2010 HAITI EARTHQUAKE

Final Report

A WORLD BANK /GFDRR IMAGECAT REPORT

POST- DISASTER BUILDING DAMAGE ASSESSMENT USING SATELLITE AND AERIAL IMAGERY INTERPRETATION, FIELD VERIFICATION AND MODELING TECHNIQUES

GFDRR
Global Facility for Disaster Reduction and Recovery

ImageCat
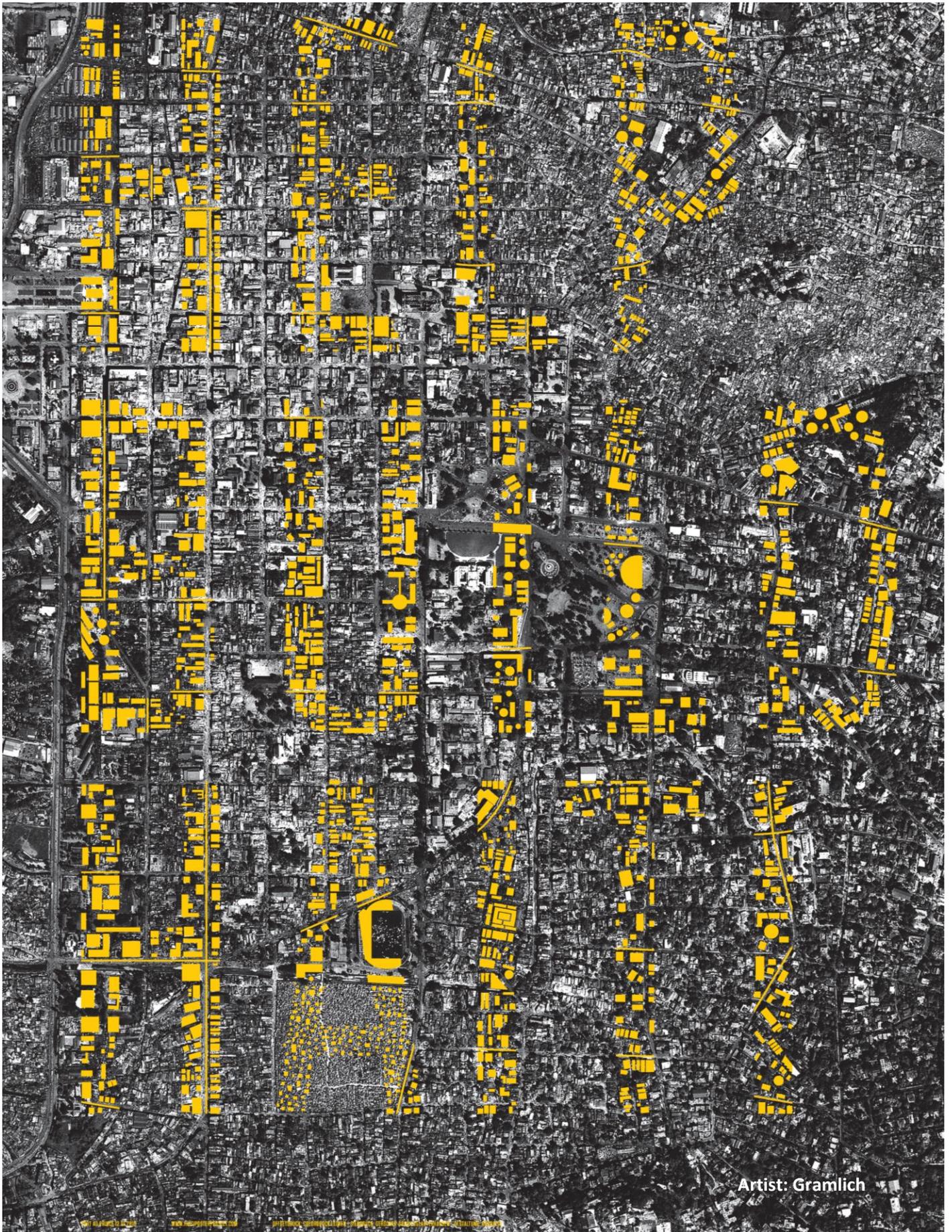
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ImageCat

Executive Summary

This report provides a detailed account of how technology, inspiration and collaboration were used to quickly assess the amount of damage caused by the January 12, 2010 Haiti earthquake. In less than a minute, this event leveled approximately 20 percent of the buildings in greater Port-au-Prince; killed close to a quarter of a million people; injured as many; and left over a million individuals homeless. While not considered a *great* earthquake (from seismological standards), this event will rank as one of the deadliest earthquakes of the 21st century.

This event will also be known as one of the first events where technology (especially high-resolution imagery) was embraced in a real operational sense. Almost from the very onset of the disaster, high-resolution satellite imagery was available to provide the first glimpse of the devastation caused by this earthquake. Days later, very-high resolution aerial imagery was available to provide even more detail on the damage caused in this event. Together, these valuable datasets allowed a small army of remote sensing experts to provide one of the more accurate assessments of building damage in the last decade. Furthermore, this information was shared with Haitian government officials in relatively short time – within two months of the earthquake – in the form of a *Building Damage Assessment Report* in support of the Post-Disaster Needs Assessment (PDNA) and Recovery Framework.

This report documents the analyses completed by the ImageCat team in support of the World Bank's initial response to the disaster. The report describes the various phases completed by the project team, including a Phase 1 damage assessment using satellite imagery and a Phase 2 assessment using very-high resolution aerial photos. We discuss the World Bank-ImageCat-Rochester Institute of Technology (RIT) remote sensing mission to collect very high resolution aerial imagery over greater Port-au-Prince (PaP) which played a central role for the Phase 2 damage analysis. In addition, participation in the PDNA damage assessment with the United Nation's UNITAR/UNOSAT unit and the European Commission's Joint Research Centre (JRC) is also discussed. Furthermore, in order to improve the damage assessment process, the ImageCat team also participated in a series of post-PDNA meetings where the focus was on developing a set of Standard Operation Procedures (SOP) for damage assessment. Reference to this last effort is made in this document; however, the details of the SOP are contained in a separate report that will be published by the three main organizations, i.e., the World Bank, UN/UNOSAT and EC/JRC.

Some of the major observations and findings in this report are:

- Satellite data over Haiti was freely available from various data providers and was distributed via the web and other channels to a broad range of users within days after the earthquake. This data proved to be extremely valuable in determining the scope of the disaster and in prioritizing both aerial and field surveys. In addition, the only pre-event images that were available were satellite images. This information was crucial in helping to discern damage patterns from the earthquake, i.e., a comparison of pre- and post-earthquake images.

- The collection of very-high resolution aerial imagery provided a unique opportunity to test and validate the assessment of urban damage using remotely-sensed data. This 15 cm data allowed analysts to "see" damage with such precision that damage that is normally difficult to see (e.g.,

partial roof collapses, shifting of buildings off foundations, etc.) were very evident in these higher-resolution images. However, logistical challenges did slow deployment to Haiti and often limited the amount of flight time over affected areas while in Haiti.

▪ The "counting" of number of severely-damaged buildings using satellite images (Phase 1) was relatively quick, requiring only a few days and a handful of analysts. However, when compared to the higher-resolution aerial images (Phase 2), these counts were found to be about a quarter of what was assessed using the aerial data. Some of the reasons for the underestimation included difficulty to discern damage using lower-resolution imagery, damage being so prevalent in many of the areas that analysts simply were not able to distinguish damage to individual buildings, and the very rapid nature of Phase 1 did not leave much time for checking before the data was released. For PaP, approximately 5,200 buildings were identified as having been completely destroyed or severely damaged.

▪ As part of the Phase 2 effort, the ImageCat team working with the World Bank and several professional engineering societies including the Earthquake Engineering Research Institute (a professional organization of about 3,000 engineers and scientists dedicated to earthquake hazard mitigation worldwide) launched a novel effort to use "crowd-sourcing" as a tool to rapidly assess earthquake damage in greater PaP. This effort – called GEO-CAN (Global Earth Observation – Catastrophe Assessment Network) involved over 600 earthquake experts representing 23 countries from 131 private, government and academic institutions (60 universities, 18 government agencies, and 53 private companies) who dedicated at least several hours each in helping to assess damage in this event. Evaluation protocols initially developed for the 2008 Sichuan, China earthquake were modified in order to use the very-high resolution aerial imagery. We estimate that the total number of hours worked by the GEO-CAN Community to be in excess of 3,000 volunteer hours, or the equivalent of a full person-year.

▪ During the Phase 2 study, close to 30,000 building in PaP and surrounding areas (Leogane, Carrefour, Grand Goave, Petit Goave, Jacmel and Hinche) were identified by the GEO-CAN community as having either Grade 5 (destroyed) or 4 (very heavy) damage according to the European Macroseismic Scale – 98 Scale. This represents roughly 10 percent of the total building stock in the affected area. It must be noted that because the GEO-CAN damage assessment protocol emphasized the importance of accurate damage assignments, many buildings that were known to have experienced severe damage were not counted. In an independent assessment of damage counts, it was found that the GEO-CAN assignments were accurate in over 90 percent of the cases when compared to other data including field information. However, the GEO-CAN building damage total was roughly half of the total reported by the joint PDNA damage assessment. One of the recommendations for future work is to study the current GEO-CAN damage assignment protocol to determine whether changes need to be made to allow for a more comprehensive assessment of severe earthquake damage.

▪ As part of the Phase 2 damage assessment, it became very evident that a significant portion of the damage count was being omitted because the type of damage that was occurring was not visible in the aerial images. For example, there were many instances of "soft-story" or

"pancaked" building failures that were not picked up in the aerial damage analyses. These failures, as well as lesser damage states, can only be seen from the ground or with the use of oblique imagery. In order to address this deficiency, the ImageCat team initiated two major activities: field work to develop damage distributions that could serve as the basis for extrapolating aerial results to other lower damage states, and evaluation of oblique imagery (Pictometry data) to supplement the field results in areas that were physically hard to access or were in remote locations. These additional studies were critical in estimating the "total" amount of building damage caused by the Haiti earthquake.

- Using the field and Pictometry data, we estimated that the Grade 5 and 4 building counts were underestimating the amount of building damage by at least a factor of two in some cases, i.e., in some cases, there were double the number of buildings with measurable damage. This number or factor varied by land-use type and location. As part of the ImageCat assessment, a series of damage distributions (i.e., tables) were produced that were eventually used by the joint PDNA team to extrapolate the aerial damage results to the full damage total. As a result of this joint analysis, close to 300,000 buildings were analyzed with approximately 20 percent of these buildings in the destroyed or heavily-damaged categories.

- One of the key products from the GEO-CAN analysis was the delineation of building footprints for buildings experiencing at least Grade 4 damage. This information was crucial in quantifying the amount of building floor space that was eliminated by the earthquake. This information, in turn, is helpful in determining a rough order-of-magnitude cost for replacing and/or repairing damage buildings. In order to complete this analysis, field and Pictometry information that described the distribution of building heights by land-use category was used to estimate the total floor space associated with all damaged buildings. Based on the use of these floor area models, the total amount of floor area associated with all damaged buildings (as determined by the joint PDNA damage assessment) was about 41 million square meters, of which 18 percent is associated with Grade 4 and 5 buildings. These latter buildings are expected to be completely rebuilt as opposed to being repaired.

- As part of ImageCat's revised scope-of-work, a series of Post-PDNA interviews were conducted with the purpose of understanding how the WB-IC-RIT imagery and ImageCat/GEO-CAN damage results were used by a broad set of users, including the World Bank. Questions regarding ease of use, value of the information, conformance to existing workflow processes, and future applications were covered in these interviews. In general, there was a reluctance to fully embrace many of the products generated by the study. Some of the reasons for this reluctance were 1) not sure how to integrate the products into existing workflows, 2) a lack of trust in the data, either because of the results did not appear to coincide with "ground truth" information or a general distrust of the technology (e.g., skeptical about the accuracy that could be achieved from sole use of remotely-sensed data), 3) poor communication between data providers and users, 4) a tendency not to share data between agencies, or 5) lack of metadata to go alongside of key datasets. The report attempts to make recommendations to address these issues or concerns, such as pre-event training to ensure that all users understand the

value and the opportunities associated with better data and the reliance on new and emerging technologies.

- Finally, the report contains a series of recommendations that are focused on better use of the technologies described in this report and a roadmap on how some of the products can be used for pre- and post-event planning. One of the key recommendations is the creation of an imagery fund that can be accessed for pre-event planning. Had better databases on what was exposed to the Haiti earthquake been available before the earthquake had occurred, a more rapid and comprehensive analysis of damage would have been possible. In order to create these key databases, up-to-date and robust imagery is needed that will result in a quantification of physical assets. Some of this data includes: number of buildings by occupancy or land-use type; important structural information such as building construction types, building floor areas and heights, and age; and other information that could suggest special vulnerabilities, e.g., building configurations, soft-stories, etc. And to the largest extent possible, these databases should address multiple hazards, including earthquake, hurricanes, floods, landslides, and tsunamis. Other recommendations on improving the overall damage methodology are also provided.

Contents

List of Figures

List of Tables

1.0   INTRODUCTION

On January 12, 2010, a magnitude (Mw) 7.0 earthquake struck the Port-au-Prince region of Haiti. The epicenter was located immediately to the west of the city of Port-au-Prince at 18.457°N latitude and 72.533°W longitude at a depth of about 13 kilometers. According to official estimates, the impacts caused by this event included 222,570 people killed, 300,000 injured, and 1.3 million people displaced (USGS, 2010). In addition, significant damage to buildings, infrastructure and other critical services was observed.

On March 3rd of this year, the World Bank and the Global Facility for Disaster Reduction and Recovery, working jointly with the United Nations Institute for Training and Research (UNITAR)- Operational Satellite and Applications Programme (UNOSAT), the European Commission (EC) through the Joint Research Centre (JRC) and the Centre National d'Information Geo-Spatial (CNIGS), submitted to the Haitian Government the *Building Damage Assessment Report* that supports the Post Disaster Needs Assessment (PDNA) and Recovery Framework. The results of this assessment were based on the best available data and information at the time of publication. Image analysts at UNITAR/UNOSAT and EC JRC used manual photo-interpretation methods to classify buildings into different earthquake damage classes. The World Bank, working with ImageCat and a network of engineers and scientists that formed the GEO-CAN (Global Earth Observation – Catastrophe Assessment Network) community, produced its building damage assessment. This latter assessment was also based on manual photo-interpretations where building footprints of destroyed and very heavily damaged buildings were mapped.

Since the *Building Damage Assessment Report* was submitted, comprehensive studies have been undertaken to 1) refine the ImageCat/GEO-CAN damage assessment methodology, 2) develop - in collaboration with UNOSAT and JRC - a set of *Standard Operating Procedures* (SOP) that will ensure more consistent and reliable application of remote sensing data for the purpose of building damage assessment, and 3) understand more fully the potential for new uses and applications of damage assessment data, including ways in which the high-resolution imagery can be used for pre-disaster planning. In addition, a set of interviews with key informants (many working for the World Bank) was conducted by ImageCat to help assess the value and timeliness of the ImageCat/GEO-CAN damage data in supporting key decisions in the immediate aftermath of the earthquake. Ultimately, the goal is to better understand the workflow process during and after a major disaster so that the damage assessment products, including high-resolution imagery, will have the most impact and value for end-users.

The report is illuminating in several respects. First, we document the unprecedented use of high and very-high remotely-sensed data[1] for the purpose of rapid damage assessment. Although there have been many studies published where remote sensing technology has been instrumental in the assessment of post-disaster effects, this particular effort is unique in both scope and the rapidity at which these datasets were made available. Very-high resolution (VHR) imagery at a scale of 15 centimeters was made available to a broad set of users which eventually led to multiple damage datasets that could be cross-correlated in order to improve the accuracy and reliability of the final damage totals for Haiti. In developing these integrated damage datasets, significant benefits were

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[1] In this report, we associate the resolution of satellite imagery as high-resolution (50 cm) and that of aerial imagery as very high resolution (15 cm).

accrued through the strong partnership formed among the three key organizations, i.e., the World Bank, the UN through its UNOSAT group, and the EC's Joint Research Centre. Although mandated several years ago to work together to prepare joint PDNA assessments, the Haiti earthquake is the first event in which technical collaboration took place.

Second, the speed at which these high-resolution imagery datasets were made available to end-users was phenomenal. Part of the reason for this was the decision to contract with commercial airborne companies to fly targeted missions using a rich set of sensors, including very-high resolution aerial optical imagery, LIDAR and thermal infra-red imagery. The World Bank led this effort by commissioning the Rochester Institute of Technology (RIT) to fly a seven-day mission over Port-au-Prince (PaP) and areas west of PaP. The eventual users – besides ImageCat and the GEO-CAN community – included over a dozen universities and several federal agencies, including the U.S. Geological Survey who is a key member of the International Charter. Because of the rapid collection of these key datasets, dissemination via online web services, and a very large network of people conducting analysis of the data, a full and comprehensive damage assessment was produced in less than two months.

Third, this effort was unique in that crowd-sourcing as a post-disaster data collection tool was implemented on a large scale for the very first time. Over 600 engineering and scientific experts from around the world participated in an unprecedented "experiment" to use VHR imagery to perform rapid damage assessments using the internet as the primary data platform. Because of the enormous support provided by this volunteer group, the ImageCat/GEO-CAN team was able to produce relatively complex damage information on over 30,000 buildings in Haiti in a matter of days.

Finally, the move to "standardize" a set of damage assessment protocols is introduced in this report. Working jointly with the UN (UNOSAT) and the EC (JRC), we developed a standard set of rules and guidelines that will help to ensure that future damage assessments are both transparent and utilize the same conceptual models. We understand that flexibility is still a requirement – largely because the details of each disaster, as well as the details of the data collection efforts will vary. However, it is imperative that standard protocols be followed that will enhance the richness of each dataset and also allow for easy integration of different datasets. To address this issue, we discuss efforts taken to formalize the damage assessment process. Three separate meetings (the first in Geneva, Switzerland, the second in Ispra, Italy and the final meeting in Washington D.C.) have formed the basis for implementing this standardization.

In this report, we discuss the damage assessment process, our interaction with the UNOSAT and EC teams in assembling a joint damage assessment, the field validation process that helped to flesh out many of the damage details not especially evident from the aerial imagery, and the interviews that were conducted several months after the earthquake that are currently forming preliminary post-event damage protocols that will be vetted over the next several months. We begin with a discussion of the scope.

2.0 PROJECT SCOPE

Because the priorities for post-earthquake data collection changed as the disaster unfolded, the scope of this particular project also changed. There were two change orders that were associated with the original scope of work. The first change order was needed in order to expand the scope of the aerial data collection mission. Instead of a few days of flying, the WB-IC-RIT remote sensing mission was

extended to 7 days. The second change order occurred after the PDNA report was submitted to the Haitian government. This change order focused on a review of damage assessment procedures and recommendations to improve the overall use and value of the damage datasets. As part of this activity, meetings in Geneva, Switzerland and Ispra, Italy were conducted. A final meeting in Washington D.C., as part of the Understanding Risk conference, was also conducted in order to present the findings of the joint effort.

Initial Scope: The initial objective of this study was to deliver a comprehensive building damage assessment of Port-Au-Prince at the earliest possible juncture in a format that could be used for search and rescue activities and to prioritize resource allocations. As part of the scope, an initial interpretation was to be made of the locations of collapsed structures using available satellite data from GeoEye and DigitalGlobe. This assessment would then be followed by a more refined analysis of damage using high-resolution aerial imagery. The Virtual Disaster Viewer (VDV) - developed by a consortium of universities and non-profit entities - would serve this data online so that distributed damage interpretations could be made by a larger group of remote sensing experts. ImageCat was to release a preliminary but actionable damage interpretation dataset, with refinements over the next several days. In addition to the interpretation of the satellite data (GeoEye and DigitalGlobe data), the Rochester Institute of Technology's (RIT) WASP (Wildfire Airborne Sensor Program) system would collect very-high resolution panchromatic, multispectral, FLIR, and LIDAR data. All of the raw data that was collected by the World Bank-ImageCat-RIT remote sensing mission was to be a significant part of the final deliverable to the World Bank.

Table 2-1 Initial Project Timeline (modified during the course of the project because of expanded scope and various political and logistical constraints)

Date	Activities	Deliverable
Friday 1/15	Launch VDV with GeoEye and DigitalGlobe Imagery, with any pre-disaster imagery available. Start damage interpretations – collapse/non-collapse.	VDV, serving post-event satellite imagery
Saturday 1/16	RIT to fly to Haiti. Using satellite imagery, produce first dataset of collapsed structures.	First estimation of collapsed structures- served through VDV and available as KML or in GIS
Sunday 1/17	Use satellite data results to plan RIT flight paths in order to collect optical, IR, LIDAR data.	Second estimation of collapsed structures from satellite data analysis
Monday 1/18	RIT fly back to US. Process data during flight. Finish processing data in US, and deliver data to VDV servers at SUNY, Buffalo. Upload to VDV. Begin more detailed interpretations.	15 cm optical data served through VDV.
Tuesday 1/19	Further interpret aerial data in VDV	Provisional estimates of building damage based on higher resolution data, with classification of building damage states.
Wednesday 1/20	Further interpret aerial data in VDV	Final estimates of building damage.

This initial scope and schedule was changed for a number of reasons. First, RIT was not immediately able to obtain clearance from the State Department to transport its camera equipment outside of the U.S. ITAR (International Traffic in Arms Regulations) details the regulations governing the export of defense-related materials and technologies, including hardware, software, and services. Specifically, the thermal infrared cameras and the inertial navigation system used by the RIT flight team are ITAR controlled. An ITAR waiver was received from the Department of State on 18 January 2010; clearance to fly over Haiti was received on 21 January 2010. In addition, based on subsequent information of the magnitude of the disaster, two additional days of flying were added on to the contract. The first set of damage results based on satellite imagery was completed on 17 January 2010. The more detailed analysis using the higher-resolution aerial imagery was completed on 15 February 2010.

First Change Order – Expanded Flight Coverage and Damage Assessment: A modified scope for expanded coverage of four new areas around Port-Au-Prince was later approved by the World Bank and the Global Facility for Disaster Reduction and Recovery (GFDRR). Working with the World Bank, NOAA, USGS, International Charter members and others (including Google), a series of four new data collect areas by RIT and subsequent building damage interpretation were defined around Port au Prince (PaP). These included developed areas severely affected by the earthquake but located some distance from PaP; and areas identified as High Priority areas of interest (AOI) by USGS and others that include areas of extreme geophysical interest (fault rupture and landslides). The modified scope was structured so that all four areas or a subset of this grouping could be selected based on World Bank's requirements.

The flight planning approach was to apportion the area around Port-Au-Prince and adjacent areas into "Plans" that could be flown in one day or possibly less. This would enable the flight team to execute each area as a single mission which greatly simplifies planning, processing and data management. Depending on how well things go on a given day, if one plan is completed early, the flight team would then proceed to the next priority area.

The selection of particular areas was dictated by requests from various agencies as well as from an analysis of maps showing populated areas (see Figure 2.1) likely to have been impacted by the earthquake. Even areas that were not directly located in heavily-populated zones but contained key transportation (road and rail) corridors were candidate areas because of the need to assess area access by relief convoys.
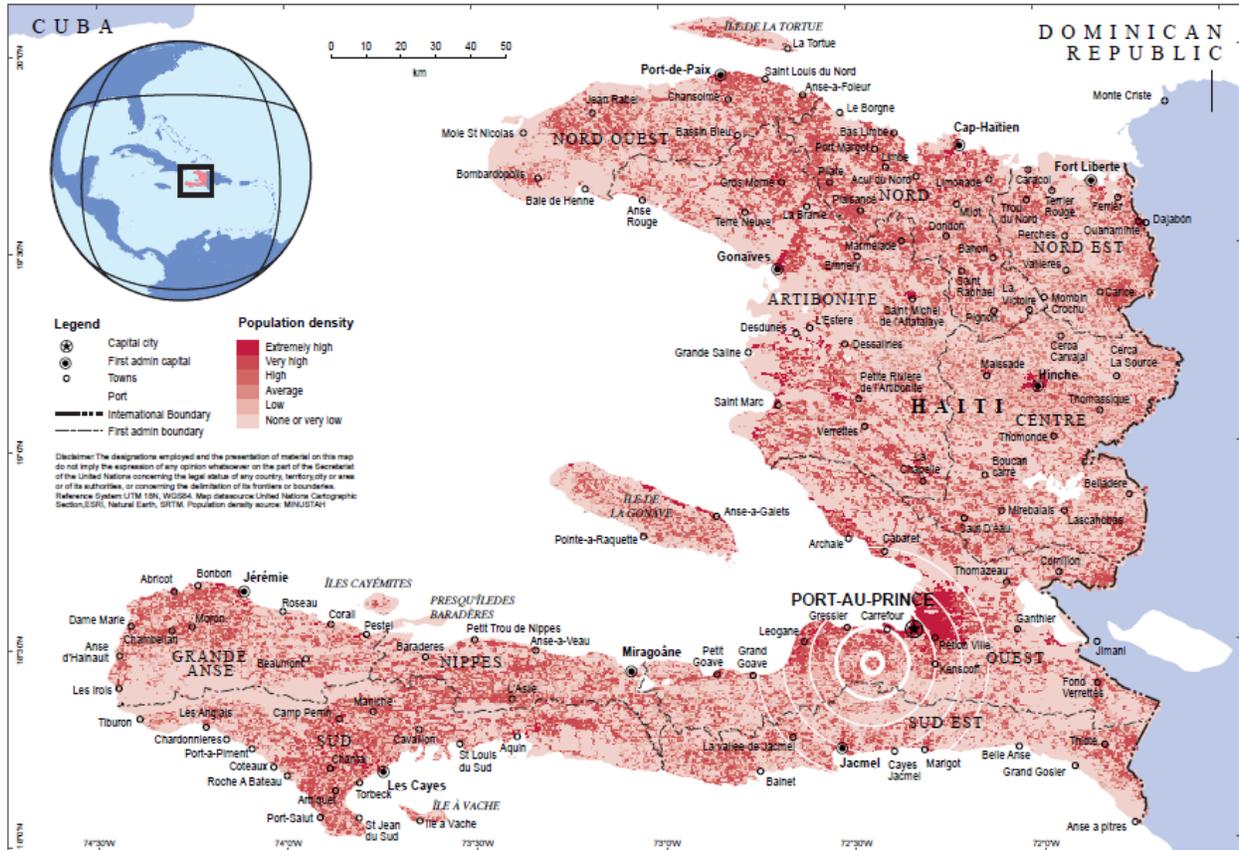
Figure 2.1 Haitian Population Density near Earthquake Impacted Zone
(source: http://www.reliefweb.int/haiti)

Figure 2.1 shows a population density map of Haiti that was published by OCHA (United Nations Office for the Coordination of Humanitarian Affairs). This map shows extremely high concentrations of people in and around PaP and extending into broad areas east and north of PaP and along the coast to the west.

A map of the proposed flight lines for all areas around greater PaP is shown in Figure 2.2. The plans are identified as Plan areas A through E. A detailed description of each area is provided below.
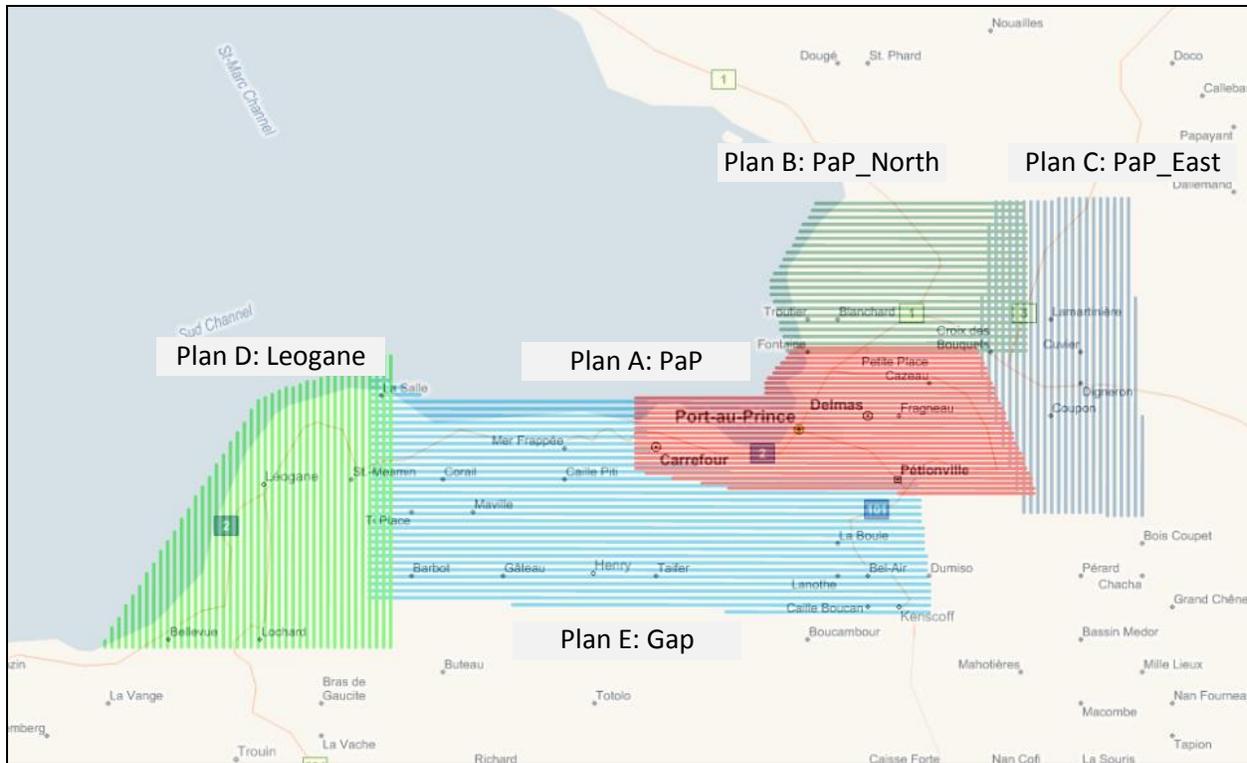
Figure 2.2 Flight Plans Apportioned into Five 1-Day Coverage Areas

Plan A - PaP: originally planned as Port-au-Prince metro area (most severely impacted area)

> This area is in the heart of the disaster-impacted region. This data collect will provide rich datasets in terms of high-resolution optical imagery, spectral coverage and very-high definition 3D measurements (LiDAR).

Plan B - PaP North: north of original area; an addition in scope

> This area extends north of the central PaP core with numerous roads and populated areas. This area experienced significant but lesser earthquake intensities.

Plan C - PaP East: east of original area; an addition in scope

> This area extends east of the central PaP core with numerous roads and populated areas. Although less populated, this area also experienced high earthquake intensities.

Plan D - Leogane: area approximately 30 km west of PaP; an addition in scope

> Significant population density and many reports of building collapse.

Plan E - Gap: stretch of coast line and rough terrain between PaP and Gressier; an addition in scope

> Sparsely populated but contains the fault zone. Coastline area contains roads and rail lines. USGS has indicated significant interest in the fault zone to measure slip and refine ground motion maps to provide better direction to prioritize and deploy resources to the heaviest damage areas. The high-resolution LiDAR data was invaluable here.

In addition to the areas above, three other areas were added to the flight plan: Grande Goave, Petite Goave, and Jacmel. These areas are located west (Grande Goave and Petite Goave) and southwest (Jacmel) of PaP and were considered high priorities for the data collect mission because of reports of significant earthquake damage.

To complement these data collects, the ImageCat/GEO-CAN team analyzed earthquake damage in all areas where very-high resolution imagery was available. The scope involved not only the identification of severe damage but the delineation of building footprints for all buildings included in the ImageCat/GEO-CAN database. Section 6 of this report discusses the methodology used by the ImageCat/GEO-CAN team to assess different building damage states and criteria for delineating the footprints of damaged buildings.

