BUILDING COLLAPSE AND LIFE ENDANGERMENT RISKS FROM INDUCED SEISMICITY IN THE CENTRAL AND EASTERN UNITED STATES

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Abstract

An increasing number of studies indicate that the elevated earthquake rates in the Central and Eastern United States are induced by fluid injection associated with the oil and gas production. In early 2015, the U.S. Geological Survey (USGS) published a sensitivity study of alternative probabilistic hazard models that incorporate the induced seismicity in a sensitivity study. The final USGS seismic hazard model that includes induced and natural earthquakes was released in 2016. This study investigates the risks of building collapse and non-structural component falling by combining the USGS induced seismicity hazard models from the 2015 sensitivity study and the fragility curves defined in the *2015 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. As expected, the risks are increased compared with those due to natural seismicity only. This increase varies from a few times to more than a few hundred times depending on the key hazard modeling decisions, including declustering and the slope of the magnitude-recurrence relations, and the location of the site. The increases of risk for different risk objectives are similar, but are more significant for short-period than moderate-period buildings. In addition, the paper explores how induced seismicity could impact risk-targeted ground motions and seismic design category assignments used for building design.

Keywords: induced seismicity; hazard curves; building collapse fragility; risk

1. Introduction

In the Central and Eastern United States (CEUS), the number of earthquakes of magnitude 3.0 or greater has increased dramatically over the past few years. These earthquakes have occurred especially in Oklahoma, but also in Arkansas, Colorado, Kansas, New Mexico, and Texas [1]. An increasing number of studies indicate that the elevated number of earthquakes is due to wastewater injection associated with the oil and gas production activities [1-5]. While most of the induced earthquakes are small, a number of events with magnitude greater than 5.0 caused damage to homes and masonry buildings [2, 3], and many more induced events have been widely felt. The frequent occurrence of such events has raised significant public concerns about the potential damage to, or even collapse of, buildings that may be caused by the induced earthquakes.

In early 2015, as a first step to quantify the seismic hazard associated with the induced earthquakes, the U.S. Geological Survey (USGS) published an open-file report [5], a sensitivity study of alternative induced seismicity probabilistic hazard models to show the effect of various input parameter choices. Of those probabilistic hazard models, the report shows five models that are each combined with the 2014 National Seismic Hazard Model (NSHM) [5]. These models demonstrate that the hazard assessment is sensitive to several key modeling considerations including induced seismicity catalogs, rates, locations, minimum magnitudes of the earthquake catalog, maximum magnitudes, and ground motion models. The sensitivity analyses indicate: (i) the seismic hazard increases significantly due to the induced earthquakes, especially for regions where these earthquakes are occurring frequently; and (ii) there are notable differences between the hazard estimated by the alternative models. A consensus seismic hazard model that considers both induced and natural earthquakes for the CEUS was published by USGS in March 2016 [6]. Although the 2016 model has much lower seismic hazard near some areas of active induced earthquakes compared to several of the models included in the 2015 USGS open-file report, the 2016 model forecasts the one-year seismic hazard to be considerably higher than that due to the natural earthquakes alone. It is expected that the elevated seismic hazard due to induced seismicity will lead to greater seismic risk. Given that the design ground motion levels in current building codes for the CEUS (high induced seismicity region) are not as high as those in the western United States (high natural seismicity region), it is of interest to quantitatively assess the impacts of these alternative models on the risk of building collapse and life endangerment. Specifically, no falling risk for non-structural component is considered for the prevention of life endangerment.

In this study, we focus on the estimation of mean annual frequency of failure (MAFF, from which probabilities of failure can be calculated) of the building performance targets for the alternative induced-seismicity hazard models, calculated by combining (i) hazard curves from the 2015 alternative induced seismicity models [5], and (ii) building fragility curves from the *2015 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* [7] (referred to hereafter as the *2015 NEHRP Provisions*). Specifically, we consider a structural performance target, namely, no collapse of ordinary-use buildings and essential facilities, as well as a nonstructural performance target, corresponding to no falling hazard and egress maintained for noncritical nonstructural components. The calculated risks are compared with the risk levels accepted in the *2015 NEHRP Provisions* (and the *2016 ASCE Minimum Design Loads for Buildings and Other Structures* [8]), which considers natural seismicity alone. For exploratory purposes only, we also calculate revised ground motions values for building design, so called "risk-targeted ground motions", to lower the risks at sites impacted by induced seismicity to currently accepted levels. Although it is debatable whether design spectral accelerations should be increased in response to induced seismicity, which is potentially transient and controllable, quantitative assessment of the increase in risks due to induced seismicity is important.

2. Calculation of risk based on hazard curve and fragility curve

The mean annual frequency of failure (i.e., expected number of failures per year) of the performance objective (PO), λ[failure of PO], is used to quantify the seismic risk in this study. The rate can be calculated through the so-called risk integral by the convolution of a hazard curve and a fragility curve [9, 10]:

$$\lambda\left[\text{failure of PO}\right] = \int_0^\infty \lambda\left[SA > c\right] f_{Capacity}\left(c\right)\mathrm{d}c , \qquad (1)$$

2

where $f_{Capacity}(c)$ represents the probability density function (PDF) of the uncertain capacity and is the derivative of the fragility curve, c; and $\lambda[SA > c]$ is the mean annual frequency of exceedance of the ground motion hazard (i.e., spectral acceleration, SA) exceeding the capacity of the given performance objective.

It is common to use the lognormal distribution for the fragility curve. Usually, lognormal distributions are parameterized by median (50th percentile) and standard deviation β. However, they can also be parameterized by β and the pp^{th} percentile of the distribution, as described by Luco et al. [10]:

$$f_{Capacity}(c) = \frac{1}{c} \cdot \phi \left\{ \frac{\ln c - \left[\ln c_{pp\%} - \Phi^{-1}(pp/100) \cdot \beta \right]}{\beta} \right\}, \quad (2)$$

where ϕ represents the standard normal PDF and Φ is the standard normal cumulative distribution function. The superscript -1 denotes the inverse function. Once the risk (in terms of MAFF) is obtained using Eq. (1), the failure probability of the performance objective in t years (i.e., at least one occurrence in t years) is calculated following the typical assumption that such occurrences can be modeled by a Poisson process.

