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REAL-TIME SHAKEMAP SYSTEMS FOR IMPLEMENTATION IN SPARSE NETWORKS

Gail ATKINSON
Professor of Earth Sciences, Western University, Canada
gmatkinson@aol.com

Karen ASSATOURIANS
Research Associate, Western University, Canada

Behzad HASSANI
Ph.D. Candidate, Western University, Canada

Sebastian BRAGANZA
M.Sc. Candidate, Western University, Canada

Hadi GHOFRANI
Post-doctoral fellow, Western University, Canada

Arpit SINGH
M.Sc. Candidate, IIT Rourkee, India

Emrah YENIER
Post-doctoral fellow, Western University, Canada

ABSTRACT: Real-time ShakeMaps provide valuable information to emergency managers and the public regarding the strength of earthquake shaking in the immediate aftermath of an earthquake. We describe an Automated Response System (ARS) we have developed and implemented in southern Ontario, making use of real-time seismographic data from a sparse network of 25 stations distributed over an area that stretches for hundreds of km. The ARS is similar to ShakeMap in concept, but uses a number of innovative concepts to improve the reliability and utility of ground-motion mapping for the type of sparse networks that typify applications in most parts of Canada. The recorded motions are used to develop (in real-time) a calibrated event-specific ground-motion prediction equation with distance for each event. Site amplification is computed from a validated approach that uses mapped geological information on drift thickness and soil type to specify site amplification curves across a grid of sites that covers the region. Resulting ground motions are provided in a number of formats, including clickable maps with buttons to download motions at desired points in space. Engineering tools such as the ability to request automatically-processed, detailed ground motion information for recording sites of interest are also provided. These ARS products enable the ground motions and likely damage to be rapidly assessed at sites across the region, within 5 to 10 minutes of earthquake occurrence.

1. Introduction

Real-time ShakeMaps (Wald et al., 1999), showing the intensity of earthquake shaking across a region and/or at specific sites of interest, have become a valuable tool for real-time hazard and risk management worldwide. The essence of a ShakeMap is that recorded ground motions on seismographs and/or strong-motion instruments are used in combination with regional ground-motion prediction models to develop an interpolated map of shaking intensity, which is posted online within minutes of earthquake occurrence. Because of the popularity of these tools, calculation of ShakeMap ground motion parameters has become routine on many standard seismological platforms. The ShakeMap parameters include peak ground acceleration (PGA) and velocity (PGV), and the 5% damped pseudo-spectral acceleration response (PSA) at selected frequencies, typically 0.33 Hz, 1 Hz, 3.33 Hz, and 10 Hz. In many regions of low to moderate seismicity, such as southern Ontario, ground-motion estimates are required for the small to moderate events that happen several times per year. Such events may not be damaging but rapid information on the amplitudes of shaking is required to inform the public, and government or regulatory officials as appropriate. In particular, the availability of accurate ground-motion data for the sites of critical infrastructure, such as nuclear power plants or major dams, facilitates rapid engineering analyses; this in turn enables timely decisions regarding what responses, if any, are required in the aftermath of a felt event.

In this paper, we describe an Automated Response System (ARS) we have developed and implemented in southern Ontario. As shown in Figure 1, southern Ontario is a region of low-to-moderate seismicity. Regional seismicity is monitored in real-time by the Southern Ontario Seismograph Network (SOSN; www.es.uwo.ca); SOSN stations in eastern Ontario tend to be sited on hard rock, while those in the southwestern regions are on glacial sediments. The SOSN is a sparse network of 25 stations, each of which includes a three-component broadband seismometer, digitizer, and satellite or internet telemetry that transmits signals to the central data processing hub at Western University. A continuous archive of signals (velocity, at 100 samples/sec) is created in a standard seismological format (miniSEED) using the ApolloProject software (Nanometrics Inc.). These signals are processed continuously in real-time by the ARS to calculate engineering representations of the ground motions and produce interactive ground-motion (IGM) maps for all events of moment magnitude (**M**) ≥3 in the region.