These modifications to the original scope-of-work were necessary because the full extent of damage in the earthquake was not known until after the WB-IC-RIT remote sensing mission was started. Because of requests from many organizations, including the Haitian government, the coverage of the WB-IC-RIT mission was expanded during the first month after the earthquake and the decision to also perform detailed damage assessments was made at the same time. In addition, one of the requirements was to have the data open and easily available to the public.

Second Change Order – Post-PDNA Analysis: The second change order occurred after the results of the damage assessment (included as part of the PDNA) were submitted to the Haitian government. In order to fully leverage the experience and knowledge gained in the first few months of the earthquake by the project team and to ensure that the damage protocols and procedures developed for this event could be used for future disasters, the World Bank authorized additional time and resources for the ImageCat/GEO-CAN team to thoroughly review, document and modify the damage assessment protocols applied in Haiti. To ensure consistency and compatibility with damage protocols used by the other PDNA partners (UNOSAT and JRC), a series of meetings were planned with these organizations to develop a set of Standard Operating Procedures (SOP) that could serve as the basis for future damage assessments. The scope-of-work for this second change order included:

- Compilation of Field Data – a significant amount of field data from the Earthquake Engineering Research Institute (EERI) and the Earthquake Engineering Field Investigation Team (EEFIT) was collected and used for the PDNA damage assessment. In addition, data from other teams was invaluable in scaling aerial damage results to assessments of damage at lower levels (Eduardo Fierro of BFP, Inc. and Stanford University/Pacific Earthquake Engineering Research team). This data was compiled and included as a set of photos that was delivered to the World Bank. A complete list of the different datasets is contained in the appendices.

- Damage Analysis Report and input to Standard Operating Procedures – This task focused on two elements of the ImageCat/GEO-CAN damage assessment: summarizing and documenting the procedures used by the project team to determine building damage states using both satellite and aerial imagery and contributing to the joint post-PDNA effort to standardize damage assessment procedures. The latter effort was done in conjunction with World Bank personnel, and researchers and scientists from both UNOSAT and JRC. As part of the process, three separate meetings were conducted. The first in Geneva, Switzerland (April 27 and 28, 2010) where an open discussion on all damage assessment methods applied as part of the Haiti earthquake experience were discussed; the second in Ispra, Italy (May 20 and 21, 2010) where the format and content of the Standard Operating Procedures (SOP) document were discussed

- and agreed upon; and the final meeting in Washington D.C. during the World Bank Understanding Risk Conference (June 1-4, 2010) where the joint collaboration between the World Bank, the UN and the EC was discussed before a wide audience of experts and decision-makers from around the world. The results of the SOP document are expected to be published by the three main organizations sometime during the summer of 2010.

- An Assessment of the Usability of the ImageCat/GEO-CAN Products and Methods – In order to explore a broader application of damage assessment products and the imagery used to perform the analyses, ImageCat conducted a series of interviews with World Bank staff and some of its consultants who were actively involved in supporting the PDNA process in Haiti. The purpose of these interviews was to better understand the workflow process of key relief teams – within the context of the Haiti response – so that integration of the damage assessment results can be enhanced. Furthermore, there was significant interest on the part of the World Bank to find other ways in which the data produced for the Haiti earthquake could be used for recovery or reconstruction planning and to also support pre-disaster planning for future events. The results of these interviews are contained in Sections 9 and 10.

- GEO-CAN Review and Business Plan – In order to "institutionalize" the GEO-CAN community, ImageCat working with EERI and the World Bank to develop a long-term business plan that will ensure the GEO-CAN community will be active for future disasters. Some of the key elements that are being discussed include a) technical nodes that will be comprised of experts in specific areas of earthquake engineering and analysis, b) a membership list that will be maintained by EERI, c) training materials and courses that will ensure that GEO-CAN volunteers will have the proper knowledge and expertise to accurately assess building and infrastructure damage using satellite and aerial imagery, d) protocols that will define how EERI will work with other organizations such as the World Bank, the UN and the EC, and e) access to a global imagery dataset that will help facilitate rapid post-disaster damage analysis, as well as producing information for pre-event planning. Some of the ideas are discussed in Section 5 and in the appendix that contains the EERI Post-Haiti earthquake Workshop report.

3.0   DAMAGE ASSESSMENT TIMELINE

A multi-phased analysis was undertaken by the ImageCat/GEO-CAN team to develop a comprehensive building damage database using visual interpretations of satellite and aerial imagery. A phased approach was adopted in order to effectively utilize the different datasets that became available shortly after the event. Table 3-1 summarizes the three phases of the damage assessment activity. Phase 1 involved identifying building damage points using high-resolution satellite imagery (~50 cm resolution); in Phase 2 (a and b), VHR aerial imagery (~15 cm) from the World Bank-ImageCat-RIT Remote Sensing Mission and Google were utilized to delineate building footprints of collapsed or very heavily damaged buildings[2]. In addition, visual interpretation of the VHR images was used in creating land use information for Port-au-Prince and in estimating the total square footage of buildings that require significant repairs or reconstruction. Phase 3 involves the identification and delineation of evidence of liquefaction associated with the earthquake.

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[2] Damage grades 4 and 5 of the EMS-98 scale were used to classify buildings that were very heavily damaged or destroyed, respectively.

As discussed in the previous section, the initial objective was to quickly assess building damage in Port-au-Prince using satellite and aerial photography. The project team undertook this challenge by adopting an approach in Phase 1 that entailed placing points on damaged buildings that were clearly visible from the highest resolution data available at the time. The details of the damage interpretation methodology including protocols is discussed in Chapter 6, Methodology. The platform used to conduct the damage interpretations was Google Earth (www.earth.google.com) which was freely available and offered the flexibility of creating simple GIS layers. In addition, Google Earth had high-resolution pre-event imagery built into their framework already, so this helped to facilitate the analyses.

The protocol established for Phase 1 for associating points with damaged buildings was expanded during Phase 2 where a much larger area was analyzed. In addition to locating severely-damaged buildings, a high priority was placed early on, on estimating the amount of square footage (i.e., building area) that had been destroyed by the earthquake and thus, would require rebuilding. Phase 2, therefore, required that the footprints of severely-damaged buildings be delineated and the number of stories associated with these buildings be estimated. Given the difficulty in interpreting lower damage levels (no damage, or slight to moderate damage generally indicating non-collapse conditions) from satellite and nadir aerial imagery, the project team focused its efforts on identifying Grade 4 (very heavy damage) and Grade 5 (destroyed or collapsed buildings) buildings, according to the European Macroseismic Scale (i.e., EMS-98).

The Phase 1 dataset (building damage points) was comprised of approximately 5,000 buildings. This dataset was delivered to the World Bank within 48 hours of the start of the assessment and covered roughly 130 sq. km. of Port-Au-Prince. Phase 2A - building footprints of severely-damaged buildings - covered about 350 sq. km. or roughly 2 ½ times the Phase 1 coverage. The number of buildings identified as having severe damage (including collapse) was over 19,000 buildings; this dataset was delivered to the World Bank within 8 days of the start of the project. The final phase of the building damage assessment (Phase 2B) was completed within 19 days of the start of the project and covered over 600 sq. km. of area. This phase resulted in the identification of close to 30,000 very heavily damaged or collapsed buildings.   The complete coverage area included Greater Port-au-Prince, Carrefour, Leogane, Grande Goave, Petite Goave, Jacmel and Hinche.

Table 3-1 Damage Assessment Timeline

Start-end date	Time	Description of Activities	Imagery Used	Coverage Area	Coverage Communities	Total Number of Buildings Identified
1/16/10 – 1/17/10	48 hrs	Phase 1 Detection of building damage (point locations)	Pre-event imagery: High-resolution satellite data served through Google Earth from various sources, including DigitalGlobe, GeoEye Post-event imagery: GeoEye scenes 5V100113C0004594564B523010701382M_001567312.tif & 5V100113C0004594564B523013801682M_001567312.tif from 13January 2010	~ 130 sq km	Port-au-Prince	5,189
1/18/10- 1/26/10	8 days	Phase 2A – Delineation of damage building footprints	Pre-event imagery: High-resolution satellite data served through Google Earth from various sources- DigitalGlobe, GeoEye Post-event imagery: 15 cm Aerial imagery WB-IC-RIT remote sensing mission and Google http://www.google.com/relief/haitiearthquake/imagery.html http://www.google.com/relief/haitiearthquake/geoeye.html http://waspftp.cis.rit.edu/	~ 350 sq. km.	Port-au-Prince	19,785

Date	Duration	Phase	Imagery	Area	Location	Count
1/27/10-2/15/10	19 days	Phase 2B – Delineation of damage building footprints	Pre-event imagery: High-resolution data served through Google Earth from various sources- DigitalGlobe, GeoEye Post-event imagery: 15 cm Aerial imagery WB-IC-RIT remote sensing mission and Google http://www.google.com/relief/haitiearthquake/imagery.html http://www.google.com/relief/haitiearthquake/geoeye.html http://waspftp.cis.rit.edu/	~ 200 sq. km.	West PaP* Grand Goave Petit Goave Jacmel Hinche Total * West PaP includes Leogane and Carrefour	8,240 272 408 337 14 9,271
3/5/10 – 4/30/10* * As of 7/5/10, work is still ongoing to complete this analysis		Phase 3 Detection of liquefaction	Pre-event imagery: High-resolution satellite data served through Google Earth from various sources- DigitalGlobe, GeoEye Post-event imagery: 15 cm Aerial imagery WB-IC-RIT remote sensing mission and Google http://www.google.com/relief/haitiearthquake/imagery.html http://www.google.com/relief/haitiearthquake/geoeye.html http://waspftp.cis.rit.edu/	~ 150 sq. km.	Coastal area from Petit Goave on the west to Port-au-Prince on the east, and several rivers in the greater Port-au-Prince area.	

3.1 Monitoring and Tracking of External Post-Earthquake Datasets and Assessment Activities

The devastation caused by the earthquake inspired a great mobilization of people, expertise, and other critical resources. Perhaps for the first time, the Internet and Web2.0 technology allowed for more dynamic, and in many cases, two-way interactions during the disaster. Not only were news reports from the earthquake-stricken nation broadcast across the globe for Internet consumption, but the Internet itself became a platform for globally-distributed mobilization activities. It should also be noted that this particular event catalyzed an unprecedented degree of data and information sharing on the part of commercial data providers whose products are typically not widely distributed to the general public and/or fall under strict limitations on use or distribution.

The disaster response and geospatial community (i.e., international civil service organizations, national governments, private industry, academia, professional societies, and concerned individuals) played very critical roles both in Haiti and from remote locations. Given the primary focus of the World Bank-ImageCat-RIT remote sensing mission (damage assessment), maintaining a real-time and comprehensive view on all related post-earthquake activities was crucial to meeting study objectives. Therefore, a significant part of our study was devoted to monitoring and documenting activities related to the production and distribution of remotely-sensed imagery, GIS feature datasets, cartographic products, and other damage assessments. This monitoring began in earnest in the immediate days following the January 12th earthquake and continued through the end of February. Daily updates were reported to the World Bank in detailed progress reports.

Our monitoring activities concentrated on three specific sources:

a) Organizations performing damage assessments and/or releasing products that defined the scope of the disaster,

b) Pre- and post-event imagery, and

c) Geospatial data portals and infrastructure

These activities are summarized below.

3.1.1. Organizations Performing Damage Assessments and/or Releasing Products

- **European Commission's Joint Research Centre (JRC)**, http://dma.jrc.it/ - Beginning on January 13, 2010, the day immediately following the earthquake, JRC released near-daily reports updating progress in visual interpretation of damaged structures. In addition to these reports, they also made available interpretive maps and KML files of damaged structures. Working closely with UNOSAT so as not to duplicate efforts in the same areas of Haiti, JRC released a comprehensive damage assessment map which included building damage counts and damage ratios for Leogane, which complemented UNOSAT's damage map for Port-au-Prince. In the end, this dataset was combined with the UNOSAT damage data and the damage data collected by the World Bank – ImageCat/GEO-CAN team.

- **United Nations Operational Satellite Applications Programme (UNOSAT)**, http://unosat.web.cern.ch/ - Immediately following the earthquake, UNOSAT produced an early

damage assessment of 110 critical facilities in Port-au-Prince. In addition, various maps of bridge damage, road closures, and locations of internally-displaced person (IDP) camps were produced. These preliminary assessments were followed by a series of updated maps showing damage in Port-au-Prince, i.e., "Comprehensive Building Damage Assessment for Port-au-Prince Commune, Haiti." The damage maps displayed the locations of heavily-damaged buildings and damage ratios for three commune sections in Port-au-Prince: Turgeau, Morne l'Hopital, and Martissant. Later versions included Carrefour as well as aggregated totals according to five dominant land-cover classes: high-density built-up, medium-density built-up, low-density built-up, shanty, and other. Data was released in the form of PDF maps, KMLs, and ESRI Geodatabase formats. A set of detailed atlases showing the results of the building damage assessment were also produced jointly with JRC and the World Bank – ImageCat teams. In the end, the UNOSAT dataset was combined with the JRC damage data and the damage data collected by the World Bank – ImageCat/GEO-CAN team.

- **Information Technology for Humanitarian Assistance, Cooperation and Action (ITHACA)**, http://www.ithaca.polito.it/- Taking full advantage of the 15cm high-resolution imagery captured on January 17, 2010, and made available in Google Earth (as well as for download), ITHACA manual interpreted damage assessment from this imagery focusing on roads (closed and restricted), collapsed bridges, and temporary shelters. Subsequent updates were released in ESRI shapefile formats. ITHACA also produced maps displaying data from the International Organization for Migration, Camp Coordination and Camp Management (IOM/CCCM) for: 1) the master list of IDP camps, 2) planned IDP camps, and 3) IDP camp spontaneous sites. Cartographic products resulting from this analysis are being published in conjunction with the UN's World Food Programme (WFP).

- **Service de Cartographie Rapide (SERTIT)**, http://sertit.u-strasbg.fr/ - SERTIT released various cartographic products that quantified damaged building density.

- **MINUSTAH GIS and UN Cartographic Section,** http://www.un.org/Depts/Cartographic/english/htmain.htm - MINUSTAH published various GIS base layer datasets of Haiti and Port-au-Prince, including communes, departments, landmarks and roads along with regional and country base maps. MINUSTAH also collaborated with G-MOSAIC Project Partners and DLR in the production of a series of damage assessment, gathering areas, and landslide risk maps for Port-au-Prince.

- **OpenStreetMap WikiProject Haiti (OSM),** http://wiki.openstreetmap.org/wiki/WikiProject_Haiti/ - As both an internet-based platform visualizing, creating and distributing geospatial data and a community of volunteers, OpenStreetMap has been gaining momentum in the disaster response world. With regard to Haiti, open access to the platform and data placed it in a unique position with regard to other geospatial endeavors. Veteran OSM community members as well as novices turned to OSM to respond to immediate data/information needs of responders on the ground by digitizing natural and built environment features throughout Haiti. An OSM data extracting service was set up at [http://labs.geofabrik.de/haiti/] to download timely and aggregated datasets (as tagged by digitizers) of building footprints, natural features, places, railways, roads and waterways.

- **DLR Center for Satellite Based Crisis Information,** http://www.dlr.de/ - DLR produced a steady stream of map products (JPEG images) concerned with a) population distribution at the national

level; b) 2-D ground motion measured from TerraSAR-X Data; c) pre-disaster Port-au-Prince maps detailing roads and landmarks like the national palace, hospitals, etc.; and d) aggregated damage assessment maps (sparse, extensive, and vase for each 250m grid cell) for Port-au-Prince and the surrounding area.

- **World Food Programme (WFP),** http://www.wfp.org/ - A series maps from the WFP were circulated to the Haitian geospatial community at large. These maps addressed "Haiti: Earthquake Affected Areas outside Port-au-Prince," "Haiti: Jimani to Port-au-Prince Transport Corridor." In addition, this group collaborated with ITHACA to produce a series of damage maps for Léogane.

- **Purdue University,** http://www.purdue.edu/-Researchers from Purdue University conducted a land-use classification analysis for the central/downtown portion of Port-au-Prince based on the January 13, 2010 GeoEye-1 satellite imagery. The classification scheme assigned all space within the area-of-interest to one of the following categories: roads, buildings, water, vegetation, shadow, open land, and miscellaneous. Additionally, utilizing the World Bank-ImageCat-RIT LIDAR elevation data acquired on January 21st and 22nd, researchers at Purdue extracted building footprints and heights for central Port-au-Prince. See Figure 3.1 below.
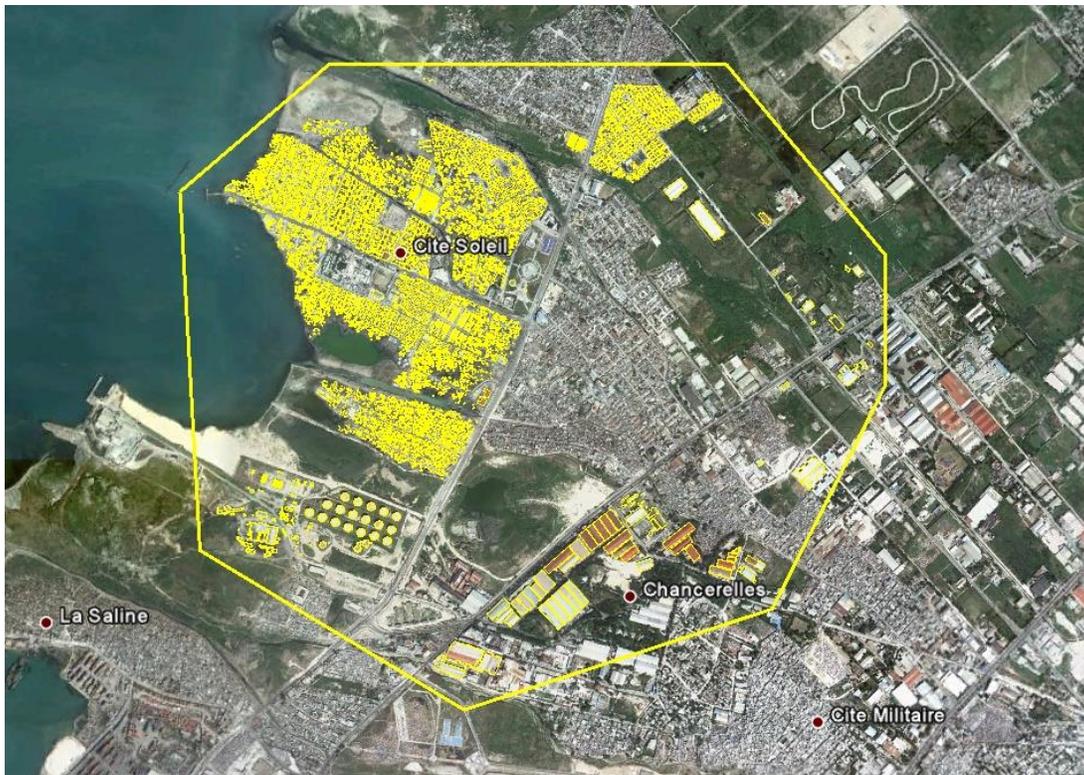
Figure 3.1 Purdue's Analysis of Building Footprints using Imagery from the January 21st and 22nd World Bank–ImageCat–RIT LIDAR data mission. Footprints are displayed in yellow.

- **U.S Navy Research Laboratory (NRL),** http://egeoint.nrlssc.navy.mil/ – Via ftp site, the public could access approximately 650 unclassified JPEG image and PDF map documents detailing damage assessment (areas of minimal, moderate, and severe identified), road surveys,

helicopter landing zones, and other USG points of interest, as well as ALIRT LIDAR data product details.

- **The Chinese Academy of Sciences (CAS), Institute of Geography,** http://english.cas.cn/ – CAS released a GIS feature dataset of Port-au-Prince that identified collapsed buildings, the road network, and Riviere Frorse valley landslides extracted from post-event GeoEye imagery.

3.1.2 Pre- and Post-event Imagery

Primary pre- and post-event imagery providers and/or satellites are listed below. The data providers are noted in parentheses. Additional details regarding these datasets may be found in the Appendix A8. The details of the World Bank – ImageCat – RIT remote sensing mission are discussed in the next section.

- ALIRT LIDAR (National Geospatial-Intelligence Agency)
- ASTER (NASA Jet Propulsion Laboratory)
- DigitalGlobe Quickbird and Worldview-2 (DigitalGlobe)
- EO-1 (NASA Goddard Space Flight Center)
- GeoEye-1 and Ikonos (GeoEye)
- Google Aerial (Google)
- ImageSat EROS-A and –B (ImageSat International)
- JAXA ALOS (Japan Aerospace Exploration Agency)
- USGS Landsat ETM and TM (U.S. Geological Survey)
- Microsoft Aerial (Microsoft Corp.)
- MODIS Rapid Response (NASA)
- NAVOCEANO (Naval Oceanographic Office)
- NOAA Aerial (National Oceanic and Atmospheric Administration)
- RADARSAT (MDA Corp.)
- SPOT (Spot Image Corp.)
- UAVSAR (NASA Jet Propulsion Laboratory)

3.1.3 Geospatial Data Portals, Infrastructure, and Social Networks

A number of important internet-based data and social resource hubs for knowledge, expertise, and data distribution and sharing emerged in the weeks following the earthquake. These became critical nodes for many sectors of the response community.

- **ReliefWeb Map Centre**
  - http://www.reliefweb.int/rw/dbc.nsf/doc108?OpenForm&emid=EQ-2010-000009-HTI&rc=2
  - The ReliefWeb Map Centre served as a kind of one-stop-shop or clearing house by aggregating major map documents, details, and internet links made available by key organizations.

- **Harvard University's Earthquake Geospatial Research Portal**
  - http://cegrp.cga.harvard.edu/haiti/
  - This portal aggregated free GIS datasets and online resources.

- **CrisisCommons**

  - http://crisiscommons.org/

  - CrisisCommons identifies itself as "a grassroots organization that facilitates partnerships and maintains a network of technology volunteers to respond to specific needs in times of crisis." Much of the OpenStreetMap mapping and digitization requests were being organized and facilitated through this online community linking needs with volunteer human resources.

- **Ushahidi**

  - http://haiti.ushahidi.com/

  - Ushahidi for Haiti has been an online web application and volunteer backend for reporting submissions by interested onsite or remote parties. Robust geo-locational and temporal attributes of all submissions and reports was provided for.

- **WikiProject Haiti**

  - http://wiki.openstreetmap.org/wiki/WikiProject_Haiti

  - WikiProject Haiti has been an online wiki serving as a hub for support on ongoing OpenStreetMap operations including the distribution of maps and data and instructional resources for utilizing OSM.

- **Haiti Crisis Map – Telescience**

  - http://haiticrisismap.org/

  - Hypercube super computers hosted at Telascience is used as a geodata repository and perform data related tasks. Haiti Crisis Map on these Hypercube machines powered by OpenStreetMap operations served WMS layers of Haiti imagery and data from multiple sources including Google, WB-IC-RIT, DigitalGlobe, NOAA, GeoEye, and Spot.

- **Virtual Disaster Viewer- VDV**

  - www.virtualdisasterviewer.com

  - VDV is an online GIS web application for serving imagery, field photos, and damage interpretation conducted by a large group of remote sensing experts (GEO-CAN). The VDV web portal was also used to manage the distributed group of experts by setting up a check-in check-out mechanism thus helping to keep track, aggregate and publish the damage interpretation work efficiently.

4.0   RIT DATA COLLECTION MISSION

This section describes the World Bank-ImageCat-RIT Remote Sensing data collect mission over Haiti. A key partnership that existed before the earthquake was one formed under Rochester Institute of Technology's IPLER program. IPLER, which stands for Information Products Laboratory for Emergency Response, is focused on understanding user needs in terms of disaster management and response and sharing remote sensing disaster R&D with the private and public sectors. ImageCat, which is a member

of IPLER, requested RIT's support on behalf of the World Bank to fly over Haiti after the earthquake to collect very-high resolution aerial imagery for the purpose of performing detailed damage assessments. RIT deployed the WASP (Wildfire Airborne Sensor Platform) camera system and a LiDAR sensor from Kucera International over Haiti nine days after the earthquake.

The details of the mission timeline, coverage, data collection systems and data specifications are discussed below.

4.1   Sensors

The RIT Wildfire Airborne Sensor Platform (WASP) was deployed to Haiti to acquire very-high resolution imagery and LIDAR data in support of the World Bank's mission to provide aid to the victims of the recent earthquake. RIT's unique collection of sensing modalities covered both the visible and infrared spectrum as well as high-resolution 3D measurements. When combined together, these sensing modalities offered an extremely rich information set. Examples of high-resolution image and LIDAR products are presented in Figure 4.1 (a) and (b). The WASP resolution, the richest collected data, and diversity of sensors is described in Table 4-1 and in Figure 4.2

Table 4-1 Imaging Instruments

Sensor	Wavelength	Resolution	Utility
Color	400 - 900 nm	0.15 cm	Visual damage assessment
Shortwave IR	1000 - 1700 nm	0.83 cm	Water detection, smoke penetration
Midwave IR	3000 -5000 nm	0.83 cm	Fire detection, smoke penetration
Longwave IR	8000 - 9200 nm	0.83 cm	Water surface contamination, storage tank fill levels

3D Measurement Instrument: Leica ALS-60 LiDAR, 2 points/m2; allows precision measurements of building and ground surface displacements.

Aircraft: Piper PA-31 Navajo, tail number N350GB

4.2   Operational Overview

The RIT Haiti Response Team, the aircraft and sensors departed from Rochester, NY on the 19th of January 2010. Data acquisition began over Port-au-Prince the next day, 20 January, 2010. A temporary export license was granted by the State Department clearing RIT to transport the sensor to the Dominican Republic. Due to a restriction in the license that prohibits data transfers from the aircraft while outside the US, the base of operations was moved to Raphael Hernandez Airport in northwestern Puerto Rico. This location served as the launching point for daily flights with refueling stops as needed in the Dominican Republic.

(a)

(b)

Figure 4.1 (a) Example of Color High-Resolution Aerial Imagery Collected over Haiti. (b) Combined LiDAR and High-Resolution Aerial Imagery for the Presidential Palace Area in Port-au-Prince. .
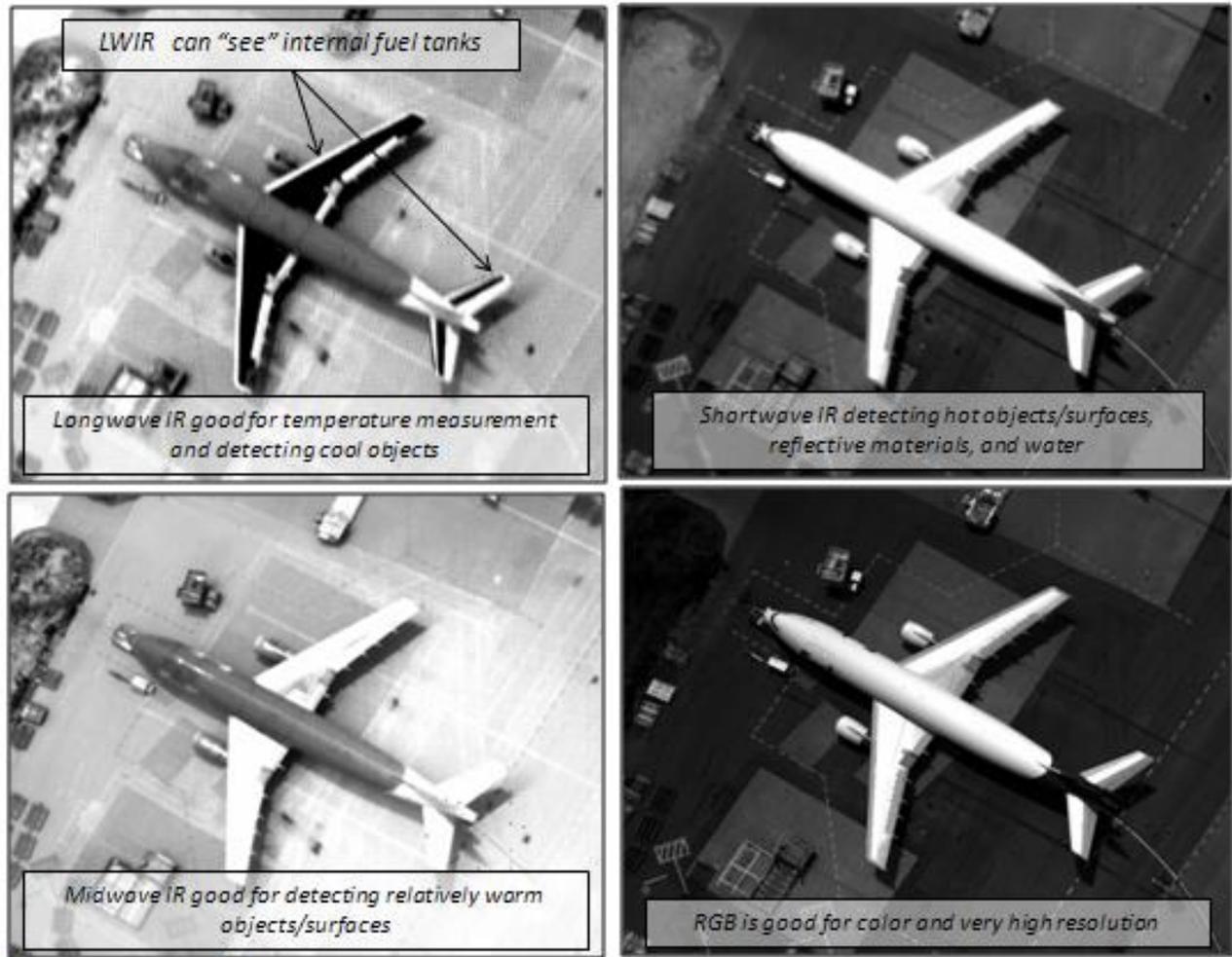
Figure 4.2 Four Cameras for Color and Infrared Imaging

One major issue affecting the execution of the mission was airspace control over Haiti. Air traffic was prohibited over Haiti without clearance from the Haitian authorities and coordination with US military controllers. For the RIT team, airspace coordination for flights over Haiti was possible with help from the US Air Force and SOUTHCOM. RIT's contacts were very cooperative and supportive. A well-defined process was put in place for all flights during the mission to Haiti.

After each flight day, the aircraft returned to Puerto Rico for crew rest and to transfer data from the aircraft. Data was transferred from a portable hard drive to a high-speed internet connection at the University of Puerto Rico at Mayaguez, about 1 hour drive from the airport. An RIT imaging science graduate student assisted in the field operations. Data was transferred to a server at RIT for processing overnight and delivery to University at Buffalo (UB) the next morning, approximately 12 hours after the aircraft landing.

