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ORIGINAL PAPER

Assessing building vulnerability to earthquake and tsunami hazard using remotely sensed data

M. Mück · H. Taubenböck · J. Post · S. Wegscheider · G. Strunz · S. Sumaryono · F. A. Ismail

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Abstract Quantification of building vulnerability to earthquake and tsunami hazards is a key component for the implementation of structural mitigation strategies fostering the essential shift from post-disaster crisis reaction to preventive measures. Facing accelerating urban sprawl and rapid structural change in modern urban agglomerations in areas of high seismic and tsunami risk, the synergetic use of remote sensing and civil engineering methods offers a great potential to assess building structures up-to-date and area-wide. This paper provides a new methodology contextualizing key components in quantifying building vulnerability with regard to sequenced effects of seismic and tsunami impact. The study was carried out in Cilacap, a coastal City in Central Java, Indonesia. Central is the identification of significant correlations between building characteristics, easily detectable by remote sensing techniques, and detailed in situ measurements stating precise building vulnerability information. As a result, potential vertical evacuation shelters in the study area are detected and a realistic vulnerability assessment of the exposed building stock is given. These findings obtained allow for prioritization of intervention measures such as awareness and preparedness strategies and can be implemented in local disaster management.

Keywords Building vulnerability · Remote sensing · In situ assessment · Tsunami hazard · Earthquake hazard · Vulnerability assessment · Vertical evacuation

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M. Mück (✉) · H. Taubenböck · J. Post · S. Wegscheider · G. Strunz
German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), Oberpfaffenhofen,
82234 Wessling, Germany
e-mail: matthias.mueck@dlr.de
URL: www.dlr.de

S. Sumaryono
BAKOSURTANAL, Bogor KM. 46, Cibinong 16911, Indonesia

F. A. Ismail
Andalas University, Padang 25163, Indonesia

1 Introduction

Natural hazards are an ever-present threat to lives, to infrastructure and to economic activity throughout the world. The visual images from recent catastrophic events flashed across television revealed the vulnerability of the human society and its environment in case of such natural hazards—that is, the earthquake in Padang, Indonesia 2009, in Puerto Prince, Haiti 2010 or the disaster in Japan 2011 with a subsequent tsunami. A dramatic increase in losses caused by natural catastrophes has been observed in the last few decades. Reasons include the rapid growth of world population attended by the development of modern societies and technologies, often located in zones of high seismic and tsunami hazard (Calvi et al. 2006).

In the framework of earthquake and tsunami disaster risk reduction, the hazard component can mostly be regarded as a given factor almost out of human control. Thus, vulnerability analysis plays a key role in disaster risk reduction as the development of strategies on reduction and mitigation of losses and damages is crucial pre-condition for an effective disaster management. Physical vulnerability factors encompasse susceptibilities of location and the built environment, and can be represented through such factors as remoteness of a settlement, location, and construction materials and techniques to build infrastructure. For this reason, physical vulnerability is seen as a measure of the possible damage of a building that it is likely to experience harm subjected to ground shaking of specified intensity (Erdik 2002).

In this respect, the biggest risk for the population in case of an earthquake emanates from buildings (Parsons 2004) and the demand for reliable analysis is great. Extensive and accelerating urban sprawl and rapid change in urban structures, in particular in developing countries, need efficient and fast techniques for mapping and analysing to support sustainable urban planning and management. Such information about buildings is usually derived from field measurements based on selected parameters that determine the level of vulnerability (Sinha 2004). However, relying only on such direct measurements requires resources beyond acceptable time and cost. The combination of in situ building surveys and remote sensing/GIS technology is a challenging and promising approach to overcome this problem. The availability of commercial high-resolution satellite imageries such as Ikonos, Quickbird or WorldView enables area-wide and up-to-date analysis of highly structured and dense urban areas.

Consequently, the central aim of this paper is to describe a methodological framework that contextualizes the key components and underlying processes in quantifying building vulnerability to earthquake and tsunami hazards. The following research questions are addressed within this article:

- What are the key determinants describing building vulnerability related to earthquake and tsunami threats?
- How can these determinants be identified by a combined approach using remote sensing technology and in situ measurements?
- How can these determinants be framed into a coherent model quantifying building vulnerability?
- What are the prospects to identify potential vertical evacuation buildings using remote sensing?
- How can gained research findings be implemented in an easy applicable, transferable and robust methodological concept?

Major challenge in this study is the consideration of dependencies in the earthquake and tsunami disaster impact chain related to building stability as well as the identification of significant correlations between building characteristics, easily detectable by remote sensing techniques, and detailed in situ measurements stating precise building vulnerability information.

2 Study site and data

2.1 Study site

The city of Cilacap is one of the most populated urban-coastal areas in the province of Central Java, Indonesia. Cilacap has regional relevance with a port connection and is connected to the rail network. Furthermore, the city has a special economic role with its oil mining industry and large agricultural sector. The dynamically growing urban environment is located directly at the coast and partially sited beneath the sea level; thus, in a zone at high risk of severe earthquakes and potentially triggered tsunamis.

