The Earth’s rotation-triggered earthquakes preceding the occurrence of the 2019 M7.1 Ridgecrest earthquake

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ABSTRACT

For earthquakes ($M \geq 2.0$) occurring in and around the aftershock zone of the M7.1 Ridgecrest earthquake between January 2000 and June 2019, we analyzed the correlation between the phase of Earth’s rotation and the occurrence of earthquakes. The Schuster’s test and the two-rate Poisson model were used to statistically examine the correlation between the phase of Earth’s rotation and the occurrence of earthquakes. For the Schuster’s test, the results were judged based on the $P$-value. When the $P$-value is smaller, the correlation is higher. In general, if $P \leq 5\%$, the correlation is significant. For the two-rate Poisson model, the results were evaluated by $R$. When the 95% confidence lower limit on $R (R_l)$ is over one, earthquakes could be non-random. We calculated the temporal variation on the $P$-value for earthquakes that occurred in the study region and found lower $P$-values, corresponding to significant correlation for earthquakes ($2.0 \leq M \leq 2.4$) occurring before the M7.1 event. When the $P$-value reached the lowest, the earthquake nucleated when the Earth’s acceleration of rotation is increasing or near the peak acceleration. This correlation is also confirmed by the two-rate Poisson model. The spacial distribution of the $P$-values for earthquakes ($2.0 \leq M \leq 2.4$) occurring from Jul. 2013 to Jun. 2019 shows that areas of low $P$-value were located mainly in and around the northwest segment of the aftershock zone of the M7.1 Ridgecrest earthquake. The lower $P$-value obtained in this study emphasises that the Earth’s rotation can triggered earthquakes in and around the aftershock zone prior to the M7.1 Ridgecrest earthquake and hence it may be considered as one of the precursors.

ARTICLE HISTORY

Received 6 April 2021
Accepted 8 October 2021

KEYWORDS

The M7.1 Ridgecrest earthquake; Earth’s rotation; correlation; Schuster test; two-rate Poisson model

1. Introduction

When the tectonic stress in the Earth’s crust increases to a critical value to liberate a stronger earthquake, the focal fault could become extremely unstable where the stronger earthquake would be triggered by a change of stress. Cyclic stress variations in
the crust are caused by the Earth’s tide and rotation. Although these stress variations are small in comparison to tectonic stress, their rates are often larger than the rates of accumulation for tectonic stress. With regards to tidal stress considered as one of the possible triggers for earthquakes, many scientific studies have been conducted to investigate the correlation between stronger earthquake occurrence and the Earth’s tide. Some researches had found that tidal stress has significant effect on triggering earthquakes (Heaton 1975; Gao et al. 1981; Tsuruoka et al. 1995; Wu et al. 1999; Tanaka et al. 2002a; Beeler and Lockner 2003; Cochran et al. 2004; Zhang et al. 2007; Li and Zhang 2011; Xu et al. 2011; Sun et al. 2014; Bucholc and Steacy 2016), but some researches had revealed no significant correlation between tidal stress and earthquake occurrence (Simpson 1967; Knopoff 1964; Shlien and Toksoz 1970; Shudde and Barr 1977; Heaton 1982; Stothers 1990; Rydelek et al. 1992; Vidale et al. 1998). Therefore, the tidal triggering of earthquakes still remains controversial. But some researches showed that highly significant tidal triggering of small earthquakes or foreshocks may be expected to appear more clearly prior to a stronger earthquake (Xu et al. 1981; Tanaka et al. 2002b; Tanaka 2010, 2012; Li and Chen 2018).

Relationship between the occurrence of earthquakes and the Earth’s rate of rotation has been investigated since the late 1960s. It has been found that there is a significant correlation between the irregular variation of the rate at which the Earth rotates and seismic energy released by strong earthquakes of medium and deep sources (Stoyko & Stoyko 1969). Seismic activity in the globe is triggered by the increase in the Chandler wobble amplitude, which accelerates the movement of the plate to eventually result in great decoupling earthquakes (Kanamori 1977). A positive correlation was revealed between monthly incidence of earthquakes \((M_S \geq 7.0)\) and the seasonal variations in the Earth’s rotation rate (Gao 1981), whereas earthquakes \((M_S \geq 7.5)\) that occur on an annual basis have a negative correlation with the 10-year variations in the Earth’s rate of rotation (Ma et al. 2007). Earthquakes in different regions could have different relations with the variations in the Earth’s rate of rotation (Li et al. 1973; Yu et al. 1974; Fu 1984; Zhao 1990; Zheng and Zhou 1995; Fu et al. 2004).