4.3 Coverage

Figure 4.3 shows a summary of the areas covered by RIT in 7 days of flying over Haiti. RIT covered 250 sq. miles (650 sq. km) in 148 flight lines that added up to a total of 1,933 line-miles (3,115 km). All Haiti campaign imagery has been reprocessed, based on the LiDAR-derived 1m digital elevation model, and has been released to the general research community and various response organizations, including the ImageCat/GEO-CAN team. RIT has also provided *.tar compressed files for all imagery for quicker and easier downloading. LiDAR data are available as 1m and 10m bare earth (DEMs) and surface elevation models (SEMs; 1st return surface) in ERDAS *.img and in TIFF formats. LiDAR data are also available as point clouds in *.las format: classified point clouds.
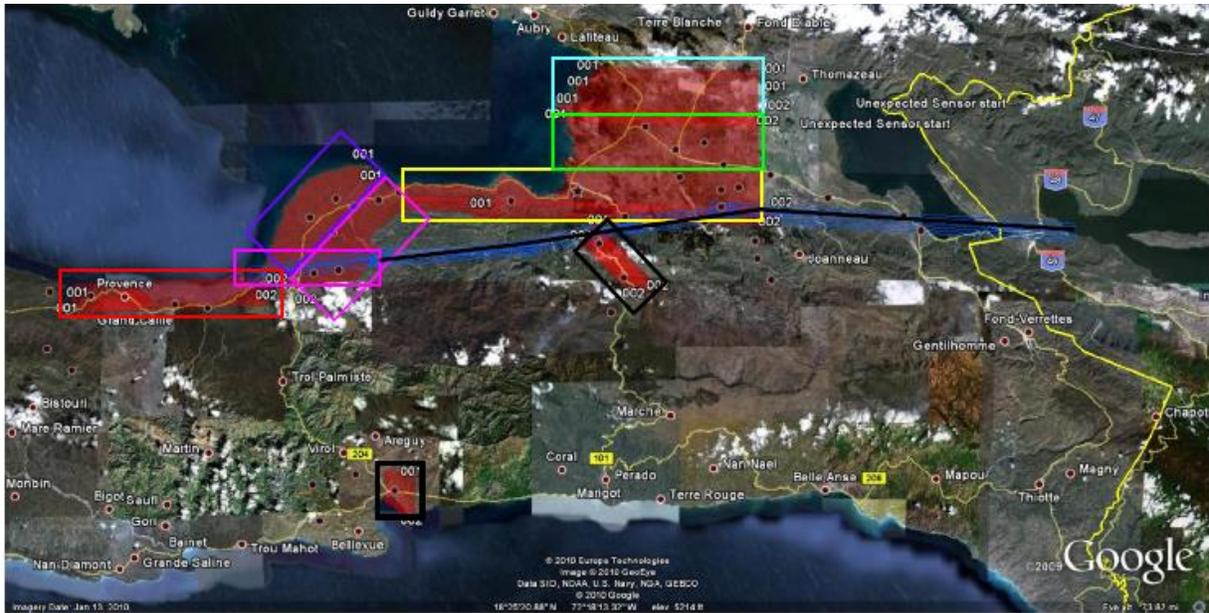
Day 1 – 1/21/2010: Southern Port-au-Prince and coast
Day 2 – 1/22/2010: Central Port-au-Prince
Day 3 – 1/23/2010: Northern Port-au-Prince
Day 4 – 1/24/2010: Western Léogâne
Day 5 – 1/25/2010: Eastern Léogâne & western fault line section
Day 6 – 1/26/2010: Petit Goâve & Grand Goâve
Day 7 – 1/27/2010: Fermate & Jacmel & central fault line (east of Léogâne)

Figure 4.3 Image Data Collection Footprints and Timeline

4.4 Data Set Description

Data has been processed and placed by RIT onto an ftp server for dissemination, http://waspftp.cis.rit.edu. In Appendix A16, Table 16-1 describes the different imagery datasets generated from each of the four RIT imaging cameras, and Table 16-1 describes the LiDAR datasets acquired using the Leica ALS-60 owned and operated by Kucera International. Images can be accessed on the ftp server by selecting the folder that corresponds to the collection date of interest. (Refer to Figure 4.3 to identify areas and corresponding dates).

4.5   Data Distribution

In addition to ImageCat and the World Bank, there has been a tremendous utilization of data by other users. Processed data was made available via FTP server and, in some cases, delivered on portable hard drives. Datasets on hard drives were delivered to:

- ImageCat
- World Bank
- Google
- University at Buffalo
- Columbia University
- ITT
- Harris

As of July 2010, over 40 TB of Haiti data products have been downloaded from the RIT FTP server. Some download users were not identifiable but many were. The following list illustrates the very broad dissemination of data to the worldwide disaster response community enabled by the World Bank's insistence on open access to the Haiti data. Some examples of identified users include world leaders in data sharing and cloud computing:

- *Google*
- *Yahoo*
- *Softlayer*
- *Amazon*
- *Internet Archive*

US Government, commercial contractors:

- *U.S. Geological Survey (USGS)*
- *National Geospatial-Intelligence Agency (NGA)*
- *U.S. Army*
- *U.S. SouthCom*
- *Lawrence Livermore National Laboratory*
- *National Public Radio*
- *Harris*
- *Aerospace Corp*
- *SAIC*
- *BAE*
- *ITT*
- *ERDAS*

United Nations and NGOs:

- *UNOSAT*
- *UN SPIDER*

- *UN OCHA*
- *World Food Program*
- *MapAction*
- *CrisisCommons*

International Search Engines:

- *Yandex (Russia)*
- *Access Haiti (Haitian ISP)*

Universities worldwide:

- *University of California (includes UC Davis and UC San Diego)*
- *University of North Carolina, Charlotte*
- *University at Buffalo*
- *Purdue University*
- *US Naval Academy*
- *Massachusetts Institute of Technology*
- *Ohio State University*
- *Carnegie Mellon University*
- *California Institute of Technology*
- *California Institute for Telecommunications and Information Technology (CalIT2)*
- *Drexel University*
- *University System of Georgia*
- *University of Texas*
- *Hunter College (City University of NY)*
- *Cambridge University (United Kingdom)*
- *University of Twente (Netherlands)*
- *Osaka University (Japan)*
- *Waterloo University Canada)*
- *University of Auckland (New Zealand)*

4.6   New Information Product Development

Rochester Institute of Technology (RIT) received a grant from the National Science Foundation (NSF) under its RAPID program for the development of a Blue Tarp Detection Tool, an algorithm that automatically analyzes imagery and identifies the location of blue tarps used for emergency shelters thus allowing disaster managers to locate concentrations of Internally Displaced Persons (IDPs). An early example output is shown in Figure 4.3. This tool is currently being configured into a standalone application for field deployment as part of NSF RAPID grant (GRANT # 1034639, Automated Target Detection Tool for Disaster Response) awarded to RIT in May 2010.

Figure 4.4 Prototype Example of Automated Target Detection Map Product

5.0   GEO-CAN

5.1   Background

Gathering damage information from remotely-sensed data is not a new phenomenon, and has been the mainstay for the scientific community for well over a decade. Following the 2008 Sichuan, China earthquake, a highly-motivated consortium of scientists volunteered their time to test a prototype community-based method of damage assessment. It resulted in the development of the online Virtual Disaster Viewer (www.virtualdisasterviewer.com) – an integrated system allowing pre- and post-event very high spatial resolution imagery to be used for damage assessment. It incorporates additional information collected by ground field teams for the understanding of natural disasters by a global audience. Using VDV, a prototype on-line damage assessment was completed for the city of Ying Xiu, several months after the earthquake. Damage to buildings, infrastructure, landslide effects, and presence of Internally Displaced People (IDP) camps, was mapped by 85 volunteers, who reported a positive impression of this first-of-its-kind initiative.

As the extent of the Haiti earthquake became apparent, the global scientific community sought to find ways to become actively involved in helping with the response. This coincided with the need to analyze vast amounts of imagery that was being collected and posted at a daily rate, from the WB-IC-RIT aerial mission, to the Google and NOAA missions, and from satellite imagery.

The first phase of the WB-IC-RIT Haiti damage assessment initially focused on identifying collapsed buildings within the capital city of Port-au-Prince, and was conducted by scientists and engineers at

ImageCat. The study area was greatly expanded in Phase 2, to include both collapsed and heavily-damaged buildings (Grades 4 and 5, EMS-98) in areas of Port-au-Prince, Carrefour, Delmas, Léogâne, Jacmel, Grand Goave and Petit Goave, a greater than seven-fold increase in the area targeted in Phase 1. Analysis of these areas was also more in-depth, with each heavily-damaged or completely collapsed building identified and its image footprint digitized into a GIS database.

ImageCat and its partner organizations identified the strength and availability of a distributed analysis using expert volunteers, and there was a surge in interest in the project in days following the earthquake. Social networking and crowd-sourcing technologies were also being used in other aspects of the response in Haiti. Online networks such as Ushahidi.com aided people on the ground through mobile communications technologies and an army of volunteer translators, and mappers. The OpenStreetMap (OSM) community (in partnership with CrisisCommons) geared up in the days following the earthquake to update the basic open-source maps of Haiti, to provide the most detailed mapping of locations of road networks and critical infrastructure. Both of these examples were made possible by the internet, mobile communications, and an eager pool of volunteers, willing to donate time and professional expertise to aid in the post-earthquake response. The GEO-CAN initiative described in this section was made possible by these factors, combined with the availability of very high spatial resolution aerial and satellite images showing Haiti before, and after the earthquake.

5.2   The Community

GEO-CAN - which stands for Global Earth Observation Catastrophe Assessment Network - represents an initiative to mobilize engineers and scientists around the world to help assess the impacts of the Haitian earthquake. Motivated by the need to quickly and as accurately as possible assess damage to buildings and critical infrastructure around Port-au-Prince and surrounding areas, ImageCat and its partners – Rochester Institute of Technology, the Earthquake Engineering Research Institute, the State University of New York (MCEER[3] and LESAM[4]) and others – working with the World Bank and the Global Facility for Disaster Reduction and Recovery (GFDRR) took the lead in forming this network with the purpose of providing a remote damage assessment using very high resolution optical imagery collected by the World Bank–ImageCat–RIT Remote Sensing Mission and by other data collectors (e.g., Google, NOAA).

5.2.1   GEO-CAN Participation

The initial GEO-CAN participants largely consisted of the volunteers who took part in the China earthquake trial in 2008. The Earthquake Engineering Research Institute (EERI; who had partnered on the China prototype) invited its members to participate, providing outreach to an impressive 2000 members in 56 countries. These include engineers, scientists, and policy and decision-makers, making EERI the premier professional organization dealing with earthquake hazard assessment and reduction.

Other strategic partners in GEO-CAN mobilized significant numbers of their members for GEO-CAN. The Earthquake Engineering Field Investigation Team (EEFIT), which specializes in issues of earthquake safety and mitigation in Europe, was one of these. A UK-based organization similar to the Earthquake Engineering Research Institute (EERI) in the U.S, EEFIT spearheaded efforts that focused on areas to the west of Port-au-Prince.

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[3] Multidisciplinary Center for Extreme Engineering Research
[4] Landscape-based Environmental System Analysis & Modeling
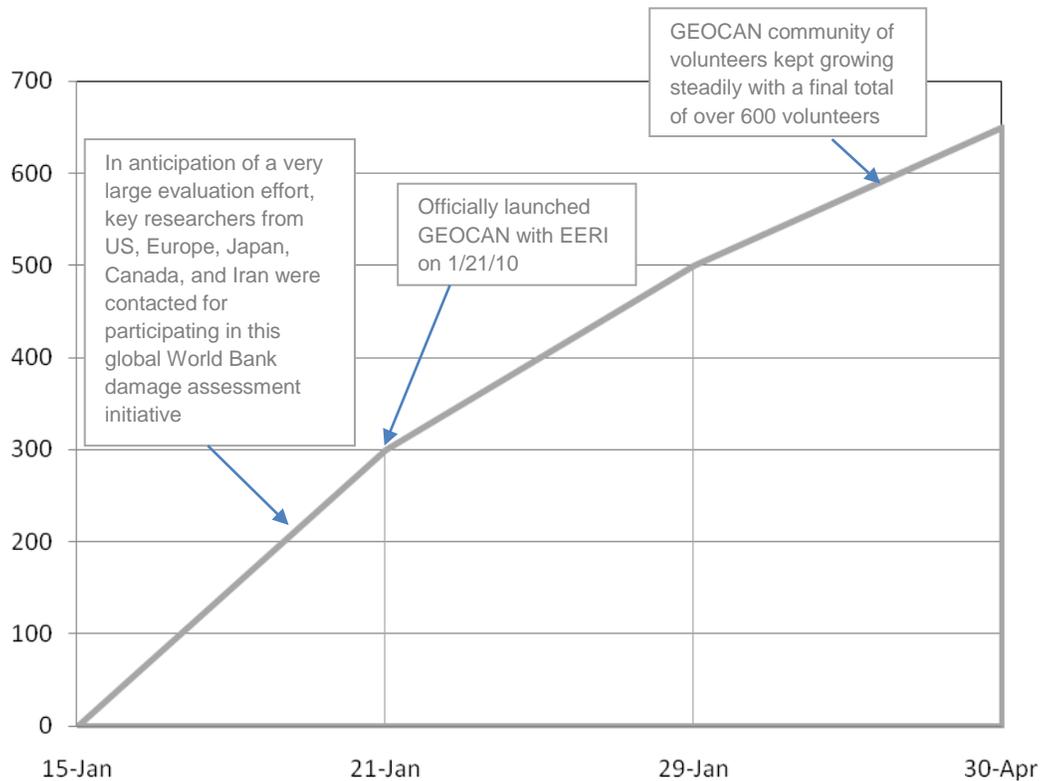
Figure 5.1 Total Number of Volunteers Registering Over Time

Figure 5.1 shows the cumulative number of volunteers registering their interest to aid the Haiti initiative. At its height, GEO-CAN consisted of over 600 individuals. 23 countries were represented by 131 private and academic institutions, including 60 universities, 18 government agencies and non-profit organizations, and 53 private companies (40 individuals who donated their time that did not list an affiliation). Contributors volunteered from USA, Austria, Barbados, Canada, China, Costa Rica, Czech Republic, Finland, France, Germany, Greece, Japan, India, Iran, Italy, Mexico, Netherlands, Poland, Portugal, Turkey, United Kingdom, Spain, and Sudan (Figure 5.2), with an organization from New Zealand also offering help.

In anticipation of a large evaluation effort, key researchers were contacted for their interest in participating in the global World Bank damage assessment initiative. In the initial call that occurred between 1/15/10 and 1/21/10, researchers from Japan, Europe, Canada, Iran and the US agreed to be a part of the effort. In addition, several large university networks in India and within the US were contacted regarding their interest in joining the global effort. Motivated by the need to quickly and accurately assess damage to buildings and critical infrastructure around Port-au-Prince and surrounding areas, GEO-CAN was officially launched on 1/21 by ImageCat and its partners – the Earthquake Engineering Research Institute (EERI), Rochester Institute of Technology (RIT), the State University of New York (MCEER and LESAM) and others – working with the World Bank and the Global Facility for Disaster Reduction and Recovery (GFDRR).
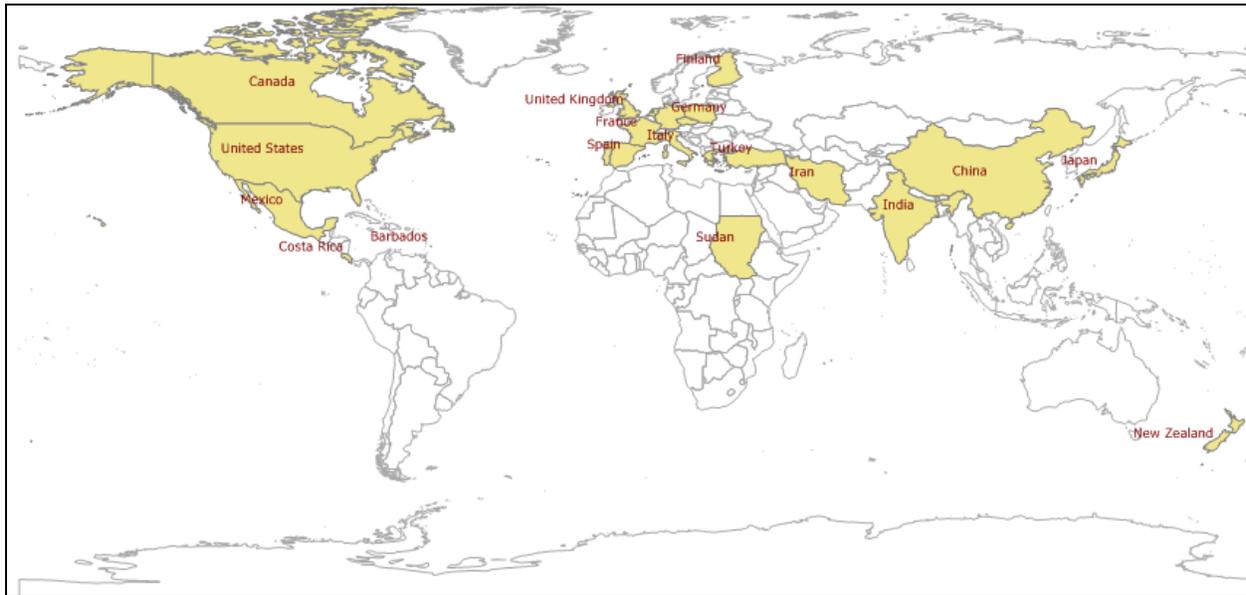
Figure 5.2 Nations with Participating GEO-CAN Members (in yellow)

5.3 Damage Assessment

A multi-phased damage assessment was implemented to effectively utilize experts' experience in image analysis, earthquake engineering and other disciplines. The study area was divided into a grid of square cells, with volunteers using the online Virtual Disaster Viewer to check-out a cell for analysis, and check-in the completed cell, along with damage information for buildings within the cell. Each grid cell was automatically locked for editing by VDV until the cell was checked-in as completed. The discussions below describe the analysis platform used by each expert in assigning damage levels to each building. Since there were multiple phases, a separate discussion on damage protocols for each phase is presented in detail in Section 6.

5.3.1   Analysis Platform

Google Earth was chosen as the platform for the image analysis, for the following reasons:

- It is freely available across the globe
- It has a large user base – people are familiar with it
- It has a readily available pre-event imagery archive for Haiti
- It can incorporate imagery captured at multiple dates
- You can create simple GIS datasets within the system

Once the analysis of a grid cell was complete, a KML file containing the GIS vector features was submitted for QA by ImageCat scientists.

5.3.2 Guidelines

A set of guidelines was produced for each phase of the analysis, tailored for the GEO-CAN community, and updated as the analysis progressed. These included the check-out-check-in allocation process for grid cells, guidelines for using Google Earth, data descriptions and instructions on data usage. The guidelines included sections on the use of the Google Earth interface, creating GIS features, and a systematic procedure of how to identify damage within imagery. The complete guideline document can be found in Appendices A1 and A2**).** The guideline document was paired with a reference document showing examples of damage to buildings within the imagery. This was an especially useful reference for the volunteers, that is, to provide examples of the types of damage that could be identified using the very high resolution aerial imagery. The complete Damage Reference Document distributed to GEO-CAN Volunteers can be found in Appendix A3.

5.3.3 Workflow

Figure 5.3 shows the operational workflow that volunteers followed in the Phase 2 damage assessment. Volunteers registered their interest with the GEO-CAN administrators (geocan@imagecatinc.com). They provided information on their level of expertise in analyzing remotely-sensed imagery, and their experience in engineering, image analysis or other relevant disciplines. From this, the GEO-CAN administrators were able to assign grid squares to suit the analysts experience level, with grid cells containing the most complex building configurations reserved for ImageCat scientists.

To the analysis, each volunteer was assigned a unique login to the Virtual Disaster Viewer. Once logged in, an analyst could check-out one of grid cell at a time. This cell was then locked – it could not be reassigned – until it was checked-in as completed. The imagery kml files were added into Google Earth, and the analyst worked around the grid in a systematic fashion, toggling between the pre and post imagery. The changes in the building features were found, the building was assigned a damage level (either Grade 4 or 5 based on the EMS-98 damage scale). In addition, the building perimeter was digitized as a polygon (from the pre-earthquake image) and was included in the dataset provided back to the GEO-CAN Administrator. In addition to the building footprint or perimeter and the assigned damage level, a level of confidence for that damage assignment was provided back to the GEO-CAN Administrator by the analyst.

Once the analysis of each cell was complete, the user checked the grid cell back into VDV and registered the tile as complete. The analyst then had the opportunity to continue his or her analysis on a new cell. The data was then uploaded to a central repository, where a thorough QA and consistency check was performed by ImageCat scientists. Once all cells were collated and checked, the data was sent to the World Bank client.
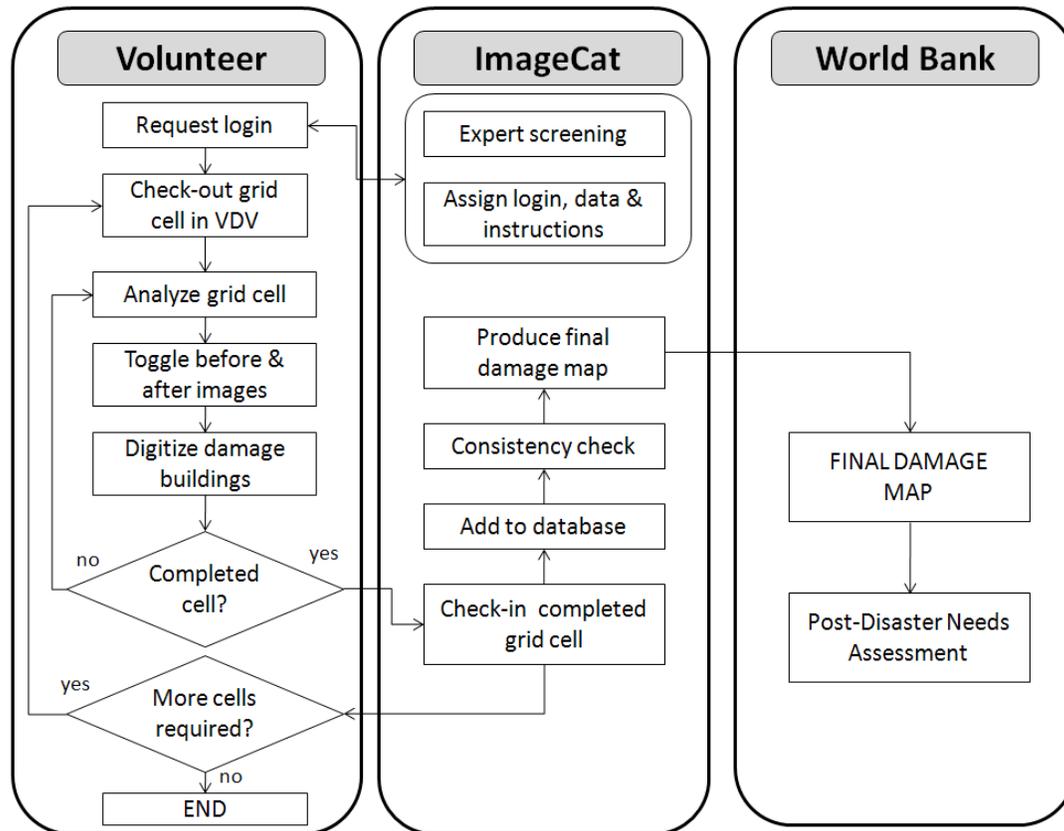
Figure 5.3 GEO-CAN Operational Workflow

5.4 GEO-CAN in Future Events

Discussions have been held with EERI – one of the key partners in GEO-CAN – to discuss ways in which GEO-CAN can sustain itself in order to respond to future earthquakes. One possible idea is the enhancement of EERI's current Information Technology (IT) infrastructure so that reaching the membership of EERI is more efficient and can be used to address not only post-earthquake response needs but to comment on pre-earthquake issues such as planning and mitigation priorities as well as issues dealing with re-building. As an independent, engineering-based organization, the membership of EERI could play an important role in bringing important resources to the World Bank and other humanitarian organizations.

In a separate document, ImageCat will be working with EERI to develop a business plan that can be shared with the World Bank, as well as with other relief organizations. The purpose of the plan is to lay out a set of milestones and resource requirements that will institutionalize the GEO-CAN community. The plan will include short- and long-term objectives; key partnerships with other relief organizations, as well as with government agencies and industry; resource requirements, and a charter which will guide the operation of this multi-organizational entity. Some of the opportunities that are envisioned for GEO-CAN are establishing and maintaining a data archive on field reconnaissance information (much of it collected through EERI-sponsored reconnaissance missions), defining the requirements of annual imagery reserve fund, and preparing post-earthquake damage reconnaissance reports that would supplement PDNA damage assessment studies.

Appendix A10 contains a report prepared by EERI and ImageCat that summarizes the discussions and recommendations made during a one-day technical workshop organized by EERI and sponsored by the World Bank. The purpose of the workshop was to perform a post-mortem review of the GEO-CAN experience with the long-term objective of improving the overall damage assessment process. Many of the recommendations that are contained in that report will provide valuable insights into how GEO-CAN can be institutionalized for future earthquakes.

Some of the key recommendations from that workshop include:

1. Highlight the role of crowd-sourcing in remote sensing analysis

   Specifically, publicize the results within the realm of emergency response. Also, make sure that the data can be shared easily – that is, create a single portal for access. Finally, warehouse the data and analyses for future use.

2. Improve the interactions with the volunteer participants

   One of the key recommendations was to make sure that the purpose of the analysis is clear, i.e., who will use the data; how will it be compiled; and how will it be used. Also, in order to institutionalize GEO-CAN, maintain a mailing list and/or website that can regularly update users or members on new developments. Also, make sure that everyone who contributes to the analysis is individually acknowledged for their efforts.

3. Improve the Virtual Disaster Viewer Interface

   One of the important recommendations that came out the workshop was the notion of acquiring before-event imagery for especially vulnerable areas that could be pre-loaded into the system. That way, the data is there as soon as the earthquake occurs, and more importantly, analyses that can support pre-disaster planning can be implemented, e.g., creating urban exposure models showing vulnerable areas. Recommendations were also made that would improve the ease of use of the current VDV interface, i.e., log-in and check-out process.

4. Improve the training associated with the damage assessment process

   One recommendation here was to develop a 7 to 10 minute training video for each volunteer that would include a simple quiz or test at the end to gauge their level of competence. Also, it was recommended that more documentation be prepared that would help in interpreting specific building damage states, e.g., how to evaluate shadows, blow-outs (when a building explodes outward), skewed buildings (how to interpret misalignments), and changes in building elevation.

A full discussion on these recommendations, along with a detailed description of how the GEO-CAN emerged during the Haiti earthquake, is contained in the EERI-ImageCat Workshop report, see Appendix A10.

6.0 METHODOLOGY

6.1 A Multi-Phased Approach to Damage Assessment

This section describes the processes and workflow used in conducting the remote sensing based damage assessment for Haiti. The methodological components include a) utilizing both high (50cm) and very-high resolution (15cm) imagery datasets, b) imagery interpretation and remote sensing techniques for data processing and preparation, c) a systematic and scientific basis for building damage interpretation, d) an easy-to-use Internet-based platform for viewing and analyzing imagery, and e) leveraging the subject matter expertise of a globally distributed network of volunteers to accomplish as much as possible as quickly as possible. This section also addresses the critical dependencies between the available data (e.g., imagery resolution and dates), assessment techniques, platforms for distribution, and availability of a "social network" of volunteers comprising the Global Earth Observation - Catastrophe Assessment Network (GEO-CAN) – see previous section. In this way, the methodology described herein represents a combination of innovation and adaptation of best practices for application in what was a very dynamic and complex situation in post-disaster Haiti.

The rapid and remote sensing based damage assessment performed in this project was implemented in three broad phases:

- Phase 1 – Satellite Imagery
- Phase 2 – Aerial Photos
- Phase 3 – Liquefaction Analysis

Phase 1 was initiated in the very first week of the disaster. The focus was on identifying the locations of collapsed buildings by visual interpreting orthographic high-resolution (50cm) pre- and post-event satellite imagery viewed in Google Earth. The location of each collapsed structure was recorded by the analyst by digitizing the approximate center of each building within Google Earth. Phase 1 only considered building damage within Port-au-Prince.

Phase 2 was started about a week after the earthquake. In this phase, the ImageCat project team utilized very-high resolution (VHR) post-event aerial imagery.   At a resolution of 15cm, this VHR post-event imagery provided the visible detail required to identify a wider range of building damage states than in Phase 1. Additionally, the study area in this phase was expanded to include many more developed regions of Haiti that were located outside of central PaP. These included western Port-au-Prince (Carrefour and Leogane), Grand Goave, Petit Goave, Jacmel, and Hinche. In addition to providing the locations of severely-damaged buildings, Phase 2 also included a task where the pre-earthquake footprint of damaged buildings was delineated. The intent of this task was to create data that could more effectively estimate the amount of building space or floor area that had to be replaced or repaired. Combined with estimates of number of stories, the output from this phase were two-fold: number of severely-damaged buildings and total amount of floor area to be repaired or replaced.

Phase 3 – which used the GEO-CAN platform for data collection - was led by GEER (Geo-engineering Extreme Events Reconnaissance Association). As described in the earlier section, the focus was on identifying areas of liquefaction ground failure. This effort began much later than Phases 1 and 2 and involved a separate group of experts (geotechnical engineers).

6.2   Phase 1 Methodology

This phase resulted in the identification and digitization of over 5,000 heavily-damaged or destroyed buildings in PaP. The survey was based on using available high-resolution satellite imagery from GeoEye (GeoEye-1, IKONOS) and DigitalGlobe (QuickBird). Identifying collapsed buildings in the imagery was done by a team of ImageCat analysts and associated researchers throughout the world. The first step in this analysis was to divide the area of interest (AOI) into 0.5 km x 0.5 km grids where each grid cell was assigned a unique index number. A total of 535 grids were mapped within the city of PaP, see Figure 6.1.
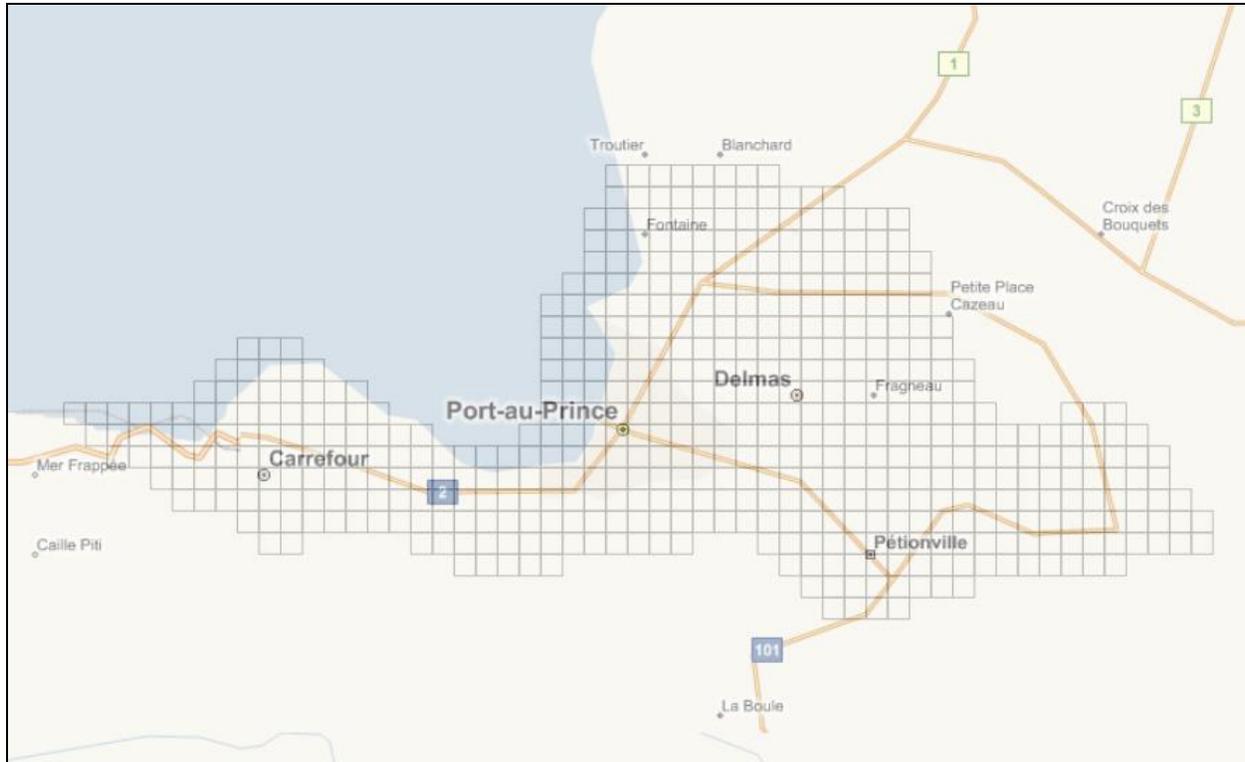
Figure 6.1 Phase 1 Area of Interest for Port-au-Prince defined as a 0.5km x 0.5km Grid System

The urban area surrounding Port-au-Prince was mapped by examining satellite imagery and noting areas of dense population. 500-meter grid cells were then overlaid onto the imagery to form the analysis footprint.   An online grid cell management system, herein referred to as the *user management module*, was implemented through the Virtual Disaster Viewer (VDV). Grid assignments were then handed out to experts throughout the U.S., Canada, and Europe. Experts were identified and selected based on recommendations from the Earthquake Engineering Research Institute (EERI – see *eeri.org*), the Earthquake Engineering Field Investigation Team (EEFIT – see *istructe.org/eefit*) and several other international research universities. This initial group was limited both in terms of size and study scope (i.e., only the point locations of severely-damaged buildings was requested).   The damage interpretations were performed within desktop installations of the Google Earth platform using the high-resolution pre- and the post-event satellite imagery. Each analyst was asked to follow the protocol below:

1. Log in to the VDV user management module and check out assigned grid cell
2. Utilizing Google Earth, review all buildings contained within assigned grid cell
3. Identify and point-digitize the locations of collapsed structures in a new data layer
4. Check the grid cell back into the user management module upon completion of grid cell review
5. Email a KML file of all digitized points to a central repository for aggregation with damage assessment data from other completed grid cells.

