# The use of remote sensing for post-earthquake damage assessment: lessons from recent events, and future prospects

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**SUMMARY**
This paper discusses methods for the application of remote sensing in post earthquake damage assessment, and reports on a GEO-CAN crowd-sourcing study following the 22.2.2011 Christchurch event, and its validation using field studies. It describes the principal datasets used, discusses in detail the problems of validation, and considers the extent of omission and commission errors. It is clear that although commission errors in the GEO-CAN damage estimation are low, there are significant omission errors; but the precise extent of these is difficult to define, because of the nature of the datasets used. The paper concludes with some recommendations for improving data collection for future investigations.

*Keywords: Damage assessment, remote sensing, Christchurch earthquake*

## 1 INTRODUCTION

Since their first availability a decade ago, high-resolution optical satellite images as well as aerial images have been increasingly employed for early post-earthquake damage assessments. The potential benefits of such deployments are huge: large damaged areas can be surveyed rapidly without being hampered by the emergency operation on the ground; rescue services can be directed to areas or buildings of greatest need; and the extent of damage can be assessed, leading to a reasonable estimate of reconstruction costs or insurance payouts, of value to international aid organizations, bi-lateral/multi-lateral donors and to the insurance industry.

The development of web-based crowd-sourcing techniques in recent years has created a further boost to the potential of such methods, enabling a large team of experienced people to share the task of building-by-building assessment over a large damaged area, so that an overall assessment can be produced very rapidly. After the 2010 Haiti earthquake, the GEO-CAN team of more than 600 people was assembled by EERI within a few days of the earthquake, and produced a first damage map of the urban area of Port-au-Prince within a week of the occurrence of the event; and within 3 weeks a second more extensive and detailed study was prepared by the same team the result of which was used for the validation of ground-based assessment results carried out for the World Bank/UN/EU Post-Disaster Needs Assessment. (Corbane et al 2011). There are thus considerable financial implications for the accuracy of such estimates, indicating the importance of good validation studies. However, to date, such validation studies are few.

The authors have been involved in damage-assessment exercises and subsequent ground validation for a number of recent earthquakes, and some studies have been reported elsewhere (Booth et al, 2011,Brown et al, 2011). The evidence from these earlier studies was that while remotely sensed images (aerial or satellite) can reveal much damage, a significant proportion of the damage cannot be detected. However, it was considered that, with further studies, it might be possible to find ways to extrapolate from the visible damage to make an approximate, but useful, early assessment of the overall damage based on the detectable part of the damage.

The Christchurch earthquake of 22.2.2011, with the extensive datasets which were gathered, provided an opportunity to test this hypothesis. Both satellite reconnaissance and an aerial reconnaissance was carried out within a few days of the major event; and this coincided with the extensive Building Safety Evaluations (BSE) which were carried out by the Christchurch City Council around the same time; additional data was also provided by many geolocated photographic studies of particular buildings by various reconnaissance teams.. This provided an opportunity for a GEO-CAN damage evaluation, and a validation study based on a much larger set of direct observation data than had been previously available. The GEO-CAN volunteer network was again assembled for this purpose, and was able to make use of a new platform developed by TOMNOD, giving more detail of the types of damage to be assessed than had been used in the Haiti exercise. The GEO-CAN study has been described elsewhere (Greene et al 2011).

The results of the GEO-CAN study, and relevant fields of the City Council's BSE data were made available to the authors for validation. This paper describes the principal datasets used, discusses in detail the problems of validation, considers the extent of omission and commission errors, and how these differed according to different types of construction, type of imagery used, and the level of experience of the volunteers. Preliminary attempts are made to quantify these errors by focussing on the performance of GEO-CAN in a study area. The paper concludes with some recommendations for improving data collection for future investigations.

## 2 THE CHRISTCHURCH GEO-CAN VALIDATION STUDY: AIMS AND DETAILS

The purpose of this study was to see how well remote sensing technologies (as used in GEO-CAN) perform in identifying buildings which have suffered earthquake damage. The main building damage data to be compared with the GEO-CAN data was the field survey information obtained by Christchurch City Council, although some photographs of damaged areas as well as expert opinion were used. There were three aims: firstly, to discover in roughly how many cases GEO-CAN identified a damaged building. Secondly to find to what extent GEO-CAN provided an estimate of the level of building damage commensurate with the actual level of damage suffered by the building. Thirdly, to identify the key factors that affect the remote-sensing assessment of damage.

