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TOWARDS THE DEVELOPMENT OF A METHOD FOR GENERATING ANALYTICAL TSUNAMI FRAGILITY FUNCTIONS

Joshua MACABUAG[1], Tristan LLOYD[2], Tiziana ROSSETTO[3]

ABSTRACT

The onshore flow of a tsunami can generate significant loading on buildings and infrastructure leading to various levels of damage or failure. Analytical tsunami fragility functions are derived from structural analyses and relate damage (via an Engineering Demand Parameter, EDP) to a tsunami Intensity Measure (IM). They allow for quantification of risk, even in the absence of empirical building damage data, and so are vital for land-use and emergency planning, human and financial loss estimation and Performance Based Tsunami Engineering.

This paper presents the first steps towards defining a framework for generating analytical tsunami fragility functions, using iterative structural analyses. A simple case study is presented and a set of rudimentary fragility functions are produced in order to illustrate the proposed process. Inter-storey drift is selected as the EDP to enable the use of a seismic damage scale definition. Inundation depth is selected as the IM to enable comparison with empirical fragility functions.

It is shown that the seismic damage scale selected does not capture an adequate range of structural behaviour under tsunami loading, and so a preliminary tsunami damage scale is proposed. The generated fragility functions are order-of-magnitude comparable with empirical functions derived from damage data from the 2011 Japan Tsunami.

NOMENCLATURE

h = inundation depth, u = flow velocity, z = building elevation above sea-level, ρ = density,
R = maximum tsunami run-up (max height above sea level that tsunami reaches on-land),
$q(y)$ = design tsunami wave pressure at height y above ground, g = acceleration due to gravity,
k = constant (indicating proportionality), C_d = drag coefficient, m = mass of debris,
Δt = debris impact duration, V_{void} = volume of trapped air voids below the inundation depth,
V_{water} = volume of trapped water on suspended floors,

[1] EngD Student Researcher, EPICentre, Department of Civil Environmental and Geomatic Engineering,
University College London, Gower Street, London, United Kingdom, WC1E 6BT
[2] PhD Student Researcher, EPICentre, University College London, United Kingdom, WC1E 6BT
[3] Professor, EPICentre, University College London, United Kingdom, WC1E 6BT

INTRODUCTION

Compared to seismic studies, few fragility functions for buildings affected by tsunami exist, and the vast majority have all been based solely on empirical data (post-tsunami building damage surveys). However, the applicability of empirical tsunami fragility functions for buildings is limited by the availability and quality of data from past events. Similar construction types from different countries or regions can perform very differently under the same tsunami conditions (A. Suppasri et al. 2013), and so the correct application of empirical fragility functions is therefore very specific to the locations from where damage data was taken. Analytical techniques are required to generate tsunami fragility functions for the majority of at-risk locations around the world where tsunami damage data is not available.

Analytical fragility functions are based on damage data generated from structural analysis. The use of seismic analytical fragility functions is well established (Baker 2013; Meslem and Ayala 2012; Tiziana Rossetto and Elnashai 2005), but to date no analytical tsunami fragility functions have been published. Analytical fragility functions provide a probabilistic link between a tsunami Intensity Measure (IM) and the structural response, represented by an Engineering Demand Parameter (EDP). Multiple damage data points are formed by repeating structural analysis for a range of IMs and a range of building configurations within the constraints of the building type being considered. Statistical regression methods are then applied to this damage data set to generate fragility functions.

PROPOSED METHOD OF GENERATING ANALYTICAL FRAGILITY FUNCTIONS

Fragility functions are specific to a particular building type and location. After selecting a location and building type, damage data points (also referred to as performance points: the simulated damage state of a structure for a given local tsunami intensity {ds, IM}) can be obtained. This is achieved by estimating the intensity of the hazard (IM) for the given location, calculating the forces on a structure representative of the building type being considered, and analysing the structural response to obtain the expected damage state for the given hazard intensity. Multiple data points (i.e. a dataset) are then formed by repeating this procedure for a range of hazard intensities and a range of building configurations within the constraints of the building type being considered. Statistical regression methods are then applied to this damage dataset to generate fragility functions.

This paper presents work being conducted at University College London towards the development of a method for constructing analytical fragility functions based on structural analyses. The proposed procedure comprises the iterative process shown in Figure 1.

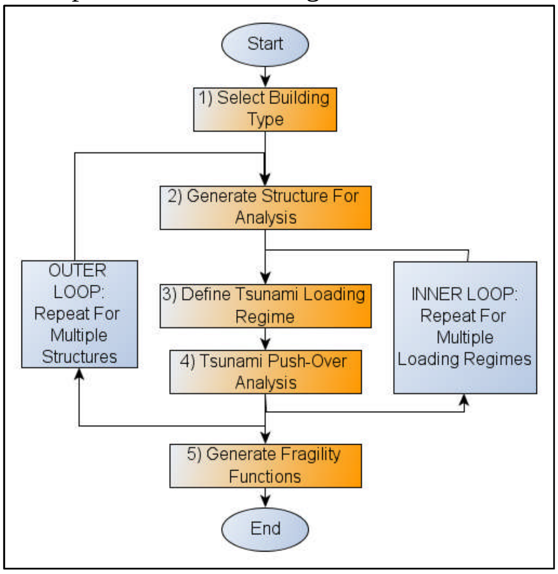


Figure 1: Proposed procedure for deriving analytical tsunami fragility functions.