6.2.1 Visually Assessing Damage

The Remote Sensing for Earthquake Scale[5] (RSE) – - which equates to the European Macro-Seismic Scale (EMS98) was used to make the initial determinations of collapsed buildings. Although all of the analysts that participated in this phase had training in GIS or remote sensing, the protocol for identifying significant building damage was reviewed with the entire team. Examples of the damage protocol were used to train the eye to recognize the chaotic/debris/rubble patterns of building damage that are frequently visible when a building collapses. The patterns are often influenced by the type of building materials used in construction and the type of building itself.

Collapsed buildings were often observed as being much brighter than the surrounding buildings and in many cases, had rough textures. This was frequently seen in the images for PaP; however, analysts had to be careful that these signatures were not associated with materials in empty lots. Another example of the protocol involved looking for discontinuities in the before and after images of rectangular buildings. In flipping back and forth between the two images, damaged buildings appear to shift suggesting that they may have collapsed. Lastly, changes in relative shadow heights may indicate possible soft-story failures or "pancaking." This type of failure occurs when the bottom or lower story of a building is softer (i.e., less stiff) than the uppers stories and thus collapses completely under the load of the earthquake. This type of failure can show up in high-resolution images by demonstrating a stair-step appearance on the side of the roof, or explosion of debris on the sides of the building. The eye can be trained to identify these conditions by toggling between before and after imagery. Examples of some of these failures are viewed in Google Earth as presented in Figures 6.2(a) and 6.2(b) below.

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[5] This building damage scale developed for use with the Virtual Disaster Viewer (VDV) incorporates both engineering and remote sensing observations, with classes ranging from Indistinguishable to collapse that correspond to the EMS-98 scale

(a)

(b)

Figure 6.2 (a) and (b) Examples of Collapsed Buildings as viewed in High-Resolution Imagery (50cm) in Google Earth; pre-event imagery is shown on the left and post-event imagery on the right.

With each new disaster, the protocol for identifying building damage adjusts slightly (or in some cases significantly) to accommodate the cultural and building practices of the region. Haiti was certainly no exception. Of particular concern were buildings without roofs seen in "before" imagery. These appeared very much like damaged buildings in the "after" imagery, particularly with changing shadow conditions between images or when a few internal walls fall. An internal wall falling does not constitute a collapsed structure, so the project team was very careful to examine the before imagery to assure open-roofed structures were classified correctly. Another issue was the prevalence of rubble or mud in

the after imagery that was very easy to mistake as building damage, particularly where there had been debris flows. Whenever possible, analysts located buildings in the before imagery to make sure a building was present. There was considerable development as well as destruction in PaP, so identification of individual buildings was not always possible. Frequently, a damaged building was not in the pre-event imagery, sometimes only 6 months old. Without building codes, newer structures appeared as vulnerable as older structures. Some areas were so decimated that structures could only be identified in the before imagery. For example, in extremely dense areas, such as that depicted in Figure 6.3, it is often difficult to identify single structures in the after imagery (right). The before imagery (left) is used as a guide, but may not always distinguish individual structures.

Figure 6.3 Pre- (left) and Post-event (right) Imagery of Dense Development

Well-known and significant structures were identified and double-checked in all the images. Figure 6.4 shows the National Palace before and after the earthquake.

Figure 6.4 Pre- (left) and Post-event (right) Imagery of the National Palace

Analysts were also careful to review all tall structures, specifically looking for "stair step" effects which could indicate the presence of a "pancaked" structure (see Figure 6.5)

Figure 6.5 Pre- (left) and Post-event (right) Imagery of "Pancaked" and "Stair-step" Damage Patterns

Many structures elicited signatures that are typically associated with building collapse; however, upon more careful examination revealed either structures without roofs or construction in progress (Figure 6.6). Analysts were careful to crosscheck these sources.

Figure 6.6 Pre- (left) and Post-event (right) Imagery displaying examples of Recent Construction and Structures without Roofs

6.3   Phase 2 Methodology

The ImageCat mission in Phase 2 was adjusted to focus on the identification of all heavily-damaged and destroyed buildings (as opposed to just destroyed buildings in Phase 1). A refinement of the building damage assessment protocol was also required in order to accommodate the very-high resolution (VHR) aerial imagery datasets. Fifteen-centimeter Google aerial imagery was acquired on January 17th for the Western portion of Port-au Prince (see Figure 6.7). Although this data covered only a portion of the area of interest, it provided an opportunity to test the new damage assessment protocols. Protocol modifications focused on two changes: a) revising the determination of building damage using the European Macroseismic Scale (EMS-98), and b) expanding the set of damage state examples included in the training document. The earlier remote sensing scale (see discussion of RSE in Section 6.2.1) had been based on using the coarser satellite imagery (60 cm); therefore, any damage state other than

collapse was not easily discernable. Using the VHR aerial imagery, the project team found it easier to identify the different mechanisms associated with heavy damage and completely destroyed structures. In some cases, observations of destroyed buildings could be quite complex, particularly if a single floor experienced a pancaked failure or a given structure was surrounded by other buildings. The VHR data provided the visual resolution required to identify these conditions with a greater degree of reliability.
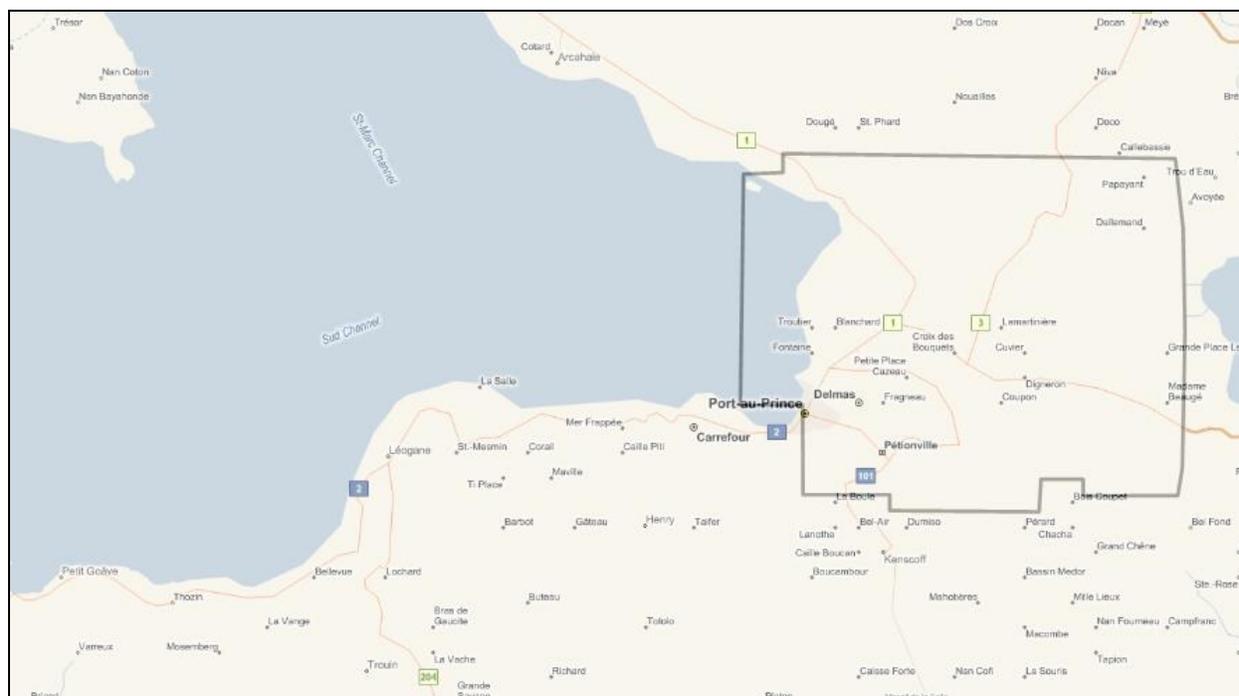
Figure 6.7 Extent of 15-centimeter Data initially available for Port-au-Prince, as provided by Google (outlined area)

Logistically, Phase 2 was implemented in a manner very similar to Phase 1 with one major exception. In order to analyze the much larger area in Phase 2 and to collect more information on damaged buildings, the ImageCat effort was significantly expanded by formally creating the GEO-CAN community. By utilizing crowd-sourcing principles and technology, we were able to expand our analytical base from tens of analysts to hundreds.

The *user management module* was implemented through the Virtual Disaster Viewer (VDV) to allow each analyst to login, check out a grid cell, identify severely-damaged or collapsed buildings and digitize their pre-earthquake footprints, check the grid cell back into the system when completed, and email a KML file to a central repository for aggregation with other data. The Phase 2 protocol followed the steps below:

1. Log-in to the VDV user management module and check out assigned grid cell

2. Utilizing Google Earth and the Phase 1 building damage layer (points), review Phase 1 damage points using the VHR imagery and assess/assign a more detailed classification of damage (heavily-damaged or collapsed, EMS-98 Damage Grades 4 and 5, respectively)

3. Digitize the pre-earthquake building footprint from the pre-earthquake satellite imagery for each Grade 4 or 5 building in a new data layer

4. Using the VHR imagery, assign damage levels to all remaining buildings not identified in Phase 1; also, delineate pre-earthquake building footprints

5. Check the grid cell back into the system

6. Email the KML file with building footprint polygons to GEO-CAN central repository for aggregation with other damage assessment data from other completed grid cells.

A detailed set of damage protocols were developed that enabled each analyst to consistently assign a building damage grade to all heavily-damaged or destroyed buildings. Damage levels were based on the European Macroseismic Scale, 1998 (EMS 1998). The 500m-mesh grid layer that was developed for Phase 1 was expanded in Phase 2 to cover the complete area flown by the WB-IC-RIT remote sensing mission. These grids are mapped in Figure 6.8 along with the Phase 1 coverage.
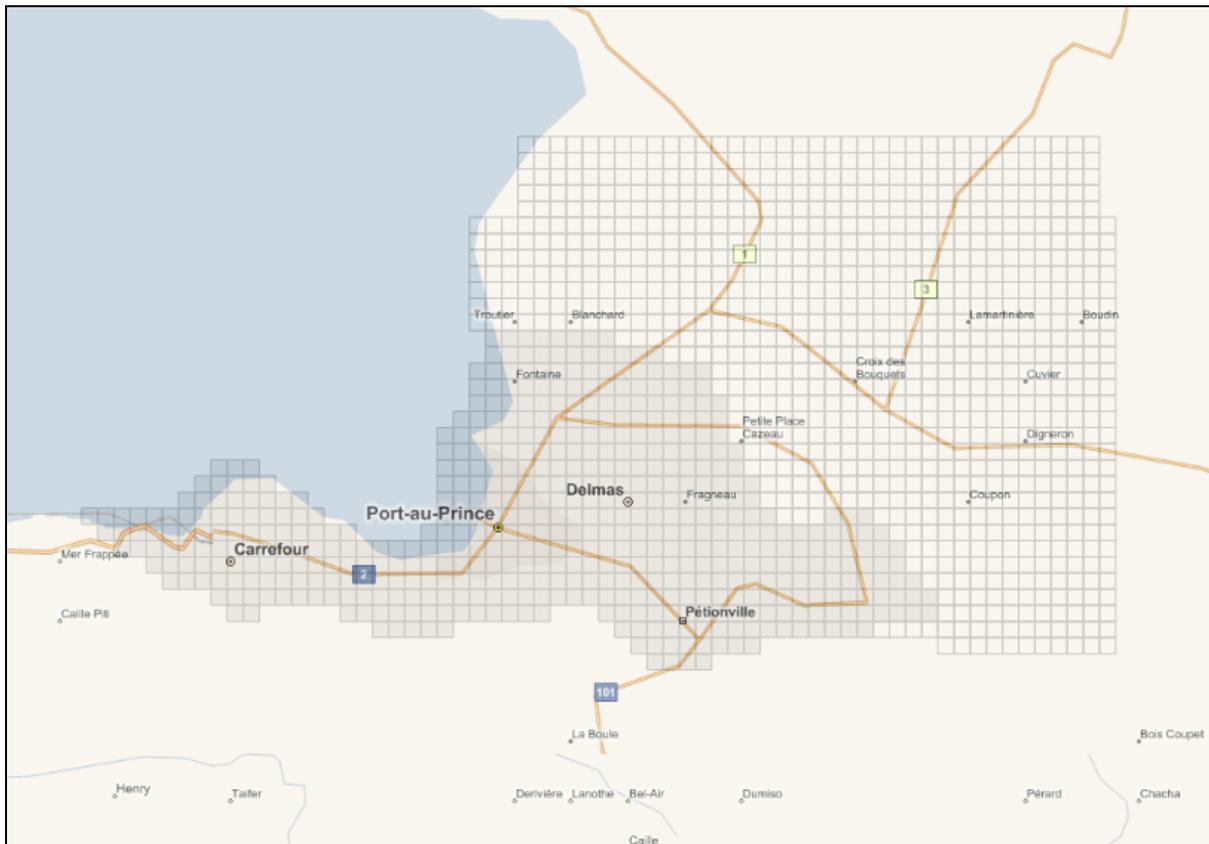
Figure 6.8 Port-au-Prince Area showing 0.5km x 0.5km expanded Grid System for Phase 2. The grid cells shaded in gray show the extent of the Phase 1 assessment.

6.3.1   Achieving a Comprehensive View of Damage

As discussed earlier, the Phase 1 and 2 damage assessments focused explicitly on identifying severely-damaged and completely-destroyed buildings.   Even though the level of detail was unprecedented, the imagery still lacked the ability to identify damage at all levels or for specific types of failure, e.g., soft-

story failures. In order to provide as comprehensive an assessment of damage, the following additional activities were implemented by the ImageCat project team.

- Estimate the number of buildings in EMS-98 Damage Grades 1 (negligible to light), 2 (moderate) and 3 (substantial to heavy),
- Estimate the total building floor area associated with all buildings that require replacement or repair, and
- Estimate the total number of buildings whether damaged or not in the entire area of interest.

In order to organize all damage results, it was necessary to create a land-use database for greater PaP and other outlying areas. This step of the methodology is discussed in the next section.

6.3.2   Land-Use Analysis – An Intermediate Step

A land-use analysis was a key component in helping to explain the results of this study. First of all, there seemed to be a difference in building vulnerabilities between residential and commercial/industrial construction.   In addition, there were significant differences observed between different types of residential construction, e.g., shanties versus other housing. Second, the structural configuration - that is shape and number of stories – differs depending on occupancy type. Finally, estimating replacement or rebuilding costs is highly dependent on the type of occupancy associated with the structure. For these reasons, the ImageCat project team undertook an early study to create a coarse land-use map that could infer the occupancy types throughout the affected areas in Haiti.

Land-use classes were devised as a means to visually identify and organize developed areas according to construction type and occupancy use. The land-use classes adopted in this project were:

1. Agricultural
2. Commercial
3. Downtown
4. Industrial
5. Residential High-Density
6. Residential Low-Density
7. Shanty
8. Open land

An initial version of the land-use map was prepared early in the disaster using satellite imagery. Once the VHR aerial imagery began to emerge, the preliminary land-use was revised to account for additional information afforded by the higher resolution data. Figure 6.9 shows the final land-use map for this study.

6.3.3   Estimation of Less Severe Damage States, Total Building Floor Area, and Total Number of Buildings

In order to deliver a comprehensive and complete picture of earthquake damage, an approach was needed in order to estimate building counts for structures experiencing less severe damage states. The reason for this is that damage associated with these lower levels is often not visible from nadir views (i.e., imagery which shows only the tops of buildings). Referring to the EMS-98 scale, these lower

damage states are represented by grade levels 1 (negligible to light), 2 (moderate) and 3 (substantial to heavy). Unfortunately, given the state of current remote sensing technologies, estimating non-collapse building damage requires the use of field or ground surveys. These surveys would be conducted on small but representative areas.
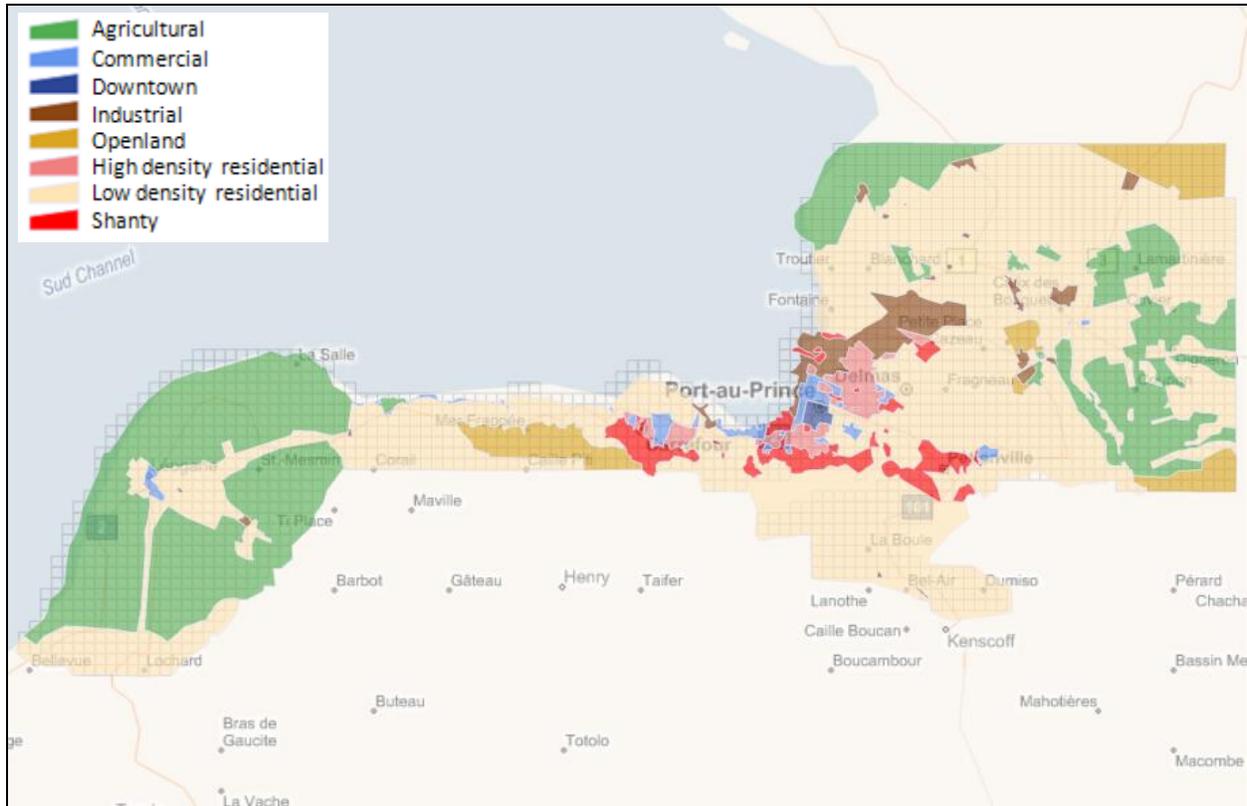
Figure 6.9 Final Land-Use Map for Greater PaP

6.3.3.1 Estimation of Less Severe Damage States

A set of models were developed in this study that extrapolated the results of the aerial damage surveys (Grades 4 and 5) to lower damage levels. These models are based on summarizing the results of several field surveys – in the form of damage distribution matrices – so that the relative percentage of buildings in each damage state or grade are presented for each land-use type. Normally, ground shaking intensity is also added as an independent parameter; however, in the Haiti earthquake, most areas with earthquake damage were rated as having at least a Modified Mercalli Intensity (MMI) of 9 – see Appendix A12 for a description of the MMI scale. That is, all areas experienced significant levels of ground motion. The MMIs in PaP are shown in Figure 6.10 – source: McCann and Mora, 2010.

Damage levels should also be a function of building construction type or design. However, because little or no seismic design considerations were employed in the building of structures in Haiti, all buildings were highly vulnerable to the effects of earthquakes. Therefore, construction type was not a major factor in determining whether a building experienced damage or not.
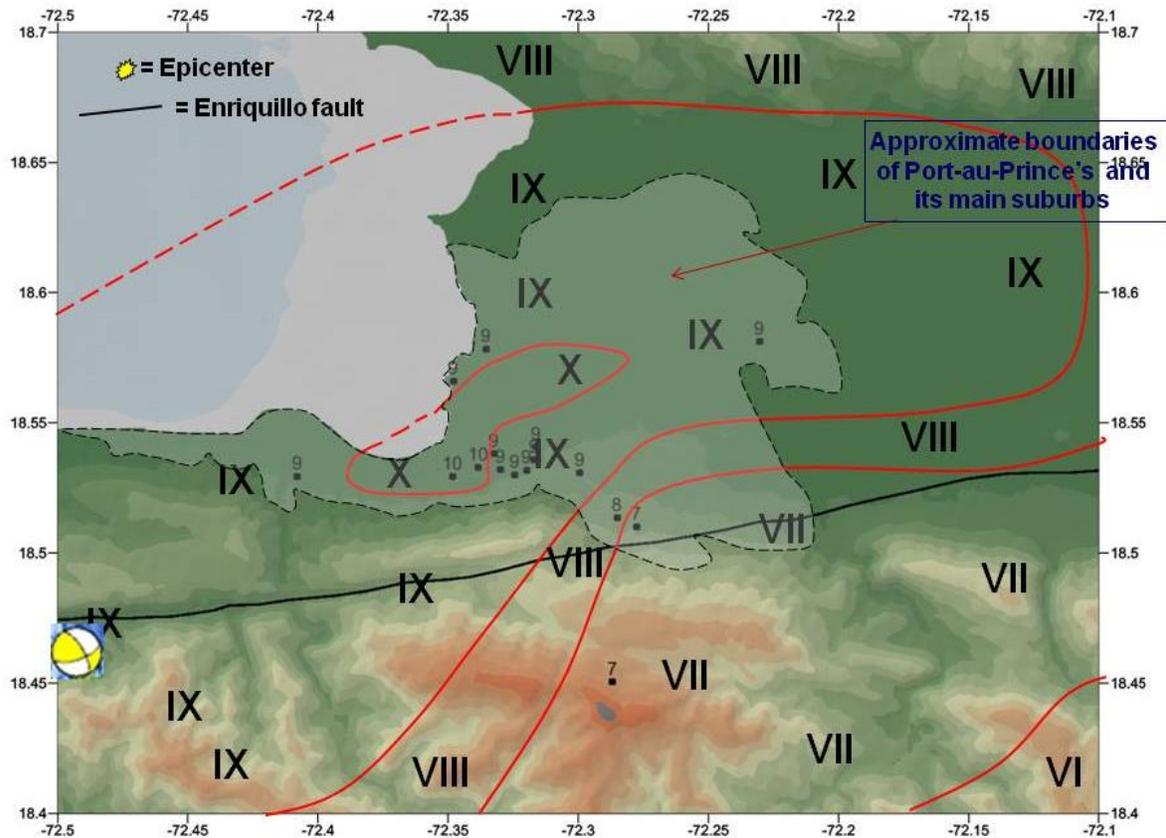
Figure 6.10 Haiti Main Shock January 12, 2010 Modified Mercalli Intensities around PaP (McCann and Mora, 2010)

The ImageCat project team worked with various investigators in constructing the damage models used in scaling aerial damage results to lower damage levels. The groups that contributed directly to the ImageCat/GEO-CAN effort include:

- Cambridge Architectural Research (CAR) Ltd. (Professor Robin Spence and Dr. Keiko Saito)

    This team helped to determine the damage levels associated with targeted areas where Pictometry (oblique) imagery was used. In total, this team assigned damage grades, number of stories, construction types to over 1,200 buildings located throughout PaP. Their effort is described in a report which is attached as Appendix A9 to this final report.

- BFP Engineers, Inc. (Eduardo Fierro and Cynthia Perry)

    This team collected photographs and assigned damage grades to over 70 buildings in the central portion of PaP.

- Stanford University and Pacific Earthquake Engineering Research (PEER) team (Professor Eduardo Miranda, Stanford University; Ayse Hortacsu, Applied Technology Council; Veronica Cedillos, Geohazards International; Carlos Cabrera, Risk Management Solutions; and Chris Sams, Risk Management Solutions

This team collected field data from central PaP and contributed damage assignments to the ImageCat team. This information was directly used in establish the relative numbers of buildings in each damage grade level.

Table 6-1 shows the combined count of buildings in each damage grade level for four major land-use types: commercial/downtown/industrial; residential high density; residential low density; and shanty or informal housing. The land-use types for commercial, downtown and industrial were combined because the types of construction that were associated with these land uses appeared to be roughly similar or the amount of field survey data was lacking (in the case of industrial facilities).

In each of these cases, the project team had several sources from which to create these damage distributions. For the commercial/downtown/industrial category, it was decided that using the field observations from the BFP and Stanford/PEER surveys provided the best source of information from which to judge damage for this category. Figures 6.11 and 6.12 provide a sample of the data used by these teams to determine the damage grade for each building.

Figure 6.11 Plan View of Damage Assignments Completed by BFP for Central PaP (Fierro, 2010)

Figure 6.12 Typical Photo used by BFP in assigning specific Damage Grades to Buildings in Central PaP (Fierro, 2010)

For the other land-use types, the ImageCat team used the results from the CAR Pictometry analysis. Because of access issues (e.g., tall walls), it was felt that using oblique imagery to determine the damage levels in residential areas was the best source of information for this land-use type. Figure 6.13 shows a typical Pictometry image in central PaP.

The Pictometry Online system was used extensively by all members of the PDNA team to evaluate building damage within PaP – see http://www.pictometry.com/government/product_online.shtml. Access to this data was critical in determining damage in targeted areas within PaP. Because it was not easy to get to many areas via field surveys, the Pictometry online system allowed the ImageCat project team to virtually survey these harder to get to areas without leaving their work stations. This facilitated a more comprehensive evaluation, although the level of detail for any particular building was not as good as having the results of the field surveys. More is reported on the use of this unique dataset later in the report.

Both the Pictometry and field survey datasets were shared with all members of the PDNA team (i.e., UNOSAT and JRC). In addition, the relative damage percentages shown in Table 6-1 were used to extrapolate the aerial damage totals (Damage Grades 4 and 5 totals) from the combined building counts (i.e., UNOSAT, JRC and World Bank-ImageCat) to all other levels of damage.

a. Aerial Photo (Nadir)   b. Pictometry Image

Figure 6.13 Comparison of the Very High Resolution Aerial Imagery used by the GEO-CAN Team (Photo a) and the Pictometry Images for the same area (Photo set b)

To estimate building counts for these lower damage categories or states, the ImageCat project team used a series of simple equations that calculated the number of buildings in Damage Grades 1, 2 and 3 based on the proportion of buildings in each of these categories (see Table 6-1) and the number of observed Damage Grade 4 and 5 buildings.   In addition, land-use type is a key factor in selecting the proper equation.

To illustrate this process, Equation 6.1 is provided for Grade 3 buildings.

No. of Grade 3 buildings = $p_3 (p_4 + p_5)^{-1} (n_4 + n_5)$ 6.1

where p_3 is the percentage (in terms of a ratio) of Grade 3 buildings in Table 6-1 for commercial, downtown, and industrial buildings, p_4 is the percentage for Grade 4, p_5 is the percentage for Grade 5, n_4 is the number of counted Grade 4 buildings from the aerial damage survey, and n_5 is the number of counted Grade 5 buildings from the survey. The procedure is applied separately for each land use area.

If we use for demonstration purposes, Damage Grade 3 commercial/downtown/industrial buildings and assume that the combined count of Grade 4 and 5 buildings is 100, then the number of Grade 3 buildings (using the damage percentages in Table 6-1) is 41 buildings.

In the analysis of total damage for the PDNA, the ImageCat/GEO-CAN results for Damage Grades 4 and 5 were combined with the UNOSAT and JRC damage totals for those two categories. The damage ratios – as reflected in Table 6-1 – were then applied using this combined database to estimate the total number of buildings in all damage categories. This analysis is discussed in Section 8 of this report.

6.3.3.2 Estimation of Floor Area by Building Land-Use Type

A key element of the rebuilding cost equation is an estimate of the total amount of floor area to be repaired or replaced. To estimate this parameter, the ImageCat project team used information from both the aerial damage surveys (i.e., GEO-CAN damage survey) and the field reports.

The first step of this analysis was to collate information on typical building footprint sizes by land-use type. Using the information collected by the GEO-CAN team, ImageCat tabulated the median footprint size for all communes, Table 6-2. This information was then averaged for each land-use type resulting in mean footprint sizes ranging from 63.2 m^2 (shanty) to 90.7 m^2 (commercial).

The next step was to estimate the number of stories associated with different building occupancies or land-use categories. By knowing the distribution of story heights (number of stories) for each land-use category, we could then calculate the total floor area by multiplying the building footprint area by the number of stories. In Haiti, buildings are generally three stories or less. Using data from about 400 buildings in the PaP area (source: field surveys and Pictometry analysis by CAR Ltd), we calculated the relative number of buildings that fell into the one-story, two-story and three-story categories. These percentages are reflected in the first several columns of Table 6-3. For example, for commercial construction, 38 percent of the buildings examined fell into the one-story category; 49 percent in the two-story category; and 12 percent in the three-story category.

We then distributed the total building counts that were recorded by the GEO-CAN damage assessment (a total of 29,056 buildings) into the different story height categories by using the story height distributions shown in Table 6-3. The estimated total story count for all damaged buildings identified by the GEO-CAN team was 44,495. The corresponding footprint area associated with all buildings considered in our analysis was 3,281,802 m^2. Finally, using the average footprint area (by land-use) calculated in Table 6-2, the average floor area per land-use type was estimated. These values are reflected in the final column of Table 6-3.

Application of the floor area per building values is discussed in Section 8 where we present our final damage totals.

Table 6-1 Haiti Building Damage Functions for Significant Ground Shaking (no ground failure)

Commercial/Downtown/Industrial [6]			
Damage Grade	*Description*	*Count*	*Percentage*
D1	Negligible to slight	6	6%
D2	Moderate	21	22%
D3	Substantial to heavy	20	21%
D4	Very heavy	14	15%
D5	Destruction	35	36%
		96	100%
Residential high density[7]			
D1	Negligible to slight	148	62%
D2	Moderate	17	7%
D3	Substantial to heavy	27	11%
D4	Very heavy	19	8%
D5	Destruction	27	11%
		238	100%
Residential low density[8]			
D1	Negligible to slight	64	69%
D2	Moderate	6	6%
D3	Substantial to heavy	10	11%
D4	Very heavy	4	4%
D5	Destruction	9	10%
		93	100%
Shanty[9]			
D1	Negligible to slight	33	63%
D2	Moderate	1	2%
D3	Substantial to heavy	5	10%
D4	Very heavy	5	10%
D5	Destruction	8	15%
		52	100%
Grand Total		**479**	

[6] a. Decided to use the field study results directly for these landuse categories. b. Reason: expect more damage at D3 which is difficult to identify in aerial photos. c. Application to industrial facilities may result in higher levels of damage than observed.d. Probably highest level of confidence in this landuse category.