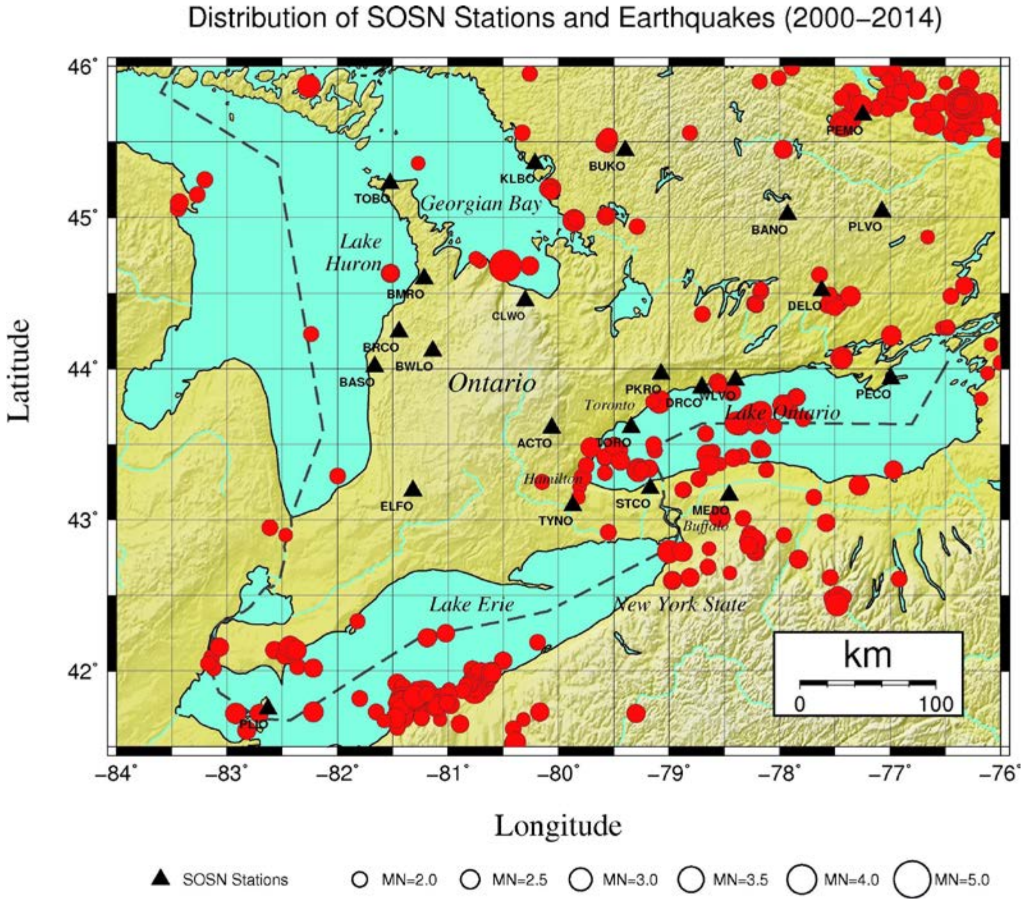


Fig. 1 – Stations of the Southern Ontario Seismographic Network. Earthquakes with catalogue magnitude (Nuttli magnitude, MN) 2 and greater for the period from 2000-2014 are shown.

The ARS is similar to ShakeMap in concept, but uses a number of innovative concepts to improve the reliability and utility of ground-motion mapping for the type of sparse networks that typify applications in most parts of Canada. Engineering tools such as the ability to request automatically-processed, detailed ground motion information for recording sites of interest are also provided. In the following, we describe the key elements of the ARS. These include: the real-time development of a calibrated event-specific ground-motion prediction equation (GMPE) with distance for each event; a regional site amplification model that uses mapped geological information on drift thickness and soil type to specify site amplification curves across a grid of sites that covers the region; and the posting of ground motions in engineering formats at selected sites, as well as the production of clickable maps to download motions at desired points in space.

2. ARS Methodology

The ARS is currently configured to process earthquake ground motion information and generate IGM-maps whenever an email alert from the Geological Survey of Canada (GSC) is received at Western University; such emails are sent whenever an event of MN>2.5 is detected in the region (where MN is Nuttli magnitude). A small program (the Event Notification Checker) runs every 10s to check an email account that receives these alerts, and triggers the ARS (by sending it an email request). The ARS processes the ground-motion signals to develop response spectra and instrument-corrected accelerograms at all SOSN stations; a streamlined version of the ICorrect algorithm of Assatourians and Atkinson (2010) is used (QCorrect) to reduce processing time. The processed data are analyzed to determine the moment magnitude (**M**) and stress drop for the event, from which we develop an event-specific GMPE. This calibrated GMPE is used to calculate expected motions for all ShakeMap parameters on a grid of sites over the region, for the reference ground condition of hard rock. A regional site amplification model is then used to amplify the motions on the grid of sites according to the site conditions at each grid point. Finally, the grid of motions is used to make the IGM-map, using a clickable google-map interface. All products are posted on an ftp site and the link to the maps is posted on www.seismotoolbox.ca, within about 5 minutes of earthquake occurrence. Figure 2 illustrates the program flow. Details of the model components are provided in the following sections.