For the prevention of structural collapse, the *2015 NEHRP Provisions* set the performance target such that the probability of collapse of an ordinary-use building (Risk category II) does not exceed 10% given the occurrence of a very rare ground motion, as reported in Table 1. This target essentially defines the capacity model by its 10th percentile (i.e., $pp = 10$) in Eq. (2). These very rare ground motions are known as the risk-targeted maximum considered earthquake (MCE$_R$) ground motions. Table 1 summarizes the anticipated performance targets for structural (no collapse) and nonstructural (no falling hazard, and egress maintained) performance objectives for life safety protection under MCE$_R$ ground motions that are adopted in the *2015 NEHRP Provisions*. The dispersion of the uncertain capacity is modeled using $\beta = 0.6$ consistent with the *2015 NEHRP Provisions*.

Table 1 – Performance targets for structural (no collapse) and nonstructural (no falling hazard, and egress maintained) performance objectives for life safety protection under MCE$_R$ ground motions (*2015 NEHRP Provisions*). Cases considered in the following sections are marked in bold.

Performance target	Risk category	Risk probability conditioned on MCE$_R$ (%, i.e., pp)	Absolute risk probability in 50 years (%)
No collapse (structural)	I	20	~2
	II	**10**	**1**
	III	5	< 1
	IV	**2.5**	**<< 1**
No falling hazard, and egress maintained (nonstructural)	**Position retention I$_p$* = 1.0**	**25**	**5**
	Operational I$_p$ = 1.5	10	1

*I$_p$ is the component importance factor. Position retention means the component is restrained in its place to prevent falling hazards and distinguishes these components from additional operational requirements which apply to essential structural components (I$_p$ = 1.5).

3. Risk due to the induced seismicity

Using the risk integral and structural and nonstructural fragilities presented in the previous section, the impact of the alternative induced seismicity hazard models on the seismic risk is investigated. For the calculation, the collapse risk for ordinary-use buildings (Risk category II) and essential facilities (Risk category IV), as well as the falling risk for noncritical nonstructural components (I$_p$ = 1.0) are considered. These cases are marked in bold in Table 1.

3.1 Benchmark collapse risks

To establish a benchmark for comparison, we first calculate the collapse risk for ordinary-use buildings due to the 2014 National Seismic Hazard Model (2014 NSHM, [11]), which considers natural, non-induced earthquakes only. To determine the fragilities needed for the risk integral, we consider that, according to the *2015 NEHRP Provisions*, for most sites in the conterminous United States (U.S.), the MCE_R ground motions are computed in an iterative fashion ensuring the collapse probability for ordinary-use structures in 50 years is 1% [10]. One-percent probability of collapse in 50 years corresponds to a MAFF of 2.01×10^{-4} per year. This risk level is based on 10% probability of collapse conditioned on the MCE_R shaking occurring, which defines one point on the fragility curve (Eq. (2) and Table 1). For areas near faults that produce frequent, large earthquakes (e.g., along the San Andreas Fault in California), the MCE_R ground motions are capped by deterministic seismic hazard analysis considering the 84th percentile ground motions due to characteristic earthquakes. In other words, the MCE_R ground motions are the lesser of the probabilistic (risk-targeted) ground motions and deterministic ground motions. As a result of the deterministic cap, the collapse risk of these areas goes beyond 1% in 50 years. This collapse risk is implicitly accepted by the *2015 NEHRP Provisions*.
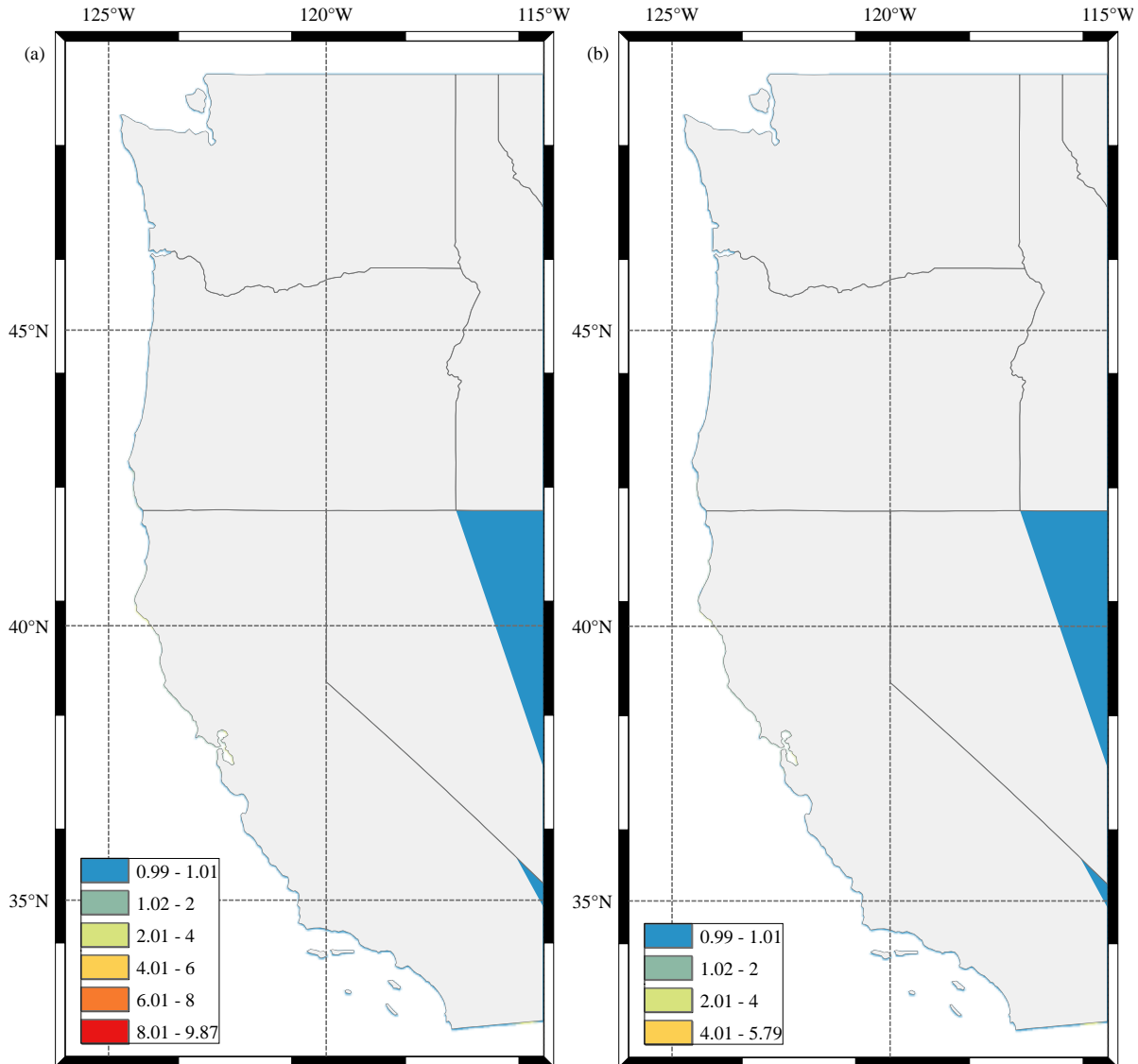