[7] a. Might have missed some lower levels of damage but should not greatly influence final loss number.

[8] a. Might have missed some lower levels of damage but should not greatly influence final loss number.b. Might expect slightly lower rates of destruction because of lower likelihood of adjacent buildings causing damage.

[9] a. Does not apply to damage that might result from ground failure, e.g., landslide. b. Damage rates from landslide and liquefaction would be significantly higher.

Table 6-2 Median Building Footprint Area (m²) as determined from an Analysis of the GEO-CAN Aerial Damage Data

	Agricultural	Commercial	Downtown	Industrial	Residential high density	Residential low density	Shanty
Carrefour		42.8		84.9	96.4	102.8	61.3
Cite Soleil				79.6		53.4	43.4
Croix-Des-Bouques	46.4					73.2	
Delmas		107.7		69.8	78.9	113.6	84.0
Grand-Goave				105.5	47.1	52.0	66.1
Gressier	122.0	87.8				103.1	
Jacmel		105.5				100.9	
Leogane	78.2	97.6				111.8	
Petion-ville						78.6	69.6
Petit-Goave		82.1			66.6	64.8	
Port-Au-Prince		111.4	96.9	84.2	84.3	114.3	55.1
Tabarre				111.0		106.8	
Mean	82.2	90.7	96.9	89.2	74.7	89.6	63.2
Standard deviation	38.0	23.6		15.8	18.8	23.7	13.7

Table 6-3 Average Floor Area per Building by Land-Use Category

	# of stories[a]			Number of Buildings				Total stories	Total Footprint Area[d] (m²)	Median Footprint Area[e] (m²)	Floor Area per Bldg[f] (m²)
	1	2	3	Total[b]	1 Story[c]	2 Story[c]	3 Story[c]				
Agricultural	1.00	0.00	0.00	1,244	1,244.00	0.00	0.00	1,244.00	131,557	82.2	82.2
Commercial	0.38	0.49	0.12	2,347	891.86	1,150.03	281.64	4,036.84	363,829	90.7	156.0
Downtown	0.38	0.45	0.17	907	344.66	408.15	154.19	1,623.53	123,847	96.9	173.5
Industrial	0.50	0.50	0.00	581	290.50	290.50	0.00	871.50	134,885	89.2	133.8
Residential high density	0.36	0.51	0.13	4,315	1,553.40	2,200.65	560.95	7,637.55	473,826	74.7	132.2
Residential low density	0.27	0.63	0.10	12,607	3,403.89	7,942.41	1,260.70	23,070.81	1,584,006	89.6	164.0
Shanty	1.00	0.00	0.00	6,011	6,011.00	0.00	0.00	6,011.00	469,156	63.2	63.2
Total				28,025				44,495.23	3,281,802		

Notes:
a. # of stories: derived from a sample of field surveys (Fierro; Miranda; RMS) and Cambridge Pictometry analysis
b. Total No. of Buildings: GEO-CAN damage assessment survey of Port-au-Prince, Carrefour and Leogane areas
c. Building totals calculated from percentage breakdown (item 1) and total building count (item 2)
d. From GEO-CAN survey for Port-au-Prince, Carrefour and Leogane areas
e. Taken from median floor size per commune and land use (see Table 6-2)
f. Calculated from estimated number of buildings in each story and median footprint area

6.4   Phase 3 - Liquefaction Assessment

The focus of Phase 3 was on identifying areas of liquefaction ground failure. As with the building damage assessment, before- and after-earthquake imagery were visually examined for evidence of sand ejecta, lateral-spread cracking, and/or soil slumping. All analyses were performed using Google Earth as a platform.

6.4.1   Phase 3 Methodology

Observations of liquefaction ground failure were essentially limited to coastal areas, although some liquefaction effects were observed along river and stream beds. The ground shaking intensities in these areas were generally high, ranging from Modified Mercalli Intensity (MMI) IX to X, with some areas (Grande Goave and Petite Goave) experiencing MMI VIII – source: McCann and Mora, 2010.

Figure 6.14 shows the extent of the Phase 3 investigation. Because of the shape and size of the area, the grid system for this assessment consisted of non-uniform grid cells that followed the coastline and rivers. The grids were created using GIS routines which produced trapezoidal grid cells roughly 0.75 km by 1.5 km. Even though the area of investigation was narrow in extent, it still covered a great deal of land.   For this reason, the Geotechnical Engineering Earthquake Reconnaissance (GEER) network decided to use the GEO-CAN platform to identify and classify areas of liquefaction.
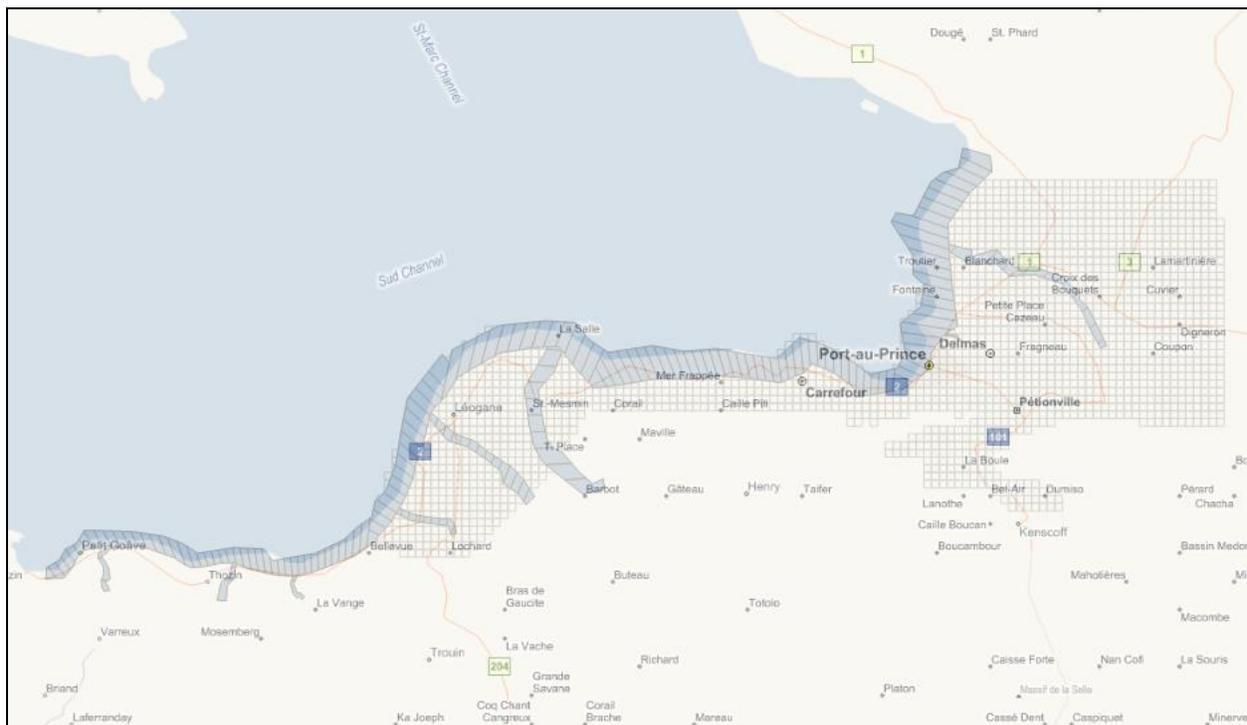
Figure 6.14 GEO-CAN Liquefaction Study Area (in blue); GEO-CAN Building Assessment Grid is also shown in gray

To help analysts identify liquefaction effects using VHR aerial imagery, the GEER investigators created a set of examples that showed what these effects could look like when viewed using aerial imagery.

Figure 6-15 shows some examples that were provided as part of the liquefaction damage assessment protocol. The complete protocol is contained in Appendix A4.

(a) Sand ejecta overlies the ground surface, and may be a lighter color than the adjacent areas. If the ejecta has vented through a crack, the feature will be linear

(b) In some instances, sand ejecta will be darker than the natural ground surface due to its large water content. Sand blows will be circular in shape.

(c) For coastal slumping, it is most useful to compare pre- (left image) and post-event (right image) shorelines. Coastal slumping will show significant coastal retreat and loss of beach zone.

GFDRR
Global Facility for Disaster Reduction and Recovery
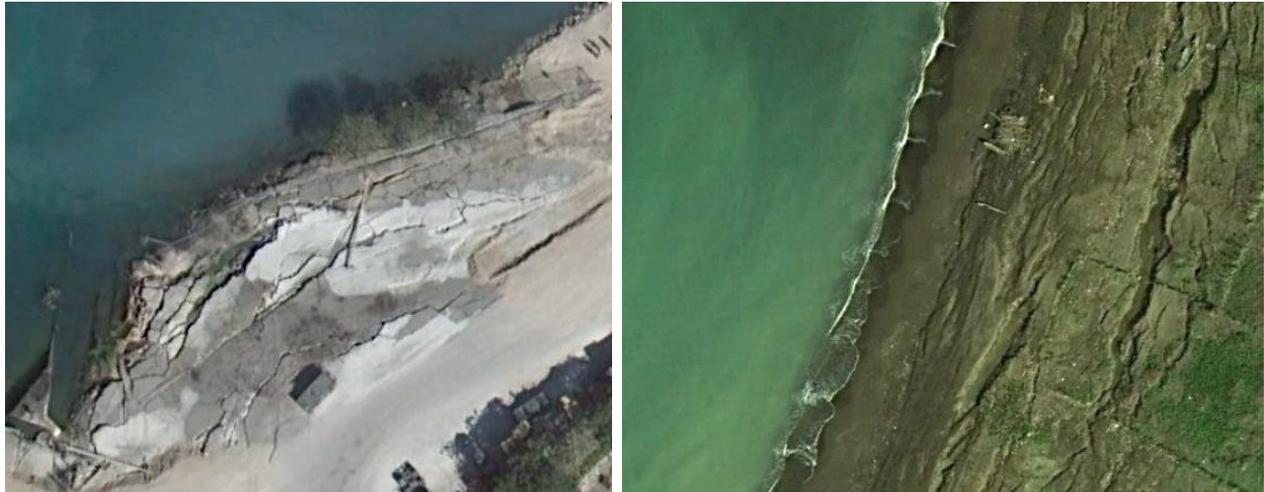
(d) Ground cracking is readily apparent parallel to the coastline (both left and right images show ground cracking)

Figure 6-15 Examples of Liquefaction Ground Failure Effects

The same check-in and check-out process used in the building damage assessment was used here for liquefaction. A preliminary map showing the results of Phase 3 is available on the Virtual Disaster Viewer (http://virtualdisasterviewer.com/haitiGrids/liquefaction). Figure 6.16 shows the most recent data layer (as of 24 May, 2010). The data can also be downloaded from the VDV site.
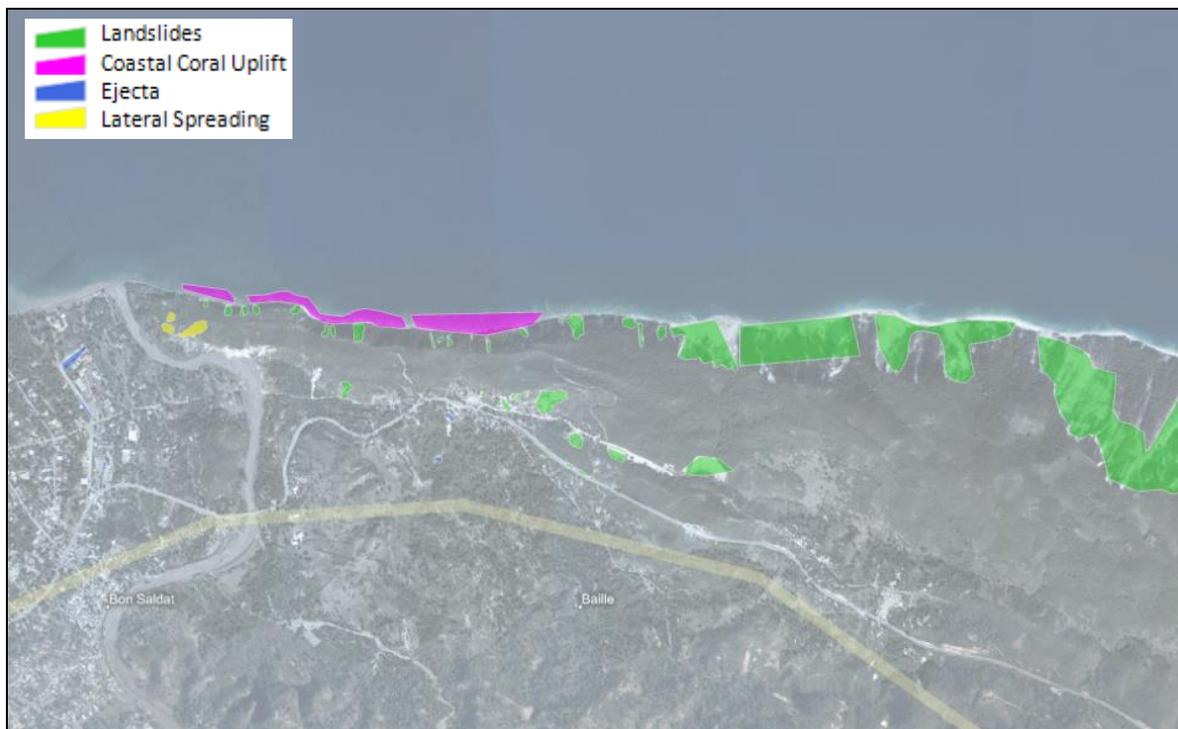
Figure 6.16 Liquefaction Assessment Data Layer - available for download via the VDV site

7.0   FIELD DATA COLLECTION

Post-earthquake field missions were undertaken in some of the hardest hit communities including Port-Au-Prince. The main objective of the field deployments was to collect damage information on buildings and infrastructure that would help support the PDNA effort and provide a validation dataset for the rapid remote sensing based damage assessment. The data collected in the field included over 7,000 geo-tagged digital still photographs and close to 100,000 geo-referenced digital photographs extracted from more than 21 hours of high-definition digital video footage. This section discusses the data and information collected by the different field teams, as well as the rational for selecting certain areas.

7.1 Earthquake Investigation Teams

The ImageCat team worked with over a half dozen earthquake investigation teams over a span of several months. A listing of the teams including size, duration of investigation, focus, and team contact is provided in Appendix A6. In some cases, in order to calibrate or validate early damage results, ImageCat worked with several teams to cover specific areas affected by the earthquake. The purpose of these investigations was to calibrate our initial damage results, i.e., quantify the level of accuracy in our assessment of heavily-damaged buildings and to assess how much of the total damage picture was being missed because of limitations of the imagery, e.g., not being able to see the sides of buildings. In addition, the project team discovered that in order to extrapolate the aerial damage results (which focused only on severe damage) to lower damage states, it was necessary to create complete damage summaries for at least several whole blocks. That is, classify damage according to the EMS-98 scale for every building in a block.

In addition to the earthquake investigation teams that collaborated with ImageCat, there were a number of other missions that were tied to the award of National Science Foundation (NSF) Rapid Grants which were released shortly after the earthquake. The details of these deployments are not discussed in this report. For more information on these grants, please refer to the NSF website: www.nsf.gov.

7.2   Sample Grids for Field Surveys

In order to prepare for the field deployments, the project team examined the Phase 1 building damage and land-use datasets for Port-Au-Prince to identify possible survey areas. The following criteria were used when prioritizing survey areas:

- Samples with a high concentration of Damage Grade 4 and 5 building,

- Samples that were spatially distributed throughout the greater Port-Au-Prince area; in addition, the historic city of Jacmel was also selected for field survey,

- Samples for each of the representative land-use or occupancy types,

- Reasonable number of samples so that scaling of damage data at Levels 4 and 5 could be used to statistically predict damage for Levels 1 through 3

Figure 7.1 shows some of the high priority areas, as defined by the criteria above. Of particular importance were the downtown and commercial areas of PaP, since much of the reported damage had been associated with these areas. The different colored areas in Figure 7.1 correspond to the different

land-use categories as developed by the ImageCat project team. The development of the land-use map was discussed in Section 6.3.2. The points in Figure 7.1 reflect the locations of severely-damaged buildings (created from the Phase 1 results).
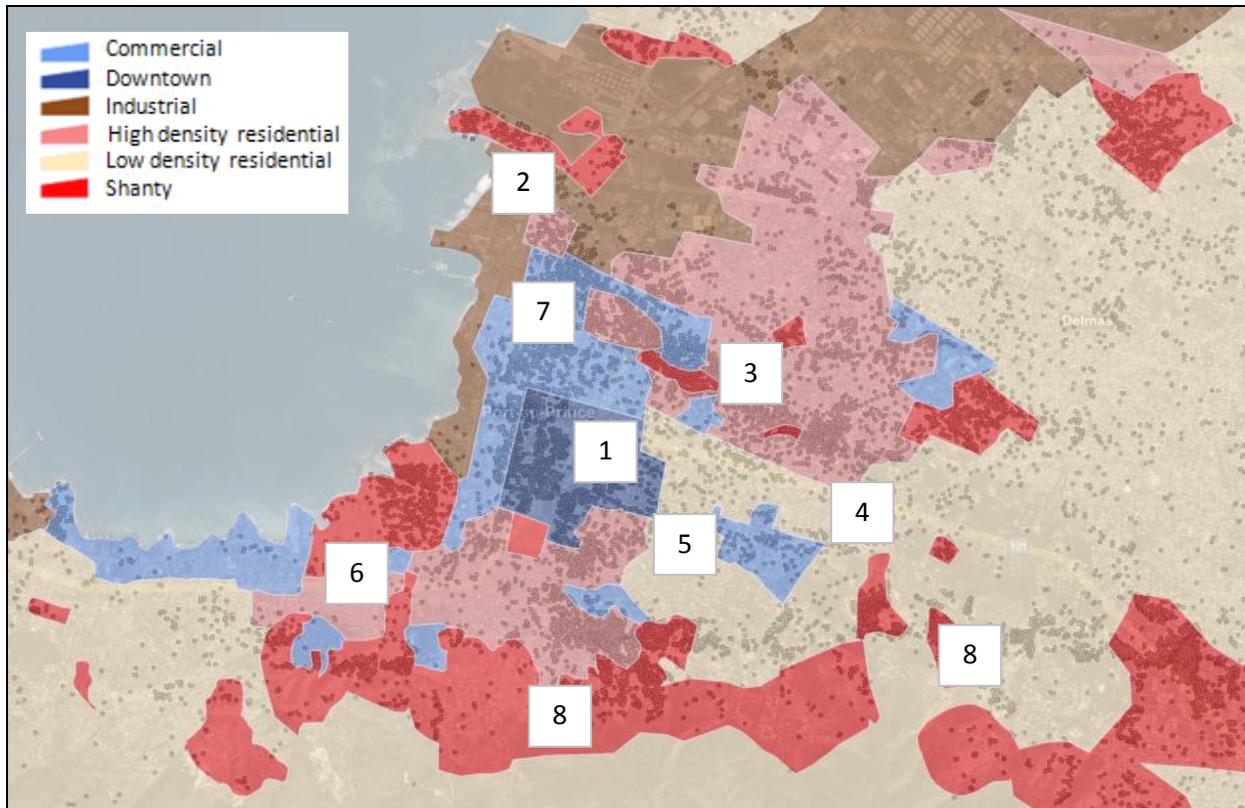
Figure 7.1 Survey Areas recommended by ImageCat to Different Investigation Teams
Legend 1. Downtown; 2. Port facilities; 3. High-density residential areas; 4. Low-density residential areas; 5. Heavy damage, mixed construction; 6. Commercial construction with low damage; 7. Commercial/ mixed construction with heavy damage; and 8. Shanty areas with both extensive and slight damage.

Figure 7.2 shows a six-cell grid area that the project team focused early on in the study. The priority in this assessment was to collect as much field information on damaged structures in this area in order to validate the results of the aerial damage analysis. As is evident in the figure, many buildings in this area were classified as being completely destroyed or severely damaged. It was important for the aerial damage assessment team to identify factors that could lead to misinterpretations or bias the final damage totals. The project team felt this was a good area to evaluate since it is comprised of mostly commercial construction and was reported to contain many collapsed buildings.

One team that deployed specifically to the area for the World Bank study was the BFP team – see discussion in Section 6.3.3.1. The BFP team surveyed several blocks within this six-block area. For six complete blocks, BFP provided damage assignments (using the EMS-98 Scale). This information was used in establishing the damage ratios discussed in Section 6.3. Appendix B1 contains the results from their field survey.

In addition, a joint team made up of Stanford University engineers and researchers from the Pacific Earthquake Engineering Research (PEER) Center also contributed their data to this study. See Appendix B2 for a summary of this damage survey.
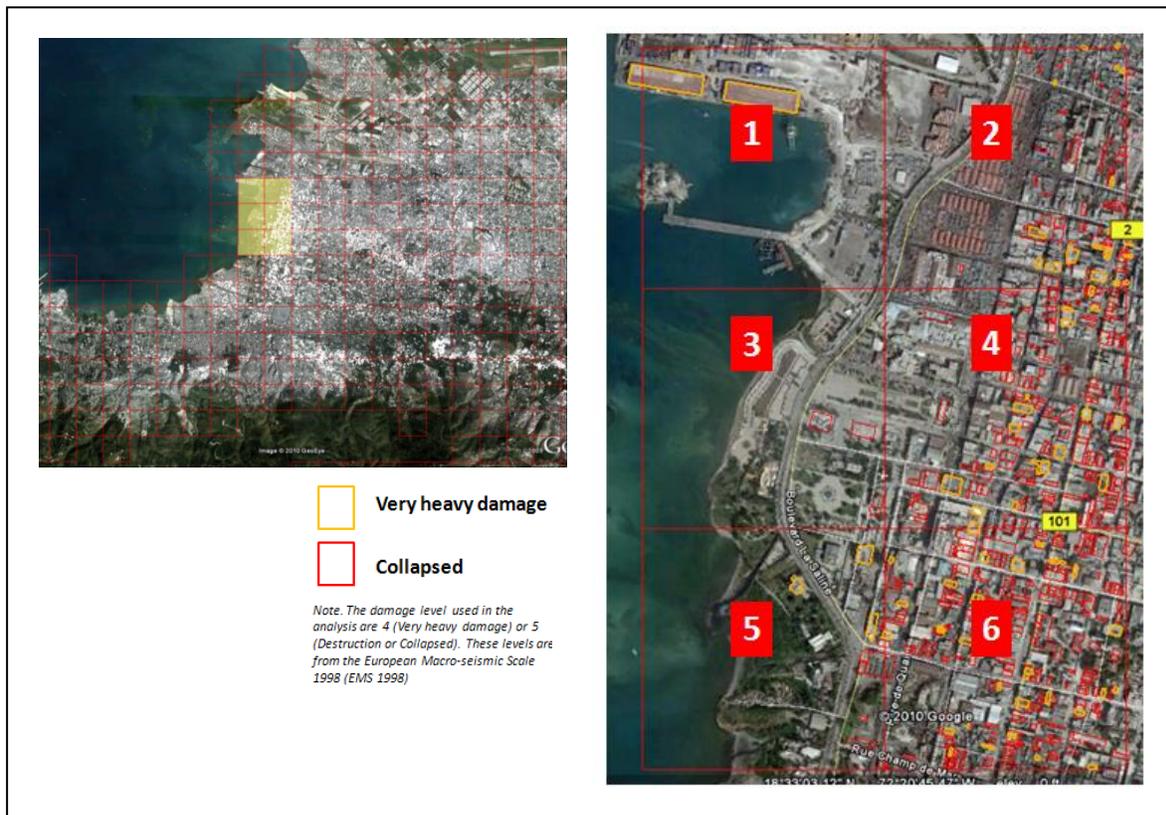
Figure 7.2 Six-grid Sample for Detailed Field Surveys

Figure 7.3 shows the targeted sites/areas visited by the Cambridge Architectural Research Ltd. (CAR) group and the EC's Joint Research Centre. These field surveys helped to establish three key pieces of information: 1) the level of omissions associated with the aerial survey results, 2) the distribution of damage at lower damage grades, and 3) building attribute information (number of stories, structural type and occupancy). The details of the CAR survey are discussed in a detailed report prepared for ImageCat and the World Bank. This report is contained in Appendix A9.

In addition to the surveys discussed above, ImageCat deployed a team of 8 members to Haiti in early May. Although the purpose of that trip was to conduct a series of interviews for the World Bank and the National Science Foundation on recovery issues and how the damage data produced by the project team was being used by the Haitian government and other non-profit organizations, the ImageCat team was able to the deploy the VIEWS™[10] software system to collected additional field videos of many areas within the greater PaP area. This information, while too late to incorporate into the PDNA damage

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[10] VIEWS™ is a notebook-based data collection and visualization system, which integrates GPS-registered digital video footage, digital photographs and observations with high-resolution satellite imagery collected before and after a disaster.

assessment, will be useful in re-calibrating the overall damage assessment methodology for future events. More discussion on the VIEWS™ deployment is provided in the next section.
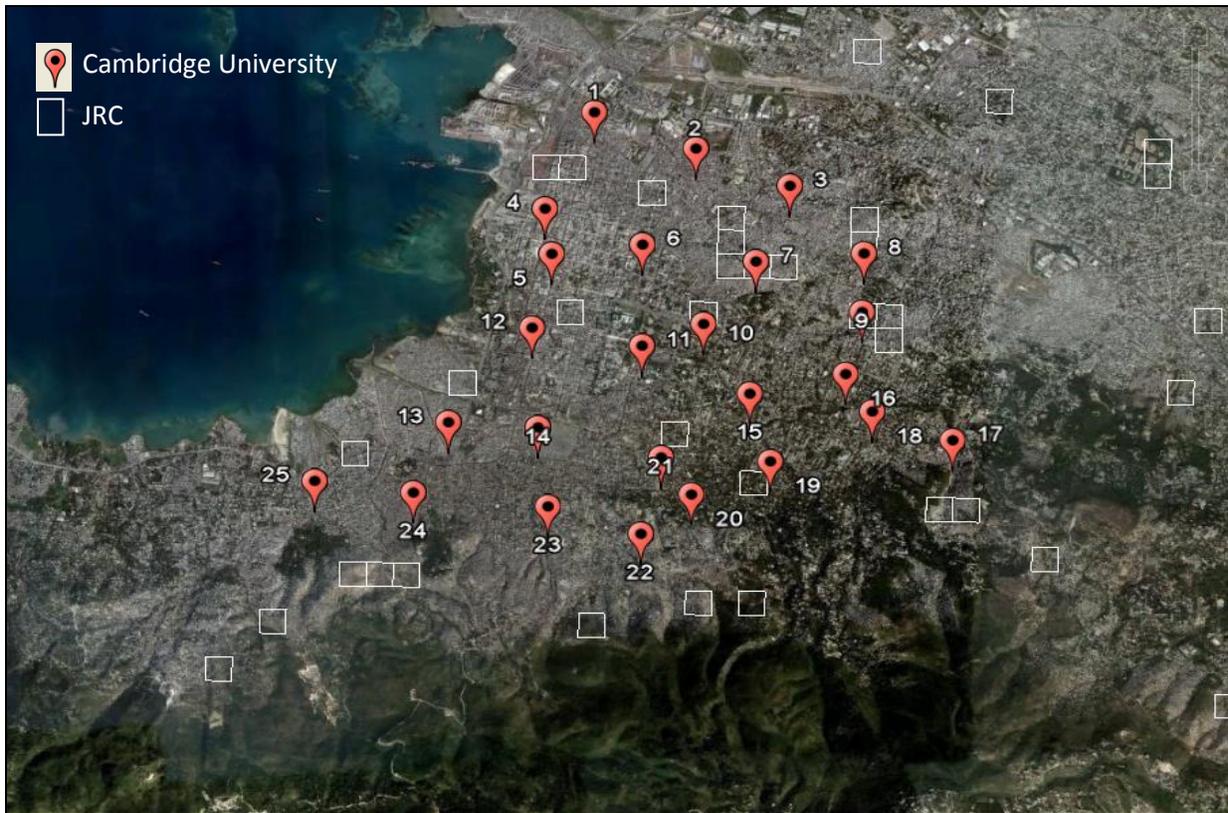
Figure 7.3 Field Survey Areas analyzed by the Cambridge Architectural Research Ltd. and EC's Joint Research Centre.

7.3   Data Catalog of Field Survey Datasets

Besides the wealth of data provided by the World Bank – ImageCat – RIT Remote Sensing Mission, there were many other datasets that were either produced or used by the project team. These data, in general, fell into one of two categories:

▪   Geo-referenced photographs

▪   VIEWS™ ground-based high-definition (HD) photo data

Figure 7.4 and 7.5 shows georeferenced photo locations and VIEWS™ ground-based data coverage GPS trails respectively. Details of the data sets are provided in Appendix A7.

Figure 7.4 Geo-referenced Photo Locations shown in yellow

Figure 7.5 VIEWS™ Ground-based Data Coverage GPS Trails in green

8.0   RESULTS AND VALIDATION

This section contains the results of the World Bank – ImageCat – GEO-CAN damage assessment. This is presented in two parts, with the first part reporting on the Phase 1 effort and the second part dealing with the Phase 2 results. In addition, we also summarize the final damage totals, as reflected by the joint PDNA analysis where the major contributors were the UN's UNITAR/UNOSAT group, the EC's JRC, and the World Bank's damage assessment group (ImageCat and consultant, and the GEO-CAN Community). We begin with a summary of the WB – IC - GEO-CAN Phase 1 damage effort.

8.1   Phase 1 Results

The Phase 1 study resulted in 5,189 collapsed buildings being identified in Port-au-Prince. Because the initial focus in Phase 1 was on search and rescue, the analysts focused their attention on identifying only collapsed or destroyed structures. Because of this, most of the identified buildings were associated with Damage Grade 5 (EMS-98 Scale). Using available satellite imagery (50 cm), the project team was confident that it had reliably identified a large portion of the building stock that had been destroyed. However, it was clear from initial field reports, that the team of analysts working in this phase had greatly underestimated the number of destroyed buildings.

Some of the reasons for the underestimate were:

- Damage was so prevalent in many of the areas that analysts simply were not able to distinguish damage to individual buildings,

- The identification of damage was conducted using lower-resolution imagery (i.e., lower than Phase 2 which utilized 15 cm aerial photos) and in many cases, it was difficult to discern different damage levels, and

- The rapid nature of Phase 1 did not leave much time for extensive data checking before the data was released, which was within 48 hours of the start of the analysis.