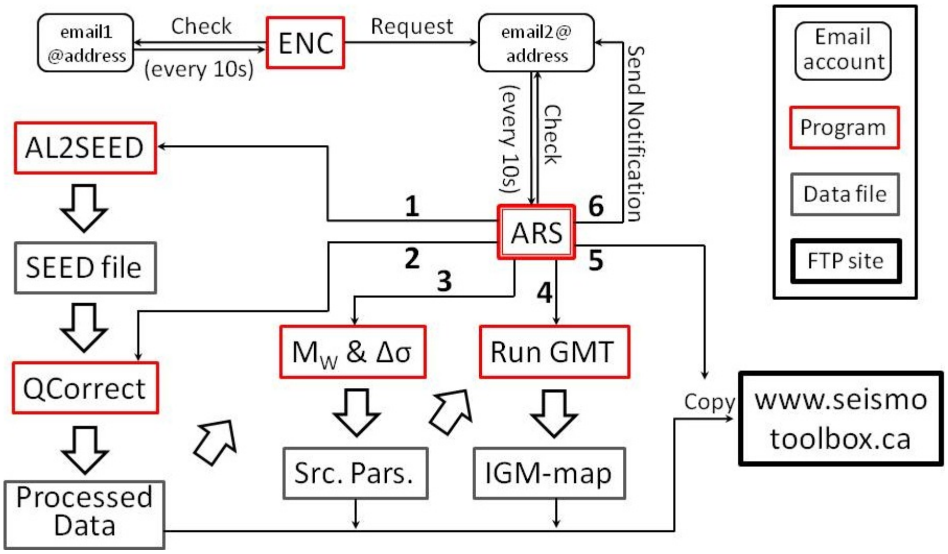


Fig. 2 – Program flow of the Automatic Response System.

3. Development of real-time calibrated GMPE

The ground-motion information used to produce the IGM-maps are instrument corrected pseudo-acceleration response spectra (PSA, 5% damped) as recorded on the stations of the SOSN. We use these parameters to estimate **M** and stress parameter (Δσ) from the observed PSA values. These source parameters are the essential input to an equivalent point-source stochastic model that has been optimized for the attenuation and site response attributes of the region, as described by Yenier and Atkinson (2015a,b). The event-specific source parameters allow rapid and automated development of a calibrated event-specific GMPE, by modifying key components of a reference model. **M**, which controls the low-frequency ground-motion amplitudes, is determined from PSA at 1 Hz, while Δσ, which controls the high-frequency ground-motion amplitudes, is determined from PSA at 10 Hz. These parameters are used to customize for each event a generic GMPE (a reference model), formulated from predictions of the stochastic point-source simulations. The generic GMPE is parameterized so as to isolate the effects of the basic source and attenuation parameters on peak ground motions and response spectra. The source and the geometrical spreading functions are obtained using the simulated ground-motion parameters from the reference model developed by Yenier and Atkinson (2015a), while the anelastic attenuation term and the overall calibration factor can be obtained using empirical data recorded over the last two decades on the SOSN. We define the generic GMPE as:

$$\ln Y = F_E + F_Z + F_\gamma + F_S + C \qquad (1)$$

where $\ln Y$ is the natural logarithm of a ground-motion intensity measure, in this case the PSA at a selected frequency. F_E, F_Z, F_γ and F_S represent functions for source, stress adjustment, geometrical spreading, anelastic attenuation and site effects, respectively. The C term is an empirical calibration factor that accounts for the residual differences between simulations and empirical data. The source function (F_E) describes the effects of magnitude and stress parameter on ground-motion amplitudes as:

$$F_E = F_M + F_{\Delta\sigma} \qquad (2)$$

where F_M is the magnitude scaling function, assumed to be the same as the magnitude scaling function for the reference model, which was obtained for Δσ=100 bars and near-surface attenuation parameter (κ_0) equal to 0.025. $F_{\Delta\sigma}$ is the event-specific stress adjustment factor, which models the effects of Δσ being different than 100 bars. The geometrical spreading function (F_Z) is also assumed to be the same as the reference model geometrical spreading function, which is a bilinear function with transition distance at 50 km. The anelastic attenuation function is defined as:

$$F_\gamma = \gamma D_{rup} \qquad (3)$$

where γ is a frequency-dependent regional anelastic attenuation coefficient which can be determined using the empirical SOSN PSA database, and D_{rup} is the closest distance from the site to the fault-rupture surface. The site effect function (F_S) is the site amplification relative to the reference site condition. In the reference model of Yenier and Atkinson (2015a), this corresponds to the NEHRP (National Earthquake Hazards Reduction Program) B/C site condition, corresponding to a time-weighted average shear-wave velocity over the top 30 m (V_{S30}) of 760m/sec.

We can readily invert the generic GMPE as described in the foregoing to estimate **M** and Δσ from the ground-motion observations of an individual event. Note that we require knowledge of the event location so that the distance to each station can be estimated; this information is provided in the email alert that initiates the ARS. The procedure to obtain **M** and Δσ for each event is as follow: 1) Remove the estimated site amplification form the observed ground-motion parameters; 2) Use 1 Hz PSA data to obtain an estimate of **M** from each observation and find the average value for all of the stations. For small to moderate magnitude events, 1 Hz data is not sensitive to Δσ and a regional Δσ value can be used to estimate **M**. This can be done either by inverting Eqn. (1) or by using a grid search pattern to find the **M** which minimizes the residuals at 1 Hz. It should be noted that for larger magnitude events one can use PSA at 0.33 Hz, as 1 Hz data become sensitive to Δσ; 3) Use 10 Hz PSA data and the estimated **M** value from step 2 to find the value of Δσ that minimizes the residuals over all of the stations. Details of the methodology are described in Yenier and Atkinson (2015 a, b).

