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ASSESSING THE DAMAGE POTENTIAL OF INJECTION-INDUCED EARTHQUAKES IN THE U.S.

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Abstract

The typical minimum earthquake magnitude (Mmin) used in probabilistic seismic hazard analysis (PSHA) is generally accepted to be about moment magnitude (**M**) 5.0 based on the lack of observed damage to modern engineered structures at smaller magnitudes. The criteria of modern engineered structures is used because PSHA is the basis for modern building codes. Evaluating the ground shaking hazard from injection-induced earthquakes resulting from oil and gas-related wastewater disposal or hydraulic fracturing in the central and eastern U.S. (CEUS) necessitates the re-evaluation of this assumption. Given the significant uncertainties of a non-stationary process such as injection-induced seismicity, PSHA is the best approach in assessing the associated hazard. However, one of several issues that has been raised is what is the Mmin threshold that should be used in PSHA.

It has recently been argued that Mmin should be lowered for induced earthquakes because their ground motions can be stronger than typical tectonic earthquakes given the same magnitude due to their shallow nature, e.g., shorter rupture distances. In contrast, recent analyses indicate that induced earthquakes may have lower stress drops resulting in lower ground motions particularly at high frequencies. To address these issues, empirical ground motion prediction models for injection-induced earthquakes are just now being developed in the U.S. as strong motion data becomes available due to the expansion of seismic networks in the CEUS. With the large number of **M** 4 and larger earthquakes that have occurred in the CEUS, principally in Oklahoma, Texas, and Kansas, we have compiled a database of observed damage and non-damage and have evaluated these data to address the issue of Mmin, and the damage potential of induced earthquakes smaller than **M** 5.0.

Keywords: induced earthquakes; oil and gas; wastewater injection; damage; ground motions

1. Introduction

Recent earthquakes associated with oil and gas activities in the central and eastern U.S. (CEUS; Oklahoma, Kansas, Colorado, Texas, Ohio, and Arkansas) have drawn the attention of the general public, the media, public officials and of course, the oil and gas industry. Across this region, the seismicity rate has doubled over the past 11 years [1]. According to the U.S. Geological Survey (USGS), this rate change can largely be attributed to earthquakes induced by fluid injection associated with oil and gas production, particularly the disposal of produced water and wastewater from hydraulic fracturing operations. Although the largest induced earthquakes have been associated with wastewater disposal (moment magnitude [**M**] > 4.5), confusion in the public and the media over the distinction between the process of hydraulic fracturing and the disposal of its wastewater has led to intense scrutiny of hydraulic fracturing.

It is critically important that induced seismicity be better understood so that any potential hazards can be mitigated, although to-date there have only been a few rare cases where fluid injection-induced earthquakes have been damaging. Specific issues that need to be addressed include: (1) the site-specific factors which can lead to induced seismicity, e.g., why some wells trigger earthquakes and the vast majority do not; (2) how to predict the maximum magnitudes and rates of potential induced seismicity; (3) how can fluid injection-induced earthquakes be controlled; and (4) how to estimate the seismic hazards posed by induced earthquakes.

To address issue (4) and assess the potential effects on population and infrastructure from injection-induced seismicity (e.g., damage), it is critical to be able to predict the resulting ground shaking. Although injection-induced earthquakes seldom exceed **M** 5 in size, their shallow nature could lead to large amplitudes particularly at high frequencies e.g., peak horizontal ground acceleration (PGA) in the near-field. Alternatively the ground motions from induced earthquakes could be lower as may be the case for shallow natural tectonic earthquakes because they occur in a weak shallow crust resulting in low stress drops. We address these factors in the following.

2. Evaluating the hazard

The most effective approach to assessing the ground shaking hazard from induced earthquakes is through probabilistic seismic hazard analysis (PSHA). PSHA is the only viable approach given the non-stationary process of induced seismicity and the very large uncertainties associated with characterizing: (1) the potential for induced events occurring in an area, (2) the maximum magnitude (Mmax), (3) activity rates, and (4) ground motions. Ideally, the characterization of the rates of induced earthquakes of various magnitudes would incorporate the stress state of local faults, hydrolological properties of the injection formations and the overlying and underlying stratigraphic units, and pressures and volumes of injection fluids. Given the large uncertainties, the potential impacts of induced seismicity should be addressed using a risk-informed decision-making process that requires the results of a PSHA.

In using the PSHA methodology, one of several issues that has been raised is what is the minimum magnitude (Mmin) that should be used. Another issue that is even more challenging is what is the Mmax that can result from wastewater disposal and hydraulic fracturing, though we do not address Mmax in this paper. The typical Mmin used in PSHAs is generally accepted to be **M** 5.0 which is based on the lack of observed damage to modern engineered structures [2]. Mmin is independent of distance although it is implicit that close distances are most important. It follows that because induced earthquakes are generally less than **M** 5.0, near-field distances (< 10 km) are those of greatest engineering relevance. Induced earthquakes are a new issue now being confronted by the hazard and engineering community such as in the USGS National Seismic Hazard Maps [3]. In the 2014 USGS National Seismic Hazard Maps and its predecessors which excluded induced seismicity, a Mmin of **M** 4.7 is used in the CEUS and **M** 5.0 in the western U.S. [4]. In the recent 2016 one-year seismic hazard maps for the CEUS which included both natural and induced seismicity for the first time (also developed by Petersen *et al*. [3]), the same Mmin for the CEUS was used.