The locations of damaged structures for Port-au-Prince are shown in Figure 8.1. The number of structures per 500-meter grid cell is mapped thematically in Figures 8.2(a) and 8.2(b).
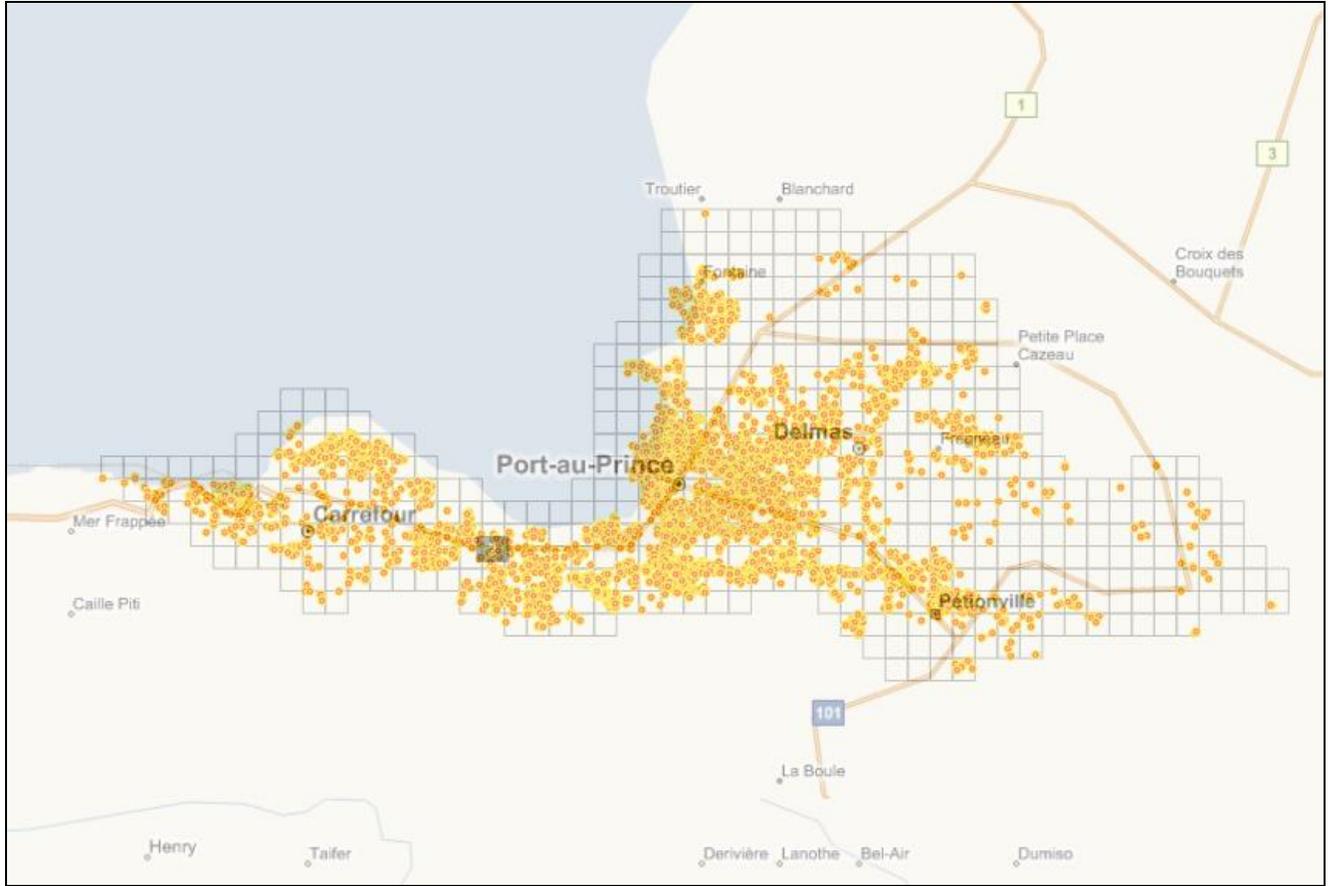
Figure 8.1 Point Locations of Collapsed Structures
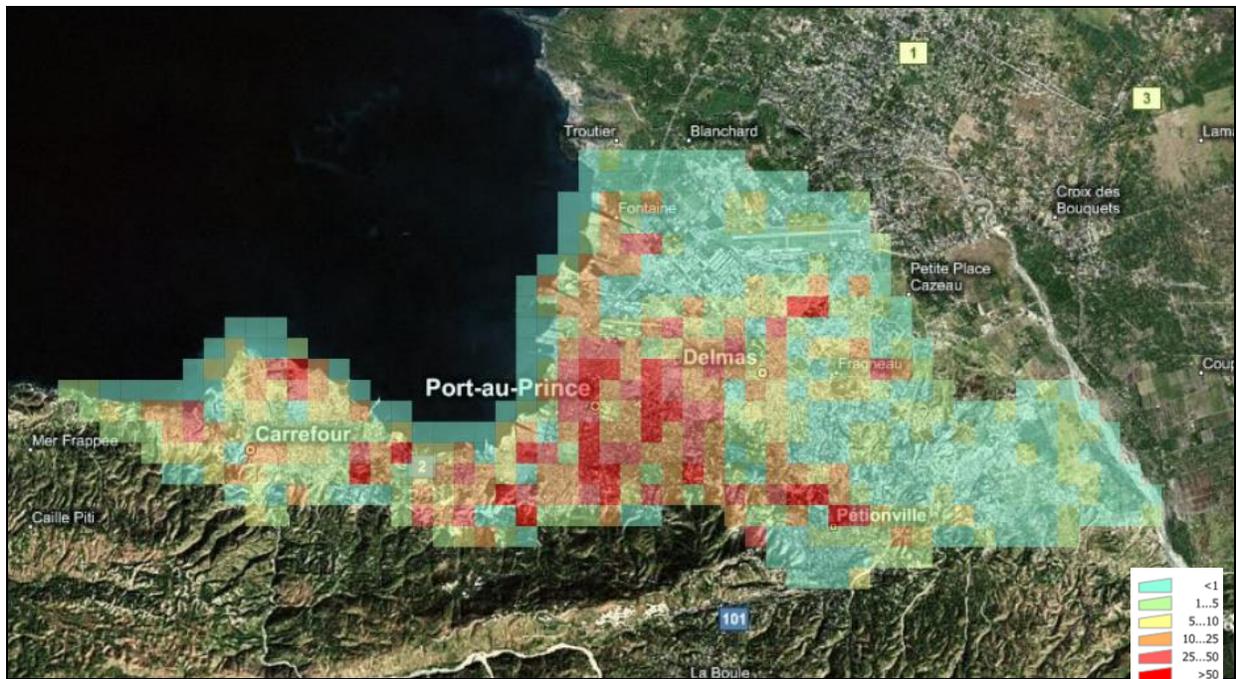
Figure 8.2(a) Number of Collapsed Buildings pejur 500 m Grid Cell
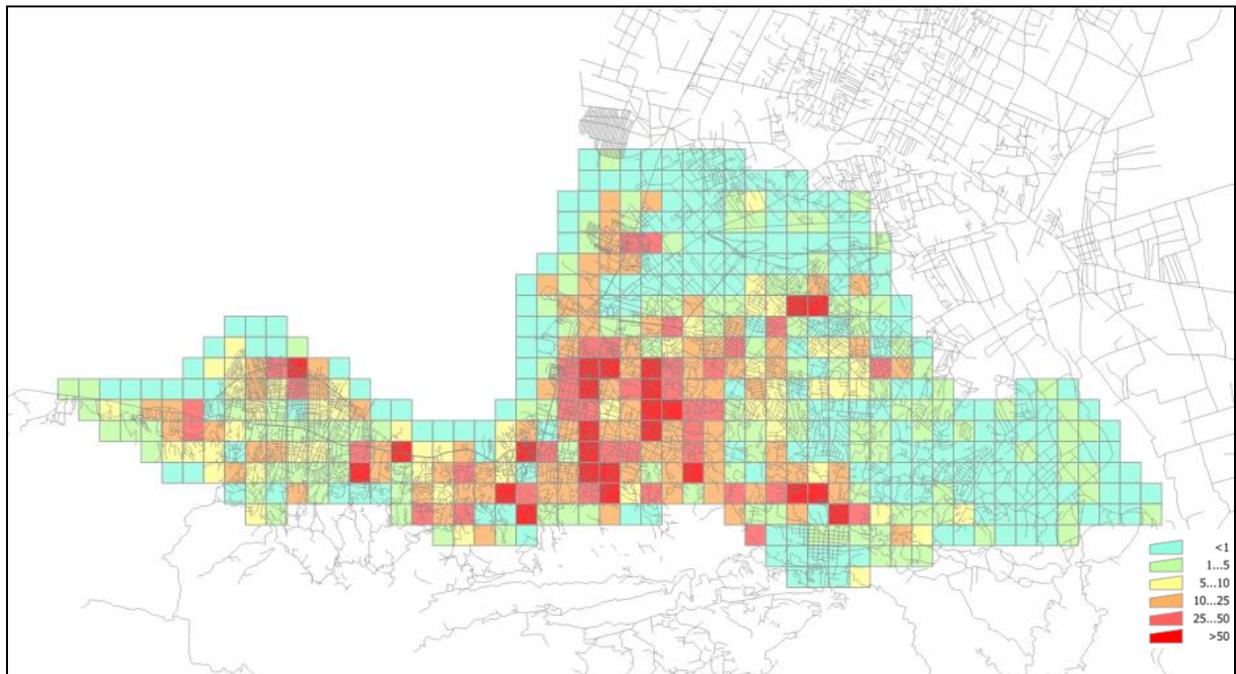
Figure 8.2(b) Number or Collapsed Buildings per 500 m Grid Cell, without Imagery Underlay

It must be noted that the number of collapsed buildings can be a function of several parameters. These include the level of ground shaking experienced in the area of interest, the density of buildings in a 500 m grid cell, and the level of vulnerability associated with buildings in region. The ground shaking levels in Greater PaP was generally the same, that is, this area was shaken by MMIs of about IX to X.

Furthermore, there is very little evidence that any of these areas contained buildings that had any significant seismic design features. Therefore, the high numbers of damaged buildings are likely a function of building density. Some of this evident in Figure 8.2(b) where the underlying road network is denser in the areas with the highest building counts.

To gain a better understanding of how damaged buildings were distributed with regard to occupancy or land-use, the project team overlaid the damaged building locations onto the land-use map discussed in Section 6.3.3. Table 8-1 shows the results of this analysis.

Table 8-1 Phase 1 Building Damage Counts in PaP by Land-Use Type

Land-Use Categories	Number of Collapsed Buildings
Residential low density	1,835
Residential high density	1,117
Commercial	559
Industrial	141
Downtown	206
Shanty/Informal	1,331
TOTAL	**5,189**

Proportionally, most of the damaged buildings fall into some type of housing category, i.e., low- or high-density residential, or shanty or informal. This is not unusual in that the vast majority of the building stock for a city is associated with housing. However, knowing the results of the Phase 2 assessment, we know that the values in Table 8-1 are low for all land-use categories. This information can still be extremely useful – even with the undercounts – because it is based on imagery that we are confident will be widely available in the next disaster. Even though it was clear that the aerial imagery does provide much more information and clarity in terms of whether damage has occurred and what type of damage, it may not be available in the next event because of the high cost associated with a deployment. Therefore, an analysis that incorporates both the satellite imagery results and the higher-resolution aerial results would be extremely useful if a rough scaling factor can be developed. This scaling factor would roughly approximate the number of missed Damage Grade 4 and 5 buildings using the satellite data results. More discussion on this issue is contained in Section 6.3.

With regard to the availability of VHR aerial imagery, it is worth considering the potential for an imagery fund that would essentially guarantee that rich datasets would always be available for future events. More is discussed on this issue in Section 11.

8.1.1 Phase 1 Review and Validation

To ensure the most robust estimate of building damage, a rigorous data scrubbing and verification process was implemented in Phase 1. Since the timing was a key issue, a subset of the damage database was closely examined for errors and/or omissions. The priority for this evaluation was to select areas that contained a high proportion of collapsed buildings. Each grid cell was reviewed for:

- False positives – Building misidentified and digitized as collapsed
- False negatives – Collapsed buildings not identified or digitized

This second level review was performed by an internal team within ImageCat. The individuals involved with this review were not involved in the initial damage assessment. The locations of all damaged buildings were overlaid onto the base satellite images (both pre-event and post-event) and the second team of analysts reviewed the results for both false positives and negatives. The outcome of this review was that a number of false positives were noted and these damage points were added to the initial Phase 1 database.

8.1.2   Comparison of Phase 1 Results with JRC Early Damage Assessment

At the same time that the ImageCat team was performing its early damage assessment, the EC JRC was also producing damage results using the same high-resolution satellite imagery. In the JRC study, the analysts were recording the locations of both destroyed and severely-damaged structures. In their early statements of the results, the JRC team also acknowledged that it was highly likely that their totals were grossly understated (Source: JRC, 2010)

At the time of this comparison, the JRC team had identified approximately 3,000 destroyed or severely-damaged buildings in PaP, as compared with 5,189 estimated provided by the ImageCat team. To further compare these results, we created two maps showing the number of damaged buildings normalized to a constant grid cell size (200 meters by 200 meters). Figure 8.3 shows this comparison. Figure 8.3(a) shows the ImageCat results; Figure 8.3(b) shows the JRC results. Noting that each study team used a different measure for building damage (ImageCat – collapsed; JRC – destroyed and severely damaged), the comparison shows a number of similarities. For example, the highest levels of damage center on the central area of PaP. There is also significant damage noted in Carrefour, the area located directly west of PaP. Also, the concentrations of damage are similar; however, this may be due to the fact that the areas with no damage are associated with more rural areas or developments.
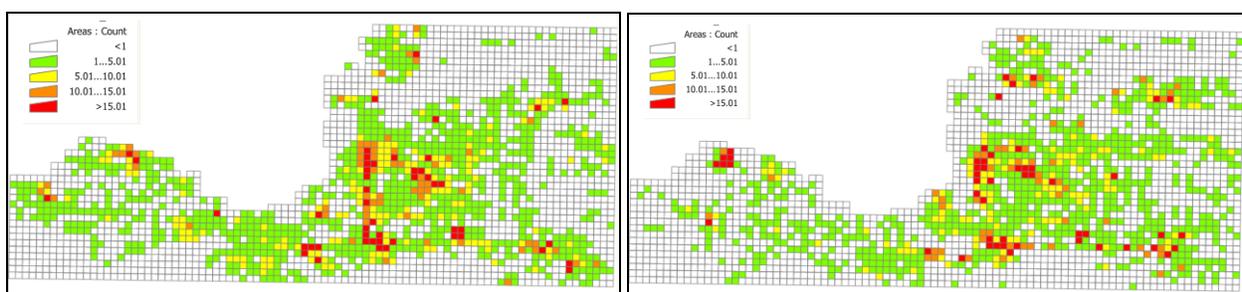
a) ImageCat – Collapsed Buildings   b) JRC – Destroyed and Severely-Damaged Buildings

Figure 8.3 Comparison of Number of Damaged Buildings per JRC 200m x 200m Grid Cell

8.2   Phase 2 Results

The Phase 2 damage assessment included Port-au-Prince, Carrefour, Delmas, Leogane, Jacmel, Hinche, Grand Goave and Petit Goave. Because the aerial imagery was delivered in several phases, the project separated the Phase 2 assessment into two parts: Phase 2A, which covered Greater Port-au-Prince, and Phase 2B, all the other areas. The areal extent of both parts of Phase 2 is shown in Figure 8.4 below. The Phase 2A area included 1384 500m by 500m cells or 346 sq. km.; the Phase 2B area was comprised of 785 cells or 196 sq. km.

Phase 2A (shown in blue)

Port-Au-Prince- 1384 grid cells 500m x 500m

Phase 2B (2B shown in red, 2A in blue)

West Port-Au-Prince- 785 grid cells 500m x 500m
(includes Leogane and Carrefour)

Grande Goave – 29 grid cells 500m x 500m
Petit Goave – 37 grid cells 500m x 500m
Jacmel – 85 grid cells 500m x 500m
Hinche – 30 grid cells 500m x 500m

Figure 8.4 Phase 2 (A & B) Study Areas

While Phase 1 only focused on the locations of collapsed building, Phase 2 expanded the damage assessment to include both collapsed or destroyed buildings and buildings with heavy damage that did not collapse (i.e., Damage Grade 4 and 5 buildings, respectively). Furthermore, the Phase 2 damage assessment also focused on delineating the pre-earthquake footprints of all Grade 4 and 5 buildings.

As explained in Section 6, the damage methodology in Phase 2 was based on manual interpretations of pre- and post-earthquake aerial imagery. Using a pre-tested protocol, analysts were asked to identify Grade 4 and 5 building damage. To estimate the number of buildings with lower damage levels (i.e.,

Grades 1, 2 and 3)[11], the damage ratios presented in Table 6-1 were used. A graphical representation of building damage for all study areas is presented in Figures 8.5 through 8.7.
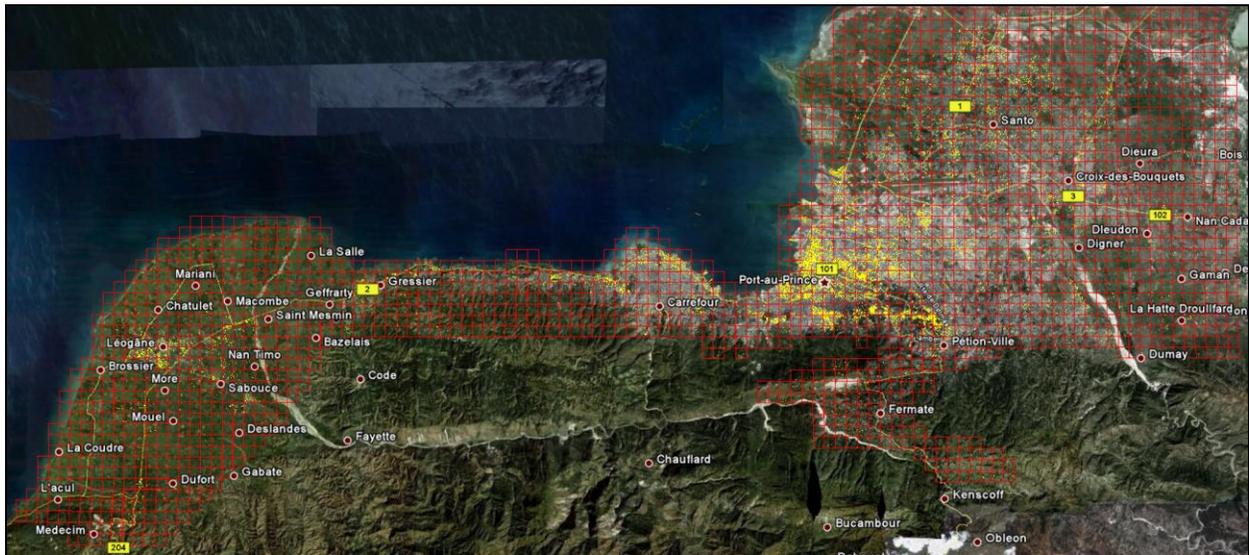
Figure 8.5 Locations of Collapsed and Heavily-Damaged Buildings in PaP, Carrefour, and Leogane (Damage Points in Yellow)
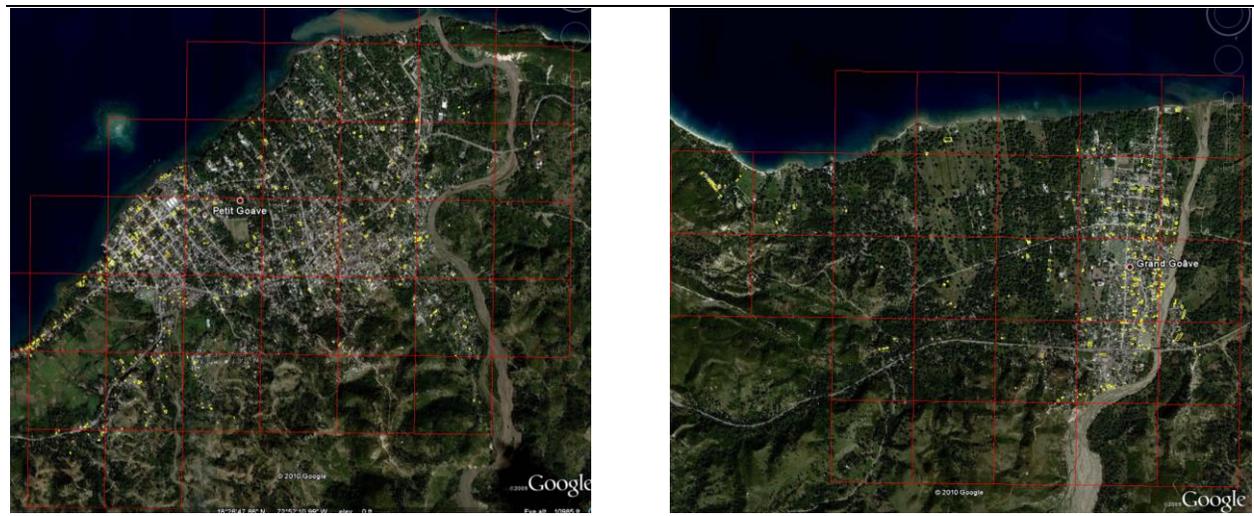
a. **Petit Goave**   b. **Grand Goave**

Figure 8.6 Locations of Collapsed and Heavily-Damaged Buildings in Petit Goave and Grand Goave (Damage Points in Yellow)

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[11] Please refer to Appendix A12 for a more detailed description of the EMS-98 damage scale.

Figure 8.7 Locations of Collapsed and Heavily-Damaged Buildings in Jacmel (Footprints in Red)

Tables 8.2 through 8.3 contain the final damage results for the Phase 2 ImageCat/GEO-CAN damage surveys. Note that these totals only reflect the work of the ImageCat/GEO-CAN team. They do not represent the final damage totals for the PDNA damage assessment. The ImageCat/GEO-CAN damage results; however, were incorporated into final PDNA report along with contributions from UNOSAT and JRC. The joint damage assessment numbers are provided as an appendix to this report (see Appendix A14).

Each of the tables below contains a tally of destroyed and heavily-damaged of buildings by land-use type as surveyed by the ImageCat/GEO-CAN team. The tables are presented separately for Port-au-Prince, West Port-au-Prince (Carrefour and Leogane), Grand Goave, Petit Goave, Jacmel and Hinche. Estimates of number of Grade 1 through 3 buildings are also provided. These were determined using the damage ratios discussed in earlier sections.

The tables also provide an estimate of the total floor area to be repaired or replaced, by damage grade and land-use type. By a large margin, the most floor area to be replaced or repaired is associated with housing units.

Finally, the tables provide an early estimate of the repair costs associated with all damaged buildings. Unit repair costs ($/sq m) for all land-use types were obtained from a report prepared by Haiti's Ministry of Social Affairs' Social Housing Promotion and Planning Institute, 24 February 2010. These costs range from $40 per sq. m. for essentially moderate to minor repairs to $500 per sq. m. for complete replacement.

Table 8-8 provides a summary for all areas combined. The total number of buildings with at least Grade 1 damage is estimated at close to 160,000, with approximately 18 percent in Grade 4 and 5, or 29,056. Of the 160,000 total, about 90 percent of the buildings fall into the housing category. About 5 percent of the total (or 7,690 buildings) is comprised of commercial, downtown or industrial buildings. From the Joint PDNA report, it is estimated that close to 300,000 buildings in Haiti were affected by the earthquake (PDNA, 11 March 2010).

The total amount of floor area to be repaired or replaced is estimated to be a little over 22 million sq. m. 6.4 million sq. m. (Grades 3 through 5) is expected require extensive repair or replacement. As in earlier summaries, the vast majority of the repairs will be to residential construction.

The repair and replacement costs are expected to exceed $3.4 billion. Even though the number of buildings with Grade 3 through 5 is lower than the total for Grades 1 and 2 (about a factor of 2.4), the estimated cost of repair or replacement for these buildings is about 80 percent of the total cost. This is because for these higher damage grades, the likely action is not repair but replacement. Replacement costs will also include removal of debris, which will also add to the total cost of replacement.

Note that these numbers are lower than those presented in the final PDNA damage assessment report. The PDNA reported a total of 298,739 buildings with damage. Of this total, about 60,000 buildings were identified by the joint World Bank/GEO-CAN – UNOSAT – JRC as having Grade 4 or 5 damage. The reason for the difference between the joint PDNA report numbers and the ImageCat/GEO-CAN values is that the ImageCat/GEO-CAN methodology emphasized accuracy over comprehensiveness, i.e., analysts were asked to only identify damage to buildings where there was a high degree of confidence in the assessment. Therefore, where damage was ambiguous or difficult to determine, these buildings were not included in the ImageCat/GEO-CAN summaries. The end result of this approach was that the ImageCat/GEO-CAN values were highly reliable but did omit many buildings that did have significant damage.

Comparing the $3.4 billion repair/replacement cost to the Joint PDNA estimate, the ImageCat/GEO-CAN estimate is a little over half of the $6.4 billion joint PDNA estimate. As part of a future study, the project team recommends the following studies: a) compare the damage assessment protocols used by the ImageCat/GEO-CAN team with those implemented by the joint UNOSAT/JRC experts to determine whether the ImageCat/GEO-CAN protocols can be expanded to include a more robust analysis of damage; b) determine whether a set of "scaling" factors can be developed that will scale up reliable estimates of Grade 4 and 5 damage to account for possible omissions for those two categories, and c) re-evaluate the damage distributions developed for Grades 1 through 3 to determine whether a fifth category representing "no damage" should be included to better balance overall damage estimates.

Table 8-2 Damage Summary for Port-Au-Prince (Phase 2A)

	Number of Buildings					
Land Use	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Res low density	42,352	3,683	6,752	2,859	5,734	**61,379**
Res high density	12,517	1,413	2,221	1,133	2,703	**19,988**
Commercial	186	682	651	420	1,161	**3,100**
Industrial	58	212	203	221	271	**965**
Downtown	59	216	206	193	308	**982**
Shanty	11,584	368	1,839	1,271	3,326	**18,388**
Agricultural	897	78	143	60	122	**1,300**
Open land	15	1	2	-	3	**21**
Total	**67,668**	**6,653**	**12,017**	**6,157**	**13,628**	**106,123**
	Total Square Meters					
Land Use	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Res low density	6,945,599	603,965	1,107,269	468,876	940,376	**10,066,086**
Res high density	1,654,810	186,833	293,595	149,783	357,337	**2,642,358**
Commercial	29,016	106,392	101,556	65,520	181,116	**483,600**
Industrial	7,745	28,397	27,106	29,570	36,260	**129,078**
Downtown	10,226	37,496	35,792	33,486	53,438	**170,438**
Shanty	732,137	23,242	116,212	80,327	210,203	**1,162,122**
Agricultural	73,733	6,412	11,755	4,932	10,028	**106,860**
Open land	1,215	106	194	-	247	**1,761**
Total	**9,454,482**	**992,844**	**1,693,480**	**832,493**	**1,789,005**	**14,762,303**
	Replacement or Repair Cost (US$)					
Cost in $US per m^2	40	100	300	500	500	Total
Total cost ($US M)	**378**	**99**	**508**	**416**	**895**	**2,296**

Table 8-3 Damage Summary for West Port-au-Prince – Carrefour and Leogane (Phase 2B)

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Res low density	19,857	1,727	3,166	1,379	2,650	**28,779**
Res high density	1,778	201	316	183	362	**2,840**
Commercial	76	280	267	181	468	**1,273**
Industrial	8	28	26	22	42	**125**
Downtown	48	177	169	187	224	**806**
Shanty	3,704	118	588	650	820	**5,880**
Agricultural	5,234	455	834	269	793	**7,586**
Open land	49	4	8	4	6	**71**
Total	**30,756**	**2,989**	**5,374**	**2,875**	**5,365**	**47,359**
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Res low density	3,256,583	283,181	519,165	226,156	434,600	**4,719,686**
Res high density	235,107	26,544	41,713	24,193	47,856	**375,413**
Commercial	11,911	43,674	41,689	28,236	73,008	**198,518**
Industrial	1,007	3,694	3,526	2,944	5,620	**16,791**
Downtown	8,389	30,761	29,362	32,445	38,864	**139,821**
Shanty	234,118	7,432	37,162	41,080	51,824	**371,616**
Agricultural	430,247	37,413	68,590	22,112	65,185	**623,546**
Open land	4,051	352	646	329	493	**5,871**
Total	**4,181,414**	**433,051**	**741,853**	**377,493**	**717,450**	**6,451,261**
	Replacement or Repair Cost ($US)					
Cost in $US per m^2	40	100	300	500	500	**Total**
Total cost ($US M)	**167**	**43**	**223**	**189**	**359**	**981**

Table 8-4 Damage Summary for Grand Goave (Phase 2B)

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	439	38	70	17	72	636
Residential high density	398	45	71	40	82	636
Commercial	3	11	11	11	15	51
Industrial	4	15	14	9	26	69
Total	844	109	166	77	195	1,391
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	71,937	6,255	11,468	2,788	11,808	104,257
Residential high density	52,630	5,942	9,337	5,288	10,840	84,037
Commercial	477	1,750	1,670	1,716	2,340	7,953
Industrial	551	2,020	1,928	1,204	3,479	9,182
Total	125,595	15,967	24,404	10,996	28,467	205,430
	Replacement or Repair Cost ($US)					
Cost in $US per m^2	40	100	300	500	500	Total
Total cost ($US M)	5	2	7	6	14	34

Table 8-5 Damage Summary for Petit Goave (Phase 2B)

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	1,173	102	187	74	164	1,700
Residential high density	215	24	38	26	40	344
Commercial	12	44	42	24	78	200
Industrial	-	1	1	1	1	4
Total	1,401	171	268	125	283	2,248
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	192,372	16,728	30,668	12,136	26,896	278,800
Residential high density	28,472	3,215	5,051	3,437	5,288	45,463
Commercial	1,872	6,864	6,552	3,744	12,168	31,200
Industrial	31	115	110	134	134	525
Total	222,747	26,922	42,382	19,451	44,486	355,988
	Replacement or Repair Cost ($US)					
Cost in $US per m^2	40	100	300	500	500	Total
Total cost ($US M)	8.91	2.69	12.71	9.73	22.24	56.28

Table 8-6 Damage Summary for Jacmel (Phase 2B)

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	1,370	119	218	51	227	1,986
Commercial	6	22	21	10	41	100
Industrial	1	3	3	-	8	16
Total	1,377	145	243	61	276	2,101
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Residential low density	224,703	19,539	35,822	8,364	37,228	325,657
Commercial	936	3,432	3,276	1,560	6,396	15,600
Industrial	126	462	441	-	1,070	2,099
Total	225,765	23,433	39,539	9,924	44,694	343,356
	Replacement or Repair Cost ($US)					
Cost in $US per m^2	40	100	300	500	500	Total
Total cost ($US M)	9.03	2.34	11.86	4.96	22.35	50.54

Table 8-7 Damage Summary for Hinche (Phase 2B)

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Residential low density	69	6	11	9	5	**100**
Total	**69**	**6**	**11**	**9**	**5**	**100**
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Residential low density	11,316	984	1,804	1,476	820	**16,400**
Total	**11,316**	**984**	**1,804**	**1,476**	**820**	**16,400**
	Replacement or Repair Cost ($US)					
Cost in $US per m^2	40	100	300	500	500	**Total**
Total cost ($US M)	**0.45**	**0.10**	**0.54**	**0.74**	**0.41**	**2.24**

Table 8-8 Phase 2 Damage Summary – All Areas

	Number of Buildings					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Res low density	65,259	5,675	10,404	4,389	8,852	**94,579**
Res high density	14,909	1,683	2,645	1,382	3,187	**23,807**
Commercial	283	1,039	992	646	1,763	**4,724**
Industrial	71	259	247	253	348	**1,178**
Downtown	107	393	376	380	532	**1,788**
Shanty	15,289	485	2,427	1,921	4,146	**24,268**
Agricultural	6,131	533	977	329	915	**8,886**
Open land	64	6	10	4	9	**93**
Total	**102,114**	**10,074**	**18,078**	**9,304**	**19,752**	159,322
	Total Square Meters					
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	**Total**
Res low density	10,702,511	930,653	1,706,197	719,796	1,451,728	**15,510,886**
Res high density	1,971,019	222,534	349,697	182,700	421,321	**3,147,271**
Commercial	44,212	162,112	154,743	100,776	275,028	**736,871**
Industrial	9,460	34,688	33,112	33,851	46,562	**157,674**
Downtown	18,616	68,257	65,154	65,930	92,302	**310,259**
Shanty	966,255	30,675	153,374	121,407	262,027	**1,533,738**
Agricultural	503,980	43,824	80,345	27,044	75,213	**730,406**
Open land	5,267	458	840	329	740	**7,633**
Total	**14,221,319**	**1,493,201**	**2,543,461**	**1,251,834**	**2,624,922**	**22,134,737**
	Replacement or Repair Cost (US$)					
Cost in $US per m²	40	100	300	500	500	**Total**
Total cost ($US M)	**569**	**149**	**763**	**626**	**1,312**	**3,420**

When we began our Phase 2 analysis, we included as part of our request to GEO-CAN participants, the designation of a confidence value (1 to 100%). The purpose of this request was to create a dataset that could be used to assess the accuracy and reliability of the results. When this information is compared with field data (photos, field work) where the actual damage state is known, we will be able to better judge the accuracy of our results by calibrating these personal judgments against the results of the field surveys.

