EARTHQUAKE AND TSUNAMI RISK PRIORITISATION OF INDONESIAN SCHOOLS THROUGH RAPID VISUAL SURVEY

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Abstract: *Located on the Ring of Fire, Indonesia is a highly earthquake- and tsunami-prone country, continuously experiencing disastrous events (e.g., the recent 2018 Sulawesi earthquake and tsunami). Educational facilities demand special attention in terms of priority for assessment and retrofit, given the strong bond between access to education and development and the higher vulnerability of school children to natural hazards. This paper first presents the results of a campaign of rapid visual surveying on 88 reinforced concrete (RC) school buildings in Banda Aceh, Indonesia. To this aim, a form has been developed by the authors allowing to collect relevant structural engineering information in a systematic and effective way. The collected data is used to define an empirical earthquake-tsunami relative risk prioritisation scheme for the surveyed buildings. This is based on a seismic risk index, recently proposed by the authors, and the revised Papathoma Tsunami Vulnerability Assessment (PTVA) index for tsunami. Consistently with the prominent trends in the geometric/mechanical data, the results show that the seismic vulnerability is similar for all the considered buildings, and the prioritisation ranking is strongly governed by the distance of the buildings from the coast, which is a proxy for the tsunami risk. The analysis of the geometrical and mechanical data further allows to identify clear trends in the construction practice, and to define an index building representing the whole portfolio. Seismic fragility and vulnerability functions of the index building can be derived through a refined nonlinear numerical model of the archetype school building.*

1. Introduction

Regional seismic risk assessment is paramount in highly earthquake-prone areas. In fact, in several countries around the world, a large portion of the building stock has been designed according to obsolete structural codes, which include little-to-no provisions for earthquake resistance and detailing. Several Reinforced Concrete (RC) buildings fall in this category, and they often represent the highest share for both residential and commercial occupancy in many countries around the world. RC structural systems are also widely used in the design of critical infrastructure, such as hospitals and school facilities. Those are the focus of this paper. Clearly, it is desirable that any risk-mitigation strategy designed by governmental agencies should be based on a rational understanding of the risk of large building groups – or portfolios – at a country level (or in a smaller region). However, it is cost-ineffective to perform detailed structural simulations for a large amount of structures, given the shortage of both financial and technical/computational resources. Therefore, a multi-level approach is usually preferred, starting with a screening based on simplified and rapid methods and performing more detailed structural analyses only for selected groups of structures at higher relative risk and for which an archetype (or index) building can be identified (e.g., FEMA P-154, 2015; Grant et al., 2007).

Common approaches for regional seismic risk assessment of RC buildings refer to typological approaches based on pre-determined building categories (e.g., Giovinazzi and Lagomarsino, 2004), or the use of Rapid Visual Survey (RVS) forms and calibrated empirical seismic vulnerability/risk indices. Although these approaches rely on various assumptions and usually involve some degree of subjectivity (mainly reflected in the choice and the assigned relative importance of the parameters involved in the analysis), such simplified methods provide valuable proxies to develop prioritisation schemes. However, given the low amount of information required, such methods do not allow to

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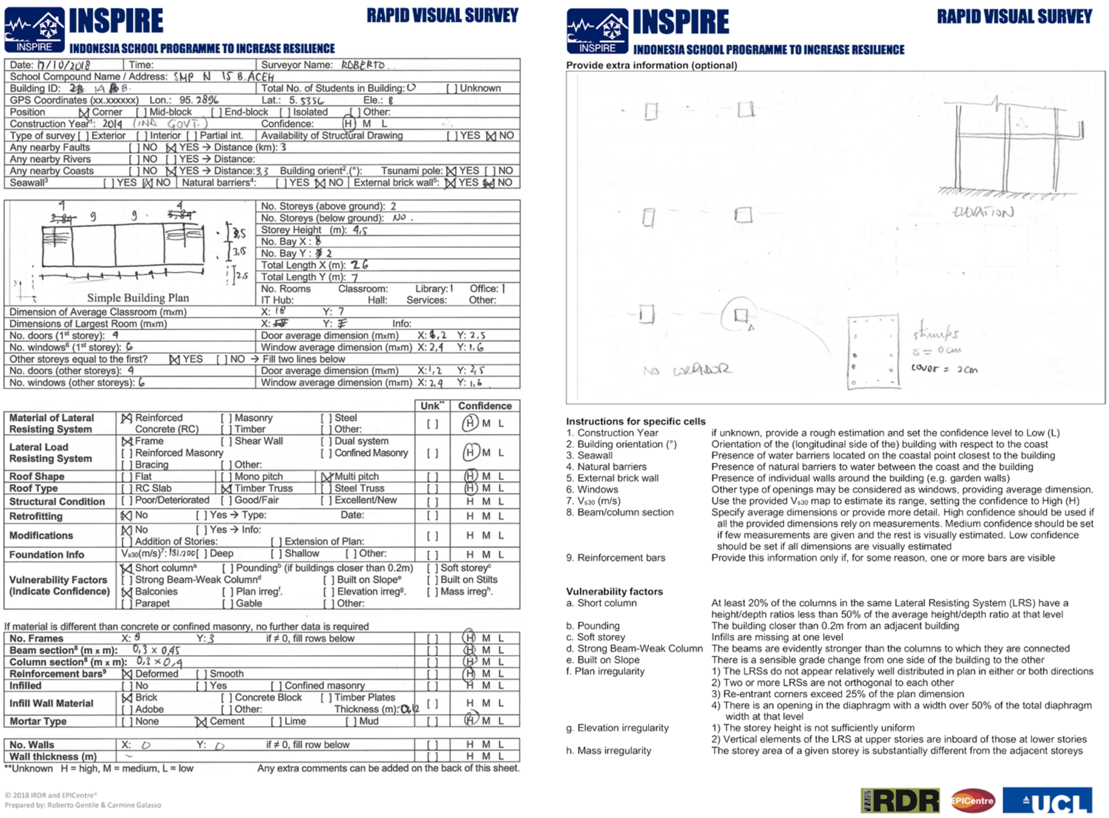
further refine the analysis, providing a more detailed, second-level seismic risk assessment. In addition, those methods mostly refer to seismic hazard, which in some countries might not be enough for the development of a rational multi-hazard prioritisation scheme.

