Pure appl. geophys. 163 (2006) 2343–2351
0033–4553/06/122343–9
DOI 10.1007/s00024-006-0125-z

Pure and Applied Geophysics

LURR and the San Simeon M 6.5 Earthquake in 2003 and the Seismic Tendency in CA

Yongxian Zhang,[1,2] Xiangchu Yin,[1,2] Keyin Peng,[1,2] Haitao Wang,[3]
Jianchang Zheng,[4] Yongjia Wu,[1] and Lang-ping Zhang[2]

Abstract—The spatial and temporal variation of LURR (Load/Unload Respond Ratio) in California during April 2002 to June 2004 was studied in this paper. The result shows that before the San Simeon earthquake (35.7 N, 121.1 W) on Dec. 22, 2003, Y/Y_c anomalous region occurred successively near the epicenter from April 2002 to June 2002, and the maximum anomaly of Y/Y_c occurred in May, 2002. The published research work pointed out that the Y/Y_c anomaly near the San Simeon earthquake appeared from March, 2002. Compared with the five earthquake cases out of the six with M ≥ 6.5 in California during the period from 1980 to 2001, the maximum Y/Y_c and duration of Y/Y_c anomaly before this earthquake are among the normal ranges, but the time delay from the maximum anomaly time to the occurrence time of this earthquake is the longest one. The result also shows that two areas with Y/Y_c anomalies occurred from Oct. 2002 and Dec. 2002, respectively. According to statistical characteristics of the relationship between Y/Y_c anomalies and the coming earthquakes, the seismic tendency in California was discussed in this paper.

Key words: LURR (Load/Unload Respond Ratio) anomaly, San Simeon earthquake, seismic tendency, California.

1. Introduction

The physical essence of an earthquake is failure or instability of the focal media. When a seismogenic system is in a stable state, its response to loading is nearly the same as its response to unloading, whereas when the system is in an unstable state, the response to loading is more sensitive than that to unloading (Yin, 1987; Yin and Yin, 1991; Yin *et al.*, 1995, 2000). Consequently a parameter LURR (Load/Unload

[1] China Earthquake Networks Center, China Earthquake Administration, Beijing 100036, China. E-mail: zhang.yongxian@263.net; yixc@btmail.net.cn; peng_keyin@163.com; wuyongj@mails.gucas.ac.cn
[2] LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China. E-mail: yin@lnm.imech.ac.cn
[3] Seismological Bureau of Xinjiang Uygur Autonomous Region, Urumqi 830011, China. E-mail: whtxj@mail.xj.cninfo.net
[4] Shandong Earthquake Administration, Jinan 250014, China. E-mail: zjcmail@yeah.net

Response Ratio) was put forward by YIN (1987) to describe if a system is in stable or unstable state, which is defined as

$$Y = X^{+}/X^{-}, \tag{1}$$

where X^{+} and X^{-} are the response rates during loading and unloading measured by some method. According to the LURR idea, when a seismogenic system is in a stable or linear state, $Y \sim 1$, whereas when the system lies outside of the linear state, $Y > 1$.

In earthquake prediction practice with LURR, the earth's tide is taken as a load and unload source, and the response parameter of X is chosen as Benioff strain calculated from magnitudes of earthquakes in this region. The periods of loading and unloading are determined by calculating perturbations in the Coulomb Failure Stress induced by the earth's tides (YIN *et al.*, 1995, as illustrated in the next part). Experimental and numerical simulation have validated LURR (MORA *et al.*, 1999, 2000; WANG *et al.*, 1999; WANG *et al.*, 2000; WANG *et al.*, 1999). In retrospective studies, high Y values have been observed months to years prior to most significant events and some successful intermediate-term earthquake predictions have been made (YIN *et al.*, 2000).