Both omission errors (number of buildings omitted from the damage assessment) and commission errors (number of buildings wrongly assigned to a damage state) are investigated. Particular attention is paid to the fact that all datasets used contain a certain level of error and although the field survey data is "ground-truth data", errors can still appear in the reported building damage information.

### 2.1 GEO-CAN

Pre- and post-earthquake aerial and satellite imagery was obtained for Christchurch. The pre-event data was collected before the 2010 Darfield Earthquake and the post-event data is from aerial reconnaissance taken two days after the February 2011 event. Approximately 200 volunteers participated in comparing the pre- and post-event images to assess earthquake damage. The level of experience of each volunteer, the type of imagery that the damage assessments were based on and the damage types identified were recorded. There are approximately equal numbers of remote sensing volunteers with each level of experience – none, moderate and expert. The majority of volunteers (132) used aerial imagery and were assessing structural damage, 52 volunteers used aerial imagery to assess structural and geotechnical damage and the remainder (16) used satellite imagery.

Each volunteer was assigned an area of Christchurch and asked to identify damaged buildings and to draw a polygon to delineate the building and then assess the level of damage. The level of damage is described using a GEO-CAN Type_ID, with 1-3 indicating a level of building damage and Type_ID 4-7 indicating geotechnical damage. GEO-CAN instructions are available via: http://tomnod.com/GEO-CAN/instructions.phpAN and Table 1 shows the descriptions found on the GEO-CAN website used for Type_IDs 1-3. Type_ID 4, 5, 6 and 7 are a smaller component of the dataset and correspond to liquefaction, lateral spreading, landslide and sand boil assignments.

**Table 1.** GEO-CAN Descriptions of Type_IDs 1-4.

| | | |
|---|---|---|
| *1* | *Substantial Damage* | • *Rooflines mainly straight and intact.*<br>• *Large amount of debris visible only at the gable ends. Very little visible at bearing ends of roof.* |
| *2* | *Very Heavy Damage* | • *Portions of wall visible on ground.*<br>• *Large amount of debris visible at gable and bearing end.*<br>• *Debris visible at roof line between structures.* |
| *3* | *Complete Destruction* | • *Near total collapse.*<br>• *Large amounts of debris visible.*<br>• *Rooflines no longer visible.*<br>• *Interior walls visible.* |

This paper differentiates between buildings:

- **Viewed:** area has been inspected or looked at by a volunteer.
- **Analysed:** building or group of buildings has been assigned a Type_ID by a volunteer (within a viewed area).

In total, 1623 polygons were analysed in GEO-CAN. These are stored as polygons in GIS. A summary of the GEO-CAN analysis data by Type_ID is shown in Figure 1.

