16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° XXXX (Abstract ID)

Registration Code: S-XXXXXXXX

SEISMIC HAZARD INPUTS TO RISK EVALUATIONS AND REAL-TIME MONITORING FOR RESILIENT GLOBAL BUILDING PORTFOLIOS

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Abstract

Seismic evaluations on global portfolios are carried out to inform life safety and economic risk mitigation actions as well as increase business continuity and resilience. The current practice is to apply one of a number of seismic evaluations methods developed in the U.S. (e.g. ASCE 41-13 or FEMA P-154). These methods are based on the current U.S. seismic design code (ASCE 7) and seismic hazard input as short period and 1-second spectral acceleration for risk-targeted maximum considered earthquake (MCE_R) ground motions corresponding to a 1% probability of collapse in 50-years. These seismic hazard input parameters are different than currently supplied by national seismic hazard mapping in many countries. Converting the available local reference ground motion to be compatible with the U.S. methodologies with rigor and certainty is import in evaluation of seismic risk across global portfolios.

This paper presents a methodology to derive seismic hazard input and guidance on estimating site class for the seismic risk evaluations based on ASCE 7 for countries outside of the US. The methodology presented has been developed through results of global portfolio assessments drawing on ~500 sites in ~50 countries on 6 continents.

While global mapping products based on SRTM can approximate the site class (Vs30), they are generally inferior to traditional geologic interpretation based on a number of readily available mapping products common for major cities. Assigning an incorrect site class will create inconsistencies in scoring across the portfolio and potentially ignores the increased risk for soft soil sites. A comparison of 200 sites where site class is derived by both SRTM Vs30 and desk study geologic interpretation is presented to highlight the advantage of the desk study.

Recognizing that a component of business continuity and resilience is not only understanding risk, but the ability to react rapidly after an earthquake, the findings of the seismic evaluations are put into practice through a real-time seismic risk monitoring and alert system to provide immediate situational awareness of the portfolio following the earthquake. An example of the real-time alerts, advice and actions for a portfolio of 40 buildings from the Taiwan 6 February 2016 M6.4 earthquake is presented.

Keywords: seismic risk evaluation, real-time monitoring, site class estimation

1. Introduction

With the cost of natural disasters to global business increasing each year, many international companies with global portfolios of building assets are carrying out seismic evaluations to better understand their risk to earthquakes, improve business continuity and enhance resilience.

Current practice is to apply one of a number of seismic evaluations methods developed in the U.S. (e.g. ASCE 41-13, FEMA P-154 RVS). These are based on U.S. earthquake design codes and related seismic hazard mapping products coupled with an assessment of building vulnerability through rapid visual assessment or more detailed inspections to determine risk. The methods are in-line with ASCE 7 which uses seismic hazard (e.g. ground motion) input as spectral response acceleration at periods of 0.2 seconds (S_S) and 1.0 seconds (S_1) for the Risk-Targeted Maximum Considered Earthquake (MCE_R). In the U.S. these are provided by the U.S. National Seismic Hazard Maps developed by the USGS and define S_S and S_1 across the country.

When applying these U.S. based methods to buildings in other countries, one has to derive seismic hazard inputs comparable to MCE_R S_S and S_1. In many countries, relevant reference seismic hazard mapping is provided by local seismic building codes, published research or global seismic hazard mapping products. These seismic hazard sources are often aligned with early versions of UBC and therefore present their reference seismic hazard input as peak ground acceleration (PGA) for a 10% probability of exceedance in 50 years (475-year return period), rather than MCE_R S_S and S_1. As a result earthquake engineering practitioners applying the U.S. based seismic methodology to countries outside of the U.S. need to derive MCE_R S_S and S_1 based on existing local seismic hazard input.

The preferred method to derive the seismic hazard inputs is through a site specific probabilistic seismic hazard analysis, but the scope to complete across a global portfolio is not commensurate with the seismic evaluation scope. The USGS previously developed a Worldwide Seismic Design Tool (Beta) which provided S_S and S_1 as an informal and incomplete collection derived from existing studies. This tool has been discontinued as the values had become considerably outdated.

This paper presents a methodology to derive seismic hazard input and guidance on estimating site class for the seismic risk evaluations based on ASCE 7 for countries outside of the US. The methodology presented has been developed through results of global portfolio assessments drawing on ~500 sites in ~50 countries on 6 continents. The influence soil amplification is essential to represent the true ground motion experienced at the site. The scale and scope of the portfolio seismic evaluation limits the completion of ground investigation to determine site class and relies on desk studies to derive site class based on global or local mapping products.

