Chapter 6
Load-Unload Response Ratio and Its New Progress

Xiang-Chu Yin, Yue Liu, Lang-Ping Zhang, and Shuai Yuan

This chapter presents the motivation, basic ideas, fundamental problems of Load-Unload Response Ratio (LURR) and elucidates the earthquake prediction status using LURR. Especially the new progress of LURR, including the evolution law of LURR before strong earthquake and the application of dimensional methods has been described in detail. The results of four methods (experiment, numerical simulation, analytical and the real seismic data) come to a consistent conclusion that at the early stage of seismic period LURR fluctuates around 1, then it rises swiftly and to its peak point (abbreviated to PP). The catastrophic events do not happen at the time of peak point, but lag behind the PP. The evolution law of LURR has great importance to actual earthquake prediction, since we can predict the occurrence time quantitatively (by scale of months) if we can make sure of the time of the PP. Above all, the variation of LURR could depict clearly the seismogenic process, offering more clear ideas and methods to earthquake prediction.

Keywords: Earthquake prediction, LURR, Evolution law of LURR, Peak point of LURR, Dimensional analysis

6.1 Introduction

Strong earthquakes are terrible natural disasters, which usually cause huge casualty and property loss (e.g., more than 200,000 people were killed in Haiti earthquake in 2010 and more than 80,000 people were killed in Wenchuan earthquake in 2008). For this reason, earthquake is regarded as principal one among all natural disasters.

Earthquake is also one of the most complicated natural phenomena. Many aspects of earthquake remain enigmas. But from the viewpoint of mechanics, the physical essence of earthquake is quite clear that is just an abrupt shear rupture in seismic source region accompanied with sudden release of strain energy in it. Consequently, the seismogenic process should be a damage process of the focal media leading to the abrupt shear rupture. In other words, the seismogenic process is one of damage evolutions which finally results in the occurrence of earthquake, so it is mainly a mechanical process, being quite different from that in engineering mechanics.

In the so-called engineering mechanics, the typical problem is to solve the governing equations under appropriate boundary and initial conditions, using analytical, numerical or experimental methods.

For any branch of solid mechanics, the governing equations consist of the equations of motion, the geometric equations and constitutive laws. The equations of motion and the geometric equations are the same for different branches below.

The equations of motion:

$$\begin{aligned}
\rho\frac{\partial^2 u}{\partial t^2} &= \frac{\partial\sigma_x}{\partial x}+\frac{\partial\sigma_{xy}}{\partial y}+\frac{\partial\sigma_{xz}}{\partial z}+X,\\
\rho\frac{\partial^2 v}{\partial t^2} &= \frac{\partial\sigma_{xy}}{\partial x}+\frac{\partial\sigma_{y}}{\partial y}+\frac{\partial\sigma_{yz}}{\partial z}+Y,\\
\rho\frac{\partial^2 w}{\partial t^2} &= \frac{\partial\sigma_{xz}}{\partial x}+\frac{\partial\sigma_{yz}}{\partial y}+\frac{\partial\sigma_{z}}{\partial z}+Z.
\end{aligned} \tag{6.1}$$

The geometric equations (or continuous equations):

$$\begin{aligned}
\varepsilon_x &= \frac{\partial u}{\partial x},\\
\varepsilon_y &= \frac{\partial v}{\partial y},\\
\varepsilon_z &= \frac{\partial w}{\partial z};\\
\varepsilon_{xy} &= \frac{\partial v}{\partial x}+\frac{\partial u}{\partial y},\\
\varepsilon_{yz} &= \frac{\partial w}{\partial y}+\frac{\partial v}{\partial z},\\
\varepsilon_{zx} &= \frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}.
\end{aligned} \tag{6.2}$$

The constitutive laws are different for different materials. It is well known for elastic, elastic-plastic or rheological media, but for the media at the depth of seismic focus, its behavior is not very clear at present. Therefore, concerning the problems related to seismogenic process, the governing equations (e.g. the constitutive relations and damage evolution law of the focal media) and the boundary and initial conditions are difficult to know precisely. Nowadays it is just able to obtain the variations of some physical parameters, such as deformation of crust, and seismicity in terms of field measurements. The problem confronting us now is how to extract the information of damage for the focus media from the measured variations of some geophysical parameters and to predict/forecast the forthcoming earthquake in terms of these measurements.

