Spatiotemporal Dynamics of Public Response to Human-Induced Seismic Perturbations

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ABSTRACT

There is general consensus that subsurface wastewater injections associated with unconventional oil and gas operations are responsible for the rapid increase of earthquake activity in the mid-U.S. Understanding the public response to these earthquakes is crucial for policy decisions that govern developing situational awareness and addressing perceived risks. However, we lack sufficient information on the reactive and recovery response behavior of the public tending to occur in the spatiotemporal vicinity of these events. Here, we review the spatiotemporal distribution of public response to the September 3, 2016, M5.8 earthquake in Pawnee, Oklahoma, USA, via a social media network (Twitter). Our findings highlight a statistically significant correlation between the spatial and temporal distribution of public response; and suggest the possible presence of a spatial distance decay, as well as a temporal far-field effect. Understanding the underlying structure of these correlations is fundamental to establishing deliberate policy decisions and targeted response actions.

Keywords

Crisis informatics, human-induced earthquake, social media networks, spatiotemporal, far-field effect.

INTRODUCTION

Saltwater disposal (SWD) is the process of injecting into deep geologic formations the highly brackish wastewater co-produced during oil and gas recovery. This process has been strongly implicated in dramatically increasing earthquake activity in the central United States since 2009, which is in close proximity to recently developed oil and gas fields (Walsh and Zoback 2015; Weingarten et al. 2015). These seismic events, which are referred to as Injection-Induced Earthquakes (Ellsworth 2013), are frequently collocated with existing SWD wells that are likely responsible for triggering these events (Ellsworth 2013; Weingarten et al. 2015). This phenomenon has led to considerable public concern as well as structural damage (McGarr et al. 2015). Moreover, in 2014, McGarr found an empirical relationship suggesting that the magnitude of an injection-induced earthquake increases with increasing SWD injection volume (McGarr 2014). Consequently, ongoing fluid injection activities in the central United States increase the likelihood of encountering larger magnitude earthquakes and thus the demand for mitigating associated risks escalates. When seeking to mitigate the risks and consequences of human-induced earthquakes and make good policy decisions, it is crucial to have an holistic understanding of the public response to these relatively uncertain events in order to be able to communicate critical information at the time and space of perturbations.

Previous efforts to improve our understanding of the public's response to the increasing frequency of human-induced perturbations has been somewhat limited due to the need to acquire large scale, timely, and location-specific data, along with data on the associated interactions. When spatiotemporally quantifying the occurrence and magnitude of

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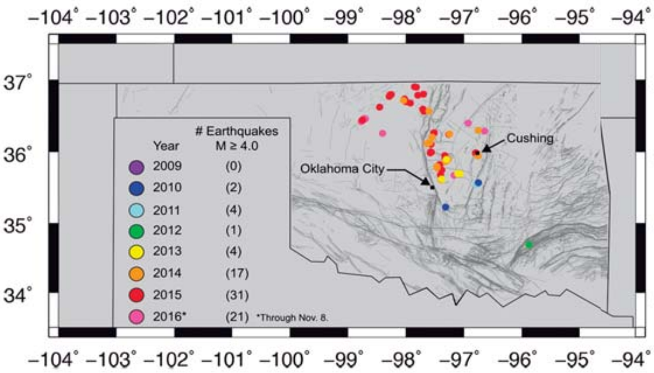

Figure 1. Spatial distribution of M4.0+ earthquakes in Oklahoma from 2009–2016. Earthquake data acquired from the ANSS Composite Catalog (NCEDC, 2014) with underlying fault layer from Marsh and Holland (2016).

public response to human-induced perturbations, one promising approach is to use the rich data available from social media networks. According to an American Red Cross 2012 survey study, 19% of general public relies on social media sites such as Facebook, Twitter and Flicker to seek information in the face of emergency (American Red Cross 2012). Seventy six present (76%) of the general public expected help to arrive within 3 hours and 36% expected help in less than an hour if they posted a request on a social media site (American Red Cross 2012). This study highlights that in emergency situations people tend to both share and seek information to better characterize the event. This implies: 55% of online users would use social media to reassure that they are safe; 55% would share their feeling and emotions about what is happening; 45% would likely share their locations; 42% would share the actions they are taking to stay safe, and 40% would share an eyewitness description of something they experienced. Additionally, 62% would seek information on the damage caused by the event, while 56% would seek the location and status of loved ones; 49% would likely seek information on how others are coping with the situation; 45% would likely look for eyewitness photographs, and 29% for what to do to keep yourself safe (American Red Cross 2012). With this magnitude of public reliance on online resources and social media in emergency situations, it is of utmost importance to better understand the underlying structure and dynamics of this communication system so that the social media platform can be better employed for emergency-related policies and interventions.