The impetus for owners to carry out global seismic assessments on their portfolio is driven by the need to reduce life safety and economic risk as well as increase business continuity and resilience. Recognizing that a component of business continuity and resilience is not only understanding risk, but the ability to react rapidly after an earthquake, the findings of the evaluations are put into practice through a real-time seismic risk monitoring and alert system to provide immediate situational awareness of the portfolio following an earthquake. An example of the real-time risk alerts, advice and actions for a portfolio of 40 buildings previously evaluated from the Taiwan 6 February 2016 M6.4 earthquake is presented.

2. Seismic hazard input estimation methodology

Earthquake engineering evolves with every earthquake, as we learn more about seismotectonic sources, propagation of seismic waves though the crust, ground response and building performance. The temporal nature of the practice limits the applicable “life” of seismic design codes and hazard studies. The steps are discussed at a high level to provide guidance. The methodology to derive S_S and S_1 inputs for countries outside of the U.S. follows five steps:

1. Select reference seismic hazard (PGA for 10% in 50 years and Site Class B)
2. Scale 475-yr to MCE_G

3. Scale PGA to S_S and S_1
4. Convert geomean to horizontal maximum
5. Calculate Risk Targeted Ground Motions

2.1 Select reference seismic hazard input – PGA, 10% in 50 years, Site Class B

The first step is to select a reference seismic hazard input. This is typically presented as PGA, 10% in 50 years, Site Class B. For a particular there are often many references and these take some professional judgment to select the most appropriate seismic hazard input to start with. A key concept of this proposed methodology is to reference the best and most current sources. Typical sources include:

- National Seismic Hazard Maps
- Site specific PSHA
- Published regional studies
- Global hazard mapping

Every site is unique as the countries national hazard products and respective seismotectonic setting vary. The assumption is that all seismic hazard was calculated by a probabilistic seismic hazard analysis (PSHA) following the methodology by Cornell (1944) [1]. Each seismic hazard source should be evaluated for:

- Recentness of earthquake catalog
- Level of detail of the seismic source zones including any fault/subduction sources, in particular for the site near a known active fault
- Recent ground motion prediction equations
- Uncertainty included in logic tree

There is no formal hierarchy as to which source to select over another. One needs to consider both the recentness and the detail in the source. Priority is given to recent PSHA and those with sufficient source characterization detail proximal to the site. Additional considerations include:

- Site specific PSHA reporting can often provide S_S and S_1 directly.
- The Global Seismic Hazard Map – GSHAP (Giardini et al. 1999) [2], now almost 20 years old, needs to be considered carefully. Beyond the additional 20 years of seismicity and updated ground motion prediction equations (GMPE), GSHAP doesn't explicitly include fault sources. For most locations there are more current seismic hazard references than GHSAP.

2.2 Scaling PGA from 475-yr to MCE

Many national seismic design codes provide scaling factors to modify reference ground motions for different return periods reflecting varying consequence or importance levels for the buildings. The national codes typically apply a single scaling factor across the country regardless of the tectonic setting

For example in Australia, the current seismic design code AS1170.4 (2007) provides a factor of 1.8 to scale from 1/500 to 1/2500 annual probability of exceedance for all of Australia. In contrast the Geoscience Australia - National Seismic Hazard Map (Leonard et al. 2014) [3] shows a variable scaling factors ranging from 2.5 to 3.0 for different cities corresponding to the seismotecotonic setting reflected in the PSHA. In this example, selection of a scaling factor from the current design code or from a more recent study could introduce a difference of almost 40% in ground motions.

Lubkowski and Aluisi (2012) [4] also provides the scaling factors to estimate seismic hazard for different return periods based on the results of over 50 site specific PSHA.

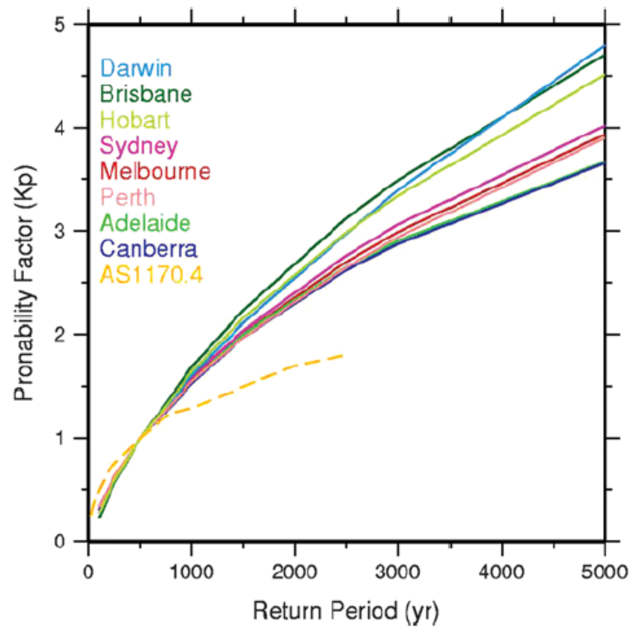

Fig. 1 – Probability factors for the eight Australian capital cities and from AS1170.4 (Leonard et al. 2014) [3]