It has been recently argued that Mmin should be lower than **M** 5.0 because induced earthquakes will generate stronger ground motions compared to tectonic events of similar size due to their shallow nature; hence, shorter distances to the ground surface (e.g., [5]). In contrast, recent analyses indicate the induced earthquakes may have lower stress drops resulting in lower ground motions particularly at high frequencies e.g., PGA (Section 4) (e.g., [6 to 8]).

One significant factor to consider when discussing damage due to induced earthquakes is that in many areas of low seismicity in the CEUS, there are large inventories of vulnerable buildings and structures which have no seismic design either because of their age or because they were designed to a building code which only had to address the ground motions from small infrequent natural earthquakes.

With the availability of recent ground motion data, ground motion prediction models are beginning to be developed for induced earthquakes from oil and gas activities in the U.S. (e.g., [9]). While the debate continues on injection-induced ground motions, we have compiled and evaluated a database of damage and non-damage reports for injection-induced earthquakes in Oklahoma, Kansas, Texas, The Geysers geothermal field, California, northeastern British Columbia, and western Alberta.

3. Damage

To date, the largest potentially induced earthquakes in the CEUS have been the 2011 **M** 5.7 Prague, and the recent 2016 **M** 5.8 Pawnee, Oklahoma earthquakes and the 2011 **M** 5.3 Trinidad, Colorado, event. No other induced events have equaled or exceeded **M** 5.0 in the CEUS despite more than 100,000 Class II wastewater injection wells in the CEUS (Environmental Protection Agency) and decades of injection. The origins of all three earthquakes, whether tectonic or induced have been highly debated (e.g., [10]). The largest induced earthquake associated with hydraulic fracturing in the CEUS has not exceeded **M** 3.0 [11].

Earthquakes of **M** 5.0 and larger can generate structural damage, but can smaller events? Damage to unreinforced masonry (URM) or adobe structures has been observed in all three **M** ≥5.0 earthquakes mentioned above but no structural collapse was observed (Figs. 1 and 2). However, none of the three earthquakes occurred in heavily populated areas. In this paper, we define "structural damage" as extensive or complete damage such that the ability of the structure to withstand collapse is compromised. Other types of damage we consider to be nonstructural. We acknowledge that this definition differs from the standard engineering definition where damage is usually related to system components. For example, damage such as to corners of doors and window openings in light wood frame buildings is viewed as "slight structural damage" according to Section 5 of the HAZUS Technical Manual [12]. In that manual, levels of structural damage are defined as: slight, moderate, extensive, and complete. In this paper, structural damage is confined to extensive or complete, levels where life safety may be compromised. All other forms of damage are considered to be nonstructural or cosmetic particularly if the damage is to a nonstructural element of the building. For example, exterior wall panels, partition walls, ceilings, and electrical-mechanical equipment, piping and ducts are nonstructural elements.

Fig. 1 – Damaged spire at St. Gregory's University in Shawnee, Oklahoma due to the 2011 Prague earthquake.

Fig. 2 – Damage to brick façade in Trinidad, Colorado due to 2011 earthquake.

4. Ground Motion Models, Stress Drops, and Site Effects

There are four major issues that need to be addressed in predicting ground motions of injection-induced earthquakes and hence hazard, damage and loss: 1) Are ground motions from injection-induced earthquakes statistically different from ground motions from natural earthquakes? 2) How do injection-induced earthquake ground motions scale with magnitude and distance? 3) Is this scaling a function of tectonic regime like natural earthquakes which are partitioned between tectonically active regions like the western U.S. and stable continental regions like the CEUS? and 4) Are any of the current ground motion models for natural earthquakes appropriate for induced seismicity or do new models need to be developed?

Strong motion and broadband data are now becoming available from seismic networks being operated by the USGS and state agencies in the CEUS particularly in Oklahoma and Kansas and in the future, Texas. These data are just starting to be used to develop empirical ground motion prediction models (e.g., [9]) but there still is a scarcity of data from events larger than **M** 4 at close-in distances (see following discussion). As previously stated, distances of less than 10 km for events smaller than **M** 5 is the range of most engineering relevance to address the issues of potential damage from injection-induced earthquakes.

