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Towards a rapid automatic detection of building damage using remote sensing for disaster management

The 2010 Haiti earthquake

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Abstract

Purpose – Satellite and airborne images are increasingly used at different stages of disaster management, especially in the detection of infrastructure damage. Although semi- or full automatic techniques to detect damage have been proposed, they have not been used in emergency situations. Damage maps produced by international organisations are still based on visual interpretation of images, which is time- and labour-consuming. The purpose of this paper is to investigate how an automatic mapping of damage can be helpful for a first and rapid assessment of building damage.

Design/methodology/approach – The study area is located in Port-au-Prince (Haiti) stricken by an earthquake in January 2010. To detect building damage, the paper uses optical images (15 cm of spatial resolution) coupled with height data (LiDAR, 1 m of spatial resolution). By undertaking an automatic object-oriented classification, the paper identifies three categories of building damages: intact buildings, collapsed buildings and debris.

Findings – Data processing for the study area covering 11 km² took about 15 hours. The accuracy of the classification varies from 70 to 79 per cent depending to the methods of assessment. Causes of errors are numerous: limited spectral information of the optical images, resolution difference between the two data, high density of buildings but most importantly, certain types of building collapses could not be detected by vertically taken images (the case of data in this study).

Originality/value – The automatic damage mapping developed in this paper proves to be reliable and could be used in emergency situations. It could also be combined with manual visual interpretation to accelerate the planning of humanitarian rescues and reconstruction.

Keywords Disasters, Emergency response, Port-au-Prince, Remote sensing

Paper type Research paper

1. Introduction

The increase in world population and the development of fast and global communication networks have brought recent earthquake disasters in the limelight, e.g. in Andaman (2004), in Sichuan (2008), in Haiti (2010) and recently in Christchurch (2011). The 2010 Haiti earthquake displays the same characteristics of this series, for which we have observed a worldwide interest and media coverage. The dramatic modifications of the natural and built environment in the central city of Port-au-Prince were observed to be hampering the relief efforts and created specific logistic challenges, with problems ranging from situation assessment to aid delivery and identification of emergency focal points. With extremely short timeframe in emergency response and the need for instantaneous access to spatial data intelligible to remote sensing non-specialist (Voigt *et al.*, 2011), the role of satellite imagery has appeared to be crucial in such crisis management (Pesaresi *et al.*, 2010).

Satellite and airborne images have been widely used at different stages of disaster management, including relief rescues and reconstruction, especially to map infrastructure damage and to estimate the severity of damage such as collapsed or damaged buildings, roads, bridges (Kerle, 2010; Voigt *et al.*, 2007). Although semi- or fully automatic techniques to detect and estimate damage have been increasingly proposed (e.g. Stramondo *et al.*, 2006; Al-Khudhairy *et al.*, 2005), they have not been used during emergency situations (Tiede *et al.*, 2011; Voigt *et al.*, 2007, 2011). One of the most important reasons is that time constraints do not allow for application of complex image processing, especially when a pre- and a post-image are integrated in damage detection. Moreover, there is still a need to improve the reliability of damage detection techniques, which are greatly affected by geometric distortion, improper co-registration of pre- and post-disaster images, changes of vegetation or buildings (that were not caused by the disaster), and car traffic (Voigt *et al.*, 2011; Chesnel *et al.*, 2008). Practical and operational use of rapid automatic methods are therefore limited (Tiede *et al.*, 2011) and visual interpretation is the most common way to quickly map the damage. A faster, automated method to assess and map affected areas is essential to efficiently and effectively carry out emergency measures. Local governments and relief supporting organisations such as UNITAR-UNOSAT rely on the results of these mapping activities.

In this paper we seek to understand and show how a fully automatic technique using only a post-disaster image can be helpful for a first and rapid assessment of building damage and for disaster management in general. Our objective is to develop a method that automatically detects collapsed buildings and debris after a disaster. More specifically, we will test our method on buildings constructed at different time periods and within different types of land cover. Given the numerous amount of geospatial data available within four days after the Haiti earthquake on 12 January 2010, Port-au-Prince is a natural choice for such a research of disaster management.

