THE HAITI EARTHQUAKE OF 12 JANUARY 2010

A FIELD REPORT BY EEFIT

EEFIT

The Haiti earthquake of 12 January 2010

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1.0 SUMMARY

The Haiti earthquake of 12th January 2010 was one of the most devastating in terms of human impact in recorded history. A shallow event of moment magnitude $M_w = 7$ centred near the capital of Haiti, Port-au-Prince, it caused at least 150,000 deaths, and rendered many more homeless; 15 months after the earthquake, 1.5 million people were still living in tented communities.

A small EEFIT team consisting of a structural engineer, a geotechnical engineer and a remote sensing specialist visited Port-au-Prince three months after the earthquake, staying for a week. Its objectives were much more limited than for most previous EEFIT missions, with the focus on comparing damage assessments made from remote images (i.e. photos taken from planes or satellites) with assessments made from the ground. This was in the context of an unprecedented use having been made of remote images to assist the vital task of assessing Haiti's enormous need for post-disaster aid and reconstruction. The EEFIT team made ground assessments of the damage to 142 buildings in Port-au-Prince; damage ratings were also available for all these buildings from both from high resolution vertical images in the GEO-CAN II international exercise, and from the more accurate technique of using oblique angle (Pictometry) images. It was found that the number of buildings assigned by remote assessment as partially or totally collapsed was a factor of 1.5 to 2 times lower than the EEFIT ground assessments. Although the sample size was too small for statistical significance, this was the first exercise in which ground and remote assessments of damage have been compared in detail. It enabled the circumstances in which remote assessments both under- and over- estimated damage to be examined in detail, and will assist the process of improving the accuracy of future remote assessments. A searchable archive of photos of all 142 buildings included in EEFIT's survey will be mounted on the EEFIT website, with damage descriptions and exact geographical locations.

Other objectives were pursued as well, although in a less systematic way. A limited study was made of the distribution of damage in Port-au-Prince, which appeared to be clustered, with pockets of near total destruction adjoining areas of low damage. This clustering was observed in steep rocky areas, as well as on alluvial plains, and may have been associated with the type of rock underlying the site in ways which do not appear to have been described previously. The extensive liquefaction, which crippled the main port of Port-au-Prince, was also studied in some detail and liquefaction effects outside the capital were observed. Notes on the observed performance of building and bridge structures have also been included in the report; masonry buildings performed poorly, including confined masonry for which EEFIT collected no evidence of an improved performance compared to unreinforced masonry or concrete frame with masonry infill, although other reports suggest otherwise. There were very few reinforced concrete buildings over five storeys; some collapsed, but it was reported that a few modern buildings of this type performed very well, although EEFIT made no inspections. Historic timber buildings generally performed quite well, and a historic cast and wrought iron market building also seems to have been little affected by the ground shaking, although it was damaged by the collapse of adjacent structures, and by fire.

A number of recommendations emerged for future EEFIT missions, including the usefulness of a security plan prepared before departure, and of posting a team blog during the mission.

2.0 THE EEFIT MISSION: BACKGROUND, OBJECTIVES AND ORGANISATION

2.1 Introduction

The magnitude 7 earthquake which struck Haiti on 12th January 2010 at 4.53pm local time has proved to be one of the most destructive recorded; at least 150,000 people are thought to have been killed, and possibly many more, although a universally accepted total has not been established. The pressing humanitarian needs in a region where transportation links had been seriously affected, and concerns about the security situation when official advice was that only essential travel to the country should be undertaken, were the two special factors which led to a long debate within EEFIT on whether an EEFIT mission was justified.

The decision to mount a mission was taken on the following basis.

1) The main thrust of the mission should be narrowly focussed on comparing ground assessments of damage with remote assessments made from aerial and satellite images.
2) There would be no attempt to gain a broad, comprehensive view of the earthquake's effects; this exercise was undertaken by other organisations, in particular by the EERI[1] and GEER teams from the USA.
3) The standard EEFIT objective for missions to train less experienced engineers was not appropriate for this mission, and a small team of experienced engineers would be chosen.
4) Appropriate measures would be taken in view of the special security situation in Port-au-Prince.

2.2 The EEFIT team composition and itinerary

A three person mission was chosen to go, as follows.

Edmund Booth - structural engineer – team leader (consulting engineer)

Keiko Saito - remote sensing specialist (Willis Research Network Fellow, University of Cambridge, UK)

Gopal Madabhushi - geotechnical engineer – (reader, Department of Engineering Soils Group, University of Cambridge)

The team arrived in Port-au-Prince on 7th April 2010, nearly three months after the earthquake occurred. Madabhushi left on 12th April and Booth and Saito on 13th April, so the team spent a total of 5 ½ days collecting field data. Most of that time was spent in Port-au-Prince, conducting surveys at the nine locations described in detail in Section 6.0. One day was spent travelling to the west of the capital, following the route shown in Figure 2.1.

[1] Acronyms are defined in Appendix D.

Figure 2.1: Route followed by EEFIT team on 10th April 2010

2.3 Mission objectives

The following mission objectives were formulated before the team left for Haiti.

a) General Objective

1. Furthering the interpretation and use of aerial and satellite imagery for post-earthquake disaster management and recovery by ground-truthing assessments in identified areas.

2. Complementing the international effort of evaluating the lessons for civil and structural engineers arising from the Haiti earthquake, and reporting the associated findings widely to the engineering and disaster relief and management community.

3. Within these objectives, assisting with international efforts to aid recovery in Haiti.

b) Mission Specific Objectives

1. Improvement of structural damage assessment from aerial and satellite imagery for buildings, bridges, ports and other items of civic infrastructure. Assessment of significant damage levels lower than partial or total collapse will be of particular concern, since they are currently hard to assess from satellite or aerial imagery. This will be done by 'ground truthing'.

2. Correlation of structural damage levels with geotechnical features, including surface geometry and topography. The team will investigate basin effects (e.g. how deep are the sediments in different parts of the basin) and seek to establish whether these relate to damage statistics.

3. Field investigation of geotechnical failures (slope instability, liquefaction) previously identified from aerial imagery and with particular reference to ports and bridges.

4. Investigation of damage levels in areas of Port-au-Prince not covered by previous investigation teams. The team will attempt to visit the areas around Léogane where the severity of ground motion and damage appears to have been even more extensive than in Port-au-Prince.

5. Assessment of lessons for post disaster management and preparedness, particularly in relation to areas connected with civil/structural engineering content (shelter and infrastructure). Use of aerial and satellite imagery for these purposes will be of particular interest.

6. Comparison of the findings in all these fields with those obtained by the EEFIT Chile team. In the event, this objective was not addressed, because of time pressures.

2.4 Security preparations

A risk assessment and security plan was drawn up before departure, attached as Appendix A.

The three team members attended a one day security briefing on Haiti, organised by RedR. Although in most respects, the security situation in Port-au-Prince was found to be much better than expected, these security preparations were found in the field to be valuable, and similar measures should be considered as standard for future EEFIT missions, where appropriate.

2.5 Blog

The team posted a blog during their stay in Port-au-Prince, which was kept updated daily. This served to keep family and colleagues informed of the team's safety at a time of some anxiety, and was also valued by the team as a way of expressing and reflecting on their experiences. It had significant professional benefits, too; writing down their findings and first technical impressions added to the team's technical effectiveness, and allowed immediate technical feedback from colleagues in the UK. It is recommended that blogs should become a standard part of future EEFIT missions, wherever possible. The blog is shown in Appendix B.

2.6 International co-operation

Before departure, the team had a number of useful conversations with Professor Reginald DesRoches, leader of the EERI mission to Haiti, and with Professor Ellen Rathje, leader of the US GEER team to Haiti. Negotiations took place with the chair of the French AFPS mission team, and an agreement in principle was taken to mount a joint mission; however, AFPS in the end decided to postpone their mission until after April, mainly for security reasons.

2.7 Dissemination of findings

The team presented their findings in a meeting organised by EEFIT on 11th May 2011, and have subsequently made a number of other presentations in the UK and elsewhere. This report forms the main written dissemination of the team's findings; Appendix C lists other papers prepared by the team on the earthquake.

An open access searchable, referenced archive of photos of the 142 buildings surveyed by the team on the EEFIT website is being mounted on the EEFIT website. Each photo is linked to a unique building number, and the geographical references of all the buildings, and the damage grade and description assigned by the team is also included.

3.0 SEISMOLOGICAL AND GEOLOGICAL CHARACTERISTICS

3.1 Introduction

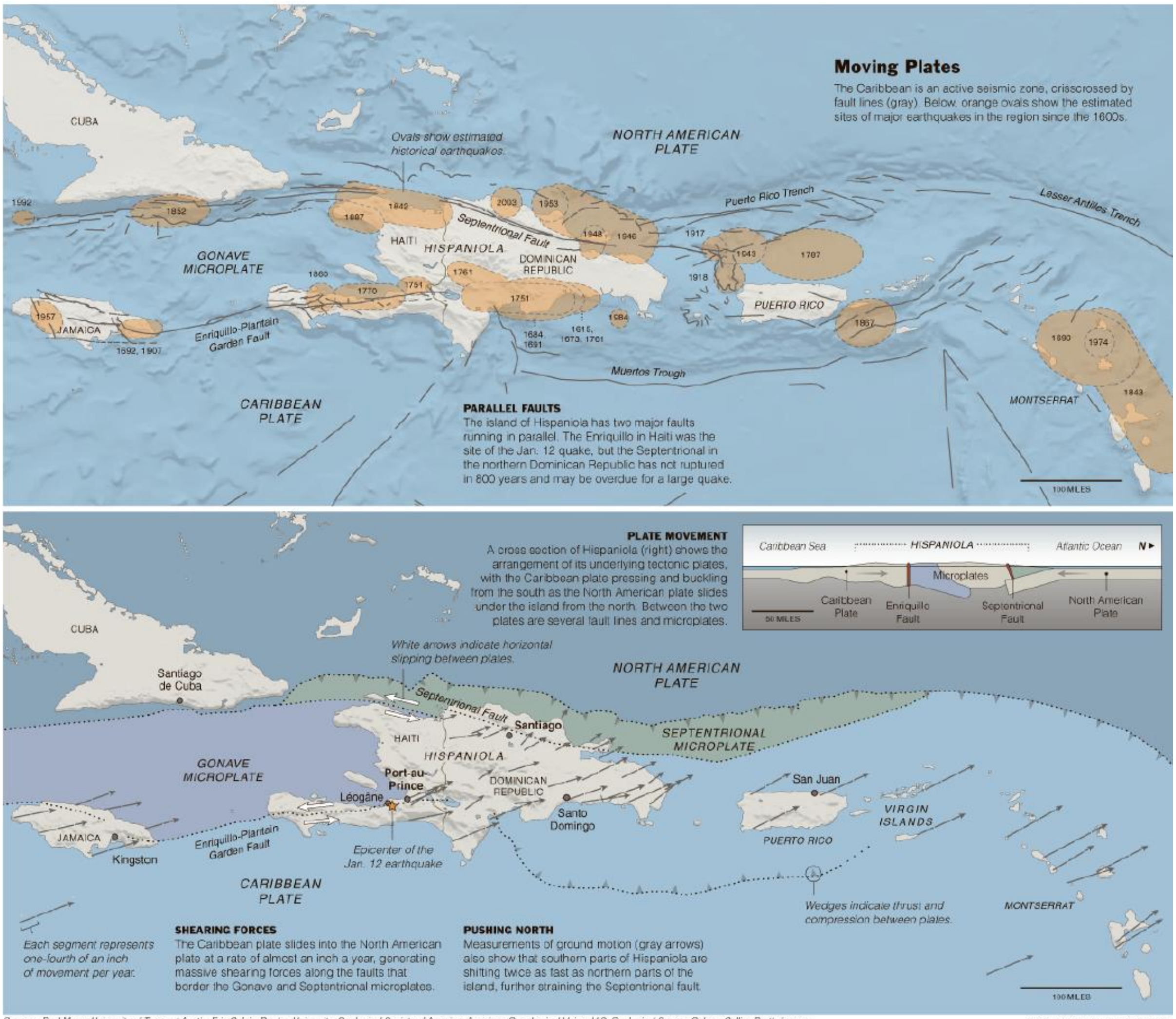
The 12th January 2010 Haiti earthquake had a moment magnitude M_W of 7.0. It occurred at the local time of 4.53pm. The epicentre of the earthquake was identified at approximately 25 km west of Port-au-Prince.

In this chapter the seismological aspects and geological characteristics are presented. The location of the epicentre of the main event relative to the capital city of Port-au-Prince is shown in Figure 3.1 approximately located at 18.451N, 72.445W. The focal depth of the event was determined by USGS to be 10 km.

Figure 3.1: Epicentre of the 12th January 2010 earthquake

3.2 Seismological aspects

The island of Hispaniola is located on a separate microplate bounded on the north by the Great Puerto Rican/North Hispanola subduction zone and trans-tensional strike-slip faults (Oriente-Septentrional Fault) that define the boundary between the North American and Caribbean plates, and the Muertos trench subduction zone and strike-slip Enriquillo-Plaintain Garden Fault Zone (EPGFZ) that define the plate interface between the microplate and Caribbean plate (Figure 3.2). The earthquake was initially presumed to have occurred on the Enriquillo-Plantain Garden Fault Zone (EPGFZ), a left-lateral, strike-slip fault with relative horizontal displacement of approximately 7 mm/yr (Figure 3.2). Large earthquakes have not occurred recently on the EPGFZ, but historical records indicate that Port-au-Prince was destroyed by earthquakes in both 1751 and 1770. These events are believed to have occurred on the EPGFZ, which shows clear evidence of geologically recent tectonic movement (Section 3.4). The general distribution of damage and distribution of aftershocks are also consistent with the earthquake having occurred on the EPGFZ. The contrary evidence is that although the EPGFZ is a strike slip fault, it appears the fault mechanism has been identified as left-lateral/oblique. Also, the coastal uplift noted in section 3.6 appears inconsistent in position with fault movement on the EPGFZ. Also, as discussed in section 3.5, no surface expression of fault movement was found on the EPGFZ (or elsewhere), although the EPGFZ evidently did break the surface in previous earthquakes. For further discussion, see the GEER report (Rathje *et al,* 2010).



Sources: Paul Mann, University of Texas at Austin; Eric Calais, Purdue University; Geological Society of America; American Geophysical Union; U.S. Geological Survey; Gebco; Collins Bartholomew — JONATHAN CORUM/THE NEW YORK TIMES

Figure 3.2: Historical earthquakes and fault zones in the region around the island of Hispaniola (New York Times, January 26, 2010)

No near-field strong motion recordings were obtained from the main event, but instrumentation laid out by USGS and other agencies in areas surrounding Port-au-Prince captured aftershocks. Aftershocks for the first 10 days after the earthquake are plotted in Figure 3.3, which also shows the contours of slip along the Enriquillo Plantain Garden Fault, as estimated by Caltech. The aftershocks seem to cluster around Petit Goave which interestingly also had liquefaction induced damage (see Chapter 4.0).

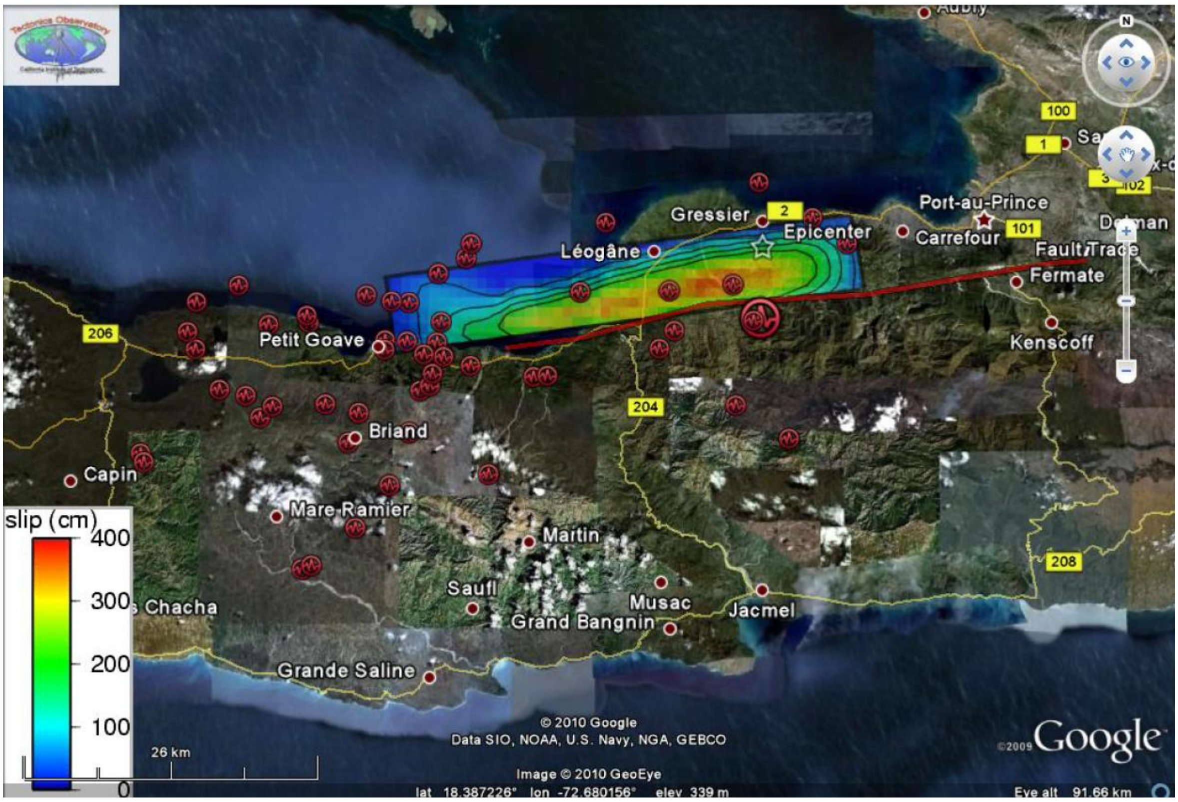


Figure 3.3: Aftershock distribution for the 2010 Haiti earthquake through 21 January 2010 (from USGS), along with slip inversion by Caltech

3.3 Ground motion intensity

The high seismic hazard in Port-au-Prince was widely recognised before the earthquake; see for example Figure 3.4. However, since no near-field strong motion records were obtained for this earthquake, the ground motion intensity must either be inferred from the observed damage or be estimated from the earthquake magnitude and distance, using ground motion prediction equations. The USGS have produced a shaking intensity map (Figure 3.5) from the USGS software ShakeMap, which uses both these methods. Thus, Figure 3.5 combines direct observations of damage based on rapid telephone surveys made in the immediate aftermath of the earthquake with information about local geology, earthquake location and magnitude to estimate shaking variations throughout Haiti. In this Figure it can be seen that the regions surrounding Port-au-Prince are marked as having received ‘extensive shaking’ and would have suffered ‘very heavy damage’.

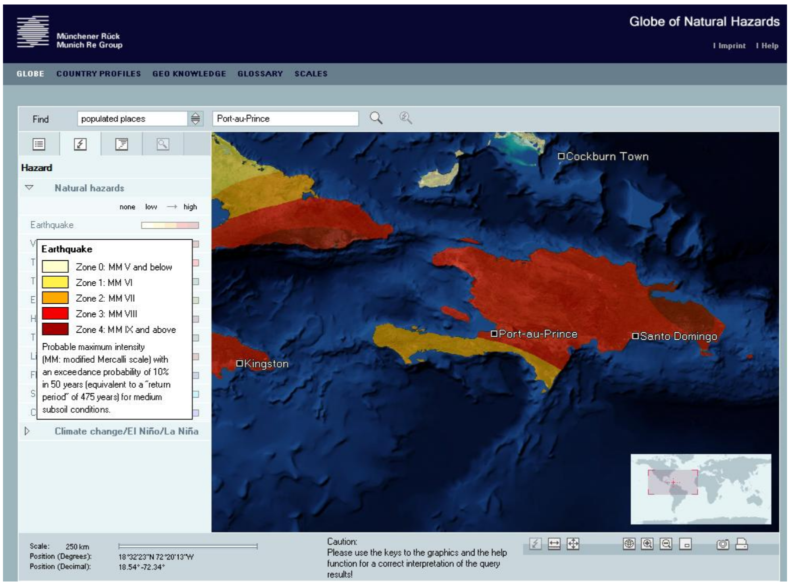
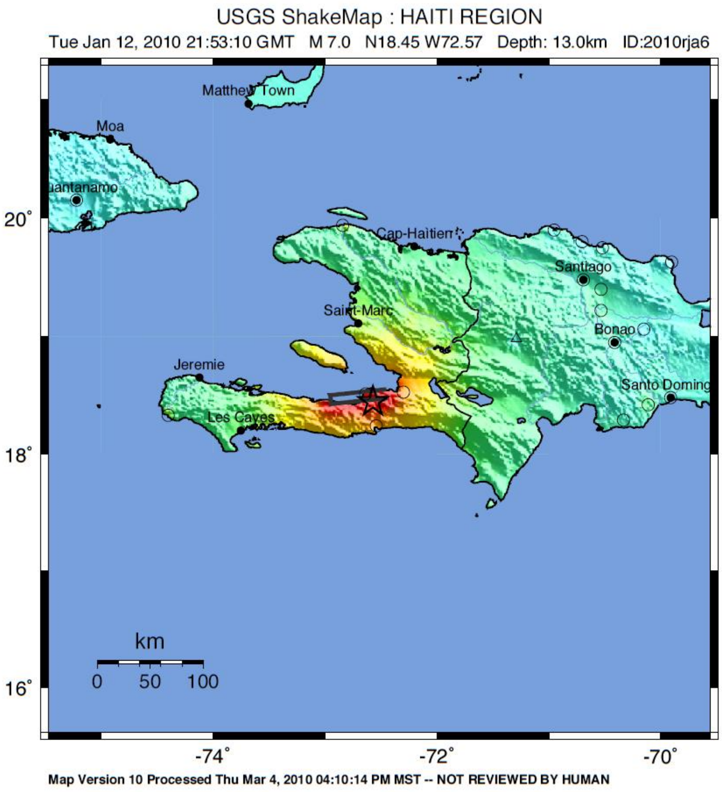


Figure 3.4: Seismic hazard map of Hispaniola
From the Munich Re Globe of Natural Hazards, 2009



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3.5: USGS ShakeMap showing contours of inferred shaking intensity from the Haiti Earthquake of 2010
http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2010rja6/

3.4 Geological aspects

The causative fault of the earthquake has not been definitively established (Section 3.2). It may have been associated with the major fault zone of the region, the Enriquillo-Plantain Garden fault zone (EPGFZ), a major tectonic element with a sustained history of deformation and slip. The fault traces roughly west-east along the north portion of the southern Haiti peninsula and has exerted a substantial topographic/geomorphic influence since the Tertiary period. Quaternary displacement along the fault has formed a classic strike slip fault geomorphology including linear valleys and bounding uplifted mountains, shutter ridges, sag ponds, and elliptical basins at extensional stepovers and bends along the fault trace. Some stream reaches, such as within the deep valley of the Frorse and Momance rivers that follows the EPGFZ trace, are apparently the result of both stream capture by recent displacements along the fault and preferred incision along sheared and locally weaker rocks along the fault zone. An example of this is presented in Figure 3.9 and is discussed later.