Fig. 1 – Collapse risk for ordinary-use buildings normalized by the MAFF of 2.01×10^{-4} per year (equivalent to a Poissonian 1% in 50 years collapse probability) due to the hazard of the 2014 NSHM for the Western U.S. for: a) short period (0.2 s); b) moderate period (1.0 s). These risk levels are accepted by the *2015 NEHRP Provisions*.

In Fig. 1, we map the collapse risk (quantified in terms of MAFF) for short- and moderate-period ordinary-use buildings based on the 2014 NSHM, normalized by the MAFF of 2.01×10^{-4} per year. As the normalized collapse risk for most of the conterminous U.S. equals unity, only the results for the Western U.S. are shown in the figure. Fig. 1a shows that for short-period buildings (0.2 s), the collapse risk at some sites can be as much as about 10 times higher than the risk level for which the probabilistic ground motions are targeted, due to the deterministic ground motions governing the design values. The geographic distribution of the increased risk is similar for moderate-period buildings (1.0 s) in Fig. 1b, although the spread is less significant, with a maximum of about 6 times.

3.2 Effects of different induced seismicity hazard models on collapse risk

In the 2015 USGS sensitivity study [5], five alternative induced seismicity hazard models are presented in combination with the 2014 NSHM. These models use different key modeling decisions aimed at investigating their effects on seismic hazard. In addition to these five models, we introduce a sixth model considers a different maximum magnitude for induced seismic events, combined with the 2014 NHSM. All six models are summarized in Table 2. Model A considers declustered earthquake catalog; minimum magnitude of 2.5; slope of magnitude-recurrence relations equal to 1.0; smoothing distance of 5 km; eight ground motion prediction equations; and a maximum magnitude model for the CEUS consistent with the 2014 NSHM. This model represents the most similar modeling decisions to the 2016 USGS one-year hazard model [6]. Note that the 2016 hazard model uses an updated catalog with minimum magnitude of M2.7 to calibrate the magnitude-recurrence model, although a minimum magnitude of M4.7 is used for the hazard calculations. The 2016 hazard model also has partial weight for a new approach that does not differentiate between natural and induced earthquakes, an M6 maximum magnitude, and an additional ground motion prediction equation [6]. The other models (B-F) consider different key modeling decisions including minimum and maximum magnitudes, induced seismicity catalogs, rates and locations.

Table 2 – Alternative induced seismicity hazard models considered in this study.

Models	Catalog	M_{min}	b	Smoothing distance	GMPEs	M_{max}
Model A	Declustered	2.5	1.0	5 km	CEUS GMPEs[2]	CEUS M_{max}[3]
Model B	Nondeclustered	2.5	1.5	5 km	CEUS GMPEs	CEUS M_{max}
Model C	Declustered	2.5	1.0	50 km	CEUS GMPEs	CEUS M_{max}
Model D[1]	Nondeclustered	2.5	1.0	5 km	CEUS GMPEs	6
Model E	Nondeclustered	2.5	1.0	5 km	CEUS GMPEs	CEUS M_{max}
Model F	Nondeclustered	3.0	1.0	5 km	CEUS GMPEs	CEUS M_{max}

[1]This model is included in the 2015 USGS open-file report, but it is not combined with the 2014 NSHM [5].
[2]GMPEs that are used for CEUS in 2014 NSHM.
[3]M_{max} used for CEUS in 2014 NSHM.

