edge *bidonvilles* that ring central Port-au-Prince.

## The *bidonvilles* – are they only slums?

Earthquakes have the potential to profoundly test buildings in ways that make visible what is usually invisible – a quality of structural capacity that can be suddenly and profoundly transformative. All at once – a hidden but essential ingredient often taken for granted – a building's structural character and quality, is brought to the fore – either tragically or worthy of celebration. As one scans the news photography of the *bidonvilles,* not surprisingly, the impression one gets is that most of the houses were destroyed. There are many views of hillsides of shattered houses. The Pictometry flights however were designed to cover every part of the landscape – and while the smashed areas are also visible in the Pictometry views, they must be searched for – a search sometimes over large areas with little or no evidence of collapsed buildings.

15a. Aerial view of Cité Eternal, located on a combination of fill and an alluvial fan in central Port-au-Prince. *Images © Pictometry. Mosaic of images into a single view by Randolph Langenbach*

On the hillsides to the east and south of Central Port-au-Prince, there were some baffling areas where whole clusters of buildings were devastated while other areas were largely intact, but in most of the areas which had large swaths of damage, using stereo pairing of the Pictometry images, it was possible to see that often such areas were the steepest slopes in the particular district. The foundations and retaining walls of many of the squatter houses were of undressed river rock – the most vulnerable of masonry types.

15b. Typical detail of Cité Eternal showing that two story buildings with one four story building – most of reinforced concrete. © *Pictometry*

Then it may be worth looking at one area where steep hillsides are not a factor. One such area, presciently called *"Cité Eternal,"* is located immediately adjacent to the devastated city center (figure 15a&b). It is on land where one would expect to find the most damage – at the edge of the sea on fill and unconsolidated alluvium. The area consists mainly of one, two, and three story concrete block masonry buildings, with concrete slabs and roofs mixed into structures of lighter construction.

While the largest number were one story buildings, there were many two story concrete masonry buildings – and not an insignificant number of three and four story buildings. Some buildings did collapse – but they were isolated examples – unlike the downtown where block after block was in ruins. Why?

Perhaps it is the honeycomb of small rooms in many of the buildings constructed by the poorer population. Perhaps the soil was so bad there, it was actually good – in so much as the stiff buildings did not resonate with the earthquake waves in the soft soil. Perhaps it is the simple fact that the buildings – essentially being solid wall masonry and confined masonry buildings with few windows and openings – actually conformed more closely to the calibrating measure used originally by Mercalli and later modified by Richter in the setting of the damage thresholds in the Modified Mercalli Scale – which as observed above may place them one level more robust than the performance of the reinforced concrete infill frame buildings that largely made up the city center.

Shocking? Perhaps – but then again, maybe not.

While most downtown commercial and residential buildings in Haiti are contractor built, with architects and engineers involved in the design of the larger and more complex ones, many are not more than rudimentarily engineered. Construction quality is unpredictable, and often of low quality. There are no building codes, and inspection is almost non-existant.

Until the introduction of ductile detailing in the quantity and layout of the reinforcing steel of reinforced concrete buildings through code changes in places that do have and enforce codes, reinforced concrete buildings have been subject to collapse in large earthquakes. More disturbing is the fact that is that many of the RC buildings can go from little apparent damage to fully collapsed very quickly, once the forces exceed their elastic capacity.

## Reinforced concrete frame construction with masonry infill walls

More than most recent earthquakes, the Haiti earthquake shines a light on the serious flaws in the increasingly common use of reinforced concrete frame with infill masonry construction as a default choice for new construction – even in ex-urban areas. A full understanding of what happened in Haiti, as well as Christchurch, requires going back to review some of the recent history of building construction.