A new RVS form and a seismic risk prioritisation index for RC buildings are proposed in this study to address the above-mentioned gaps. The INSPIRE (INdonesia School Programme to Increase REsilience) RVS form (Figure 1) is designed to be completed by trained engineers in approximately 20-30 minutes by means of a sidewalk survey. This is a one-page form including various sections related to the general identification and geolocation of the building, its geometric properties, its structural characteristics and deficiencies, including the structural typology and the dimensions/details of the main structural members. It is also possible to assign a “confidence level” for each parameter, allowing for a better classification and weighting of the data after a campaign of RVSs. The collected data is fully compatible with both the Global Earthquake Model (GEM) Building Taxonomy (Brzev et al., 2013) and the HAZard United States (HAZUS) model (Kircher et al., 2006).


INSPIRE — RAPID VISUAL SURVEY
INDONESIA SCHOOL PROGRAMME TO INCREASE RESILIENCE

General Info.

Date: 17/10/2018 · Time:	Surveyor Name: ROBERTO
School Compound Name / Address: SMP N 15 B.ACEH	
Building ID: 14A	Total No. of Students in Building: 0 · [ ] Unknown
GPS Coordinates (xx.xxxxxx) Lon.: 95.2896	Lat.: 5.5356 · Ele.: 8
Position [X] Corner [ ] Mid-block [ ] End-block [ ] Isolated [ ] Other:	
Construction Year[1]: 2014 (IND GOVT.)	Confidence: (H) M L
Type of survey [ ] Exterior [ ] Interior [ ] Partial int.	Availability of Structural Drawing [ ] YES [X] NO
Any nearby Faults [ ] NO [X] YES → Distance (km): 3	
Any nearby Rivers [ ] NO [ ] YES → Distance:	
Any nearby Coasts [ ] NO [X] YES → Distance: 3,3	Building orient[2] (°): · Tsunami pole: [X] YES [ ] NO
Seawall[3] [ ] YES [X] NO	Natural barriers[4]: [ ] YES [X] NO · External brick wall[5]: [X] YES [ ] NO

Building Info.

Simple Building Plan	No. Storeys (above ground): 2
	No. Storeys (below ground): NO
	Storey Height (m): 4,5
	No. Bay X: 8
	No. Bay Y: 2
	Total Length X (m): 26
	Total Length Y (m): 7
	No. Rooms · Classroom: · Library: 1 · Office: 1 · IT Hub: · Hall: · Services: · Other:
Dimension of Average Classroom (mxm)	X: 18 · Y: 7
Dimensions of Largest Room (mxm)	X: · Y: · Info:
No. doors (1st storey): 4	Door average dimension (mxm) X: 1,2 Y: 2,5
No. windows[6] (1st storey): 6	Window average dimension (mxm) X: 2,4 Y: 1,6
Other storeys equal to the first? [X] YES [ ] NO → Fill two lines below	
No. doors (other storeys): 4	Door average dimension (mxm) X: 1,2 Y: 2,5
No. windows (other storeys): 6	Window average dimension (mxm) X: 2,4 Y: 1,6

Structural Info.

		Unk**	Confidence
Material of Lateral Resisting System	[X] Reinforced Concrete (RC) [ ] Masonry [ ] Timber [ ] Steel [ ] Other:	[ ]	(H) M L
Lateral Load Resisting System	[X] Frame [ ] Shear Wall [ ] Dual system [ ] Reinforced Masonry [ ] Confined Masonry [ ] Bracing [ ] Other:	[ ]	(H) M L
Roof Shape	[ ] Flat [ ] Mono pitch [X] Multi pitch	[ ]	(H) M L
Roof Type	[ ] RC Slab [X] Timber Truss [ ] Steel Truss	[ ]	(H) M L
Structural Condition	[ ] Poor/Deteriorated [ ] Good/Fair [ ] Excellent/New	[ ]	H M L
Retrofitting	[X] No [ ] Yes → Type: Date:	[ ]	H M L
Modifications	[X] No [ ] Yes → Info: [ ] Addition of Stories: [ ] Extension of Plan:	[ ]	H M L
Foundation Info	V_{s30}(m/s)[7]: 181-200 [ ] Deep [ ] Shallow [ ] Other:	[ ]	H M L
Vulnerability Factors (Indicate Confidence)	[X] Short column[a] [ ] Pounding[b] (if buildings closer than 0.2m) [ ] Soft storey[c] [ ] Strong Beam-Weak Column[d] [ ] Built on Slope[e] [ ] Built on Stilts [X] Balconies [ ] Plan irreg[f]. [ ] Elevation irreg[g]. [ ] Mass irreg[h]. [ ] Parapet [ ] Gable [ ] Other:		

If material is different than concrete or confined masonry, no further data is required

		Unk**	Confidence
No. Frames	X: 9 Y: 3 if ≠ 0, fill rows below	[ ]	(H) M L
Beam section[8] (m x m):	0,3 x 0,45	[ ]	(H) M L
Column section[8] (m x m):	0,3 x 0,4	[ ]	(H) M L
Reinforcement bars[9]	[X] Deformed [ ] Smooth	[ ]	(H) M L
Infilled	[ ] No [ ] Yes [ ] Confined masonry	[ ]	H M L
Infill Wall Material	[X] Brick [ ] Concrete Block [ ] Timber Plates [ ] Adobe [ ] Other: Thickness (m): 0,12	[ ]	H M L
Mortar Type	[ ] None [X] Cement [ ] Lime [ ] Mud	[ ]	(H) M L
No. Walls	X: 0 Y: 0 if ≠ 0, fill row below	[ ]	H M L
Wall thickness (m)	–	[ ]	H M L