From the microscopic viewpoint, the damage process for geo-material (rock, or rock-like) has incredible richness in complexity (Meakin, 1991; Bai et al., 1994; Krajcinnovic, 1996; Wei et al., 2000; Xia et al., 2002). In any rock block there must be a large number of disordered defects (cracks, fissures, joints, faults, caves, etc.) with different sizes, shapes and orientations. The damage process involves the nucleation and extension of micro-damages, coalescence between micro-damages and the formation of a main crack that leads to the eventual fracture. It is an irreversible, far-from-equilibrium, nonlinear, multi-scale and multi-physics one, which has been intensively studied for decades, but many fundamental prolems are still open.

From the macroscopic viewpoint, the constitutive relation (stress-strain curve) is a comprehensive description of the mechanical behavior of any materials. A typical stress-strain curve for focal media (rock) is shown in Figure 6.1. For being more universal, in Figure 6.1 the ordinate denotes general load P instead of stress σ and the abscissa is the general response R to load P instead of strain $\boldsymbol{\varepsilon}$. If the load acting on the material increases monotonously, the material will experience the regimes of elastic, damage and failure or destabilization. The most essential characteristic of the elastic regime is its reversibility; i.e., the positive process and the contrary process are reversible. In other words, the loading modulus and the unloading one are equal to each other. Contrary to the elastic regime, the damage one is irreversible, hence the loading response is different from the unloading one, or the loading modulus is different from the unloading one. This difference indicates the deterioration of material due to damage.

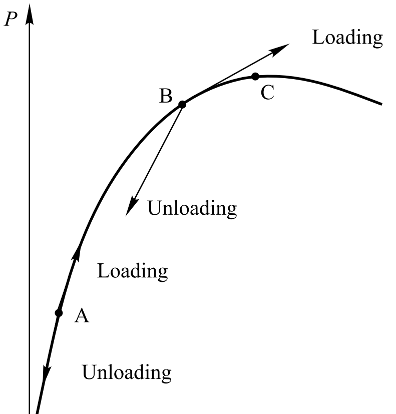


Fig. 6.1 The constitutive relation (stress-strain curve) of geo-material (rock).

In order to measure quantitatively the difference, two parameters are defined bellow. The first one is the response rate X defined as

$$X = \lim_{\Delta P \to 0} \frac{\Delta R}{\Delta P}, \tag{6.3}$$

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

The second one is the Load/Unload Response Ratio (LURR) Y,

$$Y = \frac{X_+}{X_-}, \tag{6.4}$$

where X_+ and X_- refer to response rate under loading and unloading respectively.

It is obvious that LURR should be unity ($Y = 1$) for the elastic regime due to $X_+ = X_-$ and $Y > 1$ for the damage regime due to $X_+ > X_-$. The more severely the material damages, the higher the Y value will be. Therefore, the Yvalue (LURR) could measure quantitatively the damage degree or degree in proximity to failure of media and also could act as a precursor for earthquake prediction/forecasting.

In order to calculate LURR, we have to select specific geophysical parameter as the response. The straightest one is the rigidity or compliance of the examined crust block, but it is very difficult to measure it now. Many scientists have studied the rigidity of a block which contains cracks. According to Oda (1983), this problem could be solved by the fabric tensor, but calculating the fabric tensor of a crust block needs the full information of all the cracks in it, e.g. the shape, size, orientation and status (open or closure) for all cracks (faults). It is almost impossible to get all information of all faults in any rock block in the earth at present so that we have to find another way to clear away such obstacles. It is known that a crack or seismic fault with size a corresponds to an earthquake with specified magnitude and energy release (Kanamori and Anderson, 1975). Therefore, it would be better to define the Y value directly by the released seismic energy in seismology or AE energy in laboratory as follows（Yin et al., 2000; Zhang et al., 2006):

$$Y = \frac{\left(\sum\limits_{i=1}^{N^+} E_i^m\right)_+}{\left(\sum\limits_{i=1}^{N^-} E_i^m\right)_-}, \tag{6.5}$$