2.3 Site Factor Considerations

Ground conditions, also known as Soil Type or Site Class, determined by Vs30 measurements (the average shear-velocity down to 30m) has a major influence on amplitude and duration of earthquake shaking, and thus structural damage. In FEMA P-154, the Soil Type Score Modifier is applied to consider the soil effects on ground motion. In ASCE41-13, the soil factor directly affects the seismicity level when determining S_{DS} and S_{D1}.

The seismic evaluation methodologies note that soil type cannot be readily identified by visual methods and recommend derivation through desk studies during the planning stage. If information is lacking they recommend the using the USGS Global VS30 Map Server which uses SRTM (Wald and Allen, 2007) [5] or assume a Site Class D.

Wald and Allen (2007) [5] describe a methodology for deriving maps of seismic site conditions using topographic slope as a proxy. Vs30 measurements (the average shear-velocity down to 30 m) are correlated against topographic slope to develop two sets of coefficients for deriving Vs30: one for active tectonic regions that possess dynamic topographic relief, and one for stable continental regions where changes in topography are more subdued. Although SRTM Vs30 has become an accepted input, Wald and Allen (2007) [5] note significant limitations to this simplified approach. They advise users to be aware of these limitations, exercise caution in using this approach for anything other than regional scale and use site-specific Vs30 values should be used at finer scales or at particular locations.

In practice, for most cities anywhere in the world there exists a variety of readily available geologic mapping sources that makes a desk study estimate of site class feasible and at a level of effort consistent with the evaluation methodologies. These sources include aerial photographs, global topography (SRTM), water courses, geologic mapping, and often geotechnical investigation reports.

To explore the practical effectiveness in deriving Vs30 from SRTM vs desk study, the resultant Vs30 Site Class for ~200 sites are presented in Table 1. The comparison shows that, while global mapping products based on SRTM can readily approximate the site class (Vs30), they are generally inferior to supplementing the Vs30 mapping with desk study geologic interpretation based on a number of readily available mapping products. The results show that 20% of the 200 sites considered Site Class D, where revised to Site Class E. This has potential to ignore the increased risk from soft soil sites.

Table 1 – Comparison of site class derived from Vs30 versus a desk study

% of Total (N=200)	**Vs30-SRTM**	**Desk study**	**Ss change**	**S1 change**
60.82%	No Change		same	same
20.62%	D	E	increased	increased
8.25%	C	D	same	increased
1.03%	C	E	same	increased
5.15%	D	C	same	decreased
2.58%	C	B	decreased	decreased
1.03%	B	D	increased	increased
0.52%	B	C	increased	increased

2.4 Scale PGA to S_1 and S_S

While most seismic design codes present spectral ordinates to derive a response spectrum, these generally have a level of conservatism in them to cover the entire nation rather than a response spectrum derived from site-specific PSHA based on the local seismotecotonic setting.

Recognizing that the conversion of PGA to S_S and S_1 is dependent on the size of earthquakes in the seismotectonic setting, Lubkowski and Aluisi (2012) [4] present a methodology to convert PGA for 2475-year return period to S_S and S_1 based on PGA (Fig. 2). The methodology is based on compilation of over 50 site-specific PSHA worldwide.