In an attempt to understand the interdependencies of the underlying interactions and examine the public responses to location-specific perturbations, a number of scholars have employed geo-social networking media linked to crisis events. A growing body of research is employing social media networks such as Twitter to understand communication typologies and patterns (Bland and Frost 2013; Mohammadi et al. 2016; Sutton, Hansard, et al. 2011; Sutton, Spiro, et al. 2013), crowd behaviors (Lee et al. 2013), information cascades (Wang and Taylor 2014a), disaster responses and crisis management (McClendon and Robinson 2012), as well as sentiment analysis (Caragea et al. 2014) and public responses to extreme events such as hurricanes/typhoons, wildfires, severe storms, flooding, and earthquakes and the resulting changes in movement patterns and population displacements (Wang and Taylor 2014b; Wang and Taylor 2016). Nevertheless, we lack understanding of the spatiotemporal dynamics of the occurrence and magnitude of public response to human-induced seismic perturbations. This becomes even more challenging as these events are different than the natural earthquakes and their subsequent impacts are concentrated in regions where natural earthquakes are unexpected.

Human-induced earthquakes in Oklahoma, USA

Oklahoma is the only U.S. state that has experienced a significant increase in the number of seismic events at all magnitudes over the last 5 years (Walsh and Zoback 2015). Between 1970 and 2009, the annual earthquake rate was 21 per year for M3.0+ events in the central U.S. (Ellsworth 2013); however, Oklahoma experienced 579 M3.0+ earthquakes in 2014, and in 2015 the number of M3.0+ earthquakes increased to 903 (NCEDC 2014). Most notably, the state's level of seismic activity abruptly increased in 2009. Figure 1 shows the spatial distribution and frequency of the state's M4.0+ earthquakes over the eight years from 2009 to 2016 (NCEDC 2014). Many studies have confirmed that the increasing seismicity in Oklahoma is most likely triggered by the considerable increase in SWD activity in this area; the aggregate monthly SWD injection volume nearly doubled from 1997 to 2013 (Walsh and Zoback 2015; Keranen et al. 2013). This is particularly concerning if an induced earthquake aligns along basement faults and thus results in an exceedingly damaging seismic event in an unexpected location.

Here, we investigate the spatiotemporal distribution of the public response to a recent major earthquake near Pawnee, OK, via a social media network (Twitter). The event consisted of a M5.8 earthquake at 12:02:44.400 (UTC) on September 3, 2016. In particular, we examine whether there was a relationship between the spatial and temporal manifestations of the public response and whether the public response decayed with spatial distance from the earthquake's epicenter (36°25′48"N 96°55′55"W) and/or temporal distance from the onset of the event. Put differently, this study seeks to identify the spatiotemporal patterns in public response that form the basis of the popular United States Geological Survey (USGS) "Did You Feel It?" Maps[1].

METHODS

We collected all tweets in the state of Oklahoma that were posted from the onset of the earthquake until approximately 16 hours after the shaking ceased through the public Twitter Stream API[2]. This resulted in over 1,600 geo-located data points (i.e., tweets with geolocation information) for which we extracted those tweets related to the earthquake using a set of keywords such as "earthquake", "quake", and "shake". The extracted tweets were further manually screened to ensure the relevance of the information exchange activities, which resulted in 188 geo-located tweets related to the earthquake. Our dataset included public response measures for 12 time-lapse intervals (i.e., t_1, t_{10}, t_{20}, t_{30}, t_{40}, t_{50}, t_{60}, t_{70}, t_{80}, t_{90}, t_{100}, t_{200}, t_{300}, t_{400}, t_{500}, t_{600}, t_{700}, t_{800}, t_{900}, t_{1000}) from the onset of the earthquake over approximately 16 hours. We then quantified the occurrence and magnitude of this public response in order to capture the spatiotemporal characteristic activity distance.