In order to apply this methodology in southern Ontario, we require an overall model calibration, which involves defining the regional anelastic attenuation term, the site response function at each station, and the regional calibration factor. We use the empirical database from the SOSN recordings of 62 events of **M**>2.5, recorded at distances from 10 to 600 km for this exercise; additional stations in the region from the Canadian National Seismographic Network (CNSN) and some data from the IRIS Transportable Array are also used. The geometric mean of the two horizontal components is used. (Note: we use the horizontal components as our desired output is a ground-motion model for the horizontal component.)

First, we find the residuals for the recorded data with respect to the reference model, by assuming the magnitude scaling and geometrical spreading functions from the reference model of Yenier and Atkinson (2015b):

$$re_{ij} = lnY_{ij} - \left(F_{M,i} + F_{Z,ij}\right) = E_{\mathrm{i}} + \gamma_{SOSN} D_{rup,ij} + F_{S,j} \tag{4}$$

where re_{ij} and Y_{ij} are the residual and the observed horizontal ground-motion parameter for event *i* at station *j*, respectively. $F_{M,i}$, $F_{Z,ij}$, are the magnitude scaling function for event *i*, and the geometrical spreading function for event and station *j*, respectively. E_i is the source-term for event *i*, which includes both the event specific stress parameter adjustment factor ($F_{\Delta\sigma,i}$) and also the calibration factor (*C*). The regional anelastic attenuation is given by γ_{SOSN} , while $D_{rup,ij}$ is the closest distance to the rupture surface of event *i* from station *j*. $F_{S,j}$ is the site effect term for station *j* relative to the assumed reference site condition in the reference model (B/C site condition).

For solving Eqn. (4), we follow the generalized inversion scheme introduced by Andrews (1986) to solve for the event term (E_i), the regional anelastic attenuation term (γ_{SOSN}) and the site term ($F_{S,j}$). In order to remove the trade-off between the source term and the site term, we need to assume a reference site condition with known site amplification. Here we assume that the reference site condition is the very hard rock site condition that is typical of seismograph sites in eastern Ontario; this corresponds to sites with V_{S30} ~ 2000 m/sec. We assign zero site amplification to the assumed reference site condition, averaged across all such stations; therefore, the GMPE model for the SOSN application is calibrated for an average site condition of hard rock.

The first output of the generalized inversion is the site amplification term (F_S) relative to the assumed reference site condition (V_{S30} ~ 2000 m/sec) for each of the individual stations. The determined site amplifications can be used in the first step of **M** and Δσ estimation to remove the site effects and level all of the stations to the reference site condition. The second output is the regional anelastic attenuation term (γ_{SOSN}) which is shown in Figure 3. As we observe here, the anelastic attenuation term in southern Ontario indicates slower attenuation in comparison to the anelastic attenuation obtained for the broader region of Central and Eastern North America as a whole (CENA; *Yenier and Atkinson*, 2015b).