ANALTICAL MODEL

Analytical structural models are required in order to model the population of buildings for which fragility functions are to be derived. Fragility functions are generally derived by building type, where buildings should be classified according to their structural properties, as this will govern their performance under tsunami loading. Empirical tsunami fragility functions exist for several building types, including RC, steel, wood and masonry (A. Suppasri et al. 2013). Fragility functions are also specific to a particular location as similar construction types from two different countries or even regions can perform very differently under the same tsunami conditions (EERI and IAEE n.d.; A. Suppasri et al. 2012a). Therefore, the analytical model is required to represent a particular building type in a particular part of the world (step 1 in Figure 1).

Within a building type (e.g. RC frame structures), there is variation of structural and material parameters (e.g. geometry, material strength, etc.). The range of analytical models used must represent this variability in the building population.

Example Application: Structural Model

For the purposes of this preliminary investigation structural variability will not be considered, only the structural model shown in Figure 2 will be analysed, variability will still be considered in the loading. The RC framed structure analysed is the four-story, 2D bare frame shown in Figure 2. This 2D frame represents the central bay of a typical building constructed in Southern Europe in the 1950's and 60's. Non-linear analysis of the structure is carried out via the fibre-plasticity approach, using the analysis package Seismotruct. Details of the model and the analysis method are given in Macabuag, Rossetto, and LLoyd (2014).

Note that this structure has been selected as it is one of the structures used by Rossetto and Elnashai (2003) to derive the seismic damage state threshold definitions that will be used in this tsunami fragility function investigation (Table 2). Using the same building under a different loading regime (i.e. tsunami loading) will allow investigation of the appropriateness of using seismic damage scale definitions for tsunami fragility function derivation.

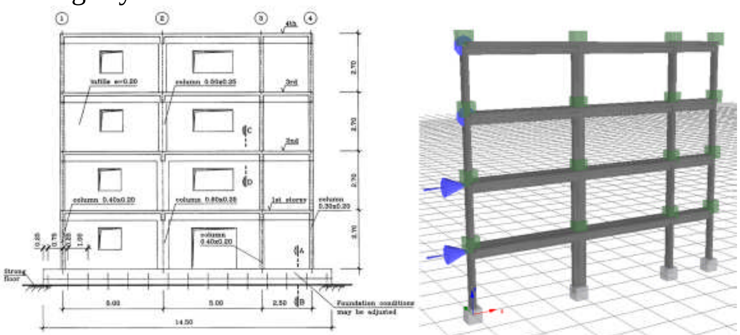


Figure 2: Structural elevation (left. Source: (Carvalho et Al 1999)) and FE model (right) with equivalent nodal forces for a tsunami rising above the 2nd floor. Not that for this analysis, openings are ignored and the structure is considered impermeable (Macabuag, Rossetto, and LLoyd 2014a).

TSUNAMI LOADING REGIME

Current tsunami guidelines and recent studies provide equations for the estimation of maximum tsunami loads on buildings from knowledge of the local building inundation. Tsunami loading relationships recommended in design-guidance documents are discussed in Macabuag, Rossetto, and LLoyd (2014a) and time-history tsunami loadings are presented in Lloyd and Rossetto (2012). However, there is a great deal of uncertainty in the spatial and temporal distribution of loads imposed by tsunami on buildings, as well as the magnitude of these loads. This variability in the loading that may be experienced by a building population must also be captured in the analytical models used for fragility function derivation (the inner loop in Figure 1).

Tsunami-induced building damage can arise due to hydrostatic forces (including buoyancy), hydrodynamic effects (drag and bore impact) and debris (impact and damming). There are several methods for grouping building damage (Chock et al. 2013; Fukuyama, Kato, and Ishihara 2013) considering global lateral deflection (Figure 3), out-of-plane failure of walls, disproportionate collapse (from the failure of load-bearing elements) and foundation effects (e.g. scour, sliding and overturning) (EEFIT 2013).

Figure 3: Global lateral deflection/failure due to lateral fluid load (hydrostatic and hydrodynamic) (EEFIT 2011).

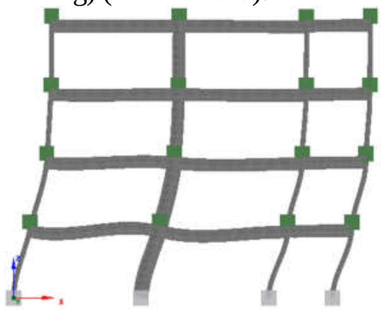


Figure 4: Structural model under lateral fluid loading.