The earthquake-affected region is an area of diverse physical geography that has undergone a complex geologic history of intrusion, tectonic activity, erosion, and sedimentation. The topography is relatively rugged, with steep mountain ranges and hill fronts, deeply incised streams and narrow intermountain stream valleys, and broad coastal delta fans and valleys. Figure 3.6 is a geologic map of the earthquake epicentral area. A more detailed map for the Port-au-Prince bay area is presented in Figure 3.7. These maps show the central mountainous core of the southern peninsula to be locally underlain by metamorphosed Cretaceous basalt/mafic volcanic basement, and Cretaceous-Eocene limestone, conglomerate, and clastic sedimentary rocks. An east-west trending band of Miocene and Mio-Pliocene sedimentary rock (including flysch, siltstone, shale, sandstone) occurs along the coast and southern margin of the Port-au-Prince alluvial valley. Contacts between the Miocene and Mio-Pliocene units are commonly faulted, and folds and faults have deformed the Mio-Pliocene bedrock in response to a regional northeast-southwest compression, oblique to the trend of the strike-slip motion along the EPGFZ fault. Further information is given by Rathje *et al* (2011).

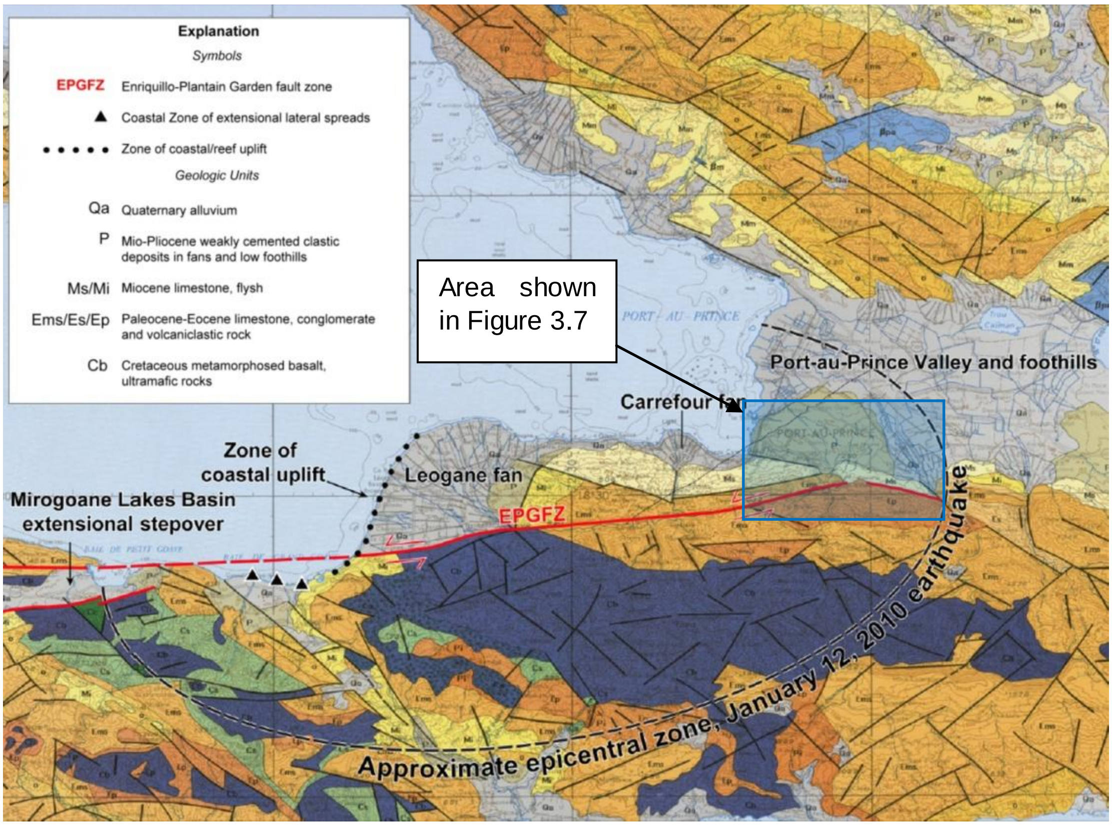


Figure 3.6: Geological map of the epicentral region, showing faulting (Lambert *et al,* 1987, modified by Rathje *et al* 2010)

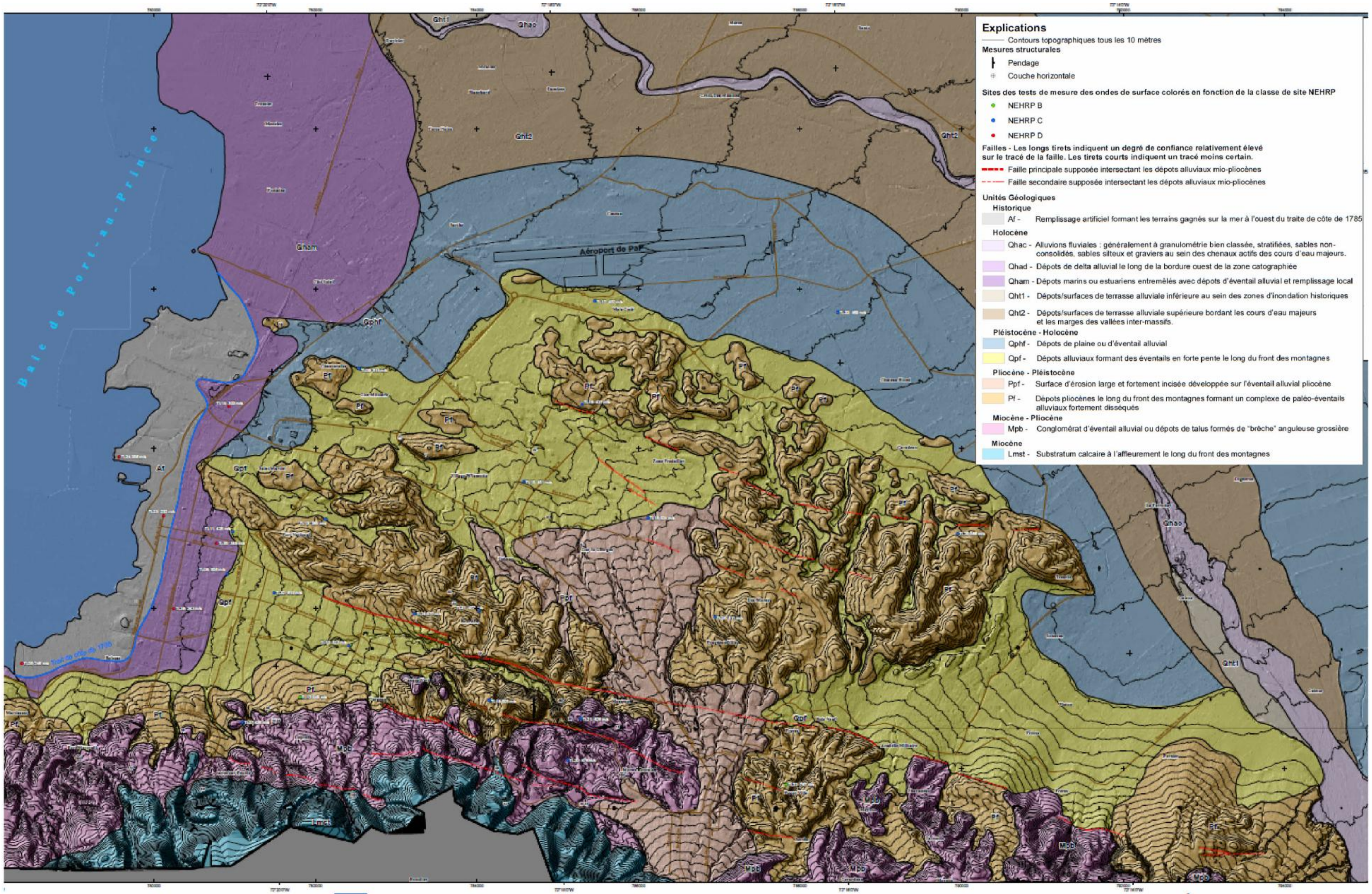


Figure 3.7: Geological map of the Port-au-Prince region (Bachuber *et al*, 2010)
See Figure 3.8 for translation of legend

Explications

Contours topographiques tous les 10 mètres

Mesures structurales

Pendage

Couche horizontale

Sites des tests de mesure des ondes de surface colorés en fonction de la classe de site NEHRP

NEHRP B

NEHRP C

NEHRP D

Failles - Les longs tirets indiquent un degré de confiance relativement élevé sur le tracé de la faille. Les tirets courts indiquent un tracé moins certain.

Faille principale supposée intersectant les dépots alluviaux mio-pliocènes

Faille secondaire supposée intersectant les dépots alluviaux mio-pliocènes

Unités Géologiques

Historique

Af - Remplissage artificiel formant les terrains gagnés sur la mer à l'ouest du traite de côte de 1785

Holocène

Qhac - Alluvions fluviales : généralement à granulométrie bien classée, stratifiées, sables non-consolidés, sables silteux et graviers au sein des chenaux actifs des cours d'eau majeurs.

Qhad - Dépots de delta alluvial le long de la bordure ouest de la zone catographiée

Qham - Dépots marins ou estuariens entremêlés avec dépots d'éventail alluvial et remplissage local

Qht1 - Dépots/surfaces de terrasse alluviale inférieure au sein des zones d'inondation historiques

Qht2 - Dépots/surfaces de terrasse alluviale supérieure bordant les cours d'eau majeurs et les marges des vallées inter-massifs.

Pléistocène - Holocène

Qphf - Dépots de plaine ou d'éventail alluvial

Qpf - Dépots alluviaux formant des éventails en forte pente le long du front des montagnes

Pliocène - Pléistocène

Ppf - Surface d'érosion large et fortement incisée développée sur l'éventail alluvial pliocène

Pf - Dépots pliocènes le long du front des montagnes formant un complexe de paléo-éventails alluviaux fortement disséqués

Miocène - Pliocène

Mpb - Conglomérat d'éventail alluvial ou dépots de talus formés de "brêche" anguleuse grossière

Miocène

Lmst - Substratum calcaire à l'affleurement le long du front des montagnes

Legend

Topographic contours at 10 meter intervals

Structural measurements

Angle of dip

Horizontal slope

Sites where V_s was measured, coloured with NEHRP classification

NEHRP B

NEHRP C

NEHRP D

Faults. The long dashes indicate relatively high confidence in location, the short dashes indicate less certainty

Principal inferred fault intersecting mio-pliocene alluvial deposits

Secondary inferred fault intersecting mio-pliocene alluvial deposits

Geological units

Af – Reclamation forming land won from the sea to the west of the shoreline of 1785

Qhac – Fluvial, generally well graded, stratified, non consolidated silty sands and gravels within the active beds of rivers

Qhad- alluvial delta deposits along the western border of the mapped zone

Qham – Marine and estuarial deposits mingled with alluvial fans and local fill

Qh1- Deposits/lower surfaces of alluvial terraces within historical flood zones

Qh2- Deposits/upper surfaces of alluvial terraces next to major water courses and the edges of inter-massif valleys

Qphf – Plain deposits or alluvial fans

Qpf – Alluvial deposits forming steeply sloping fans along mountain edges

Ppf – Large and heavily incised erosion surface formed on Pliocene alluvial fans

Pf – Pliocene deposits along the edge of mountains forming a complex of strongly dissected alluvial paleo-fans

Mpb – Conglomerate of alluvial fans or deposits of banks formed of coarse angular breccia

Lmst – Calcareous substratum levelled along the edge of mountains

Figure 3.8: Translation of legend, geological map of the Port-au-Prince region (Figure 3.7)

3.5 Fault rupture

The EEFIT team did not attempt an extensive survey to determine whether there was a surface expression of the fault rupture from the January 2010 earthquake. However, the GEER team from the USA have done a more thorough and extensive survey of the EPGFZ following the earthquake (Rathje *et al* 2010). For example they traced this fault close to the Momance river basin as shown in Figure 3.9. The overall conclusion of the GEER team was that there was no surface fault rupture arising from this earthquake.

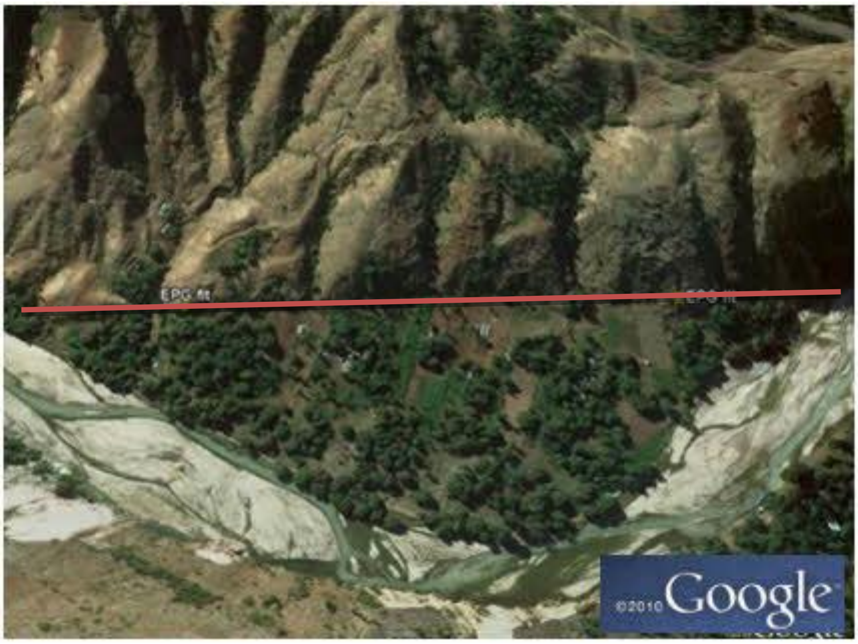


Figure 3.9: View south of prominent fault scarp crossing fluvial terrace on Momance River

Failures of the road surface were noted by the EEFIT team when travelling between Léogane and L'acul (Figure 3.10). Initially, these were thought to be evidence of a surface fault expression. However, other explanations are possible, and the GEER report (Rathje *et al* 2010) specifically rejects this possibility. The failures may have been due to the slope failure of the sides of the embankment leading to longitudinal cracks on the road surface.

Figure 3.10: Road failure at two locations of the road between Léogane and L'acul

3.6 Coastal uplift

Uplift represents evidence of broad, vertical crustal movements associated with fault rupture, and thus observations of coastal uplift help confirm the focal mechanism and slip distributions inferred from teleseismic data. The GEER team (Rathje *et al* 2010) interpreted the aerial imagery and reports from Haitians in the coastal area of Léogâne and found that several areas along the coast were uplifted as a result of the 12 January earthquake.

The EEFIT team visited a site near L'acul to observe the coastal uplift caused by the 12 January 2010 earthquake. Additionally the GEER team (Rathje *et al* 2010) observed coastal uplift at the Ca Ira area, west of Léogâne.

At the site near L'acul, coastal uplift was identified based on aerial images as shown in Figure 3.11. The local residents confirmed that the corals at this site were not exposed prior to the 12 January earthquake. However in Figures 3.12 and 3.13 the exposed corals can be clearly seen. The close up view of the coral in Figure 3.13 indicates that the coral has died as it was exposed to direct sunlight and dried following the coastal uplift caused by the earthquake.

Figure 3.11: An aerial view of the coastal uplift near L'acul

Figure 3.12: Exposed coral near L'acul

Figure 3.13: A close-up view of the coral that died due to coastal uplift

4.0 LIQUEFACTION

4.1 Introduction

Soil liquefaction may occur in loose, saturated sandy or silty soils that are subjected to cyclic loading as in the case of earthquakes. A wide variety of phenomena such as sand boils, mud volcanoes, cracking and piping of soil strata, and lateral spreading of sloping ground may occur as a result of liquefaction. In all these cases, the shear strength and stiffness of the soil is severely degraded during liquefaction. As a result civil engineering structures that are situated on such liquefied soils can suffer severe foundation movements that may cause damage or even complete collapse.

During the Haiti earthquake of 12th January 2010, soil liquefaction was observed at several locations. The most prominent site was the main port facility in Port-au-Prince which suffered extensive liquefaction induced damage. This will be discussed in sections 4.2 to 4.5. There was a very important consequence of liquefaction at the port facility in this earthquake. Due to loss of the main pier and wharf facilities, collapse of gantry cranes, and damage to storage spaces, the port became inoperable in the immediate aftermath of the earthquake. This meant that emergency relief supplies could not arrive in Port-au-Prince for a prolonged period after the earthquake. Relief aid could only be transported by air and this formed a bottle neck due to the single runway and the volume of flights coming in. Even at the time of the EEFIT visit, 3 months after the earthquake, the port was only functioning partially and only due to the floating pontoons brought in by the US Navy to facilitate the transportation of bulk materials required for relief aid and reconstruction. The damage to the port facility at Haiti offers a very good example of the importance of such facilities in seismic regions in providing post earthquake emergency response. Therefore, their design needs to ensure they can survive the effects of strong shaking, including liquefaction to which port facilities are particularly prone.

Liquefaction induced damage was also observed at other locations. The EEFIT team visited one such location near Grand Goave (Section 4.6).

4.2 Imaging of the liquefaction damage at the port facility

4.2.1 *Satellite imagery*

The extensive soil liquefaction that occurred at the port and the associated damage to port structures such as piers and wharves was investigated by the EEFIT team prior to the site visit using remote imagery, in addition to the ground truthing *in situ*. In Figures 4.1 and 4.2 the pre- and post-earthquake satellite images of the Haiti port are presented. Comparing these two figures it can be seen that the south pier has lost several sections and the north wharf has completely collapsed leaving the gantry crane in the water. These two main areas of damage are ringed in red in Figure 4.2.

Figure 4.1: Pre-earthquake satellite image of the port facility (26th August 2009)

Figure 4.2: Post-earthquake satellite image of the port facility (13th January 2010)

In addition to the ringed areas above there was other damage, such as settlement of the island that housed the harbour master's building and control facilities. The damage to this island and the bridge connecting it to the south wharf is discussed in section 4.4.

4.2.2 Pictometry images

Pictometry images offer a better 3-D perspective than vertical aerial images as they comprise oblique angle as well as vertical views. Pictometry images are further discussed in Section 6.4.

In Figure 4.3 the Pictometry image of the overview of the south pier and the island is presented. Comparing this with Figure 4.2 it can be seen Pictometry images have much higher resolution. The collapsed section of the pier is also seen on the left hand edge of this Figure. The Pictometry images were taken some time after the earthquake and therefore show the floating pontoons brought in the US Navy, which are helping unload the containers onto the intact section of the south pier.

Figure 4.3: A Pictometry image of the overview of the south pier and the island (February 2010)

In Figure 4.4 a Pictometry image of the north wharf is presented. The collapsed north wharf is clearly seen in this Figure. Also the damage to the gantry crane is clearly seen. These correspond to the red rectangular area marked in Figure 4.2 in which the satellite image showed the same damage. Comparing Figs. 4.2 and 4.4 it can be seen that the Pictometry images offer much higher resolution and therefore increase our ability to identify damage based on remote imagery. In fact in Figure 4.4 some of the lateral spreading that occurred at this site can also be seen with extensive cracking of the ground. Similarly the island that houses the harbour master's office can also be seen at the top of this Figure. However, it is quite difficult to see the settlements suffered by the island or damage to the bridge connecting the island to the south pier or to the buildings. In Figure 4.5 a Pictometry image of the mobile crane and container storage area is shown. Large silos for bulk material storage can also be seen in this image. Although there was liquefaction induced lateral spreading that occurred close to the coastline (far left of Figure 4.5) there was no damage to the silo structures or their foundations.

Figure 4.4: A Pictometry image of the overview of the collapsed north wharf and the crane (February 2010)

Figure 4.5: A Pictometry image of the mobile crane, container storage area behind north wharf and the silo structures (February 2010)

4.2.3 Ground-truthing images

The aerial imagery presented in earlier sections was confirmed by observations made on the ground. Some of the most prominent images that came soon after the Haiti earthquake were those of the gantry crane that was damaged. These are presented in Figure 4.6, where the damaged crane is presented as photographed soon after the earthquake. The collapse of the north pier has led to the severe damage of this crane structure. The collapsed crane was cleared by the time of EEFIT visit and these images were provided by Prof El-Gamal of University of California, San Diego.

Figure 4.6: Collapsed gantry crane
(Photos: Courtesy of Prof El-Gamal, UC San Diego)

In addition to the collapsed gantry crane, damage was also observed to a second mobile crane. This crane was still present at the time of EEFIT visit. This mobile crane was visible in the satellite and Pictometry images presented earlier. In Figure 4.7, a view of the damaged mobile crane is presented. The tower part of the crane has rotated as the foundations below have allowed settlement and rotation presumably following soil liquefaction. As a result of the damage to the crane structures the port was unable to off load any of the relief aid that was arriving. Only ships with self-contained cranes were seen bringing in building materials, food grains and other relief at the time of the EEFIT visit.

In Figure 4.8 a view of the collapsed sections of south pier are shown. These sections can be seen in the satellite image of Figure 4.2, identified by a red elliptical ring. In Figure 4.8 it can be seen that pile caps supporting the ends of the sections have remained while the bridging deck sections have collapsed. This could have been due to excessive settlement of the piles causing the deck sections to dislodge and collapse.

Figure 4.7: Damaged mobile crane at the time of the EEFIT visit

Figure 4.8: Collapsed sections of the south pier

4.3 Liquefaction induced damage to north wharf

There was extensive soil liquefaction in the areas close to the north wharf identified in aerial imagery presented earlier. According to Figure 4.9, based on Bachuber *et al*, (2010), the modern port facility, and an extensive area to the north and south, was constructed on fill material, which is very susceptible to liquefaction if poorly compacted fill. The extensive liquefaction in the port area of Port-au-Prince repeats a phenomenon seen in many previous earthquakes.

