Seismic drift demand on multi-storey buildings in Sri Lanka due to long-distant earthquakes

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Abstract

Intra-plate seismic activities in Northern Indian Ocean region below Sri Lanka, can be a possible threat of seismic hazard in terms of large magnitude long-distant earthquakes. Hypothesized seismic events with magnitudes 8M_W, 7.5M_W, 7M_W and 6M_W, have been simulated based on this source by using the stochastic approach with estimated parameters for the Sri Lankan region. The crustal rock stratigraphy of the country consists mostly of crystalline rocks of Precambrian age, which governs the estimation of seismo-geological parameters were found to compare well with the well-known `hard rock' conditions. Seismic response of structures from two major cities (Colombo and Hambantota) in the country was evaluated in terms of drift demands and base shears. The study includes both rock and soil sites. The soil amplification was carried out using the Extended Component Attenuation Model (ECAM) developed for typical intra-plate regions. Results show that, the base shear demands are far more significant than the drift demands for structures directly supported on rocks. Soft storey buildings directly founded on soil may experience higher drifts greater than allowable limits in some codes of practice. This suggests that important structures may need to be assessed using proper standards.

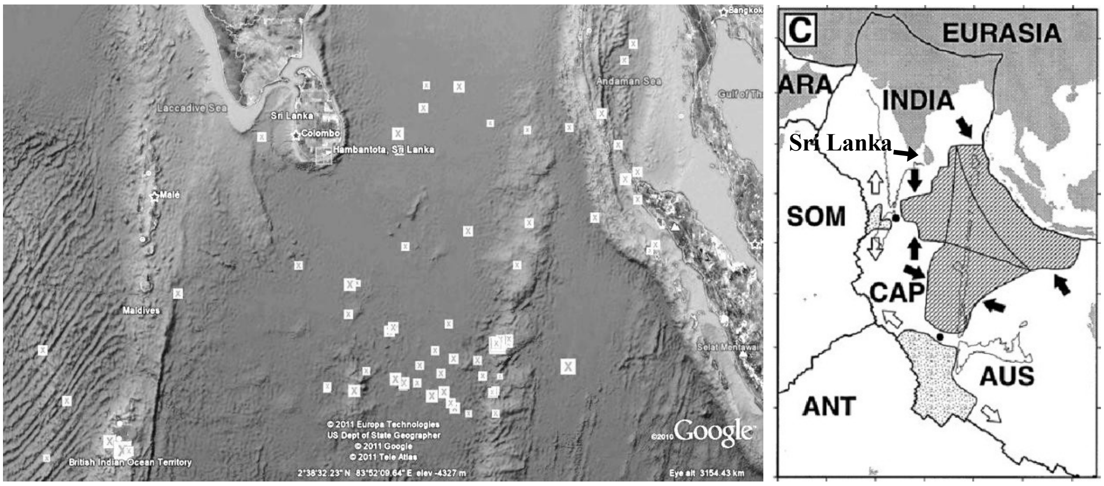
Keywords: Long-distant earthquakes, Stochastic method, Seismological parameters, Drift demand

1. Introduction

The global awareness on earthquake hazards has increased dramatically with recent devastating earthquakes, e.g. Christchurch-New Zealand and Tohoku-Japan. Sri Lanka is believed to be located in an aseismic/stable region, faraway from major plate boundaries (about 1100km away from the Sunda-Arc subduction zone and about 1500km away from the Central Indian Ridge). Subsequently, rigorous efforts to undertake a proper seismic hazard assessment for the country haven't been envisaged.