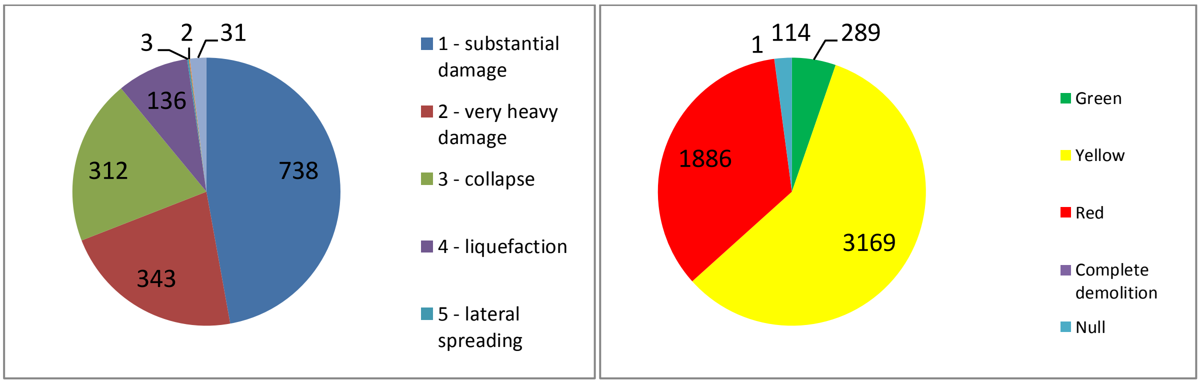


**Figure 1.** *Left:* the Proportion of GEO-CAN Polygons Assigned each Type_ID, *Right*: the Proportions of the Field Survey Data with each Usability Tag.

## 2.2 Field Survey

The field survey was the Building Safety Evaluation conducted by Christchurch City Council in the weeks following the Christchurch Earthquake which surveyed 8201 residential and commercial addresses. Teams visited buildings and filled in a one-page Level 1 assessment form. For approximately half the buildings, a more detailed Level 2 survey was conducted, superseding the Level 1 assessment. Engineers conducting both Level 1 and Level 2 surveys assessed:

- Building usability: green, yellow or red tag, level 1 or 2.
- Estimated overall building damage (% of building damaged, excluding contents): 0-1%, 2-10%, up to 100% (referred to here as *damage ratio*).
- Other pertinent geotechnical and structural issues e.g., liquefaction, non-structural damage etc.

There are 5459 field survey locations (out of 8201) in GEO-CAN **view** areas. The data for these 5459 locations are summarised in terms of usability tag in Figure 1.

For the validation exercise, only the FS tag results were selected for comparison with GEO-CAN results because the damage ratio data were considered less reliable.

### 2.3 Field survey data quality

For each field survey location, supplementary FS information was provided, such as: the building was identified as at danger from adjacent premises, or the building could not be accessed for the FS. The issues reported in the supplementary field survey information which may have had an impact on the GEO-CAN assignment are:

- The building was abandoned or unoccupied before the earthquake and therefore if in a state of disrepair, making damage difficult to assess from before and after imagery.
- There are geotechnical issues e.g., severe liquefaction, the effects of which may not be obvious from an aerial view.

## 3 COMBINING AND COMPARING THE DATASETS

The area in which the results of the Field Survey (FS) and GEO-CAN are compared is delineated by the extent of the GEO-CAN views. Figure 2 shows the extent of the GEO-CAN views (black line), the location of the GEO-CAN analysed polygons (blue points) and the field survey locations (red points).

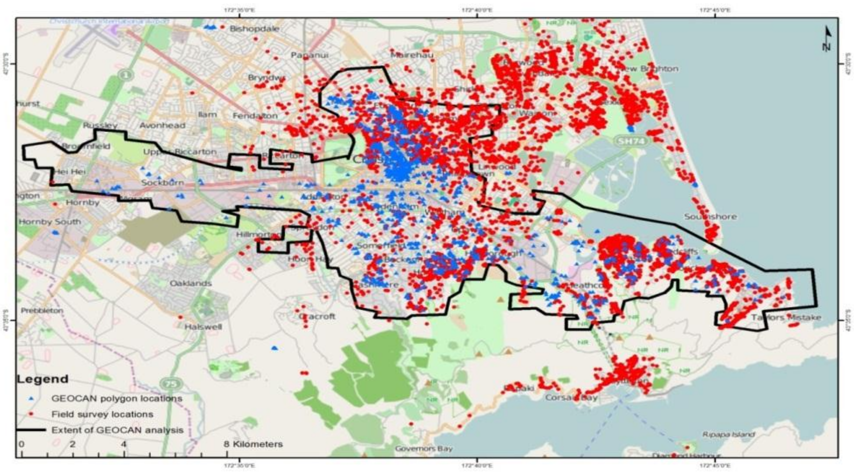


**Figure 2.** The Extent of the Area Viewed in GEO-CAN (Black Line) with the GEO-CAN Analysed Polygons (Blue) and Field Survey Locations (Red) Marked.

