SPECTRAL CONTENT OF INDUCED VS NATURAL SEISMICITY

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ABSTRACT

Spectral contents of induced earthquakes, resulting from Enhanced Geothermal System (EGS) projects in Switzerland and in California and from injection wells in Texas, are investigated and compared to naturally occurring ground motions. As a result of the EGS projects, areas that were not previously seismically active are now experiencing frequent earthquakes in the range of magnitudes 3 and 4. This is a major concern because most structures in these locations were not designed to withstand seismic activity. Unreinforced masonry is a common choice of building material for Swiss residential buildings, and implications for effects of induced motions on these structures are addressed.

INTRODUCTION

Induced earthquakes are becoming common occurrences as a byproduct of the growing use of hydraulic fracturing in underground rock formations to produce energy, either by extracting oil or natural gas, or through heat exchange. There are open questions if such induced motions have unique spectral characteristics and if they affect structures differently compared to natural earthquakes with similar magnitudes and distances. In many cases, cities that never experienced earthquakes are now experiencing them by the hundreds. Since many of these earthquakes are occurring in locations that are not naturally seismically active, structures were not designed to resist earthquake motions. Consequences of induced earthquakes could, potentially, be significant. For example, the Basel EGS project was shut down after a series of magnitude 3+ earthquakes were induced in December 2006. Not only was the initial investment lost without producing commercial energy, but further expenditures were also needed to repair the slightly damaged homes in the area. More importantly, public confidence in the technology was lost, raising the bar for future geological energy projects.

Previous studies have investigated the spectral content of ground motions resulting from blasts and compared these to natural seismic events (Dowding 1996, McGarr et al., 1990, Seed and Idriss, 1970). Motions with similar magnitudes and distances were found to produce similar spectral content regardless of the source of excitation (blast or natural earthquake), though blast excitations generally have smaller magnitudes and thus shorter dominant periods. For ground motions with increasing magnitudes recorded at similar distances, the pseudo-velocity spectrum corner period was found to shift from shorter to longer period values, and peak pseudo-velocity values were found to grow. For ground motions recorded at increasingly far distances but with similar magnitudes, the dominant period of the response spectrum was found to increase. This behavior was expected because short-period seismic waves attenuate more quickly than long-period ones as they travel through soil. For earthquakes of the same magnitude, near-field earthquakes have a narrower velocity-sensitive region than the far-field ones (Chopra, 2007).

To investigate the spectral content of induced motions compared to natural motions, seismic events resulting from Enhanced Geothermal System (EGS) projects in Switzerland and California and from injection wells in Texas are considered. In EGS projects, high-pressure water is pumped into the ground to induce minor shear failures in the rock and increase rock permeability (hydro-shearing). The water circulates through these fractures in the rock and forms steam, which is used to produce electricity. In Texas, injection wells are used to store waste water resulting from hydraulic fracturing or fracking.

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Many earthquakes have resulted from these EGS and injection well projects, generally in the magnitude range between 1 and 2. Induced earthquakes with magnitude over 3 are rare. Table 1 summarizes the stronger induced ground motions analyzed in this study, which include both induced and natural earthquakes for comparison.

Table 1. Summary of Analyzed Ground Motions

Date	Event	Station	Source	Mag.	Depth (km)	Epicentral Dist. (km)	PGA (g)
Dec. 8, 2006	Basel, Switzerland	SBAJ	EGS	3.4	5.0	2.5	0.076
July 20, 2013	St. Galen, Switzerland	STGK	EGS	3.5	4.5	4.7	0.044
Dec. 12, 2013	Sargans, Switzerland	SBUA2	Natural	4.1	3.6	11.4	0.029
Dec. 5, 2013	The Geysers, CA	GDXB	EGS	3.4	3.0	2.4	0.100
Jan. 12, 2014	The Geysers, CA	GDXB	EGS	4.5	2.5	1.9	0.310
May 27, 1980	Mammoth Lakes, CA	FIS 43	Natural	4.7	N/A	N/A	0.103
Mar. 28, 2014	La Habra, CA	Brea 13873	Natural	5.1	7.5	4.7	0.713
Jan. 25, 2013	Timpson, TX	NQETX01	Injection well	4.1	5.0	12.5	0.239
Sept. 2, 2013	Timpson, TX	NQETX02	Injection well	4.2	4.8	13.0	0.155
Sept. 2, 2013	Timpson, TX	NQETX01	Injection well	4.3	4.7	3.9	0.120

On December 8, 2006, an EGS project in Basel, Switzerland induced a magnitude 3.4 earthquake at a depth of 5.0 km. On July 20, 2013, an EGS project in St. Galen, Switzerland induced a magnitude 3.5 earthquake at a depth of 4.5 km. A natural event occurred in Sargans, Switzerland on December 12, 2013 with a magnitude of 4.1 and depth of 3.6 km (Swiss Seismological Service, 2014).