Nevertheless, considerable number of small to medium magnitude seismic events has been recorded in and around Sri Lanka. Whilst, those occurred within the country were poorly recorded, events occurred around the country were properly recorded in international archival databases such as ISC (International Seismological Centre-UK), ANSS (Advanced National Seismic System-USA), etc. Hence, the latter provides important information in identifying intra-plate seismic nature around Sri Lanka. Figure 1a, produced using historical data taken from ISC, shows clear evidences of moderate seismic nature of a region located to the south from the country. The intensity of the seismicity of the subject region is still being under investigation, however some authors (Stein and Okal, 1978) have mentioned the rate of seismic moment release of the region can be comparable to that of the San Andreas fault in California, which is considered as a seismically active zone. This is further evidenced by the occurrence of several large earthquakes having magnitude (M_w) of the order of 6 and 7, during the last century in this region. Moreover, Royer and Gordon (1997) have proposed a mechanism to understand the intra-plate tectonic behaviour of the subject region based on a comprehensive study of focal mechanisms of recorded events in the area. The study concludes that the earlier single Indo-Australian plate has been trisected (Figure 1b) by forming a large diffusing area set amidst in these trisected plates. The diffusion results the area (hatched area) to accommodate horizontal convergence due to thrust caused by surrounding plates, which in turn makes the region as seismically active. To discuss the seismicity of the subject region is beyond the scope of this paper, yet here is an effort on quantifying the seismic hazard for Sri Lanka, due to seismic activities arising from the tri-sected plate.

The "minimum site-source distance" in respect to Sri Lanka from the subject region is roughly approximated in the order of 300-350 km and the maximum possible earthquake is hypothesized as $8M_W$ in Moment magnitude scale. Three other possible events with magnitudes $7.5M_W$, $7M_W$ and $6M_W$, have been considered at the same site-source distance to estimate the hazard level in Sri Lanka. Ground motions on rock sites due to above mentioned seismic events were artificially modelled using a theoretical based approach called "Stochastic Method" by employing a "Seismological Model (SM)" with estimated and approximated regional seismo-geological parameters. Two distinct sites, Colombo (capital) and Hambantota (emerging economical centre of southern Sri Lanka), were selected in evaluating the seismic response of typical building structures in terms of drift/displacement demand and base shear demand. Sub-soil amplification effects, under resonance conditions, on predicted ground motions were estimated by applying a simple model called Extended Component Attenuation Model (ECAM).



(a) *(b)*

Figure 1: Tectonic nature below Sri Lanka: (a) Historical events (small squares) recorded in Northern Indian Ocean below Sri Lanka (Source; ISC-UK); (b) Large diffusing area (Hatched) located amidst trisected Indo-Australian plate (After Royer and Gordon, 1997)

2. Ground motion modelling on rock sites in Sri Lanka

2.1 The Seismological model and the Stochastic method

Ground motion modelling is an essential step in the process of seismic hazard assessment for a particular region. Empirical based deterministic approaches, developed by regression/parametric analysis of large amount of strong motion data in seismically active regions (such as California, Japan, etc.), are limited to apply in other low to moderate seismic regions mainly due to dissimilar seismo-geological properties between those regions, which can ultimately lead erroneous judgements. On the other hand, most of these approaches are developed to apply in a context of “known source (faults)” details for the prevalent region. Hence, it is difficult for direct application of models in low to moderate seismic regions where exact fault (source) layout is not known in detail. Therefore, as indicated by Atkinson (2004), it is always advisable to pay attention on developing more detailed ground motion attenuation models based on theory of wave propagation with due consideration on geological and seismological aspects in the region. Such a model can be widely applied in many regions including the one like Sri Lanka which is lacking enough records to develop empirical models. The following SM fulfils above requirements satisfactory to apply in low to moderate seismic regions to evaluate hazard level.

The SM was initially developed in USA and subsequently further enhanced during last few decades by several people (Brune, 1970; Boore, 1983; Atkinson and Silva, 1997). The model has unique characteristics to parameterize seismic wave modifications happening as attenuation and amplification during travel through the rock medium. Modifications are ascertained at two distinctive stages (at the deeper crust and at the upper crust) in order to maintain the final accuracy. In the model, Fourier displacement amplitude spectrum ($A_X(f)$) of seismic shear waves reaching rock outcrops, is expressed as a product of factors representing source properties of the origin and modifications (attenuations and amplifications) happening during transmission through the rock (Lam et al, 2000);

$$A_x(f) = S(f).G.An(f).Va(f).P(f) \quad (1)$$

Where,
$S(f)$ is the Source Factor – depends on Moment magnitude (M_w) of the earthquake
G is the Geometric Attenuation Factor – depends on Crustal thickness (D) and Site-source distance (R)
$An(f)$ is the Anelastic Whole Path Attenuation Factor – depends on Wave frequency (f) and the Rock quality (Q_0)
$Va(f)$ is the Upper Crustal Amplification Factor – depends on Shear Wave Velocity (SWV) gradient at shallow depths (upper 3-4 km)
$P(f)$ is the Upper Crustal Attenuation Factor – depends on Wave frequency (f) and Rock quality in upper 3-4 km, denoted by factor "Kappa (K)"

