Earthquake Research in China
Volume *19*, Number *3*, *2005*

The Spatial Variation of LURR and Seismic Tendency in Western United States[1]

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Load-Unload Response Ratio (LURR) is a new promising approach to earthquake prediction. In the previous years, a series of successful medium-term predictions have been made for strong earthquakes on the Chinese mainland using this method. In order to investigate whether the LURR method applies to different tectonic regimes, i.e., whether it is universal, the San Andreas Fault and its vicinities are chosen as the study region in this paper. The spatial variation of LURR in the western United States (30°～50°N, 100°～130°W) is studied in detail and the earthquake tendency in this region is discussed based on historic earthquake cases.

Key words: Load/Unload Response Ratio (LURR); Western United States; Spatial scanning; Seismic tendency

INTRODUCTION

The Load-Unload Response Ratio (LURR) is a new promising method for medium-term earthquake prediction put forward by Yin, X. C. (Yin, 1987; Yin, and Yin, 1991; Yin, et al., 1994; 2000). In recent years, by this method, a lot of strong earthquakes have been successfully predicted, including ten strong earthquakes that occurred on the Chinese mainland as well as the Northridge, USA, earthquake (M6.7, Jan. 17, 1994) and an earthquake in Kanto, Japan (M6.6, Sep. 11, 1996, 35.5°N, 140.9°E) (X. C. Yin, et al., 1996). Retrospective examination of more than one hundred earthquake cases indicates that for more than 80% of the examined ones, a peak of LURR will appear before the main shock. LURR method can be applied not only to predict natural earthquakes but also to forecast other geological disasters such as reservoir-induced earthquake, mine earthquake, rock burst, landslide, volcano eruption, etc. After years of earthquake prediction practice, the prediction results using LURR have been improved.

The western United States lies on the Circum-Pacific zone, the most active seismic zone in the globe where 80% of the earthquakes in the world occurred. The tectonic regime of the western United

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[1] Received on July 3, 2005.

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States is quite different from that of the Chinese mainland. In the western United States, most earthquakes occurring along the San Andreas Fault, a transform fault, are inter-plate earthquakes. But on the Chinese mainland it is intra-plate earthquakes that dominate. In recent years, many strong earthquakes on the Chinese mainland were predicted beforehand by means of LURR. In late 2003, we conducted the temporal-spatial scanning of LURR on the Chinese mainland, with the purpose of predicting $M \geq 5.0$ earthquakes in 2004 (Yin, X. C., et al., 2003). Through examination, it is found that 88% of the $M5.0$ or larger earthquakes of 2004 fell into the anomalous LURR regions except for the regions whose data are not good enough to calculate LURR (Yin, X. C., et al., 2004). Similar study was carried out on the strong earthquakes in the western United States. Zhang Yongxian et al. (2003) divided the Southern California region into 11 parts according to the fault system and stress field and studied the variation of LURR. The result shows that, from 1980 to 2001, $\frac{5}{6}$ of $M \geq 6.5$ earthquakes in that region were preceded by obvious LURR anomalies. Song Zhiping, et al. (2000) discussed the variation of LURR before strong earthquakes with $M \geq 6.0$ during 1980～1994 in Southern California. The earthquakes they studied were all preceded by obvious LURR anomalies. The time scale of LURR in these results is similar to that on the Chinese mainland. These results demonstrate that the LURR method not only is effective for earthquakes on the Chinese mainland but also may be suitable for earthquakes in other regions that have different tectonic regimes. The earthquake catalogue in the western United States (30°～50°N, 100°～130°W) is rich in records owing to the dense seismic network, therefore it is suitable for LURR calculation. In recent years, we conducted LURR spatial scanning over the region (30°～50°N, 100°～130°W) for several times.

In this paper, the Centroid-Moment-Tensor (CMT) solutions are from Harvard Centroid Moment Tensor database via internet (http://www.seismology.harvard.edu/). The earthquake catalogue is from the ANSS (Advanced National Seismic System) website (http://www.anss.org/).