where E denotes the radiated seismic energy which can be calculated from magnitude M according to the Gutenberg-Richter formula (Kanamori and Anderson, 1975), the sign "+" means loading and "–" unloading and the parameter m could be selected as $0, 1/3, 1/2, 2/3$ or 1. When $\mathrm{m} = 1, E^m$ is exactly the energy itself; $m = 1/2, E^m$ denotes the Benioff strain; $m = 1/3, 2/3, E^m$ represents the linear scale and area scale of the focal zone respectively; $m = 0, Y$ is equal to N^+/N^-, where N^+ and N^- denote the number of earthquakes occurring during the loading and unloading duration respectively. We adopt $m = 1/2$ in this chapter and it is the most of our works.

In order to predict earthquakes in terms of LURR, another problem should be solved. That is how to load and unload the crustal block with size of hundreds or even thousands of kilometers. One of the measures is the earth tide. Tidal forces exerted by the moon and sun produce continuously varying stresses in the earth's crust. How to calculate the tide-induced stress in the crust has been elucidated in earlier LURR researches (Yin, 1987; Yin and Yin, 1991; Yin, 1993; Yin et al., 1994a,b; Maruyama, 1995; Yin et al., 1995; 2000).

According to the results of rock mechanics (Jaeger and Cook, 1979), the Coulomb criterion was used to judge loading and unloading.

6.2 The Status of Earthquake Prediction Using LURR

After the proposal of the LURR idea and solving some basic problems such as the measurements of loading and unloading the crust block and calculation LURR, the first task for us is to retrospect inspections of historical earthquake cases. The retrospective inspections of hundreds of earthquake cases have been conducted (Yin et al., 1995; Yin et al., 2000). The results from these cases validated the LURR method. For more than 80% examined cases, the Y value appears high value (significantly larger than 1) before the forthcoming strong earthquakes.

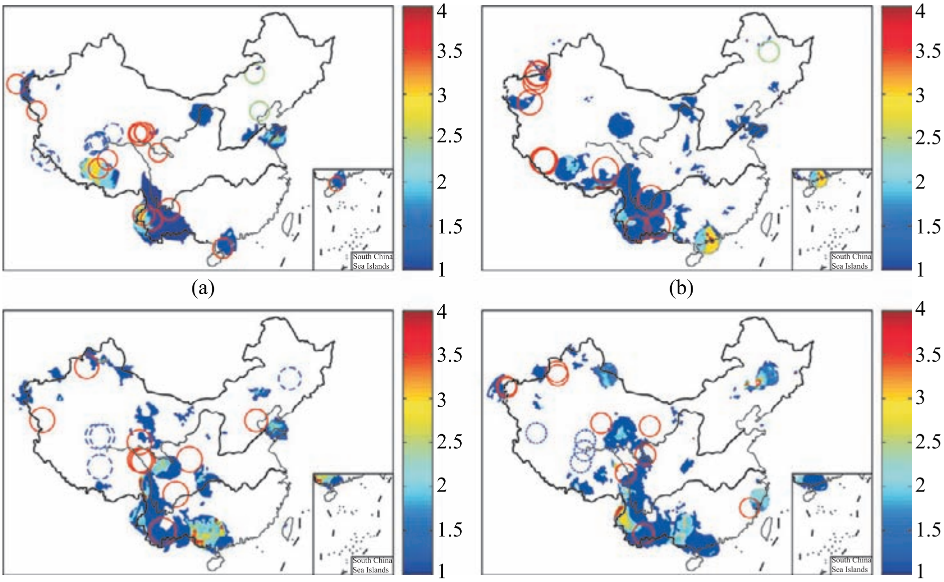
Although the case inspections are satisfactory and the laboratory modeling (Shi et al., 1994; Yin et al., 2004a; Yin *et al.,* 2004b; Zhang et al., 2006) and numerical simulation (More et al., 2002; Wang et al., 2004) also proved its validity, LURR theory has to be tested ultimately in real earthquake prediction practice. We have applied LURR to real earthquake prediction practice since 1993. At the early stage, some cases of our prediction were successful and the others failed (Yin et al., 2000). It is exhilarating that the prediction results using LURR have been getting better and better. In 2004–2007, 95% earthquakes with magnitude $M \geqslant 5$ in the mainland of China occurred in the predicted area (Institute of Earthquake Science, China Earthquake Administration, 2008) in terms of LURR except for earthquakes in those areas where data were scarce so that LURR could not be calculated, which are shown in Table 6.1.