Figure 8.8 shows a bar graph and table that links the number of building damage counts to different confidence ranges (0-20%; 20-40%; 40-60%; 60-80%; and 80-100%). This distribution is presented separately for each damage level. It is clear from this examination that the analysts' confidence levels are highest when estimating damage to collapsed buildings. Over half of the individuals classifying Level 4 damage (heavy damage) felt confident (over 60%) in their assignments.
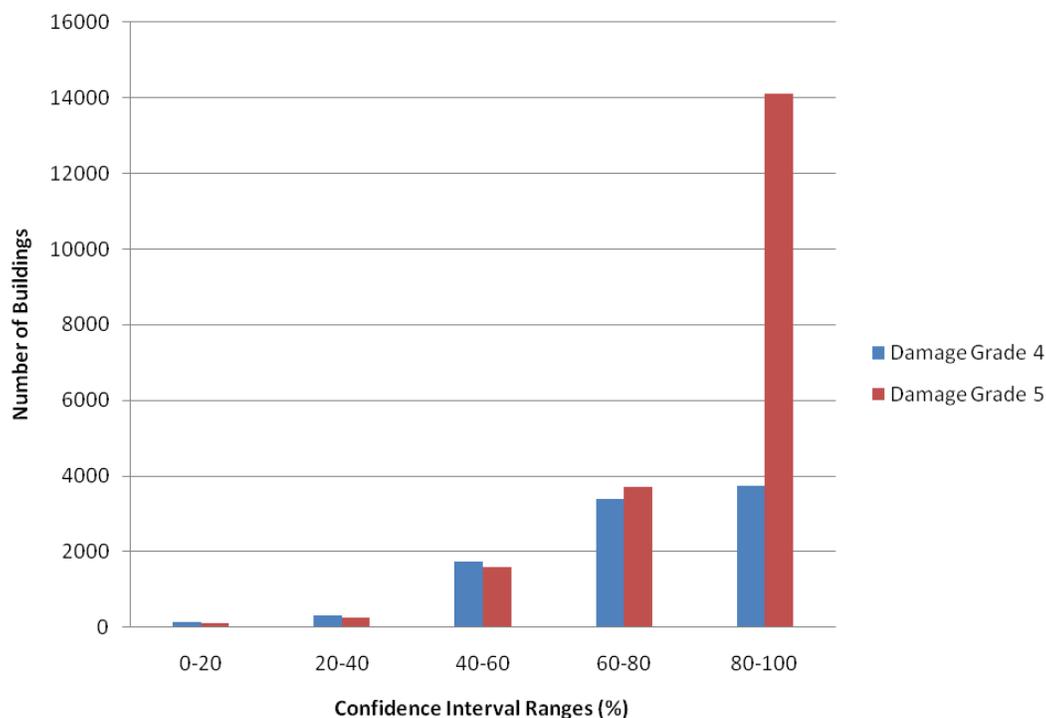
Confidence Interval Ranges Reported	Buildings assigned Damage Grade 4	Buildings assigned Damage Grade 5	Total
0-20	136	108	244
20-40	307	248	555
40-60	1732	1586	3,318
60-80	3,390	3,708	7,098
80-100	3,739	14,102	17,841
Total	9,304	19,752	29,056

Figure 8.8 Building Counts by Damage Grade and Confidence Level

8.2.1   Phase 2 Validation

The Phase 2 validation effort consisted of two parts. The first part focused on data cleaning and proper interpretation of the damage assessment protocols. The second part addressed the accuracy of the damage assessment completed by the ImageCat/GEO-CAN team. In order to assess the latter issue, ImageCat contracted the services of the Cambridge Architectural Research Ltd (CAR) team. Section 8.2.1.2 contains a summary of the CAR evaluation; Appendix A9 contains the full CAR report submitted to ImageCat.

8.2.1.1 Data Cleaning and Validation

A rigorous data scrubbing and verification process was also executed for the Phase 2. The data cleaning process was multi-staged beginning with a thorough review of each cell (close to 2,000 ½ km by ½ km cells). This process was guided by two main steps:

- Flag and correct obvious "dirty" or erroneous data; and
- Review a sample of grids for consistency, i.e., ensuring that damage assignments are consistent with the damage protocols provided to all analysts.

A number of cells that were submitted by the GEO-CAN community were either incomplete or contained unusual artifacts or anomalies. Regarding obvious dirty data, the data scrubbing and verification process focused the identification of missing values, outliers, and values that appeared to be incorrectly assigned. Semi-automated methods were utilized to flag data that was then reviewed by a team of analysts to either correct or fill in missing fields.

Digitized footprints and the resulting topology also had to be scrubbed and validated to assure correct positioning and geometry. The project team employed a number of automated GIS routines to identify and correct overlapping footprints and footprints containing sliver polygons. After these corrections, a final visual review was conducted to ensure that no geometric anomalies remained.

As far as damage assignments were concerned, about 5 percent of the GEO-CAN damage database was randomly selected for a detailed review by licensed structural engineers. The goal of this task was to apply the results from this limited sample in order to quantify the level of uncertainty associated with the damage classifications and to define an upper limit on total number of Grade 4 and 5 buildings based on what might have been missed in the initial survey. To create these statistics, 100 smaller cells (100m by 100m) were randomly selected and the number of false positives (damage incorrectly assigned) and false negatives (damage that was missed) were counted along with the total number of buildings in that grid cell. By using this approach, we estimated not only our "best estimate" at total number of heavy (Level 4) and collapsed (Level 5) buildings but the upper-bound of that total considering the errors measured in our sample.

8.2.1.2 Validation of Phase 2 Port-Au-Prince Damage assessment using *Pictometry* and *Field-Observation* data

An engineering team led by CAR performed a damage validation study using Pictometry imagery (high-resolution oblique imagery) for the Port-Au-Prince area. In addition, ground survey observations conducted by an Earthquake Engineering Field Investigation Team (EEFIT) that was deployed to Haiti were available to the CAR team. The analysis which is summarized below and discussed in detail in Appendix A9 first compares the ImageCat/GEO-CAN results to assessments made using the Pictometry data. Then a comparison is made between the results from the Pictometry analysis and that of the field surveys.

Pictometry-based damage assessment: About 60 randomly-selected sample locations were identified within the Port-Au-Prince area in order to validate/calibrate the ImageCat/GEO-CAN results – see Figure 8.9.   The sites were selected around street intersections to facilitate subsequent street-level photographic observations. At each location, about 20 adjacent buildings were selected to develop a dataset of over 1,200 buildings. For each building, the following information was inferred using Pictometry images using Pictometry's online interface setup for this project:

- Damage levels[12] D2, D3, D4, D5 or no visible damage (NVD)
- Number of stories
- Construction type (masonry or reinforced concrete)
- Use class (mainly residential or commercial)
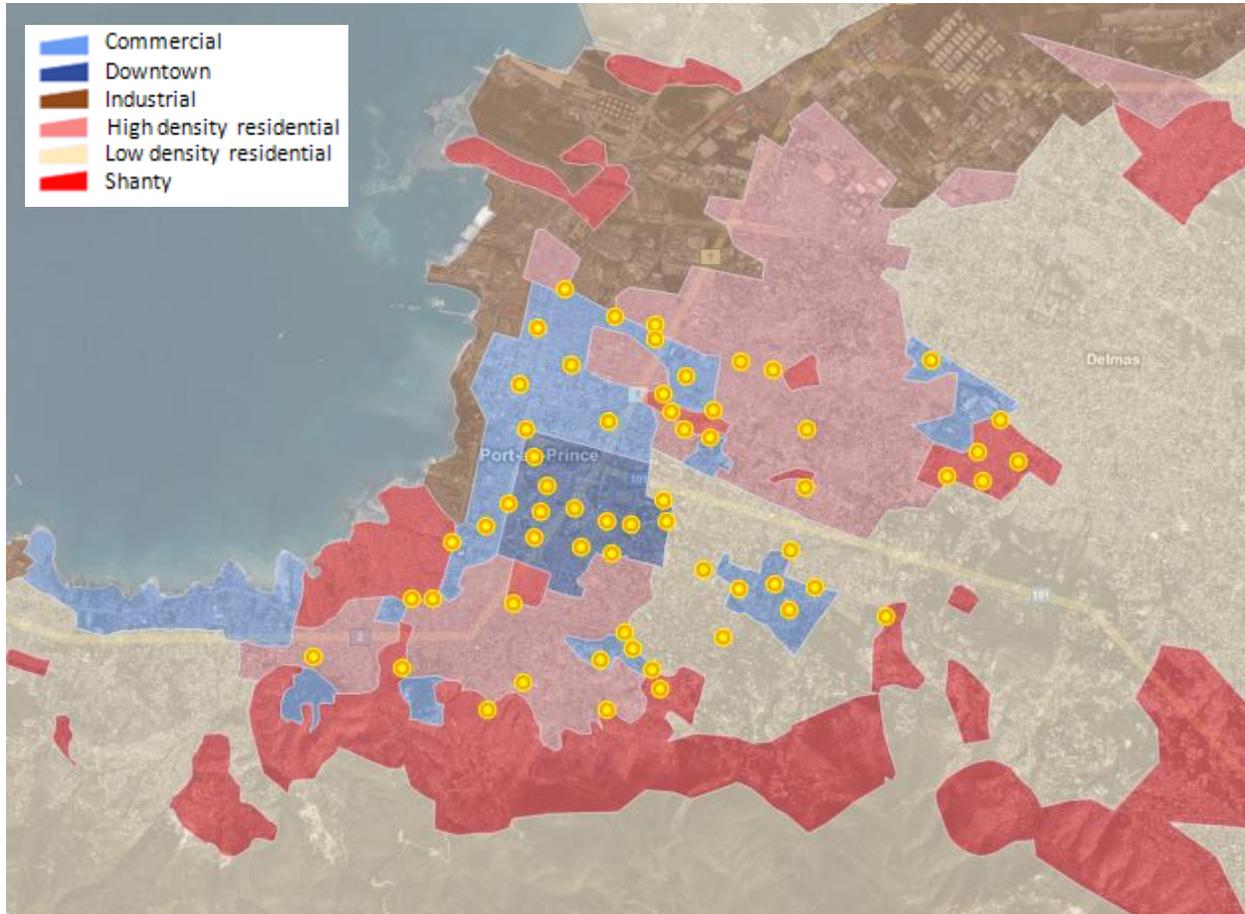
Figure 8.9 CAR Damage Survey Locations (60 total shown in yellow) in Port-au-Prince, Overlaid on Land-use Map

Figure 8.10 shows a comparison between a vertical aerial image of a building and an equivalent Pictometry or oblique image. In addition to the higher resolution, the Pictometry image also provides the opportunity to view damage to the sides of buildings. Being able to see damage from this perspective is very important, especially when failures such as soft-story effects were so prevalent in this event. Because of the catastrophic nature of this earthquake, Pictometry generously provided to the World Bank – UNOSAT – JRC damage assessment teams access to the Haiti earthquake data through its Pictometry Online system – see http://www.pictometry.com/government/product_online.shtml. Analysts from each of the relief organizations were able to match high-resolution satellite and aerial

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[12] Equates to the EMS-98 scale where D2: Minor, D3: Moderate, D4: Very Heavy, D5= Destroyed.

(vertical) photo data with the Pictometry images. This greatly helped to facilitate a more in-depth analysis of building damage in Port-au-Prince.

a)   **Vertical Aerial Photo**   b)   **Pictometry Image**

Figure 8.10 Examples of Vertical and Pictometry Imagery

Table 8-9 shows a summary table comparing the ImageCat/GEO-CAN Phase 2 results to the CAR Pictometry analysis. Direct comparison of about 300 ImageCat/GEO-CAN Grade 4 and 5 buildings with the Pictometry results was possible. Also, a comparison of non-damaged buildings in both datasets could be made. Table 8-10 shows the same data by percentages.

Table 8-9 Comparison of ImageCat/GEO-CAN and Pictometry Damage Results by Number of Buildings

		ImageCat/GEO-CAN			
		0	D4	D5	Total
Pictometry	No Visible Damage	631	16	14	**661**
	D2 - Minor	103	11	11	**125**
	D3 - Moderate	104	22	17	**137**
	D4 – Very Heavy	70	23	22	**115**
	D5 - Destroyed	46	27	130	**203**
	Total	**954**	**99**	**194**	**1,241**

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Table 8-10 Comparison of ImageCat/GEO-CAN and Pictometry Damage Results by Percentages

		ImageCat/GEO-CAN			
		0	**D4**	**D5**	*Total*
Pictometry	No Visible Damage	95.5	2.4	2.1	**100**
	D2 - Minor	82.4	8.8	8.8	**100**
	D3 - Moderate	71.5	16.1	12.4	**100**
	D4 – Very Heavy	60.9	20.0	19.1	**100**
	D5 - Destroyed	22.7	13.3	64	**100**

From the analysis, the CAR project team was able to provide the following conclusions and observations:

1. Of the 1241 data points, the proportions given as D5 and D4 were 16.4% and 9.3% by Pictometry, and 15.6% and 8.0% by ImageCat/GEO-CAN. Thus the overall estimate of the major levels of damage given by the two studies is quite close.

2. Of 203 individual buildings identified as D5 by Pictometry, 130 (64%) were identified as D5 by ImageCat/GEO-CAN, and 157 (77%) as D4 or D5.

3. Of the 661 buildings identified by Pictometry as having no visible damage, 95.5% were also not recorded as damaged in ImageCat/GEO-CAN.

4. Of 318 buildings identified as D4 or D5 by Pictometry, 202 (63.5%) were identified as D4 or D5 by ImageCat/GEO-CAN.

5. Of the 194 buildings identified by ImageCat/GEO-CAN as D5, 130 (67%) were also identified as such by Pictometry, and 152 (78%) were identified as either D4 or D5.

6. Of the 293 identified by ImageCat/GEO-CAN as D4 or D5, 69% were also identified as either D4 or D5 by Pictometry; a further 13% were identified as D3, 7.5% as D2, and 10% (30 buildings) had no visible damage in Pictometry.

The CAR team concluded "Pictometry was therefore recognizing a slightly larger proportion of D4 and D5 than GEO-CAN, but the overall level of damage estimated by GEO-CAN was rather good." The report goes on to say that a number of those buildings identified as collapsed using the Pictometry images were pancaked or lower story collapses where the roof shape was unchanged and therefore was not visible from the vertical satellite or aerial data. The CAR report (Appendix A9) discusses in detail some of the reasons for the discrepancies between the two damage datasets.

Ground-based survey: The ground survey mission led by the British Earthquake Engineering Field Investigation Team (EEFIT) had as one of its primary goals, the assessment of the accuracy of the Pictometry-based damage assessment. The mission – spanning from April 6th to April 13th - planned to cover some of the same buildings studied in the Pictometry analysis. In the end, 8 of the 60 Pictometry study locations were selected for more detailed ground-based reviews. These sties covered a diverse set of land-use categories. Figure 8.11 shows the locations of the eight sites visited. In total, 124 buildings were surveyed as part of this validation analysis.
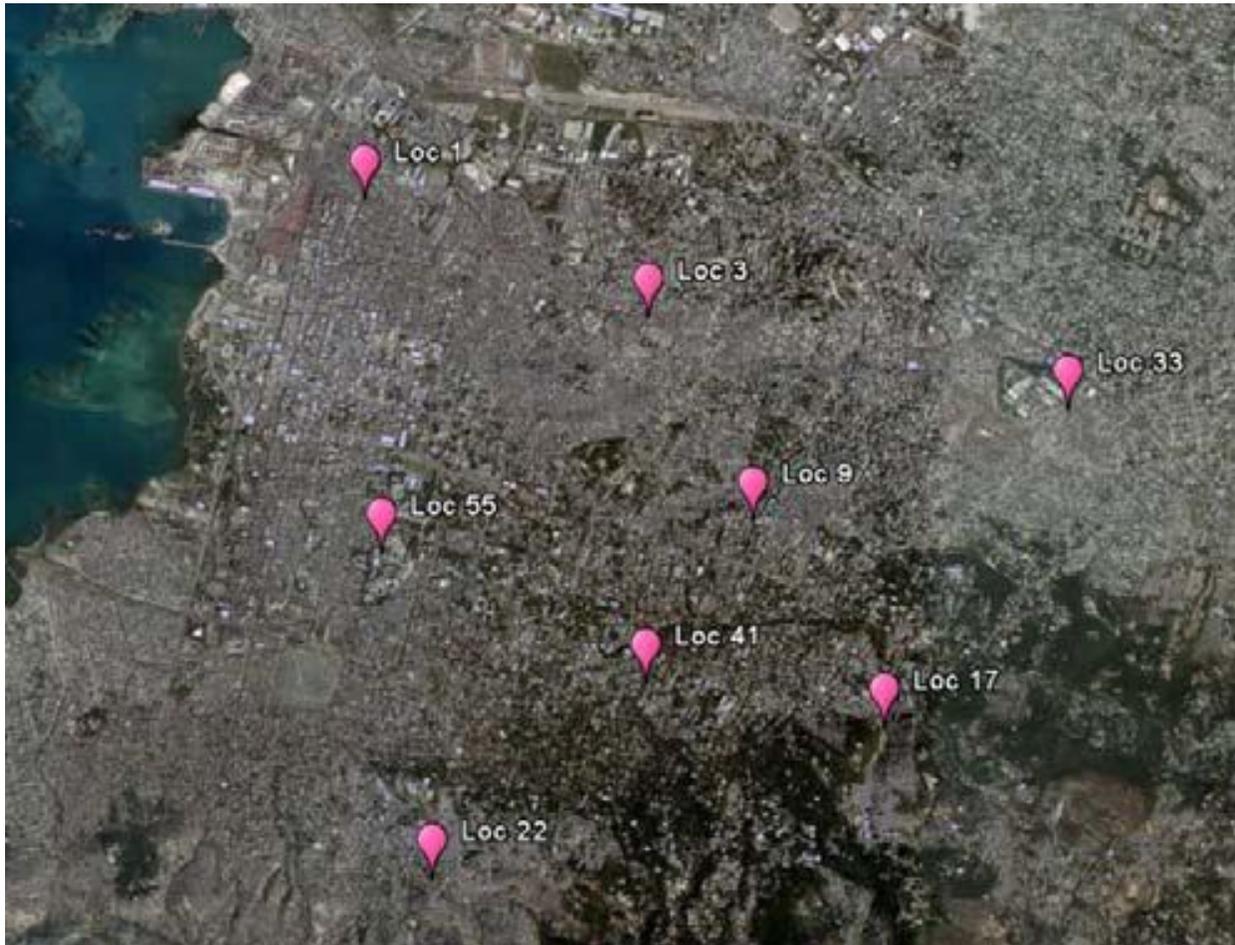
Figure 8.11 Sites visited by the EEFIT Investigation Team in support of the ImageCat/GEO-CAN Damage Validation Study

Each of the 124 buildings were visited on foot with the team gaining inside access to 17 of these and making highly confident assignments of damage. The same parameters as the Pictometry study were recorded to compare the information extracted remotely and in the field.

The results of this field investigation to validate the Pictometry results is presented in Figure 8.12. The ImageCat/GEO-CAN Phase 2 results are also included in the figure. Since GEO-CAN only identified D4 and D5 damage, comparisons are shown for only those 2 levels.
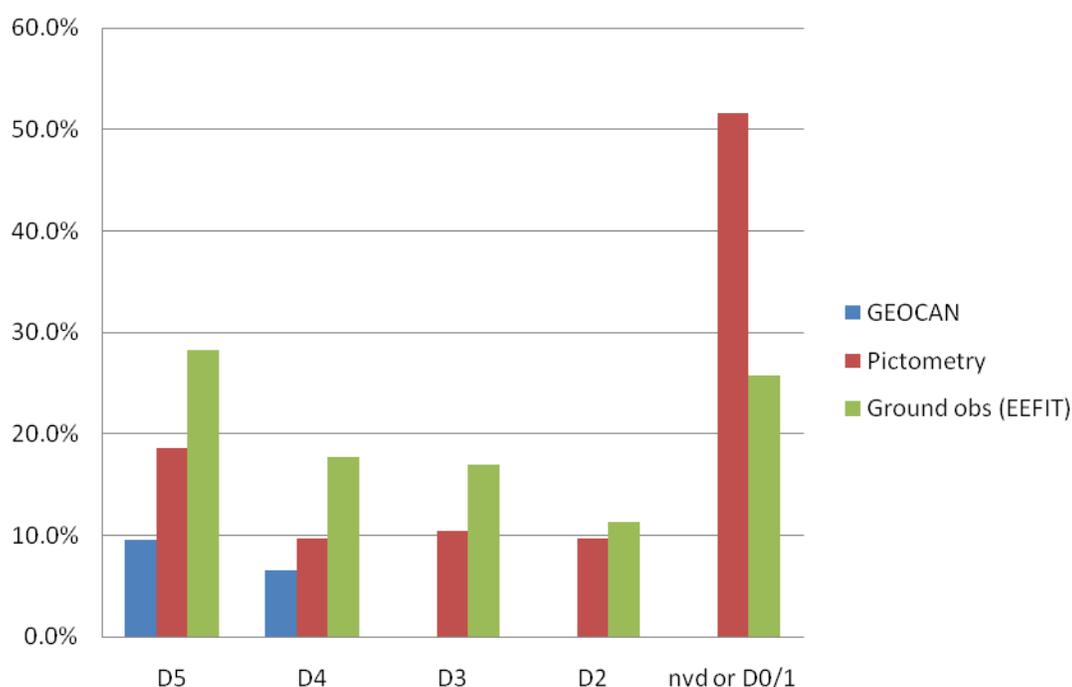
Figure 8.12 Comparison of GEO-CAN, Pictometry and EEFIT Damage Results. Sample size = 124

Some of the key conclusions made from this comparison by the CAR team were:

1. Ground observations remain the most reliable source of damage information. The ground-based assessment shows that even the Pictometry images may not good enough to identify all of the damage at the most serious levels. The ImageCat/GEOCAN Phase 2 effort, although highly accurate, identified the lowest number of D4 and D5 buildings.

2. Among the 124 buildings included in the ground observation survey, the in-field observed proportions at damage levels D4 and D5 were 18% and 28% respectively. The proportions in the Pictometry survey were 10% and 19% at D4 and D5, while those identified through the ImageCat/GEOCAN study were 7% and 10% at D4 and D5 respectively.

3. Studies of individual buildings show that the principal causes of these discrepancies are lower-story collapses which were not visible even in some Pictometry photos, and cases where the key Pictometry image was obscured either by trees or adjacent buildings. Pancaking effects were also responsible for discrepancies between ImageCat/GEO-CAN and the two other studies.

4. It seems probable that proportions determined from Pictometry should be increased by about 50% for a good estimate of the proportions of buildings damaged at level D4 and D5; and that proportions determined from the GEO-CAN approach should be doubled for a good estimate of buildings damaged at levels D4 and D5.

5. Sample size has a direct bearing on the discrepancies observed among the three studies. The discrepancy observed in the small sample (N=124) between the D4 and D5 of the Pictometry results and the ImageCat/GEO-CAN data was unexpected, as these two assessments produced

comparable results with the larger sample of 1241 buildings. In conclusion, it is important to consider the effects of sample size on the assessment of overall proportion of damage levels.

More detailed discussion on these conclusions, along with an elaborate discussion of the methodologies is contained in the CAR report, see Appendix A9.

9.0 POST-PDNA INTERVIEWS

9.1 Background

This section describes the follow-up interviews that were conducted by the ImageCat project team following the PDNA, and later in 2010. The purpose of these interviews was threefold: 1) to discuss how the damage assessment data were used by the different relief groups in Haiti, including the World Bank and Haitian government officials, 2) to identify issues or impediments that prevented the effective use of these data, and 3) identify areas of improvement for future events.

Several users of the data were interviewed on location in Haiti, and also by telephone from the UK, and in person in the US. The World Bank recommended key contacts and facilitated many of the meetings with strategic players in the post-earthquake response phase. These contacts were either direct users of the data or were aware of the remote sensing response effort, but did not directly use the aerial imagery or damage data. A second set of interviews were carried out remotely with data users during August 2010. These included data producers and volunteers that responded to the Haiti earthquake, but not specifically as part of the GEO-CAN initiative.

This section is divided into the following sub-sections: 1) Main findings from the consultation process, organized by type, and 2) Key recommendations for future events. The organizations and individuals that were interviewed are listed in Table 9-1. Note that all of the recommendations and comments contained in this section are those of the interviewees and not of ImageCat or its subcontractors. All responses have been attributed to the respondent's affiliation only, to respect individual anonymity.

Table 9-1 Organizations and Individuals Interviewed by ImageCat

Role	Affiliation
Sub-contractor to WB	Telescience / Fortius One
Consultant	World Bank
Operations Officer	World Bank
Project Coordinator	UNOPS
Senior Consultant	World Bank
Humanitarian Affairs Officer	UNOCHA
Information Management	MapAction
Operations Support Coordinator	UNOPS
Technical Director	CNIGS

Table 9-2 Summary Table of Interview Discussions

Organization	Positives	Negatives	Recommendations
World Bank	The products allowed targeting of resources. The data also showed areas of vulnerable people.	There was a feeling that the data was just "parachuted in."	▪ Umbrella framework should be created for multi-lateral agencies: Who will unite in a crisis and whose materials will be used. ▪ Creation of response protocols. ▪ Training would also be useful if provided with the datasets.
GFDRR	There was huge governmental interest in collecting this data – right up to the prime minister.	People didn't know what to do with the data or how to use it.	▪ Use of these technologies to entice investment and insurance markets in Haiti. ▪ Data can be used to improve the country by scenario testing for planning decisions, and risk modelling.
UNOPS	Data was useful for prioritizing field surveys (i.e., don't need survey buildings with Damage Grade 5). Aerial imagery was useful to them for backdrops on maps.	Remote sensing derived data is too inaccurate (estimated at 30%), and needs to be validated. They worked with JRC and UNITAR/UNOSAT collecting ground truth data.	▪ Need simple interfaces for disseminating data. ▪ Need for institutional frameworks, common data standards, or a data librarian. ▪ Damage assessment would be trusted more if oblique-view data were used also.
UNOCHA	Remote sensing derived data is useful for nationwide analysis. Identification of pockets of vulnerable people.	Image analysis takes too long in response phase. Difficult operationally to validate which datasets are useful. Danger of official-looking maps being used as "truth" by non-technical people.	▪ Need for metadata showing limitations, methodology, accuracy reading, and disclaimers for error.
CNIGS	Availability of up-to-date OpenStreetMap data.	Took too long to get the raw data and damage data delivered to Haiti.	▪ A primary rapid analysis is needed. ▪ Raw data should be delivered faster. ▪ Better communication between groups.
WB-Contractors	Reported that IOM and UNOPS were confirmed users of the WB data.	Many agencies were overloaded at first. Difficult for them to use this new aerial data. Most people used the first remote sensing dataset they had, and continued to use this (mostly GeoEye-1).	▪ Send metadata ahead of the main dataset. Manage people's expectations of what they will get, and when. ▪ Need pre-styled kmls and pdfs. People need to understand the data "in 10 seconds."

9.2   Findings from Post-PDNA Consultations

The World Bank-ImageCat-RIT remote sensing data was delivered to several agencies (including IOM, UNOPS, and CNIGS) on high-capacity hard drives during the response phase of the Haiti earthquake. The data was passed through Georgetown University (Internet 2), and transferred to drives there. These drives included the aerial optical and LiDAR imagery. The ImageCat/GEO-CAN per-building damage assessment data, showing every heavily-damaged or completely destroyed structure, was delivered via ftp download when the distributors were in the field. Contractors from companies such as Fortius One were hired to help distribute these large datasets to agencies such as UNOCHA, UNOPS and CNIGS. This occurred approximately 2 months after the earthquake. Data was then passed on to third parties (e.g. IOM), and included OSM layers, aerial imagery, and offline versions of the Telescience browser interface.

A summary of responses to the consultation process is shown in Table 9.2. The table is formatted to highlight the main positive and negative aspects of the mission, its data, and dissemination. The remainder of this section provides an insight into how the data was received.

9.2.1 Data Delivery

In general, respondents were happy with the speed of the data provision, although the damage data arrived in Haiti after the aerial imagery datasets. CNIGS felt the data arrived too slowly, and would have preferred a quicker damage analysis followed by more detailed datasets. This view was partially shared by UNOCHA, who claimed that remote sensing datasets took too long to produce to be useful for response, yet found the high-level overview produced in Phase 1 of the damage assessment (identifying all collapsed buildings as points) to be particularly useful for identifying those areas most-affected by the earthquake.

There were several instances of a lack of expectation as to what data would be arriving, and when. Agencies were not expecting the damage information, did not always have time to understand it (they were still responding to the event), and could not always use it in their existing workflows. One respondent suggested that technical experts could have delivered the data in person to provide training on delivery. A one-day workshop or training event was even suggested by another respondent. Another response suggested that communicating metadata information ahead of the damage or aerial datasets would have given key users a "heads-up" on the type of data to expect and timescale for delivery.

9.2.2 Data Usage

Of the remote sensing data collected after the earthquake, most respondents tended to use the first imagery available (GeoEye) - most practical for their use. Government agencies did use the raw imagery captured by the WB-IC-RIT aerial collection mission, and the data was generally used to identify pockets of vulnerable people that the ground surveys were slow to reach. This was a shared view by UNOCHA, who found the imagery useful at a regional level to focus on remote pockets of vulnerable populations. The Ministry of Public Works and UNOPS used the aerial data as a backdrop to their building structural survey that took place in the months following. The Phase 2 damage assessment information was used to exclude areas from their structural survey (i.e., there was no need to survey buildings that had totally collapsed – Grade 5, EMS-98).

9.2.3 Accuracy

UNOPS was skeptical about the accuracy that could be achieved from a purely vertical remote sensing damage assessment. They claimed that their initial research showed that only a 30% accuracy rate could be achieved when compared to "ground truth" data. A difficulty in operationally validating the precision of the data was also complex due to the heavy demands on their organization. Because they did not have the time or resources to validate the data for their needs, they were hesitant to distribute the data further.

This underlying concern with accuracy of post-disaster data resulted in a reluctance of agencies to share data. When data is shared, the user is reluctant to trust it due to inaccuracies or collection limitations, and often these are not explicitly stated in the data. Therefore, there is a need for metadata to go alongside datasets including the limitations, assumptions, date of capture, etc. It was suggested that a common filtering system should be used for all datasets to verify their accuracy, source, and usefulness. This would be hard to implement, however, as every organization uses data for different purposes, and at different stages of response.

9.2.4 Intra-organizational Issues

One key finding deals with the hierarchy of users of post-disaster response information. Respondents suggested there is often a lack of a "middle tier" of organizational staff that can help bridge the gaps between technical staff (the analysts who understand the limitations of the data) and management (who must use the data and information to make key decisions). Managers often don't know enough about the data (and thus, there is a distrust of the information); technicians or analysts don't know how the data can be used for the wider good.

9.2.5 Inter-organizational Issues

Several issues were raised across multiple organizations. Firstly, there is a need to compile data in a common format. This does not currently happen outside of UNOPS. The delivered data in kml files should be customized to provide symbols that are intuitive. The data needs to be understood in 10 seconds by users. There is a need to provide a PDF report with the data detailing metadata and previewing the data. This is especially important for non-specialists, and pdfs are also essential for users to create paper maps which are still widely used and trusted. Also, maps need to be produced without imagery backgrounds, as operationally, these use a significant amount of ink to print, and cannot be reproduced quickly.