Based on the theory of LURR and its recent development, spatial and temporal variation of Y/Y_c (value of LURR/critical value of LURR) in Southern California and its adjacent area (32° N to 40° N, 114° W to 125° W) during the period from 1980 through March, 2002 has been studied (ZHANG *et al.*, 2004). The scanning results show that obvious Y/Y_c anomalies occurred before five out of the total six earthquakes with $M \geq 6.5$. The areas with Y/Y_c anomaly are near the epicenters of the strong earthquakes and the Y/Y_c anomalies occur months to years prior to the earthquakes. According to the contour of LURR in March 2002, a forecast of "There might be a moderate earthquake near 5 around (36° N, 119° W) and (36° N, 121.6° W) within about 1 year. If the Y/Y_c anomalous region grows larger and persists for one half to one year or more, there might a stronger earthquake in these regions." (Presented at the 3rd ACES Workshop in May, 2002 in Hawaii, ZHANG *et al.*, 2003, 2004).

What happened from April 2002 to Dec. 2003 in California? Two earthquakes with $M \geq 5.0$ occurred in the studied area. One was an M 5.4 (34.31° N, 116.85° W) earthquake on Feb. 22, 2003, and the other was the San Simeon M 6.5 (35.7° N, 121.1° W) earthquake on Dec. 22, 2003. The San Simeon M 6.5 earthquake occurred very near one of the LURR anomalous regions mentioned above (36° N, 121.6° W). In order to obtain the evolution process of LURR before this quake, an earthquake catalogue from April 2002 to June 2004 has been downloaded from ANSS (the former CNSS). Under the same calculation parameters, snapshots of Y/Y_c contours for each month from April 2002 to March 2004 are obtained. From these snapshots, the feature of anomalous Y/Y_c before the San Simeon M 6.5 earthquake was abstracted, and a comparison of this earthquake with the former five cases was given in this paper.

2. Method to Calculate LURR

2.1. Determination of Loading and Unloading Periods

YIN *et al.* (1995) resorted to the Coulomb failure criterion (JAEGER and COOK, 1976) to determine the loading and unloading periods. We calculate perturbations in the Coulomb Failure Stress (CFS) (e.g., HARRIS, 1998; RESERNBERG and SIMPSON, 1992) induced by the earth's tides.

$$CFS = \tau_n + f\sigma_n, \tag{2}$$

where σ_n stands for normal stress, τ_n denotes shear stress, f represents the coefficient of internal friction (taken as 0.6 in this paper), and n is the normal direction of the fault plane on which CFS reaches its maximum. When the increment of Coulomb Failure Stress (ΔCFS) is positive, it is in a loading state; otherwise, when ΔCFS is negative, it is in an unloading state.

As we know, stress in the crust σ_{ij} consists of tectonic stress σ_{ij}^T and the stress induced by the earth's tide σ_{ij}^t. Since the level of σ_{ij}^T (on the order of 10^6–10^8 Pa) far exceeds the level of σ_{ij}^t (10^3–10^4 Pa), directions of the principle stress in the crust and the direction of n can be determined from the tectonic stress only. However, the rate of change of the tidal stress is considerably larger than that of the tectonic stress (VIDALI *et al.*, 1998), thus ΔCFS is mainly due to stress induced by the tide, which can be calculated precisely, and could be resolved along the dominant fracture mechanism determined in each region.

2.2. Tectonic Stress Field in Southern California

An outline of the stress field in Southern California can be obtained from the world stress map (ZOBACK, 1992). The stress field is supplemented by the fault system in Southern California which is provided by SCECDC (Southern California Earthquake Data Center). With these two sets of information, we divided the Southern California region into eleven parts, in each of which the fault property stress field is almost uniform, as shown in Table 1.

With the fault property and basic stress field in Southern California, we can calculate ΔCFS along the dominant fracture mechanism with time, and determine the loading and unloading periods.

2.3. Calculation of LURR

As mentioned in the reference (ZHANG, 2004), Y is determined by the ratio of Benioff strain during the loading period over the unloading period.