It could be concluded from Table 6.1 that from 2004 to 2007, the annual prediction using LURR is pretty good. This result was confirmed by the Institute of Earthquake Science, China Earthquake Administration (Institute of Earthquake Science, China Earthquake Administration, 2008).

Table 6.1 The count of earthquakes with $M_L \geqslant 5$ occurring in the mainland of China in every year from 2004 to 2007 respectively and the count of earthquakes with $M_L \geqslant 5$ occurring in the predicted area of LURR in the same period. Statistics does not include figures for earthquakes occurring in data scarcity regions where the data are unavailable to calculate LURR

Years	Earthquakes with $M_L \geqslant 5$ in every year	Earthquakes with $M_L \geqslant 5$ in the anomaly area of LUR R	Percentage
2004	17	15	88%
2005	13	12	92%
2006	9	9	100%
2007	12	12	100%

Figure 6.2 shows the maps of the LURR anomaly regions in the mainland of China calculated in the ends of 2003, 2004, 2005 and 2006, and also the epicenters distribution of earthquakes with magnitude $M_L \geqslant 5$ occurring in the following years (2004, 2005, 2006 and 2007).



(a) (b)

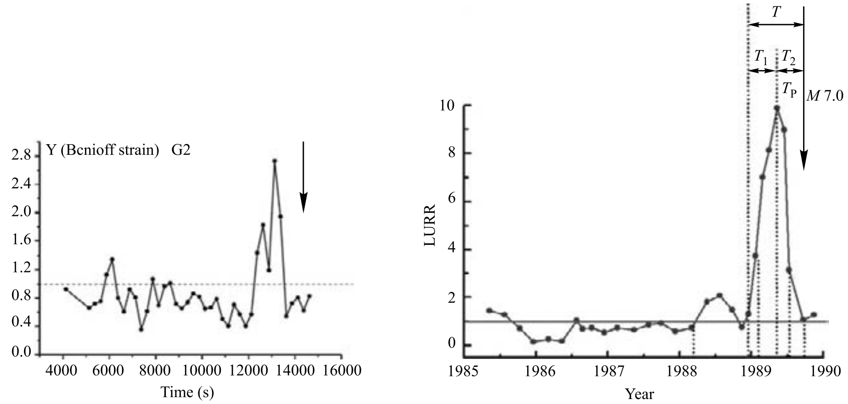
(c) (d)

Fig. 6.2 The LURR anomaly regions in the mainland of China at the ends of 2003(a), 2004(b), 2005(c)and 2006(d) and strong earthquakes ($M \geqslant 5$) occurring in the mainland of China in 2004(a), 2005(b), 2006(c) and 2007(d) respectively. The solid line circles denote earthquakes ($M \geqslant 5$) in regions where the data is available to calculate LURR and dash line circles denote earthquakes ($M \geqslant 5$) in data scarcity regions where the data are unavailable to calculate LURR. Among the solid line circles, the earthquakes occurring in the predicted area of LURR are denoted by red thick circles and the earthquakes occurring in the unpredicted area of LURR are denoted by fine green circles.