Public Response Radius of Gyration

We opted to capture the characteristic activity distance of the public response using the public response radius of gyration $r_{g(pr)}(t)$ $(Eq.2)$ as an indicator for the characteristic activity distance of the public response when observed up to time t after the earthquake, which represents the deviation of the $r_{g(pr)}(t)s$ from their corresponding center points $(Eq.1)$. This indicator was then used to track the abundance patterns of the public response over time after the earthquake corresponding to the earthquake's United States Geological Survey (USGS) ShakeMap[3]. We determined the centroid of public responses at each time-lapse interval and calculated the public response radii of gyration accordingly.

$$\vec{p}_c = \frac{1}{n}\sum_{i=1}^{n}\vec{p}_i \tag{1}$$

$$r_{g(pr)}(t) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\vec{p}_i - \vec{p}_c)^2} \tag{2}$$

here, n equals the total number of public response records per time-lapse interval.

We plotted the public response centroids and radii of gyration in the first minute (t_1), the first 10 minutes (t_{10}), the first 100 minutes (t_{100}), and the first 1000 minutes (t_{1000}) and superimposed the results on a map of the region's geological fault lines (Marsh and Holland 2016) to capture the spatiotemporal characteristic activity distance. to capture the spatiotemporal characteristic activity distance. Figure 2 depicts the spatial distribution of these centroids and radii of gyration over the total time frame of the study along with the epicenter of the earthquake. Interestingly, the t_1 tweet occurred outside of the area within which the USGS maps indicated the earthquake was felt, after which the centroids between t_1 to t_{1000} progress towards the epicenter of the earthquake, with the average radius of gyration reaching its greatest extent at t_{10} and then gradually subsiding over the next two time periods.

Distance Decay of Similarity

The results shown in Figure 2 led us to consider two questions: Does the occurrence and magnitude of the public response found in the social media networks exhibit similar distance decay patterns in time and space from the earthquakes' epicenter to those of the seismic wave attenuation revealed in the USGS's ShakeMap and "Did You Feel It Map"(Figure 3)?; If so, does the decay in the public response similarly relate to the degree of proximity to the epicenter and its associated vulnerabilities or is it a far-field effect associated with the structure of such networks, for example population density or social connections?

[1] "Did You Feel It? (DYFI) collects information from people who felt an earthquake and creates maps that show what people experienced and the extent of damage." [https://earthquake.usgs.gov/data/dyfi/]

[2] https://dev.twitter.com/streaming/overview

[3] "ShakeMap is a product of the USGS Earthquake Hazards Program in conjunction with the regional seismic networks. ShakeMaps provide near-real-time maps of ground motion and shaking intensity following significant earthquakes." [https://earthquake.usgs.gov/data/shakemap/]

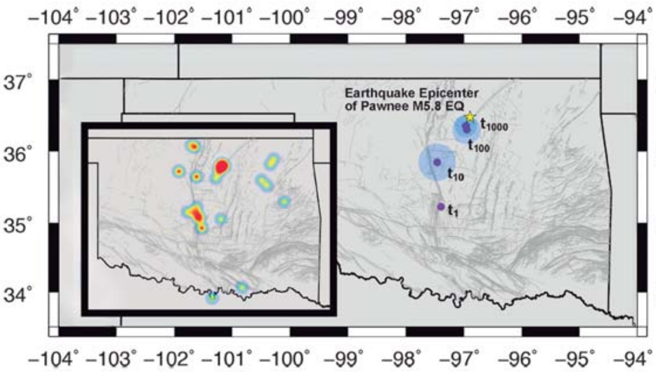

Figure 2. Spatial distribution of public response following the Pawnee, OK M5.8 earthquake, showing the centroid (dark points) and radius of gyration (shaded area around the dark points) for the first minute (t_1), the first 10 minutes (t_{10}), the first 100 minutes (t_{100}), and the first 1000 minutes (t_{1000}) in proportion to one another. The inset heat map aggregates all the spatially distributed geo-tagged social media postings from t_0 to t_{1000}. The underlying fault layer data is from Marsh and Holland (2016).