These alternative hazard models are combined with the same fragility curves used above to compute the collapse risk for each model. To assess the effect of induced seismicity hazard from the alternative models on the collapse risk for ordinary-use buildings, we take the ratio between the MAFF of collapse risks of the induced seismicity models divided by those accepted in the *2015 NEHRP Provisions*, which are taken as the benchmark. Fig. 2(a) maps the ratio for the CEUS for short-period buildings due to the hazard of Model A. The most significant increase of the collapse risk (larger than 50 times) is in northern Oklahoma and southern Kansas. Other locations with noticeable increases are in Texas, Colorado, New Mexico, and Ohio/Pennsylvania, which overlaps well with the known areas of induced seismic activity. This spatial pattern is by design because the 2015 USGS sensitivity study only includes induced seismicity that falls within several defined polygons, and then combines the resultant seismic hazard with the 2014 NSHM. A similar geographical distribution for the significance of induced seismicity is observed for moderate-period buildings, which is shown in Fig. 2b, although the increase is not as significant as for short-period buildings.
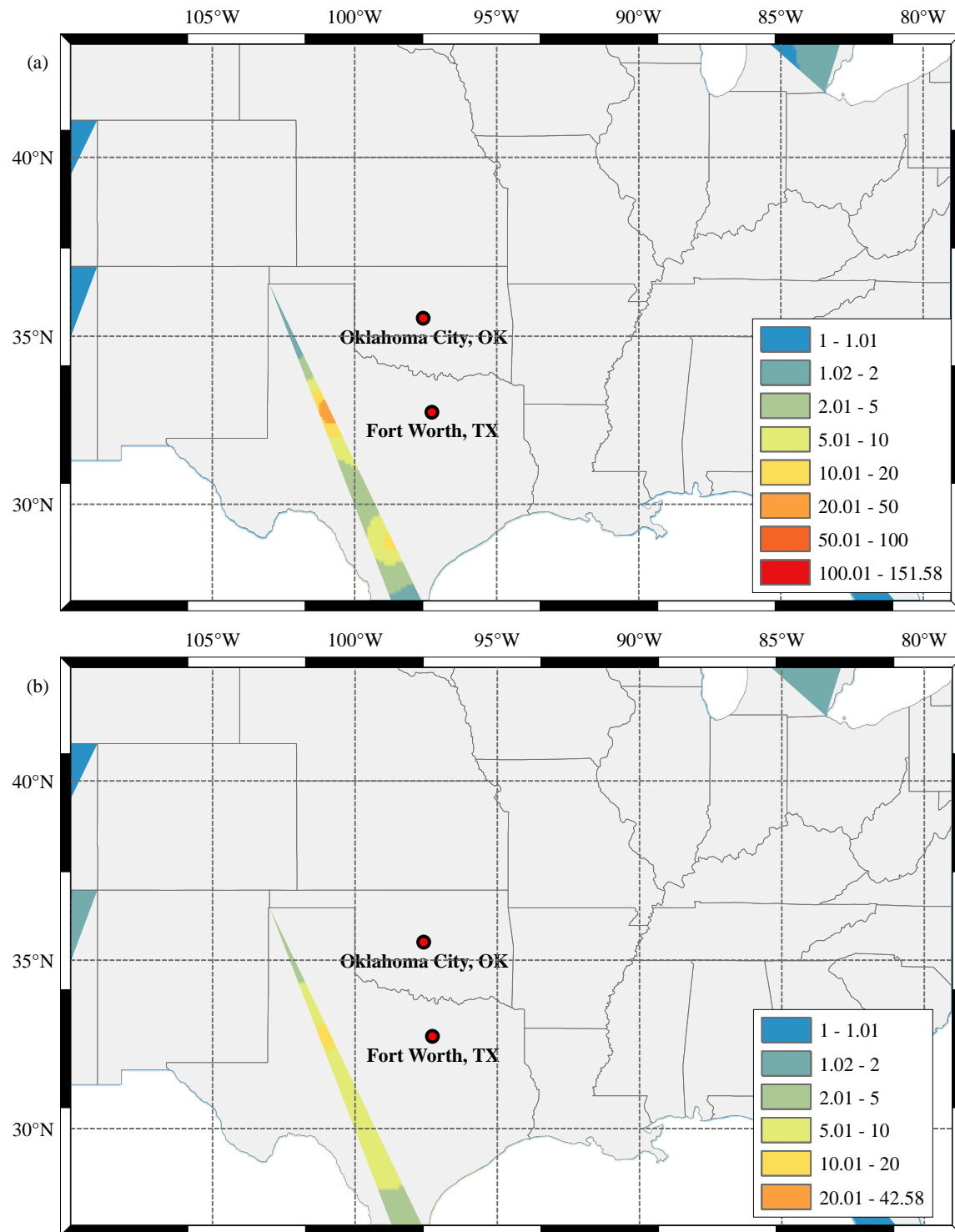
Fig. 2 – Ratio of the collapse risk (in terms of MAFF) of ordinary-use buildings from the induced seismicity hazard Model A divided by their counterparts accepted in the *2015 NEHRP Provisions* for the CEUS, for periods of: a) 0.2 s; b) 1.0 s.

To better examine the effects of induced seismicity from the alternative hazard models, we take Fort Worth, Texas ([latitude, longitude] = [32.75, -97.25], hereafter FTW) and Oklahoma City, Oklahoma ([latitude, longitude] = [35.50, -97.55], hereafter OKC) as example sites. The seismic hazard curves for each alternative induced