6.3 Peak Point of the LURR and Its Significance

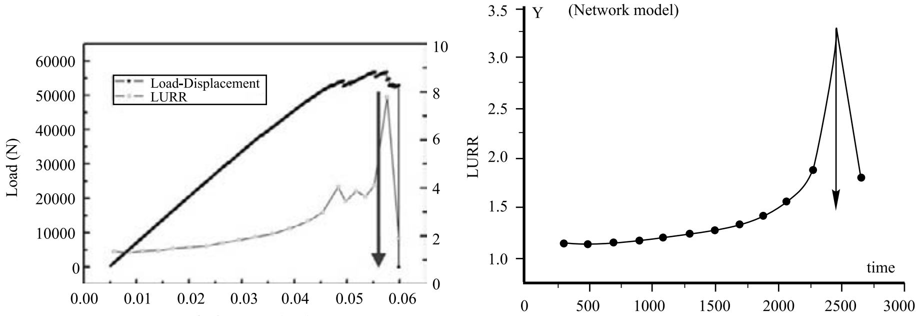
In recent years, we figured out the evolution laws of LURR before strong earthquakes by a lot of means. The a, b, c, d of Figure 6.3 mean respectively: (a) evolution of LURR vs. time in an acoustic emission experiment for rock sample; (b) evolution of LURR before the October 17, 1989 Loma Prieta Earthquake from actual earthquake data; (c) damage evolution of non-uniform brittle medium simulated by network model and evolution of LURR with time (Liang et al., 1998; Zhang, 2009); (d) the damage evolution of non-uniform brittle medium simulated with Lyakhovsky's model and analytic result of LURR (Lyakhovsky et al., 1997, 2001; Zhang, 2009). The arrows indicate catastrophic events (earthquakes or catastrophic failure of specimen). The results of the four methods come to a consistent conclusion that at the early stage of seismogenic regime, LURR fluctuates around 1, then it rises swiftly and reaches to its PP. The catastrophic events do not happen at the peak point, but the catastrophic events lag behind the PP. The lagged time is denoted by T_2, the time from the beginning of LURR anomaly to the PP is denoted by T_1 and the total abnormal time of LURR is called T,

$$T = T_1 + T_2. \tag{6.6}$$



(a) LURR curve of experiment of rock

(b) Loma Prieta Earthquake (*Ms* 7.0) in California on 1989.10.17



(c) LURR curve of numerical simulation

(d) LURR curve using damage mechanics (Lyakhovsky's model)

Fig. 6.3 The evolution of LURR before strong earthquake or catastrophic rupture in experiment.

According to research (Zhang , 2006),

$$T = 80(1 - 2.5 \times 10^{-0.09M}), \tag{6.7}$$

$$T_2 = 60(1 - 2.3 \times 10^{-0.08M}), \tag{6.8}$$

where M denotes the earthquake magnitude and T scales with month. It is indicated from Table 6.2 that T_2 is quite a long period, e.g. T_2 is about 14 months for an earthquake with magnitude 6 and T_2 is even more than 2 years for an earthquake with magnitude 7.

The above results have great importance to actual earthquake prediction, since we can predict the occurrence time quantitatively (by scale of months) if we can make sure of the time of the PP. Above all, the variation of LURR could depict clearly the seismogenic course, offering more clear methods and approach to earthquake prediction.

However, it also brings about some complexity. To predict the future earthquake, we should not only consider the value of LURR at one time window, but also study the spatio-temporal evolution of LURR systematically. Take the point T_{f2} in Figure 6.2b as an example, even though the value of LURR is much higher than 1, there is still a relatively long time to the future earthquake, since it is before the peak point, but at point T_{b2} LURR is smaller than T_{f2} (sometimes it is even smaller than 1, which means LURR has returned to "normal"). Actually it is right at the future earthquake because it has passed the PP. So, in order to predict earthquake reliably, we have to trace the variation of LURR, especially discover the emergence of the PP. Then according to formula 6.2, we can calculate T_2 for different magnitude of earthquakes, which are shown in Table 6.2. This Table tells that T_2 is a quite long time for large earthquakes. For example, T_2 could be 36 months (28 ± 8) for earthquakes of magnitude $M8$. It means the earthquake does not happen at the PP (where LURR reaches the highest value), then LURR decreases (sometimes even smaller than 1), and the earthquake happens several years later. This was exactly the case of 2008 Wenchuan Earthquake, although we had discovered anomaly of this area for a long time, but we did not make the short-time prediction successfully due to the misunderstanding that after the elapse of time for 2 years from the PP we thought the anomaly of LURR in that region might be false.