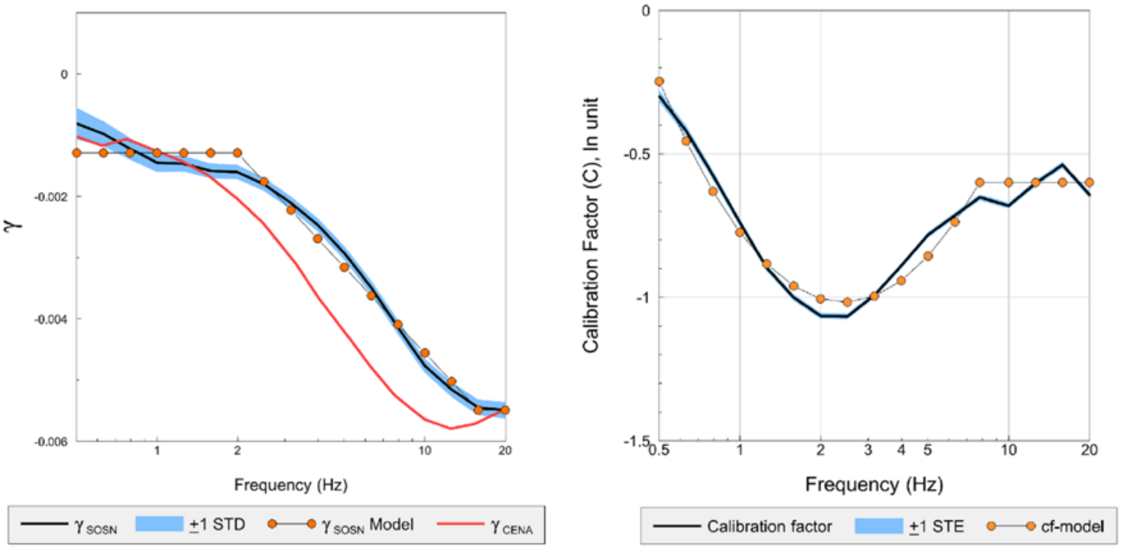


Fig. 3 – Left: Derived anelastic attenuation as a function of frequency. Right: Derived calibration factor as a function of frequency. Blue band indicates one standard deviation about the determined value for southern Ontario.

The next step is to find the event-specific stress parameter ($\Delta\sigma_i$) and the regional calibration factor (*C*) using the derived source term (E_i). We find the event-specific stress parameter by matching the shape of the source term (Yenier and Atkinson, 2015a,b) for each event. We generalize the resulting values as a stress parameter model ($\Delta\sigma_{SOSN}$), which is a function of depth (*d*) and magnitude (***M***):

$$ln\Delta\sigma_{SOSN} = 6.10 + \min[0,0.37(d-7.5)] + \min[0,1.12(\boldsymbol{M}-3.5)] \quad (5)$$

The average regional calibration factor (C_{SOSN}, Fig. 3) can then be found by removing the stress parameter adjustment factor ($F_{\Delta\sigma}$) from the source terms (E_i). This factor compensates for the average difference between the observed ground-motion parameters and the simulated ground-motion parameters. The final formulation of the regionally-adjusted GMPE can be written as follows, in which Y is the predicted ground-motion parameter:

$$\ln(Y) = F_M + F_Z + F_{\Delta\sigma,SOSN} + \gamma_{SOSN} D_{rup} + F_S + C_{SOSN} \quad (6)$$

After developing the regionally-adjusted GMPE for southern Ontario, we implement the derived equation for real-time **M** and Δσ estimation using just the SOSN stations. Our approach is to produce a large set of predicted ground-motion parameters based on alternative values for the model parameters, and then use a grid search to estimate **M** and Δσ from the ShakeMap parameters recorded for the event. We produce the expected ground-motion values for 2.5≤ **M** ≤6 in 0.1 **M** increments for 50 equally log-spaced distances from 1 km $\leq D_{rup} \leq$600 km, and for 30 equally log-spaced stress parameters from 10 bars ≤ Δσ ≤1000 bars. To do this, we remove from each recording the site amplification terms (F_S) as obtained from the generalized inversion results. Then using the observed and predicted PSA data at 1 Hz (for the reference site condition), we find a magnitude value (**M**$_{SOSN}$) which minimize the residuals at 1 Hz, assuming the regional stress parameter model (Eqn 5). Finally we use the observed and predicted PSA data at 10 Hz and find an event-specific stress parameter value ($\Delta\sigma_{SOSN}$) to minimize the residuals at 10 Hz, assuming the **M** value obtained from the 1 Hz PSA. We can iterate these steps one or two more times in order to obtain more precision in the results.

Figure 4 shows an example for the 2010-06-23 Val-des-Bois earthquake (**M**5.1). All observations have been corrected to the reference site condition of hard rock, using the applicable value of F_S at each station. The derived event-specific GMPE closely matches the observed ground-motion parameters on average over a wide frequency range. Figure 4 also shows the comparison between the estimated magnitude and the known moment magnitude for all study events. There is good agreement between the estimated and the known values of **M** on average. Thus for any event we can produce a calibrated GMPE for the reference site condition of hard rock.