The seasonal changes of length of day are mainly caused by atmospheric effects (Richard and David 1985; Zharov 1995; Höpfner 1998). The amplitude of seasonal change of length of day is approximately 1 ms, the corresponding relative change for angular velocity of Earth’s rotation is about \(1 \times 10^{-8}\). The induced stress by this change value is roughly 0.2 Pa on the focal fault plane of the 2019 M7.1 Ridgecrest event, calculated by means of method proposed by Chen et al. in 2018 (Chen et al. 2018). It’s quite apparent that the induced stress is too weak to trigger earthquakes. It was found based on slider-block models of slip that slip can amplify dramatically under the action of given stress within a narrow band of resonant periods (Perfettini et al. 2001). Slip response amplifies significantly for a narrow range of periods near the critical period \(T_c\) when stiffness \(k\) is equal to the critical stiffness \(k_c\), and at shorter periods when \(k\) is greater than \(k_c\) (Lowry 2006). Therefore, for convenience, we can use the seasonal change of the Earth’s rotation rate to analyze triggering of earthquakes to avoid the complicated calculation of the stress induced by meteorological processes. We have investigated the
correlation between the occurrence of small earthquakes in and around the after-shock zones of the Tangshan Ms7.8, the Wenchuan Ms8.0 and the 2011 Mw9.1 Tohoku-Oki Japan main-shocks in the pre-mainshock period and the phase of Earth's rotation (Wei et al. 2018; Chen and Li 2019; Chen et al. 2020). In this study, we will focus on the M7.1 Ridgecrest earthquake in eastern California, USA (date of occurrence: July 6, 2019) to examine the correlation between the changes of the Earth’s rotation rate and the occurrence of earthquakes occurring in the Ridgecrest aftershock zone and its surrounding region prior to the occurrence of the M7.1 Ridgecrest earthquake.

2. Data and method

On July 6th, 2019, the M7.1 Ridgecrest earthquake occurred in southwest of Searles Valley, eastern California. Its focal mechanism solutions indicate a steeply dipping nodal plane striking NW-SE with a right lateral slip, or left lateral slip on the SW-NE oriented nodal plane. Aftershocks of the Ridgecrest main-shock spread along the direction of NW-SE (Figure 1a). Accordingly, the Ridgecrest earthquake ruptured on a right-slip plane striking NW-SE, due to the relative motion between the Pacific plate and the North American plate. Figure 1(b) shows the spatial distribution of event count for the aftershocks in Figure 1(a).

We use earthquakes in the USGS earthquake catalog (https://earthquake.usgs.gov/earthquakes/search/) for our analysis. We considered an area of 125 km × 55 km containing the aftershock zone of the M7.1 Ridgecrest earthquake as the study region, we selected earthquakes of M ≥ 2.0 that occurred within the study region from January.
The spatial distribution of event count for earthquakes ($M_C \geq 2.0$) that occurred from January 2000 to Jun 2019 and location of the study region are shown in Figure 2, where the dashed black rectangle denotes the study region. On the basis of the G-R relation it can be considered that earthquakes of $M \geq 2.0$ in the study region should be complete since 2000 (Figure 3). In total, 2728 earthquakes were selected in the study region.

Magnitude and two-day number versus time for these selected earthquakes are shown in Figure 4. Some clusters or aftershocks are revealed by two-day number in Figure 4(b) and are removed manually. So, we used this catalog with aftershocks and clusters removed to assess the changes in the influence of Earth’s rotation over the approximate past two decades, in total 1303 earthquakes were analyzed herein.

