Nat Hazards (2016) 83:1229–1256
DOI 10.1007/s11069-016-2387-9

ORIGINAL PAPER

Revision and improvement of the *PTVA*-3 model for assessing tsunami building vulnerability using "international expert judgment": introducing the *PTVA*-4 model

F. Dall'Osso[1,4] · D. Dominey-Howes[1] · C. Tarbotton[2] · S. Summerhayes[3] · G. Withycombe[3]

Received: 9 May 2015 / Accepted: 18 May 2016 / Published online: 3 June 2016

Abstract This work reviewed, assessed, enhanced and field-tested one of the most widely used index-based methods for assessing the vulnerability of buildings to tsunamis: the Papathoma Tsunami Vulnerability Assessment (*PTVA*) model. The review and assessment were undertaken through a participatory survey process engaging authors of scientific literature during 2005–2015 in the field of building vulnerability to tsunamis. Expert respondents updated the weights of the *PTVA* building vulnerability attributes based on their expertise and insights from the 2011 Tohoku Tsunami. The respondents were also free to suggest additional *PTVA* building attributes and to provide open comments on the model. We then analysed the outcomes of the questionnaire and we used them to generate a new improved version of the model, the *PTVA*-4, which we field-tested in the area of Botany Bay (Sydney), New South Wales. Using a cohort of over 2000 buildings and a tsunami scenario numerically simulated using state-of-the-art hydrodynamic modelling techniques, we applied the *PTVA*-4 model and compared the outcomes against its predecessor (i.e. the *PTVA*-3). Results showed the *PTVA*-4 model is significantly more accurate and more sensitive to variations in the tsunami demand parameter, the attributes of the exposed buildings and their surroundings. The *PTVA*-4 model is the first tool of its kind to integrate the judgment of specialised scientists worldwide. It constitutes a viable option to

Electronic supplementary material The online version of this article (doi:10.1007/s11069-016-2387-9) contains supplementary material, which is available to authorized users.

✉ F. Dall'Osso
filippodallosso@gmail.com

✉ D. Dominey-Howes
dale.dominey-howes@sydney.edu.au

1 Asia–Pacific Natural Hazards and Disaster Risk Research Group, School of Geosciences, The University of Sydney, Sydney, NSW 2006, Australia

2 Asia–Pacific Tsunami Research Lab, University of New South Wales, Sydney, Australia

3 Sydney Coastal Councils Group Inc., Sydney, Australia

4 Molino Stewart Pty Ltd, Suite 3, Level 1 20 Wentworth St, Parramatta, NSW 2150, Australia

assess the vulnerability of buildings in areas where no tsunami vulnerability curves have been developed yet, or to consider the contribution to vulnerability given by a significantly wider range of building engineering and physical attributes. An ArcGIS toolbox that automatically calculates the relative vulnerability of buildings using the new *PTVA-4* model is attached to this paper.

Keywords Tsunami vulnerability · PTVA model · Building vulnerability · Fragility curves · Catastrophe modelling

1 Introduction

In the last decade, 21 tsunamis with a run-up larger than 3 m have occurred globally, causing a total damage to buildings and infrastructure exceeding $US260 billion (NGDC/WDS 2014) (Table 1). In most instances, the likely impact on coastal assets was unknown.

The capability of a building to withstand the impact of a tsunami depends on a variety of factors, including structural elements, construction material, foundation type, the design of the ground floor, the building orientation and the building's surroundings (IOC UNESCO 2011). These factors or "attributes" may coexist in numerous possible forms and combinations, making the assessment of vulnerability a building-by-building exercise. Vulnerability assessment is further complicated by the relatively low number of tsunami damage data and the wide variety of construction techniques adopted throughout the world (Tarbotton et al. 2015).

Before the 2004 Indian Ocean Tsunami, only one building vulnerability assessment tool was available, the Papathoma Tsunami Vulnerability Assessment (*PTVA*) model (Papathoma 2003). The *PTVA* model is an index-based tool offering a Geographic Information System (*GIS*) framework to weight and combine the contributions from various building physical and engineering attributes to the total building vulnerability level. The attributes used by the model have repeatedly proved to influence the damage level during a tsunami inundation (IOC UNESCO 2011).

The relative vulnerability level of a building is ultimately described through a non-dimensional score, named the Relative Vulnerability Index (*RVI*).

After the first version of the *PTVA* model was developed in 2003, the tool was successfully applied in many regions of the world, including Greece (Papathoma et al. 2003), the Republic of the Maldives (Dominey-Howes and Papathoma 2007), United States (Dominey-Howes et al. 2009), Australia (Dall'Osso et al. 2009a, b), Italy (Dall'Osso et al. 2010), and Japan (Voulgaris and Murayama 2014). Using post-tsunami damage observations following the 2004 Indian Ocean Tsunami (2004 IOT) in the Maldives, Papathoma and Dominey-Howes and Papathoma (2007) field-tested the model and addressed some of the shortcomings of the original version (e.g. introducing new building attributes to be considered by the model), which led to a second generation of the model (*PTVA*-2). The most recent version of the model, version 3, was developed by Dall'Osso et al. (2009a, b) in Australia, then validated in Italy (Dall'Osso et al. 2010) by comparing the model outputs with the damage actually sustained during the 2002 Stromboli tsunami. The work by Dall'Osso et al. (2010) was the first validation of the *PTVA* model, which proved to be fairly accurate in predicting the relative damage to different building types in response to a given tsunami inundation depth (Tarbotton et al. 2012). A review of the evolution of the

Table 1 Tsunamis occurred in the last decade (2004–2014) with run-up exceeding 3 m above mean sea level (after the NOAA National Geophysical Data Center)

Source location	Date (yy/mm/dd)	Tsunami source	Earthquake magnitude	Max run-up (m)	Deaths	Damage (million $)
West Sumatra (Indonesia)	2004/12/26	Earthquake	9.1	50.9	226,898	10,000
Indonesia	2005/3/28	Earthquake	8.7	4.20	10	N/A
Columbia River, WA USA	2006/1/16	Landslide	–	9.0	N/A	N/A
Seram Island (Indonesia)	2006/3/14	Earthquake	6.7	3.5	4	N/A
Java (Indonesia)	2006/7/17	Earthquake	7.7	20.9	802	55
Kuril Islands (Russia)	2006/11/15	Earthquake	8.3	21.9	N/A	N/A
Solomon Islands	2007/4/1	Earthquake	8.1	12.1	52	N/A
Southern Chile	2007/4/21	Earthquake and landslide	6.2	7.6	N/A	N/A
Peru	2007/8/15	Earthquake	8.0	10.05	3	N/A
Sumatra	2007/9/12	Earthquake	8.4	5.00	N/A	N/A
Honduras	2009/5/28	Earthquake	7.3	4.00	N/A	N/A
Samoa Islands (Samoa)	2009/9/29	Earthquake	8.0	22.35	192	275
Solomon Islands	2010/1/3	Earthquake	7.1	3.0	N/A	N/A
Haiti	2010/1/12	Earthquake	7.0	3.0	7	N/A
Central Coast (Chile)	2010/2/27	Earthquake	8.8	29	156	30,000
513 Lake (Peru)	2010/4/13	Landslide	–	23.0	1	N/A
Sumatra (Indonesia)	2010/8/25	Earthquake	7.8	7	431	39
Honshu Island (Japan)	2011/3/11	Earthquake	9.0	38.9	15,854	210,000
British Columbia (Canada)	2012/10/28	Earthquake	7.7	12.98	1	N/A
Solomon Islands	2013/6/2	Earthquake	7.9	N/A	10	N/A
Northern Chile	2014/4/1	Earthquake	8.2	4.4	N/A	N/A

PTVA model is provided by Tarbotton et al. (2012) and compared against similar index-based approaches to assess building vulnerability to tsunamis (e.g. Omira et al. 2009). In addition to assessing the vulnerability of buildings, the *PTVA*-3 model has been used to create evacuation maps and underpin emergency management strategies (Dall'Osso and Dominey-Howes 2010a, b). More recently, Voulgaris and Murayama (2014) coupled the *PTVA*-3 model with a building population estimation tool, in order to investigate the distribution of residents in each building vulnerability class.

Index-based methods such as the *PTVA* model incorporate many idealised structural attributes in the calculation of the total vulnerability of a building. This allows the differences between different building structures to be determined to a fine scale. However, index-based methods are relative, so the final vulnerability scores (e.g. the *RVI* scores) have no stand-alone meaning and are useful in comparisons of the expected performance of different buildings (e.g. building A is more/less vulnerable than building B), rather than to predict the absolute level of damage that a single building will incur in response to a given tsunami flow depth (e.g. building A will collapse when the tsunami flow depth exceeds 3 m).

1.1 Absolute methods: fragility curves

A non-relative approach for predicting building damage can be achieved via the use of vulnerability functions, or fragility curves. These are statistically developed continuous curves that associate the intensity of the tsunami (i.e. the tsunami "demand parameter") to the expected response of a particular building type. Although this approach is widely used for other hazards (i.e. earthquakes, floods), no tsunami vulnerability functions were available in English when the *PTVA* model was first developed, although we note that some works on fragility curves had already been undertaken in Japanese (Shuto 1987; Aketa et al. 1994). The first studies (in English) proposing tsunami vulnerability functions were published after the 2004 IOT, and to date about 15 sets of functions have been developed in different parts of the world. Tarbotton et al. (2015) undertook a comprehensive review and comparison of the existing empirical tsunami vulnerability curves for different building types.

Tsunami vulnerability functions have been developed using a variety of techniques. Some describe the building damage "deterministically" (e.g. using the ratio "cost to repair/cost to replace" to identify the damage level corresponding to a given the tsunami demand parameter) (Valencia et al. 2011; Reese et al. 2007), whilst others adopted a probabilistic approach estimating the conditional probability that a given building type will reach or exceed a specific damage state (Charvet et al. 2014; Suppasri et al. 2013a, b; Suppasri et al. 2012; Reese et al. 2011; Suppasri et al. 2011; Koshimura et al. 2009). Most of these curves are empirical (i.e. based on observations after the actual tsunamis), but some studies employed analytical techniques (i.e. referred to a theoretical building prototype, whose damage-state equation is solved for various tsunami loads) (Nadal et al. 2010; Dias et al. 2009).