seismicity model as well as the 2014 NSHM curves are compared in Fig. 3 for FTW and OKC. The comparison indicates the seismic hazard from the various models in the 2015 sensitivity study is increased by 10 to about 100 times at FTW relative to the benchmark, whereas the increase is as much as 3 orders of magnitude higher (1000 times) at OKC using the 2015 sensitivity study models (the most significant difference is apparent for Model F).
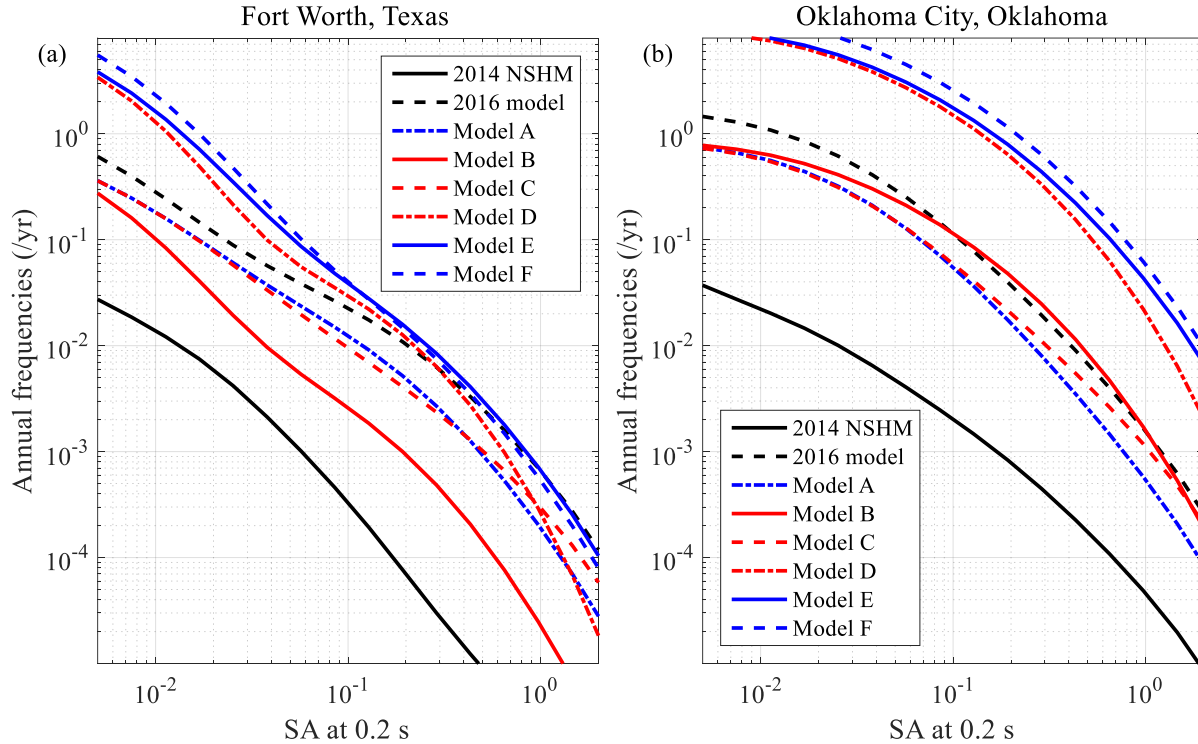

Fig. 3 – Seismic hazard curves for the 2014 NSHM and adding the induced seismicity component considering different modeling decisions for: a) Fort Worth, Texas; b) Oklahoma City, Oklahoma.

The ratios between the collapse risks of the alternative induced seismicity models divided by those accepted in the *2015 NEHRP Provisions* are plotted in Fig. 4 for FTW and OKC. A quick look at the ratios in Fig. 4 indicates that the collapse risks are increased, which is expected because the induced seismicity models combine both natural and induced earthquake hazards. However, such increases are highly sensitive to the induced seismicity model employed. For example, the collapse risk for a short-period building located at OKC is increased by about 20 times (relative to the benchmark) if the hazard model uses a declustered earthquake catalog and $M_{min} = 2.5$ (Model A); whereas the risk for the same building is increased by almost 1,000 times or even more if a nondeclustered earthquake catalog is considered (Models E and F). However, Models D, E, and F do not represent the best estimate, and are likely not ideal models. These three models yield much higher values than the consensus 2016 hazard model (Fig. 3). The building capacity is unchanged since the design levels are unchanged; so the elevated risks are caused by the increased seismic hazard of the induced seismicity.

Generally speaking, the use of a declustered earthquake catalog or steeper slope in the magnitude-recurrence relations (larger b value) leads to lower collapse risk. This is essentially because the declustering process and the change in the slope of the magnitude-recurrence relation, respectively, decreases the overall seismicity rate and reduces the number of events with large magnitude. Although the results depend on the location, Models A, B and C that use either a declustered earthquake catalog or a b value of 1.5 tend to be associated with the least increase in the collapse risk compared to the accepted values, indicating the seismicity rate as assumed in the hazard modeling has the most significant impact on the collapse risk.
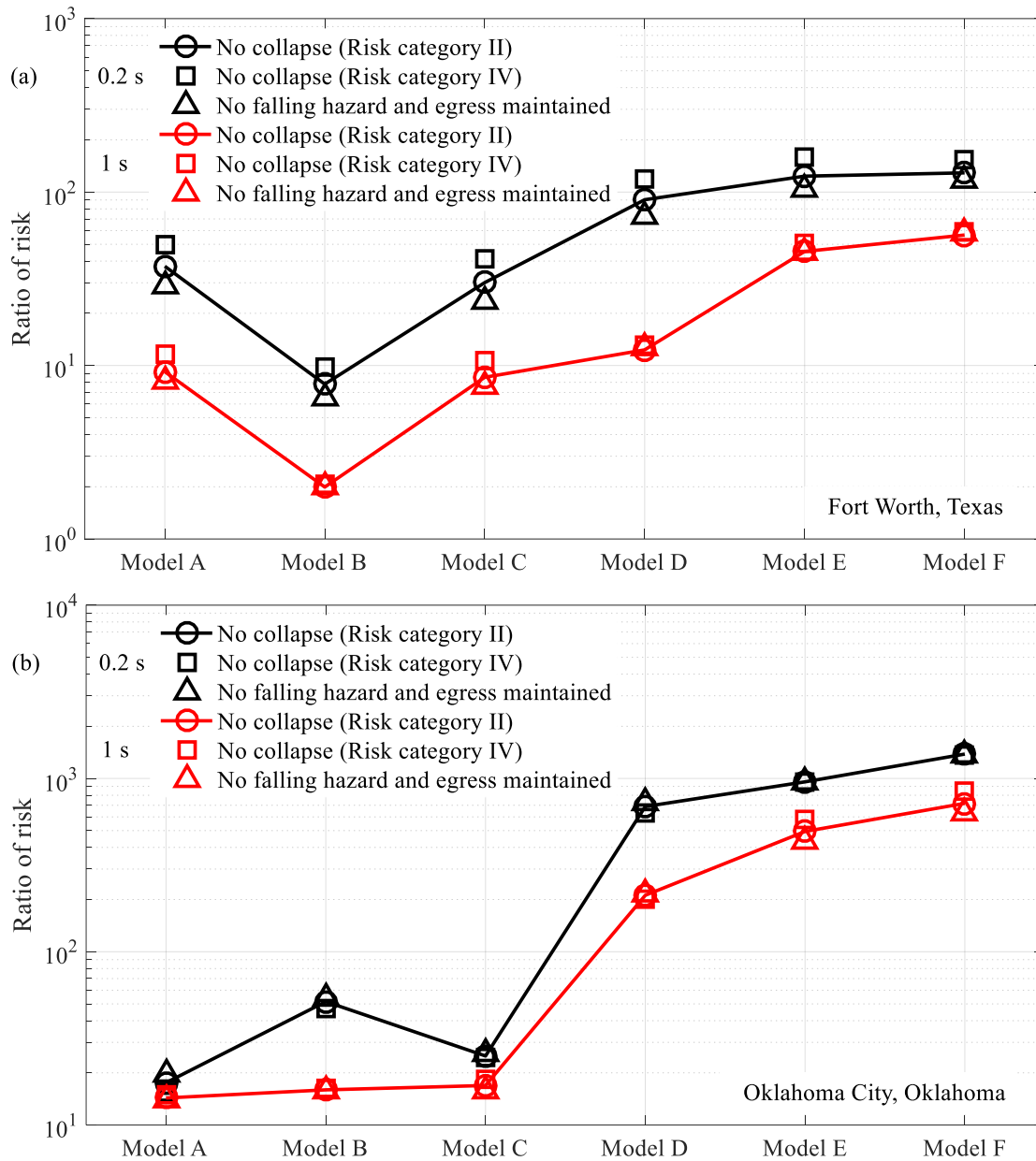
Fig. 4 – Ratio of the risk (MAFF) obtained from the alternative induced seismicity models divided by their counterparts accepted in the *2015 NEHRP Provisions* at: a) Fort Worth, Texas; b) Oklahoma City, Oklahoma.