2. Literature review

2.1 Building damage typology

The classification of building damages proposed by the European Macroseismic Scale 1998 (EMS-98) is now largely accepted and used in remote sensing studies (e.g. Al-Khudhairy *et al.*, 2005; Rezaeian and Gruen, 2007). The EMS-98 typology consists of five categories (from Grades I to V) according to the severity of the damages (Figure 1; Grünthal and Levret, 2001). However, from satellite images, the detection of Grades I and II is virtually impossible, which explains why these two classes are usually combined to form the intact class of buildings. Previous authors have also

mentioned Grade III is sometimes confused with Grade IV while Grades IV and V can be detected and recognised much more easily (Yamazaki *et al.*, 2004, 2005). In rapid damage mapping, other alternatives have hence been proposed such as rubble (Hussain *et al.*, 2011), damage density (Voigt *et al.*, 2011) and damage indicator (Tiede *et al.*, 2011).

2.2 Remote sensing-assisted disaster management

Arguably, the idea of using remote sensing for disaster management is not novel; in 1991, David Alexander was writing that: “two inventions, the satellite and the microprocessor, have revolutionised the way in which natural disasters are monitored and managed” (Alexander, 1991). Although, the idea was at the embryo stage at that time, it has developed into complex practices, which are nowadays oriented towards an almost real-time delivery of information for field practitioners. Part of this realm concerns the monitoring of environmental hazards, in order to measure and quantify the effects of events such as earthquakes (e.g. Liu *et al.*, 2012), floods (e.g. Haq *et al.*, 2012), tsunamis (e.g. Romer *et al.*, 2012) and even predict some of them (e.g. Hooper *et al.*, 2012).

The other advantage in using remote sensing is in post-disaster monitoring, which is essential to assess the spatial extent of a disaster, facilitate relief work and deploy effective logistics in the field. Both pre- and post- disaster monitoring activities have been sustained by the improvements of both passive and active sensors, and the increased availability of data (Gillespie *et al.*, 2007). Post-disaster management has benefited from improvements in the temporal resolution of optical sensors and in the spatial resolution of very high resolution (VHR) optical imagery, e.g. Quickbird offers 0.60m resolution in panchromatic mode and 2.8m in multi-spectral band; GeoEye1 offers even more details to see at 0.5 m resolution in panchromatic and 1.65 m in multi-spectral bands.

2.3 Manual detection of building damage in emergency situation in Haiti

In the aftermath of the Haiti earthquake, a number of damage maps were produced by different international organisations, most of which were based on visual interpretation and manual mapping, except one map from G-MOSAIC (Table I) which also used the eCognition software for automated image classification. Only four days following the earthquake (16 January), UNOSAT posted their first map entitled “Damage Assessment for Major Buildings/Infrastructure in Port-au-Prince, Haiti” produced by photo interpretation of the GeoEye images. The damaged buildings were only identified in point form and classified into Grades III-V. A more complete building damage classification was available one month later (UNITAR-UNOSAT *et al.*, 2010).

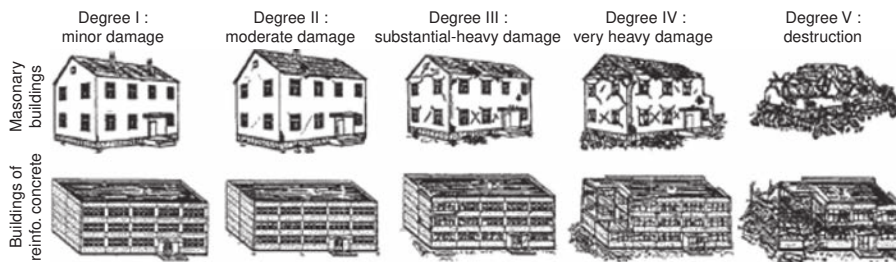


Figure 1. Illustrations of five grades of damages according to the EMS-1998

Source: Figure adapted from Grünthal and Levret (2001, pp. 15-16)