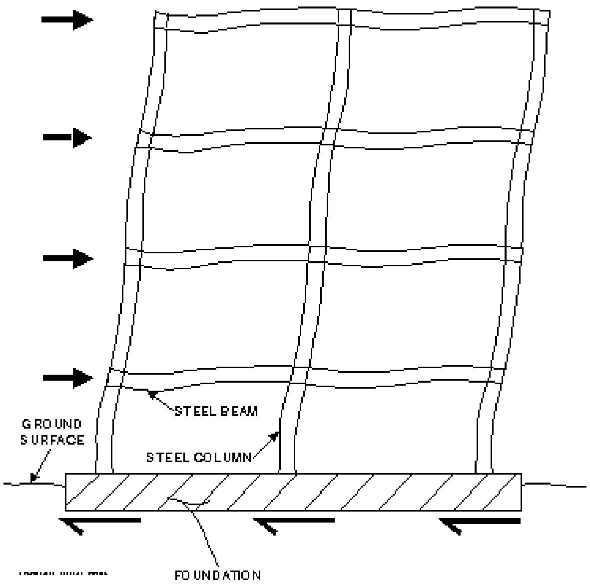
Over the past half-century, RC frame construction has driven out almost all other structural systems – particularly traditional forms of solid wall masonry construction – becoming almost universal in many areas – often with the active encouragement and even subsidy by governments and large corporations. This has represented a transformation of the building process from an indigenous one to one more dependent on outside contractors, specialists, and nationally-based materials producers and suppliers of cement and extruded fired brick, and hollow clay tile. In places like Haiti, reinforced concrete has been introduced into a building construction process that continues to exist much as it did in the past. The system of local builders with a rudimentary knowledge of the science of materials was sufficient only as long as they were working with timber, unfired clay, and stone and fired brick masonry. With concrete moment frames, it has proved woefully inadequate.

In fact, there is a fundamental engineering problem with standard reinforced concrete moment frame construction that has been recognized for decades, but which has not been fully dealt with. Multi-story reinforced concrete structures most often continue to be calculated and constructed as ‘moment frames’ without the benefit of shearwalls.

Moment frames provide resistance and stability by both shear and flexure of the framing members in addition to the support of loads along the axis of the members. Their lateral capacity if primarily determined by the strength and ductility of their joints between the beams and the columns. The enclosure and partition walls that turn this open framework into a useable building are ignored in the engineering design and simply treated as dead weight in the structural calculations.

The advantage of this approach is that it has allowed for a coherent mathematically-based engineering approach to building design by separating the infinite complexity of a finished building with all of its parts from that of the primary structural system – the frame. But there is an important caveat that in practice has largely been lost along the way: standard portal frame analysis is predicated on the existence of “frame action.” This means that the building design is based on the assumption that the frame will deform in a geometrically coherent way so that all of the elements can share the loads.

There is a significant problem with this assumption. In most parts of the world the enclosure and partition walls are most often of stiff brittle masonry that is strong enough to prevent the ‘frame action’ on which the portal frame analysis is predicated. Because these walls are considered by the design engineers to be “non-structural,” these infill masonry walls are often not themselves designed to resist the lateral forces of an earthquake and their impact on the overall deformation of the building is often not properly considered.



16. Moment frame showing uniform bending of the frame in response to a lateral force unencumbered by infill masonry walls.[10]

As a result, moment frame buildings are severely handicapped going into a design-level earthquake. To come to grips with the reason for this engineering problem, a brief review of the early 20th century evolution of the modern skeleton frame system of steel and concrete construction is in order.

### From the invention of the Skeleton Frame to the “Modern Movement”

Structural engineering has gone through its own revolution over the past century. The 19th century was an era of enormous ferment, producing engineering giants like Brunel and Eifel, along with Jenny and the other engineers of the first “skyscrapers.” In the first decades of the 20th century, buildings went from a height of 10 to 20 stories to over 100 stories. To accomplish this, engineering practice shifted from a largely empirical process working with masonry walled structures to one of rigorous mathematics – almost exclusively of frames.

Up until the middle of the last decade of the 19th century, structural calculations for the increasingly taller buildings consisted of the analysis of the frame for each floor separately. In order for the construction to conform to this, each frame had to be very rigidly braced, and constructed with a pin connection at each floor level so as not to transmit bending forces from floor to floor. A more efficient way to design a multi-story frame was invented in the mid-1990’s with the invention of portal frame analysis based on the contraflexure methodology of isolating moments, which is the design methodology for moment frames described above.

This provided the theoretical basis on which the “invention” of the skeleton frame system of construction used for what then came to be called “skyscrapers” in Chicago, and later New York City and San Francisco. This portal frame analysis method was both simple and precise enough for it to have remained in use through the entire 20th century, to the present for the design of most multi-story frame structures over this long era. This method was able to account for the value of the cantilever effects of beams and columns that run from floor to floor and across the building as continuous members with moment connections at the beam/column intersections.