**Unknown H = high, M = medium, L = low · Any extra comments can be added on the back of this sheet.

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Provide extra information (optional)

Instructions for specific cells

1. Construction Year — if unknown, provide a rough estimation and set the confidence level to Low (L)
2. Building orientation (°) — Orientation of the (longitudinal side of the) building with respect to the coast
3. Seawall — Presence of water barriers located on the coastal point closest to the building
4. Natural barriers — Presence of natural barriers to water between the coast and the building
5. External brick wall — Presence of individual walls around the building (e.g. garden walls)
6. Windows — Other type of openings may be considered as windows, providing average dimension.
7. V_{s30} (m/s) — Use the provided V_{s30} map to estimate its range, setting the confidence to High (H)
8. Beam/column section — Specify average dimensions or provide more detail. High confidence should be used if all the provided dimensions rely on measurements. Medium confidence should be set if few measurements are given and the rest is visually estimated. Low confidence should be set if all dimensions are visually estimated
9. Reinforcement bars — Provide this information only if, for some reason, one or more bars are visible

Vulnerability factors

a. Short column — At least 20% of the columns in the same Lateral Resisting System (LRS) have a height/depth ratios less than 50% of the average height/depth ratio at that level
b. Pounding — The building closer than 0.2m from an adjacent building
c. Soft storey — Infills are missing at one level
d. Strong Beam-Weak Column — The beams are evidently stronger than the columns to which they are connected
e. Built on Slope — There is a sensible grade change from one side of the building to the other
f. Plan irregularity — 1) The LRSs do not appear relatively well distributed in plan in either or both directions 2) Two or more LRSs are not orthogonal to each other 3) Re-entrant corners exceed 25% of the plan dimension 4) There is an opening in the diaphragm with a width over 50% of the total diaphragm width at that level
g. Elevation irregularity — 1) The storey height is not sufficiently uniform 2) Vertical elements of the LRS at upper stories are inboard of those at lower stories
h. Mass irregularity — The storey area of a given storey is substantially different from the adjacent storeys

Figure 1. INSPIRE Rapid Visual Survey form completed for building with ID 14A (Section 3).

The collected information allows to 1) calculate a newly-proposed seismic risk prioritisation index, introduced in Section 2; 2) calculate the Papathoma Tsunami Vulnerability Assessment index (PTVA4, Dall’Osso et al., 2016), in any of its variations, described in Section 3.2; 3) define one or more representative archetype buildings consistent with the local building codes and practice; 4) derive detailed numerical models of the archetype buildings, provided that simulated design is used to cross-check the model assumptions. This latter point is not discussed in this paper due to space constraints; however, the reader can refer to Gentile and Galasso (2019a,b) in the same proceedings.

In this study, the INSPIRE RVS form and proposed multi-hazard risk prioritisation index are applied to a portfolio of 85 RC school buildings in Banda Aceh, Indonesia, highlighting the simplicity and rapidity of the whole process.

2. Definition of the INSPIRE seismic risk index

The INSPIRE index (I_V) is an empirical proxy for the relative seismic risk of various buildings within a given building portfolio. The index is specifically defined for RC buildings, although its definition can be extended to other building types, and it consists of two parts: the baseline score (I_{BL}) and a performance modifier (ΔI_{PM}), which are summed up to obtain the final index (Eq. 1). In its current version, the baseline score is based on the fragility curves available in the HAZUS MH4 framework (Kircher et al., 2006), which allows to have a transparent and consistent fragility estimation for a wide range of structural typologies. HAZUS fragilities are defined by three “primary” parameters: RC Basic Structural System (BSS: Frame, Infilled frame or Wall), building height (Low-rise, Mid-rise or High-rise) and seismic design criteria (Pre-, Low-, Moderate- or High-code). On the other hand, the performance modifier is based on the score of the building regarding eight “secondary” parameters (preservation condition, plan shape, storey height uniformity, added storeys, infills at ground storey, short columns, pounding, unfavourable soil), which, if present, are deemed to jeopardise the performance of the building.

$$I_V = I_{BL} + \Delta I_{PM} \tag{1}$$

2.1. Baseline score

The HAZUS MH4 framework provide, among other information, an extensive set of fragility curves representing the seismic performance of archetype buildings which are classified based on four parameters: material (Mat), BSS, building Height and seismic Code level (defined according to the Uniform Building Code 1994, UBC 1994). Adopting the HAZUS fragility database as a reference is further motivated by the fact that several countries around the world have adopted seismic provisions which are, to different extents, consistent with the recommendations of the UBC 1994. For each archetype building category, four fragility functions are provided in HAZUS, respectively for the Slight, Moderate, Extensive and Complete Damage States (DS), or limit states. The fragility functions are defined as lognormal Cumulative Distribution Functions, or CDF (Eq. 2), in terms of different Intensity Measures, among which the Peak Ground Acceleration (PGA). The curves are defined by a median PGA (μ) and a dispersion term (β).

$$P(DS \geq DS_i \mid Mat, BSS, Code, Height, PGA) = \Phi\left(\frac{ln(PGA/\mu)}{\beta}\right), i = 1:4 \tag{2}$$

For the scope of this paper, the HAZUS fragility database has been filtered to consider only the curves related to RC buildings (namely, categories C1, C2, C3). Moreover, only the fragility curves corresponding to the Extensive Damage limit state (DS3) have been considered, which are mainly related to the Life Safety performance objective according to modern seismic codes. The details of the selected fragility curves (Figure 2.b) are reported in Gentile et al., 2019, together with the definition the involved HAZUS parameters.