2.2 Satellite and airborne data

Urban environments are physically characterized by a small-scale alignment of buildings, infrastructure and open spaces with their specific types and dimensions. To cover this high spatial heterogeneity and small-scale spatial differences of urban objects, geometrically high-resolution satellite data with the capability of separating individual buildings from each other are required. The sensor Quickbird provides a geometric resolution between 2.4 m and 60 cm and is thus suitable to extract area-wide and up-to-date information on the urban landscape. Other high-resolution sensors (e.g. Worldview 2) were also considered but finally not used due to high cloud cover rates. A high-resolution DEM derived from airborne radar with 5-m resolution covering the City of Cilacap was used to derive building height information. These building heights represent a relative measure for the extracted elevations as they were computed by subtracting two elevations at the building roof (central point within a certain building polygon) and base.

2.3 Survey

A field survey has been conducted on 500 structures, comprising structural engineering and remote sensing experts, conducting measurements according to pre-defined parameters (see Sect. “3.2”). The selection of the buildings aimed at a complete coverage of physically differing housing types—from small, low-height shacks to large, high-rise building types including residential buildings as well as critical facilities like schools, hospitals, power plants and telecommunication facilities. Additionally, spatial coverage of the complete urban landscape was aspired—from the urban centre to the periphery (suburbs) as well as close from the coast to the hinterland.

To meet the above criteria, a “systematic stratified sampling technique” is used to divide settlement areas into homogeneous building groups. Based on local expert knowledge from scientists, civil engineers and authorities, a pre-selection of representative building types and structures determining the city scape of Cilacap was conducted. Random samples from each building group (integrating equal or similar building types and structures) were selected and weighted according to the proportion in the cityscape of Cilacap. Therefore, a selection of 500 buildings was considered as sufficient.

Figure 1 provides a selected insight in the complex structure of the city and the building stock.

Fig. 1 Quickbird imagery of Cilacap with selected zoom windows (Sumaryono 2010)

3 Methodology

3.1 Methodological framework

The use of various satellite data sets and remote sensing methods for post-earthquake and tsunami damage detection was and is still topic of several studies (Eguchi et al. 2000; Huyck et al. 2005; Saito and Spence 2003; Yamazaki et al. 2004; Pesaresi et al. 2007; Voigt et al. 2007; Adams et al. 2009; Leone et al. 2010; Koshimura et al. 2009). Therefore, research mostly concentrated on post-disaster reaction and predominantly on a particular observation of either earthquake or tsunami hazard.

This study aims to shift the focus from post-disaster reaction to pre-disaster strategies. As recent studies focusing on building vulnerability using remote sensing techniques (and thus concentrating on mitigation options) mostly investigate single hazard effects on building structure (Calvi et al. 2006; Münich et al. 2006; Taubenböck 2008; Taubenböck et al. 2009; Wang et al. 2008; Jelínek et al. 2009; Borfecchia et al. 2010; Taubenböck 2011; Ricci et al. 2011; Tinti et al. 2011; Wieland et al. 2012), we also consider dependencies in the earthquake and tsunami disaster impact chain (Sumaryono 2010).

Vulnerability of buildings to earthquake and tsunami is dependent on a variety of form and functional parameters. Recent studies, mentioned above, as well as the current Global Earthquake Model (GEM) initiative (GEM 2012), identified different factor groups (e.g. building height, age, design, construction) as main indicators for building stability. The challenge in this study consists of a value-adding combination of civil engineering and remote sensing methods. Civil engineering enables an accurate stability assessment of individual buildings by an extensive house-by-house inspection, or the analysis of construction plans, which are rarely available in developing or threshold countries (e.g. Rossetto and Elnashai 2003; Crowley et al. 2004; Freeman 2004). To cover potential earthquake and tsunami impact areas, detailed but cost- and time-intensive in situ assessment results have to be extrapolated in an effective way. High-resolution satellite imagery offers a great potential for the extractability of different building parameter as vulnerability indicators (Mueller et al. 2006); for example, by an object-based image analysis, parameters like building shape, position and height can be identified and extracted from VHR optical data or in combination with digital surface models (e.g. Wurm et al. 2011; Ehrlich et al. 2012). Indirect assumptions about the house type based on the urban structure type can be derived using additional knowledge about the roof type and context information.

This assessment methodology in quantifying building vulnerability is based on a new integrated approach combining in situ data and remote sensing techniques with a clear, traceable decision logic. The workflow is presented in Fig. 2.