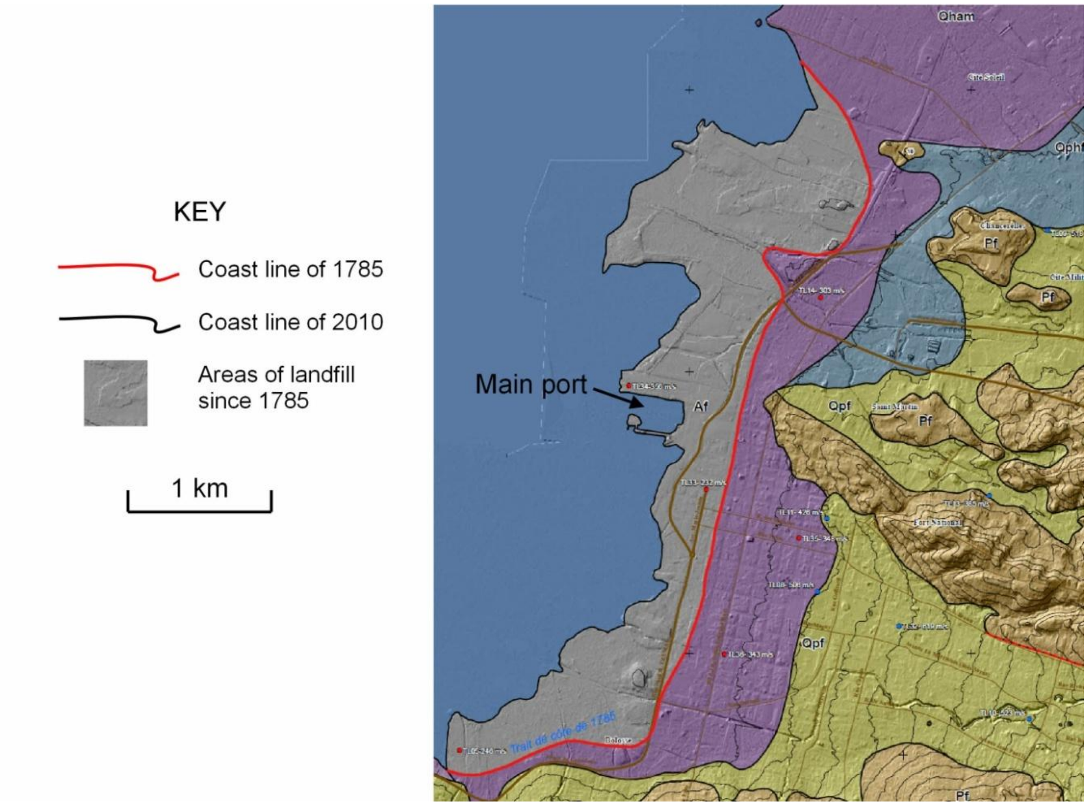


Figure 4.9: Reclaimed areas around the main port facility
(adapted detail from Bachuber *et al*, 2010)

Due to the soil liquefaction there was evidence of severe lateral spreading close to the north wharf. Some of this lateral spreading was identified on the Pictometry image of Figure 4.4. Figure 4.10 shows cracks, extending to a depth of about 1m, which were induced in the tarmac next to the north wharf. The sloping angle of the ground is quite small (< 1 degree) but nonetheless there was extensive lateral spreading towards the free face. This type of lateral spreading of gentle slopes was also seen in many previous earthquakes. Figure 4.10 shows that the crustal surface layer of denser, coarser material did not liquefy but suffered lateral spreading, apparently due to liquefaction of a deeper sandy/silty deposit.

Figure 4.10: Cracks induced by lateral spreading close to north wharf
extending to a depth of about 1m

As was evident from the aerial images of Figures 4.2 and 4.4, the entire north wharf Section has completely collapsed. A view of the collapsed Section is seen in Figure 4.11. The reason for this collapse was the extensive soil liquefaction observed at this site. Liquefaction and lateral spreading may have caused the foundations supporting the wharf to settle and rotate leading to the complete collapse of the wharf structure.

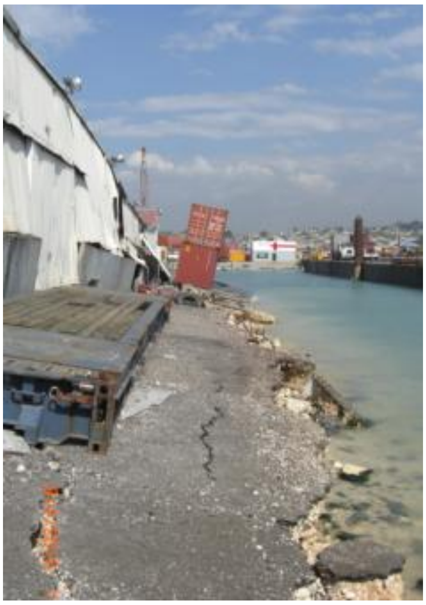


Figure 4.11: Collapsed Section of the north wharf

The storage facility next to the wharf also suffered extensive damage as seen in Figure 4.11. The foundations of the supporting columns of the storage facility suffered extensive settlement following liquefaction, as discussed further in Section 7.4.

4.4 Liquefaction-induced settlement of the island

The south pier connects via a bridge to an island that houses the harbour master's building that controls the traffic movement in and out the port. The island has suffered severe liquefaction and consequently settled extensively following the earthquake. An overview of the bridge is shown in Figure 4.12. In this Figure the severe rotation suffered by an electricity pole can also be seen.

Figure 4.12: An overview of the connecting bridge linking the south pier and the island

Soil liquefaction and subsequent lateral spreading was clearly evident at the island. The electricity poles have clearly suffered severe rotation owing to the lateral spreading of the ground. This is shown in Figure 4.13.

Figure 4.13: Lateral spreading causes an electricity pole to rotate

The settlement of island was noted to be nearly 1.0 m relative to the south pier. However the pile foundations supporting the connecting bridge have settled even further. This has led to severe distress in the deck sections connecting to the pier head which have cracked and allowed a hinge to be formed. The bridge seemed to have self-articulated itself to accommodate the settlement of the piers as shown in Figure 4.14.

Figure 4.14: Settlement of pile foundations causes self-articulation of the connecting bridge

A pile supported wharf structure was present at the island to allow the mooring of boats and pontoons. This wharf structure has suffered severe damage as shown in Figure 4.15. A view of the underside of this wharf is shown in Figure 4.16 that shows the damage to the piles supporting the wharf.

Figure 4.15: Severe damage to a pile supported wharf structure

The piles supporting the wharf were passing through the liquefied and laterally spreading soil below that is moving in a westerly, seawards direction, away from the west end of the settling island and transversely to the bridge. This has led to a classical failure mechanism with plastic hinges forming at the pile heads. In Figure 4.17, the concrete at the pile heads cracked revealing the reinforcement and indicating loss of moment fixity and clear formation of a plastic hinges. This type of failure mechanism was observed earlier in dynamic centrifuge tests and was proposed as one of the possible failure mechanisms for piles in laterally spreading liquefied soils as shown in Figure 4.17 (Madabhushi *et al*, 2009).

Figure 4.16: A view of the underside of the wharf showing the damaged piles

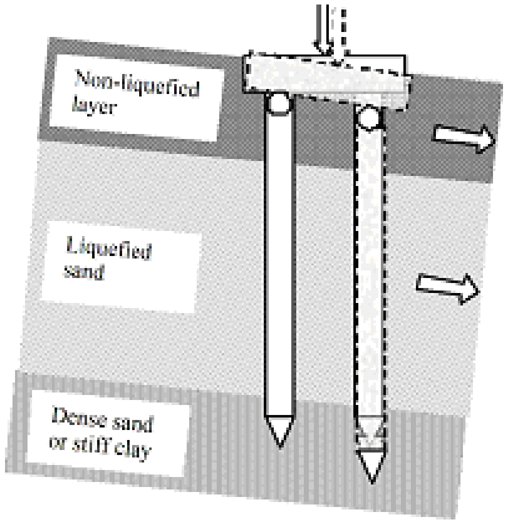


Figure 4.17: Failure mechanism of a pile group proposed by Madabhushi *et al* (2009)

4.5 Liquefaction-induced lateral spreading behind silos

Liquefaction induced lateral spreading was observed at other locations in the port area. There was extensive lateral spreading observed behind the silo structures adjacent to the container storage facility within the port area. These silos are identified in the image shown in Figure 4.18. In this Figure the lateral spreading is clearly identified along the boundary wall. A view of the silo structures from ground is presented in Figure 4.19. The silos themselves were undamaged by the earthquake, despite the lateral spreading. However, the building adjacent to the silos had a collapsed roof and the supporting wall closest to the shoreline, seemed to have moved with laterally spreading soil causing the roof to collapse.

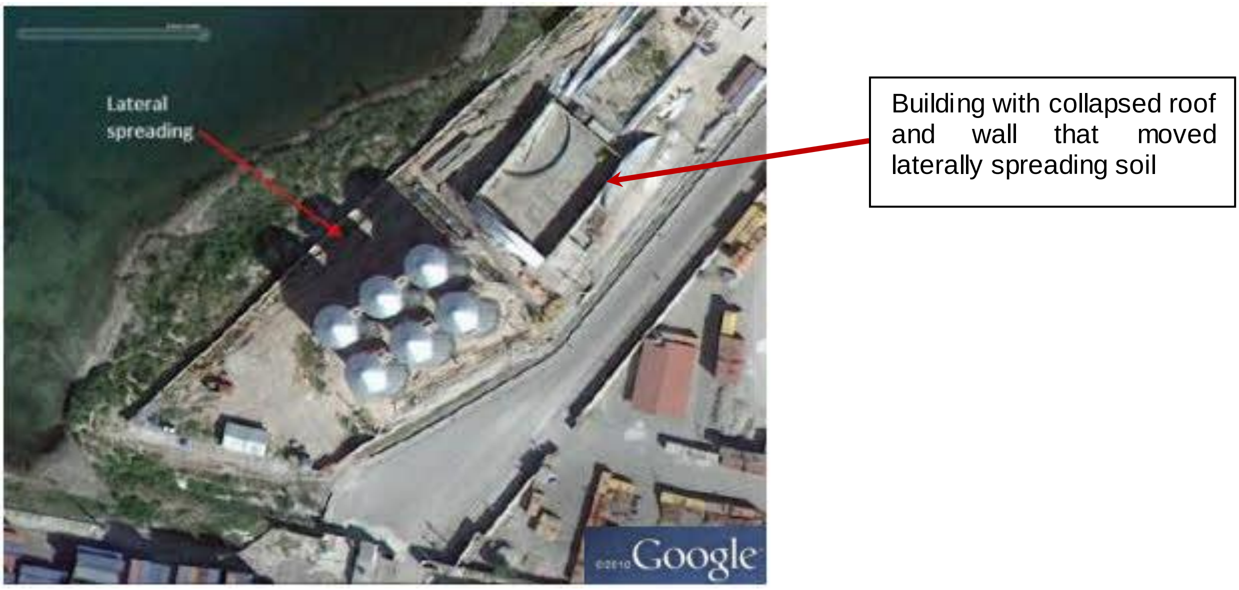


Figure 4.18: Lateral spreading behind the silo structures

Figure 4.19: Silo structures that are undamaged with building with collapsed roof in the background

4.6 Liquefaction near Grand Goave

Liquefaction was also observed at several locations other than the port facility in Port-au-Prince. The EEFIT team visited one such location near Grand Goave. The GEER team (Rathje *et al* 2010) reported other locations where liquefaction was also observed. The location of Grand Goave is shown in the satellite image in Figure 4.20. It can be seen in this Figure that a river flows bounds the eastern edge of the township and joins the sea, suggesting that the area may be underlain by recent alluvial deposits, including layers of loose, non-cohesive materials prone to liquefaction. Liquefaction induced lateral spreading was seen quite close the shoreline.

Figure 4.20: Google Earth image of Grand Goave

The EEFIT team visited a group of new houses constructed close to the shoreline. It is thought that these were constructed by an NGO. The houses showed extensive cracking as seen in Figure 4.21. These cracks have been induced by the laterally spreading ground following liquefaction although the construction quality and materials used seemed to be of relatively good quality.

Figure 4.21: Damaged houses displaying extensive cracking

At this site the surface layers appeared to be clayey silt. Long tension cracks were visible viewed from the ground close to the buildings as seen in Figure 4.22. It appeared that this surface layer has spread laterally over a liquefied sandy layer below. As the surface layer is clayey silt with low permeability, it is likely that it was able to hold the excess pore pressures generated in the sandy layers below for an extended period, giving rise to a greater lateral spread. Buildings supported on this soil also move laterally and suffered damage as explained earlier. In Figure 4.23 a close-up view of the steps that got separated from the buildings is presented to confirm the lateral spreading of the ground.

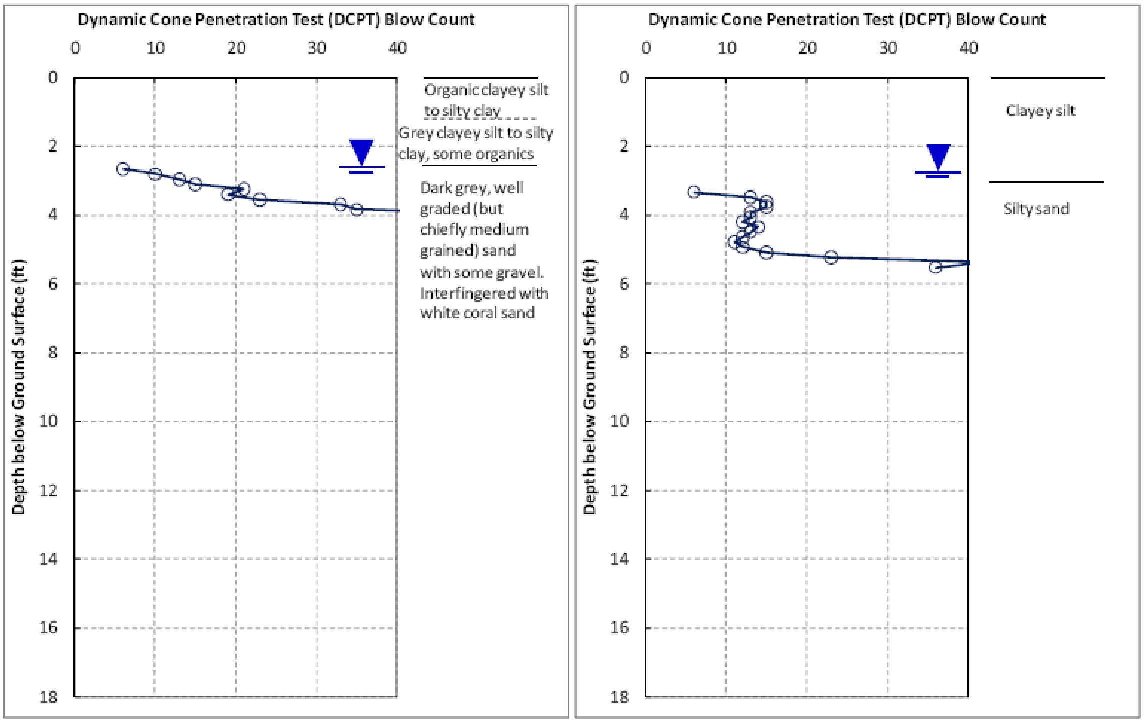
Figure 4.22: Evidence of lateral spreading close to the buildings

Figure 4.23: Close-up view of the steps that separated from the buildings

Figure 4.24: Lateral spreading continuing for some distance from the building site

The laterally spreading has continued for a long distance past the building site described above. In Figure 4.24 a view in the other direction is presented to confirm the extent of lateral spreading. This has led to several buildings with poor construction quality to completely collapse. In Figure 4.25 a view of a completely collapsed building is presented.

Figure 4.25: Collapsed building adjacent to laterally spreading ground



(a) NW of Grand Goave (b) Grand Goave, near Figure 4.22

Figure 4.26: Dynamic cone penetration test data from two sites around Grand Goave group (Rathje *et al* 2010)

The GEER group (Rathje *et al* 2010) were able to do some site characterisation of soils close to the coastal regions based on the dynamic cone penetration test data. In Figure 4.26 an example of the dynamic CPT data obtained from two sites around Grand Goave is presented. The data from both sites confirm the presence of a surface clayey silt layer that extends to about 2 to 2.25m depth. Below that there is silty sand layer or medium grained sand layer that are quite susceptible to liquefaction. Also the presence of a shallow water table just below the clayey silt layer is a contributing factor for the liquefaction of these layers. Once these layers liquefy, the clayey silt layers can undergo lateral spreading even on quite gentle slopes.

5.0 LANDSLIDES

The Haiti earthquake of 12th January 2010 caused a number of landslides. Given the hilly topography of the region this may have been anticipated. However, the landslides were relatively small scale and involved only relatively small soil volumes

The EEFIT team came across some of the landslides on their way to Léogane. Also some large scale sand quarries were visited in the hills close to Pétionville discussed in Section 5.2. Figure 5.1 shows the locations of the photos discussed in Sections 5.1 and 5.2.

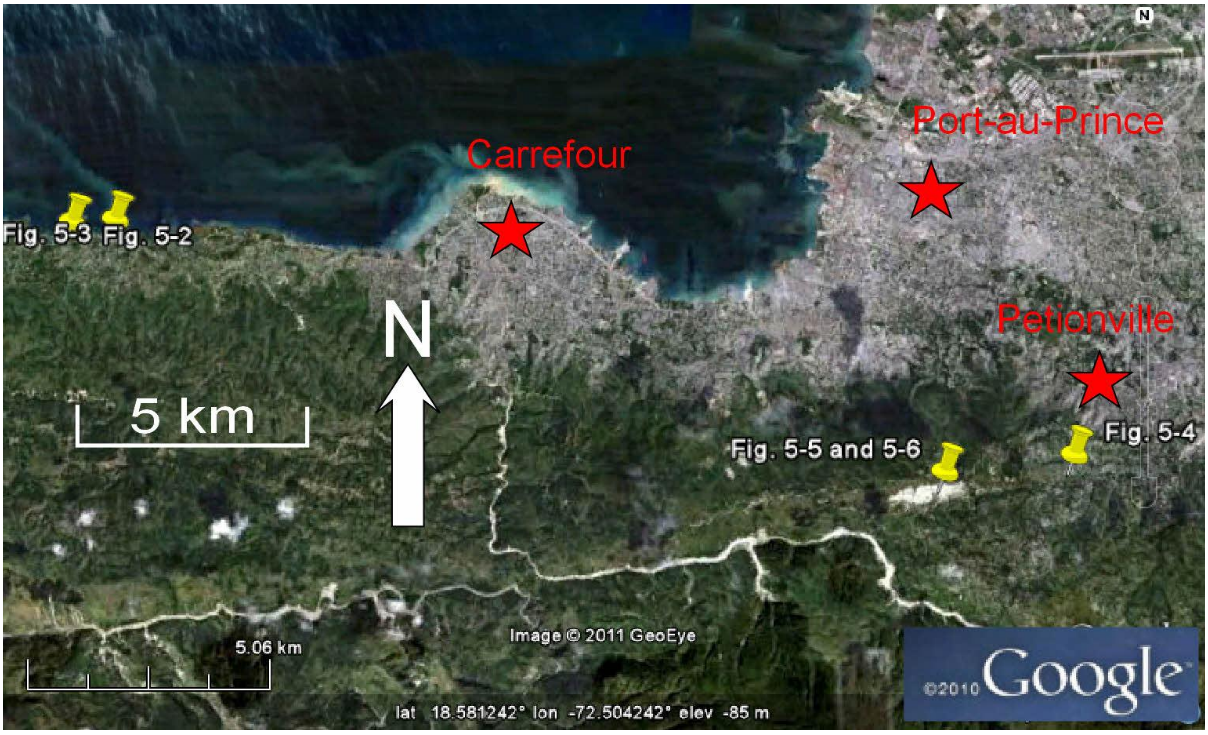


Figure 5.1: Location of photos shown in Sections 5.1 and 5.2

5.1 Earthquake induced landslides

Landslides and in general failure of slopes were observed in the road cuttings next to the highway leading from Port-au-Prince to Léogane. An example of a slip failure of the road cutting is presented in Figure 5.2. This slip was caused by the earthquake as evident from the fresh rock visible in this Figure. The sandstone rock forming the slope of the cuttings seemed to be heavily weathered and fractured, thereby making it susceptible to failure under earthquake loading. However the quantity of material involved in these kinds of slips was fairly small and the highways were able to operate following the clear up of the debris material. There were many examples of these kinds of rock slips.

Figure 5.2: Slip failure in a cutting next to the highway

A more substantial landslide is presented in Figure 5.3 again next to the same highway from Port-au-Prince to Léogane. Again quite steep slopes were cut in silty/clayey material to form the highway. The earthquake loading has induced a landslide in these steep slopes. Luckily there was enough space between the slope and the carriageway and therefore the debris did not travel onto the highway. There were many examples of this type of landslides.

Figure 5.3: A substantial landslide next to the highway

The EEFIT team also visited the hills close to Pétionville. There was evidence of some substantial landslides in this region following the earthquake. An example of one such landslide is presented in Figure 5.4. This landslide occurred downslope of a building that was protected by a retaining wall. The building itself and the retaining wall remained undamaged. It appeared that the landslide involved only the top soil but not the deeper layers of soil and rock. However the total volume of soil that suffered slipping was quite substantial and is estimated to be a few thousand cubic meters.

Figure 5.4: Landslide in the hills close to Pétionville

5.2 Sand Quarries

In Haiti sand quarrying provides a substantial part of building materials used in construction of buildings in Port-au-Prince and other cities and towns. The presence of weathered sandstone from Pliocene and Miocene periods (Section 3.4) that form the hills is an attractive source of building materials. In fact large sand quarries are visible from the airport itself as soon as one lands in Port-au-Prince. An example of a large sand quarry near Pétionville is shown in Figure 5.5. This sand quarry is close to residential buildings located both at the top of the slope as well as the foot of the slope.

Figure 5.5: A large sand quarry near Pétionville

Another close-up view of the slopes formed by sand quarrying is presented in Figure 5.6. In this Figure it can be seen that the slopes are quite substantial. The slope height is estimated to be about

30 to 45 meters. Localised landslides were observed within the sand quarry following the earthquake although no wholesale movement of the slopes was observed. There are many such slopes in and around Port-au-Prince. The slopes formed by these sand quarries can induce landslides particularly during the hurricane season. Each of these sand quarries should be carefully monitored for movements based on their proximity to buildings and ensure slope stabilisation measures are carried out, if required.

Figure 5.6: Localised landslides within the sand quarry

Samples of the soil were obtained from the sand quarry described above. A close-up view of the soil is presented in Figure 5.7. The Figure shows lumpy sand that is weakly cemented and is readily crushable by hand. Given this material is used in most of the constructions in and around Port-au-Prince and other cities in Haiti, it is interesting to investigate it further. The normal practice observed by the EEFIT team during the rebuilding activities currently going on in Haiti is to mix this material with cement and use it as mortar or concrete.

Figure 5.7: A close-up view of the soil from the sand quarry

The soil obtained from the sand quarries was analysed at the Schofield Centre, Department of Engineering, University of Cambridge (Courtesy of Mr Mark Stringer, PhD Student, Schofield Centre). Two methods were used to analyse the samples obtained from two different sand quarries. The first method involved conventional sieve analysis. In addition to this the particle size distribution was determined using an optical accusizer. The results of these analyses are presented in Figure 5.8.

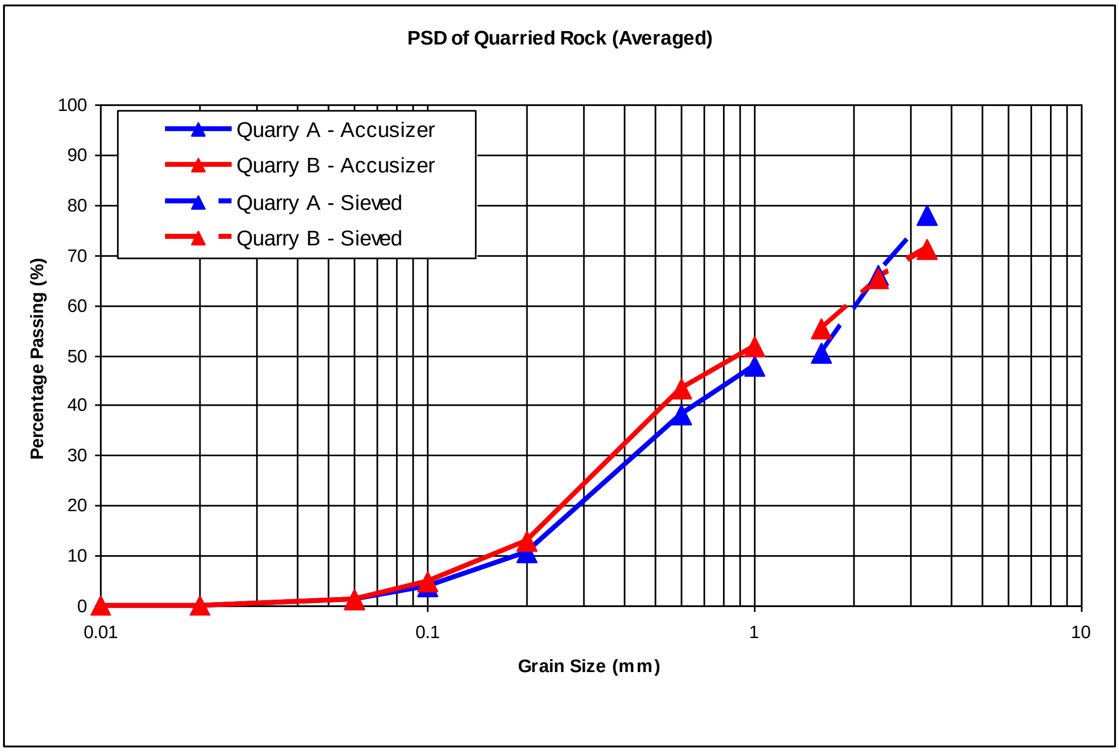


Figure 5.8: Particle size distribution curves of soil recovered from the sand quarries

In Figure 5.8 it seems that two samples from different sand quarries provide very similar particle size distribution curves. The material has particle sizes between 0.05 mm to 0.6 mm and therefore has fine to coarse sand particles. There were also few large sized particles of 2 mm to 4 mm. Both methods of analyses i.e. the sieve analysis and the optical accusizer analysis gave almost identical results for both the samples investigated.