Since the preparation and occurrence process of earthquakes is controlled not only by deterministic dynamical law but also affected by stochastic or disorder factors, ZHUANG and YIN (1999) studied the influence of random factors on LURR

Table 1

Fault property and basic stress field in Southern California

Subdivision	Fault Property	P-axis direction/(°)	T-axis direction/(°)
Sc01	right-lateral strike-slip	−15	75
Sc02	right-lateral strike-slip	−5	85
Sc03	reverse, right-lateral	45	0
Sc04	right-lateral strike-slip	−15	75
Sc05	normal, right-lateral	0	−20
Sc06	right-lateral strike-slip	−10	80
Sc07	normal, right-lateral	0	80
Sc08	right-lateral strike-slip	−5	85
Sc09	reverse right-lateral	45	0
Sc10	right-lateral strike-slip	0	90
Sc11	right-lateral strike-slip	10	100

in order to estimate the threshold Y value which can be regarded as an earthquake precursor within a specified confidence level. They gave the critical value of LURR Y_c that depends on the number of earthquakes under different specified confidence levels. For instance, at the confidence level of 90%, Y_c is equal to 3.18 if the number of earthquakes in the time and space window is 20, which means that Y should be equal to or greater than 3.18 for the medium to be considered in an unstable state when the number of earthquakes is 20. For the confidence level of 99%, Y_c is 7.69 if the number of earthquakes in the specific time and space window is 20. The greater the earthquake number is, the lower the Y_c (critical value of LURR) is.

In this paper, we give critical space-time regions of LURR by Y/Y_c instead of Y under a confidence level of 99%. When $Y/Y_c \geq 1.0$, the seismogenic system lies outside of the linear state.

3. Data and Scanning Parameters

The earthquake catalogue we use in this paper is from ANSS (Advanced National Seismic System).

In order to speed up the calculations and avoid disturbance from outstanding earthquakes, we chose magnitude thresholds according to the Gutenberg-Richter relation in each unit area. The threshold of minimum magnitude for each unit area is M 2.0, and the threshold of maximum magnitude for each unit area is M_{max} ($M_{max} = 3.5$ when the magnitude intercept of line $\lg N = a - b\mathrm{M}$ is among M 4.0 and M 5.9, and $M_{max} = 4.0$ when the intercept of line $\lg N = a - b\mathrm{M}$ is equal or larger than M 6.0).

A circle region with a radius of 100 km was selected as the spatial window within which a value of Y/Y_c (LURR/critical LURR) was calculated for a specific time window (1 year), then the circle center was moved step by step in both latitude and longitude by increments of 0.25 degrees, and the contour of Y/Y_c in each month could be obtained.

4. The Feature of Y/Y_c Anomaly before the San Simeon Earthquake and Tendency of Earthquake Occurrence in Southern California

4.1. The Feature of Y/Y_c Anomaly before the San Simeon Earthquake

The results show that Y/Y_c anomalous region (with $Y/Y_c \geq 1.0$) occurred successively near the epicenter of the San Simeon earthquake from March 2002 to June 2002, and the maximum anomaly of Y/Y_c occurred in May 2002 (Fig. 1).

The maximum Y/Y_c and duration of Y/Y_c anomaly before the San Simeon earthquake are 1.4 and 15 months, respectively. The interval between the occurrence time of maximum Y/Y_c and the occurrence time of the earthquake is 19 months. Compared with the 5 earthquake cases out of the 6 with M $\geq$ 6.5 during the period from 1980 to 2001, the maximum Y/Y_c and duration of Y/Y_c anomaly before this earthquake are among the normal ranges, however the interval between the occurrence time of maximum anomaly and the occurrence time of this earthquake is the longest one (Table 2).