The same EGS methods are being used at The Geysers, California, where a magnitude 3.4 earthquake occurred on December 5, 2013 at a depth of 3.0 km and a magnitude 4.5 earthquake occurred on January 12, 2014 at a depth of 2.5 km (CESMD, 2014). A natural earthquake with magnitude 4.7 occurred at Mammoth Lakes, CA on May 27, 1980 (PEER, 2014). A natural earthquake with magnitude 5.1 and depth 7.5 km occurred at La Habra, CA on March 28, 2014 (CESMD, 2014).

In Timpson, Texas, a magnitude 4.1 event occurred on January 25, 2013, and magnitudes 4.2 and 4.3 events occurred on September 2, 2013 (Baker and Gupta, 2014). No naturally occurring earthquakes were recorded near this location.

GROUND MOTION ANALYSIS

The Swiss ground motions were downloaded from ArcLink (Swiss Seismological Service, 2014) at the Swiss Seismological Service in miniSEED format. ObsPy (ObsPy, 2014), which is an open-source Python framework for processing seismological data, was used to read and then filter the motions using a bandpass filter from 0.3 Hz to 50 Hz. For each ground motion, the horizontal component with the maximum peak ground acceleration was selected for the analysis. The acceleration history was imported into Bispec (Bispec 2014) to perform a spectral analysis with 5% damping for a period range of 0.01-5 seconds. Figure 1 shows the pseudo-acceleration, pseudo-velocity, and spectral displacement response spectra for the Swiss ground motions. The induced motions are plotted as solid lines and the natural motion is plotted as a dotted line.

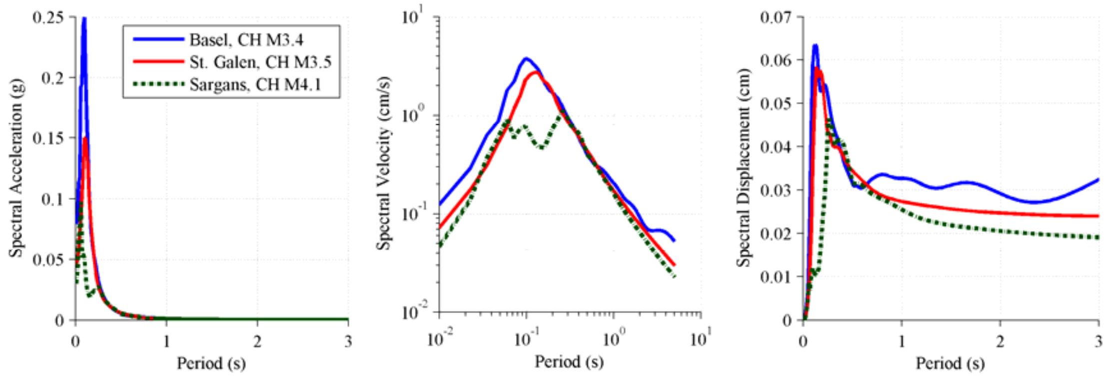

Figure 1. Spectral Acceleration, Velocity, and Displacement for Swiss Ground Motions

The Sargans motion was recorded slightly further from the epicenter (11.4 km) and is characterized by a constant velocity plateau, while Basel and St. Galen are nearer-field motions (2.5 km and 4.7 km, respectively). This matches trends observed with natural earthquakes.

Induced motions at The Geysers, California and the natural motion at La Habra, California were downloaded from the Center for Engineering Strong Motion Data (CESMD, 2014) as processed acceleration time histories. The natural motion at Mammoth Lakes, CA was downloaded from the PEER Ground Motion Database (PEER, 2014). Figure 2 shows the pseudo-acceleration, pseudo-velocity, and spectral displacement response spectra for the California ground motions. The induced motions are plotted as solid lines and the natural motions are plotted as dotted lines.