Starting with the structural assessment of the 500 building samples, the stability of the structure itself is analysed. For buildings where the requirements for stability are fulfilled

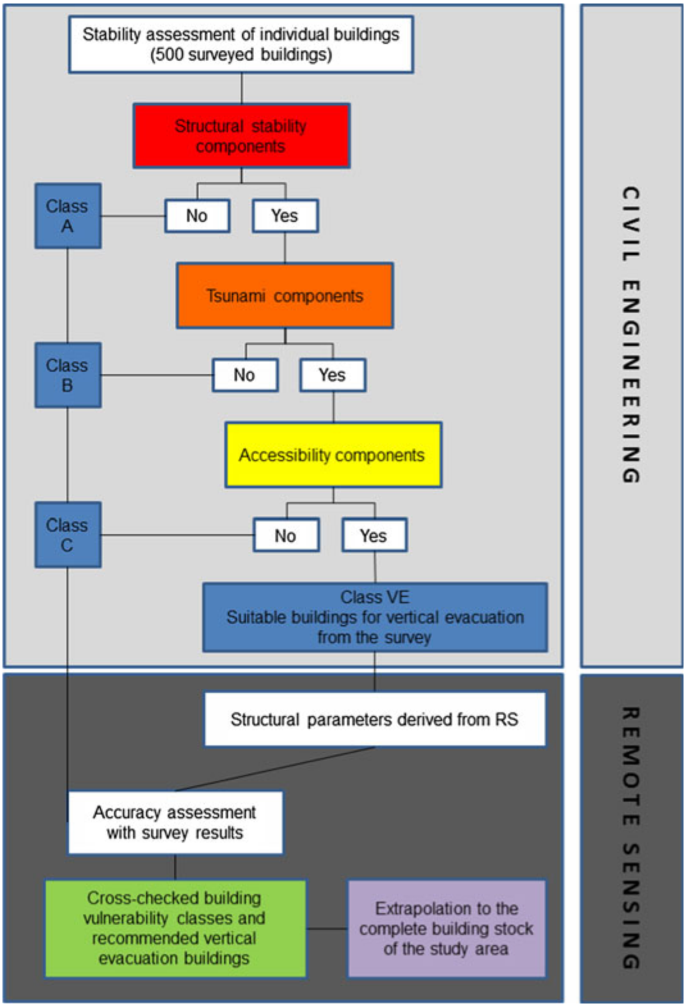

Fig. 2 Methodological framework for the assessment of building vulnerability to seismic and tsunami impact based on survey and remote sensing results

(threshold analysis (e.g. Gandica 2005), see Sect. 3.2), a successive analysis regarding tsunami components is performed. Buildings remaining qualified for vertical evacuation are subsequently analysed with respect to accessibility. This resulted in a certain number of building structures potentially suitable for vertical evacuation.

Each vulnerability class is defined using a scoring method with particular threshold values marking the intersections between the vulnerability classes. A building that, for example, does not fulfil structural stability requirements and, thus, stays under the defined threshold value will not be considered for further investigations and will be identified as Class A (most vulnerable) building. Such buildings will most likely collapse during an earthquake. Buildings fulfilling the criteria of all categories are potentially suitable for vertical evacuation in case of an earthquake and following tsunami event.

In the next step, remote sensing algorithms are developed to determine a classification rule set based on spatial parameters of the surveyed building samples, using object-based image analysis. Central to this assessment is the identification of key parameters for building vulnerability to earthquake and tsunami hazard in order to be able to extrapolate sample information effectively to a broader scale. An accuracy assessment comparing in situ and remote sensing results shows to what extent building vulnerability gained by civil engineering can be explained by remote sensing techniques. Conducted assessment steps are described in the following.

3.2 In situ building assessment

The vulnerability of a particular building structure is predominantly conditioned by its specific physical characteristics, the location with respect to the coastline and the location within the urban environment. The assessment of the 500 sample buildings was carried out in detail using ground survey data. A questionnaire—including physical tests at the structure (e.g. hammer test), visual assessment and interviews with the owners—is used to evaluate the building capacity to withstand against earthquake and tsunami impact. The data surveyed are transformed into numerical terms, and different levels of vulnerability are adopted. As shown in the workflow (Fig. 2), the identification of suitable structures for vertical evacuation contains 3 separate steps:

1. Building stability components
2. Tsunami-relevant components
3. Accessibility components

3.2.1 Building stability

Building parameters are required to determine the level of building stability at the time of an earthquake. Consequently, this category is a prerequisite requirement for further analysis of tsunami-related components as buildings categorized as highly vulnerable to seismic impact will not be taken into account for further analysis. The assumption of an exact earthquake magnitude as benchmark for the building stability assessment is difficult. Seismic impact is influenced not only by a magnitude value but also by distance to the epicentre, type of earthquake, length of shaking, soil type, etc. (e.g. Bin Alam et al. 2008). Thus, we are underlying a tsunami-genic earthquake between magnitude 7 and 8.5 as a base for our assessment. Identified building stability parameters are listed in Table 1 and contain the following three major aspects: (1) *Structural* aspects including stability assessment on columns, beams, perimeter beams, plate and truss of the building; (2)

Table 1 Identified building stability factors, thresholds and respective weighting factors

No.	Parameter	Threshold	Weighting
1	Height	15 m	4
2	Material of concrete	Lab mix	8
3	Proportion of mortar	1:4	8
4	Type of foundation	Foot	4
5	Existence of column	Available	6
6	Ring balk	Available	4
7	Truss beam	Available	4
8	Column anchored	Available	4
9	Wall anchored	Available	4
10	Truss anchored	Available	4
11	Reinforcement	Available	4
12	Truss roof brace	Available	4
13	Hammer test value	15–20 MPa	10
14	Roof material	Clay	0
15	The builder	Skilled labour	4

Material aspects, including concrete strength, strength of the timber or steel, quality of the walls and reinforcement bars; and (3) *Connections* between structural as well as non-structural elements.