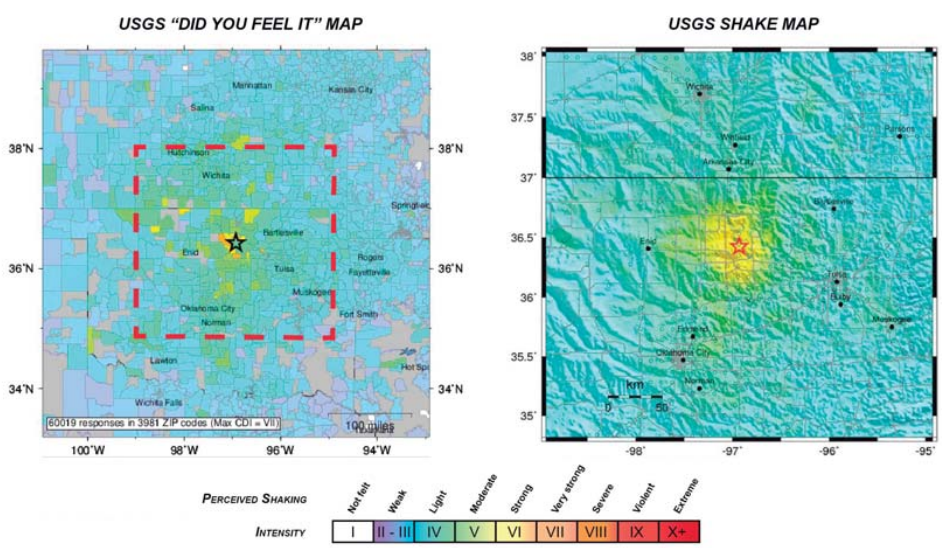

Figure 3. Area of influence for the September 6, 2016, M5.8 earthquake in Pawnee, OK. The earthquake epicenter is denoted as a star in each map. Left panel is the USGS "Did You Feel it" Map, which is compilation of crowd-source data for evaluating the extent of felt seismicity. Right panel is the corresponding USGS ShakeMap reporting earthquake intensity on the basis of ground motions with a categorical scale (I –X+). Area of ShakeMap is denoted as dashed red box in "Did You Feel It" Map. Adapted from USGS (2017).

We applied the Mantel statistic test (Mantel 1953) to examine the relationship between two distance matrices (i.e. spatial and temporal) subjected to a random permutation. The spatial distance for the public responses is measured here by the Euclidean distance between the response centroids and the epicenter of the earthquake against the temporal distance for the magnitude of the public response radius of gyration during the aforementioned time-lapse intervals from the onset of the earthquake (Figure 4(a)). The Mantel test consists of generating two distance matrices: one containing spatial distances between the public response radii of gyration (spatial distance matrix) and one containing distances between the public response radii of gyration at given temporal points (temporal distance matrix). The test consists of calculating the correlation between the two matrices under permutations. The normalized Mantel's test statistic r ($Eq.3$) ranges between (-1, +1) with an r value of 0 indicating no correlation.

$$r = \frac{1}{n-1} \sum_{j=1}^{n} \sum_{i=1}^{n} \frac{(x_{ij} - \bar{x})}{s_x} . \frac{(y_{ij} - \bar{y})}{s_y} \tag{3}$$

where x and y are variables measured at locations i and j, respectively, n represents the number of elements in the distance matrices, and s_x and s_y are the standard deviations for variables x and y, respectively.

FINDINGS

Table 1 shows the result from the Mantel test. Based on these results, we can reject the null hypothesis that spatial and temporal public response, are unrelated with 0.95 percent confidence interval ($\alpha = 0.05$). The observed correlation, $r = 0.4447$, suggests that the spatial and temporal matrix entries are relatively strongly positively associated. This indicates that smaller differences in the temporal public responses measures (i.e., public response radii of gyration) are generally seen among pairs of time-lapse intervals that their centroids are more spatially close to each other than far from each other in relation to the epicenter of the earthquake. In fact, the relatively small p-value confirms that the observed relationship between the spatial and temporal distance matrices for public response could have been obtained by any random arrangement in space (or time) in the study area, thus rejecting the null hypothesis that the two matrices are unrelated. Positive values for the normalized Mantel's statistic (r), representing a positive correlation indicate that smaller differences in temporal distance (for example public response radius of gyration at t) are found for pairs that are spatially close to each other in relation to the earthquak's epicenter. This explains why the arbitrary public responses (e.g., t_1) do not belong to a larger neighborhood. However, since the temporal occurrence of the public response has a reverse proximity with the earthquake's epicenter, this suggests that although the abundance and magnitude of the public response decays spatially, it exhibits a counter behavior temporally; as the time distance increases the abundance of public response also increases.