Most of the available functions have adopted the maximum tsunami flow depth as the tsunami demand parameter, assuming that this is the main driver of building damage, although some recent work has looked also at the effect of debris trapped in the tsunami flow (Muhari et al. 2015). In terms of the engineering attributes influencing the vulnerability to tsunamis, almost all the existing vulnerability functions considered only the construction material, and only recently Suppasri et al. (2013b) added the number of stories. To date, no other building engineering attributes have been considered when

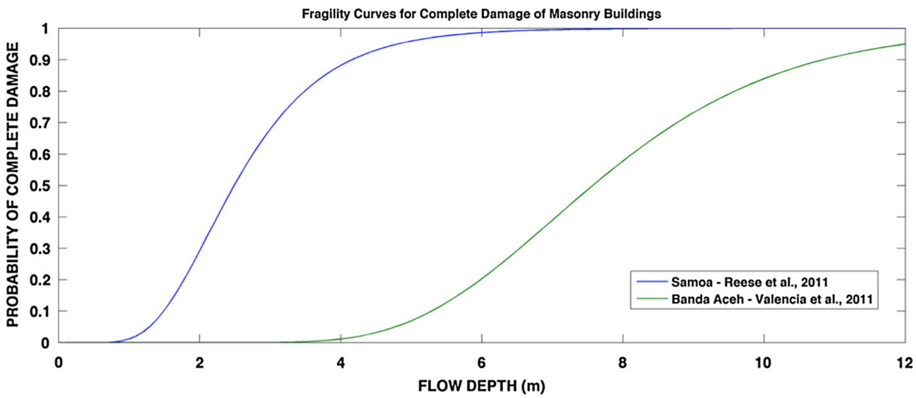


Fig. 1 Example of fragility curves for residential masonry buildings developed in Samoa after the 2009 tsunami (Reese et al. 2011) and in Banda Aceh, Indonesia, after the 2004 IOT (Valencia et al. 2011). The curves express the probability of collapse at different tsunami flow depths. Although the building type is described in a similar way by the authors (i.e. residential masonry buildings for Reese et al. 2011, and one storey masonry building for Valencia et al. 2011), the resulting curves are different

developing vulnerability functions and this stands as a significant limitation of absolute methods. In addition to this issue, the variety of techniques employed (and assumptions made) to develop tsunami vulnerability functions renders the existing curves hard to compare and difficult to apply in locations different from where they were developed (Tarbotton et al. 2015).

By way of example, in the case of empirical approaches, the curve of a masonry building developed in Samoa may differ significantly from that of a masonry building in Indonesia (Fig. 1). This may be due to different building standards, survey techniques or statistical analyses adopted by researchers (Tarbotton et al. 2015; Gardi et al. 2011; Schultz et al. 2010). As a consequence, index-based methods such as the *PTVA* model can be useful where no vulnerability curves are available, or to compare the expected performance of different building types by considering their main engineering and physical attributes.

1.2 Limitations of the PTVA-3 model and development of the PTVA-4 model

The main limitations of the *PTVA*-3 model are:

1. The PTVA-3 does not account for the new data obtained after the 2011 Tohoku tsunami (it was developed before 2011).
2. *RVI* scores are calculated as a weighted sum of the contributions made by different engineering attributes. Weights were obtained through a multi-criteria analysis undertaken by Dall'Osso and Dominey-Howes (Dall'Osso et al. 2009a). After publication, it was suggested that the model could be improved by increasing the expert input in the determination of the weights attributed to building attributes.

We addressed the limitations of the *PTVA*-3 model by developing a survey utilising a self-administered coded questionnaire of 16 questions (open and closed). The questionnaire was distributed to all the corresponding authors of scientific papers published in the last 10 years (2005–2015) in the field of building vulnerability to tsunamis. Specifically, the questionnaire asked each author to re-weight the attributes of the *PTVA*-3 model and to incorporate information from the 2011 Tohoku Tsunami. The results were evaluated and utilised to upgrade the *PTVA*-3 to a new improved version of the model: the *PTVA*-4. A copy of the questionnaire is attached to this paper in the original MS Excel format.

This paper includes the presentation of the questionnaire (Sect. 2), a description of the questionnaire outcomes (Sect. 3), the application of results to generate the new *PTVA*-4 model (Sect. 4), and a case study in which we demonstrate the differences between the *PTVA*-3 model and the *PTVA*-4 in a real-world application (Sect. 5).

2 Methodology: the questionnaire

The questionnaire included two main sections. The first asked respondents to suggest alternative weights for the *PTVA*-3 model attributes, based upon their expertise and including information they may possess from recent tsunami events, particularly the 2011 Tohoku event. Using the same approach as the *PTVA*-3, the attributes to be weighted were divided in two groups: those influencing the building structural vulnerability (e.g. material, number of stories, foundations), and those describing the degree of shielding/protection provided to the building by its surroundings (e.g. natural barriers, building row, seawall). For a comprehensive description of the *PTVA*-3 model, including the attributes and the weighting system, readers are referred to Dall'Osso et al. (2009a).

The respondents were also free to suggest (and weight) any additional attributes not originally included in the *PTVA*-3 model.

The second section of the questionnaire provided a blank space for open comments regarding the model or explaining the suggested weight changes or additional attributes. This section allowed respondents to fully contribute to the development of the new iteration of the model (Bird 2009). The original version of the questionnaire is attached to this paper (Online Resource 1).

We sent the survey electronically to 30 primary and/or corresponding authors of scientific papers in the field of vulnerability of buildings to tsunamis published from year 2005 to 2015. The selected time span covered all the publications generated after the 2004 Indian Ocean Tsunami, when the attention of the scientific community in regard to building vulnerability assessment significantly rose. The response rate to the survey was 47 % (14 responses).

3 Results and discussion

The results of the questionnaire survey included: (a) new weights for the existing *PTVA*-3 model building attributes (Sect. 3.1, Tables 2, 3); (b) open comment fields addressing the rationales supporting the proposed weights (Sect. 3.2, Table 4); (c) suggestions for additional attributes to be considered (Sect. 3.3, Table 5); (d) additional comments/questions about the *PTVA* model (Sect. 3.4).

3.1 New weights for the existing PTVA-3 model attributes

We obtained the new weights to be implemented in the *PTVA*-4 model by calculating the average value of the weights suggested by the respondents. According to Forman and Peniwati (1998), the mathematical mean is the best method for aggregating quantitative judgments in an Analytic Hierarchy Process framework when contributors have different value systems. Results are shown in Tables 2 and 3.

Table 2 Original weights to the building vulnerability attributes of the PTVA-3 Model given by Dall'Osso et al. (2009a), compared to the average weights suggested by the international experts who completed the questionnaire described in Sect. 2

Attributes of the building	Original weight (*PTVA*-3) (0–100)	Average suggested weight (0–100)
Number of stories (*s*)	100	85
Main construction material (*m*)	80	100
Ground floor hydrodynamics (*g*)	63	69
Foundation type (*f*)	60	69
Shape and orientation (*so*)	46	52
Preservation condition (*pc*)	23	34

Table 3 Original *PTVA*-3 model weights to the attributes influencing the degree of protection provided to a building by its surroundings (Dall'Osso et al. 2009a), compared to the average weights suggested by the international experts who completed the questionnaire described in Sect. 2

Attributes of building surroundings	Original Weight (*PTVA*-3) (0–100)	Average Suggested Weight (0–100)
building row (*br*)	100	100
seawall (*sw*)	73	84
natural barriers (*nb*)	73	72
large movable objects (*mo*)	51	58
brick wall around the building (*w*)	55	42

Thirteen of the 14 respondents agreed on the need to retain all the existing *PTVA*-3 model attributes to fully determine the overall vulnerability of buildings (only one respondent suggested that the "preservation condition"—i.e. the state of preservation of the building structure—would not affect its overall vulnerability). This finding may partially explain the variability of available building vulnerability functions for tsunamis, in which buildings are usually grouped by considering only one attribute (i.e. the construction material).

In terms of the specific weights suggested for each attribute, results show a reasonably good degree of consistency between the respondent's opinion and the weights used in the *PTVA*-3 model. The main differences are:

- Respondents considered the construction material to be more important than the number of stories, whereas in the *PTVA*-3 model the number of stories was the most important attribute, and directly ahead of the building material.
- The building preservation condition (*pc*) was weighted higher (i.e. suggested weight = 34, was 23 in the *PTVA*-3 model)
- The foundation type (*f*) was weighted slightly higher (i.e. suggested weight = 69, was 60 in the *PTVA*-3 model)
- The presence and type of a seawall (*sw*) was weighted higher (i.e. suggested weight = 84, was 73 in the *PTVA*-3 model)
- The brick wall around the building (*w*) was given a lower weight (i.e. suggested weight = 42, was 55 in the *PTVA*-3 model)

Table 4 Rationale provided by the respondents to the questionnaire supporting the weights assigned to the building vulnerability attributes and building surroundings attributes

Attribute	Comments about the existing attributes of the *PTVA*-3 model	Authors' response
Number of stories (s)	The number of stories is still probably the dominant factor, because of the weight contribution to stability The number of stories is not quite relevant, tsunami damage was observed up to maximum of 3 stories. Even one or two floor concrete structure has adequate weight to resist water forces Number of stories is an indirect way to take into account the construction material, which in my opinion is the most important attribute influencing the buildings vulnerability	The number of stories is considered as a proxy for the structure weight, not the construction material. During the 2011 Tohoku tsunami the number of stories proved to be directly correlated with the degree of damage, although the construction material was more important (Suppasri et al. 2013b). The new weights of the attributes m (i.e. construction material) and s (i.e. number of stories) are assigned according to the reviewers' preferences and are consistent with observations made during the 2011 Tohoku Tsunami
Shape and orientation (so)	"Shape and orientation" of the building should be assigned an important weight only to buildings in the first row: once the flood is inside the urbanised area, it is too difficult to establish the exact direction of the flow impact (and thus the orientation of the constructions with respect to it) due to interactions with the buildings and to turbulence effects	In the *PTVA*-4 model, the attribute so was renamed as sh (i.e. shape) and it accounts only for the shape of the building footprint. No assumption about the tsunami flow direction is required. For example, L-shaped buildings or narrow and rectangular buildings are considered to be generally more exposed to the flow than buildings that are square or round
Foundations (f)	Deep foundations are very useful, because the only way in which 2 storey buildings collapsed in Sri Lanka is because of scour	Foundations type is considered in the *PTVA*-4 model through the attribute f (i.e. foundations)
Movable objects (mo)	Almost all concrete well-designed structures survived the tsunami forces (except damage due to impact of boats and cars on columns and walls) Large movable objects probably do not cause total collapse I would include the presence of large movable objects (marinas, parking areas, etc.) in the *Prot.* component rather than in the *BV* component (it concerns the surroundings conditions rather than structural vulnerability, even if it will affect the structure) I would suggest that the attribute 'Large Movable Objects' should be in surroundings of buildings (Prot. component)- I do not think this a structural attribute (BV component) in the context of the other attributes given	Although the impact of large movable object may not cause the total collapse of a building alone, it can certainly contribute to the total damage level. In the *PTVA*3- Model, the attribute mo is not included in the component *Prot* (i.e. Protection) as this accounted only for the degree of protection provided to the building by its surroundings. However, we understand the confusion that including mo in the *BV* component may cause, being the movable objects an attribute of the building surroundings. As suggested by the reviewers we have changed the component name *Prot* into *Surr* (i.e. Building Surroundings), and we have included the attribute mo in the *Surr* component