Lam et al (2000) have reviewed the model characteristics and combined it with the stochastic process to simulate seismograms to fit with the frequency contents defined by the SM (a detailed description of the process is given in Lam et al (2000)). This method of estimating seismic hazard based on artificially generated earthquakes, provides enormous opportunity to assess the hazard level accurately in low to moderate seismic regions, over other conventional approaches. Therefore, once the SM parameters for a given region are readily available, the stochastic method can be employed to simulate earthquakes. However, determination of these parameters for a given region, requires to follow a series of recommended methods with correct assumptions and approximations. Some of these methods involve with analysis of recorded seismic data of the subject region (for example, wave transmission quality factor-Q_0) and some need to be verified with instrumental data (SWV profile at shallow depth). Hence, the determination of seismological parameters is an onerous task which needs raw data with sufficient time. In this paper, the most parameters have been estimated using well established approaches. Moreover, it should be emphasized that the accuracy of the inferred parameters is yet to be confirmed by comparison with some recorded events in the country. Efforts are being undertaken by the authors to develop and verify appropriate parameters. Determination of model parameters for Sri Lankan region adopted in this paper is discussed in the next section.

2.2 Determination of seismo-geological parameters for Sri Lanka

Fourier displacement amplitudes of seismic waves at the source (fault) are defined using the relationship developed by Atkinson and Silva (1997), which is reproduced below;

$$s(f) = CM_0\left[\frac{(1-\varepsilon)}{1+(f/f_a)^2} + \frac{\varepsilon}{1+(f/f_b)^2}\right] \quad (2)$$

In the above equation, C is called the Scaling factor, M_0 is the seismic moment, f_a and f_b are corner frequencies related to duration of rupture at the source and to frequency at which the spectrum attains half of the high-frequency amplitude level, respectively. ε is a weighting parameter. For an Intra-Plate event following semi-empirical approaches are valid to find above parameters. (Lam et al, 2000)

$\log f_a = 2.41 - 0.533M$, $\log f_b = 1.43 - 0.188M$ and $\log \varepsilon = 2.52 - 0.637M$

C is determined as $4 \times 10^{-6}\ s^3/kg$ for the hard rock conditions in Central and Eastern North America (CENA) and should be multiplied by 1.28 to adjust the scaling occurred in Fourier amplitudes of waves due to different density (2800 kg/m^3) and SWV (3500 m/s) values at the source area in the subject region. These density and SWV values for the region are inferred by averaging data pertaining to shallow crustal depths (7-8 km) taken from CRUST2.0 model (2001). The frequency content and the general "shape" of the CENA source spectrum, are proven to be used as a "generic source spectrum" in other intra-plate seismic regions outside USA. Normally, the final wave frequency content at the rock outcrop is little affected by changes in source spectrum characteristics for a particular magnitude of earthquake. In other words, final shape of the spectrum is governed mainly by due modifications happening during the wave travel through the rock medium in terms of attenuations and amplifications.

The term G used in Eq. (1) represents geometrical attenuation occurred during wave travel, which accounts for attenuation happened mainly as a result of spreading and scattering of waves (not as energy dissipation). Further, wave modifications done as a result of reflections and refractions, are also included. Proposed frequency independent tri-linear hinged shape attenuation model used for G is given below (Atkinson and Mereu, 1992);

$$\left.\begin{array}{ll} G = R_0 / R & \text{for } R<1.5D \\ G = R_0 / (1.5D) & \text{for } 1.5D<R<2.5D \\ G = R_0 / (1.5D) \times \sqrt{2.5D / R} & \text{for } 2.5D<R \end{array}\right\} \quad (3)$$

Here, R_0=1 km and D is the crustal thickness in the region. R, the site-source distances are taken as 300 km and 475 km for Hambantota and Colombo, respectively. The crustal thickness of the source region, according to the CRUST2.0, is found to be of the order of 10 km. This relatively thinner crust results lesser attenuation in waves due to comparatively little energy spreading.