Example Application: Input Loads

Given the complexity of the full tsunami loading regime, this preliminary investigation will look to examine a simplified case whereby only lateral hydrodynamic fluid loads will be considered. I.e. debris, buoyancy and net hydrostatic effects will not be considered.

To represent uncertainty in the tsunami loading, for this preliminary investigation, the structure will be analysed under loading from several tsunami design guidance documents. The results from all analyses will then be combined in order to create fragility functions which represent a range of possible loading regimes which can be experienced within the population of buildings. It is noted that this is not proposed as an accurate method for capturing loading variability (the inner loop shown in Figure 1), but the variation in design-code loading will be used in this example application to demonstrate how fragility functions may be formed.

Figure 5 shows the input loads calculated for all load cases given in Table 1. For further discussion on the forces, codes and load cases chosen see Macabuag, Rossetto, and LLoyd (2014).

Tsunami PO Curve Ref	Design Standards	Description of Loading
1	MLIT 2570	Equivalent hydrostatic pressure. No shelter from the incoming wave.
2	MLIT 2570	Equivalent hydrostatic pressure. >500m from the water source with shelter from the incoming wave.
3	MLIT 2570	Equivalent hydrostatic pressure. <500m from the water source with shelter from the incoming wave.
4	FEMA 646	Impulse loading based on the maximum momentum flux at each inundation depth. Uniform vertical distribution. Runup taken as that of the maximum credible tsunami at the site, assumed as 10m for the purpose of this investigation.
5	FEMA 646	Impulse loading based on the minimum momentum flux at each inundation depth. Uniform vertical distribution.
6	ASCE 7-16	Simplified pseudo-static approach. Hydrostatic pressure distribution with density multiplied by 3.
7	ASCE 7-16	Hydrostatic drag (no bore impact).
8	ASCE 7-16	Bore impact over standing water. At each step of inundation depth (h_i), bore height = 50% of inundation depth and standing water is assumed to a depth of 15% of the bore height.
9	ASCE 7-16	Bore impact over a dry bed. At each step of inundation depth (h_i), bore height = 50% of inundation depth.

Table 1: Load cases used to generate tsunami push-over curves. Based on current and upcoming design standards (Chock 2013; FEMA 2012; MLIT 2011; Robertson and Riggs 2011).

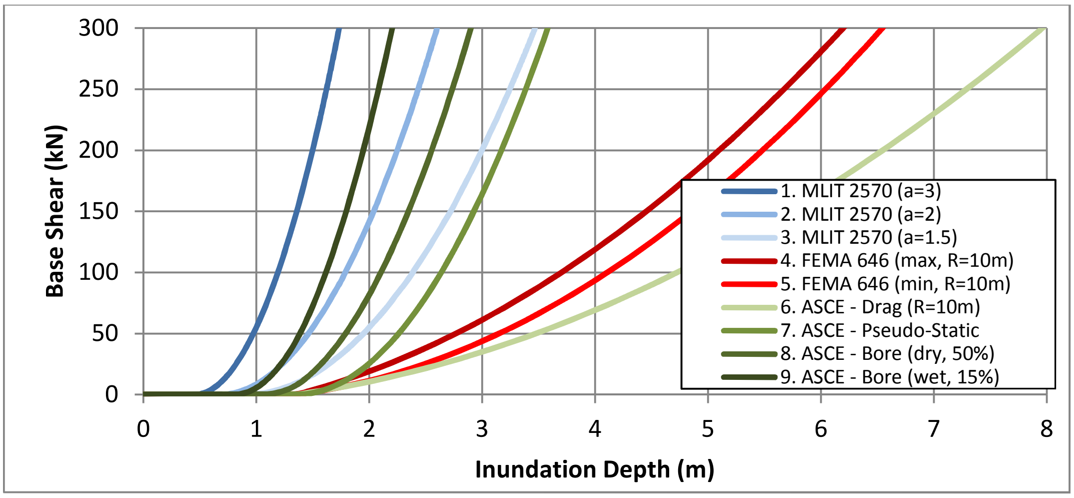


Figure 5: Comparison of input loads. See Macabuag, Rossetto, and LLoyd (2014) for discussion on the various loading scenarios described by these different loadcases.

STRUCTURAL ANALYSIS

Tsunami pushover analysis is carried out in order to rapidly assess structural performance over a range of tsunami intensities (the inner loop shown in Figure 1). Tsunami pushover analysis is a novel methodology whereby a structural model is loaded by tsunamis of various heights in order to generate tsunami pushover curves characterizing the structural performance under tsunami loading. See Macabuag, Rossetto, and LLoyd (2014b) for a discussion of the method and its relation to conventional seismic pushover analysis.