	Map title	Date	Image	Method
UNOSAT	Damage assessment for major buildings	16 January	GeoEye ^a	Manual
	Satellite-identified damages in	16 January	GeoEye ^a	Manual
	south-eastern part of Port-au-Prince			
	Port-au-Prince building damages	13 February	WorldView-2 ^b	Manual
	summarized by Dominant Landcover			
	Comprehensive Building Damage	13 February	WorldView-2 ^b	Manual
	Assessment for Port-Au-Prince Commune			
GEO-CAN	Intensity of Building Damages in	15 February	WorldView-2 ^b	Manual
	downtown Port-au-Prince			
	Intensity of Building Damages Across	25 February	WorldView-2 ^b	Manual
	Port-au-Prince and Carrefour			
	Port-au-Prince atlas of building damage	26 February	WorldView-2 ^b	Manual
	assessment			
	Damage map – point location of collapsed	17 January	GeoEye ^a	Manual
buildings (134 km ²)				
DLR/ZKI	Damage map – polygon footprint of	26 January	Photo ^c	Manual
	collapsed or heavily damaged buildings			
	(346 km ²)			
G-MOSAIC	Estimate of square footage requiring	15 February	Photo ^c	Manual
	reconstruction (1,025 km ²)			
	Preliminary damage assessment analysis	16 January	GeoEye ^a	Automatic
	Block damage assessment	16 January	GeoEye ^a	Manual
	Complete damage assessment analysis	18 January	GeoEye ^a	Manual
ITHACA	Damage assessment (low-high density)	18 January	GeoEye ^a	Manual
	Damage Assessments as of 13 January	14 January	GeoEye ^a	Automatic
	2010			(eCognition)

Notes: ^aGeoEye-1, image acquired on 13 January 2010 (spatial resolution of 50 cm); ^bWorldView-2, images acquired on 19 December 2009 and between 7 and 15 January 2010 (spatial resolution of 50 cm); ^cPhoto, aerial photography acquired during January 2010 with a spatial resolution of 14 cm

Source: UNOSAT, http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=52; G-MOSAIC, http://spatial.telespazio.it/G-MOSAIC_haiti/; ITHACA, www.ithaca.polito.it/maps.php?country=Haiti; GEO-CAN (ImageCat and EERI, 2010)

Table I.
Damage maps produced after the earthquake in Port-au-Prince

The World Bank, together with a network of volunteers of GEO-CAN and the ImageCat company also produced maps of the damage zones. This network of more than 500 volunteers from 23 countries (60 universities, 18 governmental agencies and NGOs; 53 private companies) actively participated in digitising damaged buildings of Grades IV and V in polygonal form (footprint) (ImageCat and EERI, 2010).

The German Aerospace Center's DLR/ZKI team, involving 20 people, also produced a first damage mapping on 16 January and updated it on 28 January (Voigt *et al.*, 2011). This team divided the area into 250 × 250 m grid cells to simultaneously work and rapidly produced and published the damage density map of Port-au-Prince. An average level of damage is estimated for each cell by using a qualitative analysis: severe, medium and slight.

Several authors have attempted to evaluate the accuracy of these published maps by comparing them with on-the-ground inventory and with oblique aerial images (Pictometry image). Kerle (2010) has used a damage map produced by an extensive house-to-house survey conducted by the Gadjah Mada University after the earthquake

in Yogyakarta (Java) in May 2006. By visually comparing this database with the DLR-ZKI and UNOSAT maps, he revealed that there is a good agreement between the three maps. The UNOSAT map is quite accurate, but both of them underestimated the damage. For the case of Port-au-Prince, Spence and Saito (2010) using oblique images showed that the proportions of buildings in types IV and V damage degrees are relatively similar and the agreement with their method is very good for intact buildings. However, the manual approach developed by GEO-CAN underestimates the heavily damaged buildings (Grades IV and V).