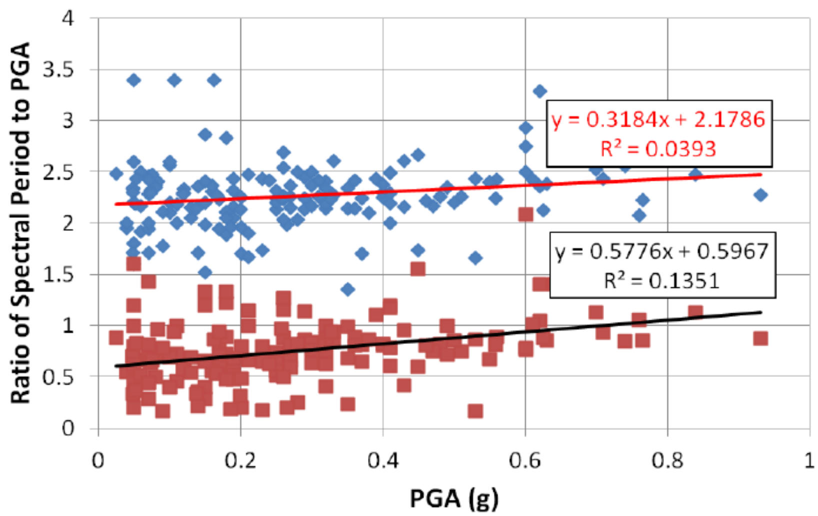

Fig. 2 - Ratio of spectral period to PGA from Lubkowki and Aluisi (2012) [4]. SS in blue and S1 in red.

2.5 Convert geomean to horizontal maximum

The calculation of MCE_R require the ground motions rotated into the maximum horizontal direction. This is in contrast to most existing mapping products and output of PSHA which report geometric mean. Huang et al. 2008 [6] presents a method to rotate into the maximum horizontal component following a factor of 1.1 for S_S and a factor of 1.3 for S_1 spectral periods.

2.6 Calculate Risk Targeted Ground Motions

Previous U.S. seismic hazard map products and most seismic codes use the assumption that the capacity against collapse of structures designed for uniform hazard is equal to the seismic hazard value without uncertainty. So the probability of collapse in 50 years is uniform. As there is uncertainty in structural capacity and the site-to-site variability in the shape of the ground motion hazard curves results in a lack of uniformity. A major change from previous seismic hazard map products in the U.S. to their current hazard maps is the inclusion of a risk-target ground motions (Luco et al., 2007) [7] to result in uniform collapse probability. To achieve this the ground motions are adjusted for a target select collapse probability (target risk).

The USGS provides a tool to derive the 1% collapse risk-targeted ground motions, based on a hazard curve and generic fragility curve similar to those found in HAZUS.

In practical application to other countries one needs to consider the two inputs: the complete hazard curve (ground motions at all return periods) and appropriateness “generic” fragility curve to the local building population.

3. Real-time monitoring for resilient global building portfolios

Seismic evaluation following ASCE 41-13 was undertaken for a global portfolio of 400 buildings of which 40 are located in Taiwan. The results of the evaluation were primarily intended for corporate risk management practice to enforce safe work place requirements and inform decisions on property management such as lease renewal.

After the completion of the evaluation, the results were put into practice through a real-time seismic risk monitoring and alert system to provide an immediate situational awareness of the portfolio following an earthquake. The system developed by Arup is called Hazard Owl and takes real-time multi-hazard data feeds, compares them to vulnerability, to trigger custom alerts and action advice.

At approximately 20:00 UTC 5 February 2016 (4am local Taiwan Time Saturday 6 February) a M6.4 damaging earthquake occurred in southern Taiwan. The event occurred early Saturday morning local Taiwan time during the Chinese New Year Holiday. A global network of seismographs located the event and the USGS shortly afterward disseminated an estimate of the amount of ground motion as a ShakeMap through their RSS feed.

The ground motions estimated in the ShakeMap feed were extracted for each of the properties and compared to the seismic design basis. Five of the properties felt earthquake ground motions up to 0.1g at SA 1-sec. The previously completed seismic evaluation, showed that these buildings were designed following the Taiwan Seismic Design Code for S_{D1} of 0.3g, so the felt ground shaking was < 30% of their design load. The seismic evaluation also noted that two of the properties were altered structurally, by removal of a wall to create more open space, and potentially unsafe.

Within minutes following the event, Hazard Owl sent out risk alerts to the portfolio seismic risk management team with the percentage of shaking versus the design basis and findings from the previous seismic evaluation. This provided the portfolio manager a contextual situational awareness of performance that could not be realized from traditional news feeds noting a M6.4 occurred in Taiwan. The alerts noted the two problematic buildings, which led to recommendations cautioning re-occupancy and prioritizing inspections.

It is important to note that the real-time monitoring doesn’t reduce the vulnerability of the building and it was inevitable that the buildings in the portfolio would be inspected in due course, but by integrating the results of the seismic evaluation with real-time hazard information, it allows for a response and ultimately recovery to occur faster. This is a key component of a resilient system.