Table 6.2 T, T_1 and T_2 of different magnitudes of earthquakes

Magnitude	T(month)	T_1(month)	T_2(month)
5	9	4	5 ± 2
6	22	8	14 ± 4
7	33	11	22 ± 6
8	42	14	28 ± 8
9	49	15	34 ± 10?

6.4 Earthquake Cases in 2008–2009

Predicted T_2 which is calculated by formula 6.8 (noted by $T_{2\mathrm{p}}$) and actual T_2 (noted by $T_{2\mathrm{a}}$) for the earthquake cases in 2008 and 2009 occurring in the mainland of China are listed in Table 6.3 and Table 6.4.

At the same time, the differentials $\Delta T_2 = T_{2p} - T_{2a}$ are also listed in Tables 6.3 and 6.4. When ΔT_2 is positive, it means T_{2p} is larger than $T_{2\mathrm{a}}$, namely, the actual earthquake is earlier than predicted one and vice versa. From Table 6.3 we can see the biggest ΔT_2 occurred in Yutian and Wuqia earthquakes, both of which occurred in Xinjiang. In Table 6.4, the maximum ΔT_2 happens in the Atushi earthquake, in Xinjiang. So we recognized that T_2 depends on not only the earthquake magnitude but something else (e.g. geological regimes) needed to be involved. Except for these three earthquakes, the differentials ΔT_2 are very small, which means the prediction is pretty good. On the other hand, the differentials ΔT_2 of the 13 earthquakes in 2008–2009 are all positive except the earthquake in Haixi in Qinghai, which means there existed systematic errors in our prediction and which could be reduced or eliminated.

Table 6.3 The contrast between $T_{2\mathrm{p}}$ (the predicted T_2) and $T_{2\mathrm{a}}$ (the actual T_2) for earthquakes occurring in the mainland of China in 2008

Location	Time	Place	Magnitude(M)	$T_{2\mathrm{a}}$(month)	$T_{2\mathrm{p}}$(month)	ΔT_2(month)
Gaize	2008-01-09	32.5°N, 85.2°E	6.9		Scarce data	
Yutian	2008-03-21	35.6°N, 81.6°E	7.3	8	24	16
Wenchuan	2008-05-12	30.95°N, 100°E	8.0	26	24	−2
Zhongba	2008-08-25	31.0°N, 83.6°E	6.8		Scarce data	
Panzhihua	2008-08-30	26.2°N, 101.9°E	6.1	14	15	1
Wuqia	2008-10-05	39.5°N, 73.9°E	6.8	13	20	**7**
Dangxiong	2008-10-06	29.8°N, 90.3°E	6.6	18	19	1
Haixi	2008-11-10	37.6°N, 95.9°E	6.3	19	17	−2

Annotation: $T_{2\mathrm{a}}$ (month)—actual T_2 **;** $T_{2\mathrm{p}}$(month)—predicted T_2;
ΔT_2 (month) $= T_{2\mathrm{p}} - T_{2\mathrm{a}}$; The special window (radius) is 200 km.

Table 6.4 The contrast between $T_{2\mathrm{p}}$ (the predicted T_2) and $T_{2\mathrm{a}}$ (the actual T_2) for earthquakes occurring in Chinese mainland in 2009

Earthquakes	Internet	Catalog	Epicenter	Occurrence Time	Peak Point	$T_{2\mathrm{a}}$	$T_{2\mathrm{p}}$	ΔT_2
Chabuchaerxibo	5	5.4	43.3°N, 80.9°E	2009-1-25	2007-11-30	14	5	2
Keping	5.2	5.6	40.7°N, 78.7°E	2009-2-20	2007-10-31	16	7	2
Huichun	5.3	5.6	42.7°N, 130.7°E	2009-4-18				
Aheqi	5.5	5.8	41.3°N, 78.3°E	2009-4-19	2007-10-31	18	10	1
Atushi	5	5.4	40.1°N, 77.4°E	2009-4-22	2007-10-31	18	5	6
Yecheng	5.2	5.6	36.4°N, 77.6°E	2009-5-21	2008-3-31	14	7	0
Yaoan	6	6.3	25.6°N, 101.1°E	2009-7-9	2007-6-30	24	14	2
Nima	5.6	5.9	31.3°N, 86.1°E	2009-7-24				
Qinghai	6.4	6.6	37.6°N, 95.8°E	2009-8-28	2008-1-31	19	18	0

Annotation: $T_{2\mathrm{a}}$ (month)—actual T_2; $T_{2\mathrm{p}}$ (month)—predicted T_2;
ΔT_2 (month) $= T_{2\mathrm{p}} - T_{2\mathrm{a}}$; The special window (radius) is 200 km.