One of the best known tests allowing an accurate assessment of reinforced concrete properties is the Schmidt rebound hammer test, which gives a statement about the seismic vulnerability of a building (Yakut et al. 2012). Further structural analysis is required, but completed structural survey results in the study area confirmed the hammer test results as the most important indicator. Thus, hammer test values have the highest weighting factor in this analysis (cf. Table 1). The availability of structural elements such as columns and beams as well as a connected inner and outer structure of the building is a further pre-condition for building stability and therefore set as threshold value for further decision tree analysis. Roof colour as an obvious and easily derived parameter from remote sensing was also part of the in situ data collection; however, the high variability of roof colours does not enable any correlation to the stability of the structures (Taubenböck 2011). Thus, the weighting factor is 0.

3.2.2 Tsunami components

After being hit by an earthquake, buildings may face a second hit by the strength of a tsunami wave. Buildings that are expected to be still standing after the earthquake are taken into consideration during the analysis of tsunami-related components. Tsunami-related factors causing damage to buildings are manifold and cannot be quantified easily. According to several post-tsunami observations, the level of building damage is clearly linked to the inundation height and flow velocity of the affected area and the type of the observed buildings (Gauraz et al. 2009). Further factors affecting the damage level are the impact of debris, the proximity of buildings to the shoreline, hydrodynamic forces, total number of waves, backwash events and flood duration. As very few of these factors can be easily assessed, a reductive approach considering the measurable dimension of the tsunami (also with regard to available remote sensing techniques) is recommended (Tinti et al. 2011). Identified parameters are listed in Table 2.

Building shape and building orientation are crucial parameters when looking at the tsunami run-up energy impact and water pressure. Building shapes can generally be categorized into simple, multi-part and long-span geometry. Buildings with simple geometry accumulate less run-up energy compared to buildings with long-span geometry and multi-part constructions, and irregular building shapes may induce undesirable forces, such as torsion in structural elements (Pimanmas et al. 2010).

The effect of building orientation on tsunami impact energy is concluded by several post-tsunami damage assessments as building mass orientation clearly influences the building resistance against tsunami (Dominey-Howes and Papathoma 2007; Budiarjo 2006). While long-span buildings with a perpendicular orientation to wave direction are less vulnerable to the wave impact, a parallel orientation has a converse effect.

3.2.3 Accessibility parameters

Buildings identified as resistant to earthquake and tsunami impact will be further investigated regarding its suitability as vertical evacuation shelters. Access ways to buildings should be free of any obstructions, access ways between floors inside the building have to be wide enough, and steep steps have to be avoided (Pimanmas et al. 2010). Furthermore, minimum requirements concerning evacuation space and facilities for short-term evacuation, based on international standards (e.g. FEMA P646 2008), have to be considered. Respective parameters are listed in Table 3.

3.2.4 Scoring method

A scoring method was employed by using a simple tabular operation and multiplying scores and weights. A score indicates the quality of a particular building property, while a certain weight indicates the significance of this parameter. Threshold score values were defined based on expert judgment defining minimum requirements for each classification category. After determining all parameter scores and weights, the tabular operation follows the decision tree steps to calculate a total score of each sample building component. Buildings with scores under the structural component threshold were grouped into Class A and not considered in the next step of calculation. Buildings with scores over the structural

Table 2 Building vulnerability parameters related to tsunami impact

No.	Parameter	Threshold	Weighting
1	Building shape	Multi-part (complex)	16
2	Building orientation	Diagonal to wave direction	25

Table 3 Building accessibility parameters

No.	Parameter	Threshold	Weighting
1	Width of main access	3–5 m	11
2	Accessibility to the building	2 direction	11
3	Tsunami evacuation plan	Available	5
4	Space for tsunami evacuation	Available	22
5	Floor level for tsunami evacuation	2	22
6	Access to evacuation floor	Stairs	22

Table 4 Building vulnerability classes and respective properties

Building class	Building properties
A	Buildings not fulfilling minimum structural stability requirements (see Table 1) to resist earthquake impact. These buildings will most probably collapse during a stronger (tsunamigenic) earthquake
B	Buildings fulfilling minimum structural stability requirements (see Table 1) to resist earthquake impact, but potentially not withstanding a subsequent tsunami impact. Due to an adverse geometry and orientation to the coast (see Table 2), these buildings will most probably not withstand tsunami wave impact
C	Buildings fulfilling minimum structural stability requirements (see Table 1) to withstand earthquake and tsunami impact (see Table 2), but not fulfilling accessibility criteria (see Table 3) enabling the use as vertical evacuation building. Robust buildings but bad accessibility during an evacuation situation
VE	Buildings fulfilling all structural stability requirements and characteristics to withstand earthquake and tsunami impact (see Tables 1, 2) and to enable vertical evacuation during a tsunami disaster (see Table 3). These buildings can officially be designated as vertical evacuation buildings (VE)

component threshold were further included in the assessment according to the decision logic (Fig. 2). Table 4 gives an overview of all identified vulnerability classes and the respective properties.