Within the extent marked by the black line, locations visited by the field survey have also been viewed by a GEO-CAN volunteer. However, GEO-CAN does not have the facility to assign a building no visible damage (NVD). Therefore, it is not possible to assess if a GEO-CAN view means that all of the buildings in the view area have been analysed. Hence, a damaged building not analysed in GEO-CAN may have been identified by the volunteer as having NVD, a commission error; or may not have been identified at all, an omission error.

### 3.1 Combining the datasets

The first step was to obtain field survey information and GEO-CAN tag for the same building. The points representing field survey locations were joined based on spatial location with the GEO-CAN analysed polygons, using the "Intersect" geoprocessing tool in ArcGIS. Two datasets were created:

- Preliminary dataset: spatial join of GEO-CAN analysed polygon with a field survey point location.
- Extended dataset: spatial join of GEO-CAN analysed polygon with field survey point location + 5m buffer.

Both datasets have an associated error. The preliminary dataset will miss some buildings that have both field survey and GEO-CAN information if the point or polygon assignment is not accurate and therefore the point and polygon for the same building do not intersect. However, the expanded dataset may attribute points to incorrect polygons, for example, there may be two closely-spaced buildings and a point for a building may be within 5m of a GEO-CAN polygon for the adjacent building. Both datasets will also miss some locations. For example, for a large structure such as the Cathedral, a 5m tolerance is too small to encompass both the main building and the tower, so a point located on the main part of the cathedral will not be joined with a polygon delineating only the tower. The work presented in this paper is based on the preliminary dataset.

The join procedure was checked at a number of locations and any inconsistencies found in later parts of the analysis were checked for inconsistencies in the dataset join procedure. The datasets are summarised in the Table 2.

**Table 2**. Summary of the individual GEO-CAN and Field Survey Datasets and the Dataset of Combined GEO-CAN and FS Information.

| *Number of:* | *Preliminary dataset (A)* | *Extended dataset (B)* |
|---|---|---|
| *GEO-CAN analysed polygons* | *1623* | *1623* |
| *Field survey locations* | *8201* | *8201* |
| *Field survey locations in GEO-CAN view areas* | *4988* | *4988* |
| *Joined points and polygons* | *1075* | *1363* |
| *Unique field survey locations with polygons* | *647* | *758* |
| *Polygons with field survey information* | *538* | *605* |

Using the combined data, an approximate estimate of how many damaged individual FS addresses GEO-CAN identifies can be obtained:

- FS data & GEO-CAN **view** = 4988 addresses
- FS Yellow/Red tag & GEO-CAN **view** = 4615 addresses
- FS Yellow/Red tag & GEO-CAN **analysis** ≈ 703 addresses

These values show that in the GEO-CAN view area, of the 4615 addresses that were recorded as damaged in the field survey (yellow or red tagged), 703 were analysed in GEO-CAN as damaged (15% of the total number of FS yellow or red tagged buildings in the GEO-CAN view area). This raises two questions. The first is whether a viewed building which is not analysed is an omission or commission error. The second is the factors that give rise to commission errors, i.e. which types of red and yellow tag buildings are being identified and which are not.

## 3.2 Comparison of datasets

The second step is a comparison of the two datasets. For this analysis, the metrics in each dataset which would be considered to constitute an agreement between FS and GEO-CAN are shown in Table 3. The circle in the usability range indicates the most likely usability for a given GEO-CAN Type ID.

**Table 3.** The Expected Field Survey Usability and Overall Building Damage Ranges for GEO-CAN Type_IDs 1, 2 And 3.

| *GEO-CAN TYPE_ID* | *Assumed FS usability tag range* |
|---|---|
| *1 (Substantial damage)* | *G Y R* |
| *2 (Very heavy damage)* | *Y R* |
| *3 (Collapse)* | *Y R* |

# 4 ANALYSIS

## 4.1 Omission errors

Using the values presented in Table 2, it initially appears that the omission error of GEO-CAN is relatively high. However, it is important to differentiate between the address-based field survey and building-based GEO-CAN analysis. This is because a single building may contain a number of addresses, e.g. flats and therefore, a proper estimate of the omission error of GEO-CAN in Christchurch can only be obtained if the number of buildings visible from the air is known. For this reason, the omission errors have been investigated through a sample study area (Section 5). This helps to quantify the portion of the omission error which is actually commission error.