To define the baseline score of the INSPIRE index, for each considered archetype building category, and its corresponding fragility curve, the probability to exceed DS3 (Extensive Damage) is calculated (Figure 2.a) for three levels of PGA, 0.1g, 0.25g, 0.4g, respectively corresponding to low, moderate and high seismicity levels. The analyst will select the seismicity level appropriate for the considered building portfolio/geographic area. The process above is repeated for each archetype building category in the HAZUS database, such that it is possible to map the building basic parameters to the exceeding probability of the DS, conditional to the considered PGA value, $P(DS \geq DS_i \mid Mat, BSS, Code, Height, PGA)$. The baseline score of the risk index is set to be proportional to such exceeding probability, after a re-scaling in a range [1%, 50%] based on the minimum/maximum DS3 exceeding probability in the complete (non-filtered) HAZUS database and calculated according to Eq. 3. In such equation, $P_{HAZUS,max}$ and $P_{HAZUS,\min}$ are the maximum and minimum DS3 exceeding probability in the HAZUS database for the chosen levels of PGA (indicated with dots in Figure 2.b), while P_{HAZUS} is the DS3 exceeding probability of the considered building, for the chosen level of PGA.

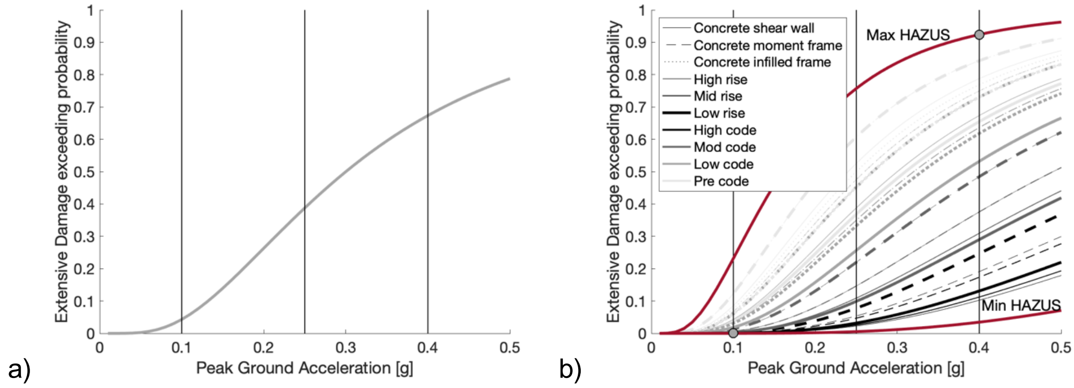

Figure 2. a) Example baseline score for a given archetype building typology. b) HAZUS fragility curve database related to the Extensive Damage limit state for RC buildings.

$$I_{BL} = \left(\frac{50-1}{P_{HAZUS,max} - P_{HAZUS,min}}\right)\left(P_{HAZUS} - P_{HAZUS,min}\right) + 1 \tag{3}$$

2.2. Performance modifier

Eight secondary parameters are used to define the performance modifier, which are deemed not explicitly considered in the HAZUS framework (and therefore in the baseline score) but at the same time, if present, can jeopardise the seismic performance of a given building. Firstly, a score ($SCORE_i$ in the range [0%, 100%]) is assigned for each secondary parameter (preservation condition, plan shape, storey height uniformity, added storeys, infills at ground storey, short columns, pounding, unfavourable soil); details on the assignment of such scores is provided in Gentile et al., 2019. Therefore, the performance modifier (ΔI_{PM}) is defined as a weighted sum of each of these scores (Eq. 4, where w_i is the weight of parameter i), finally scaling the result in the range [0%, 50%]. It is worth mentioning that, according to this definition, the performance modifier can only increase the baseline score, therefore denoting an increase in seismic fragility. For a more simplified utilisation, it is also possible to calculate the INSPIRE index considering the baseline score only. In such case, a default performance modifier equal to 25% is assigned (average of 0% and 50%). It is worth mentioning, however, that any uniform value of the performance modifier will not have effects on the overall prioritisation, since it will shift all the calculated indices by the same amount.

$$\Delta I_{PM} = \frac{1}{2}\sum_{i=1}^{8} w_i SCORE_i \tag{4}$$

The secondary parameters defining the performance modifiers are deemed to complement the information in the HAZUS fragility curves. The idea is that the baseline score (HAZUS fragility database) provides the (conditional) seismic risk of a given building class, while the secondary parameters are related to building-specific vulnerability factors. The secondary parameters have been selected based on the fundamental rules of seismic design (e.g., Paulay and Priestley, 1992) and the commonly observed post-earthquake damage on RC structures (e.g., Elnashai and Di Sarno, 2008). The score for each alternative has been defined based on a uniform partitioning of the range [0%, 100%].

Clearly, the secondary parameters defining the performance modifier do not have the same influence on the overall vulnerability and risk. For example, the absence of infill walls at the ground storey can lead to a soft-storey mechanism, which in turn can results in local or global collapse. On the other hand, the addition of storeys to a building can increase its risk to a lower extent, considerably less likely leading to collapse. Therefore, the weight of the former parameter should be higher than the latter, to reflect such a different effect on the overall seismic risk.