There may implications in using predominantly fine sands for mortar and concrete in the construction of buildings. The quality and strength of the mortar/concrete obtained by mixing this sand may need to be investigated further. Given the widespread collapse of the buildings during the 12th January 2010 earthquake in Haiti, the role of quality of construction materials and methods of construction should be re-evaluated before the reconstruction efforts are undertaken.

6.0 VALIDATION OF REMOTE DAMAGE ASSESSMENTS

6.1 Introduction

A unique characteristic of the EEFIT Haiti survey was that before the team deployed to the field, a complete desktop building damage assessment had already been carried out using satellite and aerial images for Port-au-Prince. Given the scale of the disaster with an estimated 1.5 million people affected (Government of Haiti, 2010) and the chaotic situation on the ground, compounded by the reduction of the Haitian government's ability to function, the international community was called upon to assist in dealing with the aftermath of the earthquake. As a result, a Post-Disaster Needs Assessment (PDNA) was carried out jointly by the World Bank, the Inter-American Development Bank, the UN system, the European Commission and the Economic Commission for Latin America and the Caribbean. Of the sectors for which damage and needs assessments were being carried out, the housing sector faced a huge task of assessing the damage to the buildings in the entire region. However, the chaotic situation and restricted access to many of the affected areas meant that ground based building damage surveys was not feasible, given the timescale needed for the PDNA. As a result, a major campaign to carry out damage assessment remotely using satellite images and aerial photographs took place.

6.2 Overview of the remote damage assessment

JRC (Joint Research Centre of the European Commission), UNOSAT and the World Bank GFDRR[2] jointly carried out this remote damage assessment, which covered 13 administrative units (Government of Haiti, 2010) (11 towns) in the Port-au-Prince area, including Port-au-Prince itself, to assess the damage to the buildings from the earthquake. During the process, a group of experts consisting of civil and structural engineers, architects, engineers and other scientific discipline was formed. Comprised of approximately 600 such volunteers, the group was named GEO-CAN (Global Earth Observation – Catastrophe Assessment Network), and provided damage assessment by interpreting satellite images and aerial photographs of the affected areas. GEO-CAN was organised and led by ImageCat Inc., through professional organisations including EEFIT and EERI. JRC and UNOSAT were also carrying out damage assessments in parallel and the three efforts were eventually merged. The consolidated final assessment formed part of the PDNA for the housing sector (Government of Haiti, 2010). The final estimated direct loss for the housing sector derived from the remote damage assessment was US $6.1 billion.

6.3 Remote Damage Assessment methodology

A detailed account of how the joint remote damage assessment was carried out can be found elsewhere (Kemper *et al*, 2010; Corban *et al*, 2011). Hence, here only a brief overview of the joint assessment methodology will be provided.

The Haiti event was unique in that numerous pre- and post-event remotely sensed images were provided for free for the first time. The types of images ranged from high-resolution satellite images (optical; e.g. IKONOS, Geoeye-1, Quickbird, World View-1) with less than 1 m spatial resolution, to LiDAR data and optical images taken by unmanned aerial vehicles (UAV). Aerial photographs with 15 cm spatial resolution were commissioned by the World Bank (GFDRR)-RIT-ImageCat group as well as Google and released to responding agencies free of charge. Pictometry provided their oblique aerial photographs taken from four directions to organisations responding to the disaster in a similar way. Pictometry images are further described in Section 6.4**Error! Reference source not found.**.

In the early days, many international organisations responding to the disaster were producing maps in parallel, at times duplicating efforts by producing similar information (Figure 6.1). Coordination was lacking and as a result, statistics show that over 500 maps were produced in the first week alone and in the next 75 days the total went up to over 2000 (Bjorgo, 2010). As a result, the responders in the field were confused as to the reliability of the maps, and were completely overwhelmed by the amount of information[3]. It was the same with damage assessment maps; however, after three weeks, JRC,

[2] Acronyms are defined in Appendix D

[3] MapAction comment made during technical session at the UNOSAT hosted workshop on the Haiti Earthquake in May 2010.

UNOSAT and the World Bank (GFDRR) agreed on undertaking a joint assessment of the building damage using the remotely sensed images.

The joint damage assessment employed visual interpretation to estimate the building damage distribution. Various semi-automated damage assessment methods using remotely sensed data have been proposed in the past (Corban *et al*, 2011); however, none have been proven so far to be reliable, which is partly due to the lack of validation data to carry out accuracy assessments. Hence a decision was made to employ visual interpretation for Haiti. For the damage scales, the European Macroseismic Scale 1998 (EMS98, Grünthal *ed*., 1998) was used.

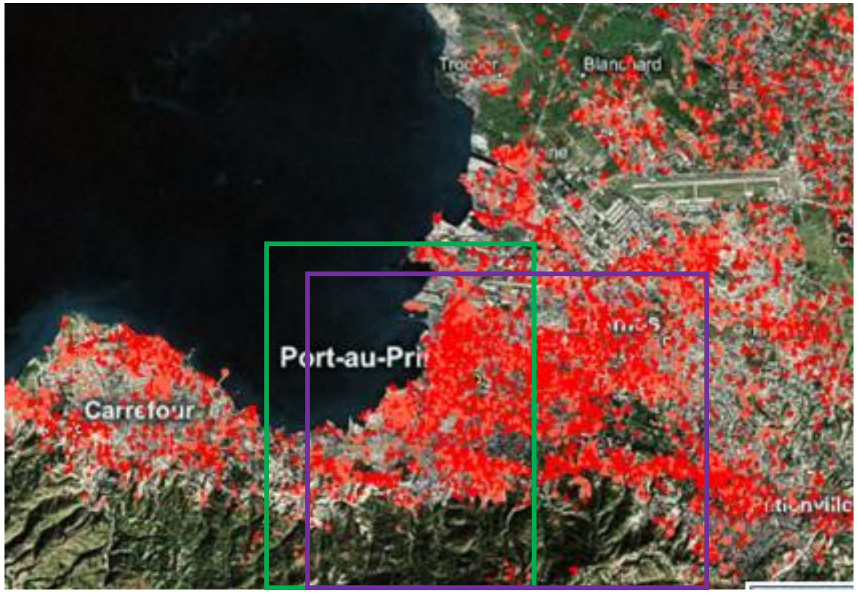
UNOSAT, in collaboration with SWISSTOPO, mapped each building as points using the pre-earthquake images. This map was used to count the total number of buildings as well as a base map to carry out the post-earthquake damage assessment.

The GEO-CAN assessment led by the WB-RIT-ImageCat group was carried out in two phases. Phase I was completed within 24 hours and made use of the high-resolution optical satellite images. Damaged buildings were marked using points in Google earth and a damage grade was assigned. For phase II the aerial photographs were used where the footprints of the partially collapsed and collapsed buildings, (i.e. D4 and D5 in EMS98 scale) were delineated. Eventually, for the joint assessment, all of the data was converted into points to be consistent with the other damage assessments being used.

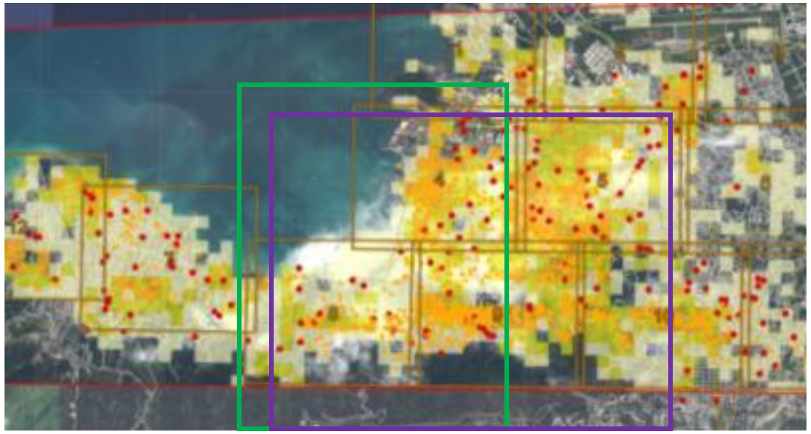
6.4 Estimating the lower damage grades using Pictometry

During the joint assessment, a way to estimate the distribution of the lower damage grades was needed, due to the difficulties in identifying damage grades D3 and below using remote images taken from above. To address this problem, a team based at Cambridge Architectural Research Ltd, UK, including Keiko Saito from the EEFIT Haiti team, took on the task of assessing the damage to buildings, particularly the lower damage grades, using a set of high-resolution oblique aerial photographs produced by the Pictometry International Corp (www.pictometry.com). Taken from four directions, Pictometry data allows the viewer to see the façade of the buildings, unlike vertical aerial photographs (Figure 6.2). Pictometry images have a nominal spatial resolution of 15 cm.

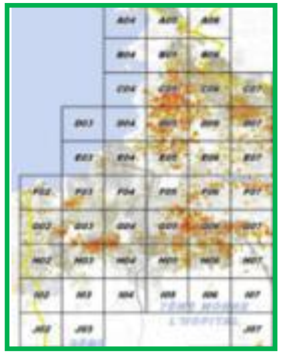
Figure 6.2: A set of Pictometry oblique aerial images for a commercial area in Port-au-Prince. A red spot is placed on the same building in the four directional images.



(a) WB GFDRR/RIT/ImageCat



(b) DLR



(c) UNOSAT

(d) JRC

Figure 6.1:. Building damage distribution maps created using satellite images and aerial photos : examples from WB GFDRR/RIT/ImageCat, DLR, UNOSAT and JRC. Images are shown approximately to the same scale, with UNSAT and JRC areas boxed green and purple respectively

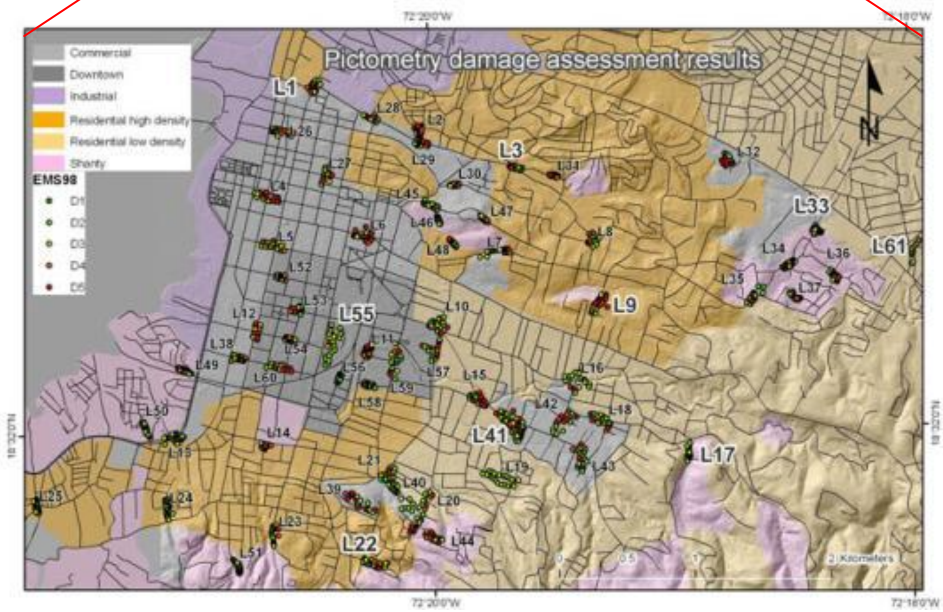
Using Pictometry, buildings in 60 locations across Port-au-Prince were assessed. The 60 locations were selected using random stratified sampling methods. A land cover map was used to choose equal number of locations from each land cover category (Figure 6.3). Sampling was used to maximise the limited human resources available to the team. In each of these locations, approximately 20 consecutive buildings were assessed, which resulted in a total of 1241 buildings. For each building, the construction type, number of storeys, use type and damage grade was interpreted and recorded using Google Earth. A detailed description of the methodology and results can be found in Spence and Saito (2010). Following the EEFIT survey, one location was added which brought the total number of buildings up to 1251. Table 6.1 shows the results of the Pictometry assessment.

In the PDNA report, an estimate of the building damage distribution for all buildings in Port-au-Prince by land cover type was carried out by extrapolating the damage ratios in Table 6.1 across the entire Port-au-Prince (Kemper *et al*, 2010).

Table 6.1: Distribution of damage assessed using Pictometry by land cover type. From Spence and Saito (2010). Damage grades D2 to D5 and nvd are defined in Table 6.2.

	Count					%			
	Comm-ercial	Down-town	Resid-ential	Shanty	Total	Commercial (n=380)	Downtown (n=199)	Resid-ential (n=318)	Shanty (n=354)
D5	90	32	40	42	203	23.7%	16.1%	13%	11.9%
D4	36	24	21	35	115	9.5%	12.1%	6.8%	9.9%
D3	54	10	31	42	137	14.2%	5.0%	10.1%	11.9%
D2	34	24	25	43	125	8.9%	12.1%	8.1%	12.1%
nvd	166	109	201	192	661	43.7%	54.8%	65.3 %	54.2%
TOTAL	380	199	318	354	1251	100%	100%	100%	100%
					(D4+D5)	**33.2%**	**28.2%**	**19.8%**	**21.8%**

a) Overview of greater Port-au-Prince area, Haiti. Background map taken from Open Street Map.



(b) The 61 locations assessed for building damage using Pictometry overlaid on a land cover map. The 9 locations subsequently visited by the EEFIT survey team are highlighted using larger font sizes. A total of 1251 buildings were assessed using Pictometry.

Image courtesy of Cambridge Architectural Research Ltd. Land cover map provide by ImageCat Inc. LIDAR data obtained through Open Topography.

Figure 6.3: Pictometry and EEFIT survey locations

6.5 EEFIT Haiti ground validation data collection

The EEFIT Haiti survey provided the opportunity to visit some of these locations in Port-au-Prince that were assessed for damage using Pictometry and through the GEO-CAN exercise. At the time of the EEFIT survey, the lack of ground validation data has been one of the obstacles for the progress of remote sensing based damage assessment, hence the EEFIT survey provided invaluable data to carry out validation of the various remote damage assessments mentioned in the previous Section. Of the 60 locations described in Section **Error! Reference source not found.**, 9 were visited by the EFIT team. The 9 locations are marked in Figure 6.3b. A total of 142 buildings in Port-au-Prince were assessed for damage in 4 days; a further 43 buildings were assessed in Léogane, but are not included in the following comparisons. Following the remote damage assessment, there was a need to supplement data on the damage to residential areas, hence one residential location was added to the EEFIT survey locations which was not in the original 60 Pictometry locations (Location 61). Some of the buildings in the original Pictometry survey could not be reached, due to security conditions. In these locations, additional buildings originally not included in the Pictometry survey were visited. In this case, the building was assessed using Pictometry upon return from the field by interpreters who had not visited the field. As a result, the total number of buildings assessed using Pictometry increased from 1251 to 1261. Figure 6.3b also colour codes the damage grades assessed for the individual buildings viewed from the ground by the EEFIT team.

6.5.1 Damage grades

Both the EEFIT survey and the damage assessment using Pictometry used the damage grades defined in the European Macroseismic Scale EMS98 (Grunthal et al, 1998). Table 6.2 defines the grades.

The damage grades below were designed to be described using integers. However, in reality damaged houses do not always fit neatly into one category. In cases where the EEFIT ground survey assessed that a building lay between two damage grades, it was assigned as 0.5 of a building to both grades in Tables 6.5 to 6.14.

Table 6.2: Definition of the damage grades used for the EEFIT mission as well as the Pictometry and remote joint assessment

Damage level	Damage description
nvd (Pictometry)	**No visible damage.**
D1 (ground observations)	**Negligible to slight damage (no structural damage, slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
D2 (Pictometry and ground observations)	**Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
D3 (Pictometry and ground observations)	**Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels
D4 (Pictometry and ground observations)	**Very heavy damage (heavy structural damage, very heavy non-structural damage)** Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
D5 (Pictometry and ground observations)	**Destruction (very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

6.5.2 Characteristics of the EEFIT survey locations

a) Estimated intensity for the EEFIT survey locations

The intensity distribution in the Port-au-Prince area mapped by Mora (2010) based on description of damage in news articles and telephone interviews is shown in Figure 6.4. According to Mora (2010) most areas where significant earthquake damage was found had at least Modified Mercali Intensity (MMI) of IX. The 9 locations visited by the EEFIT team are within the intensity X and IX areas. However, as discussed in Section 8.0, the distribution of damage appeared to be much more complex than is suggested by Figure 6.4.

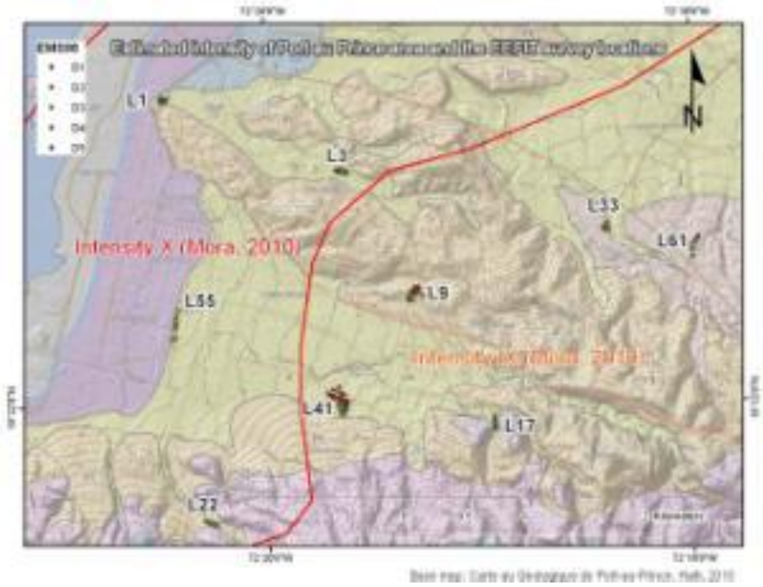


Figure 6.4: Intensity distribution by Mora (2010)

b) Land use/topography characteristics

Table 6.3 shows the characteristics of the 9 locations visited in Port-au-Prince.

Table 6.3: Characteristics of the Port-au-Prince locations visited by the EEFIT team.

ID	Land use from Figure 6.3b	Topography	Soils	Number of buildings surveyed by EEFIT team in location
L1	Commercial	Flat	Reclaimed land, loose, sandy soil with shallow water table	12
L3	Residential (Shanty edge)	Moderate slopes, but close to steeper slopes	Dense sandy/silty soil	17
L9	Residential	Steep	Rocky	18
L17	Residential (Shanty edge)	Moderate to steep slopes	Rocky, weathered	15
L22	Residential	Steep	Rocky, Lateritic	8
L33	Shanty edge	Steep	Alluvial deposits, dense sandy soil	13
L41	Residential	Moderate slopes	Dense sandy soil	41
L55	Downtown	Flat	Alluvial deposits, moderately dense sandy soil	9
L61	Residential	Moderate to steep slopes	Rocky, weathered	9

The general make up of the built up area in Port-au-Prince can roughly be categorised into the following land cover types: commercial, downtown, residential (high density/low density) and densely-packed informal low-income settlements referred to here as shanty-towns. The locations visited by the EEFIT team were selected from each of these categories, excluding the shanty areas because of security concerns. Historically, the development of Port-au-Prince started from the area close to the sea and has been expanding inland towards the east into the Pétionville area[4]. Shanty towns can be found sprawling in the outskirts, as well as in the middle of the built up areas. Table 6.4 shows the breakdown of the number of buildings that were surveyed by EEFIT by land cover type. The land cover map used to classify Port-au-Prince was produced by ImageCat and can be found in Figure 6.3b.

Table 6.4. The number of buildings surveyed by the EEFIT team by land cover type.

Residential (Low density)	76	53.5%
Res (Hig density)	45	31.7%
Commercial	12	8.5%
Downtown (hospital buildings)	9	6.3%

c) Topography of Port-au-Prince

Port-au-Prince is surrounded by mountains on its three sides that have an elevation of up to 1000m, with the fourth side bordering the sea. The north half of the built up area is hilly, with steep hills as seen in Figure 6.6 and 6.7. The south half is relatively flat, as seen in the topographical map in Figure 6.8.

Figure 6.5: Aerial view showing the mountains to the south of Port-au-Prince as the aeroplane takes off from the international airport located in the northern periphery of the built up area

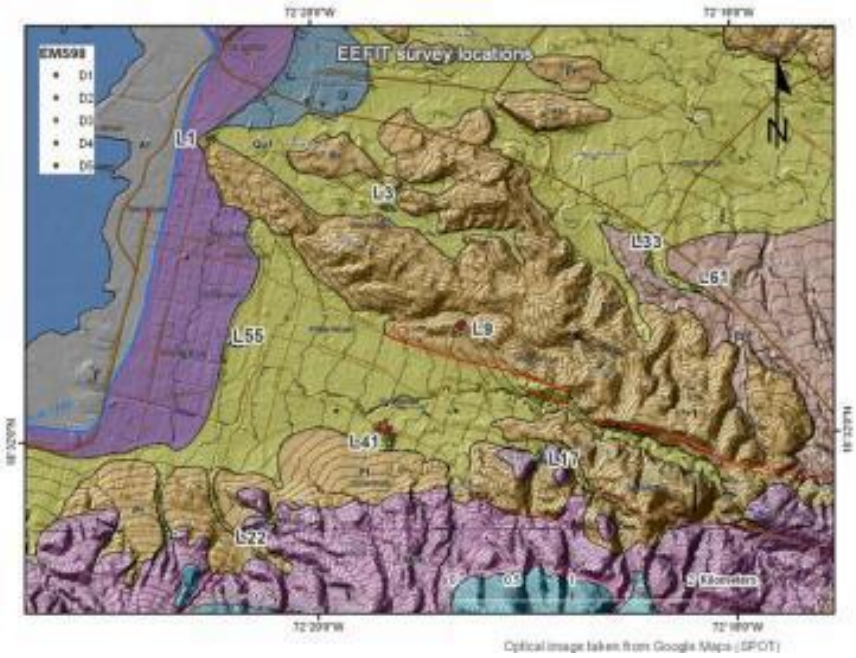
Figure 6.6: Steep slopes commonly seen in the northern part of Port-au-Prince

[4] The middle class are moving inland to residential areas where relatively large properties and low housing density can be found.