## 4.2 Commission errors

For the 1363 joined locations in the extended dataset, an assessment of the level of agreement between the estimated damage in GEO-CAN and the ground-based damage assessment is quantified using the tag assigned in the FS. Figure 3 summarises the GEO-CAN and FS characteristics for all locations in the extended dataset, and shows that 94% of locations analysed as damaged in GEO-CAN (either substantial damage, very heavy damage or collapse) were also damaged according to FS (red or yellow tagged). If levels of damage can be adequately assessed in GEO-CAN, it could be expected that the FS red tag would correspond to a larger number of GEO-CAN Type_ID 3 analyses. However, Figure 3 shows, conversely, that there is no clear correlation between the level of GEO-CAN analysed damage and the level of FS reported damage.

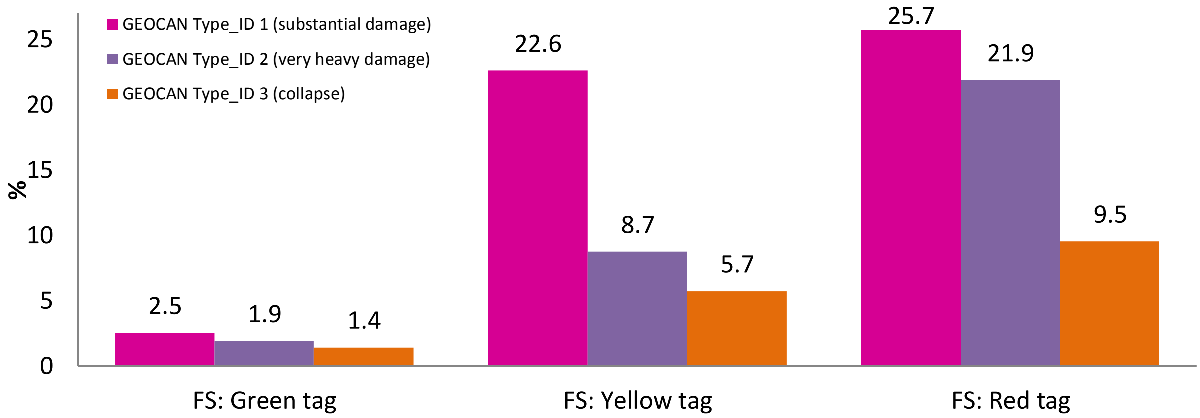


**Figure 3.** The Distribution Of GEO-CAN Type ID with FS Usability Tags.

This comparison of results indicates that GEO-CAN can assess whether or not a building is damaged, but is not consistently assigning the correct level of damage. Potential reasons for the inconsistency in GEO-CAN analysed damage and FS damage were therefore further explored with the aim of giving guidance on the future use of remotely-sensed damage assessments with particular focus on the situations in which they are most and least effective.

Three main factors were investigated which might contribute to the performance of GEO-CAN in identifying building damage: the level of experience of GEO-CAN volunteers related to remote sensing; whether the GEO-CAN analysis was based on aerial or satellite imagery; and the ability of remote sensing to identify damage to different building typologies. This study is reported in detail elsewhere (Foulser-Piggott et al 2012), but its main findings are as follows:

- the more experienced volunteers tended assign proportionally fewer collapsed buildings.
- the satellite imagery group tended to identify relatively lower levels of damage than those using aerial photographs.

- different building typologies have very different patterns of damage assessment, with relatively more ID-2 (very heavy damage) assignments for masonry buildings than for either RC or timber buildings.

# 5 STUDY AREA

## 5.1 Defining the study area

The study area is a gridcell 500 x 500 m and was selected as a representative area of the Central Business District (CBD). The study area contains 254 field survey (FS) points and 87 GEO-CAN analysed polygons. There are three steps necessary to allow a building-by-building comparison between GEO-CAN and FS.