3.3 Urban parameters derived from remote sensing

3.3.1 Image analysis

An urban land cover classification derived from a high-resolution QuickBird image provides area-wide and up-to-date knowledge on the environment. A multi-level classification algorithm was performed to extract non-building objects such as water, vegetation types, shadow and ground. Remaining objects were regarded as building objects. In order to get individual building attributes, buildings were separated based on roof colour. To ensure correct identification of building edges and different roof colours, a multi-level image segmentation process was required. The whole process chain is shown in Fig. 3.

Due to the complexity of the study area's cityscape (i.e. high building density, heterogeneous roof colours at a single building, low contrast of buildings and surrounding objects), an integrative analysis approach was required. Image filtering was performed to provide better image pre-conditions for the following segmentation process, especially for edge detection. Separability analysis was conducted to identify object feature characteristics using a statistical approach based on training objects. Comprehensive threshold definition for object classification based on feature range updaters was necessary to face the complex urban structure of Cilacap. Finally, a fuzzy logic algorithm was employed to identify membership values and to ensure definite classification results.

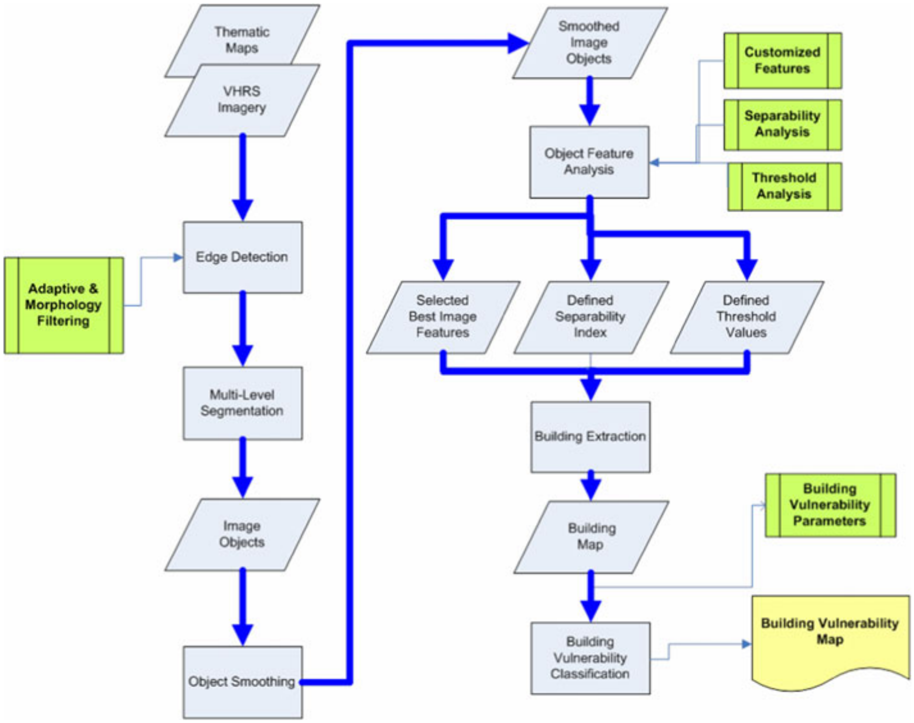

Fig. 3 *Flow chart* of the building extraction algorithm (Sumaryono 2010)

To evaluate the quality of the building detection analysis, an accuracy assessment using an error matrix was performed comparing the classification results, gained by object-based image analysis, with a reference map, generated by manual digitization of building samples.

3.3.2 Building vulnerability classification

Statistical analysis was carried out to investigate spatial key parameters of in situ assessment that are suitable for remote sensing analysis and, thus, able to “explain” building vulnerability to earthquake and tsunami hazard. Thus, these parameters can be regarded as connectors of in situ and remote sensing assessment as ideally buildings are classified identically by both methods. Selected building characteristics with a decisive influence on building vulnerability (based on survey results) and high potential for extrapolation with remote sensing data are explained in Table 5.