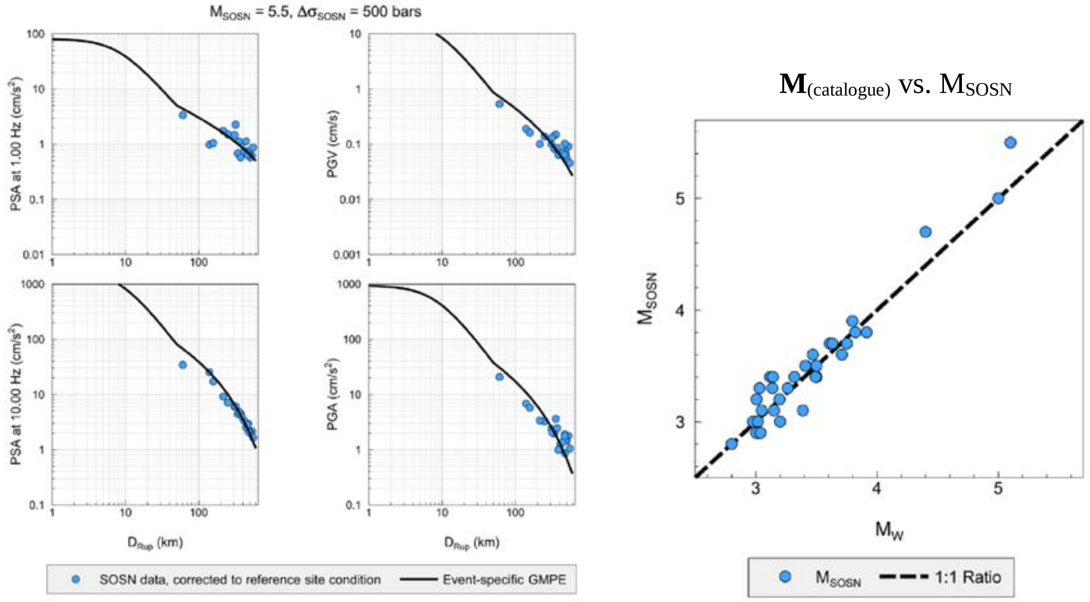


Fig. 4 – Left: Event-specific GMPE for Val-des-Bois earthquake (M5.1). Right: Comparison between the estimated M using the techniques of this study to the corresponding known catalogue values of M.

4. Preliminary Site Response Model for Southern Ontario

The previous section described how we can develop an event specific GMPE for the reference condition of hard rock (geometric mean of the horizontal components). Moreover, we have also developed the site amplification factors (F_S) for each recording station. Thus we have completely specified the ground motion parameters of interest for the reference condition, and for the individual station locations of the SOSN. However, if we wish to map the actual ground motions across the region, we require a regional site response model. This model provides an estimate of the amount of site amplification at each grid point throughout the region based on local surficial geological information. Often, such models are developed using V_{s30} as the parameter to describe site condition. However, this parameter is not readily estimated across a regional grid based on available information. Typical proxies that are used to estimate Vs30, in particular the topographic slope (Wald and Allen, 2007), are not well-suited to applications in regions of low topographic relief such as southern Ontario, because they cannot distinguish between bedrock sites and soil sites. Moreover, in eastern Canada the site conditions are characterized by shallow to deep soil layers that overlie much-harder glaciated bedrock. The high impedance contrast results in strong amplification at the peak frequency of response for the site, which depends on the depth and stiffness of the soil deposit. We thus require a site amplification model that is appropriate for the typical site conditions in the region, and can be developed based on available regional information on surficial geology.

In previous studies in regions of similar site conditions, it has been demonstrated that the horizontal to vertical component ratio (H/V) is a good first-order measure of site amplification (Ghofrani and Atkinson, 2014). The H/V ratio may underestimate the amplitude of site response, but accurately predicts its peak frequency (f_{peak}). In southern Ontario, we have found that the peak frequency is well correlated with the depth of the soil layer (the drift thickness), as shown in Figure 5. Moreover, the Ontario Geological Survey (OGS) has compiled a digital database of drift thickness across the province, allowing us to make at least a preliminary estimate of f_{peak} on a grid of sites across the region. The OGS map also provides an estimate of the soil type at each grid point, which we have discretized as: bedrock; till; sand/clay; or organic materials. The SOSN sites (including the additional stations from the CNSN) are mostly on bedrock (13 sites), till (15 sites), or sand/clay (7), with one site (TORO) being on organic material.

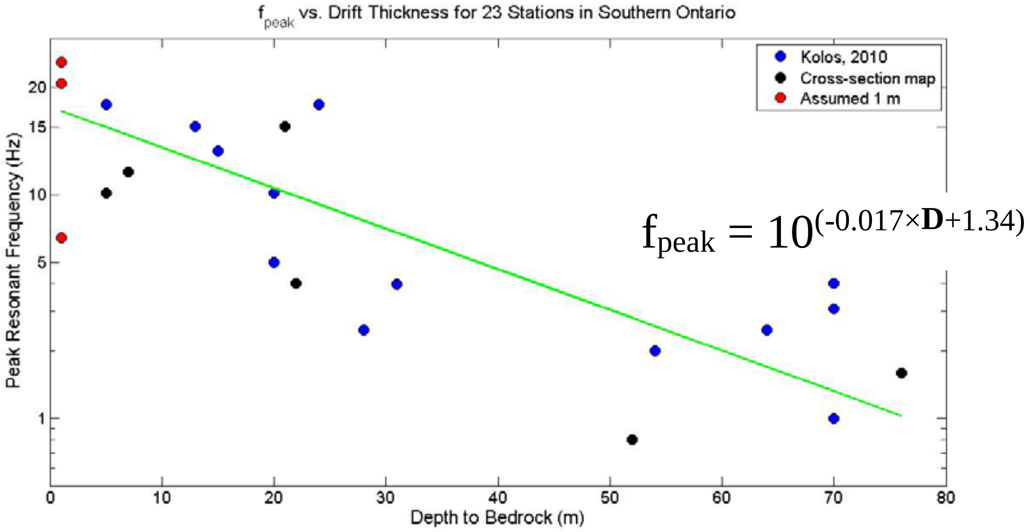


Fig. 5 – Station peak frequencies plotted against drift thickness (D, in meters). Details provided in Braganza (2015).