Table 4 continued

Attribute	Comments about the existing attributes of the *PTVA*-3 model	Authors' response
Building row (*br*)	I agree to consider the "building row" as the most important attribute of the building surrounding factor, but it should be kept in mind that in some cases buildings in the second row could incur higher damage due to positive interaction of the waves moving around and adding up behind the first row buildings	We acknowledge this limitation of the *PTVA*-4 model, but specific cases like the one mentioned by the respondent require a level of detail that transcends the scope of the *PTVA* model
Brick wall around the building (*w*)	Boundary walls (i.e. brick walls around the building) may reduce energy but can fall and kill people	We agree with the respondent, however the risk to people is not directly in the scope of the *PTVA* model

The third column includes the authors' response to the rationale provided by the respondents

3.2 Comments about the existing PTVA-3 model attributes

Eight respondents provided additional open comments about the existing *PTVA*-3 model attributes. These are listed in Table 4, divided according to the attribute. Table 4 also includes our responses to each comment. Interestingly, some comments are quite contradictory (see for example the observations about the number of stories, or movable objects in Table 4), which emphasises the need for additional tsunami damage observations, consistent survey techniques and improved communication between researchers.

3.3 Recommendations for additional attributes to be considered

Table 5 shows additional attributes recommended by respondents, their preference ratio (i.e. the percentage of respondents who recommended that attribute) and their comments.

In the following sub-sections, we examine these recommendations and we discuss their implementation in the new version of the model, the *PTVA*-4.

3.3.1 Engineered/not engineered buildings

The distinction between engineered and non-engineered buildings has often been considered an influential proxy for the vulnerability of buildings to tsunami damage (Valencia et al. 2011; Koshimura et al. 2009). Whilst none of the papers dealing with this topic defines the term "engineered", we interpret it as a reference to construction codes and regulations in force at the time of construction or survey.

Since construction codes vary significantly in space (e.g. from state to state) and time, the term "engineered" may have different meanings in different study areas. For example, an engineered building in Samoa may have different structural characteristics from an engineered building in Japan, or even in the same study area, depending on when the survey is undertaken. That is, an "engineered" building today may differ from an "engineered" building tomorrow, if the construction law requirements are modified. Further, "engineered" buildings implementing seismic regulations or other safety standards may not necessarily provide a lower vulnerability to tsunamis.

Table 5 Additional attributes to be considered in the *PTVA* model suggested by the respondents

Suggested additional attribute of buildings	Description/comment provided	Preference ratio (%)
1. Engineered/not engineered building	Of importance is also whether the building was engineered or not and since tsunamis follow earthquakes, the proper seismic design of the structure becomes significant so that structural damage does not occur before the tsunami hits	21
2. Elevation of the ground floor above ground level	Buildings built on raised foundations would have lower 'effective flow depth' acting on the structure	21
3. Coastal morphology (as a proxy of tsunami flow velocity)	During the 2011 Japan tsunami, buildings located in ria-like coastal areas were more severely damaged than similar buildings located in plain coastal areas	14
4. Ground slope (as a proxy of tsunami flow velocity)	Ground slope is also important. There was a major train catastrophe in Sri Lanka where the rail line was at a negative slope to coast	7
5. Width of adjacent roads (as a proxy of the degree of protection provided to the building by its surroundings)	I am thinking on the "width of adjacent roads" as a possible factor that decreases the local hydrodynamic features of tsunami affecting the building making the structure less vulnerable to tsunami according to its location in the row and considering urban layout	7
6. Structure location	Flow velocity in addition to water level	7
7. Proximity to water channels	Proximity to water channels (e.g. canals, rivers) may allow tsunami flow inland and over-bank	7
8. Type of tsunami overland flow (surge vs. turbulent).	A turbulent tsunami flow would cause more damage than a surging tsunami	7
9. Building age	The respondent did not provide comments supporting the inclusion of "building age". However, a different respondent reported that "based on data from fragility curves [obtained after the 2011 Japan tsunami], the construction material is the most important parameter and the construction year (or building age) has no influence at all	7

One of the respondents noted that near-field tsunamis may be preceded by strong earthquakes, which could undermine the stability of some buildings (particularly if not seismically engineered) and increase their vulnerability to the incoming tsunami. This would not happen for mid- and far-field tsunamis (the earthquake epicentre would be too distant from the study area to cause damage), nor it would for tsunamis triggered by underwater landslides and volcanic activity. Beyond this consideration, the *PTVA* model is not a multi-hazard tool and as such it does not account for the damage caused by earthquakes. Comprehensive vulnerability assessments for near-field tsunamis should use the *PTVA* model in combination with seismic fragility curves or other seismic vulnerability tools.

For these reasons, we did not include the "engineered/not engineered" attribute in the *PTVA*-4 model.

3.3.2 Elevation of the ground floor above the ground level

This attribute identified a gap within the *PTVA*-3 model. Whist the *PTVA*-3 accounts for buildings with an open ground floor (used for storage or other non-residential purpose), it does not consider the lower vulnerability of buildings having the ground floor slightly elevated above the terrain level, which is a common artefact to achieve better ground insulation or for protection in flood-prone areas. To address this issue, the *PTVA*-4's component *WV* (i.e. Water Vulnerability, accounting for the damage to building parts due to prolonged contact with water) considers only the "effective" water depth inundating the building—that is only the water depth above the ground floor. This is obtained as the difference between the water depth above the terrain level and the elevation of the building ground floor, which can be measured during field surveys with a ruler, or more simplistically by counting the number of steps to the entrance door, as previously done by Maqsood et al. (2013).

3.3.3 Coastal morphology and ground slope (as a proxy of tsunami flow velocity)

One of the main limitations of the *PTVA*-3 model, as well as of existing tsunami vulnerability functions, is that the tsunami force on the structure—the "demand parameter"—is only measured through the maximum water depth. Although the hydrodynamic force acting on a building depends both on the water depth and on the flow velocity, the latter is very hard to measure or numerically simulate, and it is seldom considered explicitly (Reese et al. 2011). In addition to this approximation, in the *PTVA*-3, the water depth impacting each building is obtained using a simplistic bathtub-filling approach, in which all inland areas having an elevation less than the water level on the shoreline (and being hydraulically connected to it) are considered to be equally inundated. Bathtub-filling methods neglect the hydraulic interactions of the water flow with inland morphology, and how these affect hydraulic storage, connectivity, resistance and ultimately water depth and flow velocity.

In using the *PTVA*-4, we strongly recommend a hazard assessment using a hydrodynamic numerical model which accounts for interactions with local coastal morphology and topography. Tsunami hydrodynamic models such as Method of Splitting Tsunamis (*MOST*) (Titov et al. 2005; Titov and Gonzalez 1997) are open-source, easy to use and have been repeatedly validated (Wei et al. 2013; Synolakis et al. 2007). Whilst these models provide a more accurate estimate of the maximum inundation depth and inundation extent, flow velocity impacting each building is still very challenging to obtain, as it is significantly influenced by local terrain and built environment features whose scale often exceeds the resolution capability of the model (Koshimura et al. 2009). Some of these features are considered in the *PTVA*-3 model through the factor *Prot*, which estimates the shielding effect—resulting in a local decrease of water depth and flow velocity—provided to buildings by their surroundings. *Prot* includes the protection provided by surrounding buildings, vegetation, coastal dunes, seawalls and brick walls around the building. As suggested by 3/14 respondents, other environmental features affecting the tsunami flow depth and velocity impacting buildings include coastal geomorphology (2/14) and ground slope (1/14). The contribution of these features to water depth can be simulated with a reasonable accuracy by numerical models. The same thing cannot presently be said about flow velocity, unless the numerical model results are validated using real-world (on-site) measurements of flow velocity, which could only be achieved if the selected tsunami scenario is the reproduction of an historical event during which flow velocity was measured (Koshimura et al. 2009). It would be therefore reasonable to address the contribution of ground slope and geomorphology to flow velocity though additional attributes of the *PTVA* model, similarly to what has been done for the degree of protection provided to a building by its surroundings. However, in regard to coastal geo morphology, there is currently insufficient evidence to associate different costal morphology to tsunami flow velocity or damage levels. Although during the 2011 Japan Tsunami buildings located in ria-like coasts suffered on average a damage higher than buildings in open plain areas (Suppasri et al. 2013a, b), it is unclear if tsunamis have a more severe impact on buildings in other types of coastal morphologies, such as delta coast, rock coast, estuary coast, etc. Moreover, the effect of ground slope on local flow velocity may vary significantly based on other conditions such as the flow direction, the slope direction and the location of the buildings on the slope (before the crest vs. after the crest). Although in some cases slope can cause an increased flow velocity, in other cases—for example if the flow slows-down when going up-hill—it may provide protection to buildings (Dall'Osso et al. 2010; Reese et al. 2007). Because the relationship between slope and building damage is equivocal, we did not include the ground slope in the *PTVA*-4 model attributes. The contribution of coastal morphology and ground slope to damage will be more easily integrated into the hazard assessment using high-resolution hydrodynamic models able to accurately calculate flow velocity impacting each building, once these are fully validated and available to the wider scientific community.

Other attributes used as proxy for tsunami flow velocity or inundation extent.

These include suggested attributes number 5–8 in Table 5, namely "width of adjacent roads", "structure location", "proximity to water channels", "type of tsunami overland flow (turbulent vs. surge)". These suggested attributes have been grouped together because they better represent the tsunami hazard impact to buildings. These attributes might have been suggested to overcome the use of a simplistic bathtub-filling approach to represent the tsunami hazard in the *PTVA*-3 model. The *PTVA*-4 uses a hydrodynamic model to simulate the inundation process, allowing more accurate estimate of inundation extent and maximum water depth. If very high-resolution hydrodynamic models and *DEMs* are available, such estimates may account for local features such as roads, channels and other buildings.

3.4 Additional comments/questions about the PTVA-3 model framework

This section considers additional open comments, questions and our responses.

Comment #1:

The components *BV* and *Prot.* should range in the same numerical interval as they are obtained through the same procedure of weighted sum.