Fig. 3 shows the ground motion prediction models that are being used in the U.S. for induced earthquakes. A **M** 4.5 event and a generic firm rock site condition (time-averaged shear-wave velocity in the top 30 m [Vs 760 m/sec]) are shown as an example. None of the models are based on data from induced events. The model by Atkinson [5] which is applicable to events in the magnitude range of **M** 3.0 to 6.0 is based on the NGA-West2 strong motion database of tectonic earthquakes. Her model has two versions, with and without near-field saturation. The NGA- West 2 ground motion models [13 to 16] also are for tectonic earthquakes. A very recent model not shown is that of Yenier *et al.* [9] which we have not been able to compare and evaluate as of yet. The significant issue pointed out by the difference between the Atkinson [5] model and the other models is how do ground motions saturate or not saturate at short distances (< 10 km)? Hopefully as more strong motion and broadband data is collected, the near-field ground motions can be appropriately modeled.

Fig. 4 compares the Atkinson [5] ground motion prediction model without saturation and the mean of four NGA-West 2 models with the available recorded data for induced events of **M** 4.0 and larger in Oklahoma and Kansas for the period November 2011 to September 2016 showing the small amount of data within 10 km. To our knowledge, there are no Vs30 information for the Oklahoma and Kansas seismic stations and so we have assumed a generic Vs30 for soil of 370 m/sec. The data available to date for **M** < 5.0 suggest that there is a low level of saturation at distances less than 10 km (Fig. 4).

The Atkinson [5] model illustrates one view that induced earthquakes can produce relatively high ground motions because they are shallow and therefore can be at short distances (Figs. 3 and 4). However, some recent observations suggest that ground motions from induced earthquakes like shallow tectonic earthquakes are relatively low. The physical model is that both induced and shallow tectonic earthquakes have low stress drops because the very shallow crust is very weak and thus cannot sustain high stresses or that it attenuates ground motions.