We follow the methodology of Ghofrani and Atkinson (2014) to develop a generic site amplification model for the SOSN and CNSN sites that is parameterized by f_{peak}, using the recorded H/V ratios (for response spectra) at the stations as a proxy for site amplification. Details of this development are provided in Braganza et al. (2015). We find that for each recording site, the H/V ratio and hence the inferred site amplification is very stable when averaged over multiple event recordings. Moreover, the shape and peak amplitude of the H/V curve can be generalized by site class (i.e. till, bedrock, etc.). Only the peak frequency changes from site to site, depending on the depth to bedrock, as per Figure 5. Thus we can develop a generic site amplification model by site class.

Figure 6 shows the generic amplification model, normalized by peak frequency. To apply this model across a grid of sites, we use the OGS surficial geology map to obtain the drift thickness and soil type for each point. From the relation shown on Figure 5, we estimate the peak frequency of the site (if it is a soil site). The normalized function of Figure 6, for the appropriate site class, is then shifted to the correct frequency by multiplying the x-axis by f_{peak}. We then divide the site response for the soil site by the corresponding average function for bedrock (as shown on Fig. 6), to obtain the response at that site relative to the reference condition of hard rock. This provides the horizontal-component site amplification, which is multiplied by the predicted event-specific GMPE for the reference site condition of hard rock, in order to obtain the site-corrected horizontal component PSA values for the site. By applying this procedure to each point on a grid of sites across the region, we can develop a map of expected ground-motion amplitudes.

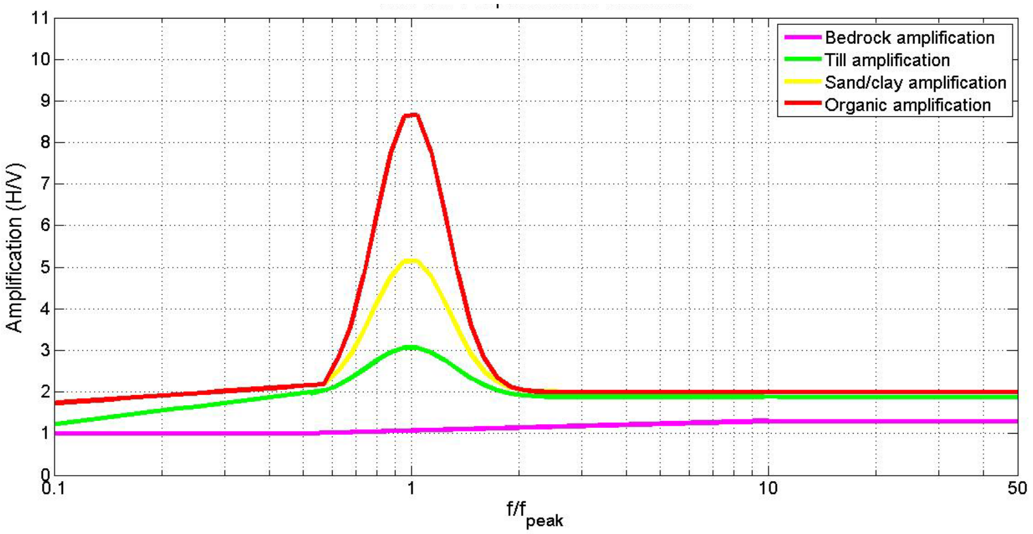
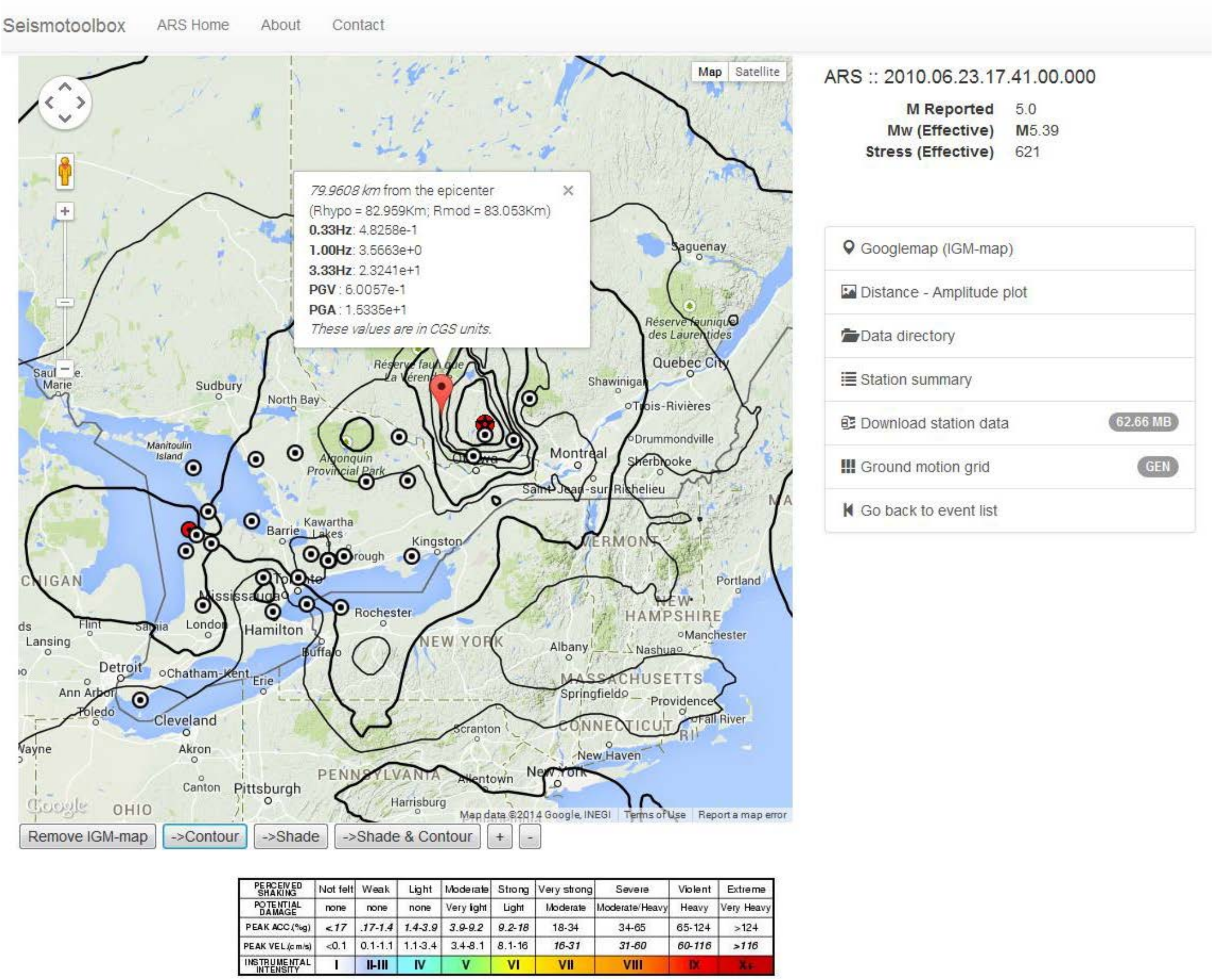