6.5 Improving the Prediction of Magnitude *M* and T_2-Application of Dimensional Method

Integrating with the dimensional method (Buckingham, 1914; Sedov, 1959), LURR could be a hopeful methodology of earthquake prediction. An earthquake prediction should include three parts: prediction of the location, magnitude and occurrence time of the predicted earthquake.

6.5.1 Location

The location of the predicted earthquake should fall into the LURR anomaly region.

6.5.2 Magnitude

The equivalent physical parameter E_{s} of magnitude M is the radiated energy of an earthquake. They are related by Gutenberg formula ($\log E_{\mathrm{s}} = 4.8 + 1.5M_{\mathrm{s}}$). E_{s} could be involved with the following parameters: $J_{\mathrm{PP}}, E_{\mathrm{a}}, \gamma_{\mathrm{r}}$ and h.

(i) J is defined as

$$J(t)=\iint\limits_{Y\geqslant 1} Y dxdy = Y_{\mathrm{a}}\cdot A, \tag{6.9}$$

which is used to denote the LURR anomaly region weighted with Y (LURR) and represents the expanse and degree of the seismogenic zone (anomaly region of LURR) during a specific time window [from $(t-t_{\mathrm{w}})$ to t]. In formula 6.9, A is the area of LURR anomaly

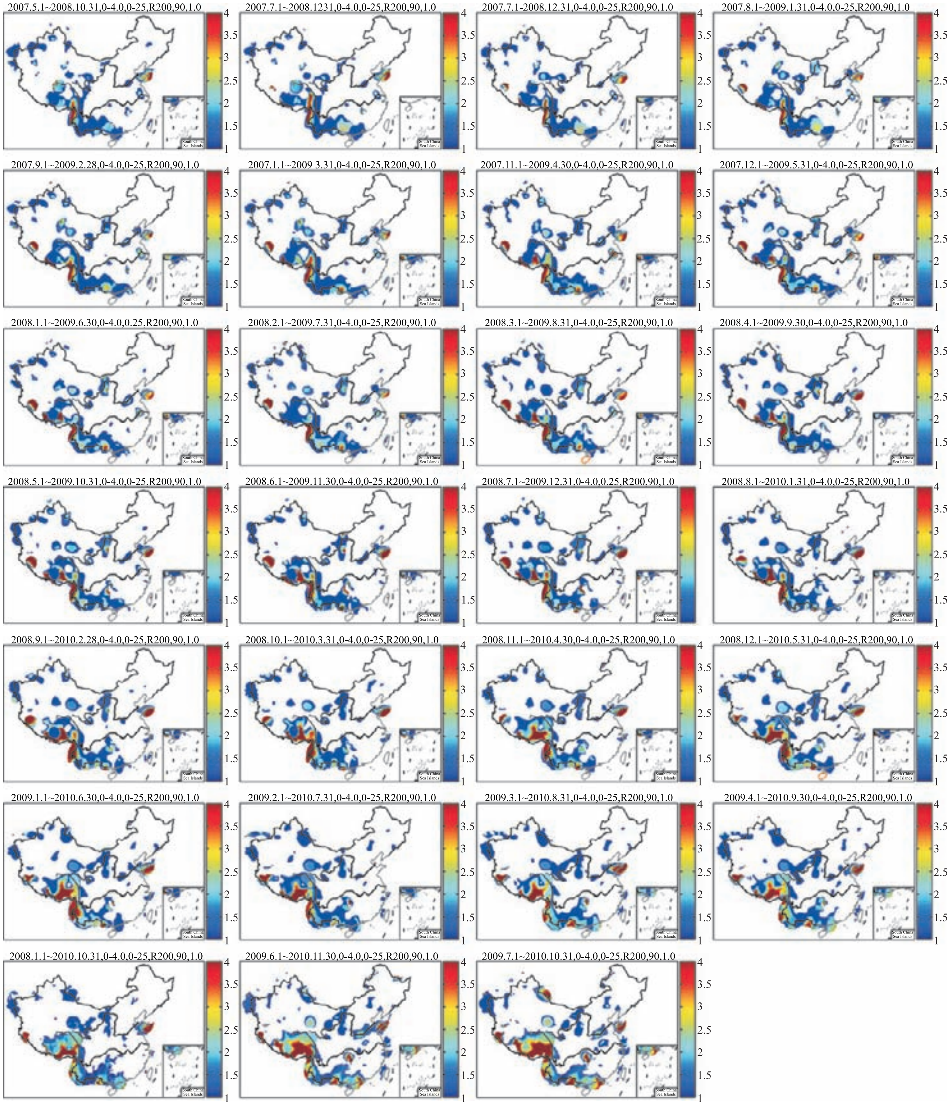


Fig. 6.4 The map of LURR scanning results in the mainland of China in recent years.

region and Y_a is the average value for the whole LURR anomaly region. J_{PP} means the value of J at peak point or the maximum of J. In order to get the value of J_{PP}, the spacial scans of LURR in the mainland of China should be conducted for a serious time window at first (Figure 6.4) and then calculated $J(t)$ according to expression 6.9. As an example, Figure 6.5 shows us the curve of $J(t)$ *for* Kaifeng-Heze region at the border between Henan Province and Shandong Province in China.