To this extent, the Analytic Hierarchy Process (AHP), originally proposed by Saaty (1980) is used to calibrate the weights in the proposed procedure. This allows to have a rational and mathematically-consistent assignment of the weights which is based on all the possible pairwise comparisons between the secondary parameters and eigenvalues theory. Hence, the selected weights can reflect the relative importance of each parameter with respect to the others in the determination of the performance modifier. The relative importance of each parameter is expressed in the range [1/9 9]. For the calibration proposed in this paper, the pairwise comparisons are performed considering the relative influence of the secondary parameters on the Life Safety performance objective. The details related to the AHP for this exercise are available in Gentile et al., 2019.

2.3. Multi-hazard considerations

In many common situations, it is very likely that seismic considerations alone are not enough to define a robust prioritisation scheme for the decision-making process by a governmental agency or the owner of a large building portfolio. To deal with such scenario, this paper presents a simple methodology to include other hazards in the prioritisation scheme.

Simplified analytical indices are available for the estimation of the vulnerability of buildings to natural hazards different than seismic hazard, such as Tsunami, Flood, Wind, etc. Once the desired single-hazard vulnerability indices (I_k) are computed, a combined, multi-hazard index can be defined as the multi-dimensional distance from the origin of the system of reference (Eq. 5). This concept is applicable regardless of the number of considered hazards. For example, for a two-dimensional case, supposing that both “hazard 1 and 2” are defined over a range [1%, 100%], the combined index will be defined on the range [1%, 141.4%]. However, this can be re-scaled in any other desired range without affecting the prioritisation list of the considered building portfolio.

$$I_{multi} = \sqrt{\sum_k I_k^2} \tag{5}$$

2.4. Dealing with subjectivity

According to the definition of the seismic risk prioritisation index, it appears evident that a degree of subjectivity is always involved in the calculation. In particular:

1) The baseline score is based on the fragility functions available in the HAZUS MH4 guidelines. Although such model is largely based on numerical analyses of building models, the results are provided for a limited number of structural categories. The user should carefully select the category that best matches with the characteristics of the considered buildings, with special reference to the “Code level” parameter;

2) The weights needed for the calculation of the performance modifier are based on a subjective set of pairwise comparisons between the secondary parameters, although this is derived in a mathematically-consistent and rational way that allows to minimise the chance of having randomly-assigned weights;

3) The ratio between the maximum possible baseline score and the maximum possible performance modifier is “arbitrarily” set to unity, i.e. $I_{BL,max} = 50\%$ and $\Delta I_{PM,max} = 50\%$.

It is virtually impossible to perfectly match the considered buildings with the archetype buildings in HAZUS. However, a careful examination of the characteristics of the considered buildings should be carried out to better select the appropriate HAZUS categories. Characteristics such as the presence of strong beams vs weak columns should be considered, which can lead to a Pre-Code classification, or documented structural retrofit measures, which can lead to higher “Code level” classification. A review of the (history of the) structural/seismic codes appropriate for the considered buildings can considerably reduce the level of subjectivity. These can be compared to the different provisions in UBC1994, defining “equivalence relationships”. Any information related to the year of construction (or design) of the considered buildings is fundamental in such process. Overall, it is deemed that the assignment of the HAZUS categories to the considered buildings should reflect their expected differences in their seismic performance, rather than perfectly match the properties of the archetype in the HAZUS category definition.

As an alternative to the HAZUS definition, the baseline score can be re-defined adopting, if available, a portfolio-specific set of fragility curves. To this aim, the OpenQuake platform (https://storage.globalquakemodel.org/openquake), by the Global Earthquake Model (GEM) foundation, might be used.

An illustrative set of weights needed to calculate the performance modifier is given in this paper. However, a case-specific AHP, for instance involving groups of local experts, can be performed to derive new weights that match the characteristics of the considered building portfolio, and therefore reducing subjectivity by better-matching the parameters with the analysed buildings.

Finally, the subjectivity related to the ratio between the maximum possible baseline score and performance modifier can be tested through a sensitivity analysis. For a given building portfolio, the idea is to repeat the calculation of the seismic index with different values of the maximum possible performance modifier. This allows to check the reliability of the priority list to this assumption.

3. Illustrative application: school building portfolio in Banda Aceh, Indonesia

3.1. Description of the case-study portfolio and definition of an archetype building

The case study portfolio selected for this study consists of 85 RC buildings belonging to 44 school compounds located in Banda Aceh, the capital and largest city in the province of Aceh, Indonesia. A RVS campaign through the INSPIRE form (Figure 1) was carried out to collect administrative, geometric and mechanical data related to the investigated buildings. For all the surveyed buildings, the BSS is a reinforced concrete frame with infills. The majority (81%) of the buildings in the portfolio has a rectangular plan, with the remaining 19% composed of L-, C- or T-shaped plans (Figure 4.a). 68% of the surveyed buildings is two-storey high, while one- and three-storey buildings represent 15% and 16% of the portfolio, respectively. The year of construction for each building was retrieved from the school signboard, registry or by interview of the school principal. Figure 4.b shows that few buildings (18%) survived the 2004 earthquake-tsunami sequence; hence, the majority of the portfolio (57%) was constructed between 2005 to 2011, while the remaining 25% was built from 2013 onwards.

The accurate knowledge of the year of construction is essential for the structural characterisation of the portfolio. In fact, such information can be coupled with the history/evolution of the available structural and/or seismic codes to derive minimum-by-law dimensions of the structural members, reinforcement detailing, level of considered vertical and lateral forces in the design, etc. In this specific case, the appropriate structural code for the whole portfolio is the SKBI 1.3.53.1987 (SNI, 1987). The first seismic code appropriate for the region is the SNI 1726:2002 (SNI, 2002), which is inspired to the American Uniform Building Code 1997 (UBC 1997), which also facilitates the compatibility with the HAZUS framework. Stricter seismic provisions were adopted when the seismic code was updated in the SNI 1726:2012 (SNI, 2012), which fully consistent with the ASCE 7-10 (American Society of Civil Engineers, ASCE, 2010). Therefore, apart from a minority (12) of buildings constructed before 2002, approximately half of the buildings are constructed according to the SNI 1726:2002 (lower) standards while the other half refers to the updated SNI 1726:2012, with nominally better nominal seismic performance.