4 Results

4.1 In situ building assessment

Class A buildings cover the biggest part of Cilacap (63 %), followed by Class C (28 %), Class VE (6 %) and Class B (3 %). Class A is regarded as the most vulnerable building

Table 5 Building characteristics derived from remote sensing

Building size	Boxplot statistical analysis of in situ assessment results showed that most small building samples in the study area were classified as unstable buildings; larger buildings were mostly classified as stable
Building shape	Building shape was selected as indicator for tsunami resistance by differentiating between simple and long-span (long rectangular) buildings. The impact of direct mechanical actions like water pressure or debris is strongly dependent on the respective contact surface
Building orientation	The orientation of the main wall of buildings relative to the direction of the tsunami flow is a further indicator for tsunami resistance. The parameter was calculated by using the main direction value of the object feature
Building regularity	Structural regularity (e.g. structural simplicity, uniformity, symmetry, redundancy) has great influence on the seismic behaviour of a building. This parameter was derived from the elliptic fit feature object. First step is the calculation of an ellipse considering the proportion of the objects length and width. In a second step, the area inside and outside the ellipse is compared in order to allocate 0 (no fit) and 1(completely fitting) values
Building height	Height information was mainly used to calculate the building volume and to identify buildings with more than one storey in order to extract potential shelters for vertical evacuation. Elevation data were derived from airborne radar with 5-m resolution
Building accessibility	Building accessibility was measured using the distance of a building from the road. This parameter was applied specifically to identify buildings which might be used for vertical evacuation. Potential shelter buildings should be located close to the road network so that they can be easily accessed by evacuees

class; Class VE is the most stable building class and potentially suited for use as vertical evacuation sites. Thus, results of the civil engineering assessment indicate a high building vulnerability to earthquake and tsunami hazard in Cilacap. Statistical analysis was carried out to upscale field measurement results to the remote sensing approach in order to detect potential correlations between detailed assessment results and obvious building characteristics (e.g. shape, orientation, size) detectable by remote sensing techniques. Figure 4 depicts the results of a boxplot analysis of both building size (left) and height (right) and related building vulnerability classes.

Though no clear correlation between Class B, C and VE buildings and the building size is visible, it is obvious that mostly small buildings were classified as Class A. The analysis with building height (right) demonstrates that most Class VE buildings are higher than the other classes, and in contrast, Class A buildings are mostly smaller than others.

4.2 Remote sensing building assessment

Accuracy of the object-based image analysis was assessed by a manually digitized building reference map with 520 sample buildings. Comparison showed an accuracy of 84 %. Quality of the building vulnerability classification was also stated by an accuracy assessment. A confusion matrix was carried out comparing the classification results of the in-situ and remote sensing assessment of building stability. Table 6 shows the calculation of the error matrix resulting in an overall accuracy of about 81 %. Additionally, the table shows various values of commission and omission errors in each class, indicating incorrect classifications. Commission error means that, for example, in the remote sensing analysis, 7.56 % of buildings from other classes are classified as Class A. Omission error means that, for example, 10.29 % of the Class A buildings, identified by in situ assessment, were classified as other classes by the remote sensing analysis.

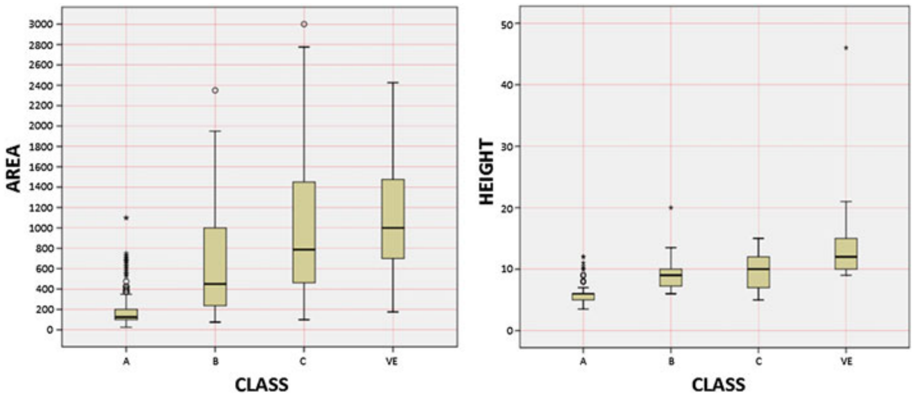

Fig. 4 Boxplot analysis of building size (*left*) and height (*right*) related to particular building vulnerability classes

Major findings of the particular classes are described in the following:

4.2.1 Building Class A

Class A is regarded as the most vulnerable class since buildings most likely will collapse or seriously be damaged during an earthquake. Table 6 shows that the error values for this class are low, which means that most of the Class A buildings, based on the in situ assessment, were also put in Class A of the remote sensing assessment. Boxplot analysis, quantifying the explanatory content of certain building parameters, showed that most of Class A building samples consist of small buildings, related to the building area. Survey results confirmed this impression, as most of the small buildings were dominated by structural instabilities. Hence, building size can be regarded as parameter with a good explanatory value for highly vulnerable buildings in the study area.