2.4 Automatic detection of building damage in “ideal” conditions

Several methodological approaches have been proposed for the automatic detection of building damages caused by a disaster (Joyce *et al.*, 2009; Tralli *et al.*, 2005). We will focus on strategies that use VHR optical images, especially when coupling with LiDAR data, because those types of data are available and have been used to detect damage in Port-au-Prince. Three detection strategies are usually favoured (Figure 2): the first one (A) uses a single image taken after the event while B and C make use of two images (pre- and post-event). Note that in Strategy B the “change image” is a raster matrix that contains changed and unchanged pixels.

In emergency situations Strategies B and C are rarely used, for several reasons. First of all, the time gap between the two images, if available, should be relatively short in order to ensure that observed changes between the two dates are only caused by the disaster. Also, georeferencing of the two images can also become complex and long to carry out, especially if they are taken with different view angles (Bitelli *et al.*, 2004; Chesnel *et al.*, 2008; Vu *et al.*, 2005). Hence, a few authors have been seeking for an easy and rapid damage detection and estimation using only one post-disaster image, i.e. Strategy A (Hussain *et al.*, 2011; Al-Khudhairy *et al.*, 2005; Kouchi and Yamazaki, 2005; Yano and Yamazaki, 2006). Given the difficulty of detecting all the five EMS-98 grades of building damage, these authors propose to identify one of the following

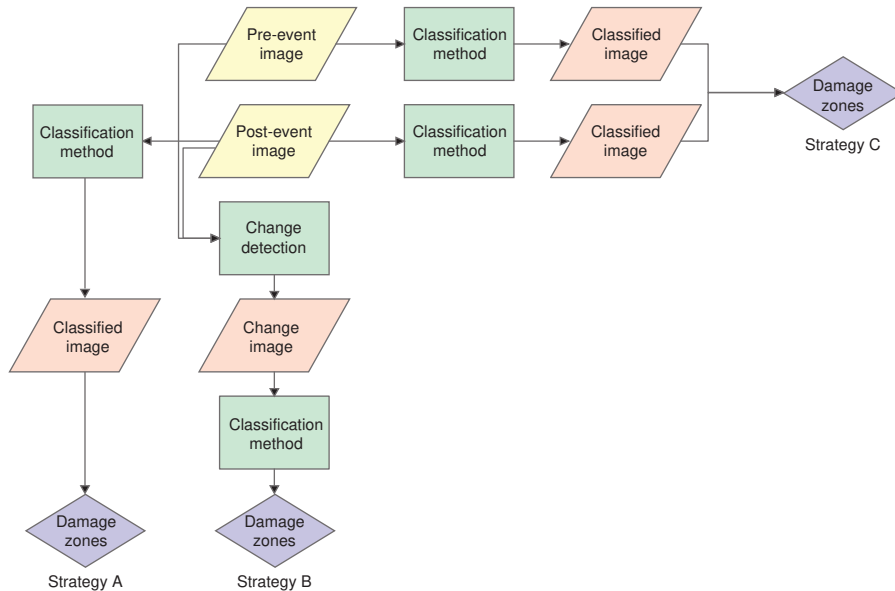


Figure 2. Processing steps in three detection strategies

classes or the combination of them: debris, heavily damaged or collapsed buildings (Grades IV and V in the EMS-98 Scale). In addition, the introduction of altitude data could give more information on the objects and thus improve accuracy (Rezaeian and Gruen, 2007; Vu *et al.*, 2005). In the case of Haiti, such data were also made available on the internet (Shan *et al.*, 2011).

Whatever the favoured strategy (A, B or C), the classification method retained can be pixel-based (e.g. Bitelli *et al.*, 2004; Kouchi and Yamazaki, 2005) which could be combined with texture or edge technique (Adams, 2004; Saito and Spence, 2004) or object-based (e.g. Al-Khudhairi *et al.*, 2005; Rehor *et al.*, 2008; Chesnel *et al.*, 2008). However, these studies show that pixel-based classification methods perform relatively poorly at the detection of collapsed buildings (Bitelli *et al.*, 2004; Kouchi and Yamazaki, 2005). For many authors, a single consideration of the spectral value (in pixel-based methods) is insufficient to detect damaged buildings, other elements must be introduced such as the geometric form, size, texture and contextual elements (Al-Khudhairi *et al.*, 2005; Bitelli *et al.*, 2004). We will therefore use the object-based approach in the present study because this approach allows us to integrate other information than only spectral values (Al-Khudhairi *et al.*, 2005; Baatz *et al.*, 2008). As our main goal is to provide a rapid damage mapping, we will only identify three classes: intact buildings (Grade I), debris and damaged buildings (Grades IV and V).