$An(f)$ represents the attenuation that happened as a result of energy dissipation along the whole travel path during wave propagation through the rock medium. This energy dissipation entails heating of the heterogeneous medium and rearrangement/dislocation of particles during vibration of the medium, which are considered as permanent losses of energy. Moreover, whole path attenuation depends on wave frequency in a manner in which high frequency waves are diminishing more rapidly than that do low frequency waves and the decaying has an exponential form, as can be seen in Eq. (4). The reason can be explained by analogizing the situation with frequency dependent amplitude decaying nature of wave motion in an elastic medium due to viscous damping, in which decaying rate increases with number of wave cycles in a unit length (frequency). Importantly, whole path attenuation is dominant in distant earthquakes where the amount of attenuation is largely depending on the quality of the travelled medium. If the rock quality is high, the wave propagation is good and vice versa. Hence, the wave transmission quality of the rock, parameterized as Q (or Q_0, equals to Q at 1 Hz frequency), is a key parameter to be estimated correctly for long-distant events such as in this study.

$$An(f) = \exp(-\pi f R/Q\beta) \quad \text{(Here, } Q = Q_0 f^n\text{)}. \tag{4}$$

Where, f is the wave frequency, R is the length of the wave travel path, β is the SWV. Several well established methods are available in determining Q_0 such as Coda Q method, Multiple Lapse Time Window analysis method, Spectral Ratio method, etc. All these methods involve careful analysis of region specific seismological monitoring data. For the Sri Lankan region, this has yet to be estimated by analysing recorded seismic data in the country and hence, for the current study purpose CENA values, $Q_0 = 680$ and $n = 0.36$, are assumed. CENA values are chosen based on Sri Lanka's regional rock stratigraphy. A number of sources indicates that more than 90% of Sri Lanka's upper crustal rock layer consists with Crystalline rocks of Precambrian age (Pathirana, 1980; Kroner and Brown, 2005; Cooray, 1994). The age of these rocks determined is said to be as old as about 550Ma at least. An interesting consistency can be noted with the data inferred from CRUST2.0 model, in which a relatively thin layer (about 0.5 km) of soft sedimentary rock is being directly rested on top of the Crystalline layer, without having a hard sedimentary layer in between. This may lead to speculate about any geological weathering/erosion occurred in sedimentary rock layer underlain Sri Lanka over millions of years. Hence, Q_0 value for the Sri Lankan region can be comparable to that with CENA regions, where famous Precambrian "Shield" regions are lying. This is further supported by approximated Q_0 value determined using the following relationship developed by Chandler et al (2006). Eq. (5) gives a Q_0 value of about 600, for $V_{s,0.03}$ equals 2.45 km/s. The value of $V_{s,0.03}$ (SWV at 30m depth of rock) is inferred in accordance with the crustal rock type as described in the following paragraph. Therefore, assumed Q_0 value identical to CENA regions is reasonable for the simulation purpose until undertaking a proper data analysis to find the value.

$$Q_0 = 60 + 320(V_{s,0.03} - 0.5)^{0.8} \qquad (0.5\text{km/s} \le V_{s,0.03} \le 3.0\text{km/s}) \tag{5}$$

Shear waves pose large amplifications during travel at shallow rock depths (about upper 4 km) due to decline of velocity under relatively poor physical characteristics (i.e. hardness, rigidity, cavity content) of the medium. The amount of amplitude increase is quantified by the Upper Crustal Amplification Factor, $Va(f)$ of the Eq. (1). Boore and Joyner (1997) have suggested a methodology called "The Quarter Wave length Approximation method" to determine upper crustal amplifications based on SWV travel times averaged over quarter wave lengths at the upper crust. Methodology can be used to estimate Amplification Factors as defined in Eq. (6) with sufficient accuracy, given the SWV profile of the region is a priori.