4.2.2 Building Class B

Class B includes buildings that will most probably fulfil the structural requirements to withstand a seismic impact, but which are also characterized by low tsunami resistance related to building orientation and geometry. Table 6 shows high omission and low commission errors, which indicates that a larger number of Class B buildings identified by the

Table 6 Error matrix of building vulnerability classification

Reference	Classified					
	Class A	Class B	Class C	Class VE	Row total	Omission
Class A	61	0	6	1	68	10.29
Class B	1	6	1	1	9	33.33
Class C	4	1	24	7	36	33.33
Class VE	0	0	2	14	16	12.50
Column total	66	7	33	23	129	
Commission	7.56	14.29	27.27	39.13	Overall accuracy	81.39

in-situ assessment are classified into other classes. Main source of this inaccuracy is difficulty with the detection of the building geometry (shape), especially in very dense urban areas. Despite a multi-level image segmentation process for separating buildings from each other, some building blocks could not be dissolved appropriately. The main segmentation parameter roof colour and building edges reached their limits in building blocks where building edges were not defined sharply enough and roof colours could not be differentiated. Therefore, building geometry could not be identified properly, resulting in some buildings being wrongly classified due to the high correlation between small buildings and buildings of class A. However, building orientation could be detected properly.

4.2.3 Building Class C and VE

Class C and Class VE buildings are structurally equal. Both classes are regarded as buildings with low vulnerability to earthquake and tsunami hazard, as they are relatively large in size and non-long-rectangular as well as situated perpendicular to flow direction. Of all accessibility parameters, building height or the number of storeys is the most important indicator to differentiate between Class C and Class VE. For the purpose of tsunami evacuation, buildings should have more than 1 storey in order to ensure that potential evacuation space will not be inundated by tsunami waves. For the remote sensing assessment, building height was used as proxy parameter to permit conclusions on the number of storeys. Table 6 shows high omission and commission errors for both Class C and VE. Those errors can be explained as follows:

1. The different resolution of the QuickBird satellite imagery (2.4 m) and elevation data (5 m) in combination with image segmentation problems was influencing the accuracy of height information and, thus, the classification result. Due to the coarser resolution of the elevation data, height information in hard dissolvable building blocks (*cf. Building Class B*) was often both under- and overestimated. As height information was mainly used for the differentiation between Class A/B and Class C/VE buildings, wrong height values led to a strong dispersion of omission and commission errors over all classes.
2. Tall single-storey buildings were classified as multi-storey buildings due to the height information. As buildings with more than one storey are usually higher than single-storey buildings, the parameter building height was seen as a suitable proxy value for the number of storeys. However, in some cases, tall, single-storey buildings, such as factories or warehouses, were wrongly classified as Class VE instead of Class C. This led to an omission error of over 33 %.

Presented results show that significant correlations between in situ measurements and remote sensing techniques are identified. Connective spatial key parameter can be used for an integrated approach enabling an area-wide building vulnerability assessment with a satisfying accuracy. Error sources are in large parts based on the information value of the connecting spatial key parameters (e.g. building geometry, height), which was expected. However, only an integrated approach of both methods allows local authorities to enhance disaster mitigation measures for coastal areas of high earthquake and tsunami risk as it is described in the following chapter.

4.3 Support to disaster mitigation

The integrated assessment of building vulnerability contributes significantly to local disaster mitigation measures. Especially in complex, fast-changing and small-scale urban environments, the identification and localization of vulnerable as well as stable structures are the basic elements to implement mitigation strategies and to reduce vulnerability (Taubenböck 2011). In order to ensure effective (in terms of time and cost) measurements, mitigation strategies have to be focused on areas of high and very high earthquake and tsunami risk.

In Cilacap, various earthquake and tsunami risk products (e.g. hazard and population exposure maps) are available to identify areas of a certain risk category, focusing on potential human losses. By combining the gained results of the building assessment with available risk and in particular with hazard information, more detailed risk analysis is feasible. The identification of integrated risk pattern considering hazard, population and building vulnerability information enables local authorities to better prioritize mitigation measures. For example, areas with a high potential to be affected by earthquake and tsunami impact (based on hazard maps) and showing a high population density will be identified as high risk areas. Depending on building vulnerability information, these areas can be further downscaled and considered for adjusted and cost-efficient mitigation measures, for example, by

1. focused building reinforcement and use regulation measures for Class A and B building blocks
2. further investigation and identification of vertical evacuation shelters in areas with a certain amount of Class C and VE buildings
3. special evacuation planning procedures like horizontal evacuation options for areas dominated by Class A and B building or combined horizontal and vertical evacuation options for areas with more C and VE buildings
4. enabling important contribution for selective land use planning (e.g. building codes and zoning)

5 Discussion

Following the methodological approach of the applied analysis, the synergistic use of remote sensing and civil engineering enables the rapid identification of both highly vulnerable and potential evacuation buildings as the accuracy assessment shows satisfying results. The question is whether and to what extent gained research findings can be extrapolated in order to enable an area-wide identification of building vulnerability classes. The partly high omission and commission errors in Table 6 already indicate the difficulty to define precise rule sets and thresholds enabling more general statements regarding the vulnerability of individual buildings. However, based on this analysis and further studies, some basic correlations can be stated:

These building characteristics can be detected by remote sensing techniques and therefore allow an initial evaluation of building vulnerability in areas prone to earthquake and tsunami hazard. Furthermore, the amount of buildings to be surveyed for a final official designation as vertical evacuation shelter can be significantly reduced to a feasible number. Therefore, disaster mitigation measures for Cilacap as stated in Chapter 4.3 are seen to be transferable as the gained basic correlations in Table 7 enable further specifications of available risk products in order to improve local disaster mitigation.