3. Study area – central area of Port-au-Prince

The study area (11 km²) is located in the district of Port-au-Prince (Figure 3). This urbanised area is representative of the metropolitan area since it includes informal settlements situated near the coast or on hillsides, a big part of the historical centre and newer residential areas. In the historical centre, commercial activities are predominant but there are also informal residential areas. The coastal neighbourhoods (e.g. Cité l’Eternel, Cité Plus) and those located in the piedmont of Morne de l’Hôpital are essentially residential. The study area also reflects the geophysical diversity of the

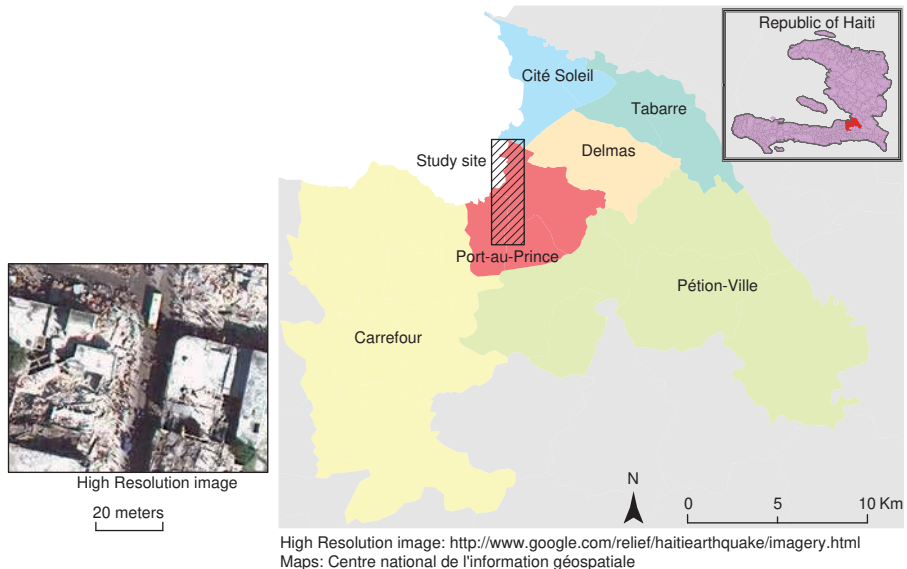


Figure 3. Study area in the metropolitan area of Port-au-Prince and example of collapsed buildings from the high resolution image

metropolis with a coastal zone composed of alluvia and calcareous formations in the northern piedmonts of Morne de l'Hôpital. In focusing on this area, we hope to test our proposed detection technique on buildings constructed at different time periods and within different types of land cover. Housing in informal settlements was predominantly constructed of bare cinder blocks often made with poor quality materials. Moreover, the absence of construction standards and the proliferation of haphazard construction contributed to the greater vulnerability of erected buildings in informal settlements (Goulet, 2006). Examples of collapsed buildings after the earthquake captured on GeoEye and high resolution images are provided in Figure 3.

4. Methodology

For this study, we used two main data sets which were made freely available by Google. Aerial images from World Bank-IMageCAT-RIT (called high resolution) combined in three bands in on true colour composite at a resolution of 15 cm, were acquired on 21st January and 22nd 2010 by the Centre for Imaging Science at the Rochester Institute of Technology. LiDAR data at a spatial resolution of 1 m were acquired from 21st January to 27th 2010, by the same organisations. The LiDAR data were already transformed into a digital elevation model (DEM) and a digital surface model (DSM). However, no details regarding the georeferencing and orthorectification of the images were provided for these two data sets. To put them in the same geographic projection, we carried out a geometric correction for these data sets based on a polynomial method in PCI Geomatica software.