The optical satellite image (SPOT, taken from Google Earth) of the Port-au-Prince area in Figure 6.7 overlaid on the topographic map shows that almost the entire area in Figure 6.7, including the steep slopes to the south, are built on. The land cover map in Figure 6.4 shows that these slopes are mainly occupied by shanty towns.

In the following section, the characteristics of the EEFIT survey locations will be summarised and some observations in terms of the types of damage that cannot be seen in vertical images.

(a) Optical satellite image (SPOT)



(b) Geological map (see Figure 3.7 for further detail)

Figure 6.7: Two images of Port-au-Prince showing the same geographical extent.

6.5.3 Location 1: Central commercial district

Location 1 is situated in the middle of a commercial area near the sea (Figure 6.8). Figure 3.7 shows that this area is on soft alluvial, marine and fill deposits, which would be expected to give rise to significant soil amplification of ground motions'. More details can be found in chapter 4.0. The buildings in location 1 are mostly commercial buildings or mixed use with long, rectangular footprints. These buildings typically are between two to five storey reinforced concrete structures as seen in Figure 68. 12 buildings were surveyed which are marked in Figure 6.9.

Figure 6.8: Typical buildings found in the commercial district in Port-au-Prince, long in one direction and rectangular in shape. (left) buildings seen from the ground, (right) buildings seen from above in Pictometry images (oblique aerial photos).

Figure 6.9: The buildings and their damage grades assigned by the EEFIT team.

The buildings behind the first row of the buildings facing the street were not visible when viewed from the ground. Table 6.5 shows the breakdown of the damage grades assigned to the buildings in location 1 by the EEFIT team. Since phase II of GEO-CAN (i.e GEO-CAN II) made no attempt to identify damage grades lower than D4, grades D2 & D3 are left blank for GEO-CAN II.

Table 6.5: Breakdown of the damage grades assigned to the buildings in Location1.

L1	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	10				1	1	12
Pictometry	5		0	4	2	1	12
EEFIT		3.5	4	1.5	1	2	12

6.5.4 Location 3: mixture of high-density residential area and shanty

In Port-au-Prince, the residential areas can be categorised roughly into high- and low-density areas. Location 3 is in a high-density residential area. Market stalls were seen on both sides of the street. The street was full of pedestrians doing their daily shopping. As can be seen from the aerial photograph in Figure 6.10, the front of the buildings are rather narrow which can be seen Figures 6.11 & 12 taken from the ground photographs below. The depth of the buildings cannot be grasped from the ground unless the surveyor goes inside the house. Number of buildings surveyed: 17.

Figure 6.10: Overview of Location 3 in Google Earth and the EEFIT assessment results.

Figure 6.11: Ground view of building (a)

Figure 6.12: Ground view of building (b)

Building (a) is a good example of where it is difficult to see from a vertical aerial photograph whether it is one building or two. Figure 6.11 shows that it is one building. Building (b) was assessed as D4 by the EEFIT team; however, the damage (fall out of the brick infill wall) is not visible in a vertical photograph. Table 6.6 shows the breakdown of the damage grades assigned to the buildings in location 3.

Table 6.6. Breakdown of the damage grades assigned in location 3.

L3	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	16				0	1	17
Pictometry	14		1	0	1	1	17
EEFIT		9	5	1	1	1	17

6.5.5 Location 9: Low-density residential

Location 9 is situated on a very steep hill. Relatively large residential buildings and some commercial buildings (e.g. private clinic, manufacturer and an educational facility) were found along the street. Near the top of the hill, some residential buildings had experienced ground failure. Some residents continued to live in their house after the earthquake. On one plot, the *cash-for-work* workers were seen to be demolishing a building that had collapsed. Figure 6.13 shows the overview of the buildings in location 9.

The EEFIT team was only able to look at building 9-1 in Figure 6.15 from the street due to the fact that the gate was locked. The façade seen from the street, despite having some vertical cracks, seemed to suggest minimal damage, hence a damage level of D2 was assigned. However both the Pictometry and GEO-CAN assessments assigned D4, possibly due to the amount of debris seen on the roof towards the back of the building. The opposite has occurred with building 9-19, where in the satellite image the building looks intact but when viewed from the ground the building is obviously heavily damaged (Figure 6.16). Table 6.7 shows the breakdown of the damage grades assigned to the buildings in location 3.

Table 6.7. Breakdown of the damage grades assigned in location 9.

L9	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	10				2	6	18
Pictometry	9		0	2	1	6	18
EEFIT		3	2	2	4	7	18

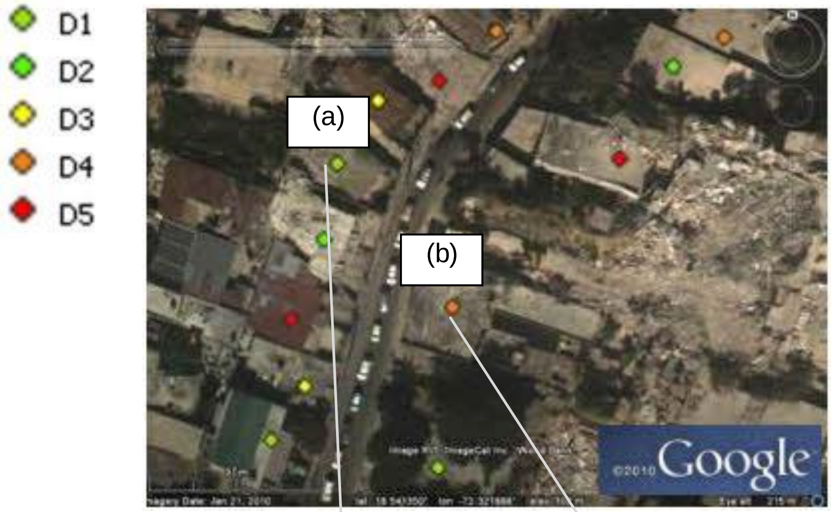


Figure 6.13: EEFIT surveyed buildings in Location 9 and the EEFIT damage grades.

Figure 6.14: Building (a) which looks intact from the outside. EEFIT team did not have access to the premise. The aerial photo of the same building in Figure 6.13 shows some disturbance on the roof. Both Pictometry and GEO-CAN assigned D4.

Figure 6.15: Building (b) which was assigned D4 by EEFIT. The same building looks intact in the aerial photograph in Figure 6.13. Pictometry and GEO-CAN assigned D1 and D0, respectively.

6.5.6 Location 17: High-density residential/commercial area

Location 17 is made up of mixed use buildings where the ground floor is used as commercial shops (Figure 6.17). The plot sizes are very small, and all buildings appeared to be reinforced concrete. The street that the EEFIT team surveyed is at the bottom of a valley. The remarkable fact about the buildings in location 17 seen in Figure 6.16 is that they had shown almost no sign of damage, including the buildings in the vicinity of the surveyed ones, although many of them were built on steep slopes.

Figure 6.16: Overview of location 17 where all buildings were assigned D1 by the EEFIT team.

Figure 6.17: Looking down the street along location 17 in Figure 6.16. Viewing direction: north to south.

Figure 6.18: Buildings almost intact in location 17, although built on a steep slope.

However, a few hundred meters further south on the same street, a lot of the buildings had collapsed as seen in Figure 6.19. Section 8.0 discusses further possible reasons for the difference in the performance of the buildings. Table 6.8 shows the breakdown of the damage grades assigned to the buildings in location 17.

Figure 6.19: Heavily damaged buildings in the area immediately to the south of location 17.

Table 6.8: Breakdown of the damage grades assigned in location 17.

L17	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	15				0	0	15
Pictometry	15		0	0	0	0	15
EEFIT		15	0	0	0	0	15

6.5.7 Location 22: Low/high-density residential area

Location 22 is situated on the foot of the hills on the south edge of Port-au-Prince. The plot size of the residential buildings is on average smaller than location 9 but larger than location 17. None of the buildings seen by the EEFIT team had collapsed completely in this location (Figure 6.20). There were a few buildings that were difficult to assign a single damage grade, particularly the building seen in Figure 6.21. All buildings surveyed in location 22 are reinforced concrete.

Figure 6.20: Overview of location 22 and the EEFIT damage grades.

Figure 6.21: Building with serious damage to the infill wall on the ground floor.

The building in Figure 6.21 was originally assigned D4 in the field and has subsequently being downgraded by half point to 3.5. This building demonstrates the difficulty of assigning a single damage grade.

Figure 6.22 shows the main street that the buildings in Figure 6.20 are facing. Table 6.9 shows the breakdown of the damage grades assigned to the buildings in location 22.

Figure 6.22: View of the main street in location 22.

Table 6.9: Breakdown of the damage grades assigned in location 22.

L22	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	8				0	0	8
Pictometry	7		0	1	0	0	8
EEFIT		1	2	2.5	2.5	0	8

6.5.8 Location 33: high-density residential area/commercial area

The buildings in location 33 are situated along a commercial street that gradually slopes downwards. The residential buildings are seen on the top of the hills whereas the commercial buildings are seen towards the lower part of the street. One building had already been demolished, marked as the D5 in the left row of buildings in Figure 6.23. The buildings are mostly 2 storey reinforced concrete, with the exception of the commercial buildings on the lower part of the street. There were no surprises in terms of the discrepancies between the remote damage assessment and the EEFIT assessment. Two buildings as viewed from the ground are shown in Figure 6.24. Table 6.10 shows the breakdown of the damage grades assigned to the buildings in location 33.

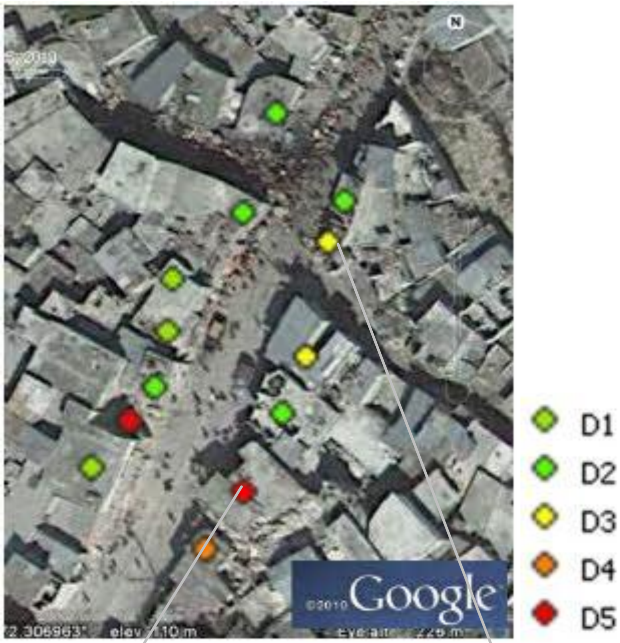


Figure 6.23: Overview of location 33.

Figure 6.24: (left) Completely collapsed building. Both GEO-CAN and Pictometry interpretations considered this building to be two separate buildings. (right) Heavy damage to infill wall on the third storey. This type of damage often cannot be seen from above.

Table 6.10: Breakdown of the damage grades assigned in location 33.

L33	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	13				0	0	13
Pictometry	6		2	2	1	2	13
EEFIT		3	3.5	3.5	1	2	13

Figure 6.25: Location 41 overview

(a) (b) (c)

Figure 6.26: (top left, *a*) Building *(i)* with soft storey collapse. The soft storey was nearly missed even from the ground. *b*) Next to building *(i)* is another soft storey building *(ii)*. (c) Street view showing the many heavily damaged buildings in location 41. View angle: north-east to south-west.

6.5.9 location 41: Low density residential area

Location 41 is a middle class residential area with generally large houses. EEFIT team focused on one side street where many soft storey collapses were observed (Figure 6.25). Due to the focus on residential buildings, the team surveyed 41 buildings in this location, which is by far the largest sample size among the locations. The soft storey buildings were mostly not captured by the remote damage assessment, and prove to be the most difficult in identifying using satellite imagery and vertical aerial photographs. It is not clear as to why so many buildings had soft storey on this one street. Heavy damage was also seen in the neighbouring streets. Two traditional timber frame buildings described in a later Section (Section 7.5.2) were in this location.

The heavily damaged buildings on this street were mostly not identified either by GEO-CAN or Pictometry. The view of this street using Pictometry is shown in Figure 6.27 where the soft storey buildings ***(i)*** and ***(ii)*** in Figure 6.26 are marked. Table 6.11 shows the breakdown of the damage grades assigned to the buildings in location 41.

Figure 6.27: Pictometry image of part of location 41

Table 6.11:. Breakdown of the damage grades assigned in location 41.

L41	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	35				3	3	41
Pictometry	12		6	5	6	12	41
EEFIT		2	3	6.5	6.5	23	41

Figure 6.28: Overview of the buildings in location 55, surveyed by the EEFIT team.

(a)

(b)

(c)

Figure 6.29: (a) A D3 building. Damage to the walls could not be seen even in Pictometry. (b) One of the main hospital buildings with no apparent damage. EEFIT team inspected the building from the inside. (c) The tent clinics erected outside the damaged buildings.

Location 55 is the Port-au-Prince General Hospital. The complex consists of engineered buildings (Figure 6.28). One of the dormitories for student nurses had completely collapsed (D5: red dot in Figure 6.28), unfortunately resulting in a considerable number of fatalities. Some buildings were unsafe to be used; hence, temporary tents were erected outside these facilities where the patients were treated outdoors (Figure 6.29). Table 6.12 shows the breakdown of the damage grades assigned to the buildings in location 55.

Table 6.12: Breakdown of the damage grades assigned in location 55.

L55	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	8				1	0	9
Pictometry	8		0	0	0	1	9
EEFIT		4.5	0.5	3	0	1	9

6.5.10 Location 61: Delmas 33, low density residential area

Location 61 is on the north side of the main road in Delmas that runs from west to east through Port-au-Prince (Figure 6.30). The area is a low density residential area, and the plots in this location are generous. According to one of the residents 8-10 people typically live in one property. Many of the houses have a wall over 2m high which restricted the view of the buildings from the street.

One building under construction had heavy damage, which was captured by the Pictometry assessment as well and assigned D5 in both cases. A soft storey building assigned D5 by the EEFIT team was assessed as D4 in Pictometry. Both buildings were missed by GEO-CAN. Table 6.13 shows the breakdown of the damage grades assigned to the buildings in location 61.

Table 6.13: Breakdown of the damage grades assigned in location 61.

L61	nvd	D1	D2	D3	D4	D5	*Total*
GEO-CAN II	9				0	0	9
Pictometry	6		1	0	1	1	9
EEFIT		6.5	0.5	0	1	1	9

Figure 6.30: Overview of the buildings surveyed in location 61.

Figure 6.31: (left) Building under construction that suffered heavy damage, (right) soft storey building. Both buildings were assigned D5 by EEFIT, D5 and D4 by Pictometry, but were missed by GEO-CAN.

6.5.11 Damage summary

Table 6.14 shows the summary of the damage grades assigned to buildings in each location visited by the EEFIT team. The EMS98 damage levels were used for the assessment. Note: when it was difficult to attribute the building to a single damage grade, the middle point between two integers was used.

Table 6.14: Summary of the damage levels assigned to buildings in each location by the EEFIT team

	D1	D2	D3	D4	D5	Total
L1	3.5	4	1.5	1	2	12
L3	9	5	1	1	1	17
L9	3	2	2	4	7	18
L17	15	0	0	0	0	15
L22	1	2	2.5	2.5	0	8
L33	3	4	4	1	2	13
L41	2	3	6.5	6.5	23	41
L55	4.5	0.5	3	0	1	9
L61	6.5	0.5	0	0	2	9

6.6 Comparison of the remote damage assessments to the damage survey carried out on the ground by EEFIT team

The EEFIT damage assessment was subsequently used to validate the remote damage assessment results described in Section 6.2. The results of the comparison between the three separate damage assessments of the 142 buildings using vertical aerial photographs, Pictometry and EEFIT ground survey is shown in Tables 6.15 to 6.17.

Table 6.15: Comparison between EEFIT ground observations and Pictometry.

		EEFIT Ground Observation					**Pictometry totals**	Commission error (note 4)
		D1	D2	D3	D4	D5		
Pictometry	nvd	43	13	15	7	4	**82** (58%)	48%
	D2	2	1.5 [a]	1.5	2	3	**10** [b] (7%)	85%
	D3	1.5	2	1.5	3	6	**14** (10%)	89%
	D4	1	4	1	3	3	**12** (8%)	75%
	D5	0	0	1	1	22	**24** (17%)	8%
Ground obs. totals		**47.5** (33%)	**20.5** [c] (14%)	**20** (14%)	**16** (11%)	**38** (27%)	**142** (100%)	
Omission error (note 4)		9%	93%	93%	81%	42%	Kappa index (note 5): 0.31	

Table 6.16: Comparison between EEFIT ground observations and GEO-CAN II.

		EEFIT Ground obs.			**GEO-CAN II totals**	Commission error (note 4)
		D1-D3	D4	D5		
GEO-CAN II	nvd	83	15	23	**121** (85%)	31%
	D4	4	0	5	**9** (6%)	100%
	D5	1	1	10	**12** (8%)	17%
Ground obs. totals		**88** (62%)	**16** (11%)	**38** (27%)	**142** (100%)	
Omission error (note 4)		6%	100%	74%	Kappa index (note5): 0.22	

Table 6.17: Comparison between Pictometry and GEO-CAN II.

		Pictometry			**GEO-CAN II totals**	Commission error (note 4)
		D1-D3	D4	D5		
GEO-CAN II	nvd	102	9	10	**121** (85%)	16%
	D4	3	2	4	**9** (6%)	78%
	D5	1	1	10	**12** (8%)	17%
Pictometry totals		**106** (75%)	**12** (8%)	**24** (17%)	**142** (100%)	
Omission error (note 4)		4%	83%	58%	Kappa index (note 5): 0.43	

Notes:

1) Matrices show numbers of buildings assigned to the damage levels of two surveys.

2) Where a building was assigned with damage intermediate between two states, it appears under both headings as 0.5 – e.g. a building intermediate between damage states D2 and D3 appears as 0.5 at D2 and 0.5 at D3.

3) Damage states are defined in Table 6.2.

4) Using the symbols shown as a, b and c for damage ratio D2 in Table 6.15 as an example:

commission errors is derived as: (1 – a/b),

omission error is derived as: (1-a/c).

5) The Kappa index is a well established discrete multivariate technique used for the accuracy assessment of classification results (Congalton, 1991). The Kappa index has a range of values between [0,1] with 1 meaning perfect agreement and 0 indicating a pattern resulting from chance. Kappa index K_{hat} is derived using the following formula:

$$K_{hat} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}$$

where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, and x_{i+} and x_{+i} are the marginal totals for row i and column i (the total rows and columns), respectively. N is the total number of observations (Jensen, 1996).

6.7 Discussion

(1) Improving the accuracy of remote damage assessments

(a) Identifying soft storey failures from remote images

Detailed assessment of the comparison between the EEFIT damage survey results and the remote damage assessment showed that missing soft storey failures contributed the most to the errors for D5 (Spence and Saito, 2010). The problem with soft storey collapse is that from above, the footprint does not look changed, but the building height is of course lowered. If accurate roof heights could be obtained before and after an earthquake, then soft storey failures would be much easier to identify. Height information is not available from vertically captured images and alternative methods are being investigated. One possibility is to use LiDAR images to identify soft storey collapses, since they measure surface heights as well as extract building footprints. However, obtaining LiDAR data is costly, and the images may well not exist pre-earthquake, even if they could be taken post-earthquake.

(b) The problem of damage level D4

The accuracy level for D4 was surprisingly low (Table 6.15) and is the most problematic (also see Corban *et al*, 2011), due to the fact that many of the clues to identify D4 are not visible in vertical images. Overall, even with the oblique Pictometry images, only 67% of the EEFIT D4+D5 buildings were identified by Pictometry (i.e 36 out of 54 – see Table 6.15). Further assessment of the D4 and D3 buildings are being planned to establish the types of damage associated with D3 and D4 that can be identified from Pictometry images.

(c) Use of Bayesian methods

Booth *et al* (2011) discuss the use of Bayesian methods to reduce the uncertainty of damage assessments of a large number of buildings based on remote images by using a ground based survey of a sample of the total number of buildings. These procedures, which were demonstrated using the EEFIT Port-au-Prince data, appear promising, although more development work is needed.

(d) Developing correction factors for remotely obtained data

The obstacle to the more general use of remote damage assessment to date has been in the lack of validation data. Without validation data, it is difficult to assign a confidence level to the remote sensing based assessment. In that sense, Haiti is the first case study where validation data is being used to analyse the reasons for misinterpretations as well as assessing the accuracy of the overall remote damage assessment. It is expected that repeating this type of validation data collection in future events and comparing the results to the remote damage assessment will allow us to come up with a confidence level to assign to the remote damage assessments. Some examples of the questions that are being asked are: can remote damage assessments achieve a relatively constant level of accuracy, or will there be variation from case to case? If so, will it be possible to establish correction factors to be applied to remote damage assessment results, which would be a function of such parameters as ground motion intensity, construction type, soil conditions and so on?

(e) Definition of damage states

One surprising finding of the EEFIT survey was that there were no satisfactory definitions of damages states suitable for applying to a comprehensive range of buildings types, and for using with a variety of remote sensing methods, as well as ground observations. Developing a universal set of damage definitions is considered an important task for the international earthquake engineering community.

(2) Sampling methodology

The size of the sample of buildings surveyed by EEFIT in Port-au-Prince was relatively small (i.e. 142), and the sample does not appear to be representative in terms of damage distribution. Statistically, it would be necessary to collect information on a considerably larger sample to come up with a representative sample. Nonetheless, it was extremely useful from the point of view of remote damage assessment, to be able to compare the EEFIT validation data against the remote damage assessments. The limitations in the number of buildings were constrained by the size of the team and time available on site to the EEFIT team. For future missions, plans can be drawn taking into account the above considerations.

(3) Importance of data preparedness

One of the difficulties of reconciling the three different datasets (GEO-CAN, Pictometry and EEFIT) was that the buildings being compared sometimes were not the same buildings. What was considered to be a building unit in the aerial photograph in some cases turned out to be two buildings, or the opposite. To reduce the errors that arise from this type of inconsistency, it would be extremely useful to have a land registry map with all the building footprints already mapped. In the case of the joint remote assessment, UNOSAT and SWISSTOPO created a dataset consisting of pre-event building points, which was used as a base map to produce the post-event damage assessment. In the event that a land registry is not available, it might be worth investing time in creating a pre-event building point (or footprint) dataset from remote images taken before a disaster, to avoid confusion.

7.0 PERFORMANCE OF STRUCTURES

7.1 Introduction

A systematic survey of structural performance in the earthquake was not undertaken. The following observations were made during the course of the assessments described in Section 6.0.

7.2 Masonry buildings

The majority of more recent buildings in Port-au-Prince are one or two storey, made from solid or hollow blocks or bricks, using cement mortars. It is reported that older buildings are of brick or rubble stone masonry, but EEFIT collected no information on these. There is a variety of roof types, including flat concrete roofs and timber truss roofs with corrugated iron cladding. Some reinforced concrete elements appear to exist in most buildings; suspended floors generally appear to be *in situ* reinforced concrete, and vertical concrete elements were also present in many buildings. Some of these vertical elements take the form of columns, many of which are free standing elements supporting entrance canopies or balconies; more rarely, they are part of a complete concrete frame infilled by masonry. However, in many cases (possibly the majority), the vertical elements are cast after construction of the masonry, to form ‘confined masonry’.