1. Each building footprint in the study area was manually delineated using aerial imagery.
2. A single field survey assessment is assigned to each building, which in the majority of cases is a one-to-one mapping, i.e. a single FS tag is available for a building. However, FS points must in some cases be aggregated so that a single unique FS tag is assigned to each building footprint. There are two ways in which this aggregation is performed:
   - Multiple attached buildings with one FS point which appeared interconnected are delineated with a single polygon.
   - Multiple field survey points located inside a single building footprint are assigned the FS tag with the highest level of damage, e.g. yellow and green tag – assigned yellow.
3. GEO-CAN analysis is joined to a building footprint by two methods:
   - **Method 1:** Centroid of the GEO-CAN polygon overlaps with the building footprint
   - **Method 2:** Extent of the GEO-CAN polygon overlaps with the building footprints.

The second method ensured that any building footprint that was intersected by the GEO-CAN polygon was classified as damaged. This leads to a higher and more accurate estimation of damage and the results of this analysis are therefore included here. Visual analysis of the two datasets revealed that GEO-CAN analysts often used one polygon to delineate several damaged buildings which could lead to omission errors.

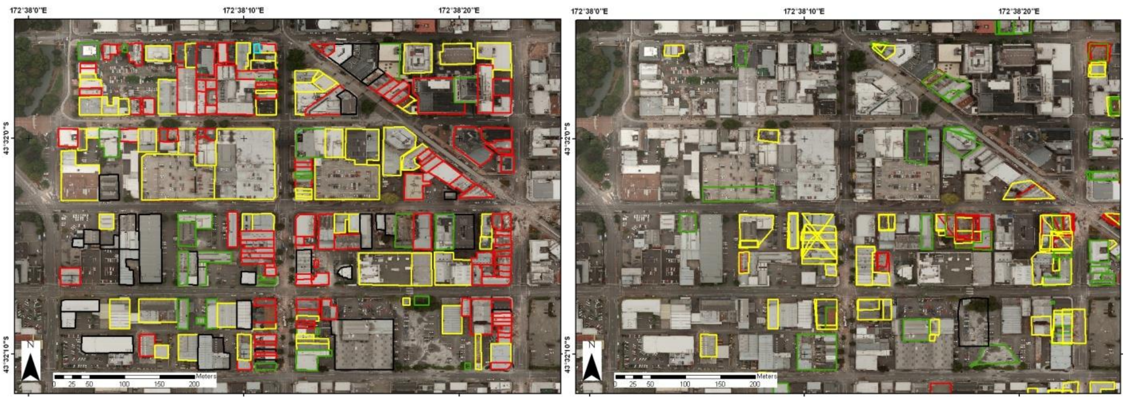

**Figure 4:** The validation exercise was applied to a 500 x 500 m grid in the Central Business District of Christchurch (Left: Field survey assessments assigned to building footprints; right: GEO-CAN Assessments)

## 5.2 Results

The study area contains 87 GEO-CAN analysed polygons and 235 dilineated buildings. The field survey tagged 178 of the delineated buildings as damaged: 64 with a yellow tag and 114 with a red tag. 106 dilineated buildings were assigned a GEO-CAN analysis using a one-to-one polygon join rule, the characteristics of these GEO-CAN analysed polygons are as follows:

GEO-CAN identified 93 of the 178 dilineated buildings with a yellow or red field-survey tag. A contingency matrix of the results is shown in Table 4. The omission and commission errors and discrepancies can be summarised as follows:

- Omission Error: 111 buildings (yellow cells) with FS tag and no GEO-CAN analysis.
- Commission Error: 13 buildings (red cells) with GEO-CAN analysis with no FS tag
- Discrepancies: 17 buildings (purple cells) GEO-CAN analysis and the expected FS tag ranges not in agreement (shown in Table 3).

| | | GEO-CAN | | | | |
|---|---|---|---|---|---|---|
| | | **None** | **1** | **2** | **3** | **Total** |
| **Field Survey** | **None** | 18 | 5 | 5 | 3 | **31** |
| | **Green** | 17 | 2 | 4 | 3 | **26** |
| | **Yellow** | 49 | 25 | 30 | 10 | **114** |
| | **Red** | 45 | 7 | 9 | 3 | **64** |
| | **Total** | **129** | **39** | **48** | **19** | **235** |

**Table 4:** A contingency matrix comparing GEO-CAN results to field survey data at per-building scale using the one-to-one polygon join method.