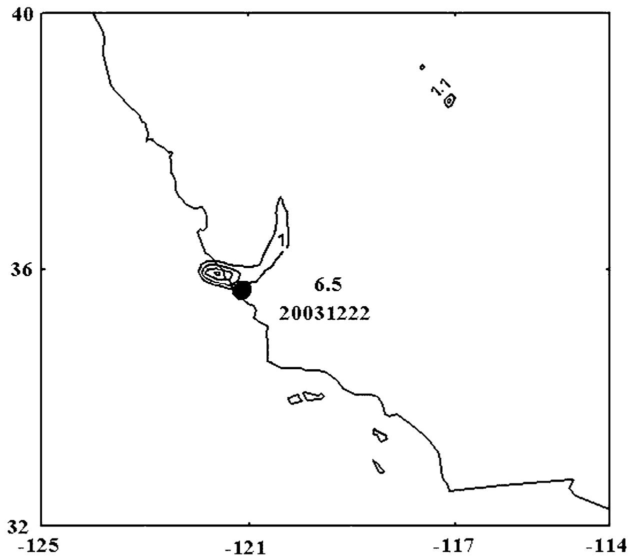

Figure 1
Contour of Y/Y_c in May, 2002. (The solid black circle represents the epicenter of the San Simeon M 6.5 earthquake on Dec. 22, 2003; Y/Y_c is among 1.0 to 1.4, and the increment of Y/Y_c is 0.1 between each two neighboring isolines.)

Table 2

Y/Y_c anomalies before seven strong earthquakes in Southern California during the period from 1980 through 2003

Date	Epicenter	Magnitude/ Δ(km)	Max Y/Y_c	Lasting time of anomalous Y/Y_c (month)	$\Delta t(m)$
1983.5.2	(36.23° N, 120.32° W) Coalinga	6.7/?	?	?	?
1987.11.24	(33.01° N, 115.85° W) Superstition Hills	6.6/0	1.4	21	11
1989.10.18	(37.04° N, 121.88° W) Loma Prieta	7.0/100	1.2	24	10
1992.6.28	(34.20° N, 116.44° W) Landers	7.3/100	1.0	18	8
1994.1.17	(34.21° N, 118.54° W) Northridge	6.6/200	1.2	25	13
1999.10.16	(34.59° N, 116.27° W) Hector Mine	7.1/100	1.4	15	1
2003.12.22	(35.7° N, 121.1° W) San Simeon	6.5/50	1.4	15	19

Note: Δ(km) is the distance between the earthquake epicenter and the maximum Y/Y_c point.
Δt is the duration between the occurrence time of maximum anomaly and the occurrence time of the earthquake.

4.2. Tendency of Earthquake Occurrence in Southern California

The results of this study also show that two areas with Y/Y_c anomalies occurred from Oct. 2002 and Dec. 2002, respectively. One is in the southern part of Southern California during Oct. 2002 to May. 2003, and the other is in the northern part of Northern California during Dec. 2002 to Aug. 2003. Figure 2 shows the contour of Y/Y_c in March 2003. This figure implies that two earthquakes with M $\geq$ 6.5 might

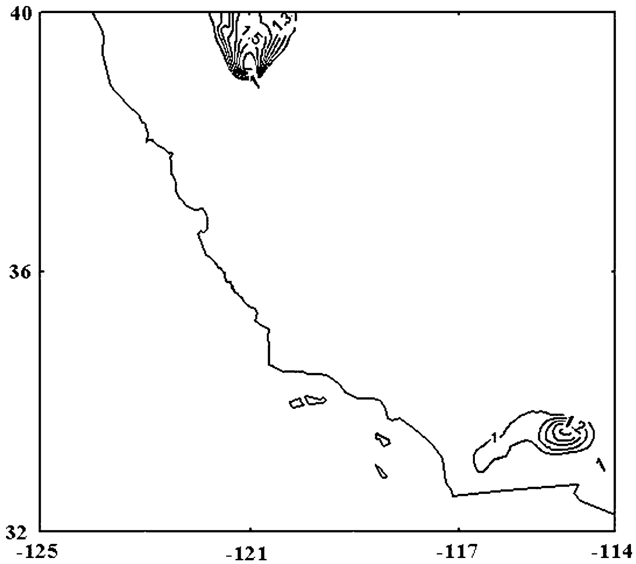

Figure 2
Contour of Y/Y_c in March, 2003. (The increment of Y/Y_c is 0.1 between each two neighboring isolines.)