The effect of smoothing distance is location dependent. Model C leads to lower risk at FTW, but higher risk at OKC compared with Model A. The use of a larger smoothing distance (50 km in Model C vs. 5 km in Model A) basically increases the uncertainty of the location of future earthquakes. As a result, the area of high hazard (and risk) in Model A tends to be geographically smoothed out in Model C. As shown in Fig. 2, FTW almost coincides with a local "bullseye", where the effects of induced seismicity are reduced by the larger smoothing distance. On the other hand, OKC is a bit farther from the highest induced seismicity risk area, so the risk is increased for Model C when the smoothing distance is increased.

The use of a lower maximum magnitude (Model D) produces lower risk (relative to Model E), which is expected because it eliminates the chances of higher magnitude events. However, the use of a larger minimum magnitude (Model F) leads to even higher risk. This is surprising because we would expect lower seismic rates and consequently lower risk as a result of a larger minimum magnitude. An inspection of the earthquake catalog

used for hazard modeling indicates that the catalog is incomplete (some of the small events are not detected) if $M_{min} = 2.5$ is adopted. The lower overall seismicity due to the incompleteness in the cases with $M_{min} = 2.5$ leads to a lower risk level.

3.3 Observations on the collapse risks for short- and moderate-period buildings

Similar to in Fig. 2, the ratios of collapse risks shown in Fig. 4 also show that the increase of the risk is more significant for short-period buildings than moderate-period buildings. This trend can be explained by noting that the events that contribute most to the risk are mostly smaller earthquakes that produce ground motions with primarily short-period content and without significant moderate- to long-period content. The results also show that the effects of different alternative models on the risks are period dependent. For example, for short-period buildings in OKC, Model B leads to an increase of about 50 times for the collapse risk, which is about twice the increase resulting from Model C. However, for moderate-period buildings, Models B and C produce fairly similar collapse risks.

3.4 Risks for other performance targets

Fig. 4 also illustrates the risk assessment for two other performance objectives: the collapse risk for essential facilities and the falling risk for noncritical nonstructural components. These cases represent the two extremes of the fragility models, which are defined by *pp* = 2.5 and *pp* = 25 (see Table 1), respectively. In all cases, the ratios are similar, showing that although the absolute values of the risk vary for different performance targets, the ratio of these values to their counterparts accepted in the *2015 NEHRP Provisions* depends more on the hazard modeling decisions than the performance target of interest. In some cases, though, the increase is higher for the collapse risk for essential facilities (Risk category IV) as compared to the other performance targets. This trend is surprising because the prevalence of small to moderate events would seem to suggest that the increase in damage is more significant than that in collapse. By examining the risk calculations, we note that this trend is caused by the larger increase in the hazard for higher ground motions. Due to the convolution of the hazard and the fragility, collapse risk for essential facilities is more sensitive to the hazard for higher ground motion levels. Communication between the authors and the USGS seismic hazard modeling team indicates that in these cases the hazard for low ground motions is controlled by remote seismic sources whereas the hazard for high ground motions is dominated by local seismic sources.

3.5 Increase in risk vs. increase in hazard

We compare the increases in risk, as shown in Fig. 4, with the increases in hazard in this section. As expected, the increase in risk usually differs from the increase in hazard, since the risk takes various ground motion levels into account through the risk integral process, whereas the hazard is only compared at a given ground motion level. Specifically, if the MCE_R ground motion is selected as the level at which the hazard is compared, the increase in hazard is almost always more than the increase in collapse risk for ordinary-use building in OKC. This is because the increase in OKC hazard at high ground motion levels, to which collapse risk is sensitive, is lower compared to the increase at low ground motion levels, regardless of which hazard model is considered. On the other hand, there is not a clear trend for FTW. If such comparison is carried out for CEUS, there are places where the difference between the increase in hazard versus risk is more than 50%.

## 4. Risk-targeted design ground motions considering induced seismicity

Given the elevated risk due to induced seismicity, a logical next question becomes: for what ground motion level could the buildings be designed to ensure that the collapse risk is within the acceptable range? Risk-targeted ground motions (RTGM) were proposed by Luco et al. [10], aiming to achieve uniform collapse risk throughout the country of 1% probability of collapse in 50 years. In this section, we use the procedure proposed by Luco et al. [10] to estimate the risk-targeted ground motions that consider the induced seismicity.