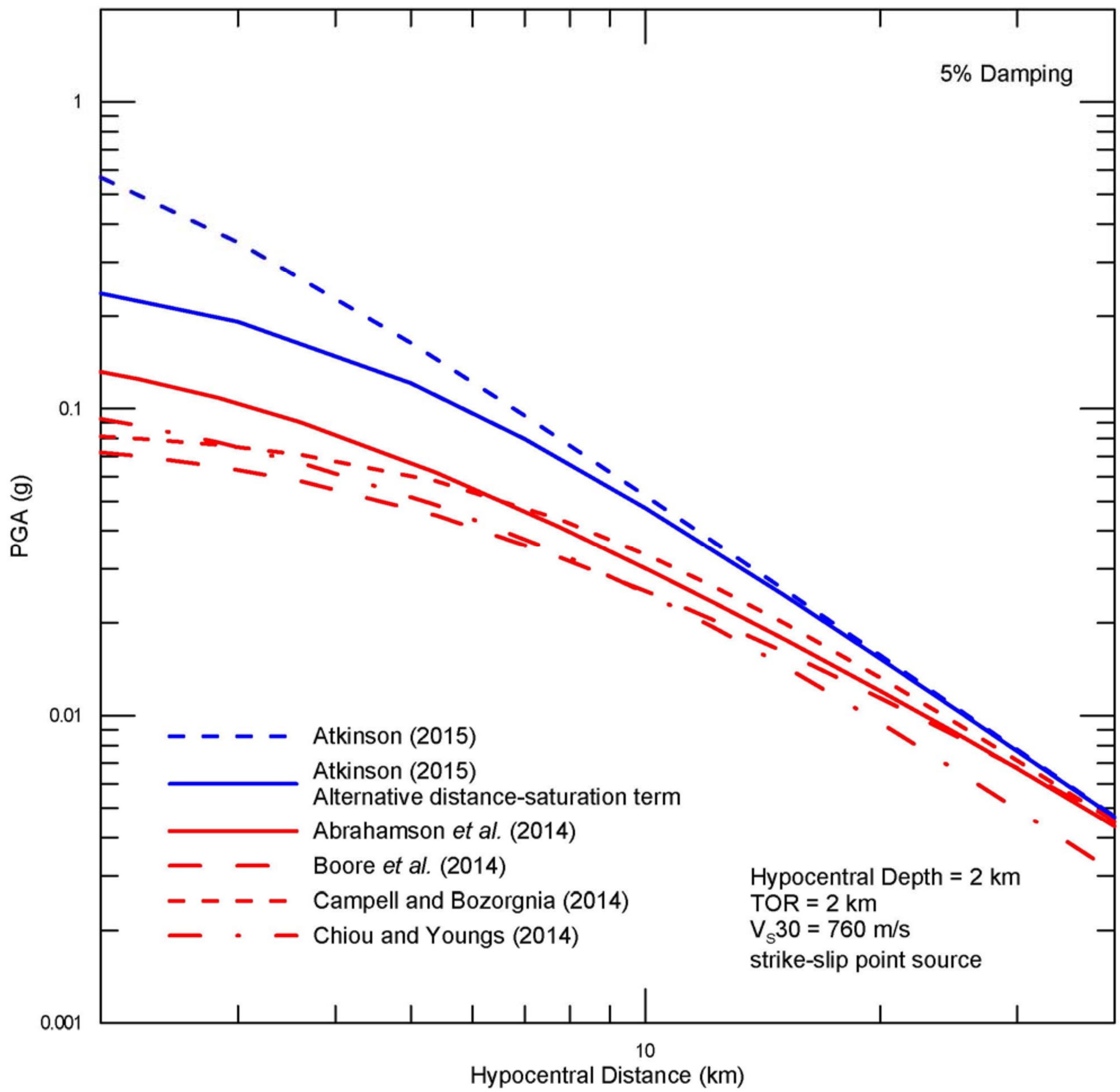
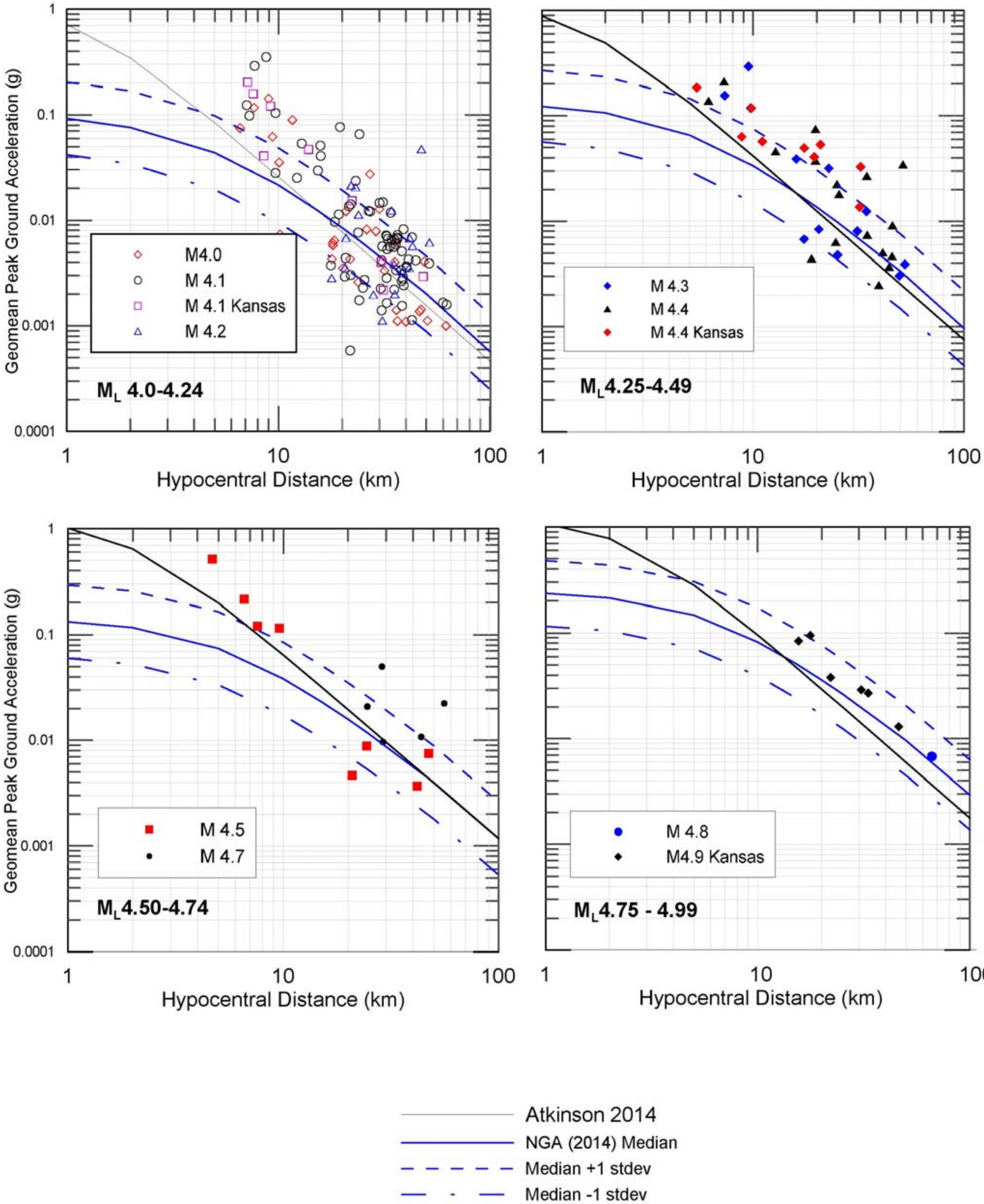


Fig. 3 – Ground motion prediction models for **M** 4.5 used for induced earthquakes in U.S.