1. LOAD-UNLOAD RESPONSE RATIO (LURR)

The LURR Y is a parameter that can quantitatively describe the approaching catastrophe of heterogeneous brittle material and is defined as

$$Y = \frac{X_+}{X_-} \tag{1}$$

where X_+ and X_- are the response rates during loading and unloading respectively.

The response rate X is defined as

$$X = \lim_{\Delta P \to 0} \frac{\Delta R}{\Delta P} \tag{2}$$

where ΔP and ΔR denote the increments of load P and response R, respectively.

The principle of LURR theory is that when a system is in elastic regime, its response to loading is nearly the same as its response to unloading, whereas the response to loading becomes quite different from that to unloading when the system is in the damage regime. The ratio of the loading response rate to the unloading response rate, called the Load/Unload Response Ratio, can be used to measure quantitatively the damage degrees.

It is clear that $Y = 1$ for an elastic regime since $X_+ = X_-$ and $Y > 1$ for the damage regime due to $X_+ > X_-$. The more serious the damage of the material is, the larger the Y value will be. As the media approach to failure, the Y value becomes larger and larger so that the Y value (LURR) can be used to measure the proximity to failure and it also acts as a precursor for earthquake prediction. Experiments and numerical simulation have proved the validity of LURR (Wang Yucang, et al., 1999; Peter Mora, et al., 2002). Some researchers simulated the physics of LURR using the method of statistic mesoscopic damage mechanics and conducted systematic researches on the general character

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and precursor of heterogeneous brittle materials. They proposed the concept of critical sensitivity to explain the drop of LURR prior to strong earthquakes (Xia, M. F., 2002; Zhang, X. H., 2004; Xu, X. H., 2004).

In order to predict earthquakes by means of LURR, there are several main problems to be solved. One is how to load and unload a seismogenic zone and how to distinguish loading from unloading. The linear dimension of a seismogenic zone may reach hundreds even thousands of kilometers. To load and unload such a large system is beyond the ability of mankind. However, the earth tide provides a means to realize it. Tidal force varies periodically, so the induced stress in the crust loads and unloads the earth periodically all the time.

To distinguish loading from unloading to rock materials in the three-dimensional stress state, we resort to Coulomb failure criterion (Resernberg, P. A. and Simpson, R. W., 1992; Harris, R. A., 1998). Coulomb Failure Stress (CFS) can be expressed as:

$$CFS = \tau_n + f\sigma_n \tag{3}$$

where τ_n and σ_n are shear and normal stresses on the fracture plane; f is the coefficient of internal friction; subscript n refers to the normal of the fault plane on which the CFS reaches its maximum. The increment of CFS is denoted by ΔCFS. The case that the increment of Coulomb failure stress $\Delta CFS > 0$ refers to loading; otherwise, $\Delta CFS < 0$ refers to unloading.

When calculating CFS, the total stress tensor at every point in the earth crust is used, including the tectonic stress σ_T and tidal stress σ_t. As to the tectonic stress field, we mainly use the results of Xu Zhonghuai, et al. (1995) for the Chinese Mainland, and Mary Lou Zoback's results for other regions (http://www.world-stress-map.org/). Based on the work of previous researchers, we worked out an independent code for calculating stress tensor at any point and time in the earth crust. The shear and normal stress on the fault plane with normal n can be obtained by stress tensor transform and then the CFS can be calculated easily according to (3).

In real earthquake prediction, Y is defined directly by the released seismic energy as follows:

$$Y_m = \frac{\left(\sum_{i=1}^{N_+} E_i^m\right)_+}{\left(\sum_{i=1}^{N_-} E_i^m\right)_-} \tag{4}$$

where E denotes released seismic energy, the signs "+" and "-" mean loading and unloading, $m = 0$ or 1/3 or 1/2 or 2/3 or 1. For $m = 1$, Em is exactly the energy itself; for $m = 1/2$, Em denotes the Benioff strain; for $m = 1/3$ and 2/3, Em represents the linear scale and area scale of the seismogenic zone, respectively; and for $m = 0$, Y is equal to N_+/N_-, where N_+ and N_- denote the number of earthquakes occurring during the loading and unloading periods, respectively. In this paper m is chosen as 1/2, which means that Y is determined by Benioff strain during the loading period and unloading period.