The definition of RTGM requires the choice of a risk target. Fig. 1 previously showed that, although the 1% probability of collapse in 50 years is targeted in the *2015 NEHRP provisions*, the actual level for collapse risk varies geographically, especially in California, due to the use of deterministic ground motions at some sites. We argue that since this higher risk is accepted in some parts in California, it may be used as the target for the risk-

targeted ground motions for the induced seismicity hazard. Therefore, this study targets collapse risks of both MAFF = $2.01×10^{-4}$ per year (1% in 50 years) and MAFF = $2.01×10^{-3}$ per year (equivalent to about 9.6% in 50 years) for ordinary-use buildings. The RTGMs needed to achieve these levels of risk is denoted as $RTGM_I$.

Fig. 5(a) shows the ratio between the $RTGM_I$ targeted at $2.01×10^{-4}$ per year (1% in 50 years collapse risk) divided by the MCE_R ground motions for FTW and OKC, indicating that the increase in the design level depends on the location, the fundamental period of the structure, and the alternative induced seismicity model. If targeted at $2.01×10^{-4}$ per year, the design level needs to be increased by up to more than 20 times of the current MCE_R ground motions to offset the increase of induced seismicity hazard. However, if targeted at the implicitly accepted risk level in California (MAFF = $2.01×10^{-3}$ per year), the need to increase the design values is reduced to less than 10 times. Indeed, for this risk target, there are cases where the $RTGM_I$ is less than the MCE_R, indicating that, if these induced seismicity models are adopted, the current building code provides sufficient protection against collapse when compared with some places in California.

We further emphasize that the calculation carried out in this section is for exploratory purposes only, since it is debatable whether the design spectral accelerations should be increased in response to potentially transient and controllable induced seismicity hazard. On one hand, the induced seismicity poses higher risk than that accepted in current building code; on the other hand, the hazard from induced earthquakes is very likely going to change before the building regulations are enacted, due to the time-dependent nature of the physical process of induced earthquakes, or the change in regulation of wastewater disposal (e.g., Reduction in Volumes for Wells Located in Area of Interest for Induced Seismicity issued by Oil & Gas Conservation Division of Oklahoma Corporation Commission [12]).
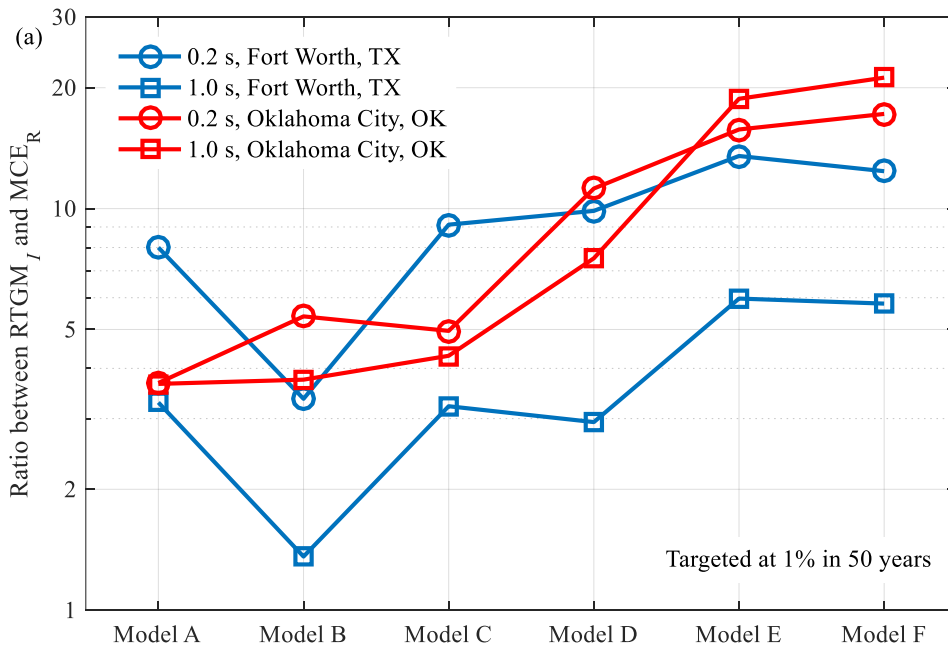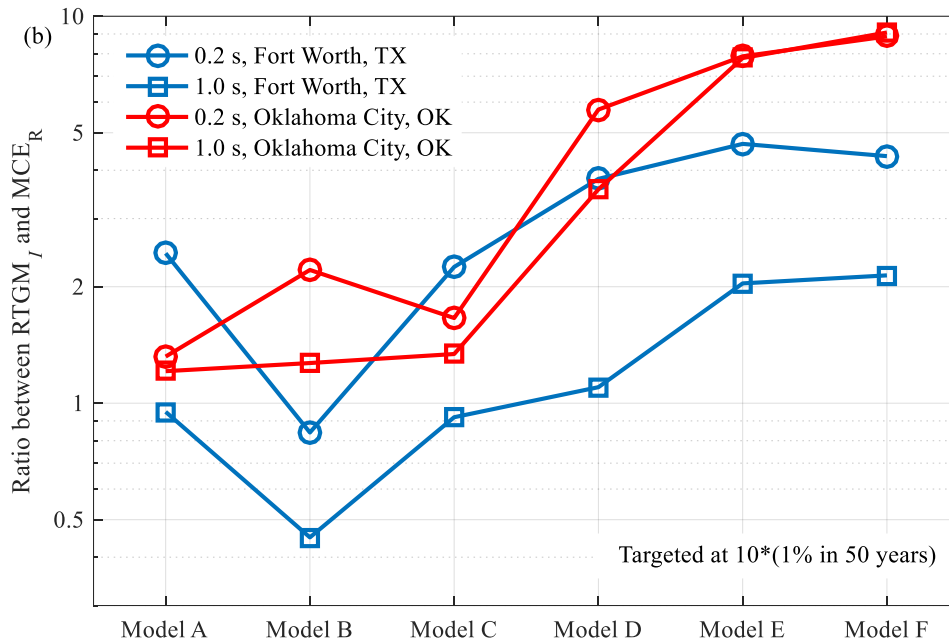
Fig. 5 – Ratio between RTGM$_I$ divided by MCE$_R$: a) RTGM$_I$ targeted at collapse risk of 1% in 50 years; b) RTGM$_I$ targeted at collapse risk of ~10% in 50 years.