Figure 3. Sample photos of the building portfolio (taken on 16-19 October 2018).

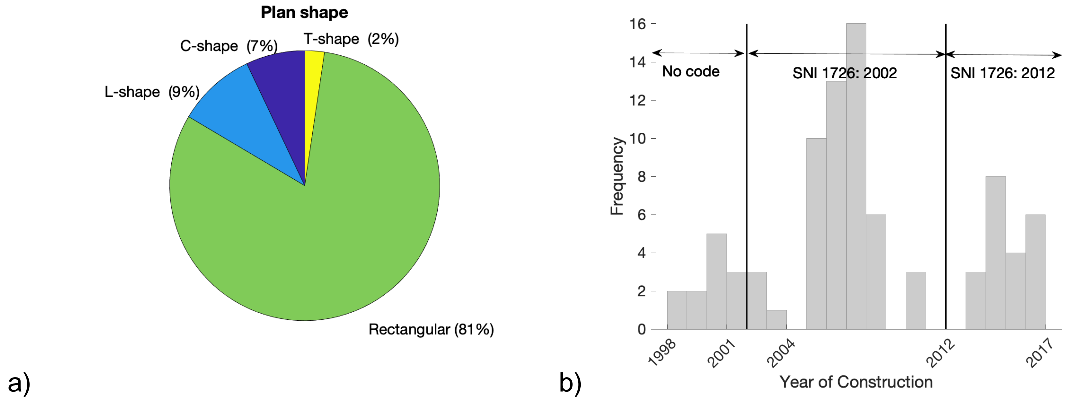

Figure 4. Statistics for the 85 surveyed school buildings. a) plan shape; b) year of construction.

The analysis above, based only on the information of the INSPIRE forms, allows to identify an archetype building which represents the construction practice for school building in Banda Aceh. The archetype building is a two-storey, rectangular RC building. Figure 5 shows the geometrical characteristics of the archetype building geometry, which are based on the modal (most frequent) values of the empirical distributions (histograms) considering only the rectangular, 2-storey buildings in the portfolio (69). The archetype has 10 bays in the longitudinal direction (one for the staircase, three for each classroom). In the transverse direction there are two 3.5m bays and a 2m corridor bay. The storey height is equal to 3.5m. 0.4x0.3m columns are adopted, except for the corridor columns, whose dimensions are 0.3x0.3m. Finally, the dimensions of the typical beams are 0.3x0.4m. The dimensions of beams and columns are validated with simulated design approaches according to the above-mentioned codes.

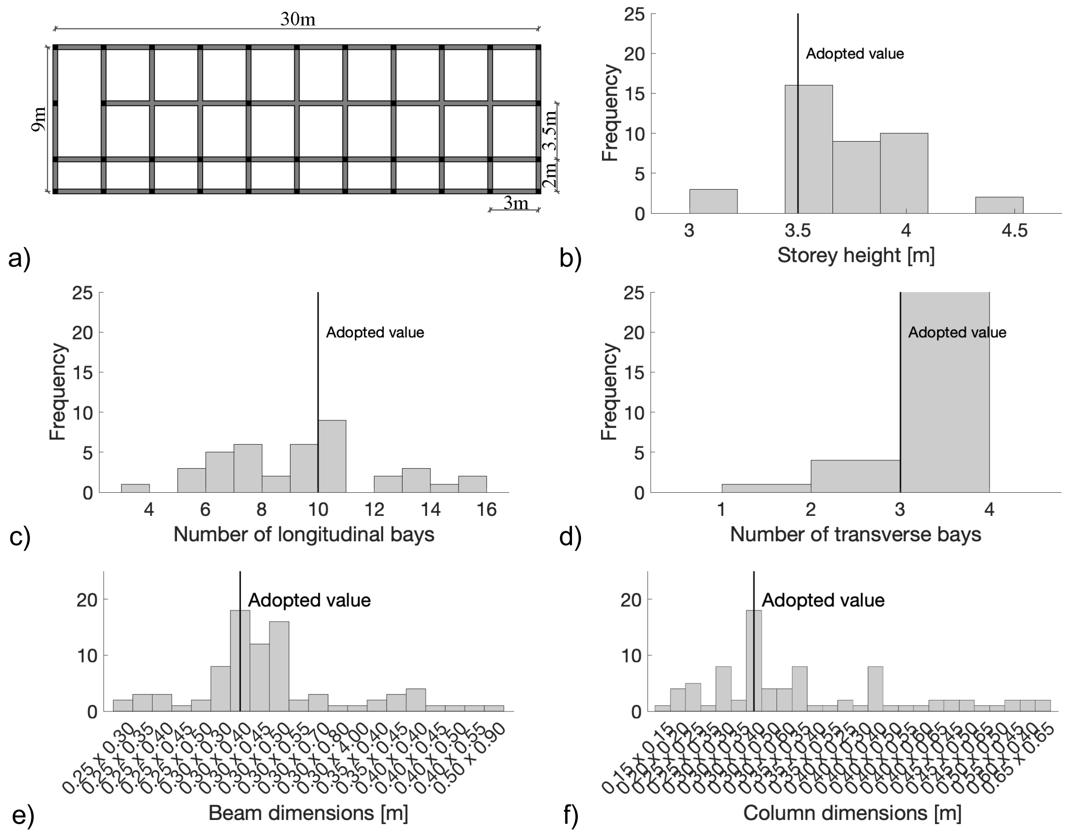

Figure 5. Two-storey, rectangular buildings: geometry trends and adopted values for the archetype building. a) plan view of the archetype building; b-h) histograms of the geometric parameters.