## 5.3 Discussion

### 5.3.1 Omission Errors

Omission errors occurred when GEO-CAN analysts failed to identify damage to a building (yellow cells). The GEO-CAN analysis omission error is 54%. Some preliminary explanations for omission and errors are now proposed:

1. *Damage-type:* Analysts missed internal damage as it is not visible in imagery and damage such as partially collapsed roofs (Missed by analysts with all levels of remote-sensing experience).

2. *Delineation of multiple buildings with one polygon:* Analysts used only one polygon to delineate several damaged buildings. This may be a result of it being difficult to determine the extent of buildings in dense urban environments.

3. *Building-Type:* Figure 5a *(left)* shows the building-type of the 111 damaged buildings omitted by the GEO-CAN analysis and Figure 5b *(right)* shows the building-type of the damaged buildings correctly identified by GEO-CAN. The results show that GEO-CAN analysts appear to identify damage to masonry buildings more often, however, the omission of building damage is equally likely for both masonry and RC. It is therefore likely that the building-type affects the level of omission errors and similar study area analyses will be repeated in different parts of Christchurch that are representative of different building-types.

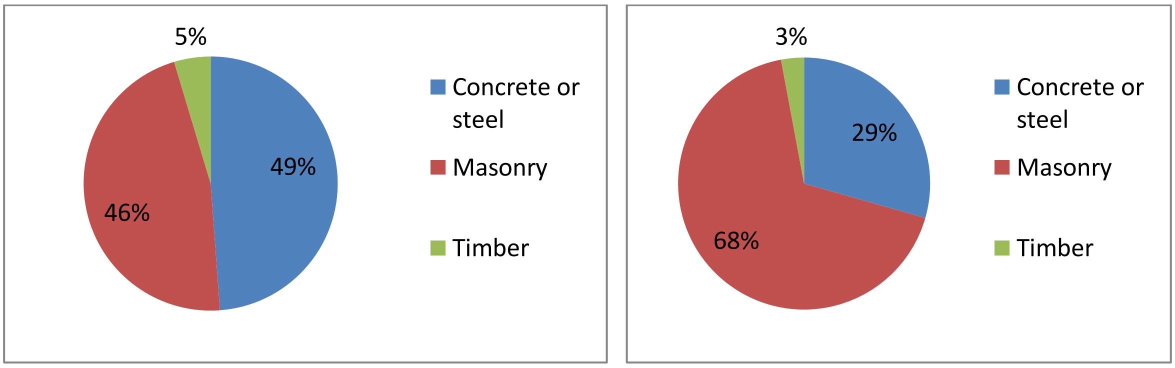


**Figure 5:** The building-types of damaged buildings **(a)** omitted *(left)*; **(b)** identified *(right)* by GEO-CAN analysts

### 5.3.2 Commission Errors

There are a relatively few commission errors, approximately 12% and some preliminary reasons for these are now proposed:

1. *Analysts' experience* - The commission errors were made by analysts at all levels of experience using both satellite and aerial imagery. However, the number of correct analyses increases with experience level.

2. *Different building typologies* - The results show that commission errors might occur when non-damaged buildings have debris or rubble near to them from near-by damaged buildings. Sometimes, the presence of debris or markings on roads or other impervious surfaces also led analysts to incorrectly identify those areas as being damaged buildings. The analysis of further study areas will aid assessment of the patterns of damage assessment for different building typologies.

For approximately 15% of GEO-CAN assignments, there is an obvious discrepancy between the level of damage recorded in the field survey and the GEO-CAN analysis, which is likely to be due in part to the two factors just discussed. A clear understanding of the reasons for these discrepancies, particularly in terms of defining the limitations of remote-sensing based damage assessment, will form the major part of the further work in this area.

## 6 CONCLUSIONS

On the basis of the experience of using remote sensing for damage assessment to date, the current situation can be summarised as follows.