Key design provisions, including the required lateral strength, drift limits and detailing specifications, depend on Seismic Design Category (SDC), which is defined by combining the Risk category with the amplitude of design ground motion at the site. To examine how changes in design *RTGM$_I$* might influence design category assignment, we compare the SDC with or without the increase in design ground motions for ordinary-use buildings (Risk category II) located at FTW and OKC. By assuming site class D, SDC B is obtained for both sites if the design motions in current building codes are adopted. However, if RTGM$_I$ targets 1% in 50 years collapse risk, the SDC is increased from B to at least D (except for FTW when hazard Model B is considered). Models E and F leads to SDC E (i.e., three categories higher) at OKC. This is expected since the design ground motions increase significantly as shown in Fig. 5a. The use of RTGM$_I$ that targets ~10% in 50 years collapse risk results in a smaller increase in SDC, with SDC D being the highest among all models at FTW and OKC.

5. Conclusions

Based on the alternative induced seismicity hazard models published by USGS in early 2015 as a sensitivity study, and the fragility curves defined in the *2015 NEHRP Provisions*, the sensitivity of building collapse and non-structural component falling risks that account for induced seismicity are investigated in this study. We show the extent to which the risks are higher than the level accepted in the *2015 NEHRP Provisions*, which only considers natural seismicity. Depending on key decisions in the hazard modeling process and the location of the site, the increases of the risks vary from a few times to more than 1,000 times. The highest increases result from the alternative models that utilize the nondeclustered catalog with a slope of magnitude-recurrence relations equal to 1.0, which are modeling choices that are not used in the 2016 USGS one-year hazard model for natural and induced earthquakes. The rate of induced as well as natural seismicity (as quantified by assumptions in the model of declustering and the slope of the magnitude-recurrence relations) has the most significant impact on the calculated risk, while the effects of smoothing distance and maximum/minimum magnitude are less significant. Generally, the impact of the induced seismicity is less significant on the risk for moderate-period buildings relative to short-period buildings, but the increases of the risk for different performance objectives are similar.

We also explored risk-targeted ground motions that consider induced seismicity hazard. Targeting the implicitly-accepted risk level in California, based on the alternative models published as a sensitivity study, the need to increase design levels varies between a few times up to 10 times of the MCE$_R$ in the *2015 NEHRP Provisions* for Fort Worth, Texas, and Oklahoma City, Oklahoma. However, the appropriateness of modifying

design values to account for induced seismicity requires careful consideration because of the controllable and transient nature of these earthquakes. Furthermore, rather than alternative hazard models from the 2015 USGS sensitivity study, the consensus 2016 USGS hazard model needs to be considered.

6. Acknowledgments

8. References

[1] Ellsworth, WL (2013): Injection-induced earthquakes. *Science*, *341*(6142), 1225942.

[2] Keranen, KM, Savage, HM, Abers, GA, Cochran, ES (2013): Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. *Geology*, **41**(6), 699-702.

[3] Rubinstein, JL, Ellsworth, WL, McGarr, A, Benz, HM (2014): The 2001–present induced earthquake sequence in the Raton Basin of northern New Mexico and southern Colorado. *Bulletin of the Seismological Society of America*.

[4] Hough, SE, Page, M (2015): A century of induced earthquakes in Oklahoma? *Bulletin of the Seismological Society of America*.

[5] Petersen, MD, Mueller, CS, Moschetti, MP, Hoover, SM, Rubinstein, JL, Llenos, AL, Michael, AJ, Ellsworth, WL, McGarr, AF, Holland, AA, Anderson, JG (2015): Incorporating induced seismicity in the 2014 United States National Seismic Hazard Model: results of the 2014 workshop and sensitivity studies. U.S. Geological Survey Open-File Report 2015-1070.

[6] Petersen, MD, Mueller, CS, Moschetti, MP, Hoover, SM, Llenos, AL, Ellsworth, WL, Michael, AJ, Rubinstein, JL, McGarr, AF, Rukstales, KS (2016): One-year seismic hazard forecast for the Central and Eastern United States from induced and natural earthquakes. U.S. Geological Survey Open-File Report 2016-1035.

[7] Federal Emergency Management Agency (2015): NEHRP Recommended Seismic Provisions for New Buildings and Other Structures.

[8] American Society of Civil Engineers (2016): Minimum Design Loads for Buildings and Other Structures.

[9] McGuire, RK (2004): *Seismic hazard and risk analysis*. Earthquake engineering research institute.

[10] Luco, N, Ellingwood, BR, Hamburger, RO, Hooper, JD, Kimball, JK, Kircher, CA (2007): Risk-targeted versus current seismic design maps for the conterminous United States. *SEAOC 2007 Convention Proceedings*.

[11] Petersen, MD, Moschetti, MP, Powers, PM, Mueller, CS, Haller, KM, Frankel, AD, Zeng, Y, Rezaeian, S, Harmsen, SC, Boyd, OS, Field, N, Chen, R, Rukstales, KS, Luco, N, Wheeler, RL, Williams, RA, Olsen, AH (2014): Documentation for the 2014 update of the United States national seismic hazard maps. U.S. Geological Survey Open-File Report 2014-1091.

[12] Oklahoma Corporation Commission (2016): http://earthquakes.ok.gov/what-we-are-doing/oklahoma-corporation-commission/ (last accessed April 2016).