Example Application: Results of Tsunami Pushover Analyses

A series of analyses were carried out of the structure shown in Figure 2 loaded by tsunamis of various heights. In order to best illustrate the tsunami pushover procedure this preliminary study focuses on the simple lateral deflection failure mechanism shown in Figure 3. This is in order to generate preliminary tsunami pushover curves characterizing the structural performance under tsunami loading. The loading procedure and analysis of structural performance and failure mechanisms is discussed in Macabuag, Rossetto, and LLoyd (2014a). The resulting capacity curves for the analysed structure under the various loading profiles are shown in Figure 6 below.

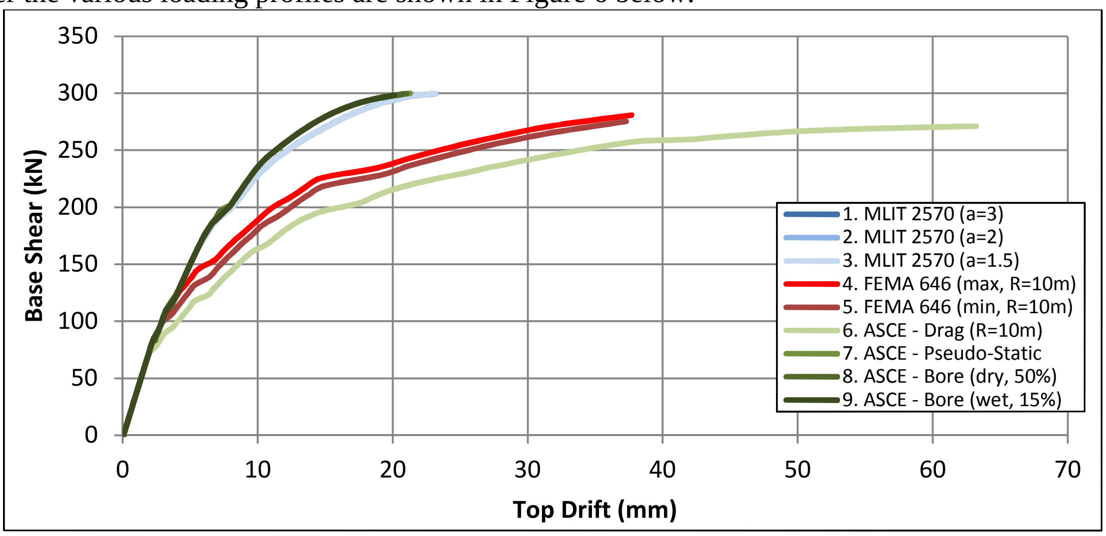


Figure 6: Applied load vs top drift. Note that cases 1, 2, and 3 all lie on the same curve, as do cases 7, 8 and 9. See Macabuag, Rossetto, and LLoyd (2014) for discussion on this result.

FRAGILITY FUNCTION DERIVATION

Using the results of structural analysis, analytical fragility functions can then be derived (Figure 7). In order to do this it is necessary to relate the structural response, represented by an Engineering Demand Parameter (EDP) to a tsunami Intensity Measure (IM).

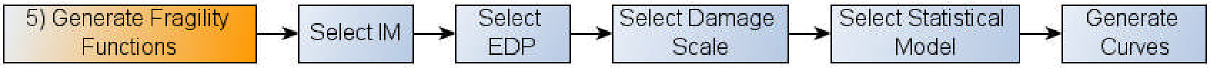


Figure 7: Procedure for deriving analytical fragility functions from structural analysis data.

Current empirical tsunami fragility functions generally use one of two IMs: flow depth and flow velocity. Tsunami flow depth is the most commonly used IM to build empirical tsunami fragility curves as it is relatively straightforward to measure in the field. Flow velocities are not usually taken into account as they are hard to determine from observations (EEFIT 2006), although numerical inundation modelling is beginning to allow for the development of empirical fragility functions which use velocity as their IM (Gokon, Koshimura, and Matsuoka 2010; a. Suppasri, Koshimura, and Imamura 2011; A. Suppasri, Koshimura, and Imamura 2009).

Very few analytical tsunami fragility functions have been published and so a suitable EDP has not yet been established in literature. It will therefore be necessary to select an EDP for the purposes of this study. Damage is then to be assessed based on the EDP values. An EDP-based damage scale is therefore required to rank the data into damage classes according to the degree of non-structural and structural damage to the analysed buildings. However, tsunami damage state definitions as a function of EDP have also not yet been developed, and so a suitable damage scale will need to be developed for this study.

Once structural performance has been transformed into damage data, fragility curves can then be fit to that data. Statistical model fitting to derive fragility functions assumes that the probability of damage exceeding a given damage state is a function of intensity (e.g. P(ds>DS|IM) = f(IM)) and calculates the nature of that function based on sample damage data (i.e. curve-fitting). Two statistical models that are commonly used in the literature are linear models (e.g. utilizing linear least squares regression (A. Suppasri et al. 2012b)) and the generalized linear model (e.g. utilizing logistic regression (Reese et al., 2011)). Linear models rely on a number of assumptions that can often not be met in practice and the Generalized Linear Model is becoming considered more appropriate for fragility function derivation (D'Ayala et al. 2013).