Other value in the real-time monitoring, from a business continuity and resilience perspective, is the knowledge that a building is not impacted following an event. In the Taiwan example, the rapid situational awareness that 35 of the 40 buildings were unaffected led to a reduction in wasted resources of uncertainty following the major event and allowed business to continue as usual in those locales.

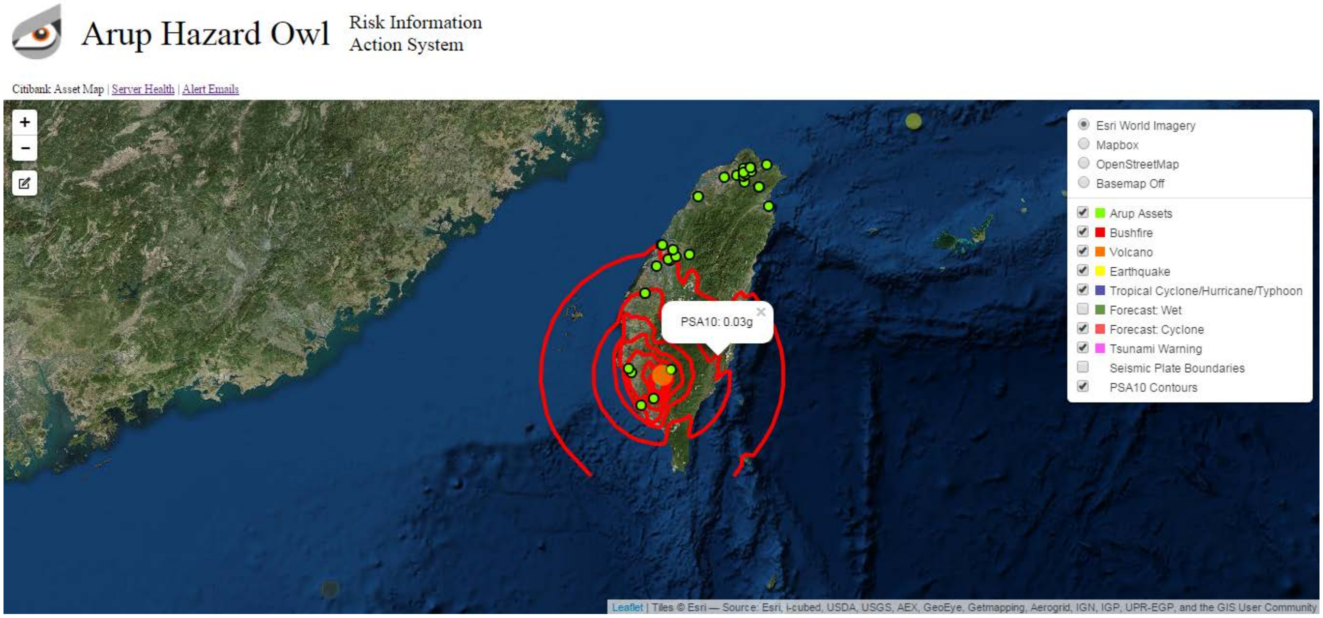

Fig. 3 – Hazard Owl showing the 6 February Taiwan M6.4 EQ, SA 1 Second contours feed form ShakeMap and portfolio.

4 Conclusions

Seismic evaluation codes following FEMA P-154 and ASCE 41 use Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motions in the maximum horizontal direction following ASCE 7. While the USGS provides these ground motions for the continental U.S., currently no country outside of the US is providing these seismic hazard inputs, particularly the inclusion of the maximum horizontal direction and risk coefficient. The process to scale from a reference ground motion (e.g. PGA at 475-year return period) to MCE_R S_S and S_1 is a multi-step process.

Soil type has major influence on amplitude and duration and thus damage, as such application of soil effects through site factors to the bedrock ground motions are essential to represent the true ground motion felt by the building asset. A comparison of derivation of Vs30 by SRTM or desk study for ~200 sits in major Asian Pacific countries show that SRTM is off 40% of the time and has the potential to ignore the increased risk from soft soil sites.

As comprehensive guidelines to scale PGA to S_S and S_1 MCE_R do not exist, global practitioners need to understand the multi-step process in estimating the hazard, which in-turn impacts the risk of the portfolio.

Real-time earthquake ground motion estimates integrated with the results of portfolio seismic risk evaluation can provide a contextual situational awareness of performance. A realized value in the alerts, from a business continuity perspective, is the knowledge that a building is not impacted following an event. The real-time monitoring doesn’t reduce the vulnerability of the building, but rather provides a rapid situational awareness to allow the response and ultimate recovery to occur faster. This is a key component of a resilient system.

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