The data of length of day relating to the Earth’s rotation was acquired from the Earth Orientation Center (EOC) (http://hpiers.obspm.fr/eop-pc/). The raw data of length of day with the standard length of day (24 hours) subtracted is shown in Figure 5(a). The change of length of day consists of different periodic components, mainly include the long period component (period over ten years), the seasonal component (period over one month and not more than one year) and the short period component (period not more than one month). We will use the seasonal component to investigate the correlation between the Earth’s rotation and the occurrence of

Figure 2. Map showing spatial distribution of event count for earthquakes ($M_L \geq 2.0$) that occurred from January 2000 to Jun 2019 and location of the study region (dashed black rectangle). Regional faults are shown as red lines. The red star represents the epicenter of the M7.1 Ridgecrest mainshock and the blue solid line box shows the aftershock zone.
earthquakes occurring prior to the M7.1 Ridgecrest event in this paper. The seasonal change in the length of day is plotted in Figure 5(b), obtained by band-pass filtering with period band between 120d and 370d.

The method used in this study has been applied to investigate tidal triggering of earthquakes (Tanaka et al. 2002b; Tanaka 2010, 2012). From a temporal change series of length of day, the phase angle of Earth’s rotation at the occurring time of each earthquake can be calculated. The phase angle at each maximum of the Earth’s rotation rate is defined as 0°, at the first minimum on the left of the maximum as −180°, and at the first minimum on the right one as 180°. The phase angle \( \theta \) at the occurring time of an earthquake was calculated according to the following formula.

\[
\begin{align*}
\theta &= -180^\circ \times \frac{t_0 - t_e}{t_0 - t_{-180}}, \quad t_e < t_0 \\
\theta &= 180^\circ \times \frac{t_e - t_0}{t_{180} - t_0}, \quad t_e \geq t_0
\end{align*}
\]

where \( t_e \) is the occurring time of an earthquake, and \( t_0 \) the time at the maximum of length of day immediately before or after \( t_e \). \( t_{-180} \) and \( t_{180} \) are the times at the minimum of length of day immediately before and after \( t_e \) respectively (Figure 6). With the phase angles of all earthquakes, we can statistically judge whether there is a significant correlation between those earthquakes and the Earth’s rotation not only by use of the Schuster’s test (Heaton 1975; Tsuruoka et al. 1995), but also by
use of the two-rate Poisson model (Vidale et al. 1998; Gu et al. 2008; Bucholc and Steacy 2016).

For the Schuster’s test the results were valued by $P$-value between 0 and 1. In general, if $P \leq 5\%$, the earthquakes could be non-random. The $P$-value of $N$ earthquakes can be obtained on the base of the following formulas.

$$
\begin{align*}
P &= e^{-\frac{r^2}{2}} \\
r &= \sqrt{\left(\sum_{i=1}^{N} \sin \theta_i\right)^2 + \left(\sum_{i=1}^{N} \cos \theta_i\right)^2}
\end{align*}
$$

where $\theta_i$ is the phase angle of the $i$th earthquake. $N > 10$. During the period between point A and point B ($-180^\circ \leq \theta \leq 0^\circ$) in Figure 6, the length of day ascends, the Earth’s rotation decelerates, and the length of day descends from point B to point C ($0^\circ \leq \theta \leq 180^\circ$), the Earth’s rotation accelerates.

**Figure 4.** Magnitude (a) and temporal variation of earthquake frequency with two day bin size (b) vs. time for earthquakes ($M \geq 2.0$).
Figure 5. The length of day relating to the Earth’s rotation vs. time. (a) The raw data (coming from EOC). (b) The seasonal variations in the length of day relating to the Earth’s rotation (filtered with period range from 120d to 370d).

Figure 6. Calculation of the phase angle. “+” indicates the occurring time of an earthquake.
For the two-rate Poisson model, the results were valued by $R$.

\[
R = \frac{N^+ (1-f^+)}{f^+ (1-N^+)} \\
R_L = e^{\ln R - 1.96A} \\
R_U = e^{\ln R + 1.96A} \\
A = \sqrt{\frac{1}{N^+} + \frac{1}{N-N^+}}
\]

where $N^+$ is the number of earthquakes which occur within a phase angle range (denoted by $\theta^+$) from $\theta_a$ to $\theta_b$. $f^+ = \frac{\theta^+}{360}$, $N$ is the total number of events. The 95% confidence limits on $R$ are given by $R_L$ and $R_U$. Generally, if $R_L > 1$, the correlation between those earthquakes and the phase angle range $\theta^+$ is significant.