Geomean Peak Ground Acceleration (g)
1
0.1
0.01
0.001
0.0001
1
10
100
Hypocentral Distance (km)
M4.0
M 4.1
M 4.1 Kansas
M 4.2
M$_L$ 4.0-4.24
M 4.3
M 4.4
M 4.4 Kansas
M$_L$4.25-4.49
M 4.5
M 4.7
M$_L$4.50-4.74
M 4.8
M4.9 Kansas
M$_L$4.75 - 4.99
Atkinson 2014
NGA (2014) Median
Median +1 stdev
Median -1 stdev

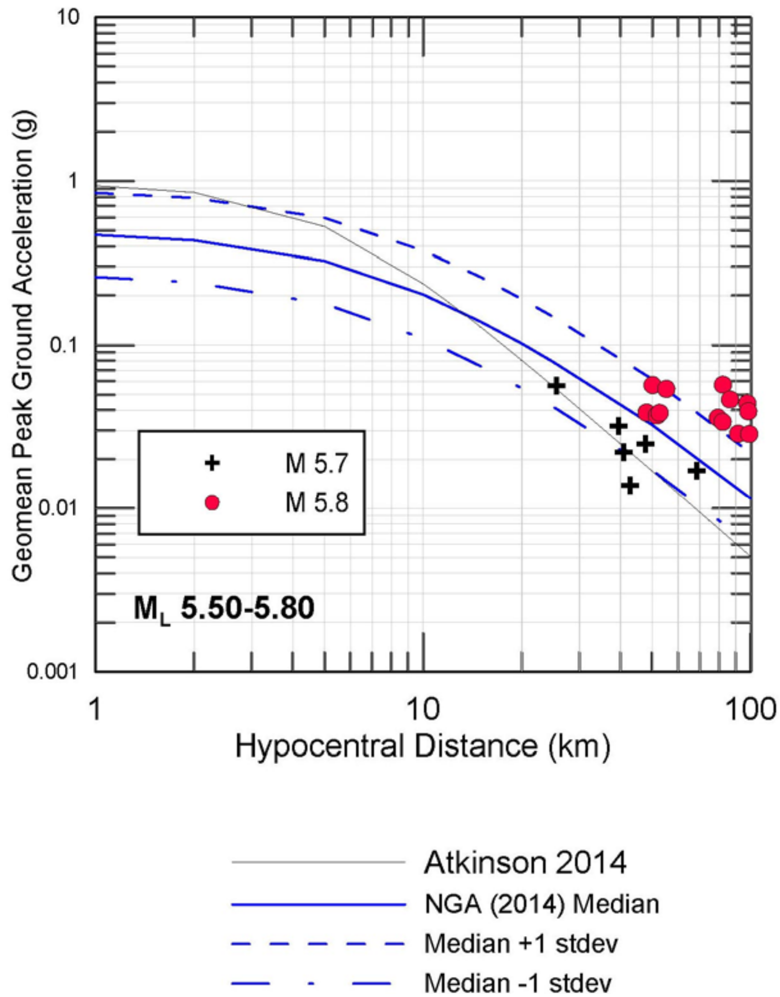


Fig. 4 – Comparison of PGA values from induced earthquakes in Oklahoma and Kansas with ground motion prediction models. The data shown in the last magnitude bin are for the 2011 Prague and 2016 Pawnee earthquakes. The site conditions are not known for the Oklahoma and Kansas seismic stations and so a Vs30 of 370 m/sec has been assumed.

Table 1 lists the most significant induced earthquakes that have occurred in the CEUS through 2012 including the 2011 **M** 5.7 Prague event and stress drops computed by Darragh *et al.* [6]. The mean stress drop of the induced earthquakes is less than 10 bars. Darragh *et al.* [6] also estimated averages of 60 and 120 bars for **M** 4.5 and 5.5, respectively, for tectonic earthquakes in the CEUS using the same analytical approach. In contrast, Huang *et al.* [17] evaluated the stress drops for the Guy-Greenbrier, Arkansas and Azle, Texas, sequences and found that these induced earthquakes had stress drops comparable to tectonic events. This issue is being targeted by a number of researchers as new data becomes available and so an improved understanding should be forthcoming.

Table 1 – CEUS Induced Earthquake Stress Drops [Darragh *et al.* (2015)]

Location	Magnitude (M)	Date	Time (GMT)	Stress Drops (bars)
Jones, OK	3.8	15 Jan 2010	15:18	5.9
Lincoln, OK	4.2	27 Feb 2010	22:22	9.6
Slaughterville, OK	4.4	13 Oct 2010	14:06	3.5
Guy, AR	3.9	15 Oct 2010	10:20	11.2
Arcadia, OK	4.0	24 Nov 2010	22:48	5.9
Bethel Acres, OK	3.2	12 Dec 2010	01:07	5.4
Guy, AR	3.9	20 Nov 2010	19:06	7.0
Greenbriar, AR	4.7	28 Feb 2011	05:00	15.2
Comal, TX	4.6	20 Oct 2011	12:24	2.8
Prague, OK	4.7	5 Nov 2011	07:12	17.5
Prague, OK	5.7	6 Nov 2011	03:53	20.1

Site effects must also be considered in predicting ground shaking from induced earthquakes as they are for tectonic earthquakes as they can control the amplitudes and frequency content of ground shaking. Oil and gas activities are conducted in sedimentary basins and hence the effects of unconsolidated sediments will affect ground shaking both in terms of amplification and deamplification depending on the frequency of the ground motions. Ground motion prediction models attempt to incorporate site effects through generic amplification models using Vs30 but often it comes down to modeling the site-specific conditions to obtain an accurate assessment of the ground shaking at a site. Also because soil nonlinearity will be a factor on how much amplification can occur as a result of an induced earthquake, understanding the source spectra from induced events will be critical in estimating the associated hazard. The ground motions from induced earthquakes are also expected to be richer in high frequencies given their generally smaller magnitudes and shorter source-to-site distances and so deamplification at longer periods is probably unlikely.