Authors' response to comment #1:

Note: in the PTVA-3, *BV* ranges between -1 and $+1$, whilst *Prot.* ranges between 0 and $+1$. The *PTVA*-4 uses the same numerical interval for the components *BV* and *Surr* (note that the component *Surr* in the *PTVA*-4 model replaces the component *Prot*), which can assume continuous values within $[-1; +1]$, where values close to $+1$ represent "higher contribution to vulnerability", and values close to -1 represent "lower contribution to vulnerability".

Comment #2:

The repetitive scaling procedure that the *PTVA*-3 model applies to the numerical value of the components *BV, Ex, Prot* and *SV* is based on intervals and as such it reduces the model accuracy.

Authors' response to comment #2:

The respondent refers to the procedure adopted to standardise the original values of *BV, Prot*, *Ex, SV and WV* so that they all range in the same interval [1,5]. In the *PTVA*-3, this is obtained through an interval-based approach, as summarised in Table 6. Although this scaling procedure simplifies the model, it introduces inaccuracy as the differences between values of *BV, Prot*, *Ex, SV and WV* falling in the same interval are lost. For instance, two buildings having fairly different original values of structural vulnerability (e.g. $SV_{[1,125]} = 1$ and $SV_{[1,125]} = 24$) will end-up having the same re-scaled value (i.e. $SV_{[1,5]} = 1$), and their structural differences will not affect the final *RVI* score.

The *PTVA*-4 model significantly improves the scaling procedure of the *PTVA*-3 model. The original values of *SV, WV, BV, Surr* and *Ex* are scaled to the interval [1,5] using continuous arithmetical transformations (Sect. 4) which avoids any loss of accuracy.

Comment #3:

In the *PTVA*-3, the component *Ex* (i.e. Exposure) has the same value (i.e. $Ex = 5$) for all tsunami water depth values higher than 4 m.

Authors' response to comment #3:

This issue is addressed in the *PTVA*-4 model by using a standardised value of *Ex*, namely:

$$Ex_{[0,1]} = \frac{WD}{WD_{\max}} \tag{1}$$

where *WD* is the water depth impacting the building, which is the water depth above the terrain level at the point of the study area where the building is located; $WD_{\max}$, is the maximum value of *WD* among all buildings whose vulnerability is being assessed and

Table 6 (After Dall'Osso et al. 2009a) Original and re-scaled variables used in the calculation of the *RVI* scores through the *PTVA*-3 model

SV (original)	1–25	25–50	50–75	75–100	100–125
Relative vulnerability index (RVI) = (2/3) × (SV) + (1/3) × (WV)					
SV (scaled)	1	2	3	4	5
SV = (Bv) × (Ex) × (Prot)					
Bv (original)	−1 to −0.6	−0.6 to −0.2	−0.2 to +0.2	+0.2 to +0.6	+0.6 to +1
Bv (scaled)	1	2	3	4	5
Ex (original)	0–1 m	1–2 m	2–3 m	3–4 m	>4 m
Ex (scaled)	1	2	3	4	5
Prot (original)	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
Prot (scaled)	1	2	3	4	5
WV = (number of inundated levels)/(total number of levels)					
WV (original)	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1
WV (scaled)	1	2	3	4	5

The re-scaling procedure is based on intervals and as such it reduces the accuracy of the model. This issue is addressed in the *PTVA*-4 model compared through the *PTVA*-4 model; $Ex_{[0,1]}$, is be re-scaled to the interval [1,5] before being used to calculate *SV* (Sect. 4, Eq. (12)).

Example:

Building A is hit by a water depth of 3.00 m above terrain level. The maximum water depth impacting all buildings in the study area is 8.00 m (i.e. $WD_{\max} = 8$ m). Then:

$$Ex_{[0,1]} = \frac{3.00}{8.00} = 0.375 \tag{2}$$

It should be noted that as the value of *Ex* is standardised to $WD_{\max}$, *RVI* scores are relative to the group of buildings from which $WD_{\max}$ is obtained. If users wish to compare *RVI* scores between different case study locations, or different tsunami events, they must ensure that $WD_{\max}$ corresponds to the maximum effective water depth among all the considered case study locations, or among all relevant tsunami events.

In case reliable measures/estimates of flow velocity are available for each building (in addition to water depth), the term $\mathrm{Ex}_{[0,1]}$ can be obtained using the Hydrodynamic Force (HF) per unit of width, as previously done by Koshimura et al. (2009). HF is a function of both water depth and flow velocity (see Eq. 15 in Koshimura et al. 2009). In case HF is used, $Ex_{[0,1]}$ will then have to be obtained as the ratio between the HF impacting the building and the $\mathrm{HF}_{[\max],}$ that is the maximum value of HF among all buildings whose vulnerability is being assessed, similarly to Eq. (1). However, we recommend using HF instead of WD only if the selected tsunami scenario is the reproduction of an historical event for which flow velocity was either measured directly during the tsunami or obtained through a model that was validated using real measurements of flow velocity.

4 The *PTVA*-4 model

We generated the *PTVA*-4 model by applying the new attribute weights as detailed in Tables 2 and 3 and integrating certain changes to the model as recommended by the respondents (see Sects. 3.1, 3.2, 3.3 and 3.4). A number of assumptions underlying the mathematical framework of the *PTVA*-4 model are inherited from the *PTVA*-3. Whilst this section presents the *PTVA*-4 mathematical structure in full, we comment only the newly introduced items.

The *PTVA*-4 model calculates the Relative Vulnerability Index (*RVI*) for each building using the same formula of the PTVA-3, namely:

$$RVI_{[1,5]} = \frac{1}{3}WV_{[1,5]} + \frac{2}{3}SV_{[1,5]} \tag{3}$$

where *WV*, vulnerability of the building to water intrusion; *SV*, structural vulnerability of the building.

Similarly to the *PTVA*-3, *RVI* scores as well as *SV* and *WV* range between the values of +1.00 (minimum vulnerability) and +5.00 (maximum vulnerability). *WV* is obtained through the same approach as the *PTVA*-3: the ratio between the building levels inundated by the tsunami and the total number of building levels. However, in the *PTVA*-4 the ground floor is only inundated if the tsunami water depth exceeds the height of the ground floor above the terrain level.

$$WV_{[0,1]} = \left(\frac{\text{Height of inundated building levels}}{\text{Total height of building}} \right)^{*} \tag{4}$$

must account for elevated ground floors and include the number of basement levels.

In order to be used in Eq. (3), $WV_{[0,1]}$ must be re-scaled to the interval [1,5] through the transformation:

$$WV_{[1,5]} = 4WV_{[0,1]} + 1 \tag{5}$$

The transformation avoids the *PTVA*-3 scaling procedure, which was interval-based, and the attendant reduction in accuracy produced by allowing only certain $WV_{[1,5]}$ values (Table 6).

The structural vulnerability of the building is obtained in the PTVA-4 as the product between the vulnerability of the building itself (i.e. *BV*, depending on the engineering and structural characteristics of the building), the building surroundings (i.e. *Surr*, depending on the protection provided to the building by its surroundings and by the risk of impact from large movable objects) and the building exposure to the inundation scenario (i.e. *Ex*, depending on the tsunami water depth impacting the building).

$$SV_{[1,125]} = Bv_{[1,5]} \cdot Surr_{[1,5]} \cdot Ex_{[1,5]} \tag{6}$$

In order to be used in Eq. (3), $SV_{[1,125]}$ is then re-scaled to the interval [1,5] using the transformation:

$$SV_{[1,5]} = \frac{SV_{[1,125]} + 30}{31} \tag{7}$$

As in the *PTVA*-3 model, the components of *SV* are obtained as weighted sums of the building physical attributes (i.e. the component *BV*) and the surrounding's characteristics (i.e. the component *Surr*):

$$\begin{aligned} BV_{[-1,+1]} &= \frac{1}{(\text{Weight's sum})}(100 \cdot m + 85 \cdot s + 69 \cdot g + 69 \cdot f + 52 \cdot sh + 34 \cdot pc) \\ &= \frac{1}{409}(100 \cdot m + 85 \cdot s + 69 \cdot g + 69 \cdot f + 52 \cdot sh + 34 \cdot pc) \end{aligned} \tag{8}$$

$$\begin{aligned} Surr_{[-1,+1]} &= \frac{1}{(\text{Weight's sum})}(100 \cdot br + 84 \cdot sw + 72 \cdot nb + 58 \cdot mo + 42 \cdot w) \\ &= \frac{1}{356}(100 \cdot br + 84 \cdot sw + 72 \cdot nb + 58 \cdot mo + 42 \cdot w) \end{aligned} \tag{9}$$

where the attributes of *BV* (i.e. *m*, *s*, *g*,…) and *Surr* (i.e. *br*, *sw*, *nb*,…) are obtained from Tables 7 and 8, and the weights are updated according to Tables 2 and 3.

$Ex_{[0,1]}$ is obtained with Eq. (1). Prior to being used in Eq. (6), $Bv_{[-1,+1]}$, $Surr_{[-1,+1]}$ and $Ex_{[0,1]}$ are re-scaled to the interval [1,5] using the following transformations:

$$Bv_{[1,5]} = 2Bv_{[-1,+1]} + 3 \tag{10}$$

Table 7 Numerical values to be assigned to the attributes of the component *BV* on the basis of the building characteristics

	−1	−0.5	0	+0.5	+1
s (number of stories)	More than 5 stories	4 stories	3 stories	2 stories	1 story
m (material)	Reinforced concrete or steel		masonry		Timber, tin, clay or light materials
g (ground floor hydrodynamics)	Completely open plan (e.g. no walls, only columns)	About 75 % open plan	About 50 % open plan	About 25 % open plan	Completely closed plan, no or very few openings at ground floor
f (foundation strength)	Deep pile foundation		Average depth foundation		Shallow foundation
sh (shape of building footprint)	Round-like or triangular	Squared or almost squared	Rectangular	Lengthened rectangular	Complex (L, T or X shaped buildings, or other complex geometries)
pc (preservation condition)	Very good	Good	Average	Poor	Very poor

Table 8 Numerical values to be assigned to the attributes of the component *Surr* on the basis of the building surroundings

	−1	−0.5	0	+0.5	+1
br (building row)	>10th	7–8–9–10th	4–5–6th	2nd–3rd	1st
nb (natural barriers)	Very high protection	High protection	Average protection	Moderate protection	No protection
sw (seawall height and shape)	Vertical and >5 m	Vertical and 3–5 m	Vertical and 1, 5–3 m	Vertical and 0–1.5 m OR sloped and 1.5–3 m	Sloped and 0–1.5 m OR no seawall
w (brick wall around building)	Height of the wall is >80 % of the water depth	Height of the wall is from 60–80 % of the water depth	Height of the wall is from 40–60 % of the water depth	Height of the wall is from 20–40 % of the water depth	Height of the wall is from 0–20 % of the water depth
mo (sources of large movable objects)	Very low risk from movable objects		Average risk from movable objects		Very high risk from movable objects

$$Surr_{[1,5]} = 2Surr_{[-1,+1]} + 3 \tag{11}$$

$$Ex_{[1,5]} = 4Ex_{[0,1]} + 1 \tag{12}$$

4.1 What if only a part of the attributes is available?

This section addresses one comment that has informally been made to the authors in more than one occasion, even though none of the questionnaire respondents noted it. The PTVA-4 model requires a relatively high number of data to describe the characteristics individual buildings and their surroundings. In some instances, a part of these data may not be available. In fact, the number of building attributes needed is significantly higher than those currently used in tsunami fragility curves (i.e. usually just flow depth) (Tarbotton et al. 2015). This is the main reason why we consider the PTVA-4 model to be still a valuable alternative to fragility curves, particularly in areas where no fragility curves have been developed before. If only a limited number of PTVA-4 attributes is available, the purpose of using the PTVA-4 over (or in addition to) fragility curves is partially defeated. With that said, the PTVA-4 model can still be used with a smaller number of attributes, although this obviously reduces its accuracy. In case limited building attributes are available, the weight's sum in the first term of Eqs. (8) and (9) will have to be adjusted accordingly. However, we do not recommend using the PTVA-4 model if at least the two most important attributes of *BV* (i.e. material, number of stories) and *Surr* (i.e. building row, seawall) are available.