Table 1. Mantel Test between Spatial and Temporal Public Response Distance.

	R	***p*-value**
Mantel Test	0.4447	0.001

Figure 4(b) shows the distribution of Mantel's test statistic (r) from the permutations. It represents the overall significance of the correlation under permutations and can be used to determine the underlying structure of the correlative relationship. Unfilled points represent conditions that are not statistically significant at the specified alpha level.

DISCUSSION

This study is part of an ongoing investigation of the coupled interactions between the public and the growing number of human-induced seismic perturbations in the state of Oklahoma. These events, many of which could result in damaging earthquakes, are increasing in frequency due to the rapid rise in the number of SWD wastewater injection operations in the state in recent years. Developing an holistic and timely appreciation of the location-specific public response to such events is thus crucial. A clear understanding of the spatiotemporal dynamics of the public response aids effective decision-making and the creation of better policies to support both immediate and long-term interventions and care for those affected. This should include, for example, the provision of credible information on the extent of an event, whether the danger has passed, and how officials are responding to secure help. Social media networks such as Twitter are already being employed as a source of situation awareness and public engagement during crisis events, identifying unintended impacts at an early stage and providing timely support to the public. Significant numbers in the general public share and seek information from social media sites

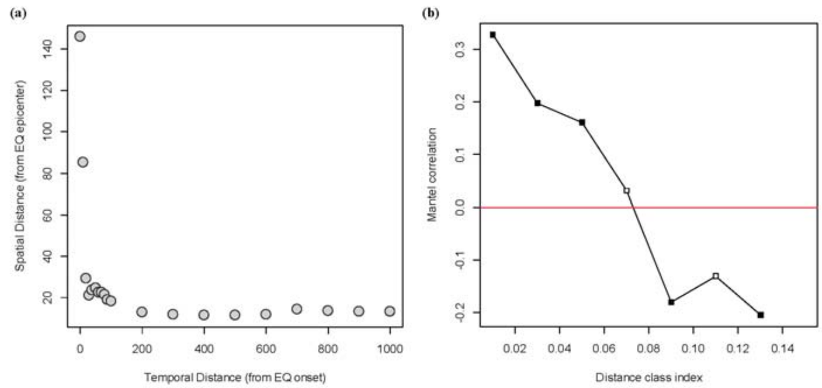

Figure 4. (a) Spatiotemporal distance distribution of public response; (b) Mantel Correlogram.

in the face of emergencies to reassure both themselves and the people in their social network are safe and aware of the situation, the damage caused by the event, and the actions required to be taken (American Red Cross 2012).

Here, we characterized the spatiotemporal dynamics of the public response to a recent human-induced seismic event in the state of Oklahoma, revealing that although the initial response was at a substantial distance from the earthquake's epicenter, the response generally trended spatially towards the epicenter over time. The spatial and temporal occurrence and abundance of the public response were statistically significantly correlated. In the event studied here, there was a reverse relationship between the spatial and temporal decay of the public response with respect to the earthquake's epicenter. Although the abundance of public response decayed as the proximity to the earthquake's epicenter decreased, this measure does not exhibit any decay in behavior as time advances after the onset of the earthquake. This condition could be the aftermath of a possible far-field effect due to an underlying mechanism associated with the social network structure, which allows for temporal proximity to the crisis event despite spatial distance at the onset of the earthquake.

Due to the dynamic and uncertain nature of human-induced earthquakes, it clearly behooves us to study the public response behavior over time and space for a longer period of time and across a wider variety of seismic events (M3.0+ earthquakes) if we are to develop a better understanding of this behavior and its subsequent effects. This ongoing study is expected to continue to observe the social media streams around additional human-induced earthquakes in Oklahoma to characterize the immediate and long-term impact of these seismic events on the public and on individuals. Such study can further facilitate an assessment of how public response behavior changes under repeated disruptions and evaluate how it may evolve in the context of repeated seismic events when faced with different policy interventions. This study represents a first step towards improving our ability to analytically characterize the human system's response to human-induced seismicity and towards developing a better understanding of the overall dynamics of coupled human and natural systems. The results from this study may inform crisis management interventions on the spatiotemporal extent and intensity of public response in relation to the location and intensity of a seismic event.

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