5. Ground Motion and Damage

Which ground motion parameter(s) are the best indicator of damage? As has been debated for the past couple of decades, probably no single ground motion parameter or metric is a robust predictor of damage. Although engineers most often use response spectra and PGA to represent the level of ground shaking in seismic design, peak ground velocity (PGV) is often cited as the best predictor of damage. However, the engineering community also recognizes that duration is an important factor in building damage.

One of the significant characteristics that needs to be accounted for in evaluating the damage potential of induced earthquakes smaller than **M** 5.0 is that they have short durations of only a few seconds or less as illustrated in Fig. 5. Thus although they may have high amplitudes as discussed earlier because of short source-to-site distances, their short durations will result in only a small number of cycles that a building or structure will be subjected to hence reducing their damage potential (Section 6). Building response such as indicated by peak displacement is determined by the intersection of the demand spectrum and building capacity curve [12]. The effect of duration can be incorporated into the spectral demand by reducing the effective demand. Fig. 6 illustrates the effect of duration on the demand spectra for a moderate-code building for a **M** 7.0 earthquake at 20 km. Of course for induced earthquakes, we are discussing much smaller magnitudes but the figure illustrates the impact of duration.

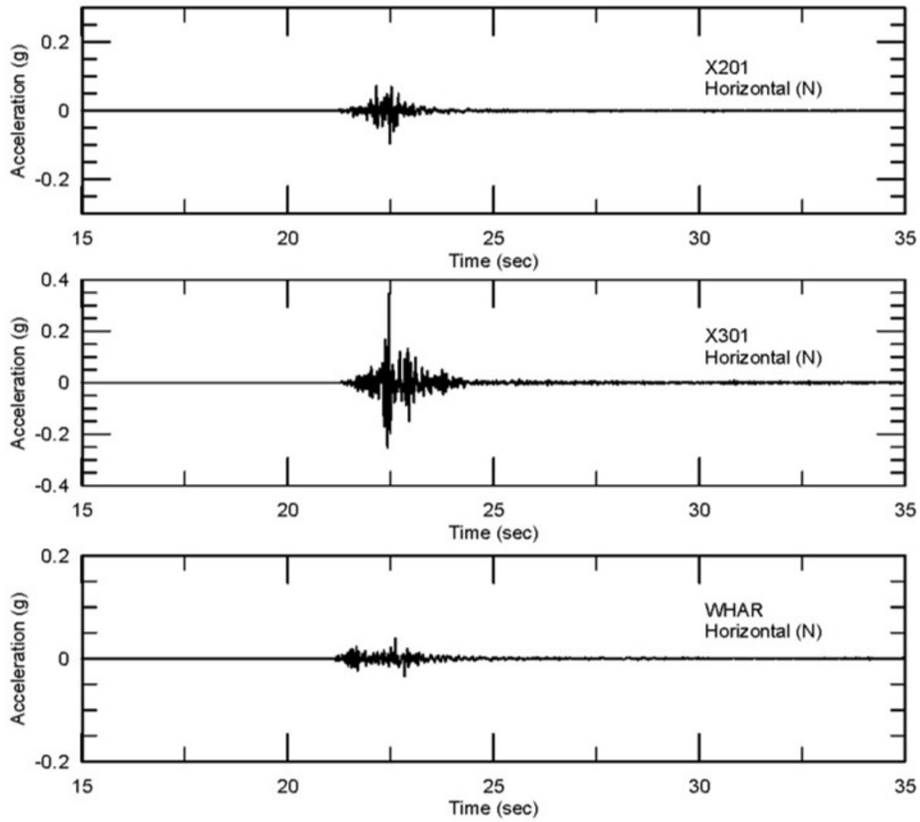


Fig. 5 – Acceleration time history of the 2013 **M** 4.1 Timpson, Texas earthquakes.