4.2 Summary of the differences between the PTVA-3 and PTVA-4 models

The changes made to the *PTVA*-3 model following the survey results are summarised in Table 9.

5 The *PTVA*-4 model: field test

We field-tested the *PTVA*-4 model in Botany Bay (Sydney, Australia), and we compared the results with those obtained using the *PTVA*-3. Botany Bay is a semi-enclosed, low-lying embayment south of Sydney Harbour, New South Wales (NSW). It is densely populated, includes residential, commercial and industrial buildings, and has high socio-economic significance, containing Sydney's International Airport and the main commercial harbour of NSW (i.e. Port Botany) (Albani and Cotis 2007) (Fig. 2).

The selected inundation scenario uses a 1:10,000 years tsunami, triggered by a submarine earthquake (magnitude = 9.05, slip = 15.6 m, rupture length = 700 km) along the Puysegur Trench, south of New Zealand. We selected this tsunami source because Puysegur is one of the trenches in the South Pacific with the highest probability of generating the 1:10,000 year tsunami in NSW (Burbidge et al. 2008). The tsunami is assumed to occur during high astronomical tide (i.e. +97 cm) under future sea level conditions (i.e. +84 cm) (NSW DECCW 2009). We chose a tsunami event with a relatively low annual probability (and, as a consequence, high intensity) to ensure an inundated area large enough to obtain a statistically robust cohort of exposed buildings ($n = 2211$) to test the model. We simulated the tsunami generation, propagation and inundation using the model Method of Splitting Tsunamis (*MOST*), accessed through the online platform Community Model Interface for Tsunamis (*ComMIT*). *ComMIT* represents an effort by the United Nations *IOC* to harmonise and increase global accessibility to validated tsunami modelling tools (Titov et al. 2011). The simulation of the inundation phase was supported by a LiDAR-derived Digital Elevation Model (*DEM*), having a horizontal resolution of 10 m

Table 9 Summary of the differences between the PTVA-3 and the PTVA-4 models

PTVA-3	*PTVA*-4
Tsunami demand parameter (water depth)	
The water depth impacting on buildings is obtained using a static bathtub-filling method	*PTVA*-4 recommends obtaining water depth using hydrodynamic models
Re-scaling procedure	
The components *WV, SV, BV, Prot* and *Ex*, once obtained, are scaled to the interval [1,5] using a technique based on discrete intervals (Table 6). This reduces the accuracy of the PTVA-3 model as different values of the same element may be transformed into the same value by the scaling procedure	The components *WV, SV, BV, Surr* and *Ex*, once obtained, are scaled to the interval [1,5] using continuous arithmetical transformations. Differences between values of the same element are preserved after the scaling. Accuracy loss is avoided
***RVI* scores**	
RVI scores range between 1 (minimum vulnerability) and 5 (maximum vulnerability). These are converted to vulnerability descriptive labels (i.e. very low vulnerability, low vulnerability, average vulnerability, high vulnerability, very high vulnerability) by dividing the range [1,5] in five equal intervals	RVI scores range between 1 and 5, but are more evenly distributed due to the new scaling procedure of the *PTVA*-4. Since RVI scores represent the relative vulnerability, we recommend obtaining the vulnerability labels (i.e. very low vulnerability, low vulnerability, average vulnerability, high vulnerability, very high vulnerability) based on standard deviation or Jenks' intervals
***WV* value**	
WV does not account for buildings with raised ground floors, that are considered as being inundated if the water depth above the terrain level is >0	*WV* accounts for buildings with raised ground floors that are considered as being inundated only if the water depth above the terrain level exceeds the elevation of the ground floor
***Ex*—Exposure**	
Ex is the water depth impacting the building, measured in metres above the terrain level *Ex* does not change for any tsunami water depth exceeding 4 m (i.e. $Ex = 5$ for any value of water depth exceeding 4 m)	*Ex* is the ratio between the water depth impacting the building (i.e. *WD* measured above the terrain level) and the maximum effective water depth in the study area [i.e. $WD_{\max}$, Eq. (1)] Different values of water depth impacting the building—including values above 4 m—correspond to different values of *Ex* (Sect. 3.4)
***BV*—Building Vulnerability**	
The weights of *BV* attributes are obtained based on the opinion of two experts only (Dall'Osso et al. 2009a, b) *BV* contains the attribute *mo* (presence of large movable objects in the building surroundings that could impact on structure when dragged by the water flow). *mo* is the only attribute in *BV* relating to the building surroundings. The attribute *so* (i.e. shape and orientation of the building footprint) requires making difficult assumptions on the direction of the water flow impacting the building	Weights of *BV* attributes are obtained based on the opinions of the authors and 14 international experts The attribute *mo* was moved to the component *Surr*. *BV* contains only attributes related to the building itself. All the attributes about building surroundings are now included in the component *Surr* The attribute *so* was changed into *sh* (i.e. shape). Orientation is not considered to avoid making wrong assumptions on the direction of the water flow impacting the building

Table 9 continued

PTVA-3	*PTVA*-4
***Surr*—Building Surroundings** (replaces the *Prot* factor of the *PTVA*-3)	
Prot accounts only for the protection provided to the building by its surroundings	*Prot* is replaced by *Surr*, which includes all attributes about the building surroundings, namely the same attributes of *Prot* plus the attribute *mo*.
Prot assumes continuous values in the interval [0, +1]	Consistently with *BV*, *Surr* assumes continuous values in the interval [−1, +1]
The weights of *Prot*'s attributes are obtained based on the opinion of two experts only (Dall'Osso et al. 2009a, b)	The weights of *Surr*'s attributes are obtained based on the opinions of the authors and 14 international experts

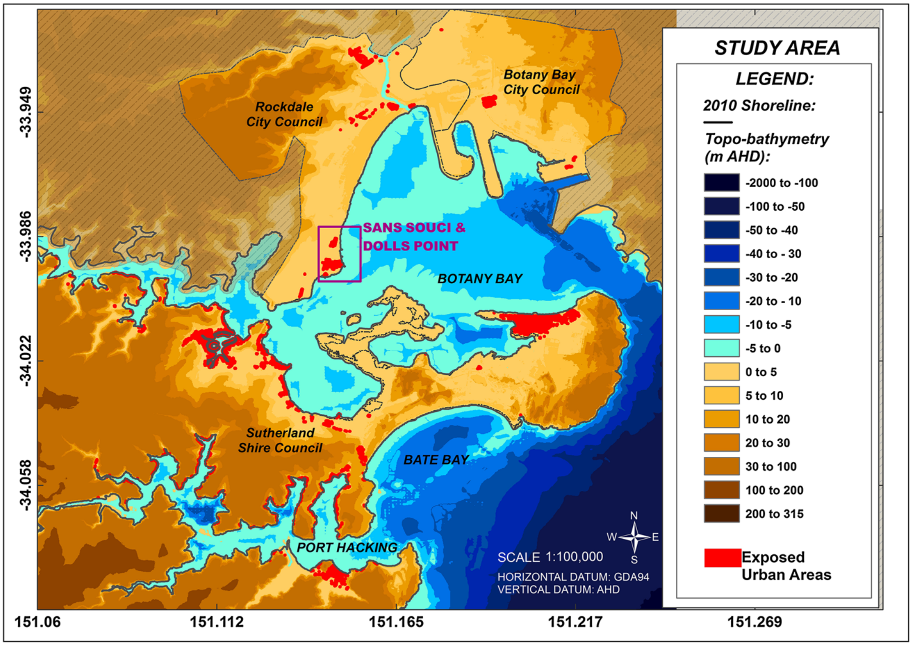


Fig. 2 View of the study area (Botany Bay, Sydney, Australia). The map was derived from the Digital Elevation Model (DEM) used to generate the inundation scenario via tsunami hydrodynamic modelling. The urban areas exposed to the selected tsunami scenario (annual probability = 1:10,000, sea level rise above year 2010's level = +84 cm, tide level = +97 cm) are depicted in red. The square identifies the area of Sans Souci and Dolls Point, for which we generated four thematic building vulnerability maps. High-resolution thematic vulnerability maps have been generated for the entire study area and are available upon request to the authors

and vertical accuracy <25 cm. *MOST* calculated the maximum tsunami flow depth in each cell of the *DEM*, which we used as the tsunami demand parameter for the buildings located within that cell. For further details about the tsunami hazard assessment including the model validation and the selection of initial conditions readers are referred to Dall'Osso et al. (2014). *MOST* produced an inundation map, which was imported into a *GIS* system and layered with aerial imagery (year 2011, resolution 50 cm) provided by the local councils surrounding Botany Bay. This allowed identification of the buildings exposed to the selected tsunami scenario, which we digitised as vectorial polygons within the *GIS*.

The selected tsunami scenario would inundate an area of over 1500 ha, containing 2623 buildings. Given the high number of the exposed buildings and the fact that they are distributed over a relatively large area, it was not possible to show the location of individual buildings on a single map. However, this information is available from the authors. The location of the exposed urban areas within Botany Bay is shown in Fig. 2.

We collected all necessary data to run the *PTVA*-4 model by visually inspecting each exposed building. Out of the 2623 buildings, 412 were not accessible/visible during the survey and were excluded from the analysis (hence the cohort is $n = 2211$). Results of the data collection were entered in the GIS and assigned to the corresponding building/polygon. We then ran both the *PTVA*-3 and the *PTVA*-4 models using ESRI ArcGIS toolboxes that we designed on-purpose (the *PTVA*-4 ESRI ArcGIS toolbox is provided in Online Resource 2).