Using the abundant seismic data of China and abroad, the theory of LURR has been examined comprehensively. The number of examined cases reached more than one hundred, including most $8.0 > M \geq 7.0$ earthquakes that occurred on the Chinese mainland (some cases could not be studied due to lack of sufficient data) since 1970, most strong earthquakes ($7.0 > M \geq 6.0$) that occurred in the North China region since 1970 and some strong or large events ($M > 6.0$) that occurred in USA, Japan and Australia region. For more than 80% of the cases examined, the LURR value fluctuated around 1 during the early stage of seismogenic process and it rose when the strong earthquake was impending. Then Y reached its maximum (much greater than 1) and decreased sharply at the eve of earthquake. The duration of $Y > 1$ ranges from months to years and is related to the magnitude.

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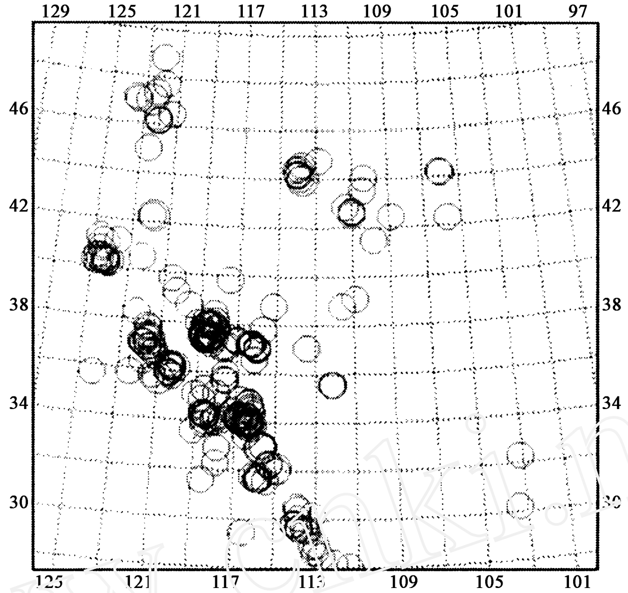

Fig. 1

The epicenter distribution of $M \geq 5.0$ earthquakes in western United States since 1980

2. THE SPATIAL SCANNING OF LURR IN WESTERN UNITED STATES

The Centroid-Moment-Tensor (CMT) solutions of the fault system for the region are obtained from Harvard Centroid Moment Tensor database via internet. Based on this set of information, we divide the western United States region (30°～50°N, 100°～130°W) into 2°×2° sub-regions with uniform CMT solutions in each area (Fig. 1). The strike, dip and rake of fault in every area can be defined according to the CMT solutions. The loading and unloading periods are determined by calculating perturbations in the *CFS* induced by the earth tide. Then a circular region with radius *R* is selected as the spatial window to calculate LURR for a specific time window. The circle center moves with given step length in both latitudinal and longitudinal directions by a certain increment.

According to the scaling relation of LURR, the size of seismogenic zone (radius *R* of circle area) should be in proportion with the magnitude of the future earthquake (Yin, et al., 2002) as follows:

$$\log R(\mathrm{km}) = 0.087 + 0.34M \tag{5}$$

The size is in accordance with the critical size defined by the CPH (Bowman, D. D. et al., 1998; Bufe, C. G. and Varnes, D.J., 1993; Jaume, S. C. and Sykes, L. R., 1999).