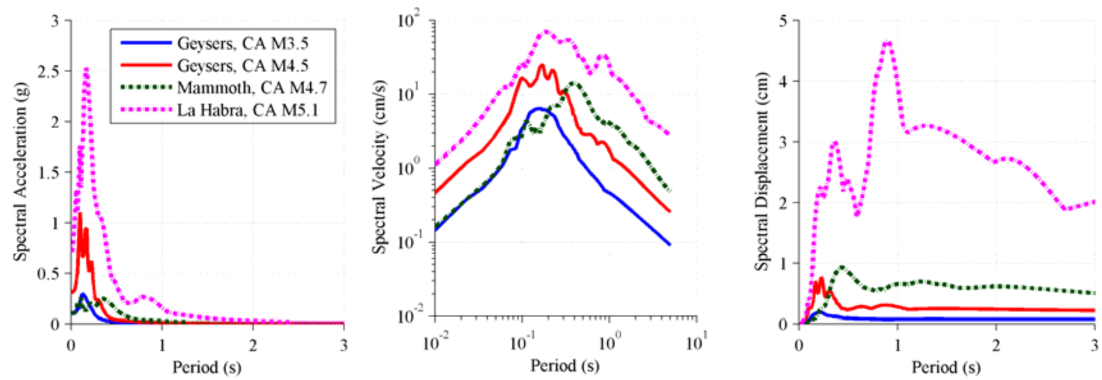

Figure 2. Spectral Acceleration, Velocity, and Displacement for California Ground Motions

The Geysers motions are at distances of 2.4 km and 1.9 km, respectively. La Habra is at a distance of 4.7 km. For the larger magnitude La Habra motion, the corner period has a larger velocity and shifts slightly from a shorter to a longer period value. This trend matches the expectations. Distance information was not available for Mammoth Lakes. It is likely a further-field motion because its peak velocity corner period is shifted to a longer period value.

The Timpson, Texas ground motions were provided by Prof. Jack Baker and Mr. Abhineet Gupta from Stanford University (Baker and Gupta, 2014). They obtained the motions from the IRIS Data Management System (IRIS, 2014) and filtered them using a second order Butter Filter. Figure 3 shows the pseudo-acceleration, pseudo-velocity, and spectral displacement response spectra for the Texas ground motions.

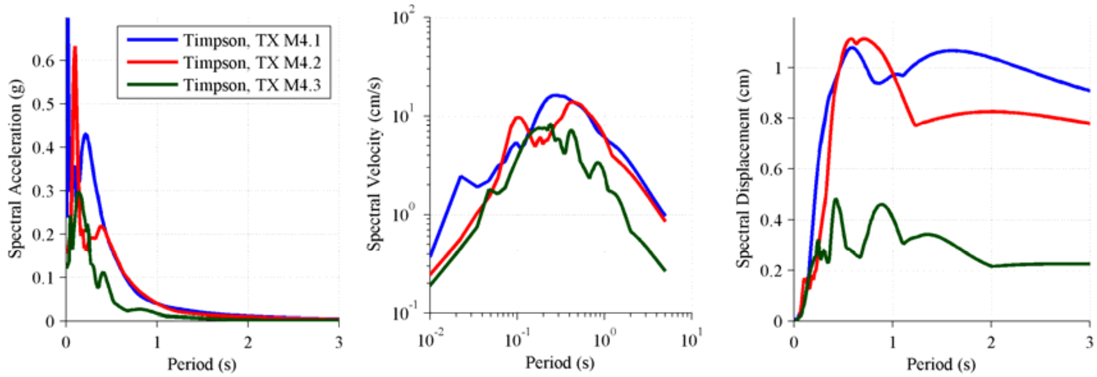

Figure 3. Spectral Acceleration, Velocity, and Displacement for Texas Ground Motions

The Timpson motions are recorded at distances of 12.5 km, 13.0 km, and 3.9 km, respectively. Natural earthquakes in Texas were not available for comparison. The slightly further-field motions show a larger constant-velocity region, as expected.

CONSIDERATIONS FOR URM STRUCTURES

In Switzerland, unreinforced masonry (URM) is a common building material. URM structures tend to be very stiff and have fundamental modes of vibration in the range where the pseudo-acceleration spectra for induced ground motions peak. The effects of induced ground motions on the existing Swiss built environment are, therefore, of particular interest. Von Rotz (2013) modeled the SIA D0237 URM building (2010) using OpenSees. This building represents a typical Swiss four-story apartment building from the 1950's. The periods of the first, second, and third lateral motion modes of an in-plane model of the building are 0.28 s, 0.10 s, and 0.07 s, respectively. A sample pushover curve for the building's short direction, computed using Cubus Promur software by Schönenberger and Zimmermann (2013), is shown in Figure 4.

