ADAPTING SURFACE GROUND MOTION RELATIONS TO UNDERGROUND CONDITIONS: A CASE STUDY FOR THE CARBON CAPTURE AND STORAGE (CCS) SITES IN CENTRAL ALBERTA

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Summary
One of the challenges in CO2 sequestration projects is the evaluation of the integrity of the cap rocks below which CO2 is stored. Probabilistic Seismic Hazard Assessment (PSHA) is a well-established procedure to assess hazard from possible future earthquakes and design considerations for critical facilities. PSHA methods have been used for the structures on the surface for many years. Ground-motion amplitudes vary with depth due to wave interaction with heterogeneities and anisotropies caused by the changes in physical characteristics of different geological units.

In this study, we derive frequency-dependent correction factors to extrapolate surface ground motion to subsurface storage depth. We account for the amplification and attenuation of an upcoming plane wave defined by the elastic properties and shear-wave and Quality factor (Q) in each layer below the surface.

PSHA model for Alberta
Figure 1 shows the simplified seismic hazard zones in Alberta (Martens and Atkinson, 2008). The highest hazard regions are in the far south-west of Alberta, the Jasper region, and in the Rocky Mountain House-Bruceau region. This hazard map is, however, for the structures located on the surface. For the case of CO2 sequestration where the reservoir depth is below 800 m (depth at which CO2 turns into a supercritical fluid) we need to modify this map to account for this depth.

Study regions
Figure 2 shows the index map of Canada showing the location of the study regions. These regions correspond with the Shell Quest CO2 sequestration project, the Wabamun Area CO2 Sequestration Project (WASP), and the Weyburn, Saskatchewan, CO2 sequestration project. Figures 3 and 4 show the maps of these regions.

Methodology
We applied the following equation to obtain the correction factor for depths equal to 800 m below the surface:

\[ C(f) = \gamma \times \left( \frac{\beta_z \times \beta_h}{\beta_z + \beta_h} \right) \times e^{\gamma f / \beta_h} \]

where \( C \) is the correction factor for each frequency \( f \), \( \gamma \) is the free surface effect (2), \( \beta \) and \( \rho \) are averaged shear-wave velocity and density over depth \( z \) and at depth \( h \) (=800 m), respectively, and \( Q \) is the quality factor. In equation (1) the second term corresponds to the amplification of an upcoming vertical plane wave due to energy conservation while the third term shows the path effect due to anelastic attenuation which is inversely related to the quality factor \( Q \). Frequency \( f \) is dependent on the shear-wave velocity and depth through the following equation (Boore and Joyner, 1997):

\[ f = \frac{\beta_z}{4 \pi z} \]

Figure 5 shows the rationale for this methodology. The effected depth \( z \) is proportional to 1/4 of the quarter-wavelength of the wave with frequency \( f \) (Boore and Joyner, 1997). Also as can be seen from figure 5 and equation (2) shallow depth materials affect higher frequencies and vice versa. This can also be seen in Figure 6 which shows the relationship between depth and frequency.

Results
Velocity and density logs were used to construct models of seismic impedance versus depth for each study region (figures 3 and 4). Almost none of the logs reach the surface so a linear dependence for shallow parameters is used to extrapolate these parameters for depths equal to 800 m. For depths at which the shear-wave velocity were not available we assumed a ratio of 1.7 (compressional to shear velocity) to obtain an estimate of the shear-wave velocity. Figures 7-12 show the well logs and the correction factors (equation 1) calculated for each location (the location for each well log is given in Dominion Land survey (DLS) format. As can be seen from figures 7-12 the correction factors show a minima at frequencies around 1 to 2 Hz and then increase with frequency with significant dependence on the values of \( Q \).

SNO experiment
The Sudbury Neutrino Observatory (SNO) is located about 2 km underground in Vale Inco’s Creighton Mine in Sudbury, Ontario, Canada (Figures 2 and 13). There are five three component broadband seismometers installed on and below the surface to observe the local and regional seismicity and the hazard associated with them to the facilities in the area. We used data from a regional event (Nuttli magnitude, MN 3.4) at epicentral distance 203 km to observe the variation in ground motion amplitudes from surface to depth 2 km. We used waveforms from station SSNO (located on the surface) and DSNO (located at depth 2073 m). Figure 14 shows the ratio of the Fourier acceleration spectra of the underground station (DSNO) to the surface station (SSNO) for three components. The minima for the correction factors (maximum amplification on the surface) happens at frequencies ~ 1 Hz for HHE and HHZ components while for the HBN component it occurs at lower frequencies (~0.1 Hz). The discrepancy between the three component regarding the observed trend might be due to the fact that the incidence angle of the upcoming wavefront is not vertical leading to different partitioning of the waves in three components. Another factor which was not considered in calculation of the correction factors from equation (1) is the effect of the surface waves and noise sources from the adjacent mining operations (especially for stations located on the surface) shifting the minima to lower frequencies.

Conclusion
Correction factors to be multiplied by ground motion amplitudes recorded on the surface were calculated to predict those at depth equal to 800 m where the CO2 reservoirs are going to be placed. Amplification and attenuation of an upcoming vertical plane wave was considered into account for modification of the ground motion amplitudes from surface to underground. The results show promising consistencies with the observed amplitudes at the Sudbury Neutrino Observatory.

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References