Considering the same geometry, two different sets of structural details are provided, to reflect the SNI2002 and SNI2012 seismic codes; see Gentile et al., 2019 for the details. It is worth mentioning that, for the Post-2012 archetype structure, the cross-section height of beams and columns are respectively 5cm and 10cm bigger than the corresponding members in the Pre-2012 archetype structure. The reinforcement of the structural members is selected by cross-checking visual information (see Figure 3) with the outcome of both gravity-based and seismic-based simulated design according to the SNI codes. To this aim, acting loads are calculated considering permanent dead loads (according to the suggested material properties in SNI1987) and live load equal to 5kPa (1kPa for the roof). Gravity axial load on columns is calculated based on a tributary area approach.

3.2. Prioritisation scheme

Based on the data collected with the forms, the INSPIRE seismic risk prioritisation index is calculated for the whole portfolio. Moreover, the Tsunami PTVA4 index (Dall'Osso et al., 2016) is calculated, finally combining these results to derive a multi-hazard index. It is worth mentioning that the resulting indices values are arbitrarily categorised in three groups, respectively "green, yellow and red tags" by defining two threshold values for the various indices. The definition of such thresholds is essentially a subjective (often political) choice that shapes the prioritisation scheme, based for instance on resources availability. As a proof of concept, in this paper the thresholds are selected to be equal to 33% and 66% for the calculated seismic, tsunami or multi-hazard indices.

The PTVA index allows to derive the relative tsunami vulnerability of a building. It is calculated as a weighted sum of two parameters: the "structural vulnerability" and the so-called "water vulnerability". The first parameter depends on three factors: the type of the lateral resisting system, the depth of the flood water at the building location, and the degree of external protection (e.g. presence of seawalls). The "water vulnerability" depends on the ratio of the inundated-to-total number of storeys. It is worth mentioning that this parameter is calculated using the (observed) inundation data from the 2004 Indian Ocean Tsunami (Iemura, 2014). It is worth mentioning that, although the name refers to vulnerability, the PTVA index somehow refers to tsunami risk, since the expected hazard is also considered. This facilitates the compatibility with the INSPIRE index.

Figure 6a,b show the application of the INSPIRE seismic risk prioritisation index to the considered portfolio. To calculate the baseline scores, the HAZUS fragility curves related to the C1 category "Concrete Moment Frame" are used. Since the infills of the investigated frames are made of a single layer of poor-quality clay bricks, their presence is neglected. According to the analysis of the year of construction and the history of the structural/seismic codes in Indonesia, the categories Pre-Code and Low-Code are adopted for the Pre-2012 and Post-2012 buildings, respectively. Given the particularly small differences in the characteristics of the buildings, the INSPIRE index is particularly similar for the whole portfolio [32%, 64%]. The slight differences in the value of the index are due to the performance modifiers, mainly governed by short columns and/or pounding for the majority of the schools. This is a further confirmation of the uniformity of the construction practice for school buildings in Banda Aceh. On the other hand, the results for the PTVA tsunami index (Figure 6c,d) show a larger variability [7%, 75%] and a clear correlation between the distance from the coast and the relative tsunami risk. This result, although preliminary, might suggest that the distance from the coast can be used as a very simple proxy for the "water vulnerability" parameter in the tsunami PTVA index.

Given the above-mentioned trends, the combination of the seismic and tsunami indices (Figure 6e,f) clearly indicates that the tsunami hazard play a substantial role in determining the prioritisation scheme for the school buildings in the city of Banda Aceh. Indeed, the overall trend of the multi-hazard results is practically equal to the trend of the tsunami index results.

To control the role of the subjectivity in calculating the INSPIRE seismic index, a sensitivity study is conducted. The seismic index is applied to the entire portfolio four times (Figure 7), by considering that the maximum value of the performance modifier is equal to 20%, and 50%. Consequently, the maximum value of the baseline score is respectively equal to 80% and 50%.

The results of the seismic index are ranked in descending order of risk. The results show that, for this portfolio, the overall priority list is rather insensitive to the maximum baseline-to-performance modifier ratio. Indeed, a small number of "swaps" in the priority list is sought and, with the same definition of the thresholds for the tags, the number of building in each category has a negligible dependency on the ratio above.

4. Concluding remarks

This paper introduces the INSPIRE index, which is an empirical proxy for the relative seismic risk of buildings within a given building portfolio and allows to define prioritisation schemes for risk mitigation measures. To this aim, a data collection form used for the rapid visual inspection of RC buildings is first developed and presented. Such form allows to calculate the INSPIRE seismic risk prioritisation