Figure 3g shows the distribution of the final *RVI* scores obtained with the *PTVA*-3 and the *PTVA*-4 models. Results show that *RVI* scores obtained with the *PTVA*-4 model are significantly better distributed across the building cohort than those obtained with the *PTVA*-3. This is due to the differences in the re-scaling procedures adopted by the models. The interval-based scaling procedure of the *PTVA*-3 removes any differences between buildings having scores of the *RVI* components within the same interval, ultimately allowing a reduced number of possible *RVI* scores. The *PTVA*-4 overcomes this issue through the use of a continuous arithmetical transformation, as discussed in Sect. 4. As such, the *PTVA*-4 model provides significantly better accuracy. This is particularly evident by observing the distributions of the *RVI* components in Fig. 3a–e.

Figure 3a shows the distribution of the water depth (*WD*) impacting each building, as calculated by *MOST*. The maximum value of *WD* (i.e. $WD_{\max}$) is 5.78 m; however, most buildings would be hit by less than 2 m of water. In both the *PTVA*-3 and the *PTVA*-4 models, *WD* is used to generate the component $Ex_{[1,5]}$. Figure 3b reveals that the distribution of $Ex_{[1,5]}$ is significantly more representative of *WD* when calculated through the *PTVA*-4 model (note that the scale of the vertical axis in Fig. 3b is different from that in Fig. 3a).

Figure 3c, d shows the distributions of $BV_{[-1,+1]}$ and $BV_{[1,5]}$. Before the re-scaling procedure, the two distributions of $BV_{[-1,+1]}$ (obtained with the *PTVA*-3 and the *PTVA*-4 models) are very similar (Fig. 3c). This is explained by the limited changes to the weights of the attributes of *BV* (i.e. *m, s, f, g, sh, pc*) introduced by the *PTVA*-4 model. Again, the differences between the two distributions of $BV_{[1,5]}$ observed in Fig. 3d are due to the different re-scaling methods used by the *PTVA*-3 and the *PTVA*-4 models, with the results obtained through the *PTVA*-4 being more evenly distributed across the possible range of values.

In Fig. 3e, the visual comparison of the distributions of the component $Prot_{[0,+1]}$ (obtained with the PTVA-3) and $Surr_{[-1,+1]}$ (obtained with the PTVA-4) is complicated by the different ranges of possible values. It can be observed that both components assume values in the top half of their respective value range, but $Surr_{[-1,+1]}$ is distributed over a wider interval and is therefore more sensitive to the attributes of the building's surroundings. This is further enhanced by the re-scaling procedure to the interval [1,5] (Fig. 3f).

Once the components, $BV_{[1,5]}$, $Surr_{[1,5]}$, and $Ex_{[1,5]}$ are multiplied together to obtain the Structural Vulnerability $SV_{[1,5]}$ (Eq. 6), the accuracy of the *PTVA*-4 model is further amplified (Fig. 3g).

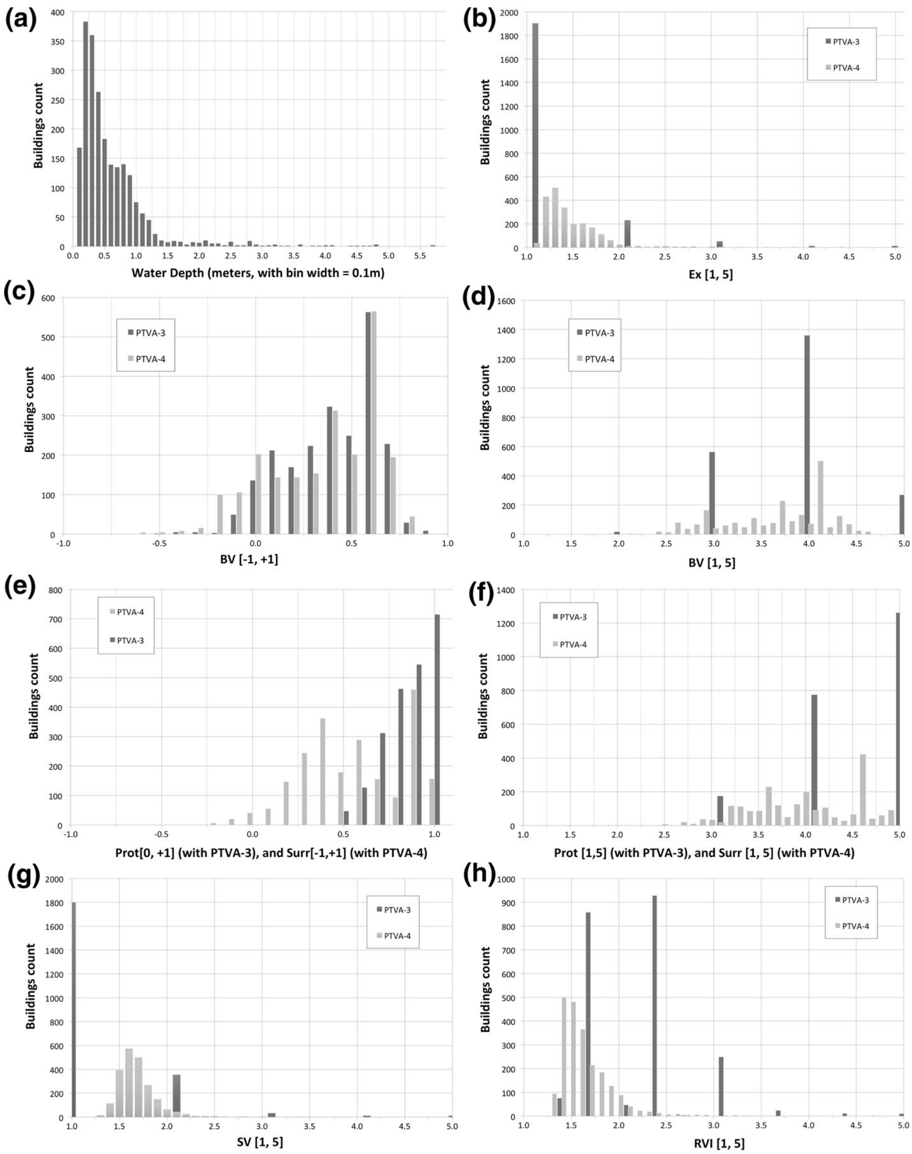


Fig. 3 Results in the form of frequency distributions (bin $= 0.1$) obtained from applying the *PTVA*-3 and the *PTVA*-4 models to the building cohort ($n = 2211$) in Botany Bay (Sydney). The following *PTVA* components are displayed: *WD* (water depth, **a**), $Ex_{[1,5]}$ (building exposure, **b**), $BV_{[-1,+1]}$ (building vulnerability original, **c**), $BV_{[1,5]}$ (building vulnerability re-scaled, **d**), $Prot_{[0,1]}$ and $Surr_{[-1,1]}$ (building surroundings original, **e**), $Prot_{[1,5]}$ and $Surr_{[1,5]}$(building surroundings re-scaled), $SV_{[1,5]}$ (structural vulnerability re-scaled, **f**) and the final *RVI* scores. Each figure compares the component distributions obtained with the *PTVA*-3 and *PTVA*-4 models

The final *RVI* scores obtained with the *PTVA*-4 model may be displayed on thematic vulnerability maps using the same colour-coded approach of the *PTVA*-3 model. However, since *RVI* scores obtained with the *PTVA*-4 are better distributed across the interval [1,5] and differences between buildings are more sensitively represented, we recommend displaying them using more sophisticated classification techniques, such as:

1. Classification based on the number of standard deviations from the mean. This technique is particularly suited for normally distributed data and has been widely used in the disaster risk reduction literature to display composite vulnerability indices (e.g. Cutter et al. 2003);
2. Classification techniques based on the Jenks' Natural Breaks Algorithm (Jenks 1977), which identifies clusters of similar data and is well suited to non-normally or unevenly distributed data.

In order to demonstrate the effect of different classification techniques on the graphics, we generated four thematic maps for the local area of Sans Souci and Dolls Point (whose location in the study area is indicated by the purple square in Fig. 2), in the southern part of the Council of Rockdale. The thematic *RVI* maps are shown in Fig. 4a–d.

We obtained the colour-coded scale by classifying *RVI* scores with the standard deviation method (Fig. 4a, b, respectively classified in 5 and 10 classes) and the Jenks' Natural Breaks method (Fig. 4c, d, respectively classified in 5 and 10 classes). Figure 4a–d shows how the better distribution of *RVI* values across the building cohort obtained through the *PTVA*-4 model allows generating more accurate thematic vulnerability maps, in which for instance *RVI* values can be grouped in 10 or more colour-coded classes, as opposed to a maximum of 5 classes available with the *PTVA*-3. This allows visual detection of smaller *RVI* differences. For example, building #2 and #3 in Fig. 4a, c (using only 5 classes) are included in the same *RVI* class (i.e. yellow), even if they have different *RVI* scores. When the number of classes is increased to 10 (Fig. 4c, d), the difference in the *RVI* scores between building #2 and #3 is displayed effectively on the map.

In Sans Souci and Dolls Point, the selected tsunami scenario would inundate 146 buildings. The overall vulnerability level (compared to the rest of the study area) is medium to low, with 108 buildings having an RVI score at least 0.25 SD lower than the mean RVI of the total building cohort in Botany Bay. Buildings located on the first row (beach-front) obtained higher *RVI* scores, with the exception of a building block in the northern part of Sans Souci, which would benefit from protection provided by the green space in front of it (Fig. 4).

The buildings identified by the *PTVA*-4 model as the most vulnerable in Sans Souci and Dolls Point are numbered from #1 to #4 (Fig. 4) and are listed in Table 10. Among these, two are public venues: the Georges River Sailing Club (i.e. building #1), and the "Le Beach Hut Café" (i.e. building #2). The tsunami flow would completely inundate the ground floor of the Georges River Sailing Club (water depth = 1.88 m) and would most likely cause structural damage, because of the building's relatively light construction material (single brick layer and corrugated tin) and its beach-front location. Building #3 ("Le Beach Hut Café") would be hit by a significantly lower water depth (i.e. 0.49 m), but the poorer construction standards and the fact the building has only a single floor would still result in an above-average *RVI* score (+0.70 SD). If a tsunami warning was issued for this area, access to these buildings should be restricted.

Buildings #4 are residential units located in the first row behind the beach. The ground floor of these buildings would be inundated by <1 m of water depth, but the lack of protection and the fact that some of these units have one storey only would still result in medium RVI scores, and great risk to the residents.