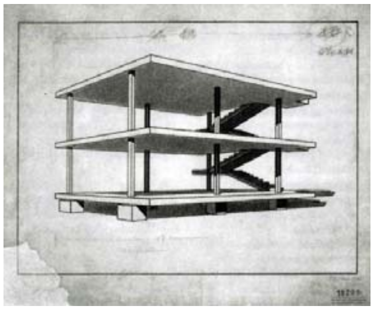
17. Flatiron Building in New York City under construction in 1902 showing the heavy stone masonry façade resting on the steel frame. The upper walls are constructed separately probably to ensure the weight is bearing on the frame rather than the lower masonry walls.

18. View of San Francisco after the 1906 earthquake and fire. The three tall buildings visible in this view were burned out by the fire that followed the earthquake, but all three were in good enough condition despite this to be repaired, and they are still extant today.

Contraflecture portal frame analysis thus made a substantial reduction in the sizes of the members of a frame possible. However, the exterior walls of the first generation of skeleton frame "skyscrapers" continued to be of thick and heavy masonry, in the same tradition as pre-skeleton frame architecture. Although no longer load-bearing to the ground, these walls still shared significant loads with the internal steel frame, as well as protecting the frame from exposure to fire.

Many architectural historians of the early skyscraper era have described the evolution of skeleton frame building design as one almost like that of a genie waiting to come out of the bottle – true transformation could only come when this traditional masonry envelope was shed, and the open frame itself made the basis for the architectural expression with flexible systems of open spaces and moveable walls. The architectural precursor for the liberation of the skeleton frame 'genie' is often identified as Swiss architect Le Corbusier's 1915 drawing of the prototype bare concrete skeleton for multi-story residences known as the Dom-Ino house. It became the icon of what he called the 'New Architecture'. As described by Le Corbusier's contemporary, Sigfried Giedion: "*Corbusier created…a single, indivisible space. The shells fall away between interior and exterior. … There arises…that dematerialization of solid demarcation…that gradually produces the feeling of walking in clouds.*" [13]

Influenced by the Dom-Ino prototype, the reinforced concrete moment frame spread through Europe, and then the rest of the world, including earthquake hazard areas. However, the 'dematerialisation' of the walls clashed directly with the usual enclosure requirements of completed buildings. As a result, masonry did not disappear. Instead, the thick infill walls of the first skyscrapers evolved into thin, weak, and discontinuous membranes while at the same time engineers eliminated the infill masonry from their engineering calculations, except as dead weight.



19. Dom-Ino House by Le Corbusier, 1915. Public Domain

20. Building under construction in Gölcük, Turkey shown after the 1999 earthquake. Because the masonry infill walls had not yet been installed, frame action was able to occur, and thus the building was not collapsed by the earthquake.

21. Building in Gölcük close to the one shown in Fig. 17 collapsed by 1999 earthquake. The heavy masonry infill walls together with open (soft) ground floors were often contributors to such collapses.

This was believed at the time to be a conservative approach, as it was thought the infill walls would add strength over and above that of the frame. However, the rigid and brittle infill walls attracted increased earthquake forces which they were too weak to resist, yet, their weight added significantly to the inertial forces that had to be resisted by the frame. To make matters worse, as described above, these walls interfered with the flexural movement of the structural frame on which the portal frame analysis was predicated. Compounding this problem was the frequent use of open 'piloti' on the ground floor as advocated by Le Corbusier – a classic "soft story" that has become perhaps the single greatest threat to the safety of these buildings. When these conditions are combined with the common construction faults endemic to reinforced concrete construction in particular, which regularly occur especially in developing countries lacking building codes and construction inspection – as is the case in Haiti, then the threshold for collapse can indeed move down the MMI scale to below that of the unreinforced masonry used to calibrate the Modified Mercalli scale.

Concrete construction requires more than just good craftsmanship; it demands a basic understanding of the science of the material itself. The problem is that the builders were often inadequately trained to understand the seismic implications of faults in the construction, thus leaving a looming catastrophe hidden beneath the stucco that was troweled over the rock pockets and exposed rebars that characterize construction done without the equipment necessary to do it properly, such as transit mixers and vibrators.