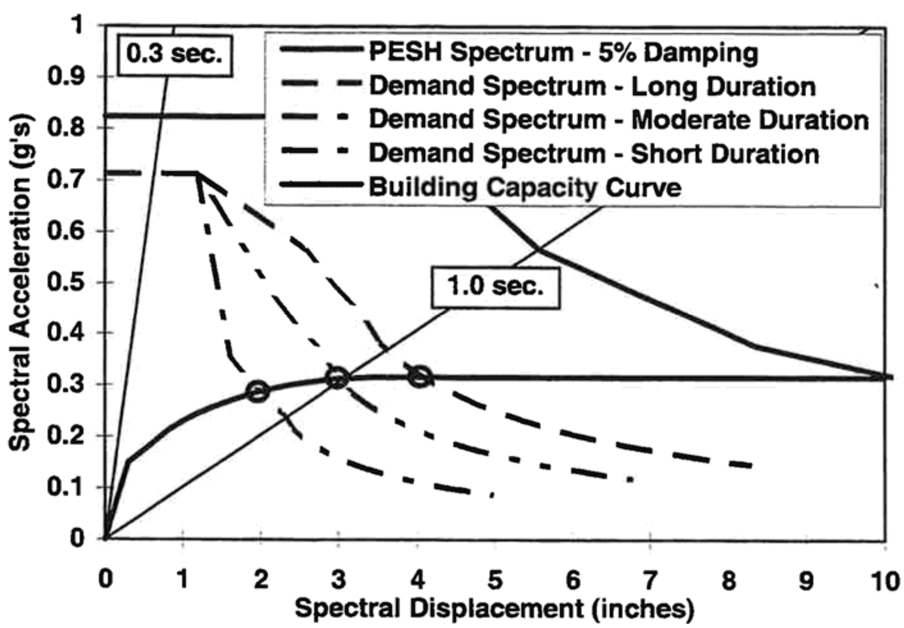


Fig. 6 – Example demand spectra – moderate-code building (**M** 7.0 at 20 km, western U.S., site class E). (Source: NIBS [12]).

6. Observations of Damage

We have and continue to compile and evaluate a database of damage and non-damage for induced earthquakes. The database includes 80 total induced or potentially induced earthquakes from **M** 4.0 to 4.9 during the period of 1989 through January 2015 (Fig.7). There are 33 events from Oklahoma, Kansas and Texas (**M** 4.0 to 4.9). We also included 15 events from northeastern British Columbia and Alberta (**M** 4.0 to 4.4 although magnitudes are of mixed scales). The CEUS and Canadian earthquakes are all associated with either wastewater injection or hydraulic fracturing. We have included 32 Geysers, California earthquakes ranging from **M** 4.0 to 4.7 because they are induced events albeit as a result of a geothermal process. They occur at shallow depths and many have been located within 5 km of population centers; hence they are valuable in terms of evaluating structural damage. A few of the Geysers events were located directly beneath the local communities. Information on damage or non-damage was compiled by examining newspaper accounts and reports found on the internet except in the case of the Geysers earthquakes where we had direct communication with the homeowners. No site visits were performed.

As part of the database, we have compiled PGA values for the CEUS induced earthquakes estimated by the USGS using their ShakeMap methodology [18]. These estimates are maximum values and so although informative, they do not necessarily reflect the ground shaking at locations where there has been damage reported. The highest PGA estimated was 0.40 g in the **M** 4.8 Prague aftershock. A more detailed analysis of these data would be required and the ShakeMap PGA estimates are not reliable enough to draw any conclusions. For the Geysers earthquakes, we have recorded PGA data for most of the events and the largest recorded values was 0.13 g. We have no PGA data for the western Canada events.

Of the 80 events, 60 have no known reported damage. Six events resulted in fallen objects, 13 events caused non-structural damage principally damage to URM and chimneys and there was structural damage in one event. The non-structural damage consisted of, for example, a fallen chimney in the 2013 **M** 4.1 Timpson, Texas earthquake. In the 2015 **M** 4.2 Cherokee, Oklahoma earthquake there was interior wall and ceiling damage on the third floor of a courthouse. In the 2012 **M** 4.8 Timpson, Texas event, there were reports of broken windows and some chimney damage in the interior of a house but no reported structural damage. The one earthquake that caused structural damage was the 2014 **M** 4.9 Conway Springs, Kansas event where two URM buildings reportedly suffered “structural” damage although we have not obtained details. No structural damage has been observed for the Geysers events.

We have not at this point been able to estimate the epicentral distances to the locations of damage, except in the case of the Geysers earthquakes, and so that factor needs to be considered in drawing conclusions from these data. However, for the events where we know the epicentral distances were only a few kilometers, no damage was reported.

We attribute the lack of structural damage in our database to the short durations of the induced earthquakes. Non-structural damage is not unexpected given that in many cases, the reported intensities were generally in the range of MM IV to VI with the 2014 Conway Springs earthquake assigned a MM VII by the USGS. The abundance of URM buildings in the CEUS also amplifies the potential for nonstructural damage.