If a complete evacuation of Sans Souci and Dolls Point was necessary, the maximum distance to a safe location (i.e. outside of the inundated area) would be less than 350 m,

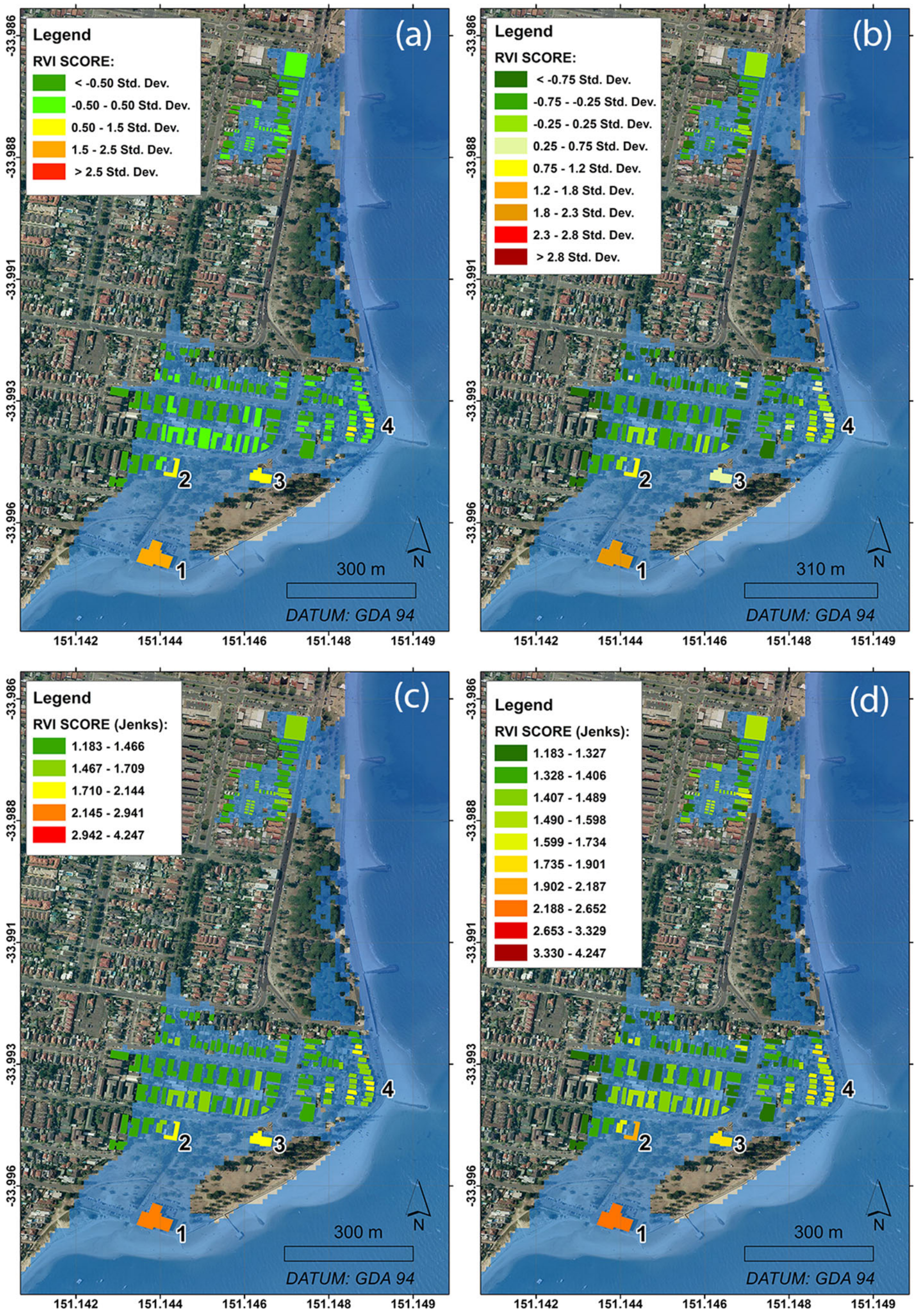
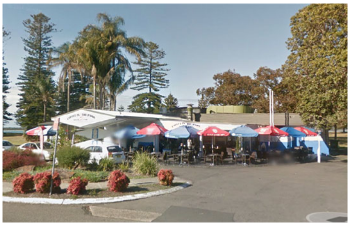


Fig. 4 Thematic building vulnerability maps for the areas of Sans Souci and Dolls Point (identified by the *purple square* in Fig. 1) obtained with the *PTVA*-4 model. The *maps* demonstrate the flexibility of the *PTVA*-4 in terms of the classification techniques that can be used to display the final *RVI* scores. **a**, **b** Use a classification based on the distance of the class from the cohort mean, measured in standard deviations. **a** Uses 5 vulnerability classes, whilst **b** uses 10 and allows identifying smaller differences between *RVI* scores. **c**, **d** Use a classification based on Jenks' Natural Breaks, more suitable for unevenly distributed data

Table 10 Characteristics of the buildings identified by the PTVA-4 model as being the most vulnerable in the area of Sans Souci and Dolls Point (Fig. 4)

Building (*s*) number	Description	Water depth (m)	RVI score [1.00–5.00]	Photo (Google, 2013)
#1	Georges River Sailing Club	1.88	2.279	
#2	Residential L-shaped building	1.52	1.908	
#3	"Le Beach Hut Café"	0.49	1.751	
#4	Residential front-row group of buildings	~0.9	1.829–1.749	

meaning that for an average pedestrian evacuating at the speed of 0.6 m/sec (Post et al. 2009) walking out of the inundated zone would take a maximum of 3.5 min. It is noted that the estimate of minimum evacuation speed of 0.6 m/sec provided by Post et al. (2009) does not account for individuals with impaired mobility.

6 Conclusion

This paper discusses our review, assessment, development and testing of a new version of the *PTVA* model. The work is the first to build upon a participative approach shared with experts globally in the field of tsunami damage to the built environment published in the last decade (i.e. 2005–2015). A survey gathered expert judgement on the previous version of the *PTVA* model (i.e. the *PTVA*-3 model). Each respondent (sample size $n = 30$, response rate 47 %) weighted the building vulnerability attributes used in the *PTVA*-3 model based on their expertise and on new evidence from the 2011 Japan Tsunami. Respondents were also given the opportunity to comment generally and make recommendations about the model. In this paper we have presented and discussed the survey results, and we have used them to generate a new improved version of the *PTVA* model, named the *PTVA*-4 model. The upgrades incorporated by the *PTVA*-4 model are classified as follows:

(a) *Improvements to the weights of the building vulnerability attributes.* Updated weights were obtained as the mathematical mean among those suggested by the survey respondents. Almost all respondents (i.e. 13 out of 14) agreed on the relevancy of all 11 building attributes adopted by the *PTVA*-3. This may partially explain the variability associated with the existing building vulnerability curves for tsunamis, that in most instances are based on one building attribute only (i.e. the construction material) (Tarbotton et al. 2015). The new weights did not differ much from those used in the *PTVA*-3 model, with one exception: the highest weight was given to the building construction material, which became the most influential attribute, followed by the number of stories.

(b) *Structural changes to the model framework.* These included the use of a widely validated hydrodynamic model (i.e. *MOST*) to simulate the tsunami inundation and obtain the maximum water depth impacting each building, the lack of which stood as one of the main limitations to the accuracy of the *PTVA*-3 model (Dall'Osso et al. 2010). In addition to this, the *PTVA*-4 introduced a more flexible definition of the component *Ex*, which is now standardised to the maximum water depth observed in the study area and can differentiate between tsunami water depths >4 m. Another important structural improvement introduced by the *PTVA*-4 model is the use of the effective water depth above the ground floor to determine the damage from prolonged contact with water (i.e. component *WV*), accounting for the lower vulnerability of buildings having raised foundations and/or elevated ground floors.

(c) *Formal changes to the model's re-scaling methodology and RVI's classification and display techniques*. Whilst being formal in their nature, these changes have improved the accuracy of the *PTVA*-4 model. The simplistic interval-based re-scaling methodology applied by the *PTVA*-3 meant each model's component assumed only certain values within the interval [1,5], ultimately resulting in a reduced accuracy of the final *RVI* scores. The *PTVA*-4 model addresses this issue by using a re-scaling technique based on continuous arithmetical transformations, which preserves accuracy throughout the computational steps required to obtain the *RVI* scores. As a result, *RVI* scores calculated with the *PTVA*-4 model are significantly better distributed across the interval [1,5] and can be displayed on the final thematic vulnerability maps using more sophisticated and detailed classification techniques.

We field-tested the *PTVA*-4 model in Botany Bay (Sydney, Australia), using a cohort of 2211 buildings and a 1:10,000 years tsunami scenario. Results were compared with those obtained with the previous version of the model (i.e. the *PTVA*-3) and showed a significantly better accuracy. We generated four thematic vulnerability maps for the area of Sans Souci and Dolls Point, and we discussed how these might be used to demonstrate the relative vulnerability of the area and to provide simple recommendations for emergency managers.

We conclude that the *PTVA*-4 represents the best version of the *PTVA* model family. It builds on the same theoretical framework of the widely applied and validated *PTVA*-3 model, but introduces significant improvements, based on the feedback from the scientific community working on the field of building vulnerability to tsunamis.

Existing building vulnerability curves for tsunamis have been developed with a variety of techniques, under different assumptions (Tarbotton et al. 2015). Whilst they provide a valuable method of estimating the absolute damage to a building, tsunami vulnerability curves are currently highly variable and difficult to apply to buildings different from those used to generate them (e.g. in a different country). The *PTVA*-4 model offers an alternative approach, which can be especially useful in regions where fragility curves are unavailable, or to compare the expected performance of different buildings using a higher number of attributes. However, similarly to all previous versions of the PTVA model, the PTVA-4 is based on a purely relative approach, meaning that the final RVI scores can be used to compare the expected performance of buildings (i.e. building A is more prone to damage than building B), but can never be used to predict which buildings will reach or exceed a given damage state (e.g. building A will collapse). In other words, buildings with a higher RVI score are more likely to reach or exceed any given damage state than buildings with a lower RVI score. However, any comment regarding the absolute expected level of damage that is solely based on the PTVA-4 model can be misleading and should be strictly avoided.