$$Va(f) = \sqrt{\rho_s \beta_s / \bar{\rho}(z)\bar{\beta}(z)} \tag{6}$$

Here, $Va(f)$ is the Upper crustal amplification factor for a given frequency, ρ, β are density and SWV respectively. Subscript "s" is for values near the source and "z" is to indicate depth that the values are averaged. The SWV profile of the subject region is modelled by using power law relationships developed by Chandler et al (2005). The regional rock stratigraphic data are inferred using the CRUST2.0 model. Averaged thickness and density values of sedimentary and crystalline rock layers underlain Sri Lanka, are shown in Figure 2a, provides evidence about geologically weathered sedimentary rocks over the course of history. This is further confirmed by abundance of crystalline rock outcroppings exposed at surface, found in many locations of the country (Cooray, 1994). One of reference SWVs i.e. the velocity at 8 km depth is taken as 3.5 km/s in accordance with the information of CRUST2.0. Kumar et al (2006) have also indicated similar order of values for crustal thickness (about 34 km) and for SWV at 8 km (about 3.4 km/s), by using receiver function analysis of broadband recorded seismic data. The shallow reference SWV near surface is derived based on geological age of crustal rock formations in Sri Lanka. As mentioned earlier in this article, the most parts of the country's rock geology consist with Precambrian crystalline rock formations with age spanning to a several hundreds of megaannums (Ma). Rock types include mainly Gneisses, Granitoid rocks, Charnokitic rocks and some Metasedimentary formations (Kroner and Brown, 2005). P-wave velocities corresponding to hard sedimentary rocks are of the order of about 4.0 – 5.3 km/s (Chandler et al, 2006). An average of about 4.7 km/s is selected as the P-wave velocity at 30m depth, which gives the relevant SWV as about 2.45 km/s for the subject region. Due to scarcity of measured SWV data at shallow depths, the assumed value can't be verified with actual data, yet the value shows consistency with shallow depth velocities found in other Precambrian shield regions such as CENA and Western Australia (Chandler et al, 2006). Modelled SWV profile for the Sri Lankan region is given in Figure 2b.

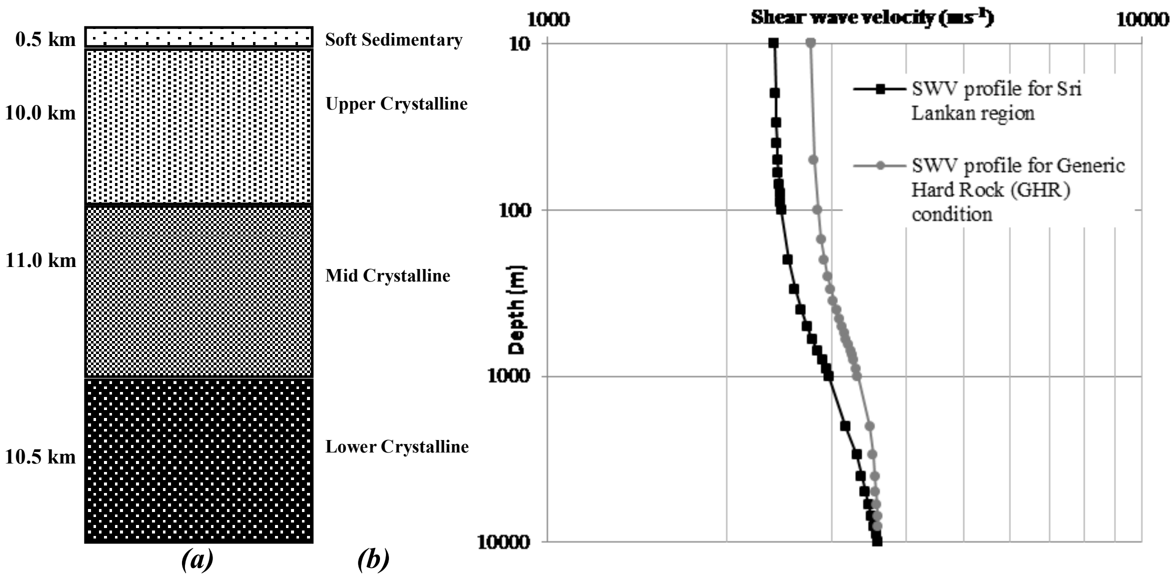


Figure 2: Crustal geologic structure and the SWV profile for Sri Lanka: (a) Regional rock stratigraphy based on CRUST2.0 model; (b) the SWV profile for Sri Lanka in comparison to GHR (Boore and Joyner, 1997) conditions.