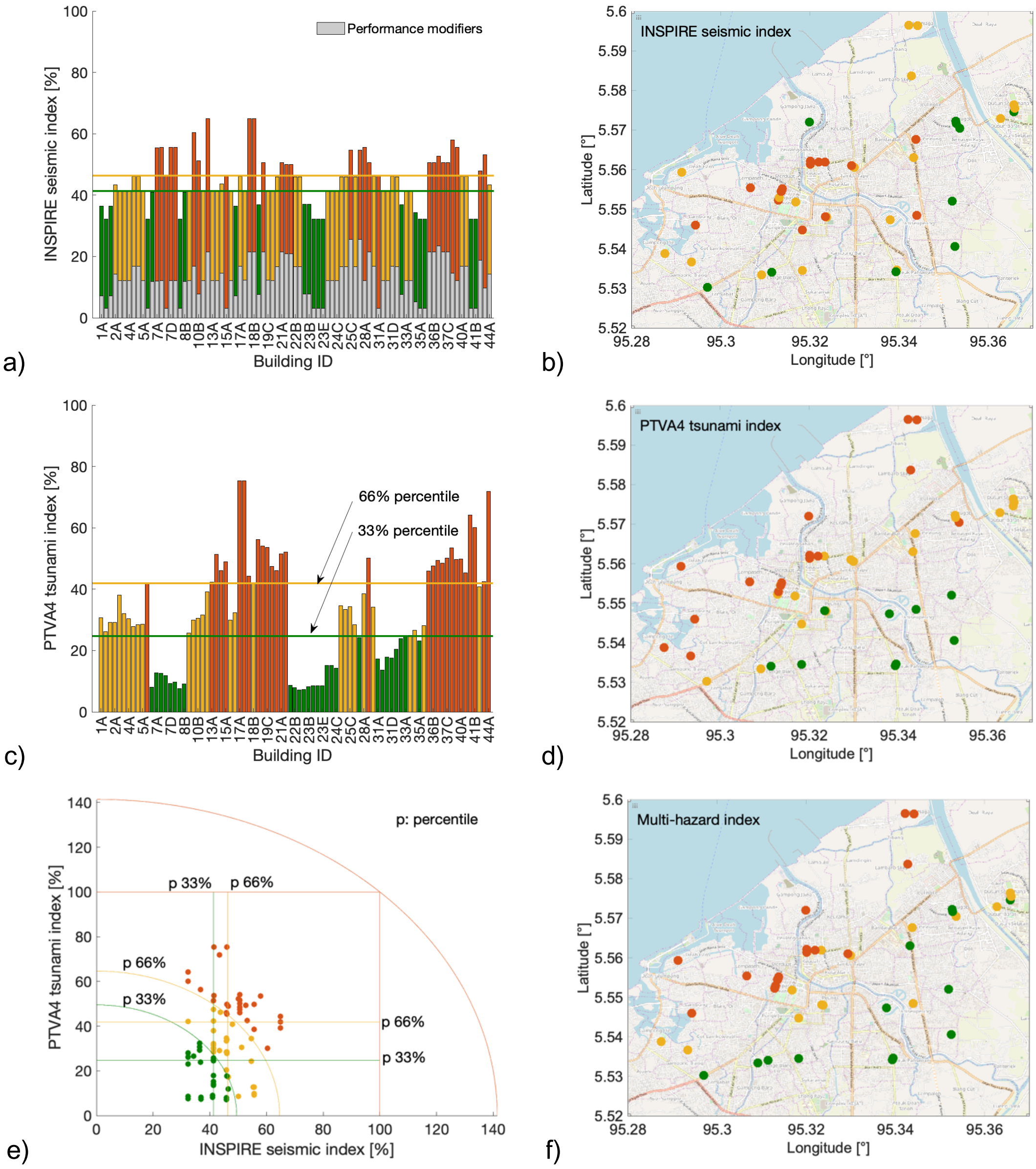

Figure 6. Application to the seismic and tsunami indices to 85 RC school buildings in Banda Aceh, Indonesia. a,b) seismic indices; c,d) tsunami indices; e,f) multi-hazard indices.

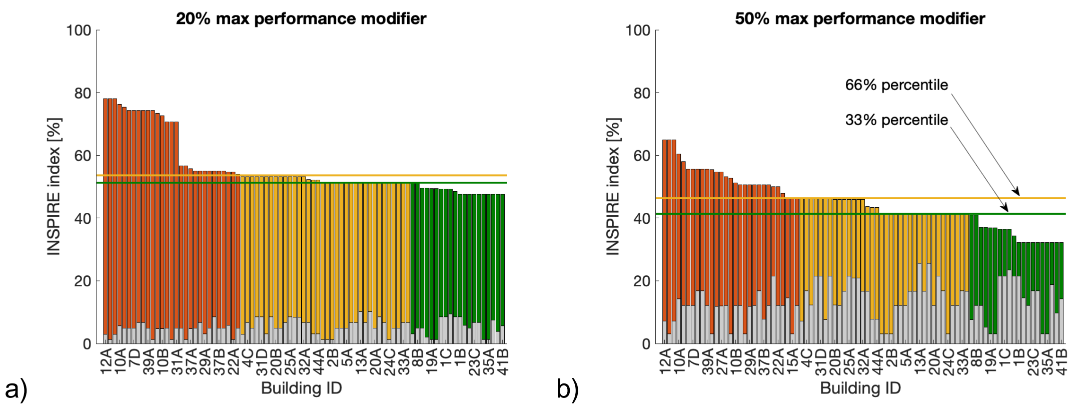

Figure 7. Sensitivity analysis: baseline-to-performance modifier ratio. a) $\Delta I_{PM} = 20\%$ b) $\Delta I_{PM} = 50\%$.

index, the Tsunami PTVA index (in any of its variations), to obtain a level of geometrical/mechanical information sufficient to define one or more archetype buildings (representative of the portfolio) and/or to build refined numerical models, provided that simulated design is adopted to cross check the available information.

The INSPIRE form and seismic risk prioritisation index are adopted for the analysis of 85 RC school buildings in the city of Banda Aceh, Indonesia. The joint application of the INSPIRE seismic risk prioritisation index and the PTVA tsunami index allow to define a clear and transparent rationale behind any prioritisation schemes for such school buildings. In fact, the relative seismic risk of the considered buildings is particularly similar, while the relative tsunami risk shows, clearly, a strong dependence with the distance from the coast. Indeed, the results show that a multi-hazard-based priority list is mostly governed by the tsunami risk for the case-study portfolio.

The results in this paper demonstrate the effectiveness of both the INSPIRE RVS form and INSPIRE seismic risk prioritisation index in providing a rational method to derive a prioritisation scheme, which can be extended including multi-hazard considerations, and in allowing the definition of an archetype building for more detailed evaluations/analyses.

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