As noted in Section 7.7, the fine aggregates used to make concrete and mortar are very poorly graded, leading to poor compressive strength. This probably played a part in the scale of destruction. However, the impression the team gained was that low strength of the blocks and bricks used was not the major cause of failure, since the masonry units did not appear to be very weak, although they may well not have complied with current seismic code standards.

The effectiveness of confined masonry under seismic loading is much less dependent on ductile detailing of the confining elements. It therefore might have been hoped that the confined masonry buildings in Port-au-Prince would have received some protection, even if the confining elements fell below current seismic code standards. There are some reports that the confined masonry houses did indeed perform better than other ‘non-engineered’ construction types in Haiti such as unconfined masonry or concrete frames with infill masonry; however EEFIT team did not see any evidence of this. Since confined masonry offers such promise as an earthquake resistant construction type suitable for owner built and other non-engineered buildings, its performance in Port-au-Prince would repay detailed study, with the view of determining what minimum standards are required. Whatever those minimum standards are, it seems that the Port-au-Prince buildings fell well below them.

7.3 Engineered concrete buildings

There are probably fewer than twenty buildings taller than five storeys in Port-au-Prince. At least one nine-storey building is reported to have collapsed, and there was evidence of damage to some that the EEFIT team passed. However, it was also reported that some buildings, including the Digicel Building which has 13 storeys, were only lightly damaged. The low rise US Embassy building, completed a year or two before the earthquake, was also reported to have performed very well.

The team inspected a curious reinforced concrete folded plate roof structure in Léogane (Figure 7.1), which was reported to have been built as a market in the ‘Papa Doc’ era and therefore presumably predates the dictator’s death in 1971. There was some spalling of surface concrete at one of the support points (Figure 7.1, bottom photo) but no other signs of damage. The structure would probably have responded as a rigid body to the earthquake (unless soil flexibility was significant, which is a possibility) so this level of damage might make a rough estimate of the peak ground acceleration possible.

Figure 7.1: Market building, Léogane

7.4 Steel structures

Apart from the occasional steel joist or column seen in predominantly concrete or masonry buildings, the only significant steel frame structures that the team encountered were a pair of large warehouses on the reclamation behind the failed wharf in Port-au-Prince main harbour; the wharf failure is discussed in Section 4.3. Figure 7.2 shows internal and external views of the eastern warehouse, which was approximately 250m long and 50m wide. The building envelope was supported by single span steel portal frames at 30m centres, clad with light weight corrugated steel cladding.

Figure 7.2: Port-au-Prince main port warehouse

The eastern warehouse was inspected internally. The failure of the wharf on which the warehouse was built resulted in large settlements of some of the southern (port side) foundations of the portals, in the order of 1 to 2 metres, and lateral displacements of up to 0.7m (Figure 7.3) . Figure 7.4 shows that this resulted in extensive buckling of the roof beams, but remarkably the structure had been able to accommodate these deformations without collapse. It is likely that the foundation settlements occurred a few minutes after the main shaking had ceased, because the liquefaction induced ground failure would have taken this length of time to develop. Therefore, ground shaking and large ground deformation would probably not have loaded the structure simultaneously. There was no evidence of any ground shaking damage to the building, which probably would have survived the earthquake essentially undamaged had there been no ground failure.

Figure 7.3: Lateral and vertical displacement of warehouse foundation

Figure 7.4: Buckling of warehouse roof beams

Figure 7.5 shows that the column foundation on the SE corner of the warehouse did not settle, while the foundation immediately to the east settled by one or two metres. It appears that the corner column held up because the braced eastern gable end of the warehouse, supported on a large concrete ground beam, acted as a beam supporting the corner column and transferring its load back northwards to part of the reclamation that suffered only minor settlement.

Figure 7.5: Settlement of columns in SE corner of warehouse

7.5 Historic buildings

7.5.1 The Iron Market

a) Introduction

This iconic structure, a symbol of Port-au-Prince appearing on some of Haiti's banknotes, was fabricated in France at the end of the nineteenth century and subsequently shipped to site. Following a fire in 2008, which destroyed nearly half of the facility, the UK architectural firm John MacAslan & Associates was engaged before the earthquake to design a refurbishment scheme for the market. Alan Baxter Integrated Design acted as structural advisors to MacAslan for the refurbishment, although detailed engineering was subsequently prepared by a US based structural consultancy, Axis.

The information and photos for this Section were kindly supplied by Robert Bowles of Alan Baxter Integrated Design. Further information can be found on the John MacAslan website (http://www.mcaslan.co.uk/projects/iron-market).

b) Description of the building

Figure 7.6 shows a model of the market as originally built. Two identical covered market buildings, called north and south, were separated by an ornate clock tower. Each covered market consisted of a single storey, 3 bay portal shed, formed from cast iron columns supporting a trussed roof, principally made from riveted wrought iron, in turn supporting a pitched galvanised iron roof with a clerestory. Each bay is 120m long, with a height to the ridge line of 25m; the central bay is 25m wide and the two outer bays are 20m wide.

Figure 7.6: Model of the Iron Market
(photo reproduced by kind permission of John McAslan & Partners)

Figure 7.7: Internal view of south market, looking towards the south end

Standing centrally between the two markets is a curious ornate clock tower (Figure 7.8), fabricated from riveted 6mm thick wrought iron plate. There are four corner columns, each surmounted by a gallery, and together supporting a central suspended chamber. It seems that the clock tower was originally intended for Cairo railway station, but that order was cancelled, and it became Port-au-Prince's iconic building instead.

Figure 7.8: The clock tower

In order to increase the covered market area, a concrete canopy supported on reinforced concrete columns was added in the space between the north and south markets and to either side of the clock tower (Figure 7.11).

c) Condition immediately before the earthquake

In 2008, a fire severely damaged the north market, which suffered almost total collapse. It appears that the south market and the clock tower were much less affected by the 2008 fire.

From structural inspections by Robert Bowles of Alan Baxter Design carried out in February and March 2010, it is clear that the clock tower was severely corroded at the time of the earthquake. For example, the mating surfaces in the vertical seams in the columns had been forced apart by corrosion products (Figure 7.9). In consequence, some of the seam rivets had failed in tension. The column bases were particularly severely corroded.

Figure 7.9: Corrosion of a column in the clock tower

By contrast, the south market was much less severely affected by corrosion. In particular, the cast iron columns, which were cast in one piece and hence were unjointed, were in excellent condition. The roof trusses and horizontal bracing at eves level was corroded to some extent, but generally this did not appear to reduce their capacity significantly. The rectangular trough guttering in the roof valleys were the most seriously corroded elements, and had been filled with concrete as a remedial measure to preserve water tightness of the roof (Figure 7.10).

Figure 7.10: Corrosion around roof valley in south market

The good corrosion performance of the markets was attributed to the use of cast iron in the columns, which is less prone to rusting than wrought iron, and to adequate detailing of the cladding around the wrought iron plate elements, which generally (except in the valley gutters) prevented ponding of rain water. By contrast, the clock tower was fabricated entirely from thin plate wrought iron, which is inherently prone to corrosion. It may also be noted that it seems to have been originally intended for a location in Cairo, which has an annual rainfall of 25mm, compared with Port-au-Prince's 1350mm and a significantly higher relative humidity.

d) Performance in the earthquake

The modern concrete canopy structure between the north and south markets collapsed entirely (Figure 7.11). The parts of the south market which were contiguous with the concrete structure also collapsed; elsewhere there were almost no signs of damage. The north market had already mainly collapsed in a fire about five years earlier.

Figure 7.11: Failure of concrete canopy adjacent to north west corner of south market

Note: the canopy elsewhere had been demolished and removed at the time of this photo; the remaining portion was kept in place temporarily to stabilize the adjacent market structure

The clock tower suffered severe damage to the bases of its four columns, which split at the seams and became partially detached from the baseplates, causing significant shortening (Figure 7.12a). This lead to a pronounced tilt of the tower, but (as can be seen from Figure 7.8) it remained stable. Infill masonry in spandrel panels at high level also cracked under high shear deformations, but remarkably remained mainly in place, possibly as a consequence of the use of lime mortars (Figure 7.12b). A fire which broke out after the earthquake is also thought to have damaged the clock tower.

(a) Column base

(b) Performance of infill masonry spandrels (composite of two photos)

Figure 7.12: The clock tower

It appears that in the absence of the concrete canopy, the south market would have performed well in the earthquake, and the sole cause of the partial collapses was buffeting by the canopy against the columns, rather than inherent design or maintenance defects. By contrast, corrosion certainly played its part in the clock tower failure, although no doubt buffeting by the canopy also played an important part.

e) Refurbishment

In order to stabilise the clock tower during its dismantling, concrete boxes were cast around the base of its columns (Figure 7.13). The four galleries surmounting the columns were then burnt free and craned off, for later reuse. The remaining parts of the clock tower were then dismantled, and the tower reassembled, reusing parts where possible and replacing with mild steel plates of similar geometry and detailing where not possible.

Figure 7.13: Refurbishment of the clock tower

Refurbishment of the south market consisted of replacing the collapsed and heavily corroded sections with mild steel equivalents and providing moment fixity to the bases of the columns, which in their original design sat on steel baseplates cast into the foundation slab, with no positive connection between column and baseplate. The base fixity was provided to resist wind rather than seismic actions. The north market was entirely demolished and replaced with a mild steel structure of similar dimensions and similar structural form.

7.5.2 Historic timber buildings

A number of two and three storey timber frame buildings were observed in Port-au-Prince and Léogane. They date from the end of the nineteenth or early twentieth century and are dubbed 'gingerbread houses' (Figure 7.14). In 1925, new timber frame construction is understood to have been banned in Port-au-Prince to prevent fire, so presumably this gives their latest date of construction. Although some of the buildings were poorly maintained, none of the fifteen or so gingerbread houses which the EEFIT team saw had collapsed. However, there are reports that some of the smaller houses were completely destroyed and many of the larger houses suffered serious structural damage including some that lost facades and walls.

(a) Front façade (b) Detail showing poor maintenance

Figure 7.14: 'Gingerbread house' in Port-au-Prince

Figure 7.15 shows a single storey timber and masonry building in the main square of Léogane in poor condition, which survived, despite being close to two or three storey concrete and masonry buildings which had collapsed. This is a form of construction known as 'colombage', consisting of timber frame with infill masonry walls. The good tensile strength of timber and its favourable strength to mass ratio are likely to have been contributory factors in its survival; it would be interesting to know if local variations in the intensity and frequency content of the ground motions also played a part. Unlike Port-au-Prince, where dramatic local variations in ground motion were found at geological boundaries (Section 8.4) , Léogane is in area which is essentially flat and has no obvious signs of variations in the surface geology.

Much more extensive information on the performance of timber and other historic buildings in Port-au-Prince during the earthquake is given by Langenbach *et al* (2010).

Figure 7.15: Single storey timber and masonry (colombage) building in Léogane

7.6 Bridges

During their journey between Port-au-Prince and Grand Goâve (Figure 3.1), the team observed four concrete river bridges. They were all of recent concrete construction, built to a high standard, with one or two river piers. The deck spans were between 20m and 30m, and each span was simple supported at each end, with expansion joints over the piers and abutments (Figure 7.16).

(a) (b)

Figure 7.16: Bridge at Lemartin west of Port-au-Prince, near Carrefour

One of the bridges was impassable, but had been rendered so by extreme river flow in a hurricane a few years earlier. The three other bridges were open to traffic and it appeared that no significant post-earthquake repairs had been carried out. The main structural damage, which occurred in two of the three bridges, was to the lateral restraining elements at the supports (Figure 7.16b). There were no significant settlements either relatively between deck spans, or of the fill at approach abutments.

7.7 Local quarry sand and its effect on concrete strength

It is understood that much of the material used in the capital as fine aggregate for concrete and mortar comes from crushed rock taken from quarries in the hills above Port-au-Prince. The grading of this material would be expected to result in much poorer concrete strength and compactability than concrete or mortar made with river dredged fine aggregates, and this is likely to have been one factor in the poor performance of concrete and masonry buildings.

The EEFIT team visited one of the largest quarries, and this is discussed in Section 5.2.

8.0 DAMAGE DISTRIBUTION

8.1 Introduction

The EEFIT team observed striking variations in damage across Port-as-Prince, with apparent concentrations of damage in the low lying areas around the port, and also in higher ground on rock in the Canapé Vert region (Section 6.5.6). EEFIT were unable to carry out a systematic study of this clustering of damage, but it appears to be confirmed by interpretation of aerial images, which all indicate that the density of damaged buildings varies widely across the built area of Port-au-Prince. Possible reasons for this clustering are now discussed.

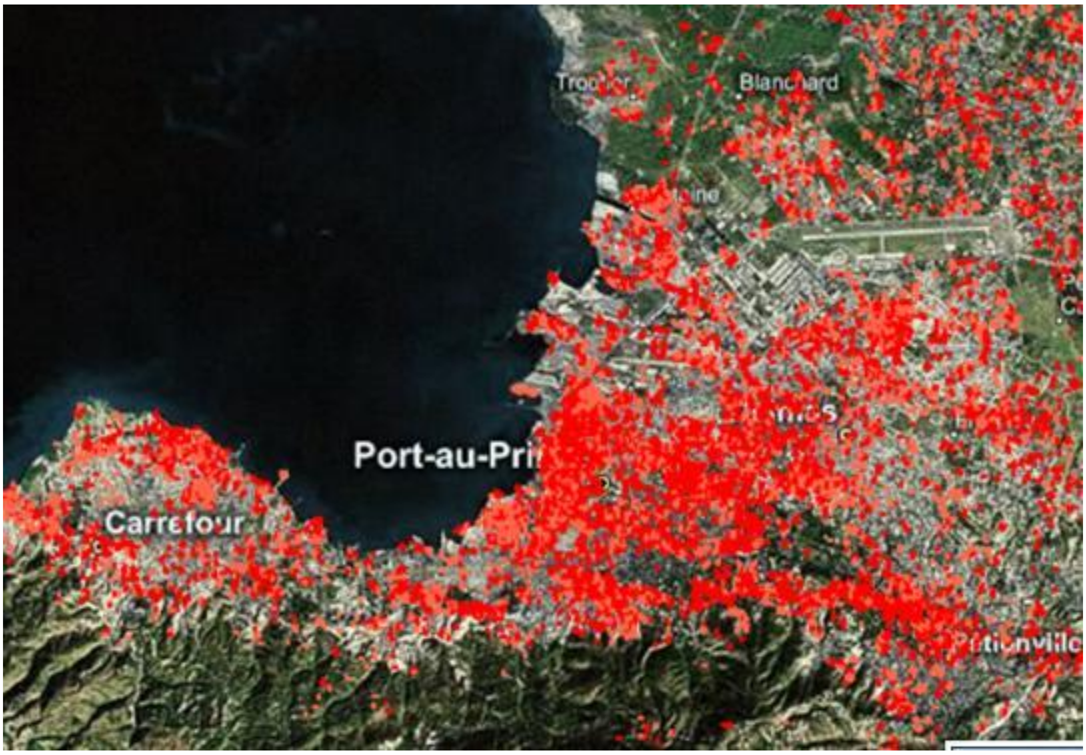


Figure 8.1: GEO-CAN damage map

8.2 Site amplification effects

From the experience of many previous earthquakes, supplemented by numerous analytical and experimental studies, the soft soil sites around the port, consisting of reclamation and alluvial materials, would be expected to amplify ground motions and lengthen their period, generally leading to greater damage. Both EEFIT observations and aerial photographs provide evidence that this did indeed occur. However, most of Port-au-Prince is built on rock, and other explanations must be sought for the clustering of damage found there.

8.3 Topographical effects

Some of the striking features of Port-au-Prince are its hills and slopes. Different parts of the city have moderate sized hills separated by valleys. This uneven topography may have resulted in topographic effects. It is well known that presence of steep slopes or hills will cause an increase in ground accelerations; a quantification for this amplification can be found in Annex A of Eurocode 8 Part 5 (EN1998-5:2004). EEFIT gathered no clear evidence for this having occurred in Port-au-Prince; there appeared to be no consistent pattern of higher damage at the tops or bases or steep slopes, as would be expected from Eurocode 8. Further studies would be needed to establish whether or not topographical effects were important in the city.

8.4 Geological boundaries

A striking example of damage clustering was found near location L17 of the EEFIT survey in the Canapé Vert district of Port-au-Prince (Section 6.5.6). Heavy damage occurred only a few hundred meters from a site on the neighbouring hill, where buildings performed very well with only minor damage (Figure 8.4). Even the dry stone retaining walls did not show any signs of distress as seen in Figure 8.4(a).

(a) Light damage (b) Heavy damage

Figure 8.4: Damage clustering in Canapé Vert

There was no obvious difference in construction type or quality between the two sites, and no immediately clear differences between topology and surface geology; both were steep and rocky. However, it appears that the boundary between light and heavy damage, which was dramatic, occurred on the junction between two geological rock types (Figure 8.5). The two rock types were:

Pliocene/pleistocene conglomerate of alluvial fans or deposits of banks formed of coarse angular breccia (light damage) and

Pliocene deposits along the edge of mountains forming a complex of strongly dissected alluvial paleo-fans (heavy damage).

A possible explanation based on the above differences in rock geology is that the differences in weathering patterns and/or differences in rock stiffnesses may have led to differences in wave propagation and topographic amplification at the two sites. This may have resulted in the vast differences in the damage patterns observed at the two sites.

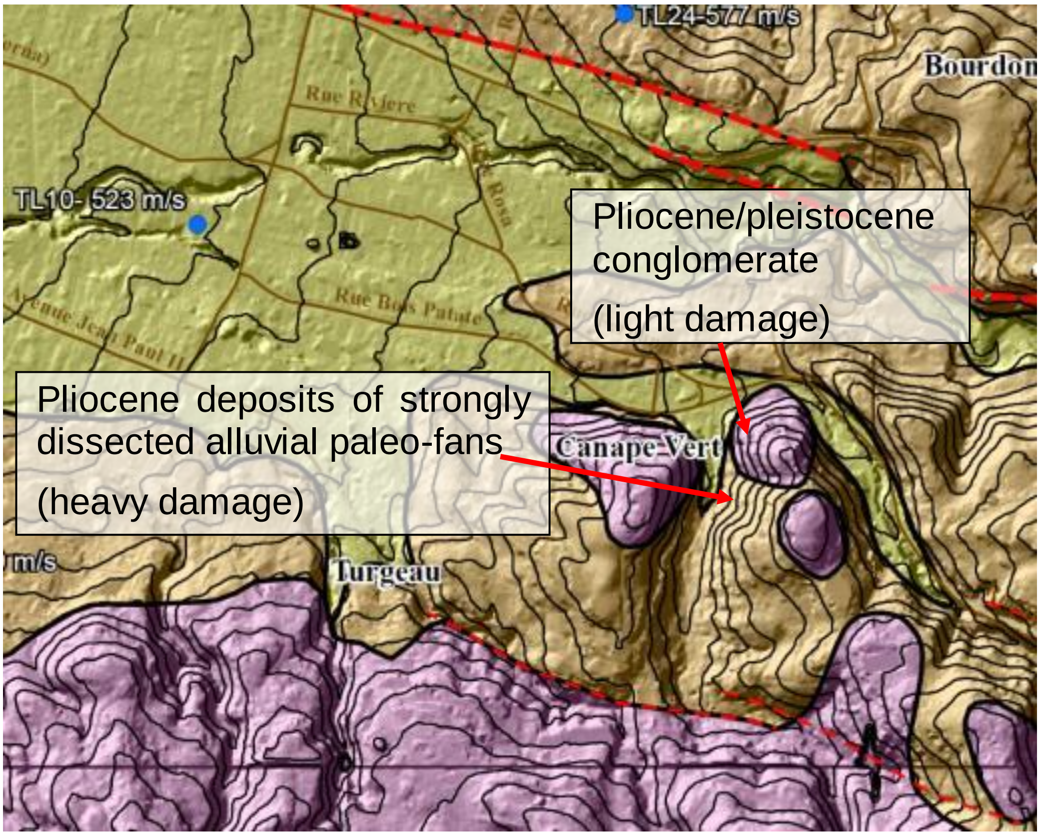


Figure 8.5: Geological boundaries in Canapé Vert
(adapted detail from Bachuber *et al*, 2010)

8.5 Landslides and soil failure

EEFIT observed a number of cases where building failure was caused by failure of the foundation soils, for example Figure 8.6.

Figure 8.6: Damage to a house in location L at the top of a 10% gradient hill

Another example of a building that was located at the top a steep slope is presented in Figure 8.7. As seen in the Figure, part of the building has completely collapsed onto buildings at lower level. Another building next to it has survived and the retaining wall protecting this part only showed minor signs of distress. A foundation pit was being dug at this site as shown in Figure 8.7, showing silty clay soil. A soil sample was recovered from this pit by the EEFIT team and was analysed on return to the University of Cambridge using the optical Accusizer. The particle size distribution curve for this soil sample is presented in Figure 8.8.

The particle size distribution curve confirms the clayey silt nature of the soil at this site, with the maximum size of particles being about 0.6 mm and D50 size of the sample being about 0.003 mm. The nature of this soil and the steepness of the slope may have contributed to the amplification of ground accelerations felt by the building at the top of the slope.

(a) Overview of failure (b) Excavation near base of slope

Figure 8.7: Site with soil failure causing building collapse in Delmas

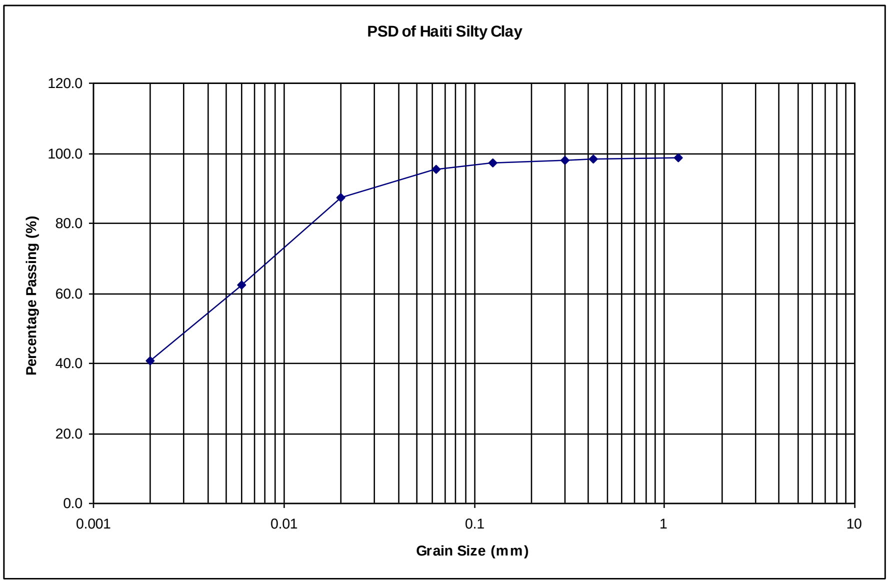


Figure 8.8: Particle size distribution curve of the clayey silt sample

On the basis of an examination of Pictometry images, Langenbach (see http://conservationtech.com/haiti.html) has postulated that the damage clustering observed in rocky areas, such as was discussed in Section 8.4, may at least in part be more generally explained by soil failure of the surface soils leading to foundation and structural failure, triggering a domino effect as houses at the top of the slope fell onto houses lower down. EEFIT was not able to gather any systematic evidence for or against this hypothesis from its ground observations, but it appears a promising line of investigation to pursue.