Finally, the Kappa (K) value, which parameterized attenuation undergone in upper crustal, has been derived using equation (7) proposed by Chandler et al (2006). The same value of $V_{s,0.03}$, used in Eq. (5), gives a Kappa about 0.008s for the region. A relatively lower Kappa value again implies about a rigid upper crust which is having enhanced wave propagating features.

$$K = 0.057/V_{s,0.03}^{0.8} - 0.02 \qquad 0.5\text{km/s} \leq V_{s,0.03} \leq 3.0\text{km/s} \tag{7}$$

2.3 Generation of synthetic seismograms

Seismograms are obtained by stochastic method employing above developed seismo-geological parameters for the region. Hypothesized large magnitude earthquakes ($8M_W$, $7.5M_W$, $7M_W$ and $6M_W$) are simulated with approximated site-source distances equal to 300 and 475 km for Hambantota and capital-Colombo, respectively. Eighteen numbers of seismograms with different phase angles are simulated for each event by using software GENQKE (Lam, 1999) and corresponding response spectrums including ensemble averaged ones are derived using ETAMAC (Lam, 1999). A sample seismogram simulated for $8M_W$ event for Colombo is shown in Figure 3. Peak Ground Accelerations (PGAs) and Velocities (PGVs) in two sites due to simulated events are shown in Table 1.

Table 1: Ground motion parameters of simulated earthquakes

M_w	*PGV (ms^{-1}) at Hambantota*	*PGA (g) at Hambantota*	*PGV (ms^{-1}) at Colombo*	*PGA (g) at Colombo*
6	*21*	*0.04*	*12*	*0.01*
7	*68*	*0.09*	*42*	*0.04*
7.5	*116*	*0.13*	*73*	*0.06*
8	*216*	*0.18*	*135*	*0.08*

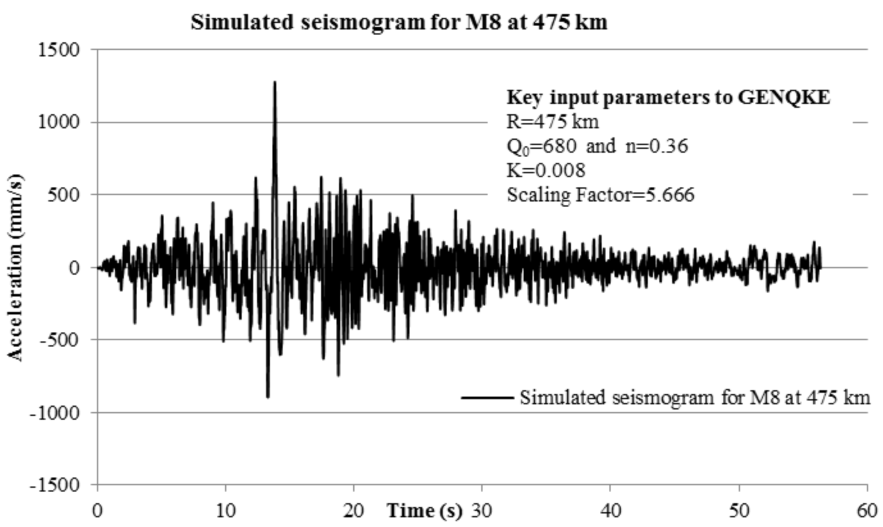


Figure 3: Example simulated seismogram by using GENQKE for $8\boldsymbol{M_w}$ event at 475 km site-source distance

3. Drift demands of building structures

3.1 Structures founded on rock sites

Ensemble averaged Pseudo-Response Spectral Velocities (PRSVs) of simulated earthquakes for 5% critical damping corresponding to two sites, are shown in Figure 4.