This methodology of treating the masonry only as part of the "architectural finishes" is also a product of the well-recognized fact that the infill masonry is very difficult to quantify mathematically. It certainly does not fit within portal frame analysis. Outside of earthquake hazard zones, under all but the most severe wind loading, ignoring the effects of the infill rarely leads to a collapse because the value of the load sharing that in reality occurs between the frame and the infill can offset any unaccounted for behavior of the frame resulting from the infill. However, in a design level or greater earthquake the situation is very different. Unlike for wind, a building's structural system is <u>expected</u> to deflect into the nonlinear range, even in code-conforming new building design in Europe and North America. In other words, the underlying structural frame is expected to go inelastic in a design-level earthquake and thus by definition, structural damage occurs. Earthquake codes are intended to reduce the likelihood of collapse, not prevent damage.

22. Reinforced concrete building in central Port-au-Prince nearly collapsed by the 2010 Haiti earthquake.

23. A formerly four story building in Port-au-Prince showing weak story collapse.

For frames, this has been recognized in codes through the use of ductility factors which are assigned based on the individual elements that make up a structural frame. Such factors, however, are unresponsive to the conditions that exist when non-structural infill masonry is added to the system as this masonry is usually a stiff and brittle membrane confined and restrained by the frame. The rigid diagonal strut provided by the masonry changes the behavior of the frame, sometimes with catastrophic results. The standard analysis method for code-conforming design, which is based on linear elastic behavior, is thus remote from the actual inelastic behavior of the infilled frame.

## Then, what is it that saved the *bidonvilles*?

It is this last point that bears more scrutiny. What perhaps can be the difference between the concrete block squatter housing and the more formal buildings? The difference is a subtle one. Indeed it is a difference in degree, rather than in kind. While the survival rate in Cité Eternal was remarkably high, there were areas on the hillsides around Port-au-Prince where there were many collapses, and had the earthquake been stronger than the MMI 7 that it was, more would have collapsed. Nevertheless the study of the Pictometry imagery showed that a vast preponderance of the squatter housing – much of which was of concrete frame and block construction – remained standing.

One plausible answer to the irony of finding vast areas of the informal settlements intact while the downtown was devastated is that most of the slum houses – while of concrete – were not of infill moment frame design even if they were of more than one story. While some of the squatter houses were simply unreinforced concrete block, many were also of a construction known as "confined masonry" where instead of forming and pouring the reinforced concrete frame and then infilling it with the walls, the walls are constructed first, with gaps left for the reinforced concrete columns and then the rebar is inserted and shuttering for the concrete is only needed on two sides of each column, and along the top of the wall for the beam along the edge of the floor slab.

The construction of the formal buildings with the higher frequency of collapse was usually the more conventional method of building and casting the frame first, and then constructing the infill walls. This may sound like a distinction without a difference, but increasingly, it has been observed that confined masonry is less likely to demonstrate catastrophic failure, even when there are conspicuous faults in the construction quality of both the RC frame and masonry. Standard RC frames, by contrast, have proven to be less forgiving.

24. View of 4 Carrefour Feuilles area *bidonville*, close to the city center, Port-au-Prince. © *Pictometry*

The distinction from an engineering viewpoint is that the framework in the “confined masonry” system is never meant to behave as a moment frame in the first place. Indeed, these buildings are not even the product of an engineering analysis or calculations. The buildings behave as a solid wall structures. With their small rooms, there are sufficient numbers of walls to provide redundancy. Also, even more important, the multi-story *bidonville* buildings are less likely to suffer from soft story the because the confined masonry system is predicated on the building of the masonry walls first. Thus they cannot be left out at the ground floor level – so a soft or weak story collapse is ruled out.

Thus these buildings are in fact more related in terms of structural typology to the pre-modern timber and masonry buildings that were of the vintage of those originally used to calibrate the Mercalli Scale. More importantly, their indigenous self-help based socio-economic context is also much closer to pre-modern rural culture than it is to the wealthier industrialized urban context where the moment frame with infill construction is more common.

25. *left,* View of 4 Carrefour Feuilles area *bidonville*, close to the city center, Port-au-Prince. *Source: Carlos Barria-Reuters Right*, Confined masonry construction photographed in Zihujatanejo, Mexico.