Future work should concurrently refine and harmonise the methodology to develop vulnerability curves and target the main limitations of the *PTVA*-4 model. These are:

a. The final *RVI* scores are relative and have no stand-alone meaning. They can only be used to compare the vulnerability of different buildings, but not to estimate the absolute damage (unless further assumptions are made, see Dominey-Howes et al. 2009);
b. The *PTVA*-4 model approximates the relationship between tsunami demand parameter (i.e. water depth) and *RVI* scores using a linear approach, whilst empirical studies (i.e. vulnerability curves) show that log-normal functions provide a better fit.
c. The *PTVA*-4 model requires a high number of input data, resulting in time-consuming surveys. Studies in countries or regions showing consistent construction standards or architectonic styles could reduce the input data load by testing the *PTVA*-4 building attributes for multicollinearity.

A copy of the *PTVA*-4 model (in the form of an ESRI ArcGIS toolbox) is provided in Online Resource 2.

Acknowledgments We thank all the experts who responded to the questionnaire and provided critical advice on how to improve the model. We thank the NSW Ministry for Police and Emergency Services and the Natural Disaster Resilience Scheme for funding the project.

Author contributions FD. undertook the research work and wrote the manuscript. D.D.H. provided guidance and contributed identifying the questionnaire respondents. C.T. helped with the statistical analysis. S.S. contributed to the writing and provided advice. G.W. provided access to data and contact with local Councils. All the authors revised the manuscript.

References

Aketa S, Yano K, Mizuno Y, Sato J, Terauchi K (1994) Reduction effect of port and fishing port facilities by tsunami damage. In: Proceedings of Coastal Engineering Conference, vol 41. Japan Society of Civil Engineers (JSCE), Tokyo, pp 1176–1180 (**in Japanese**)

Albani AD, Cotis G (2007) Port Hacking: past and present, report prepared for the Council of Sutherland Shire

Bird DK (2009) The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation—a review of current knowledge and practice. Nat Hazards Earth Syst Sci 9:1307–1325. doi:10.5194/nhess-9-1307-2009

Burbidge D, Mleczko R, Thomas C, Cumminis P, Nielsen O, Dhu T (2008) A probabilistic tsunami hazard assessment for Australia. Geoscience Australia Professional Opinion. No. 2008/04

Charvet I, Ioannou I, Rossetto T, Suppasri A, Imamura F (2014) Empirical fragility assessment of buildings affected by the 2011 Great East Japan tsunami using improved statistical models. Nat Hazards 73(2):951–973

Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards*. Soc Sci Q 84(2):242–261

Dall'Osso F, Dominey-Howes D (2010a) 'Reducing the loss': using high-resolution vulnerability assessments to enhance tsunami risk reduction strategies. Aust J Emerg Manag 25(4):24–30

Dall'Osso F, Dominey-Howes D (2010b) The emergency management implications of assessments of building vulnerability to tsunami. Aust J Emerg Manag 25:24–30

Dall'Osso F, Gonella M, Gabbianelli G, Withycombe G, Dominey-Howes D (2009a) A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage. Nat Hazards Earth Syst Sci 9:1557–1565. doi:10.5194/nhess-9-1557-2009

Dall'Osso F, Gonella M, Gabbianelli G, Withycombe G, Dominey-Howes D (2009b) Assessing the vulnerability of buildings to tsunami in Sydney. Nat Hazards Earth Syst Sci 9:2015–2026

Dall'Osso F, Maramai A, Graziani L, Brizuela B, Cavalletti A, Gonella M, Tinti S (2010) Applying and validating the PTVA-3 Model at the Aeolian Islands, Italy: assessment of the vulnerability of buildings to tsunamis. Nat Hazards Earth Syst Sci 10:1547–1562

Dall'Osso F, Dominey-Howes D, Moore C, Summerhayes S, Withycombe G (2014) The exposure of Sydney (Australia) to earthquake-generated tsunamis, storms and sea level rise: a probabilistic multi-hazard approach. Sci Rep 4:7401

Dias W, Yapa H, Peiris L (2009) Tsunami vulnerability functions from field surveys and Monte Carlo simulation. Civ Eng Environ Syst 26:181–194

Dominey-Howes D, Papathoma M (2007) Validating a Tsunami Vulnerability Assessment Model (the PTVA Model) Using Field Data from the 2004 Indian Ocean Tsunami. Nat Hazards 40:113–136

Dominey-Howes D, Dunbar P, Vernar J, Papathoma-Kohle M (2009) Estimating probable maximum loss from a Cascadia tsunami. Nat Hazards 53(1):43–61

Forman E, Peniwati K (1998) Aggregating individual judgments and priorities with the analytic hierarchy process. Eur J Oper Res 108:165–169

Gardi A, Valencia N, Guillande R, André C (2011) Inventory of uncertainties associated with the process of tsunami damage assessment on buildings (SCHEMA FP 6 EC co-funded project). Nat Hazards Earth Syst Sci 11:883–893

IOC UNESCO (Intergovernmental Oceanographic Commission of UNESCO) (2011) Reducing and managing the risk of tsunamis, IOC Manuals and Guides, pp 57–74 (IOC/2011/MG/57Rev.2), Paris. http://unesdoc.unesco.org/images/0021/002147/214734e.pdf

Jenks GF (1977) Optimal data classification for choropleth maps. Occasional Paper No. 2, Department of Geography, University of Kansas

Koshimura S, Oie T, Yanagisawa H, Imamura F (2009) Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia. Coast Eng J 51:243–273

Maqsood T, Senthilvasan M, Corby N, Wehner M, Edwards M (2013) Improved assessment of flood impact: an urban stormwater case study of a city of Sydney catchment. In: FMA Conference

Muhari A, Charvet I, Futami T, Suppasri A, Imamura F (2015) Assessment of tsunami hazard in port and its impact on marine vessels from tsunami model and observed damage data. Nat Hazards 78:1309–1328

Nadal NC, Zapata RE, Pagan I, Lopez R, Agudelo J (2010) Building damage due to riverine and coastal floods. J Water Resour Plan Manag 136:327–336

NGDC/WDS (National Geophysical Data Center/World Data Service) (2014) Global Historical Tsunami Database. National Geophysical Data Center, NOAA. doi:10.7289/V5PN93H7

NSW DECCW (New South Wales Department of Environment, Climate Change and Water) (2009) Derivation of the NSW Government's sea level rise planning benchmarks. Technical Note, ISBN 978 1 74232 465 4

Omira R, Baptista M, Miranda J, Toto E, Catita C, Catalo J (2009) Tsunami vulnerability assessment of Casablanca-Morocco using numerical modelling and GIS tools. Nat Hazards 54:75–95

Papathoma M (2003) Assessing tsunami vulnerability using GIS with special reference to Greece. Dissertation, Coventry University

Papathoma M, Dominey-Howes D, Zong Y, Smith D (2003) Assessing tsunami vulnerability, an example from Herakleio, Crete. Nat Hazards Earth Syst Sci 3:377–389. http://www.nat-hazards-earth-syst-sci.net/3/377/2003/

Post J, Wegscheider S, Muck M, Zosseder K, Kiefl R, Steinmetz T, Strunz G (2009) Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale. Nat Hazards Earth Syst Sci 9:1075–1086. doi:10.5194/nhess-9-1075-2009

Reese S, Cousins W, Power W, Palmer N, Tejakusuma I, Nugrahadi S et al (2007) Tsunami vulnerability of buildings and people in South Java: field observations after the July 2006 Java tsunami. Nat Hazards Earth Syst Sci 7:573–589

Reese S, Bradley B, Bind J, Smart G, Power W, Sturman J (2011) Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. Earth Sci Rev 107:156–173

Schultz MT, Gouldby BP, Simm JD, Wibowo JL (2010) Beyond the factor of safety: developing fragility curves to characterize system reliability (No. ERDC-SR-10-1). Engineer Research and Development Center Vicksburg MS Geotechnical and Structures Lab

Shuto N (1987). Changing of tsunami disasters. Tsunami Engineering Technical Report, 4, Tohoku University, Sendai, Japan, pp 1–41 (**in Japanese**)

Suppasri A, Koshimura S, Imamura F (2011) Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. Nat Hazards Earth Syst Sci 11:173–189

Suppasri A, Mas E, Koshimura S, Imai K, Harada K, Imamura F (2012) Developing tsunami fragility curves from the surveyed data of the 2011 Great East Japan tsunami in Sendai and Ishinomaki plains. Coast Eng J 54(1):1250008

Suppasri A, Charvet I, Imai K, Imamura F (2013a) Fragility curves based on data from the 2011 Great East Japan tsunami in Ishinomaki city with discussion of parameters influencing building damage. Earthq Spectra. doi:10.1193/053013EQS138

Suppasri A, Mas E, Charvet I, Gunasekera R, Imai K, Fukutani Y, Abe Y, Imamura F (2013b) Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. Nat Hazards 66(2):319–341

Synolakis CE, Bernard EN, Titov VV, Kânoğlu U, González FI (2007) Standards, criteria, and procedures for NOAA evaluation of tsunami numerical models. NOAA Technical Memorandum OAR PMEL-135. NOAA/Pacific Marine Environmental Laboratory, Seattle

Tarbotton C, Dominey-Howes D, Goff JR, Papathoma-Kohle M, DallOsso F, Turner I (2012) GIS-based techniques for assessing the vulnerability of buildings to tsunami: current approaches and future steps. Geol Soc Lond Spec Publ 361:115–125. doi:10.1144/SP361.10

Tarbotton C, Dall'Osso F, Dominey-Howes D, Goff J (2015) The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: comparative review and summary of best practice. Earth Sci Rev 142:120–134

Titov VV, Gonzalez FI (1997) Implementation and testing of the method of splitting tsunami (MOST) model. US Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Pacific Marine Environmental Laboratory.

Titov VV, Gonzalez FI, Bernard EN, Eble MC, Mofjeld HO, Newman JC, Venturato AJ (2005) Real-time tsunami forecasting: challenges and solutions. Nat Hazards 35(1):41–58. doi:10.1007/s11069-004-2403-3 **(Special Issue, US National Tsunami Hazard Mitigation Program)**

Titov VV, Moore CW, Greenslade DJM, Pattiaratchi C, Badal R, Synolakis CE (2011) A new tool for inundation modeling: Community Model Interface for Tsunamis (ComMIT). Pure appl Geophys 168:2121–2131

Valencia N, Gardi A, Gauraz A, Leone F, Guillande R (2011) New tsunami damage functions developed in the framework of SCHEMA project: application to European-Mediterranean coasts. Nat Hazards Earth Syst Sci 11:2835–2846

Voulgaris G, Murayama Y (2014) Tsunami vulnerability assessment in the Southern Boso Peninsula, Japan. Int J Disaster Risk Reduct 10:190–200

Wei Y, Chamberlin C, Titov V, Tang L, Bernard EN (2013) Modeling of the 2011 Japan tsunami—lessons for near-field forecast. Pure appl Geophys 170:1309–1331. doi:10.1007/s00024-012-0519-z