1. Much damage is visible from manual assessment of satellite images or aerial photos with a resolution of 1m or less. Buildings which are reported to be damaged based on remote sensing are generally confirmed to be damaged in field investigations (ie commission errors are low), though the degree of damage to these buildings often turns out to be underestimated.
2. In all validation studies carried out by the authors using field investigations, there is evidence that significant numbers of very heavily damaged or collapsed buildings are not identified in the studies using remote sensing (ie omission errors are high). Certain types of damage regularly fail to be detected. These include: failure of lower stories, settlement damage, failure of internal structural elements such as shear walls, any of which might render the building uninhabitable or require its demolition. Lower levels of damage such as wall cracking, failure of beam-column joints are also not detectable.

3. The extent of both omission and commission errors are influenced by a number of factors, including the quality and resolution of the image used, the experience of the investigator, the type of construction, and the types of damage..
4. Without contemporary field investigations of large samples of the affected area using the same damage scale as that used for the remote sensing study, a precise quantification of the omission errors cannot be made. In Haiti the number of heavily damaged or collapsed buildings found in the limited field investigation was about twice that found in the remote sensing study; in a single study area in Christchurch, the omission errors on buildings at similar high levels of damage are approximately 54%.
5. Much remains to be done to further analyse the damage from the Christchurch earthquakes using additional field data and earthquake insurance records, to identify the relative performance of remotely sensed studies for different building types and land-use categories, and in areas subject to liquefaction.
6. Further damage investigations in future earthquakes are needed to help develop approaches to infer non-visible damage based on the extent of damage which can be detected. The authors recommend that, in these studies:
   - remote sensing analysts identify non-damaged as well as damaged buildings visible in all images analysed
   - field validation studies are conducted as early as possible, covering a significant sample of the different areas damaged
   - statistical studies of field survey data be conducted to generate rough distributions of low, moderate and significant damage that can be scaled to observational data (remote sensing results) on collapsed and severely damage buildings (see Corbane et al., 2011).
7. The authors believe that damage studies using remote sensing will have an increasingly important role to play in the early assessment of earthquake damage, which will in the future be supported by the increasing range and capability of remote sensing imagery available. But there is still much to be done to enable the best possible interpretation of these images to be made.

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**REFERENCES**

Booth, E. Saito, K, Spence, R, Madabhushi, G, and Eguchi, R (2011). Validating assessments of seismic damage made from remote sensing**,** *Earthquake Spectra*, 27, 1,157-177.

Brown, D, Saito K, Liu M, Spence R, So E, Ramage M, (2011). The use of remotely sensed data and ground survey tools to assess damage and monitor early recovery following the 12.5.2008Wenchuan earthquake in China, *Bull Earthquake Eng* DOI 10.1007/s10518-011-9318-7.

Corbane, C., Saito, K., Dell'Oro, Luca, Bjorgo, E., Gill, S.P.D., Piard, B.E., Huyck, C.K., Kemper, T., Lemoine, G., Spence, R.J.S., Shankar, R., Senegas, O., Ghesquiere, F., Lallemant, D., Evans, G.B., Gartley, R.A., Toro, J., Ghosh, S., Svekla, W.D., Adams, B.J., and R.T. Eguchi, (2011). "A Comprehensive Analysis of Building Damage in the 12 January 2010 $M_W$ 7 Haiti Earthquake using High-Resolution Satellite and Aerial Imagery, *Photogrammetric Engineering & Remote Sensing*, Vol. 77, No. 10, October 2011, pp. 0997-1009.

Greene, M. Eguchi, R. Barrington, L. Bevington, J. Crowley, H. Gill, S. King, A. Lin, A. Saito, K. Spence, R. and Wood, P. (2011). Improving GEO-CAN: Crowd-Sourcing Opportunity to Analyze Imagery from Christchurch New Zealand, *International Workshop on Use of Remote Sensing in Disasters, Stanford University*, November 2011

Foulser-Piggott, R and Spence, R (2012). *Validation of the GEO-CAN damage assessment following the 22.2.2011 Christchurch earthquake*, Cambridge Architectural Research, UK.