### 3. Results

From a temporal change series of length of day, we determined the phase angle of Earth’s rotation at the occurring time of each earthquake on the base of formula (1), then calculated $P$-value with formula (2).

We examined the correlation between the seasonal variation of Earth’s rotation and the earthquake’s occurring. $P$-value as a function of time was calculated via considering a six-year time window moved by three months. A shorter time window may introduce random fluctuations, and a longer one may smooth the signals. By trial calculation we determined a six-year time window including 12 cycles of the seasonal variation in Earth’s rotation. We calculated the $P$-value of each window with formula (2), and took the occurring time of the last earthquake in each window as the time of $P$-value. The minimum number of earthquakes in those time windows is 147, the mean and the maximum are 213 and 316 respectively. Therefore the

**Figure 7.** $P$-value as a function of time for earthquakes ($2.0 \leq M \leq 2.4$) that occurred in the study region (the downward arrow ‘\#' shows the occurrence time of the M7.1 Ridgecrest event. The red area indicates the 95% confidence range as resulting from bootstrap analysis). (b) Histogram showing the frequency of the phase angle of earthquakes occurring six years before the M7.1 Ridgecrest earthquake. Thick solid curve denotes sinusoidal function fitted to the frequency distribution.
requirement of earthquake number greater than 10 for the Schuster’s test can be better met. Figure 7(a) shows $P$-value as a function of time, only six lower $P$-values (less than 1%) are found within two years prior to the occurrence of the $M7.1$ Ridgecrest earthquake since 2000. $P$-value dropped rapidly to the lowest value (0.01%) when the $M7.1$ Ridgecrest earthquake was impending.

The bootstrap method is widely used for the calculation of the statistical errors (Efron 1979; Matsuyama 2018). This method is based on the simulation of large number of data sets directly from the real experimental set of the events. The simulated data sets are used to estimate the statistical fluctuations of the parameters for the investigated phenomenon. The simulation consists of the random selections of the events from experimental data set with returning them back to this experimental set. In other words, a new data set is organized by the random event selection from the experimental data set without taking into account whether some events already have been taken to create this particular new data set or not. Thus, any value (event) from the initial set of the experimental data can be taken once, many times, or cannot be taken at all. Each simulated data set contains the same number of events as the original experimental one. When the simulation of a large number of the new data sets is done then relevant parameters are calculated for each of them. After this it is easy to get the 95% confidence ranges of these parameters. Analysis of the confidence range of $P$-value for each time window in Figure 7(a) was carried out according to bootstrap method with a simulation of 2000 simulated data sets. The 95% confidence limit of $P$-value is given by the red area in Figure 7(a), of which the lowest $P$-value was between 0.2% and 0.3%. Therefore, in the pre-event period, a significant correlation between the occurrence of earthquakes of $2.0 \leq M \leq 2.4$ and the Earth’s rotation with confidence level greater than 99.7% can be found.

For two hundred and thirty-three earthquakes that occurred when $P$-value reached to the lowest, the distribution of phase angle is shown in Figure 7(b). We found that about 56.22% of these earthquakes took place when the phase angle was between

![Figure 8. $P$-value as a function of time for earthquakes of $M \geq 2.5$ that occurred in the study region. The downward arrow ‘\downarrow’ shows the occurrence time of the $M7.1$ Ridgecrest event. The red area indicates the 95% confidence range as resulting from bootstrap analysis.](image-url)
and $90^\circ$, corresponding to the period from the later stage of the deceleration to the first half stage of the acceleration.

$P$-value for earthquakes of $M \geq 2.5$ is also computed as a function of time, the chart is shown in Figure 8. No $P$-values lower than 5% can be found from the figure. Therefore we cannot find any significant correlation between these earthquakes and the Earth’s rotation before the $M7.1$ Ridgecrest earthquake.