Fig. 6 – Amplification functions for soil sites in southern Ontario. Soil functions are all normalized by peak frequency, but the bedrock amplification curve is not normalized (it is plotted versus frequency in Hz, not f/f_{peak}) (from Braganza, 2015).

We note that an assumption of this procedure for site response is that we can make an accurate estimate of fpeak at every grid point. In reality, we know that there is significant uncertainty in f_{peak} as estimated from the mapped drift thickness; this is readily apparent on Fig. 5. To account for this uncertainty, we are working on broadening the amplification functions to make them applicable to a range of f_{peak} values, so that we have functions that are more broadly applicable to categories such as "deep till", etc. These refinements are the subject of ongoing work.

5. ARS Products

The foregoing steps provide all of the information needed to generate ground-motion data and IGM-maps, within about 5 min of the occurrence of an earthquake in the region. An example of the maps is shown in Figure 7. Note that in this example the site response algorithm has not yet been implemented, as it is still under development. The development of the ARS products is ongoing. The reader may visit www.seismotoolbox.ca for the link to the latest available products.



79.9608 km from the epicenter

(Rhypo = 82.959Km; Rmod = 83.053Km)

0.33Hz: 4.8258e-1

1.00Hz: 3.5663e+0

3.33Hz: 2.3241e+1

PGV : 6.0057e-1

PGA : 1.5335e+1

These values are in CGS units.

ARS :: 2010.06.23.17.41.00.000

M Reported	5.0
Mw (Effective)	M5.39
Stress (Effective)	621

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 7 – Example of IGM-map (zoomable, clickable, optional shading and contouring) developed for 2010 M5.0 Val des Bois earthquake. Clicking a point on the map results in display of its ShakeMap parameter values. Clicking buttons at right provides detailed data at stations, graphs of ground-motion amplitudes versus distance, etc. The site response algorithm is not yet implemented in this example.

6. Acknowledgements

The SOSN and the research to develop the ARS has been funded by Ontario Power Generation and the National Sciences and Engineering Research Council of Canada.

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