Example Application: Structural Model

The pushover curves shown in Figure 6 represent structural behaviour under tsunami loading. This structural response data must be transformed into EDP-IM space (Figure 8). Tsunami loading defined by current Japanese design codes, is defined entirely by inundation depth (Macabuag, Rossetto, and LLoyd 2014a), therefore depth will be used as the IM in this case. This will also allow for easier comparison with empirical tsunami fragility functions, the majority of which are also based on inundation depth. A common EDP for seismic analytical fragility functions is inter-story drift ratio (ISDR), which will also be adopted here.

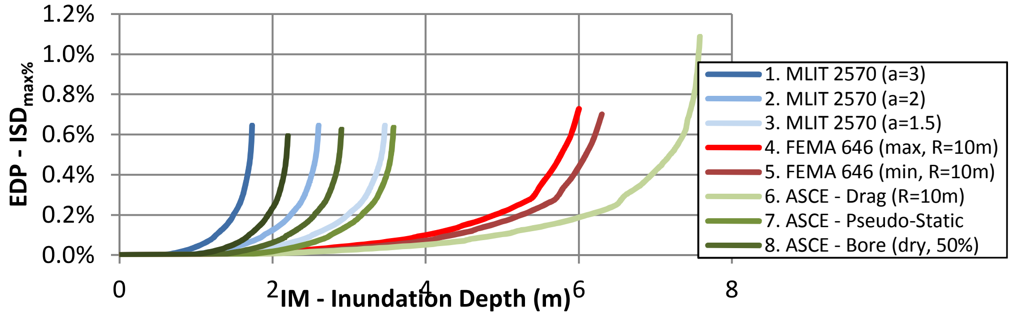


Figure 8: Maximum Inter-Story Drift Ratio vs inundation depth (i.e. EDP vs IM). Each curve ends at the point at which numerical instability of the analysis model occurred.

Tsunami damage state definitions as a function of ISDR have also not yet been developed, and so a seismic damage scale will initially be adopted. The selected damage scale (Table 2) was developed by calibration against several full-scale structural seismic experiments, including the structure used in this tsunami pushover investigation (T. Rossetto and Elnashai 2003).

Figure 10 shows fragility functions for the damage states and damage scale defined in Table 2. The procedure for deriving the fragility functions was to define several statistical models and then select a model based on the Akaike Information Criterion (AIC) relative goodness-of-fit test, which is appropriate for comparing non-nested models as outlined in T Rossetto et al. (2014). The statistical models tested considered transformed (ln|h|) and non-transformed IMs, ordered and partially-ordered models, and compared logit, probit, chauchit, loglog and complimentary loglog link functions. This is according to the procedure set out in Charvet et al. (2014). The chosen statistical model is a partially-ordered model regressed on the logarithm of the inundation depths using a probit link function (Figure 10, Equation (1), where Φ^{-1} denotes the inverse cumulative normal distribution).

Damage State	Inter-Storey Drift (ISD) Range
None	0 – 0.32%
Slight	0.04 – 0.43%
Light	0.5% – 1.02%
Moderate	1.02% – 2.41%
Extensive	2.41% – 4.27%
Partial Collapse	4.27% – 5.68%
Collapse	> 5.68%

Table 2: Seismic Analytical Damage Scale: $ISD_{max\%}$ limit state threshold values for moment-resisting RC frames designed to pre-seismic codes (T. Rossetto and Elnashai 2003).

$$\Phi^{-1}[P(DS \geq ds_i|h)] = \alpha_i + \beta_i \ln|h| \quad (1)$$

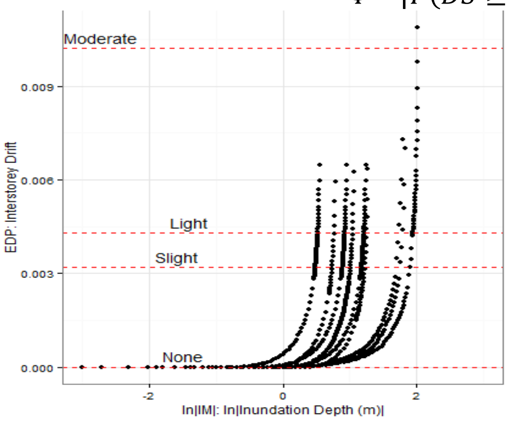


Figure 9: IM vs EDP. Performance points from structural analyses. Horizontal lines represent the thresholds defined in Table 2.

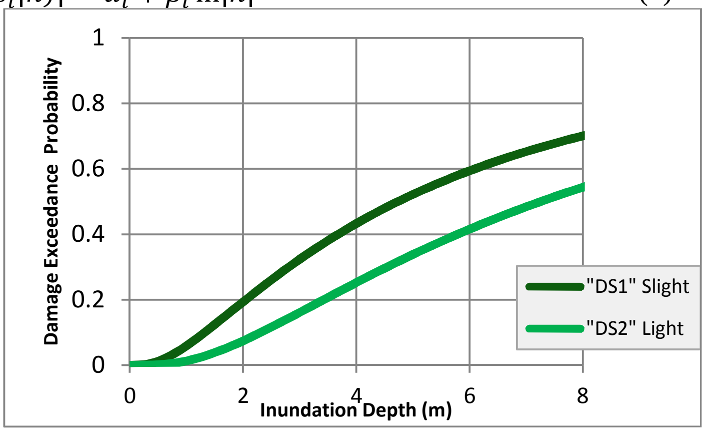


Figure 10: Fragility functions based on seismic damage state definitions.