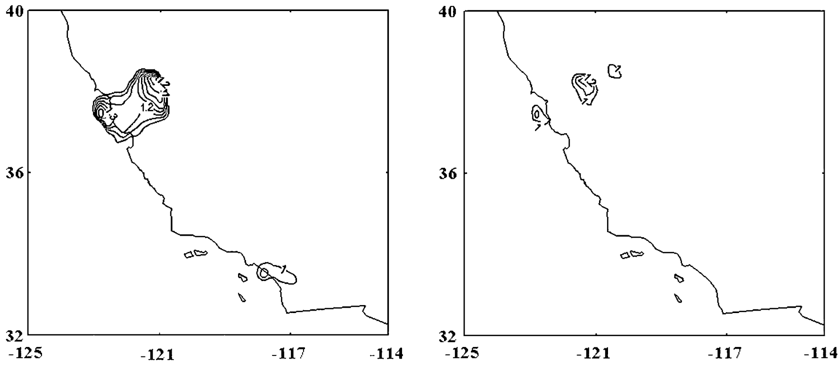

Figure 3
Contours of Y/Y_c in Feb. 2004 (left hand) and June 2004 (right hand). (The increment of Y/Y_c is 0.1 between each two neighboring isolines.)

occur in California in the future; one is in the circle region with the center of (33.7 N, 115 W) and the radius of 200 km (100 km with the possibility of 80%), and the other is in the circle region with the center of (39.1 N, 121.1 W) and the radius of 200 km (100 km with the ratio of 5/7). The former is more reliable than the latter because we obtain more detailed data about the stress field and fault system in Southern California than those in Northern California. According to statistical characteristics of the relationship between Y/Y_c anomalies and the coming earthquakes (Table 2), the most probable time for the coming earthquake is before Oct., 2004.

The above forecast was reported on the 4th ACES Workshop in Beijing in July, 2004. In fact, a new region which is involved with anomalous Y/Y_c occurred from Feb. 2004 (left contour in Fig. 3) and blossomed in June 2004 (right contour in Fig. 3). Since we had not seen the shrinkage of the area, we could not judge when there would be an earthquake near this region. The Parkfield M_w 6.0 Earthquake* on Sept. 28, 2004 is about 200 km from the point with maximum Y/Y_c value. According to Table 2, an earthquake with magnitude larger than 6.5 might occur near this region during the coming 19 months. Although the Parkfield M_w 6.0 earthquake occurred near this region, it is not the expected one because it is smaller than the lower threshold of the predicting events. In other words, there would be an earthquake with magnitude larger than 6.5 near this region during the next 19 months from June, 2004.

* Parkfield M_w6.0 Earthquake (11 km SSE of Parkfield, CA, 35.815 N, 120.374 W) occurred on Sept. 28, 2004, which is about 200 km from the northern Y/Y_c anomalous region.

5. Conclusions and Discussion

The original anomaly of LURR near the epicenter of the San Simeon earthquake was given beforehand (ZHANG *et al.*, 2004), and the feature of LURR anomaly before the San Simeon earthquake in this retrospective study coincides with those before the five strong earthquakes in the former study, which proves that LURR is a promising approach to intermediate-term earthquake prediction prior to strong earthquakes with M 6.5 or greater in Southern California.

The accuracy of earthquake prediction might be improved if detailed knowledge of the stress field in Southern California and higher quality of earthquake catalogues could be accessed. Meanwhile, suitable scanning parameters might improve the results.

Acknowledgements

Support is gratefully acknowledged by the Key Program of NSFC (Grant Nos. 10232050, 10572140) and MOST under grant's (2004CB418406, 2002CB412706). We also express our thanks to ANSS for earthquake data.

REFERENCES

BULLEN, K.E. and BOLT, B.B., *An Introduction to the Theory of Seismology* (Cambridge University Press, Cambridge Press 1985).