8.6 Building vulnerability

The quality of buildings that the EEFIT team observed was variable, although in general structural vulnerability was high. In the short space of time available, the team did not observe any clear evidence that the highly non-uniform distribution of damage referred to in Section 8.1 was anywhere primarily caused by variability in structural vulnerability. More extensive surveys would be needed to confirm this.

9.0 DISASTER MANAGEMENT AND PREPAREDNESS

The scale of the disaster that struck Haiti on 12th January 2010 was a function of a number of factors, which including seismological, engineering and social aspects. EEFIT, and the broader engineering and disaster management community in the UK, should be able to contribute to the international examination of the lessons to be learnt with respect to a number of factors, including what made Port-au-Prince particularly vulnerable to an earthquake, the features of its society which enabled it to cope in the way it did, and the effectiveness of the local and international community in responding to the disaster at a number of timescales (short, medium and long term).

In 1995 the Institution of Civil Engineers (1995) published a review of the ability of large cities in developing countries to cope with natural disasters, including but not restricted to earthquakes. Three 'megacities' (Karachi, Manila and Jakarta) were studied, with site visits to hold discussions with local personnel, and a series of recommendations were made. It is hoped to apply for funding from the Institution of Civil Engineers' Research to re-examine this study, particularly in the light of events in Haiti. EEFIT has good links to the disaster relief organisation RedR (www.redr.org.uk) and to various academic centres of study in disaster relief, including that at University College London, which would be valuable in the preparation of this re-examination.

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 Damage assessments made from remote images

1) The EEFIT ground survey in Port-au-Prince appears to have been the first detailed and systematic verification exercise to compare ground assessments of damage with those made remotely. A total of 142 buildings were compared, and significant discrepancies were found between ground assessments and those made remotely using high quality vertical and oblique aerial images. Some heavy damage was missed from the remote assessments, mainly because damage was obscured by vegetation and other buildings, or because soft storey collapses were not evident when the upper storeys were largely intact. More rarely, remote sensing overestimated damage for reasons including cases where remote assessments grouped undamaged buildings with adjacent damage ones, and where roof stored materials were mistaken for damaged structure.
2) The sample size was only 142 buildings, and while the general tendency of remote assessment to underestimate damage was, as expected, confirmed, more data are needed to establish whether the scale of the underestimate found in Port-au-Prince (a factor of 1.5 to 2 for the high damage states D4 plus D5) is more generally applicable.
3) Rapid damage assessments made by remote sensing played a vital role in the relief effort in Haiti, and will undoubtedly continue to do so in future disasters. It is therefore important to develop methods by which such assessments can be improved. A number of possibilities exist, which are discussed by Booth *et al* (2011). One possibility is the development of standard correction factors for the remote assessments, determined as a function of factors such as intensity of ground motion, terrain and construction type. Another is the use of a detailed ground survey of a small sample of buildings, originally assessed by a larger remote survey, being used to improve the original remote assessments using statistical techniques.
4) While heavy damage can be observed from vertical images, they do not reveal the proportion of buildings which are only moderately or lightly damaged.
5) The goal of producing an internationally agreed set of damage definitions is proposed as an important task. The set would need to be suitable for post-disaster needs assessments as well as for other uses, including estimates of future losses, and for damage assessments made both by ground observation and remote sensing. The definitions should cover a wide range of engineered and non-engineered building types. This task could be undertaken as a contribution to the Global Earthquake Model (www.globalquakemodel.org).

10.2 Variability of damage in Port-au-Prince

1) No strong ground motion records were obtained from the main shock of the earthquake, so the intensity and variation of ground motion across Port-au-Prince can only be inferred from observed effects, and in particular building damage, supplemented by theoretical models.
2) The EEFIT team observed significant non-uniformity in damage to buildings across Port-au-Prince; some areas were heavily damaged, while neighbouring areas in apparently similar terrain were very much less damaged.
3) This clustering of pockets of damage appears to be confirmed by aerial photos as a pattern repeating over the whole of the built up area of the Port-au-Prince region.
4) The clustering could not be explained in terms of distance from the causative fault.
5) The limited evidence gathered by EEFIT suggested clearly that differences in construction type and quality could only explain part of the clustering.
6) Soil amplification effects were likely to have caused the cluster of damage observed on the alluvial areas near the port, but there was also much clustering in rocky areas of the city.
7) Topographical effects observed in previous earthquakes, in which ground motion amplification is found at the foot and ridges of rocky slopes, may have caused some of the clustering, but EEFIT could find no clear evidence either for or against this having occurred in Port-au-Prince.
8) A cluster of damage was observed by EEFIT at one location in Port-au-Prince (the Canapé Vert district), next to a location of similar topography and building type where little damage occurred. It appears that the boundary between light and heavy damage, which was dramatic, occurred on the boundary between two geological rock types. No definitive explanation of a causative mechanism was found by EEFIT for this phenomenon. A possible

explanation is that differences in weathering patterns and/or rock stiffnesses may have led to differences in wave propagation and topographic amplification at the two sites, causing sharp differences in ground motion and hence also in building response.

9) It has been conjectured that another mechanism for the clustering in areas of steep slopes was the occurrence of shallow slips at the damage clusters, but the limited observations of EEFIT were not able to confirm or reject this hypothesis, which appears well worth investigating further.

10.3 Liquefaction

1) Extensive soil liquefaction was observed in the port area that has led to extensive damage to the gantry crane facilities, collapse of sections of the north pier and south wharf. In fact at the time of the EEFIT visit the port was operating partially with help of floating barges that were deployed by the US Army,
2) Damage to the port facilities in this earthquake had significant impact on the flow of emergency relief measures. One of the lessons from this earthquake is to mitigate the risk to port structures so that they can function in the immediate aftermath of a large earthquake.
3) Large settlements were observed following liquefaction at the island within the port area that housed the Harbour Master's offices and control gear. This has led to significant settlement of bridge piers leading to articulation of the bridge decks and the bridge deck concrete cracking to form a plastic hinge. Settlement of bridge piers in liquefiable soils needs to be well understood and mitigated to prevent damage in future earthquakes.
4) Liquefaction induced lateral spreading was observed in the port area particularly near large silos and on the island. Luckily the large silos in the port are well designed and therefore suffered very little damage. However adjacent storage facilities suffered severe damage. Lateral spreading at the island destroyed small wharf structures due to failure of piles that were subjected to large lateral loads.
5) Liquefaction induced lateral spreading was also observed at other sites. EEFIT visited a particular site near Grand Goave where a group of small houses were founded on a clay crust that suffered lateral spreading over a liquefied layer at depth. These houses were constructed recently by an NGO following the hurricane, but were damaged due to lateral spreading. Older houses in the vicinity of this site have totally collapsed.

10.4 Landslides

1) Landslides were observed in the cuttings next to road embankments and in some cases these blocked the carriage way.
2) Shallow landslides were also observed in steep slopes in the hills close to Pétionville.
3) Sand quarries with steep slopes were the main source of building materials in Haiti. While some landslides were observed in these sand quarries, these in themselves did not cause much damage. However, the risk of further landslides in future hurricanes may develop into a major issue that should be addressed urgently in Haiti, given the close proximity of housing to these features.

10.5 Structural performance

1) The majority of buildings inspected were built from masonry, generally in conjunction with some lightly reinforced concrete elements. Construction quality and concrete quality were generally poor.
2) The EEFIT team did not see any evidence that the confined masonry buildings performed any better than other construction types, such as unconfined masonry or concrete frames with infill masonry; however, other observers have suggested otherwise. Since confined masonry offers promise as an earthquake resistant construction type suitable for owner built and other non-engineered buildings, its performance in Port-au-Prince would repay detailed study, with the view of determining what minimum construction standards are required for it to perform satisfactorily.
3) There are very few medium rise engineered reinforced concrete buildings in Port-au-Prince. Some are reported to have performed very well, while others are reported to have collapsed. EEFIT did not attempt a survey of such buildings.

4) The only recent steel building inspected by EEFIT was a single storey portal frame warehouse at the main port, which appeared to have survived the shaking, and remained stable despite foundation settlements of over 1m, due to liquefaction. It is however unlikely that the building is repairable economically.
5) The Iron Market, one of Port-au-Prince's landmarks, dates from the late nineteenth century. The cast iron clock tower was extensively corroded, and its columns buckled. The wrought iron market building appears to have survived the ground shaking quite well; the main damage to was caused by a much later concrete structure, which collapsed onto part of it, leading to local failure. The market was also damaged by fires before and after the earthquake. The Iron Market has been renovated and reopened in the spring of 2011.
6) Two to three storey timber houses ('gingerbread houses') dating from about 100 year ago, generally performed well, despite poor maintenance.
7) The EEFIT team inspected three concrete bridges of recent construction, none of which were rendered impassable by the earthquake. The main structural damage, which occurred in two of the three bridges, was to the lateral restraining elements to the deck beams at pier supports. There were no significant settlements either relatively between deck spans, or of the fill at approach abutments with only minor cracks observed in the abutments. The ground shaking at the bridge sites should have been quite vigorous as collapsed buildings often were observed in the vicinity of the bridge sites. A fourth bridge inspected had been rendered impassable during a previous hurricane.

10.6 Lessons for future EEFIT missions

The EEFIT mission to Haiti was unusual because of its restricted objectives and concerns about personal security. Nevertheless, some of the lessons learnt may be useful for future EEFIT missions, as follows.

1) The preparation of a security plan was a valuable feature for the mission, and is recommended for future missions even where the level of security concerns is lower than at Port-au-Prince.
2) For the heightened security concerns which applied to Port-au-Prince, the security briefing provided by RedR to the team before departure was useful and is recommended for future missions in comparable circumstances.
3) The services of a reliable local guide/driver with knowledge of the local conditions and politics was invaluable to the safety of the EEFIT team and future teams visiting similar areas should consider this aspect seriously.
4) The mission blog (very much a team effort) provided a valuable means for the team to let off steam and keep in touch with their home contacts, as well as giving rise to feedback and support from UK based colleagues on technical issues.
5) An archive of georeferenced images of buildings surveyed in detail mounted on the EEFIT website for each mission could be a valuable resource. An archive is being prepared of the Haitian photographs, to be mounted on the EEFIT website (www.EEFIT.org.uk), hosted by the Institution of Structural Engineers, for the Haiti mission.

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Appendix A: Risk assessment and security plan

Team members

Name	Team Role	Earthquake field experience	Other preparations
Edmund Booth	Team leader; structural engineer specialising in earthquake resistance	Liège, Belgium (1984); Vina del Mar, Chile (1985); Mexico City (1985); Baguio, Philippines (1990); Erzincan, Turkey (1992); Bhuj, India (2001)	Security training: RedR, 2010 Travel insurance: ***** Emergency medical contact no ***** Medical: MASTA recommended inoculations. Avlaclor to be started on 31st March and continued to 5th May.
Gopal Madhabushi	Geotechnical engineer, specialising in liquefaction and other seismically induced soil effects	Northridge USA (1994), Taiwan (1999), Bhuj, India (2001)	Security training: RedR, 2010 Travel insurance: ***** Emergency medical contact no ***** Medical: BCG, cholera, tetanus, HEPA. Avlaclor to be started on 31st March and continued to 5th May. Medically clear
Keiko Saito	Geographic Information Systems (GIS) and Remote Sensing specialist	Gujarat, India (2002) Molise, Italy (2002) Wenchuan, China (2008) Thailand west coast (Indian Ocean Tsunami) (2009)	Security training: RedR, 2010 Travel insurance: ***** Emergency medical contact no ***** Medical: GP recommended inoculations. Avlaclor to be started on 31st March and continued to 5th May. Medically clear.

Mission objectives

I) General Objectives:

1) Furthering the interpretation and use of aerial and satellite imagery for post-earthquake disaster management and recovery by ground-truthing assessments in identified areas.
2) Complementing the international effort of evaluating the lessons for civil and structural engineers arising from the Haiti earthquake, and reporting the associated findings widely to the engineering and disaster relief and management community.
3) Within these objectives, assisting with international efforts to aid recovery in Haiti.

II) Mission Specific Objectives:

1) Improvement of structural damage assessment from aerial and satellite imagery for buildings, bridges, ports and other items of civic infrastructure. Assessment of significant damage levels lower than partial or total collapse will be of particular concern, since they are currently hard to assess from satellite or aerial imagery. This will be done by 'ground truthing'.
2) Correlation of structural damage levels with geotechnical features, including surface geometry and topography. The team will investigate basin effects (e.g. how deep are the sediments in different parts of the basin) and seek to establish whether these relate to damage statistics.
3) Field investigation of geotechnical failures (slope instability, liquefaction) previously identified from aerial imagery and with particular reference to ports and bridges.

4) Investigation of damage levels in areas of Port-au-Prince not covered by previous investigation teams. The team will attempt to visit the areas around Leogane where the severity of ground motion and damage appears to have been even more extensive than in Port-au-Prince
5) Assessment of lessons for post disaster management and preparedness, particularly in relation to areas connected with civil/structural engineering content (shelter and infrastructure). Use of aerial and satellite imagery for these purposes will be of particular interest.
6) Comparison of the findings in all these fields with those obtained by the EEFIT Chile team.

Methods of operation

1) The team will travel to and from Port-au-Prince from the UK by scheduled airline
2) The team will spend the following nights in Port-au-Prince: 7th April to 13th April (Booth, Saito), 7th April to 12th April (Madhabushi)
3) The team will stay at Hotel Le Plaza, (http://plazahaiti.com).
4) The team has prebooked hire a four wheel drive Jeep for the duration of its stay, to meet the team at PAP airport, work with it for five subsequent full days in the field and return it to PAP airport.
5) The field work of the team will be carried out by at least two members of the team travelling with the hire vehicle and driver. The team vehicle will be kept nearby at all times, preferably within view. Survey work of building and geotechnical structures will generally be carried externally, using notebook and pencil, GPS and ordinary camera, tape measure. If considered safe from a personal security viewpoint by the team leader (structural collapse risk, crime risk) part of the team may exceptionally enter buildings, but one team member will always stay with the vehicle.
6) During field work, team members will wear appropriate protection, consistent with keeping a low profile. Protection may include hard soled boots with ankle protection, hard hats with EEFIT stickers, high visibility jackets, face masks and hand protection.
7) One member of the team may be dropped off from the team vehicle for meetings with NGOs etc within PAP, and will then return to base either by being collected by the team vehicle or travelling by other secure vehicle operated by a trusted international agency.
8) While away from base, the team will keep in contact by SMS text message with Amir, security officer for RedR in Port-au-Prince. Messages will be sent at departure and arrival from stated destinations, and in any case at not more than 1 hour intervals.
9) Each team member will carry a locally enabled mobile phone at all times. Team members will carry VHF radio telephones to communicate at short range at all times. The team will bring a satellite phone for emergency use.
10) The team will plan to return to base each night by 17:30pm. It will not leave base between 6pm and 7am the following morning, except in emergency.
11) Valuables (laptops, surplus cash) will be left at base, unless essential in the field.
12) Team cash (US$2250) will be split equally between team members. Travelling money will be carried securely in money belts or neck wallet, but generally will be lodged in the hotel safe.
13) Copies of passports will be carried at all times, with the originals generally lodged at base.
14) Official EEFIT papers and EEFIT vehicle badge will be carried in the vehicle during field work, and will be displayed as appropriate, consistent with keeping a low profile where necessary.
15) Next of kin details and other personal details of each team member will be lodged with the team leader, and UK Base Contact, Professor Robin Spence, CAR Ltd, 25 Gwydir Street No 6, Cambridge CB1 2LG.

Risk assessment and security precautions

Risk category	Description	Precautions
General		Standard EEFIT Personal Details Forms will be prepared by each team member and lodged with the Team Leader, UK Mission Contact (Robin Spence) and IstructE The team has attended a Haiti security briefing on 23rd

		March 2010, arranged by RedR The team will attempt daily contact with the UK mission contact. The team will visit and seek advice on the current security situation as soon as possible after arrival from Rachel Pearse of RedR, which hosts the joint Haiti security forum The team will attempt to enlist participation by locally based national or international engineers, for at least part of its mission. The team vehicle will only carry members of the survey team, and will refuse any requests to transport other personnel.
Medical	Water borne, food borne and infectious diseases	Pre departure inoculations will be carried out. Only drink boiled or bottle water; no ice cubes Use sterilisation tabs in emergencies Ensure only well cooked food from trusted source – boil, peel, cook or reject. No salads or other fresh foods unless pealed Bring Immodium and oral rehydration supplies
	Vector borne	Use malarial prophylactic (Alvaclor) before, during and after mission Report fevers immediately for 6 months after return Cover legs and arms at all times Use insect repellents on exposed skin Use mosquito nets. Team members will bring nets with them. Insecticide spray in room at night
	Rabies	Report to doctor as soon as possible after any skin contact with mammals
Structural dangers	Collapse of buildings in aftershocks	Only enter damaged buildings if authorised by team leader in discussion with team. One team member always to stay outside near to team vehicle. Team to attempt to have ability to communicate by mobile phone at all times and will carry short range VHF phones Escape or shelter points should be considered before inspection
	Injuries from building debris	Use of hard hats, hard soles, protective gloves where necessary Team leader will carry a basic first aid kit
Traffic dangers	Traffic accidents – other vehicles, damaged road	Use only the team vehicle or another trusted vehicle operated by an international agency Look after the driver of the team vehicle (hours, rest, food, drink)

		Don't be afraid to complain if the driver doesn't appear to be driving safely Team leader will carry out basic inspection of vehicle within the first 24 hours Seat belts will be worn at all times
Civil commotion	Involvement in civil disturbance	Avoid if possible Retreat from disturbance scene Always keep with team vehicle and driver Seek driver advice If possible, work with local engineers Take advice on no-go areas Vehicle to be parked to allow immediate get away In the event of gunfire – dash, down, crawl, observe, communicate with team, act
Crime	Kidnapping	In the field, always keep with team vehicle and driver and always work at least in pairs Vary morning departure times and routes
	Mugging	In the field, always keep with team vehicle and driver and always work at least in pairs Expose valuables (wallets, cameras, laptops) to the minimum extent possible No resistance will be offered to mugging attempts
	Bribes	The team will not under any circumstances give bribes, financial or otherwise
Extreme weather	Hurricanes	Leave PAP well before the start of the main hurricane season in June Monitor weather reports by radio, internet
	Heavy rain	Be aware of landslide risk Take weatherproof clothing so that some work is possible if it rains a lot

Appendix B: EEFIT Haiti team blog

EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by The Institution of Structural Engineers

Home | Objectives | 7th Apr | 8th Apr | 9th Apr | 10th Apr | 11th Apr | 12th Apr | Afterthoughts | World Bank

EEFIT (Earthquake Engineering Field Investigation Team) has been sending teams of earthquake engineers to bring back the lessons from damaging earthquakes since 1983. After many weeks of planning and preparation, a three person team has mobilised to study the Haiti earthquake of 12th January 2010, spending the six nights between 7th to 13th April in Port-au-Prince.

All earthquakes have their unique features (that's why EEFIT has investigated so many) but the Haiti earthquake poses unique challenges not faced before by the EEFIT organisation. The team, all with many years of experience in various earthquake related fields, attended a one day security briefing course run specially for us by RedR, something no previous EEFIT mission has done, so we are aware of the issues and possible difficulties that face us. Nevertheless, we realize that if we are to achieve our aspiration of contributing to the international effort of studying the earthquake and aiding recovery in Haiti, we need to expect the unexpected. We hope to update this blog on a daily basis from Port-au-Prince. Full scientific and engineering reports of our findings will be posted on the EEFIT website in due course.

The team consists of:

Edmund Booth, a self-employed consulting structural engineer, with many years of experience in the earthquake resistant design, analysis and assessment of buildings and other structures. Edmund was a founder member of EEFIT, and has visited the scene of six major earthquakes, but he expects this to be his most challenging mission.

Gopal Madabhushi, a reader in geotechnical engineering in the engineering department at Cambridge. He is the assistant director of the Schofield Centre which houses the earthquake simulation facilities on the geotechnical centrifuge. He has a particular interest in seismically induced liquefaction and soil structure interaction. He has participated in many EEFIT missions, and led the one to Taiwan in 1999 and to Bhuj, India in 2001.

Keiko Saito, a Geographic Information Systems (GIS) and Remote Sensing specialist. Her area of interest is in the application of GIS and remote sensing to quantify and visualise the risk from natural disasters on the built environment, and she has spent the last ten years working in this field. She is the deputy director of CURBE (Cambridge University centre for Risk in the Built Environment), part of the Department of Architecture at Cambridge, and a director of Cambridge Architectural Research Ltd. She has been leading CAR's involvement in a World Bank image assessment project.

EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by The Institution of Structural Engineers

Before departure, we set ourselves the following objectives.

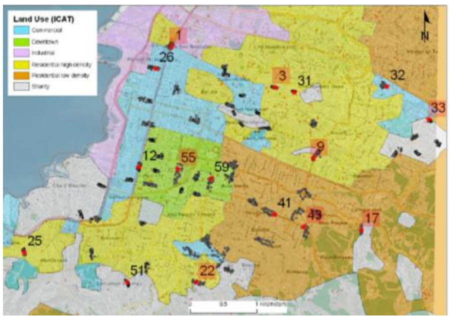
I) General Objectives:

1. Furthering the interpretation and use of aerial and satellite imagery for post-earthquake disaster management and recovery by ground-truthing assessments in identified areas.
2. Complementing the international effort of evaluating the lessons for civil and structural engineers arising from the Haiti earthquake, and reporting the associated findings widely to the engineering and disaster relief and management community.
3. Within these objectives, assisting with international efforts to aid recovery in Haiti.

II) Mission Specific Objectives:

1. Improvement of structural damage assessment from aerial and satellite imagery for buildings, bridges, ports and other items of civic infrastructure. Assessment of significant damage levels lower than partial or total collapse will be of particular concern, since they are currently hard to assess from satellite or aerial imagery. This will be done by 'ground truthing'.
2. Correlation of structural damage levels with geotechnical features, including surface geometry and topography. The team will investigate basin effects (e.g. how deep are the sediments in different parts of the basin) and seek to establish whether these relate to damage statistics.
3. Field investigation of geotechnical failures (slope instability, liquefaction) previously identified from aerial imagery and with particular reference to ports and bridges.
4. Investigation of damage levels in areas of Port-au-Prince not covered by previous investigation teams. The team will attempt to visit the areas around Leogane where the severity of ground motion and damage appears to have been even more extensive than in Port-au-Prince
5. Assessment of lessons for post disaster management and preparedness, particularly in relation to areas connected with civil/structural engineering content (shelter and infrastructure). Use of aerial and satellite imagery for these purposes will be of particular interest.
6. Comparison of the findings in all these fields with those obtained by the EEFIT Chile team.

The map below shows the 16 areas of Port-au-Prince we've shortlisted for special 'ground truthing' study. About 20 buildings in each location have been previously assessed from aerial and satellite images, and we want to compare how damage assessment from the ground compares with that. We would like if possible to spend one of our days visiting a town to the west of Port-au-Prince, perhaps Léogane which has not been closely studied, but we recognise this may not be feasible. *(Later)* The locations in pink shaded boxes are the ones we actually carried out, and we also surveyed some buildings in Delmas, off the north east edge of this map.



EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by The Institution of Structural Engineers

Edmund writes: We've finally arrived in Port-au-Prince. Some of the airport terminal buildings have clearly been substantially damaged in places, but we are led off the plane through a brand new (post-earthquake) structure into immigration, which works efficiently. Luggage distribution is a bit more chaotic, but we find our cases ok after half an hour, and proceed outside, to find our guide/driver Wisner waiting to take us to the hotel. He is proving to be a very valuable asset.

The 3km to Hotel Plaza takes about 20 minutes; we see tent cities, collapsed buildings, but strangely there are many signs of a working, reasonably ordered city. We stop to photograph the shockingly ravaged grandeur of the devastated presidential palace. Our hotel is nearby, and we'll have to admit it - it's really nice, with pleasant rooms around a central courtyard and swimming pool.

We head off to our first site which Keiko and colleagues have previously studied from aerial photos, number 55. It turns out to be a major national hospital (not something that could be easily identified from the air) with a range of one and two storey buildings dating from the 1930's to much more recent. Wisner tells us that we can enter buildings and won't be stopped if we are wearing hard hats and EEFIT reflective jackets. It's true and in fact everyone we talk to is friendly and helpful. Paediatrics was an older building with brick walls heavily damaged at first floor level, and patients are now being treated in tents in the street. Next to paediatrics was the nurses' building, which collapsed totally, killing many. Some buildings are almost totally unaffected, both structure and non-structure. None would inspire much confidence as seismically robust if viewed before an earthquake. The EERI observation that the evidence points to relatively small maximum ground displacements in the main shock seems to be borne out here.

Back to the hotel before our self-imposed 5:30pm curfew, and well before dark. There is a reasonable internet connection, so Skyping home is possible, and there is power, although no air-conditioning till 9pm.

Immigration & baggage hall at PAP airport

Wisner, our guide/driver

The presidential palace

Hospital buildings (site 55)

EEFIT

EEFIT Haiti Blog

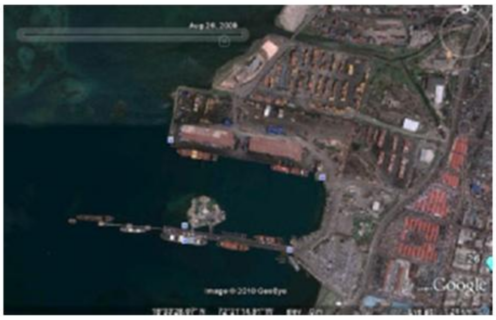
Earthquake Engineering Field Investigation Team

Administered by the Institution of Structural Engineers

Gopal writes: The EEFIT Team started its first full day of field work (having gained a very rough overview on Day 1 afternoon). The first item on the agenda was to meet with Rachael Searle at RedR in Haiti at 9.30am. This was in the Delmas area just outside of Port-au-Prince. The team set off from hotel at 8.30am and travel there was smooth. What was very interesting is the topography of the region just to the south of PAP with quite steep hill sides leading to Petionville. The team did not however travel all the way to Petionville. RedR provided excellent hospitality and were very helpful offering to monitor movement of EEFIT team via telephone/SMS messages. Also a meeting was to be set up with UN HGO offices tomorrow to inform us to the overall strategy of post disaster recovery plan and provide useful contacts for the mission team.

The EEFIT team then travelled to the Port to inspect the damage suffered by the port structures. We first introduced ourselves to the US Army who are controlling the port operations and they gave us permission to freely photograph the damage. This site has been quite famous for its soil liquefaction with CNN and BBC reporting soon after the earthquake that the port has become unusable due to collapse of wharf and Jetty structures, thereby impeding the arrival of aid to Haiti. The US Army have moved in two large floating barges which are now being used as wharfs (see right). The barges are tied to large diameter piles driven into the white sandy soil visible at the site.

The EEFIT team inspected the South Pier first.
This pier had sections that collapsed due to liquefaction induced lateral spreading as seen in photo 3. The collapsed sections can be indentified by comparing the pre and post earthquake satellite images shown in the photos below.



Close to the South pier there is an island that housed the security of port as seen in pre-eq satellite image. This island formed by fill material suffered excessive subsidence as seen in the photos of the bridge.

Also excessive lateral spreading of about 1m was also observed that caused damage to a jetty supported on piles with plastic hinging at the pile heads.

The lateral spreading at the entrance to the north pier which lost a complete wharf section was also inspected. This is illustrated in photos below.

The liquefaction induced damage to the north pier had many interesting aspects, for example the case of a storage godown that suffered extensive damage as the portal frames supporting the roof underwent sway motion with local buckling of the main beams. Similarly there was the case of the storage silos located on a site where lateral spreading was observed, but did perform quite well. These will be discussed in the full EEFIT report.

Finally the EEFIT team visited the areas surrounding the port where extensive damage was observed. A local excavation was visited to inspect the soil and it was confirmed to be silty clay. The extensive damage in this area may have been due to site amplification effects, but this needs to ascertained with further borehole and/or other geophysical site investigations.

The tired team then returned to hotel!

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EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by The Institution of Structural Engineers

Home Mission objectives 7th Apr 8th Apr 9th Apr 10th Apr 11th Apr 12th Apr Afterthoughts World Bank

Keiko writes: I can feel that I am getting more used to the heat that reaches 33 degrees centigrade by mid day. Thankfully, we have been lucky with the weather so far. Fingers crossed that it will stay this way. It has rained in the evenings on some of the days, but since there is a curfew in place after dark, it has not bothered us.
First task of the day is to survey buildings in two of our predefined locations, locations 1 and 3. For the past two months, I have been involved in interpreting damage using satellite images and aerial photographs – both vertical (Google images and World Bank images) and oblique images (Pictometry) - for the whole of Port au Prince, as part of an effort by the GEO-CAN network (http://www.virtualdisasterviewer.com/vdv/geocan.php).

Geoeye image of location 1

Google aerial photo of location 1

Pictometry figure of of location 1

So, naturally, one of my purposes of being here is to validate the assessment results done using image interpretation. The ultimate goal is to be able to carry out rapid assessment of damage using remotely sensed images alone, however we first need to establish how much variation is likely to be included in the assessments, and the likely causes of the variation. This study is intended to start answering some of these questions. This is the first earthquake that was covered by Pictometry data, and we are realising the value of having the view of the façade of the buildings.

So, naturally, one of my purposes of being here is to validate the assessment results done using image interpretation. The ultimate goal is to be able to carry out rapid assessment of damage using remotely sensed images alone, however we first need to establish how much variation is likely to be included in the assessments, and the likely causes of the variation. This study is intended to start answering some of these questions. This is the first earthquake that was covered by Pictometry data, and we are realising the value of having the view of the façade of the buildings.

We reach location 1, which is right in the middle of the downtown commercial area, then on to location 3. The survey we did on day 1 was a secluded area (hospital compound) which allowed us to move around freely (see blog for April 7). Today's location was a different story, see below what we were up against! As we drove around to reach our potential survey locations, we drove through a lot of different areas. The more survey points we reached, the more we realised that we (i.e "I") had managed to select really crowded areas (and I mean "really" crowded areas) as survey points, where there are on-street markets on narrow roads, making it difficult for us to move around. We somehow managed to survey the pre-defined buildings, which will be compared against the satellite/aerial photograph building damage assessment.

We were allowed inside some of the buildings to see the damage. Many unsafe buildings are still being used. Some locations we had to abandon due to lack of accessibility/safety issues.

After a brief lunch break at the fast food place on Delmas, the main road that runs through Port au Prince, we headed to an unusual sand quarry nested in the hillside to the south east of Port au Prince. Here, sand for cement is being produced for the buildings in Port au Prince. Our very knowledgeable driver Wismer told us that more than 90% of the buildings in Port au prince are built using this sand. Gopal told us that it is very unusual to have a sand quarry on the hillside of a mountain. After returning into the centre of the capital, we surveyed a dozen buildings in location 33.

One thing I am continuously being surprised by is the hilliness of Port au Prince. Looking at the satellite images/aerial photographs in "2D", I had failed to realise the topography of the area. One lesson I have learnt is that we need to take into account the topography of the location more when carrying out damage assessment.

We are heading to Leogane tomorrow. Let's hope the weather holds!

EEFIT

EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by the Institution of Structural Engineers

Edmund writes: today is our first and only long trip out of the capital, and we set off with Wisner shortly before 7:30am, with Robins in the back up vehicle following behind. Last night, we selected 3 points in Leogane for carrying out detailed building damage surveys, and we hope we'll be able to find them.

It takes less than two hours to reach the town and it is very hot when we arrive. Our first survey starts at the central square, now covered in tents and surrounded by devastated buildings. But interestingly, there is some sense of order; people are going about their business in a purposeful sort of way, and a small group is filling buckets with clean water from a plastic pipe laid on by one of the 950 NGOs now operating in the country. We get chatting to an American nurse, who tells us that there's been no big increase in water borne diseases, although she's worried about malaria and dengue fever when the rains start. She says that the Haitians are hard workers!

Yes, we can believe that, and they are certainly friendly. A number invite us into their houses to inspect the damage; one man (not surprisingly) wonders what good we are doing if we aren't actually working on rebuilding but philosophically accepts that it might help prevent future disasters. Our first survey point is easy to find, since it's by the main square, but the second and third are more obscure. We get there with the miracle of GPS under the expert guidance of Keiko; as someone who stopped learning geography at the age of 12 (nearly half a century ago) I am continually amazed at the locational technology that's being brought to bear on our mission.

Our final location centres around an amazing building; we're told it was built on the orders of Papa Doc Duvalier as a market place, but has stood empty for years. Actually it has withstood the earthquake very well. After 2 ½ hours in Leogane, we have given damage assignments to 43 buildings and it is time to pass the initiative to Gopal, who has geotechnical matters on his mind. Or so he claims, although it involves going to two palm lined beaches with views of distant mountains across an azure sea. One of these makes a rather good picnic spot.

But I have to admit that Gopal has interesting things to show us - a surface expression of the fault running across the road, tectonic uplift shown by coral beds raised above sea level (the coral is still alive, but must have recently been below the sea level, since otherwise it would be dead) and liquefaction induced lateral spreading which has caused some interesting damage to a group of well constructed single storey buildings, probably built by an NGO.

Uplifted coral bed

Lateral spreading has dragged forward the front of these buildings

The long road journey also gives us a chance to look at some of the concrete bridges en route, which have fared pretty well. They have simple spans of between 20m and 30m and seem very well built; the only significant structural damage is to the lateral restraint corbels on some of the rivers spans, but these have done their job, at least for this earthquake. The only bridge we can't cross was actually rendered impassable by debris damage from flooding after a hurricane 2 years ago. Generally, the road surfaces are good, with only the occasional rough patches. Britain after the great freeze of last winter isn't doing that much better.

We're back at the hotel by 5, and enjoy our buffet dinner after a planning meeting in the bar. Mangoes bought at a street side stal

rather messy sweet course. Despite the physical and mental demands of the last 4 days (yes, they have been considerable), morale is high. We all feel optimistic that we are performing useful work. In the field of photographic interpretation in particular, the data we will bring back on building damage should provide valuable validation of the technique for an earthquake for which an unprecedented amount of aerial imagery of exceptional quality has been made available. Also, we are liking the country and its people more and more; everyone is friendly, there is a lot to admire about the resilience with which they've responded to the catastrophe that has struck them (you can't put it less strongly than that) and Haiti away from the chaos and squalor of the shanty towns is a beautiful island.

Gopal writes: Today is my last full day in Haiti before I leave to the rigours of full-term in Cambridge. In my last few days I am here I lost count of how many times I went – what a country and what a people! Almost all the days we have woken to perfect Caribbean sun with a mixture of tranquillity and technology. Our hotel is also home, it seems, to the CNN Haiti broadcast.

The plan for today was to conduct damage surveys in three different areas and look at about a dozen or so buildings in each area. We started the day by going to area 43, which is best described as a leafy suburb of Port-au-Prince. The first street we conducted the survey was flat but we could see the mountains in the south directly behind . There were a lot of buildings that suffered total collapse (D5) or were very severely damaged (D4) in this area. We estimated that about 80% of the houses may fall in this category. The photos below show some of the failures.

Some houses have performed well in this street – a owner constructed house at the end of the street suffered relatively minor damage. The very thankful and proud owner can be seen to the left.

In this area there was an interesting historical structure – what we now term as the 'ginger-bread' houses. This structures is about 115 years old and was not in use since 1998. The house betrays the French architecture and the colonial past of Haiti, none the less a very beautiful building that is light, timber frame. A view of this house is seen in below. The structure was in a state of disrepair prior to the earthquake, and lost the back facing wall during the earthquake.

After surveying and classifying damage for well over a dozen buildings, the team took a well-earned break back at the hotel. Monsieur Booth can be seen hosting a small tea party on his balcony.

Afternoon the team visited two further areas and conducted damage surveys. The first area (17) was very interesting, with its hillside location and steep slopes. Very little damage was evident at this location which had the hillside covered with houses on one side and a very green hill on the other (president's house is on the top and hence very few else are allowed to live on it). But only a few hundred metres from this location the damage was wide spread. What causes such varied patterns of damage – the team pondered – site/soil conditions? Topography? Million dollar questions, no doubt.

Light to negligible damage

Heavy damage a few hundred metres away

The team finished the day by surveying the area called Nazon (area 9). Again the damage in this area has been severe. Some structures should actually have collapsed but it seems they are up there with 'shear determination' to hold them up. An example of this is shown to the left.

Others seem to hang on, although their survival seems to be totally 'baseless' from an engineering point of view as seen below.

We finally thanked our driver for the day, Monsieur Robins, and returned to home/hotel safely.

EEFIT Haiti Blog

Earthquake Engineering Field Investigation Team

Administered by the Institution of Structural Engineers

Keiko writes: Our last day in Port au Prince. I hadn't had much contact with the country Haiti nor its people before coming here. So Haiti was a blank canvas for me, and I had no idea what to expect. I have to say wherever we went, we were greeted with warm welcome. People are very friendly. Some people even thanked us for "helping them". This has happened often during other recon missions I have been on, China, India, Thailand....It is these moments I always feel uncomfortable, since we are not helping the people directly. I wonder if there is something that we can do on future missions? Food for thought.

Since Gopal had to catch a flight to Miami, we first headed to the airport. The road to the airport was unusually (?!) busy, Wisner our wise driver told us it is because the new term for schools had started. It seems some things are universal, wherever you are!! After more than half an hour on the road, we finally dropped Gopal off, then headed to Log base (short term for Logistics base) right next to the airport, where all the UN organisations coordinating the relief efforts are based in temporary shelters. The purpose of the visit was to firstly register

ourselves with the UN, and secondly to hopefully contact people who are involved in the assessment of the structural damage and other relief activities. As for the first task, the kind lady at OCHA's office told us that we can register online at oneresponse.net...ok... well, we are leaving tomorrow morning so we made a decision not to register. We also got hold of contacts who are coordinating the structural damage assessment@ UNOPS in Petion Ville. According to their website, they are going to inspect more than 200,000 buildings.....we tried our best during the past 6 days, and managed to look at an estimated 100+ buildings, the thought of inspecting 200,000 is just mind boggling. The UNOPS inspections seems to be well underway, we have seen green/yellow/red tags all over the place. There were a very small number of "interesting" tags, where they had yellow tagged, but next to it said "A demolir (for demolition)"....mmm.

Since we didn't know where the UNOPS office in Petion Ville is, we couldn't cold call them. To find out their location, we went to an office of an NGO Wisner is involved in, to borrow their computer. Since the office is in Delmas, we thought we would do a survey of some of the buildings in the vicinity as well. After leaving an email with our contact at UNOPS, the team surveyed 10 buildings in the area. Delmas, according to Wismer, is a middle class area. Each plot is large compared to the plots seen in downtown, with plenty of vegetation . This was not in our original list of places to survey, however since the set up is different from any of the other areas in PaP, it was worth investigating. Although there were some buildings that had collapsed, plenty of them had survived. According to the residents, on average one house had 8 people living before the earthquake. This number has inflated since the earthquake, with neighbours letting rooms out to people who have lost their house.

Next, we revisited location 17 , which is a location where we visited the day before. This time, we walked up the valley, where from one point onwards many of the building had collapsed due to ground failure whereas before that, there were hardly any damaged buildings. This phenomena intrigued us, therefore the revisit. We are still left with more questions than answers!

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After having another quick "tea party" back at the hotel chez Edmund's balcony, we headed into location 22. This location is in unchartered territory i.e. south part of PaP! Our driver Wismer was unfamiliar with this area, and combined with the fact that I had probably input the wrong GPS coordinate (sorry everyone!!), it took us more than half an hour to reach the location. Here we found quite a few buildings that were still standing "with sheer determination" as Gopal put it yesterday (see left). Half an hour later, it started raining, signalling the end of our surveys. We headed back to our base, the ever pleasant Le Plaza Hotel.

Since this will be our last blog from this trip, I think it is worth logging the locations that we have visited. A map will be posted shortly showing the locations that we have visited; meanwhile, see the pink coloured squares on this map, which shows where we have been. After returning to the UK, we will be putting the survey results together to compare them with the image interpretation results from the GEOCAN as well as our pictometry interpretation. We would be very happy to share our results with other organisations, if interested please get in touch with Edmund, our team leader or myself, Keiko.

Edmund writes: The plane took off from Port-au-Prince for Miami half an hour ago, and the special security and organisational issues of this mission are now firmly behind us. My principal remaining task as team leader is to ensure that a useful report gets published in the next few months, and that we tell our story to as many people as need or want to hear. This blog will help a lot in this respect; it's had other unexpected benefits, too; we've had feedback from colleagues reading the blog which has affected how we've planned our time, and it's been a good way of letting our loved ones at home know we've been safe and cared for. It's a banal thought, I know, but still the ability to communicate instantly and effectively with our colleagues and family, even from the devastation of post earthquake Haiti, would have been unimaginable on my first EEFIT mission to Liège in 1984.

I expected this to be the toughest mission I'd been involved in, and in some ways, it has. The security issues are real ones (two expatriate nurses were kidnapped the week before we left) and there are lots of both guns and desperate people in Haiti. In two other respects, though, it's been one of the easier missions. Firstly, we'd been told that 99% of the Haitian people are friendly, treating foreigners as honoured guests; that turned out not just to be true, but the help we got in carrying out our survey work was greater than I had expected, even from people who were a bit puzzled as to how it would directly help them. We'd wondered before leaving whether it would even be possible to leave our vehicle in Port-au-Prince; in the event, we felt largely unrestricted. Did we take unacceptable risks in this respect? I think Keiko and Gopal would probably say that occasionally I did, and certainly there might have been a few things I would have done differently, in retrospect. But the prize has been a respectable amount of very valuable data, which would have been impossible to have gained if we'd stayed in our four-by-four. The second great plus point of this mission has been that it's been a really great team - Madabushi/Saito/Booth formed a complimentary trio which worked very well (and harmoniously!) together, and it's been a pleasure and a privilege to work with, and learn from, two renowned experts in such different fields.

In fact, my greatest fear was not that we would get mugged or kidnapped, but that the various obstacles (riots on the street, torrential rain, and so on and so on) would prevent us from getting any useful work done at all. In the event, I'm satisfied (I think Keiko and Gopal are too) that we've more than justified the expense and time of the mission. Reading our original mission objectives, the only specific objective which we haven't really achieved yet is number 5, relating to disaster preparedness and management, but this is something I hope we can further in the UK with the contacts we have made. Not only do we have detailed and maybe unique data which should enable Keiko and her colleagues to test define (and perhaps even extend) the limits of aerial and satellite imagery use, but we also have collected data in a number of other fields, particularly in ground response and microzonation, which will I believe assist the international effort in understanding and drawing the lessons from this earthquake, even if we haven't found immediate explanations.

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World bank work:

Cambridge Architectural Research Ltd (CAR), together with EEFIT, is contributing to World Bank's effort to assess the usability of remotely sensed data to interpret damage to buildings after earthquakes. The image interpretation is done to provide rapid assessment of the overall damage, and is not intended to replace the damage assessment on the ground. The research is led by ImageCAT, and together with other organisations such as the Joint Research Centre (JRC), UNOSAT, German Space Agency (DLR), EERI and MCEER efforts are being made to standardize the methodology and the damage state definitions to be used in such assessments. There will be three meetings in the following weeks where these agencies as well as academics will be discussing these issues. CAR is conducting research in terms of assessing the variability in the interpretation results, particularly in the lower damage states. Contact Keiko for further information.

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Appendix C: Papers published by the EEFIT team related to Haiti

Madhabushi, G, Booth E and Saito K (2011). The Haiti earthquake of 2010. Bulletin of Earthquake Engineering (in preparation).

Booth E.D, Saito K, Spence R , Madabhushi G and Eguchi R. (2011). Validating assessments of seismic damage made from remote sensing. Earthquake Spectra 27, S1, Special Issue on the 2010 Haiti Earthquake, Earthquake Engineering Research Institute, Oakland, CA.

Madabhushi, S.P.G., Saito, K. and Booth, E., (2011), Post-earthquake field mission to Haiti, Proc. 9th Pacific Conference on Earthquake Engineering, Vol.1, pp 181-186, Auckland, New Zealand

Corban. C, Saito, K., Dell'Oro, L., Gill, S., Piard, Huyck, C., Kemper, T., Lemoine, G., Spence, R., Krishnan, R., Bjorgo, E., Senegas, O., Ghesquiere, F., Lallemant, D., Evans, Gartley, Toro, Ghosh, S., Svekla, W., Adams., B, Eguchi, R., (2011). A comprehensive analysis of building damage in the January 12, 2010 Mw7 Haiti earthquake using high-resolution satellite and aerial imagery. Special issue on the Haiti Earthquake, Photogrammetric Engineering and Remote Sensing , in press.

Appendix D: Acronyms

AFPS	Association Française du Génie Parasismique (French Association for Earthquake Engineering) www.afps-seisme.org/
Caltech	California Institute of Technology www.caltech.edu
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt) www.dlr.de
EC	European Commission
ECLAC	Economic Commission for Latin America and the Caribbean
EEFIT	Earthquake Engineering Field Investigation Team www.EEFIT.org.uk
EERI	Earthquake Engineering Research Institute www.eeri.org
EMS98	European Macroseismic Scale 1998
EPGFZ	Enriquillo-Plantain Garden Fault Zone
EPSRC	Engineering and Physical Sciences Research Council
GEER	Geo-Engineering Extreme Events Reconnaissance Association www.geerassociation.org
GEO-CAN	Global Earth Observation – Catastrophe Assessment Network
GEO-CAN II	GEO-CAN phase II
JRC	Joint Research Centre of the European Commission at Ispra, Italy ec.europa.eu/dgs/jrc
LiDAR	Light Detection And Ranging
MMI	Modified Mercali Intensity scale
NGO	Non-governmental organisation
PDNA	Post Disaster Needs Assessment
RIT	Rochester Institute of Technology
SWISSTOPO	The Swiss Federal Geo-Information Center www.swisstopo.admin.ch
UAV	Unmanned Aerial Vehicle
UNITAR	United Nations Institute for Training and Research
UNOSAT	UNITAR'S Operational Satellite Applications Programme
USGS	United States Geological Survey
WB	The World Bank group
World Bank GFDRR	Global Platform for Disaster Risk and Recovery
VDV	Virtual Disaster Viewer www.virtualdisasterviewer.com