Note that although seven damage states (including "no damage") are defined in Table 2, only two curves are shown in Figure 10. This is because only three damage state thresholds are crossed in Figure 9, and the third threshold (moderate damage) only has one point beyond it, which is not enough data to sensibly form a fragility function.

Figure 9 and Figure 10 show that according to the seismic analytical damage scale used, inter-story drift ratios indicating only light or moderate damage can be achieved before instability of the analysis model occurs. This is because for seismic deflection-based damage scales higher damage states defined are often defined on the post-peak softening branch of the seismic pushover curve. The tsunami pushover procedure does not generate a post-peak softening branch (Macabuag, Rossetto, and LLoyd 2014b) and so seismic EDP-based damage scales are not appropriate for defining tsunami damage states as they do not pick up higher damage states induced by tsunami loading. Therefore, the definition of a new EDP-based damage scale for the specific case of tsunamis must be investigated.

TOWARDS DEFINING AN ANALYTICAL TSUNAMI DAMAGE SCALE

Using seismic EDP and damage state definitions may not be appropriate for the definition of analytical tsunami fragility functions. Therefore, new damage state thresholds will be estimated. The same damage definitions will be used as for an empirical damage scale utilized in Japan following the 2011 Great East Japan Earthquake and Tsunami, so that analytical and empirical curves can be compared. The analytical damage state definitions will be correlated with the empirical damage states via the criteria shown in Table 3. The criteria used to define yielding, spalling and crushing of columns in the analytical model are shown in Table 4. Only structural damage states will be compared, and so minor and moderate damage will be ignored as they define damage to non-structural elements. It is noted that the selected criteria are only a first estimate and further calibration will be required.

Table 5 shows the interstorey drift ratios for each loadcase at which the criteria given in Table 4 are reached. The mean of these values is then taken as an estimate for the new damage state threshold, with the exception of damage state 6, whereby the lowest $ISD_{max\%}$ at which numerical instability of the analysis model occurs is taken as the estimate, so that all loadcases will have at least one instance where they reach damage state 6. The fragility functions derived from these estimated tsunami damage state thresholds are shown in Figure 12.

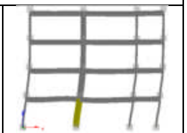
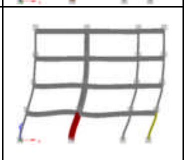
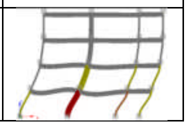
Damage State	Classification	Description	Condition	FE Model Definition	Model Image
DS1	Minor damage	No significant structural or non-structural damage, only minor flooding.	Possible to use after minor floor and wall clean up.	Not currently considered in analytical model.	
DS2	Moderate damage	Slight damage to non-structural components.	Possible to use after moderate reparation.		
DS3	Major damage	Heavy damage to some walls but no damage in columns.	Possible to use after major reparations.	1st Yield	
DS4	Complete damage	Heavy damage to several walls and some columns.	Possible to use after complete reparation and retrofitting.	1st Spall	
DS5	Collapse	Destructive damage to walls (more than half of wall density) and several columns (bent or destroyed).	Loss of functionality (system collapse). Non-repairable or great cost for retrofitting.	1st Crush	
DS6	Washed away	Washed away, only foundations remained, total overturn.	Non-repairable, requires total reconstruction.	Numerical Instability	

Table 3: Damage state classification table. Analytical damage state definitions are correlated with an empirical scale used by the Japanese Ministry of Land, Transport and Infrastructure (MLIT) after the 2011 Japan tsunami. The criteria for yielding, spalling and crushing are shown in Table 4.

Performance Criteria Description	Material Monitored	Strain Criteria	Colour
Yielding	Steel reinforcing bars	$\varepsilon > 0.0013$	Yellow
Spalling	Concrete cover	$\varepsilon > -0.0025$	Orange
Crushing	Core concrete (contained within rebar)	$\varepsilon > -0.0031$	Red

Table 4: Performance criteria indicated by coloured members in Table 3.