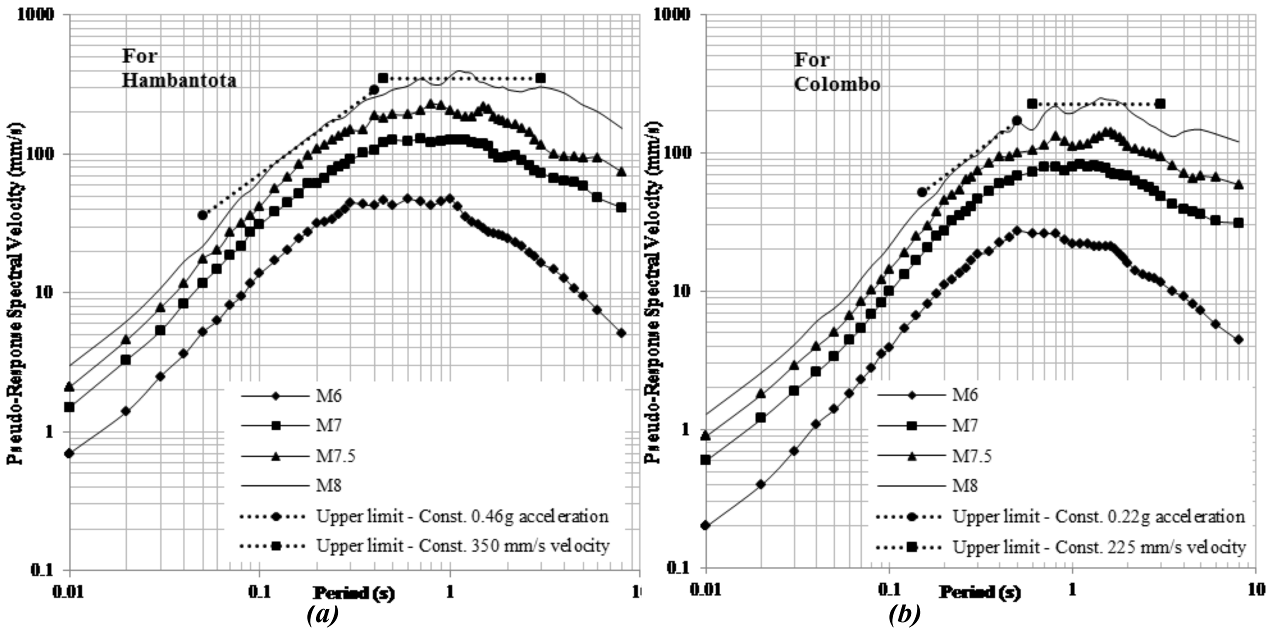


Figure 4: PRSV diagrams for 5% critical damping for two sites: (a) Hambantota; (b) Colombo

Approximated upper bound values are fitted for both cases considering acceleration and velocity controlled regions of spectra. Elastic Drift demand (Δ mm) is then calculated for single-degree-of-freedom lumped mass structure by using following basic formula;

$$\Delta = A \times (T/2\pi)^2 = V \times (T/2\pi) \qquad (8)$$

Here, T, A and V are Fundemental period, Pseudo-spectral acceleration and velocity values, respectively. The upper limit of Figure 4a (spectrum for Hambantota), for period range of 0.08s to 0.4s (low-rise buildings up to about 5-8 storeys) can be approximated as constant 0.46g acceleration. The Eq. (8) gives Δ value as around 0.3 to 18 mm for above period range, which is not posing any risk of failure due to drift demands of those low-rise structures, yet the Base shear demand shows very critical, as high as 0.46W (50% of seismic weight), needs consideration. Medium and long-period structures, where natural periods ranging from about 0.4 to 4s, govern response at a constant spectral velocity level (about 350mm/s), result comparably higher "effective drift" values of about 25 to 223 mm, respectively. A concrete frame building with height up to 15 storeys (45-55m, the highest building likely to stand at the particular site) can poses a natural period of the order of about 1s, may result to produce a "maximum inter-storey drift ratio" of around 0.0025 (considering 3 m floor height) at the ground floor level, is still well below the code allowable level, i.e. 0.02 (Uniform Building Code, 1997) and 0.015

(AS 1170.4). However, the base shear demand is still dominant, about 20% of the seismic weight (A = 0.22g). This trend can be seen further, as even for the $6M_w$ event, which produces the base shear demand of about 10% W for short-period structures. Hence, it can be concluded that, the base shear demand is far more significant than the drift demand for structures (mainly up to 15 storey in height) founded directly on rock at Hambantota.