In fact, there are three historical buildings in central Port-au-Prince that helps to reinforced this finding about the informal construction.  Better than that, they stand as remarkable examples of a hitherto unexplored direction for future earthquake-resistant construction – even as a potential model perhaps of a better approach to reinforced concrete.  The largest of these buildings is as high as the National Cathedral was before its collapse, and almost as large.  It is older, now approximately a century in age, and yet it came through the earthquake with no visible exterior damage apart from broken glass in its large upper story windows.  It is church called the Saint Louis de Gonzague Chapel (figure 26).

26.  Saint Louis de Gonzague Chapel ca. 1890 in central Port-au-Prince.

This church is constructed of load bearing masonry surrounded and embraced by lightweight riveted flat steel bars and angles imported from France that forms a cage which is an integral part of the elegant architectural detailing of the building. In the earthquake, it served to hold it together – much like confined masonry. Unlike standard reinforced concrete or reinforced masonry construction, the reinforcing is not hidden on the inside of the wall except for connector pieces from the exterior to the interior. It is exposed as part of the architecture on both the inside and the outside. It forms a framework, the the structural system is not a frame. The structural system is primarily that of a solid load-bearing masonry wall, with confinement by the steel, which in the earthquake served to prevent any apparent disruption of the masonry.

This good performance was confirmed not only with the Chapel, but also at a smaller chapel next to the collapsed National Cathedral which also came through almost unscathed, and a commercial building also near the National Palace which had thinner walls but survived with only a few missing panels.

These buildings merit further study that was not able to be done at the time of the WMF mission to Haiti, but they, especially the Chapel because of its size, stand as icons proving that with earlier construction technology, and a more limited pallet of materials at their disposal, the means was there in Haiti to build large complex structures that, unike their contemporaneous reinforced concrete neighbors, the National Palace and Cathedral, could last over 100 years, and then still be able to face the onslaught of an earthquake that felled as much as 30 to 50 percent of the buildings around them – including both school buildings also constructed by the Freres de l'Instruction Chretienne (F.I.C) (Brothers of Christian Instruction) and hundreds of buildings of much more recent vintage.

## Conclusion

Ultimately the point of this paper is not about whether the body count from the earthquake is 80,000 or over 300,000. Either number constitutes and enormous tragedy. The paper is really about the fact it is unacceptable, even scandalous, how many buildings of recent origin and of formal design and construction with structural systems in wide use around the world today have collapsed onto their occupants. These were buildings perceived by most as stronger and more resistant to earthquake collapse than were older timber and masonry buildings – and certainly were perceived to be better and stronger than the tens of thousands of informal dwellings on the hillsides that surrounded Port-au-Prince.

The analysis of the MMI intensity also serves to add an even more disturbing detail. Based on the findings that the intensity in Port-au-Prince is as low as an MMI-VII, one must ask what would happen if it were higher. In fact, EQECAT, another catastrophic risk modeling company, only two days after the 2010 earthquake issued the following warning:

> *Had the rupture been directed toward Port-au-Prince, the city would have experienced even more devastation. While this is little solace in light of such a human tragedy, it is relevant considering that this earthquake, which ruptured only a portion of the fault, increases the chances of another large earthquake in coming decades on the eastern portion of the same fault. This is because stress relieved by a rupture is transferred to adjacent segments of the fault. If additional stress on the eastern segment of this fault were to trigger another*

> *earthquake, it could impact Port-au-Prince with equal or greater severity as the recent event.*[11]

One of the problems that plague the assessment of existing buildings, and the archaic structural systems used for non-engineered buildings, is the basic difficulty of establishing a norm for earthquake safety and performance when "no damage" is neither a viable or cost effective objective, nor is required by the building code. With wind, for example, one uses real expected maximum wind speeds with an added safety factor. With earthquakes, however, it has been determined that to require all buildings to remain within their elastic range for design-level earthquakes is economically infeasible. Earthquakes of a damaging magnitude are simply too infrequent to justify the more stringent objective.