Damage State (survey)	Definition in FE Model	ISD$_{max\%}$ at DS Criteria									
		1	2	3	4	5	6	7	8	9	Estimated Thresholds
DS1		Not currently considered in analytical model.									
DS2											
DS3	1st Yield	0.21%	0.23%	0.23%	0.23%	0.24%	0.24%	0.21%	0.21%	0.23%	0.22%
DS4	1st Spall	0.36%	0.36%	0.36%	0.40%	0.38%	0.43%	0.37%	0.37%	0.37%	0.38%
DS5	1st Crush	0.46%	0.46%	0.46%	0.52%	0.51%	0.50%	0.48%	0.46%	0.48%	0.48%
DS6	Numerical Instability	0.60%	0.65%	0.60%	0.73%	0.70%	1.09%	0.64%	0.63%	0.59%	0.59%

Table 5: ISD values, by load case, at which the criteria given in Table 4 are reached.

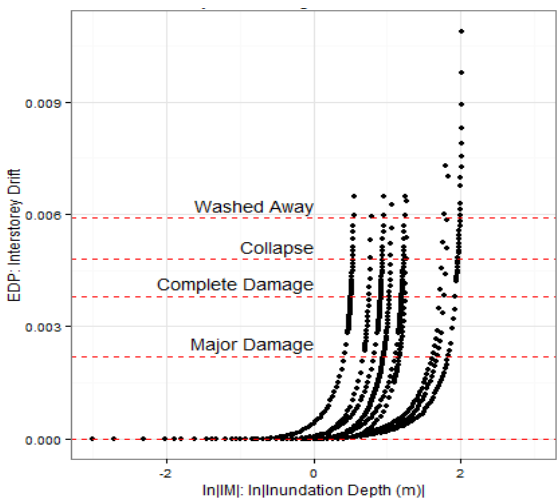


Figure 11: IM vs EDP. Note that the same performance points have been used as for Figure 9. Only the damage state thresholds have been adjusted.

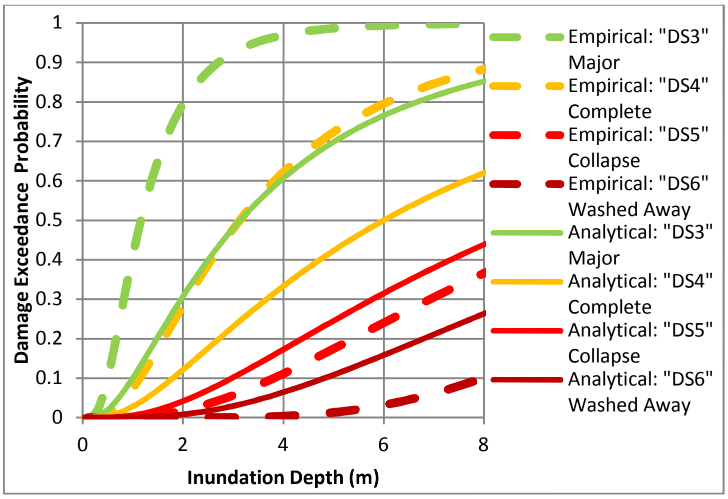


Figure 12: A comparison between the analytical and empirical fragility functions. The empirical curves are derived from data from the 2011 Great East Japan Earthquake and Tsunami, based on RC structures greater than 3 floors (A. Suppasri et al. 2013).

Example Application: Comparing Analytical and Empirical Fragility Functions

Figure 12 shows the derived analytical tsunami fragility functions plotted with empirical curves, for comparison. The empirical curves are derived from building damage survey data from the 2011 Great East Japan Earthquake and Tsunami, based on RC structures greater than 3 floors (A. Suppasri et al. 2013).

The empirical fragility functions chosen for comparison are for the closest available building type to that used in the structural analysis. However, the damage dataset used to derive these curves will include buildings of different structural properties from that analysed in this preliminary study (e.g. buildings with several floors, designed to seismic codes and of different material and geometric properties). In addition, empirical curves cannot be considered as ‘correct’ for validation of analytical curves, as they represent many factors that are not picked up in the structural analysis (some of which are biases that distort the empirical data, T Rossetto et al. (2014)). Therefore, it is not possible to make definite conclusions on the accuracy of the analytical fragility functions here, but a preliminary comparison serves to indicate whether the proposed fragility function derivation method may be considered feasible.

Given that the empirical dataset will include buildings that have more floors and are stronger than the structural analysis model, it would be expected that the empirical fragility curves should indicate lower levels of damage. This is true for the “washed away” (DS6) and “collapse” (DS5) damage states, but not the case of “complete damage” (DS4) and “major damage” (DS3).

The empirical curves appear to be spread over a wider range, so that the “major damage” curve (DS3) is higher and the “washed away” curve (DS6) is lower than the analytical curves. The analytical “major damage” curve (DS3) appears to be more closely correlated with the empirical “complete damage” curve (DS4) suggesting that the analytical criteria of yield first appearing in the loadbearing elements of the structure may be a more suitable definition for DS4, than the currently assigned DS3 (Table 3). The analytical “collapse” curve (DS5) lies close to the empirical “collapse” curve indicating that column crush may be an adequate indicator of collapse, if also accounting for vertical load redistribution (i.e. the capacity of the structure to survive losing loadbearing elements). The “washed away” curves (DS6) do not show good correlation, possibly indicating that numerical instability is likely not a reliable criteria, as this can be indicative of a number of features of the analysis and can be affected by altering the calculation parameters so is subjective to the analysis package used.