Our implementation of an object-based approach was carried out using the eCognition software and involved two main steps: image segmentation and classification (Baatz *et al.*, 2008) (Figure 4). Image segmentation was carried out on the three original high resolution image bands, two LIDAR bands (DEM and DSM) and one band indicating object height which is the difference between the DSM and DEM bands (Vu *et al.*, 2009). Three scale factors (determining object size) were chosen based on empirical tests and documented scale factors from previous studies (Al-Khudhairy *et al.*, 2005; Yano and Yamazaki, 2006). After the segmentation was done, we used rules composed of spectral, geometric and contextual attributes (eCognition, 2009) to classify segments into three types: Grade 1, debris, and Grades IV and V.

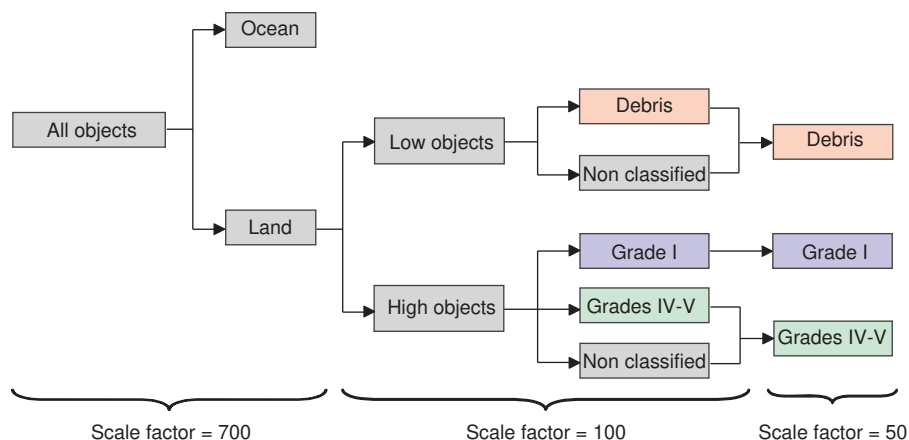


Figure 4. Segmentations at three scales and classification steps

To evaluate the accuracy of our results, we compared the classification with two sets of reference data. The first comparison is carried out with 51 points per class (in total 153 points), which is usually recommended in remote sensing (Congalton). We assigned each point to one of the three classes by taking into account the colour, texture and context around these points on the high resolution image. For each reference point, we created several buffer zones: 0.15, 0.50, 1, 2 and 5 m (using the ArcGIS software) in order to evaluate at which perimeter the classification is the most accurate – this could be of interest to field practitioners when using the classification. The superimposition with the buffer zones over the classification allowed us to assess the accuracy of the classification through the confusion matrix.

The second set of reference points was extracted from the Haiti earthquake 2010 “Remote Sensing Damage Assessment: UNITAR/UNOSAT, EC JRC, and World Bank” atlas (hereafter called the UNOSAT map), in which the five EMS-98 grades are represented as points. Following the validation method proposed by Tiede *et al.* (2011), we extracted only Grades IV and V from this database and converted them into a kernel density map with the output cell size of 20 m. From our classification, we also extracted only debris and Grades IV and V (in polygons), computed their centroid points and converted the points into a kernel density with the same cell size. The two kernel densities were then broken down into four ranks based on the 25 per cent quartiles (named from 1 to 4) corresponding to the four levels of the damage density. The two density maps were finally overlaid in order to evaluate the accuracy of the classification through the confusion matrix. The difference between the two density map varies from 0 (no difference on the two map) to -3 and $+3$ (wide difference).

5. Results

On the first assessment, the overall accuracy is close to 70 per cent (Table II). The omission errors are important for collapsed buildings (Grades IV and V), to a lesser degree for the Debris, and almost insignificant for Grade I. Errors for Grades IV and V can be explained by the difficulty to detect buildings with an inclined or symmetrical collapse of the structure (illustrated in Plate 1). Commission errors are serious for Grade I. An important proportion of reference points are not included in the objects classified (about 25 per cent of the 153 reference points), which is also caused by the difficulty to detect the two types of collapse, and therefore contributes to the omission errors of all classes.