It was suggested that a useable interface could be provided so people could understand the data quickly. Telescience included a browser in the hard drives delivered, but it was not widely used. There was a strong feeling that now (i.e., not in a live disaster situation) is the time to provide training for intended users, while the initial response demands have subsided. Attempting this training during the initial phases of the disaster has too many challenges. People revert to known and practiced protocols during an emergency, so it's difficult for new technologies to be incorporated in an effective way.

9.2.6 Technology

Several technological issues in Haiti should be noted. The limited bandwidth in the country hindered data sharing, including upload and download of information. On several occasions it was mentioned that the foreign reporting media caused a high demand on the bandwidth. However, this could not be confirmed. An issue unique to the disaster in Haiti was the damage to many of the CNIGS' computers and the death or injury of many of its operators and decision makers in the earthquake. Processing power was harnessed through USAID's machines. Finally, it was mentioned that Haiti is a low-tech country. There was a recurring sense that the country needs to be more high-tech before remote sensing and GIS can be fully embraced at all levels. Decision-making in the country does not currently consider GIS data and there is a real need to create an information-based society that allows informed planning and strategic decisions.

9.3   Recommended Improvements

Several improvements were identified through the course of consultations that could improve uptake of remote sensing and geo-spatial technologies when responding to future events.

- There is a need for multi-temporal imagery and datasets (updated weekly during the response phase). These need to be widely shared throughout the response community.

- Oblique-view data (e.g. from Pictometry) was suggested as being useful to use in combination with imagery captured directly overhead. There was a feeling of greater confidence when combining datasets, especially for damage assessment.

- Need for more topographic, bathymetric and DEM (digital elevation model) data to holistically understand risk.

- Data was unreliable on schools, power, etc. There was not enough information on these types of infrastructure in the PDNA. Access to imagery for mapping units such as OSM should be made easier, as they provide a critical service.

- The formalization of a consortium for data collection and consolidation would be effective

    - The World Bank, JRC, and UNOSAT need to mobilize a consortium (e.g., GEO-CAN) ahead of the next event. Who will do what, who will validate damage estimates, what resources will be used, and by whom, should all be part of the discussion.

    - Development of multi-lateral protocols would be valuable.

    - An umbrella framework with strategic partners is needed, but no-one is currently leading this.

A second set of consultations was carried out with data users during August 2010 (Caley, 2010)[13]. These included data producers and volunteers that responded to the Haiti earthquake, not specifically as part of the GEO-CAN initiative. Several recurring themes arose during these interviews, many of which

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[13] Caley, L. 2010 Usability of Geospatial Technologies in Humanitarian Response: A case study of the Haiti Earthquake 2010. MSc Thesis, University of Southampton, UK.

substantiate the consultations that took place in Haiti in May. A full list of these findings can be found in Appendix A15. The main recommendations include:

- Strategic commitment and coordination is required to generate a geographic information management plan for response and recovery phases.

- A dedicated resource liaison person within organizations may aid training for and utilization of geospatial data.

- Post-response evaluations of data usage are valuable to understand impact of new technologies.

10.0   OPEN DATA

10.1   Overview

The high quality aerial multi-spectral imagery and LiDAR data collected in the course of this project laid a strategic foundation for the production of derivative datasets with value above and beyond assessing damage to Haiti's build environment. The prolificacy of these datasets argues in favor of open data and sharing as various research organizations and agencies may engage and leverage their own expertise in response to overwhelming needs for analyses by responders on the ground.

As discussed in Section 4.0, the WB-IC-RIT remote sensing data mission focused on collecting visible spectrum and long-, mid- and short-wave infrared (IR) imagery along with the collection of LiDAR data for all areas flown. The visible spectrum data resulted in very-high resolution optical imagery suitable for the visible identification of ground features. Longwave IR allowed for temperature measurement and detecting cool objects. Midwave IR is suitable for detecting relatively warm surfaces and objects. Shortwave IR can detect hot surfaces and objects along with reflective materials, including water. Finally, the collection of airborne LiDAR data resulted in three dimensional surface data (Figure 10.1).
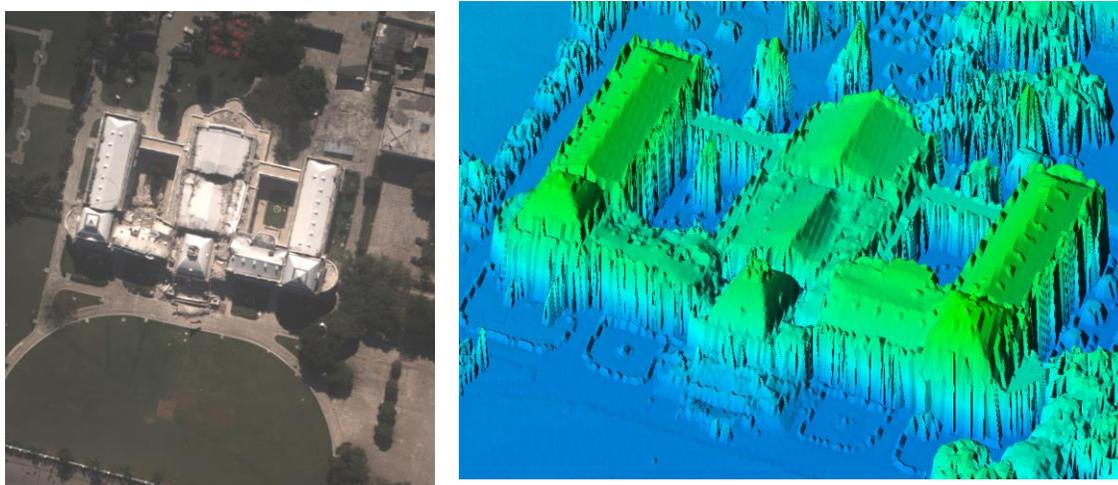

Figure 10.1 The National Palace as viewed in Optical Imagery (left) and LiDAR

10.2   Airborne LiDAR-derived Products

10.2.1 Purdue University's 3-D Building Models

Researchers from Purdue University created GIS datasets of building footprints with building heights extracted from the World Bank-ImageCat-RIT LIDAR elevation grids. The initial area of analysis was just north of central PaP to the west and southwest of the airport. Individual building footprints with extruded building heights as viewed in Google Earth is presented in Figure 10.2. The extent of Purdue's 3-D building modeling for PaP is displayed in Figure 10.3. In the future, this type of modeling could help to quantify the amount of building area in an affected region. Also, with pre-event LiDAR data (if available), change detection studies could be performed to identify in a more precise manner, the locations of collapsed or destroyed buildings. This type of analysis could also be applied to other types of infrastructure, e.g., bridges, electric power facilities, water storage tanks, etc.

**Figure 10.2 Purdue University's 3-D building Models as viewed in Google Earth**

Figure 10.3 Extent of Purdue University's Zones of 3-D Building Modeling

10.2.2 Fault Line Mapping

The 7.0 Mw earthquake produced measurable permanent ground displacements. The USGS utilized the airborne LiDAR data for both locating the Enriquillo fault line and for characterizing the permanent ground displacements (Figure 10.4).
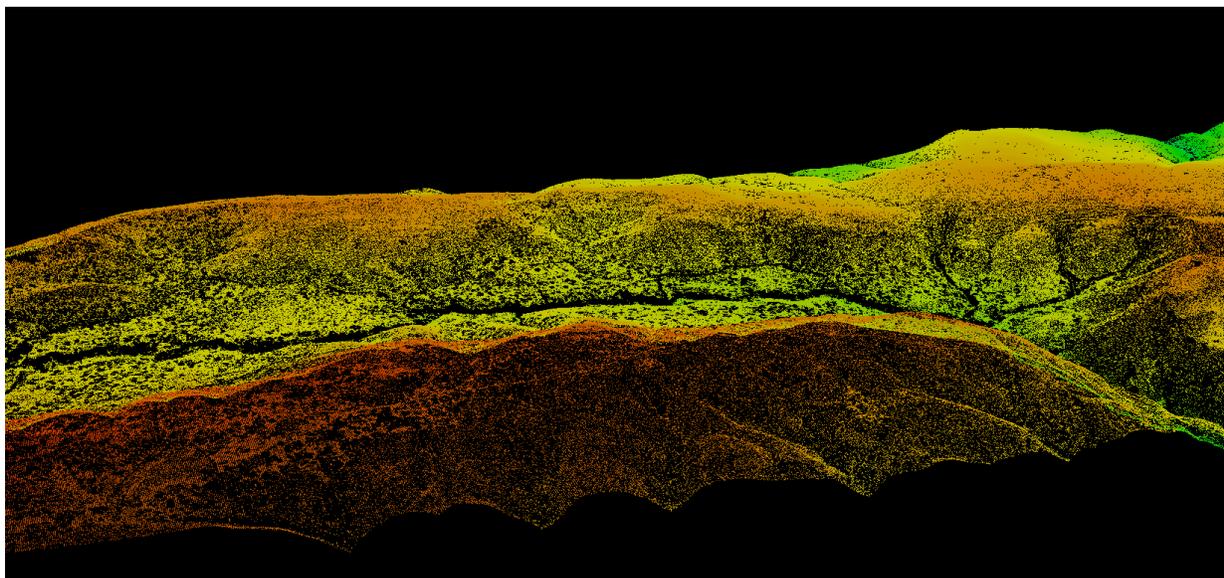

Figure 10.4 Aerial LiDAR Point Cloud of Haitian fault

10.2.3 Flooded Area Mapping

Finally, in order to assess potential flood risks in Port-au-Prince and outlying areas, the project team prepared a GIS layer showing ground elevations and mapped flood areas (by Corps of Engineers) - see Figure 10.5. The ground elevation data was sourced from the WB-IC-RIT LiDAR dataset. This data layer was delivered to UNOSAT in order to plot the locations of IDP camps onto these areas. Major areas of flood risk and areas that represent safe areas have been determined by merging this information with recent high resolution imagery.
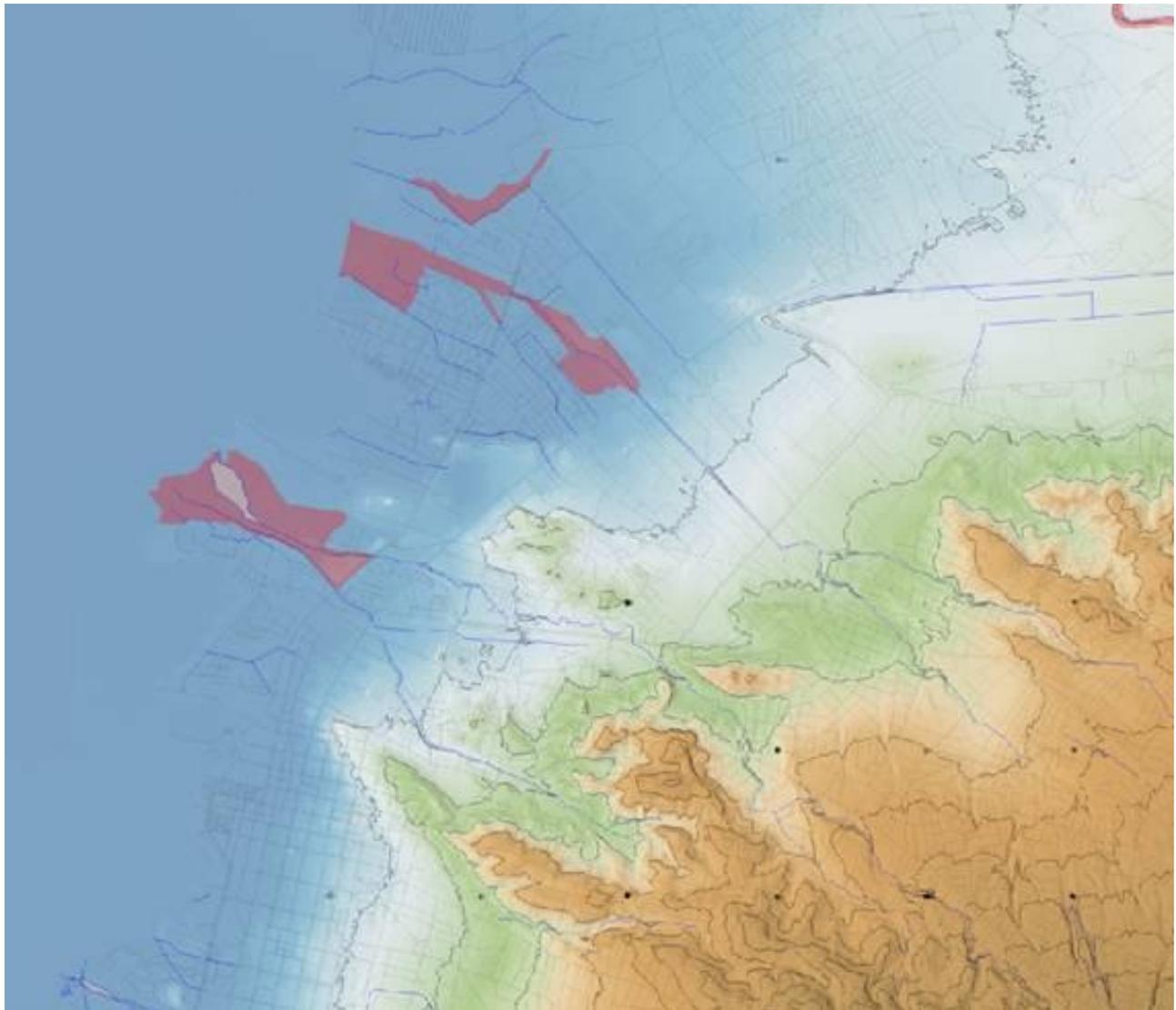

Figure 10.5 Ground Elevation GIS Layer with Flood Areas Mapped in Red (WB-IC-RIT LiDAR Data; Corps of Engineers)

10.3 Optical Imagery-derived Products

10.3.1 Temporary Shelter Locations

Rochester Institute of Technology (RIT) analyzed aerial optical imagery to identify the locations of camps of internally displaced persons (IDPs). The very high resolution imagery allowed for the counting of the number of blue tarps erected that aided in the estimation of estimating camp populations. Figure 10.6 shows the results of this analysis. In addition, an example of the aerial imagery used to perform this analysis is also provided in this figure.
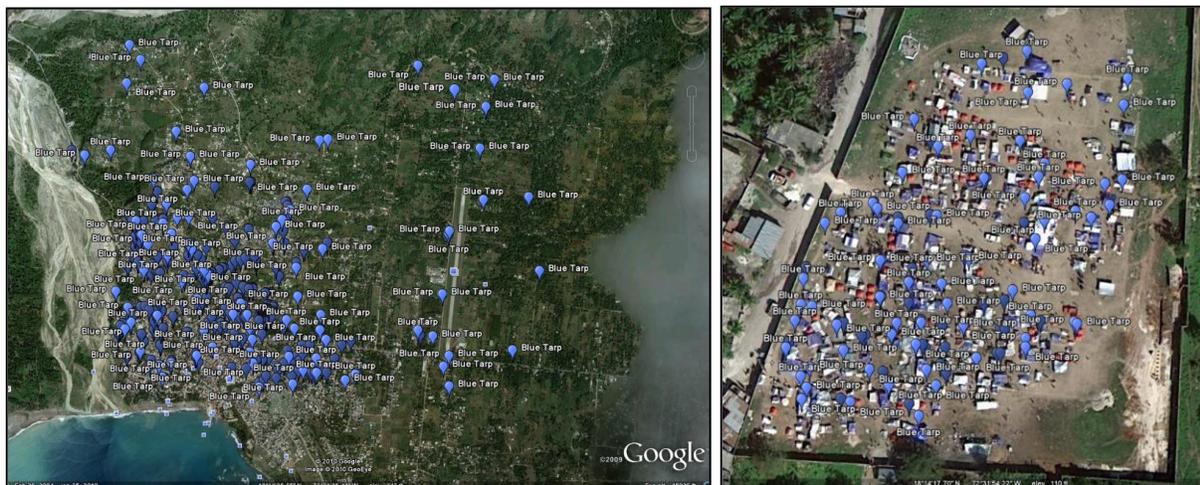

Figure 10.6 Results of IDP Camp Location (left) and Very High Resolution Blue Tarp Identification (right)

10.3.2 Rubble and Debris Assessment

Researchers from Purdue University complemented their LiDAR-based work on 3-D buildings with the results of their land-use classification for the central/downtown portion of PaP based on January 13, 2010, GeoEye-1 high resolution optical imagery. The classification scheme assigned all space within the area of interest to one of the following categories: roads, buildings, water, vegetation, shadow, open land, and miscellaneous. When combined with LiDAR-extracted elevation data, an assessment of the location and volume of rubble and debris was possible (Figure 10.7)

Figure 10.7 Identification of Building Footprints along with Rubble and Debris Areas for Downtown Port-au-Prince

10.3.3 Drainage Patterns and Flood Plain Mapping

The University at Buffalo accomplished flood plain and drainage mapping utilizing image interpretation. This is represented in Figure 10.8 below.
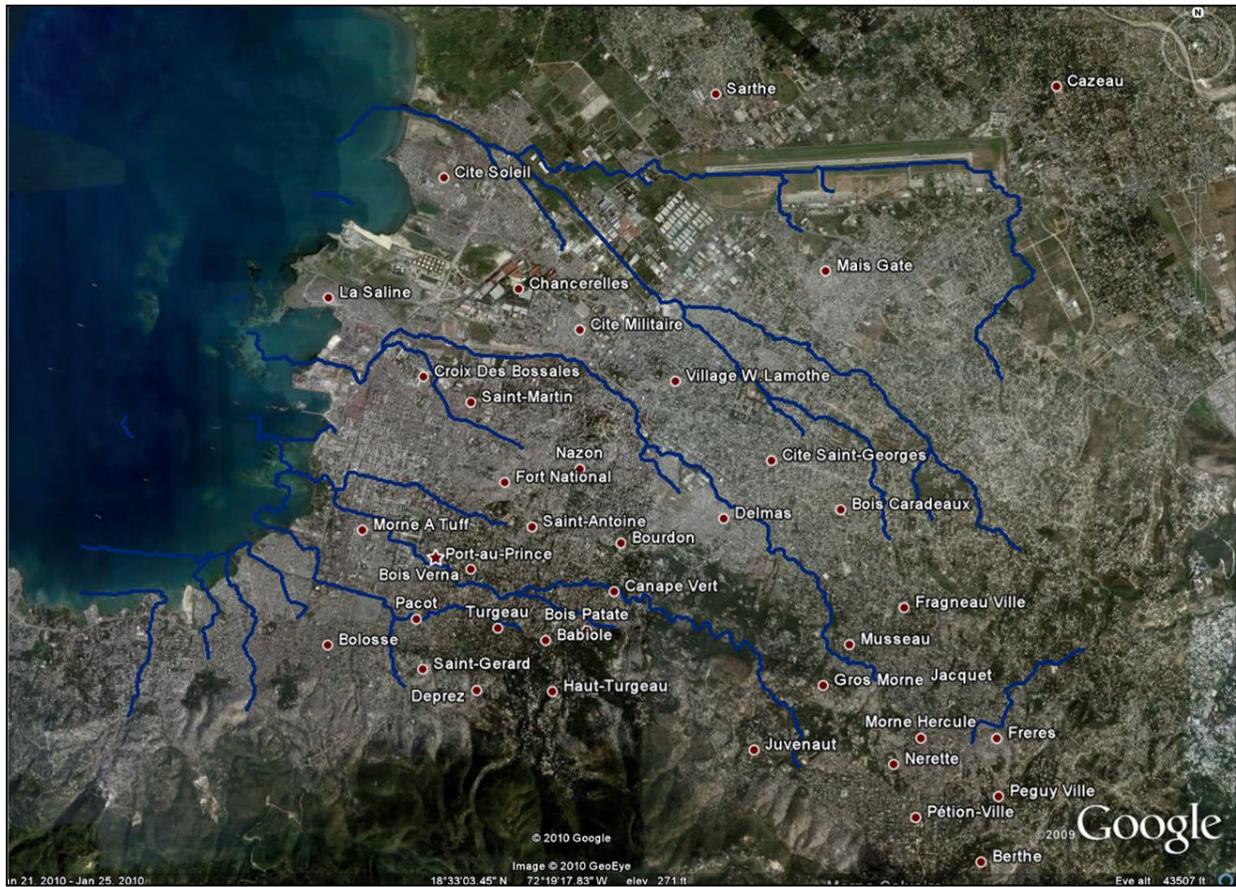
Figure 10.8 Drainage Patterns for Port-au-Prince shown in Blue

11.0   CONCLUSIONS AND RECOMMENDATIONS

1. The availability of satellite imagery was critical in performing early post-earthquake damage assessments. This imagery was available within days of the earthquake which allowed preliminary damage estimates within a week of the disaster. Even though the resolution (less than 60 cm) was less than that associated with the aerial imagery, satellite data was invaluable for the following reasons: rapid availability for a very large area, multiple temporal datasets, availability of pre-earthquake imagery, and inexpensive imagery (freely-available under the International Charter). We recommend that additional study be conducted in order to develop – even at a high level – a factor which will allow the scaling of satellite damage assessments to a more accurate summary of damage, such as that afforded by very-high resolution aerial imagery. This is needed since there may be disasters where aerial may not be available.

2. Although there were multiple missions being flown at the same time, the WB-IC-RIT remote sensing mission was key in providing timely data for the PDNA damage assessment, other sensor data that had unique applications and uses (e.g., LiDAR for creating digital elevation models), and information that can be used without restrictions for planning purposes, e.g., cadastral data. However, there needs to be more thought given to how these very large datasets can be shared with relief agencies doing work in the affected country and with the general research and scientific community. We

recommend that formal arrangements be made between the World Bank and large computing centers that could support this active dissemination of data after a major disaster. For example, formal arrangements with centers that were involved with the Haiti response (such as the San Diego State University or the MCEER center at the University at Buffalo) could be made before the next event.

3. The use of crowd-sourcing as a mechanism for performing damage assessments was clearly demonstrated in this event. However, the engineering and scientific community would benefit immensely from a) more pre-event training to more effectively recognize earthquake damage from both satellite and aerial imagery, b) a more formal structure for participating, i.e., formalizing the GEO-CAN initiative, and c) extending the protocols to address other natural hazards. As one of the key recommendations of this report, we recommend that a formal business plan be developed that will ensure that the GEO-CAN community lives on for future events. We also recommend that a broader involvement be pursued that expands the GEO-CAN community to other relief organizations such as the UN's UNOSAT group and the EC's Joint Research Centre. The Earthquake Engineering Research Institute should also remain actively involved in order to provide the technical support needed to respond to future earthquakes.

4. Comprehensive and accurate assessments of severe building damage are possible using very-high resolution aerial imagery. However, these assessments fall short when evaluating special types of building collapse (such as soft-story failures) or quantifying lower levels of damage. This was clearly evident in detailed field assessments of damage in PaP. In order to address this deficiency, we recommend that a detailed protocol be developed that utilizes both field surveys and oblique imagery that establishes where this latter information should be collected and how much. This protocol should also consider, where possible, the level of ground shaking, the type of construction in the affected regions, and the level of reliability needed in order to support key post-earthquake decisions.

5. A key factor in the PDNA process for Haiti was the agreement by all three main relief organizations (World Bank, UNOSAT and JRC) to combine the different damage databases into one consolidated dataset. To accomplish this, extensive analysis by all parties was necessary in order to ensure consistency and complete but not overlapping coverage. Although each team utilized the same damage grade classification scale (EMS-98), the protocols used by each team to determine these damage grades have not been evaluated. In order to ensure consistent application of remote sensing methods in the next disaster, the three main organizations with support from ImageCat and a few other groups, are pursuing the development of a set of Standard Operating Procedures (SOP). This SOP is being designed to identify the requirements of key datasets and sensors, the appropriate set of protocols for determining the different levels of damage, procedures for integrating field observations and results with aerial or satellite damage assessments, and procedures for quantifying the reliability associated with the final datasets. We expect this SOP to be finalized sometime during the summer (2010).

6. In order to ensure that the appropriate imagery is available for the next event, we recommend that a "living" imagery fund be developed that can be used to 1) create pre-event, planning databases that will help to quantify the vulnerability of a city or area by establishing detailed building inventories on a building-by-building level, 2) ensure that agreements with airborne data providers are in place well before the next event, 3) ensure that special imagery needs are met, e.g., LiDAR coverage, or oblique imagery in the case of earthquakes, and 4) sort out issues of restrictive air space by vulnerable nations, etc.

7. As suggested in the follow-up interviews conducted by ImageCat, more thought needs to be given to how the various post-disaster databases or products can be used to address other needs, e.g., post-event rebuilding requirements, or establish post-event mitigation strategies and programs. This is especially important for the aerial imagery. For example, using the aerial imagery to help meet cadastral data needs is a good example of how we can leverage this cost of the initial data collection. Furthermore, more education and training is needed by the end-users of this data. A better understanding the challenges and problems experienced by response organizations in this event will help to better integrate the different post-event products into the existing workflow.

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Phase 1

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Phase 2

GEO-CAN – Global Earth Observation – Catastrophe Assessment Network

The organizations involved in this World Bank – GFDRR volunteer effort are (**as of 15 June 2010**):

Universities (53)

Auburn University, USA
Bath Spa University UK
Bologna University, Italy
Cal Poly State University, San Luis Obispo
California Polytechnic State University, USA
Cambridge University, USA
Chiba University, Japan
City University of Hong Kong
Drexel University, USA
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Nigde University, Turkey
Nottingham University, UK
Oregon State University, USA
Oregon State, USA
Purdue Univeristy, USA
Rice University, USA
Rowan University, USA
Southampton University, UK
Stanford University, USA
Stanford University, USA

The George Washington University, USA
The University of Arkansas, USA
The University of Texas at Austin, USA
Tohoku University, Japan
Tufts University, USA
Università degli Studi di Firenze, Italy
Universitat Salzburg, Austria
University at Buffalo, USA
University College London, UK
University of British Columbia, Canada
University of California Berkeley, USA
University of California Davis, USA
University of California, Berkeley, USA
University of California, USA
University of Delaware, USA
University of Dundee, UK
University of Helsinki, Finland
University of Illinois, USA
University of North Carolina Wilmington, USA
University of Notre Dame, UK
University of Pittsburgh, USA
University of Quebec, Canada
University of Southern California, USA
University of Texas, USA
University of Ulster, Northern Ireland
University of Warsaw, Poland
Wageningen University, The Netherlands

Government or Non-Profits (17)

Applied Technology Council, USA
Concrete Reinforcing Steel Institute, USA
Doñana Biological Station, CSIC, Spain
Department of Homeland Security, DHS, USA
EEFIT - Earthquake Engineering Field Investigation Team, UK
Institute of Engineering Seismology & Earthquake Engineering (ITSAK)
International Institute of Earthquake Engineering and Seismology, Iran
International Organisation for Migration, Sudan
JRC - European Commission
MCEER, USA
Mid America Earthquake Center, USA
Rathgen-Forschungslabor - Staatliche Museen zu Berlin, Germany
Sahana Foundation, USA
Seismic Safety Commission, USA
The British Geological Survey, UK
The Earthquake Engineering Research Institute, USA
U.S. Geological Survey, USA
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Private Industry (53)

AthenaCorpos, USA

ABS Consulting, USA
AIR-Worldwide, USA
AMEC Geomatrix, Inc. USA
Applied Research Associates, USA
ARUP, USA
Berger/ABAM, USA
Burdon Engineering, UK
Caribbean Risk Managers, USA
CH2M Hill, USA
ConocoPhillips Alaska, USA
CORE Engineering, USA
CYS Structural Engineers, Inc., USA
DCI Engineers, USA
Degenkolb Engineers, USA
Dynamic Isolation Systems, Inc. USA
EarthLink, USA
Edmund Booth Consulting Engineer, UK
ENOVA Engineering, UK
EQ-Tec Engineering, UK
ESRI, Portugal
Exponent, USA
ExxonMobil, USA
Forell/Elsesser Engineers, USA
GEOCON,USA
Geo-Delft Environment, USA
GeoRevs, USA
Geosyntec, USA
Hattenburg Dilley & Linnell
Hilti, USA
ITC, USA
Jeffery Johnson Consultants
John A. Martin & Associates, USA
Joshua B. Kardon Company, USA
KPFF, USA
Mid America Earthquake Center, USA
MRP engineering, USA
Nabih Youssef & Associates, USA
P.E. Structural Consultants, USA
R2V Services, USA
Reid Middleton, Inc., USA
Reinforced Earth Company, USA
Risk Management Solutions, USA
Rutherford & Chekene, USA
Sandwell Engineering, USA
Serco Technical Services, USA
Shannon & Wilson, USA
SIE, USA
Sparks Engineering, USA
State Farm, USA
Thornton Tomasetti, USA
URS Corporation, USA
Worley,Parsons Westmar, USA

Phase 3

Professor Ellen Rathje of the University of Texas, Austin led the GEO-CAN Liquefaction effort in Phase 3.

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Brigham Young University
George Mason University
Georgia Institute of Technology
Illinois of University at Urbana-Champaign
Illinois University
Iowa State University
Kansas State University
Manhattan College
Michigan Technological University
Missouri University of Science and Technology
Oregon State University
Regional Academy of Natural Sciences
Rowan University
The University of Arkansas
Universidad Nacional de Colombia
Università degli Studi di Firenze
University College, Dublin
University of California, Los Angeles
University of California, Davis
University of California, San Diego
University of Connecticut
University of Hawaii at Manoa
University of Idaho
University of Illinois
University of Illinois at Urbana-Champaign
University of Texas at Austin
University of Wisconsin-Madison
Universityof Cambridge

Government or Non-Profit (2)

Office of Geotechnical Support, State of California
Aviation Safety and GIScience, Federal Aviation Administration FAA

Private Industry (14)

State Seismic
Alan Kropp & Associates
Arup
Booz Allen Hamilton
Domeight
Earth Systems Pacific
Exponent
Geocomp

GEOCON Incorporated
Geologist, Columbia
Kleinfelder
Pavement.com
Unina
URS

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ACRONYMS

| CAR | Cambridge Architectural Research Ltd. |
| CAS | Chinese Academy of Sciences |

CNIGS	Centre National de L'Information Géo-Spatiale
EC	European Commission
EEFIT	Earthquake Engineering Field Investigation Team
EERI	Earthquake Engineering Research Institute
EMS	European Macroseismic Scale
GEER	Geo-engineering Extreme Events Reconnaissance
GEO-CAN	Global Earth Observation – Catastrophe Assessment Network
GFDRR	Global Facility for Disaster Reduction and Recovery
IDP	Internally displaced persons
IOM	International Organization for Migration
IPLER	Information Products Laboratory for Emergency Reponse
ITHACA	Information Technology for Humanitarian Assistance, Cooperation and Action
JRC	Joint Research Center
LiDAR	Light Detection and Ranging
MMI	Modified Mercalli Intensity Scale
NASA	National Aeronautics and Space Administration
NRL	Navy Research Laboratory (United States)
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OSM	Open Street Map
PDNA	Post Disaster Needs Assessment
PEER	Pacific Earthquake Engineering Research Center
RIT	Rochester Institute of Technology
RSE	Remote Sensing for Earthquake Scale
SERTIT	Service Régional de Traitement d'Image et de Télédétection
SOP	Standard Operation Procedures
UNITAR	United Nations Institute for Training and Research
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
UNOPS	United Nations Office for Project Services
UNOSAT	UNITAR Operational Satellite Applications Programme
USGS	United States Geological Survey
VDV	Virtual Disaster Viewer
VHR	Very High Resolution
VIEWS	Visualizing Impacts of Earthquakes with Satellites
WASP	Wildfire Airborne Sensor Program
WFP	World Food Programme