NEXT STEPS FOR ANALYTICAL FRAGILITY FUCTION DERIVATION

Structural Modelling

It will be necessary to extend the analysis to a series of structural models which represent the population of buildings for which the fragility functions are being produced (the outer loop in Figure 1). There will be material and geometric variability within the building population and when generating analytical models it may be possible to represent this variability by considering the building as a series of parameters defined as random variables of defined distribution, mean and standard deviation (Tiziana Rossetto and Elnashai 2005). Each time an analytical model is generated (i.e. for each step in the outer loop shown in Figure 1) the building can be generated by taking a random sample of each of the parameters that define the structure.

In addition to inter-story heights, slab and beam dimensions, reinforcement details and material strengths, there are several additional factors which will affect a building’s response to tsunami loading, and so must be captured in the analytical model. The following factors are often considered in seismic fragility function derivation: the redundancy of vertical load paths, the presence of deep or shallow foundations, the building age and the design standards followed. The following factors are not considered in seismic fragility function derivation and so are new considerations for tsunami fragility function derivation: building permeability (e.g. considering the presence of openings and break-away walls), the presence of shelter in the seaward direction, and the orientation of the structure.

The range of tsunami-induced failure mechanisms will need to be incorporated in the analytical model, and the significance of conducting more detailed 3D structural analysis (and simplified single-degree-of-freedom system analysis) on fragility function accuracy will be examined in future studies.

Tsunami Loading

The differences in the IM-EDP relationships shown in Figure 8 highlight that the resultant damage predictions (i.e. the implementation of the derived fragility functions) will be different, depending on the loading regime used. This highlights that structural analysis for accurate damage predictions requires the loading applied to be as realistic as possible (in terms of both magnitude and distribution) for each inundation depth, and so simplified and conservative loading defined for design purposes may not provide the required accuracy. To ascertain the validity of using design standard forces for fragility function derivation it will be necessary to compare results with those using more detailed time-history forces from physical experiments (Robertson and Riggs 2011; Tiziana Rossetto et al. 2011).

The distribution of loading parameter variables for a given IM (e.g. range and probability distribution of loads for a given inundation depth) will also need to be examined in order to perform the inner loop iterations shown in Figure 1.

Intensity Measure (IM)

Relying on inundation depth as a single parameter to characterise tsunami hazard when other factors are also at play in a tsunami-building interaction scenario is likely to be inaccurate, as shown by (Charvet et al. 2014). Flow velocity is another major factor, which has the potential to be incorporated in analytical fragility functions. Further considerations which may affect tsunami intensity are: duration of immersion and the total number of waves, the likelihood of debris impacts, and the level of preceding seismic damage.

Engineering Demand Parameter (EDP) and Damage State Definition

The preliminary ISD threshold estimates given in Table 5 are based on analysis of only one building, and so this analysis would have to be extended to populations of buildings to improve accuracy, and provide EDP-based damage scales for multiple building types. However, it should be noted that it is difficult to correlate and validate the resulting damage state thresholds as very limited physical and experimental data exists.

In addition, ISD has been assumed as the EDP in this preliminary study, due to its propensity in seismic analytical fragility function derivation. However, this assumption will need to be examined as alternative EDPs may be more appropriate for tsunami damage prediction, or it may prove more accurate to define damage states based directly on element performance, such as the criteria shown in Table 4.

Statistical Modelling

Whilst the use of the generalized linear model in this preliminary study avoids the discussed pitfalls of linear regression, rigorous statistical modelling will require the use of model diagnostic tools (e.g. absolute goodness-of-fit tests) and quantification of uncertainty (e.g. through confidence intervals, T Rossetto et al. (2014)).

CONCLUSION

This paper has presented a proposed method for deriving analytical tsunami fragility functions, demonstrated by a simple example for an RC frame structure using design standard tsunami loadings. The main conclusions are as follows:

- The analytical fragility functions produced are order-of-magnitude comparable to empirical fragility functions derived from the 2011 Great East Japan Earthquake and Tsunami. Analysis must be carried out for populations of buildings, and considering more realistic forces and failure mechanisms, to build confidence in the fragility functions produced. However, the comparison serves to demonstrate the validity of the proposed method for generating analytical fragility functions.
- The selection of the tsunami Intensity Measure (IM), Engineering Demand Parameter (EDP), damage state definition and building type poses a number of considerations that are separate from those for seismic fragility function derivation. Therefore, each parameter must be closely examined for the unique case of tsunamis, in order to develop accurate analytical tsunami fragility functions.
- The tsunami pushover curve of a structure is very sensitive to the load distribution applied. Similarly, the definition of load as a function of the tsunami intensity measure (e.g. depth) has a large effect on the resultant damage prediction. Therefore the loading applied must be as realistic as possible for each inundation depth, and conservative design guidance loadings may give inaccurate damage prediction results.

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