On the second assessment, our classification and the UNOSAT map give similar levels of damage intensity across 79 per cent of the study area (Table III). A visual comparison between our results and the UNOSAT map is given in Figure 5. The red pixels represent areas that are identified to be more severely damaged in our classification (commission errors). The highest commission errors (ranked -2 and -3 , indicating

Distance to ref. points	Grade I		Debris		Grades IV-V		Overall acc.
	Prod. acc.	User acc.	Prod. acc.	User acc.	Prod. acc.	User Acc.	
15 cm	0.97	0.61	0.63	0.84	0.40	0.65	0.67
50 cm	0.98	0.63	0.67	0.87	0.42	0.70	0.69
1 m	0.98	0.62	0.67	0.83	0.40	0.74	0.69
2 m	0.98	0.62	0.67	0.87	0.38	0.67	0.69
5 m	0.98	0.57	0.55	0.86	0.34	0.62	0.63

Table II.
Accuracy rates at
different distances
around reference points

(a)



(b)



Notes: (a) Pancake collapse (symmetrical structural destruction); (b) inclined layers (inclined structural destruction)

Plate 1.
Examples of two types of collapse that are difficult to detect from vertical images

Difference in ranks	Number of cells	Percentage of cells	
-3	396	3.29	} Severe commission errors
-2	1,278	10.61	
-1	2,904	24.11	} Good agreement between the two maps
0	4,456	36.99	
1	2,180	18.10	
2	677	5.62	} Severe omission errors
3	156	1.29	

Table III.
Quantitative comparison between the automatic classification and the UNOSAT map

objects classified as damage are not damage in reality) make up about 14 per cent of the area. Commission errors appear to be concentrated in the central part of the study area and the northern coastal areas. This is likely due to the density of buildings and the difference in colour of roofs in those areas. In addition, since the height of buildings varies a lot in those areas, the resolution of LiDAR data is not fine enough to separate a change in height of damaged buildings. The blue pixels represent areas that are identified to be more severely damaged in the UNOSAT (omission errors). The highest omission errors (ranked 2 and 3, indicating objects that are not classified as damage) make up only about 7 per cent and they are dispersed over the study area. This is probably caused by the fact that the UNOSAT technique is more efficient to detect the two types of collapse mentioned previously.

6. Discussion and conclusion

In order to assess the efficiency of our method for rapid building damage detection, we discuss the time it took to process the data. Georeferencing of the data lasted for