The earthquake catalogue used in this paper is from ANSS (http://www.anss.org/). In order to avoid disturbance from outstanding earthquakes, we chose magnitude thresholds according to the Gutenberg-Richter relationship for each unit area. Fig. 2 is the distribution map of LURR anomaly in western United States in a time window of Jan. 1, 2003～Dec. 31, 2003, and superimposed on the map is the epicenter distribution of earthquakes with $M = 5.0$ or larger during Jan. 1, 2004～Dec. 31, 2004. Those anomaly regions would be highly probable places for earthquakes of $M5.0$ or larger to occur in 2004. The scanning parameters in Fig. 2 are as follows:

Time window: 1 year;
Space window: $R = 200$km;
Magnitude threshold: 0.0～4.0;
Moving step length: 0.125° in both latitudinal and longitudinal directions.

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Red circles in Fig. 2 denote the $M \geq 5.0$ events occurring in regions in which the observed data are good enough to calculate LURR. The results are calculated on Deepcomp 6800 supercomputer in the Computer Network Information Center of Chinese Academy of Sciences. From the figure, we can see that most earthquakes took place in the anomalous LURR regions, showing that the prediction results using LURR are satisfying. Based on this we conducted the LURR spatial scanning to study the seismic tendency in the near future in this region. Fig. 3 shows the maps of LURR anomaly regions by spatial scanning with different space and time windows. The scanning radius R is taken to be 70km, 100km and 200km, respectively. The results show that there are obvious LURR anomalies, which imply that there will be high seismic risk in western United States in the near future. According to the results, we predict that,

(1) Earthquake with $M = 5.0$ (± 0.5) or so will probably occur before July 31, 2005 in the LURR anomaly regions shown in Fig. 3a, especially in the regions where the LURR is larger than 1.5.

(2) Earthquake with $M = 5.5$ (± 0.5) or so will probably occur before Dec. 31, 2005 in the LURR anomaly regions shown in Fig. 3b, especially in the region where the LURR is larger than 1.5.

(3) Earthquake with $M = 6.5$ (± 0.5) or so will probably occur before Dec. 31, 2006 in the LURR anomaly regions shown in Fig. 3c, especially in the region where the LURR is larger than 1.5.

Based on LURR scanning result, further study has been carried out in the rectangular zone of 33°～36°N, 115°～118°W, as shown in Fig. 4. The result shows that the LURR in that region has attained a peak and began to drop. Earthquake with $M = 6.0$ or larger will probably occur before Dec. 31, 2005 or a bit later.

3. DISCUSSION AND CONCLUSION

LURR is a promising approach to medium-term earthquake prediction, and many strong earthquakes have been predicted beforehand by means of LURR with better effect, especially on the Chinese mainland. The geological structure of the western United States, where most earthquakes that occurred on the San Andreas Fault are the inter-plate ones, is different from that of the Chinese mainland, where most earthquakes are intra-plate earthquakes. In order to investigate the applicability of LURR to different tectonic regimes, the spatial scanning of LURR in the western United States (30°～50°N, 100°～130°W) has been conducted and the result is reported in this paper. Comparison of anomalous LURR regions in 2003 with the earthquakes with $M \geq 5.0$ in the region in 2004 shows that the predicting results using LURR are satisfactory. The future earthquake tendency in this region is proposed in the paper. If the future earthquakes accord with the results, it may suggest that the LURR approach is applicable for predicting earthquakes in a transform fault.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the supports from the Special Funds for Major State Basic Research Programs under Grant No. 2004 CB418406, 004DKA50740 and 2002CB412706, from NSFC under Grant No. 10232050, and the "Supercomputing Environment Construction and Application" (INF105-SCE-2-02) under the Information Construction of Knowledge Innovation Program of Chinese Academy of Sciences, and the Joint Earthquake Science Foundation (305016) of China Earthquake Administration.