The upper limit estimate of response spectrum values of Colombo for period range of 0.15 to 0.5s and 0.6 to 3s can be approximated as 0.22g constant acceleration and 225mm/s constant velocity, respectively (Figure 4b). The former range gives a safe effective drift range of the order of 1-14 mm applicable to buildings up to about 10 storeys and the latter poses drifts in a range of about 22 to 108 mm for buildings from medium range to high-rise buildings. Unlike in Hambantota, Colombo comprises many high-rise buildings with height goes up to about 50 storeys. A typical 30 to 35-storey R/C building may have a fundamental period up to about 3 s considering brick infill's rigidity. The maximum inter-story drift for the building at upper levels, is approximated as 0.002% per unit drift (Lam et al, 2009). By applying this, maximum inter-storey drift can be as high as $0.002 \times 108 = 0.21\%$ yet the value is within the safe margin.

Therefore, if the structures are directly founded on rocks (for both sites), they pose relatively lower drift demands for simulated events, however neither of sites (especially Hambantota) is safe in terms of base shear demand. This urges for a requirement of the application of proper seismic load design practices for Sri Lanka especially for medium to high-rise buildings, in which foundations are directly lying on rocks.

3.2 Structures founded on soil sites

A simple model developed by Venkatesan (2006), called Extended Component Attenuation Model (ECAM), to estimate soil amplification effects in low to moderate intra-plate seismic regions at resonance conditions, is applied to determine drift demand amplifications of structures founded on soil. In the model, site amplification S, is defined as a product of factors which account for effects of soil damping, impedance contrast, SWV profile of the soil and frequency content of waves. The site amplification is defined as given in following equation. Estimated Site Amplification Factors (SAFs) for soft clayey soil conditions with Plasticity Index (PI) of 30% having a linear SWV profile with 20% lateral spreading, are given in Table 2.

$$S = S\xi . S\lambda . S\psi . S\tau \tag{9}$$

Table 2: Site Amplification Factors (SAFs) calculated by using ECAM for two sites

M	*SAFs for Hambantota*	*SAFs for Colombo*
6	*6.35*	*6.55*
7	*5.46*	*5.96*
7.5	*5.06*	*5.46*
8	*4.07*	*4.86*

Then drift demands initially found for rock sits (in section 3.1), are multiplied by SAFs to derive drifts for structures rest on soil sites. Generally, low-rise building structures including most of the soft-storey buildings are being rested directly on soil by using pad/strip footings. In Colombo city area, majority of these soft storey buildings can be categorized as "soft first storey buildings" in which the stiffness of the first storey is significantly less than other stories above. Furthermore, natural period of these soft storey structures are in the range of about 0.2-0.5 s, where the spectral values are normally located within acceleration controlled regions (according to Figure 4). Estimated drifts for Hambantota can be as high as up to 75 (for $8M_w$) and 65 mm (for $7.5M_w$) for these structures, producing drift ratios (angle of drift) as about 0.025 and 0.022 (for 3 m floor height), respectively. In case of Colombo, the maximum drift ratio is to be estimated in the order of 0.022 for $8M_w$. In both cases, estimated drifts are not within allowable code limits, may lead to collapse of these soft storey structures.

4. Conclusion

Sri Lanka's location cannot be further justified as a seismically stable with current evidence of seismic activities near the country's southern ocean region. The stochastic method is applied to quantify hazard due to seismic activities around Sri Lanka, employing the seismological model with estimated and approximated parameters. Relatively older crustal rock profile (in the Precambrian age) beneath the country is comparable with other "shield regions" found in Canada, Western Australia, etc. Two sample sites; Colombo and Hambantota are considered to estimate seismic loads. Estimated drift demands are within the safe limits for structures directly rest on rocks, yet significantly larger for soft storey buildings directly found on soft soil. In both cases, estimated base shear demand is comparatively higher. Structures need to be designed for a proper seismic standard to account intra-plate seismic hazards surrounding the country.

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