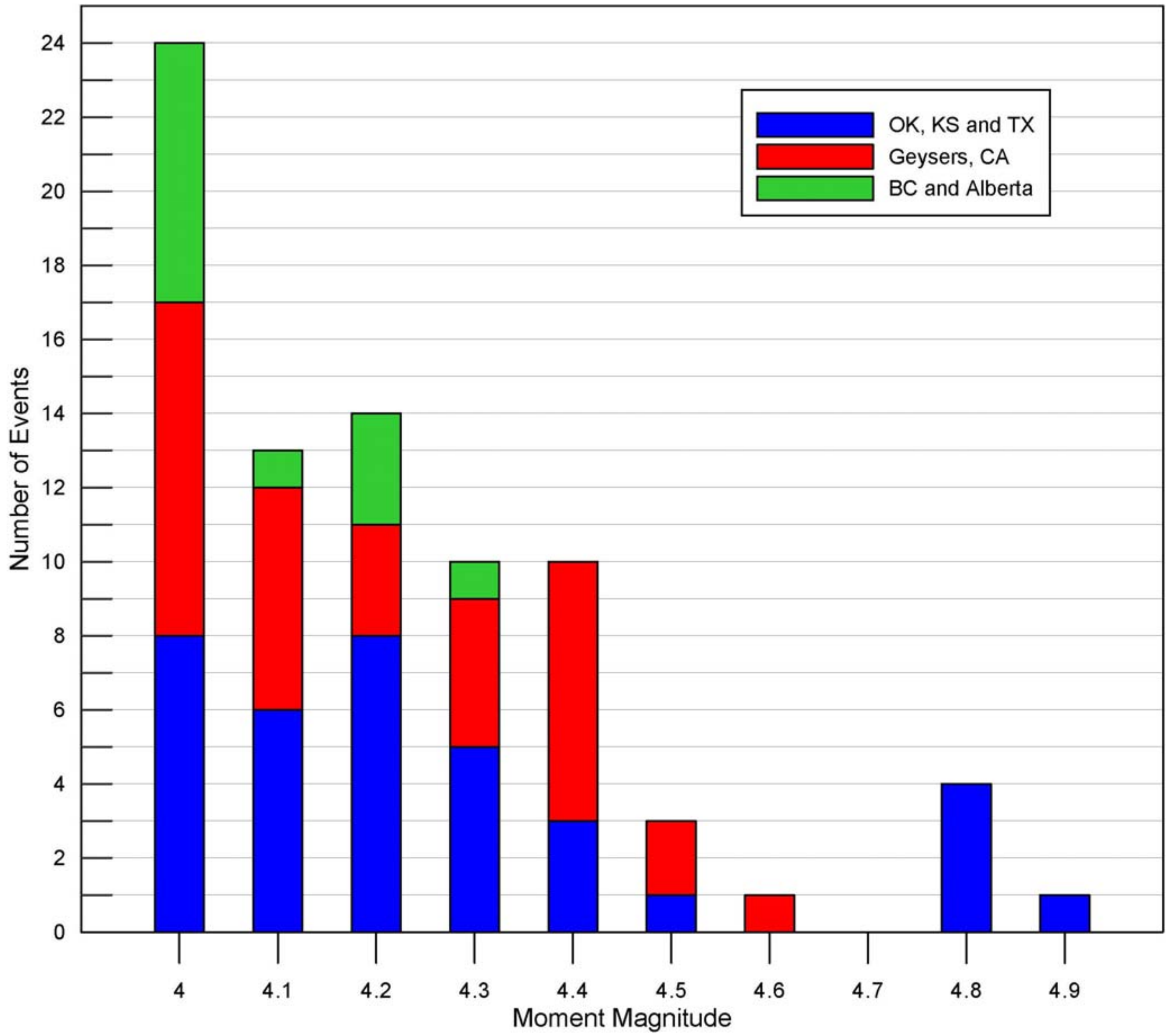


Fig. 7 – Histogram of number of induced earthquakes (< **M** 5.0) in Oklahoma, Kansas, Texas, The Geysers, and western Canada versus moment magnitude.

7. Conclusions

Modern structures are designed for life safety i.e., to prevent collapse. The damage to modern engineered structures requires sufficient duration such that the structures will be subjected to several cycles of strong ground shaking. The accepted standard for damage to engineered structures is a Mmin of **M** 5.0. Observations to date indicate that this minimum is still generally appropriate even for more vulnerable poorly engineered buildings in the CEUS. Damage to URM and adobe structures has been observed in the 2011 **M** 5.3 Trinidad, Colorado, 2011 **M** 5.7 Prague, and the 2016 **M** 5.8 Pawnee, Oklahoma events (Figs. 1 and 2). Poorly engineered structures such as URM buildings are abundant in the CEUS and although only non-structural damage is expected in events of **M** < 5, they still pose life-threatening hazards due to falling debris.

Although significant and widespread structural and nonstructural damage has not been observed for induced earthquakes in the CEUS due to their generally small magnitudes, hence short durations, and the small areas they impact, they can still pose a hazard because of the vulnerable areas in which they occur. Research must continue working with the data coming out of seismic networks operating in areas affected by induced seismicity, to develop ground motion prediction models and characterize stress drops. The value of Mmin in PSHAs should consider the purpose of the hazard assessment i.e., seismic design or hazard in vulnerable areas.

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