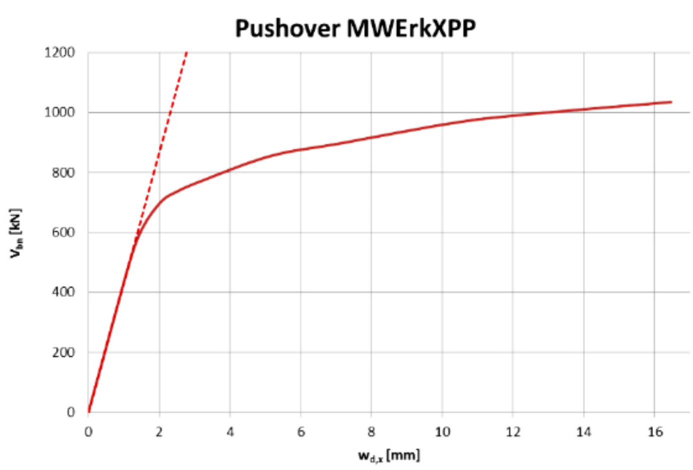

Figure 4. Nonlinear Static Pushover Response Curve for the Short Direction of the SIA D0237 URM Building

Figure 5 shows the pseudo-acceleration spectrum for all of the induced motions considered with the 0.28 s fundamental period of vibration for the SIA D0237 URM building model indicated by a black dotted line. Figures 6 and 7 show the same data, expressed using pseudo-velocity and displacement spectra, respectively. The largest EGS-induced motions in Switzerland have been the St. Galen and Basel events at magnitudes 3.5 and 3.4, respectively. The magnitude 3.5 event at The

Geysers in California has a very comparable spectral acceleration to the two Swiss events. Thus, the larger magnitude 4.5 event at The Geysers gives a good indication of what a larger EGS-induced motion in Switzerland might be.

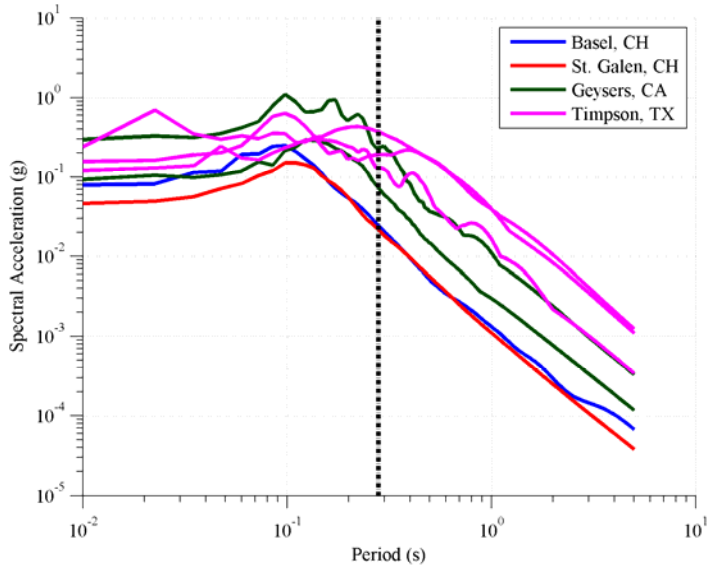

Figure 5. Comparison of Spectral Pseudo-Accelerations for All Induced Ground Motions

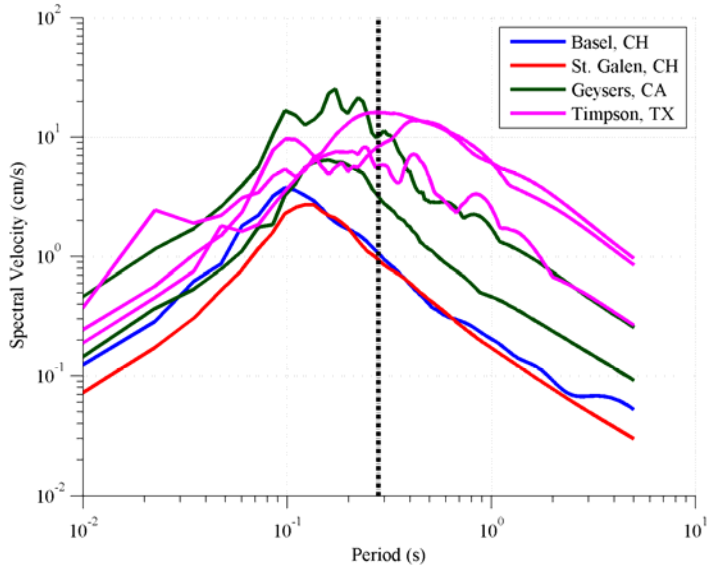

Figure 6. Comparison of Spectral Pseudo-Velocities for All Induced Ground Motions