This problem is not just academic; it is integrally connected to the longer-term issues of post-disaster recovery and regional development. Modern construction materials and methods have brought with them extraordinary opportunities for new architectural forms and ways of building. Reinforced concrete frame and concrete block construction has been promoted to the local populations as safe and modern. However, in many parts of the world they have also been disruptive of local culture, resulting in building forms and ways of building that are alien to the local society – particularly long-held traditions of self reliance that comes from the mastery of traditional crafts of carpentry and masonry.

The finding that the historic and deteriorated 100 year old timber and masonry buildings as well as the more recent concrete frame and block buildings in the informal *bidonville* settlements in Haiti on average have done better than the formal reinforced concrete buildings of the city center does not mean that the aging heritage structures or the shantytown buildings are acceptably safe, but only that the formal buildings are unacceptably dangerous. What the informal buildings also show is that the correction to this problem may not be in moving to even more sophisticated and complex engineering solutions – but rather towards simpler forms of construction based on the kind of flexibility, redundancy and energy dissipation that is the only means available for earthquake resistance in informal owner-built construction.

The *bidonville* settlements are part of a long tradition in the history of human settlements and building construction. The buildings found there are crude and unsophisticated, and certainly not engineered, but the way to improving them and the rest of the buildings in Haiti in the city center and elsewhere must be derived from working within a crafts tradition, rather than imposing engineering and high-tech standards and requirements that are rarely going to be followed because they are not understood. This then mandates a return to many traditional construction practices that need to be rehabilitated in peoples' minds, after years of associating them with backwardness and un-modern ways of living. In other words, when it comes to building construction, traditional IS modern.

It also requires a certain amount of humility and willingness to learn to listen with our eyes to the message our ancestors are telling us through the cultural artifacts they have left behind. As the world moves from an era of profligate energy use to one where fossil fuels are gradually depleted, sustainability and green have become the catchwords in building design and construction. Wood is nature's most versatile renewable building material. Stone and unfired earth, together with wood, represent the most energy efficient materials that can be used. To this can be added fired brick and lime mortar, which require far less energy to manufacture than Portland cement. Thus finding traditional vernacular construction practices that have performed well against one of the strongest forces that nature can throw at structures also can serve to provide a lens through which to see that the preservation of vernacular buildings represents far more than the saving of frozen artifacts. It is an opportunity for cultural regeneration—a reconnection with a way of building by people who traditionally had learned how to build successfully for themselves with materials readily at hand.

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27. A Port-au-Prince house of colombage construction showing slight earthquake damage behind the rubble pile of a collapsed reinforced concrete building.

## FOOTNOTES

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[1] It is hard to imagine how the Haiti earthquake could have been worse, but the second EQECAT report on this earthquake predicts that another one is a possibility. See the quote by EQECAT on p20 below.

[2] http://www.unitar.org/unosat/node/44/1425

[3] RMS FAQ: 2010 Haiti Earthquake and Caribbean Earthquake Risk, http://www.rms.com/publications/Haiti_Earthquake_FAQ.pdf & "Haiti Dominates Earthquake Fatalities in 2010" Released: 1/11/2011 12:44:35 PM, http://www.usgs.gov/newsroom/article.asp?ID=2679#.UGn8wE3A_nh

[4] Canadian Broadcasting Corporation news report on 1st anniversary of the earthquake.

[5] The difference between the maps prior to version 7 is that the fault was first mapped further to the north, under the waters of the bay (thus the fears at first of a tsunami) and later it was found to be under the land, while the later map version 10 shows the fracture zone as not extending as far east as it does in version 7, explaining the drop in estimated intensity in Port-au-Prince.

[6] Geologist Ellen Rathje of the University of Texas does see some evidence of site effects, but it is inconclusive as an explanation for such extreme differences in building performance between two adjacent structures only 175 feet away from each other.

[7] There is even a widespread perception that the shaking in Port-au-Prince was an even more extreme "10" on the MMI scale, as reported on several internet sites, including Wikipedia.

[8] http://en.wikipedia.org/wiki/Casualties_of_the_2010_Haiti_earthquake

[9] Wikipedia

[10] Source: www.propertyrisk.com

[11] http://www.eqecat.com/catwatch/m-7-0-earthquake-in-haiti-region-update-2010-01-14/ EQECAT notes that the fault rupture zone was to the west of the city, leaving the unruptured segment beneath Port-au-Prince, as shown in the version 10 of the USGS shakemap.