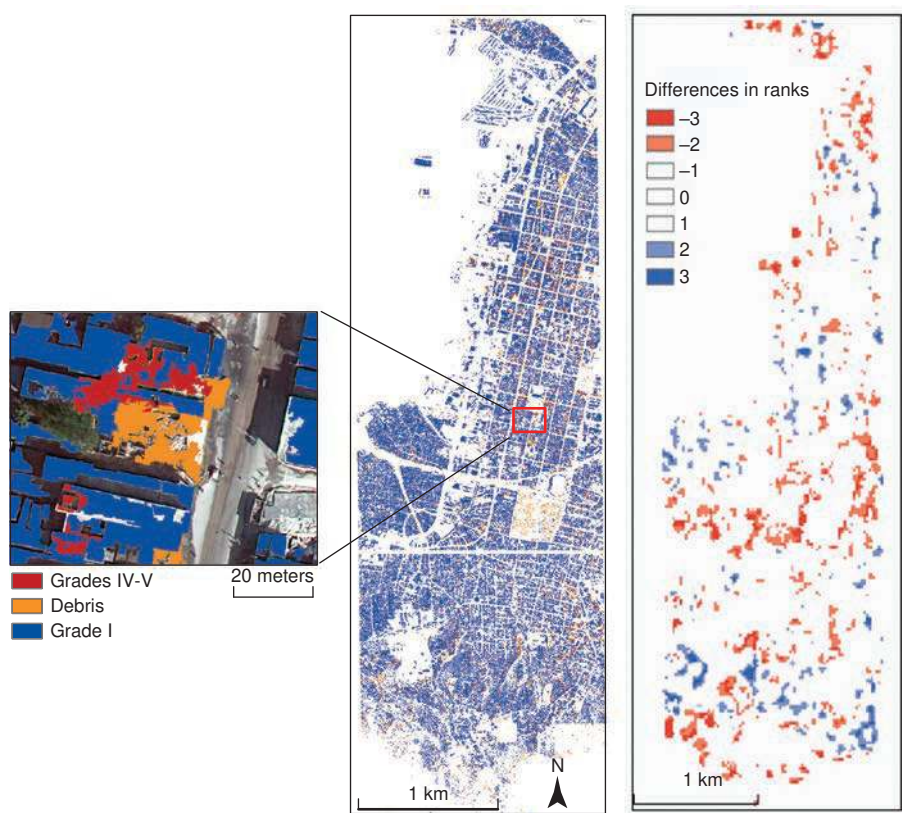


Figure 5. Image classification of building damage and rank difference map

approximately five hours and processing of the images in eCognition required ten hours on a single computer (with a 2Go RAM and two Intel Xeon processors branded CPU 3.2 GHz). Processing a larger zone would require the use of more computers, but eCognition Earth Server would also enable the batch execution of image analysis and this could help reduce time processing.

The results presented in this paper demonstrate the advantages of an object-oriented approach to the detection of building damage: a relatively short processing time (15 hours) and a relatively high global accuracy rate (near 70 per cent in the first accuracy assessment

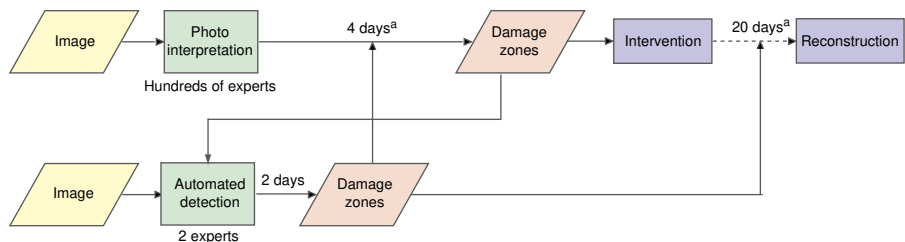


Figure 6. Proposed framework combining the manual and automatic approaches in the detection of damage

Note: ^aNumber of days estimated from the UNOSAT and GEO-CAN maps in Port-au-Prince
Source: UNITAR-UNISAT *et al.* (2010), ImageCAT and EERI (2010)

and 79 per cent in the second accuracy assessment). However, our results also show omission errors caused by different factors. First, we only had access to images created on true-color composites and not to the original four bands: this constitutes a reduction in information. We recommend posting true colour composite images online, which will be suitable for both the visual interpretation approach and the automatic approach.

Second, the difference in spatial resolution of the optical and LiDAR data sometimes generates a spatial discrepancy and thus errors in classification. Moreover, most omissions are on the symmetrical or inclined building collapses: this is true with the automatic approach as well as with a manual one as also mentioned by previous authors (Spence and Saito, 2010; ImageCat and EERI, 2010). The high density of construction in the city of Port-au-Prince and the significant variation in the height of buildings within a single neighbourhood, even in a single block, makes the detection of damage difficult.

A few lessons of automatic detection of damage by using remote sensing data are worth mentioning. Advantages of using this technique include: providing a rapid and synoptic evaluation of density and intensity of damage, especially for a large area and having information of areas that may not be accessible on the ground, for example, because of collapsed infrastructures. Disadvantages include: less accurate than a manual mapping, especially for identifying damage in building structures; time-consuming and technically difficult for non-remote sensing specialist.

Drawing from this, we propose that manual and automatic methods in satellite image classification could be conjointly used in order to improved the detection accuracy and hence provide for a better disaster management (please see proposed framework in Figure 6). Finally, we believe that from sharing and publication of such information during the whole process of damage detection could be facilitated by web-based cartography tools as earlier as suggested by Kerle (2010). Bringing approaches and diverse expertise together in such a way could reduce processing time to identify affected areas, which is crucial for planning rescue and reconstruction efforts.

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