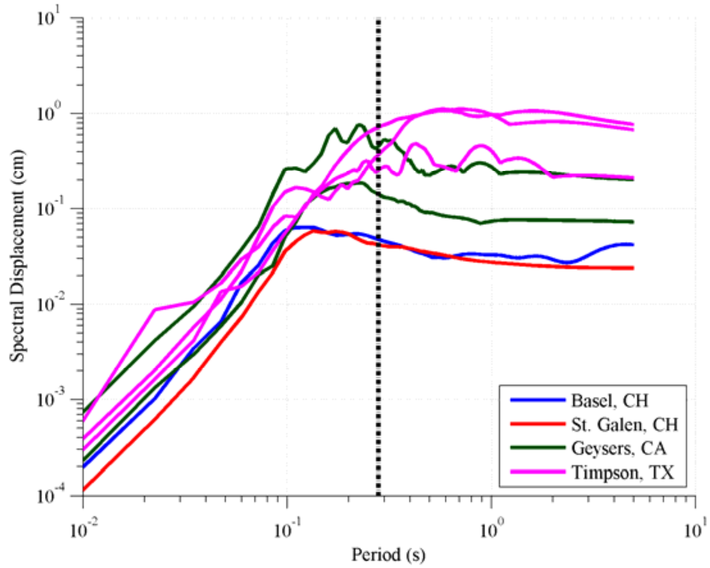

Figure 7. Comparison of Spectral Displacements for All Induced Ground Motions

The pseudo-velocities for the typical Swiss URM building range between 1 and 10 cm/s. Even though the building period is beyond the peak pseudo-velocity range for the EGS-induced St. Galen and Basel motions, it is in the peak pseudo-velocity range for the EGS-induced California motions. The relatively low values of spectral pseudo-velocity indicate that the ground motions have relatively low energy. The spectral displacement values for the induced magnitude 3.5 motions (St. Galen, Basel, and The Geysers) are smaller than 0.05 cm, while they are about 0.5 cm for the magnitude 4.5 Geysers motions. The spectral pseudo-acceleration values at the building fundamental period are less than 0.03g for the Swiss induced motions and are approximately 0.05g for the magnitude 3.5 Geysers motions. The spectral acceleration is significantly larger, about 0.3g, for the magnitude 4.5 Geysers motion. Given that the total weight of the building is approximately 15,000 kN, the expected base shear values are on the order of 500 kN for the magnitude 3.5 motions. Judging by the pushover curve shown in Figure 4, the building would be expected to respond in the elastic range to the EGS-induced magnitude 3.5 motions. Therefore, no structural damage would be expected. However, the response of the building to the magnitude 4.5 Geysers EGS-induced motion is expected to be non-linear, and some structural damage could occur in the URM walls as the interstory drifts would exceed 0.2%.

The induced ground motion pseudo-acceleration spectra attain peak values of approximately 0.3g for very short periods. However, the second and the third vibration mode periods of the SIA D0237 URM building are in that range. The effect of the high-frequency components of the induced ground motions is under investigation because, judging by the effect of high-frequency explosion-induced motions (Lu, et al. 2001), it could be significant.

CONCLUSIONS

This paper compared induced and natural ground motions in Switzerland, California and Texas. The following observations were made:

1. The spectral content of intense induced ground motions is similar to the spectral content of naturally occurring earthquakes with similar magnitude, depth, and distance characteristics. This is evident when comparing the natural Sargans, Switzerland motion to the Basel and St. Galen motions. This is also evident when comparing the natural La Habra, California motion to the two induced motions at The Geysers.

2. EGS-induced ground motions in Switzerland and California with similar magnitudes and distances have similar spectral characteristics.
3. With increasing ground motion magnitudes, the spectral intensity measures increase, as expected, and the corner frequencies shift from shorter to longer period values.
4. The effect of induced ground motions on typical Swiss URM buildings depends on the motion magnitude. The response of the investigated SIA D0237 URM building to the magnitude 3.5 induced motions is expected to be in the elastic range. Stronger induced ground motions would be expected to induce a non-linear building response and cause some structural damage. Such behavior would be expected under naturally occurring motions of the same magnitudes.

Research on structural response to explosions indicated that the high-frequency content could excite stiff sub-structures with an otherwise more flexible structure (Hao et al., 2002, Lu et al., 2001). This behavior should be assessed for the structural response to induced ground motions. With pseudo-acceleration peaks at very low periods, these induced motions could excite a building's higher modes. Additional topics of future studies include performing simulations to determine the spectral content of larger induced motions (magnitudes over 5.0), assessing the magnitude of epistemic variability of induced ground motions, and conducting hybrid simulations to experimentally verify the extent of damage in URM walls caused by induced ground motions of increasing intensity.

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