The spatial distribution of the $P$-values for earthquakes ($2.0 \leq M \leq 2.4$) occurring from Jul. 2013 to Jun. 2019 is shown in Figure 9(a). A spatial window of $50\text{ km} \times 50\text{ km}$ moving by $2\text{ km}$ in both along-latitude and along-longitude directions was considered. When the number of earthquakes in a window is over 15, $P$-value can be worked out. Figure 9(b) shows the spatial distribution of $P < 2\%$. It can be found from Figure 9(b) that lower $P$-values located mainly in and around the northwest segment of the aftershock zone (marked by the red solid-line frame) of the $M7.1$ Ridgecrest earthquake.

It is found from Figure 7(b) that most of earthquakes of $2.0 \leq M \leq 2.4$ took place more frequently when the phase angle was between $-60^\circ$ and $90^\circ$. In the following we used the two-rate Poisson model to test this correlation. We calculated $R$-value with formula (3). For earthquakes of $2.0 \leq M \leq 2.4$ that occurred in the study region, $R$-value as a function of time was calculated via taking a six-year time window moving by 3 months. The result is shown in Figure 10. It can be found from the figure that $R$-value has increased relatively rapidly since the beginning of 2017, and reached the highest value just before the $M7.1$ Ridgecrest earthquake. The highest $R$ is 1.8, and its corresponding $R_L$ is 1.4. Therefore the correlation between earthquakes of $2.0 \leq M \leq 2.4$ and the phase angles in the range from $-60^\circ$ to $90^\circ$ is significant before the $M7.1$ Ridgecrest earthquake.

4. Discussion and conclusions

We analyzed the correlation between the Earth’s rotation and earthquakes ($M \geq 2.0$) occurring prior to the $M7.1$ Ridgecrest earthquake in and around the aftershock
zone. For earthquakes of $2.0 \leq M \leq 2.4$ the significant correlation was found mainly in and around the northwest segment of the aftershock zone prior to the $M7.1$ Ridgecrest earthquake. When the $P$-value reached to the lowest, earthquakes happened more frequently when the phase angle was between $-60^\circ$ and $90^\circ$. This correlation was also confirmed by the two-rate Poisson model.

Figure 11 shows the seasonal variations of LOD (length of day) and $a_e$ which is the linear acceleration at the equator. In one year the seasonal variations of LOD consists of two cycles, the phase angle ranges from $-180^\circ$ to $0^\circ$ between point A and point B or between point C and point D, and from $0^\circ$ to $180^\circ$ between point B and point C (Figure 11). The phase angle range between $-60^\circ$ and $90^\circ$ is marked by two boxes in Figure 11. It can be seen that this phase angle range corresponds to the increasing stage of the linear acceleration of Earth’s rotation (dashed line).

Furthermore we calculated the spatial distribution of the $P$-values for earthquakes ($2.0 \leq M \leq 2.4$) occurring from Jul. 2013 to Jun. 2019 and found that areas of low $P$-value ($P < 2\%$) were located mainly in and around the northwest segment of the aftershock zone of the $M7.1$ Ridgecrest earthquake.

It is worth noting that $P$-value in and around the aftershock zone has been abnormal since the beginning of 2018, however one precursor of minimum of the variability of the order parameter of seismicity in natural time was founded within a large region that covers the Southern California Seismic Network a month before the occurrence of this earthquake (Skordas et al. 2020).

It is no doubt that not only the variation in the Earth’s rotation rate but also the meteorological processes can cause variational stresses in the crust. The variational stresses may be too weak to trigger earthquakes. It is a well-founded viewpoint that the elastic stiffness of seismogenic faults will change with time. If the elastic stiffness of a fault is equal to the critical elastic stiffness, fault slip response to the action of the changing stress with period near the critical period will amplify significantly.

![Figure 10](image-url)
In this situation, a strong earthquake could nucleate, and part of its fault will get exceedingly unstable where most of smaller earthquakes would be in phase with the perturbational stress. But the initial rupture may not have been in this part of the focal fault when the mainshock occurred. Therefore, the lower $P$-value found in this study reinforces the idea that the Ridgecrest focal fault probably was unstable, approaching failure to occur a strong earthquake, and it may be considered as one of its precursors.

Acknowledgments

The authors express sincerely thanks to the journal editors and anonymous reviewers for their help and beneficial comments to the manuscript. This study was supported by China National Key Research and Development Program (2018YFC1503400).

Disclosure statement

No potential conflict of interest was reported by the authors.

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