HARRIS, R.A. (1998), *Introduction to special section: Stress triggers, stress shadows, and implication for seismic hazard*, J. Geophys. Res. *103*, 24,347–24,358.

JAEGER, J.C. and COOK, N.G.W., *Fundamentals of Rock Mechanics* (Chapman and Hall, London 1976) 78–79.

KANAMORI, H. and ANDERSON, D.L. (1975), *Theoretical basis of some empirical relation in seismology*, Bull. Seismol. Soc. Am. *65*, 1073–1096.

MORA, P., PLACE, D., WANG, Y.C., YIN, X.C., PENG, K.Y., and WEATHERLEY, D. (1999), *Earthquake Forecasting: Retrospective Studies in Australia – the Newcastle and Burra Earthquakes and Numerical Simulation of the Physical Process*, AEES (Australian Earthquake Engineering Society) Annual Meeting, November, 2000, Hobart, Australia.

MORA, P., PLACE, D., WANG, Y.C., and YIN, X.C. (2000), *Simulation of Load-Unload Response Ratio in the Lattice Solid Model*, AGU (American Geophysical Union) 2000 Fall Meeting, San Francisco, pp. 10–17, December 2000.

RESERNBERG, P.A. and SIMPSON, R.W. (1992), *Response of regional seismicity to the static stress change produced by the Loma Preita earthquake*, Science *255*, 1687–1690.

VIDALI, J.E., AGNEW, D.C., JOHNSTON, M.J.S., and OPPENHEIMER, D.H. (1998), *Absence of earthquake correlation with earth tides: An indication of high preseismic fault stress rate*, J. Geophys. Res. *103*, 24,567–24,572.

YIN, X.C. and YIN, C. (1991), *The precursor of instability for nonlinear systems and its application to earthquake prediction*, Science in China *34*, 977–986.

YIN, X.C. (1987), *A new approach to earthquake prediction*, Earthq. Res. China *3*, 1–7 (in Chinese with English abstract).

YIN, X.C., CHEN, X., SONG, Z.P., and YIN, C. (1995), *A new approach to earthquake prediction: the Load\Unload Response Ratio (LURR) theory*, Pure Appl. Geophys. *145*, 701–715.

YIN, X.C., WANG, Y.C., PENG, K.Y., and BAI, Y.L. (2000), *Development of a new approach to earthquake prediction: Load/Unload Response Ratio (LURR) theory*, Pure Appl. Geophys. *157*, 2365–2383.

WANG, Y.C., YIN, X.C., and PENG, K.Y. (1999), *Numerical simulation on Load/Unload Response Ratio theory*, Chinese J. Geophys. *42*(4), 527–536.

ZHANG, Y.X., YIN, X.C., and PENG, K.Y.(2004), *Spatial and temporal variation of LURR and its implication for the tendency of earthquake occurrence in Southern California*, Pure Appl. Geophys. *161*(11–12th), 2359–2367.

ZHANG, Y.X., YIN, X.C., and PENG, K.Y. (2003), *Study on Spatial and Temporal Variation of LURR in Southern California and Its Implication to Earthquake Tendency in this Region*, APEC Cooperation for Earthquake Simulation (ACES) 3rd ACES Workshop Proceedings, pp. 365–371 (Chief editor: Andrea Donnellan, co-editor: Peter Mora). (Published by: APEC Cooperation for Earthquake Simulation (ACES) , QUAKES, Department of Earth Science, the University of Queensland, Brisban).

ZHUANG, J.C. and YIN X.C. (1999), *Random distribution of the Load/Unload Response Ration (LURR) under assumptions of Poisson model,* Earthq. Res. China *15*, 128–138.

ZOBACK, M.L. (1992), *First- and second-order patterns of stress in the lithosphere: The world stress map project*, J. Geophys. Res. *97*, 11,703–11,728.

(Received December 1, 2004, revised September 10, 2005, accepted September 12, 2005)
Published Online First: December 20, 2006