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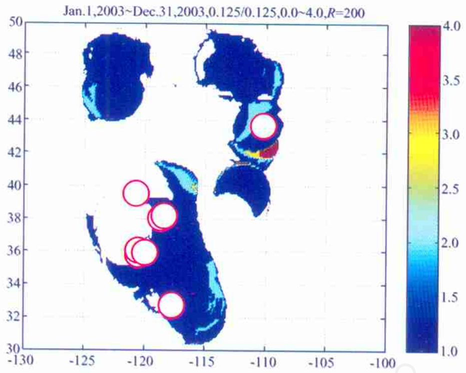

Fig. 2

The anomalous LURR regions in western United States on Jan.1, 2003~Dec. 31, 2003 and the map of epicenters of earthquakes with magnitude M5.0 or larger on Jan.1,2004~Dec.31,2004

○ Earthquakes with $M \geq 5.0$

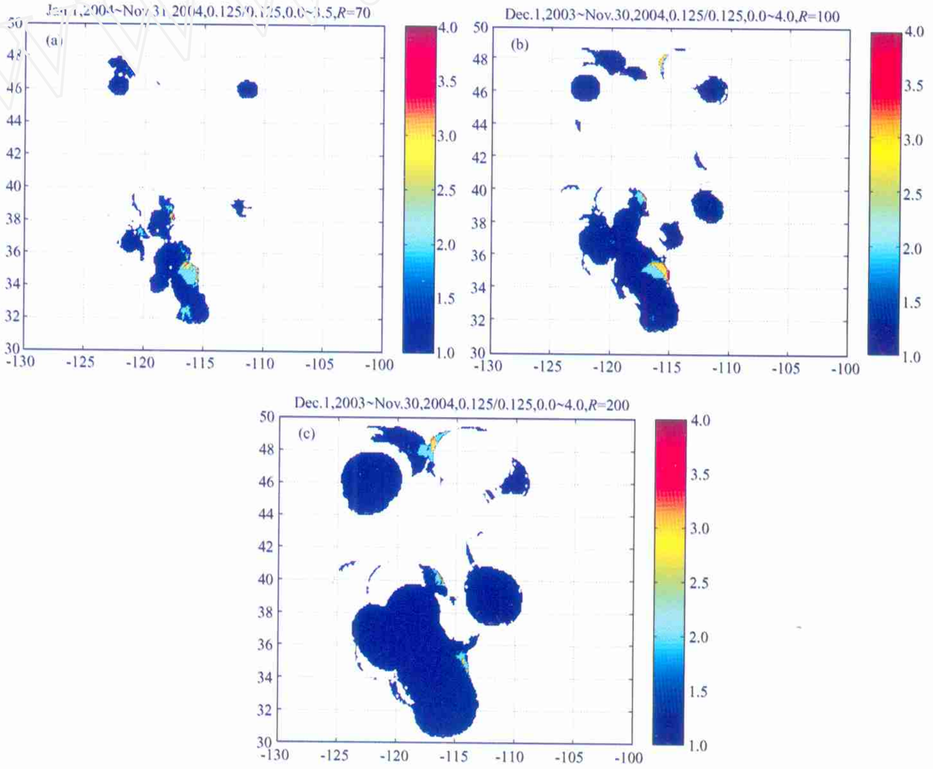

Fig. 3

The spatial scanning of LURR in the western United States with different radius

(a) R=70km; (b) R=100km; (c) R=200km

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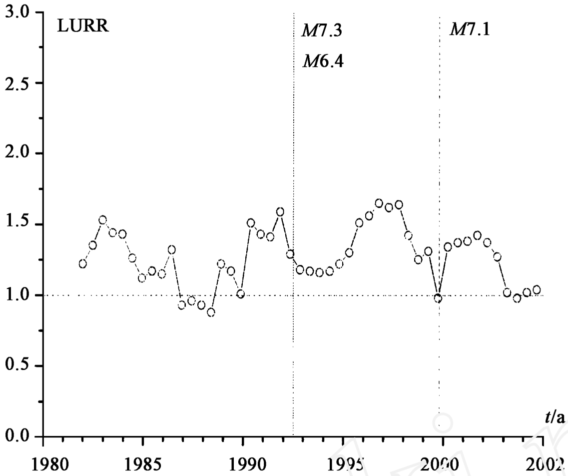

Fig. 4

The variation of LURR with time in the rectangular region of (33 °～36 °N ,115 °～118 °W)

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