The applied methodology has proven to be reliable. Limitations are seen in the lack of liquefaction data for the study area and the allocation of weighting factors for building parameters. The influence of liquefaction to the seismic behaviour of buildings is well

Table 7 Basic correlations of the integrated building vulnerability assessment

1	Smaller buildings show an above-average amount of structural deficiencies and thus a high vulnerability
2	Buildings with a higher stability (vulnerability value) predominantly show a higher building volume (Taubenböck 2011)
3	Building location and orientation significantly influence the building resistance against a tsunami (cf. Table 2 and Budiarjo 2006)
4	Building shape influences tsunami impact (cf. Table 2) and might be an indicator for seismic behaviour (Pimanmas et al. 2010)
5	Building height and surroundings are decisive parameter for potential vertical evacuation buildings

documented by a variety of studies (e.g. EERI 1994; Bird et al. 2006). Seismic waves, primarily shear waves, destroying soil granular structures and increasing poor-water pressure may cause soil deformations that are large enough to cause damage to buildings. If available, this parameter could be implemented in the methodological framework (Fig. 2) following the same decision logic. Thus, the analysis of liquefaction conditions would be further prerequisite for the identification of VE buildings.

Weighting values are based on expert judgment in the course of the building survey and therefore based on own estimations. It would be very desirable to provide a more solid basis for this method and thus establish proved standards (building vulnerability codes). Therefore, further research is needed. Current activities within the GEM (Global Earthquake Model 2012) project seem to be promising to make some progress in this field (Bevington et al. 2011).

Transferability of the methodology to other areas was tested for another coastal city with different conditions (higher building density, different traditional building characteristics). Except for some minor adoptions on the rule set of the object-based image analysis, the approach could be successfully transferred. Major adaption problems arose due to different spectral characteristics of roof colours as the used roof material in the study area was mainly ceramic and in the test area mainly metal (zinc). Transferability to other countries, especially outside of South Asia, will most probable lead to major difficulties due to different building types and structures (e.g. building codes). Thus, particular analysis steps, especially the vulnerability classification using remote sensing techniques, have to be adapted.

6 Conclusions

The main objective of this study was to develop a feasible conceptual and methodological approach to identify building vulnerability to earthquake and tsunami hazard considering both civil engineering and remote sensing methods. The combination of both research disciplines aims to overcome the shortcomings of individual approaches in order to face the rapid development in local economic activities with its related fast growing population and urban sprawl prone to analysed hazard types.

As a consequence, efficient and fast techniques for mapping and analysing these developments are needed, and research focus has to be shifted from post-disaster reaction to pre-disaster mitigation strategies.

Research questions addressed in Chapter 1 aimed at describing a methodological framework quantifying building vulnerability to earthquake and tsunami hazard. Obtained results are satisfactory as most of the research questions could be answered successfully as summarized in the following.

Based on a detailed field survey assessment, main building characteristics influencing seismic and tsunami impact could be identified. According to the developed decision tree logic, buildings were classified with respect to its vulnerability. Statistical analysis was conducted in order to detect potential correlations between detailed civil engineering assessment results and obvious building characteristics (e.g. shape, orientation, size) detectable by remote sensing techniques. Object-based image analysis was used to extract information on building objects from high-resolution satellite imagery, and building characteristics visible from a top-view were analysed concerning its explanatory content for building vulnerability. An accuracy assessment showed satisfying results as a good correlation between the survey and remote sensing assessment could be achieved. Therefore, the first three research questions, addressed to develop a coherent model quantifying building vulnerability, could be answered. As a major result, potential vertical evacuation buildings with low vulnerability and good accessibility could be identified. Naturally, this method does not allow precise and undeniable statements about building vulnerability, but still enables planning authorities to conceive a geographical magnitude order indicating the need of selected measures. The implementation of the obtained research findings in a transferable and robust methodological concept, as addressed in the last research question, could not be achieved completely. Transferability to similar coastal areas showed satisfactory results, though single-analysis steps had to be adapted. A flexible model composition including a more complex decision logic considering international building codes and detailed spectral characteristics would tackle the problem.

Future remote sensing developments will allow an improved application of this method as a better spatial resolution of satellite imagery will significantly reduce potential error sources. Biggest benefits of the research are seen on the one hand in the consideration of seismic and tsunami hazard dependencies allowing a more comprehensive view on feasible building impact. On the other hand, gained results based on an integrated approach have a great potential to contribute significantly to local disaster mitigation planning as stated in Chapter 4.3.

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