(ii) E_a is the sum of radiated energy of all earthquakes occurred in a specific region per year and per area measured during a long time duration. The radiated energy of an earthquake e_r is just a portion of the whole consumed energy of the earthquake e_t. In this context, $e_r = \eta e_t$ *and* η is named efficiency of earthquake in some books. Undoubtedly, η is less than unit and assumed roughly as constant. If the duration is long enough, we can consider that the cumulated deformation energy and the consumed energy should be balanced against each other. In this chapter we use the catalog from 1900 to 2009. That means the duration is 110 years. The distribution of E_a in the mainland of China is shown in Figure 6.6.

(iii) γ_r is the shear strain rate *in situ*. The distribution of γ_r in the mainland of China can be obtained from the measured results of GPS (Shen et al., 2003; Gu et al., 2001; Li, 2004).

(iv) The thickness of the seismogenic body is denoted with h and the volume of the seismogenic body is $A \cdot h$. According to the dimensional formula

$$[E_s] = [E_a]^{\alpha 1} \cdot [J_{PP}]^{\alpha 2} \cdot [h]^{\alpha 3} \cdot [\gamma_r]^{\alpha 4}. \tag{6.10}$$

In which the square brackets [ ] mean dimension, it is obtained that

$$E_s \propto E_a \cdot J_{PP}^{2/3} \cdot h^{2/3}/\gamma_r = E_a \cdot Y_a^{2/3} \cdot A_{PP}^{2/3} \cdot h^{2/3}/\gamma_r .$$

We introduce a nondimensional quantity β,

$$\beta = h/A^{1/2}.$$

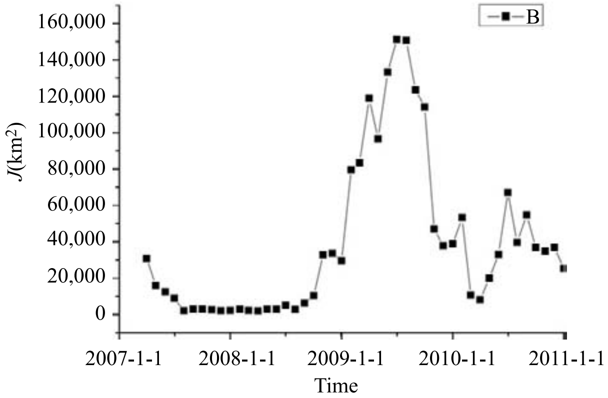


Fig. 6.5 The curve of $J(t)$ *for* Kaifeng-Heze region at the border between Henan Province and Shandong Province in east China.

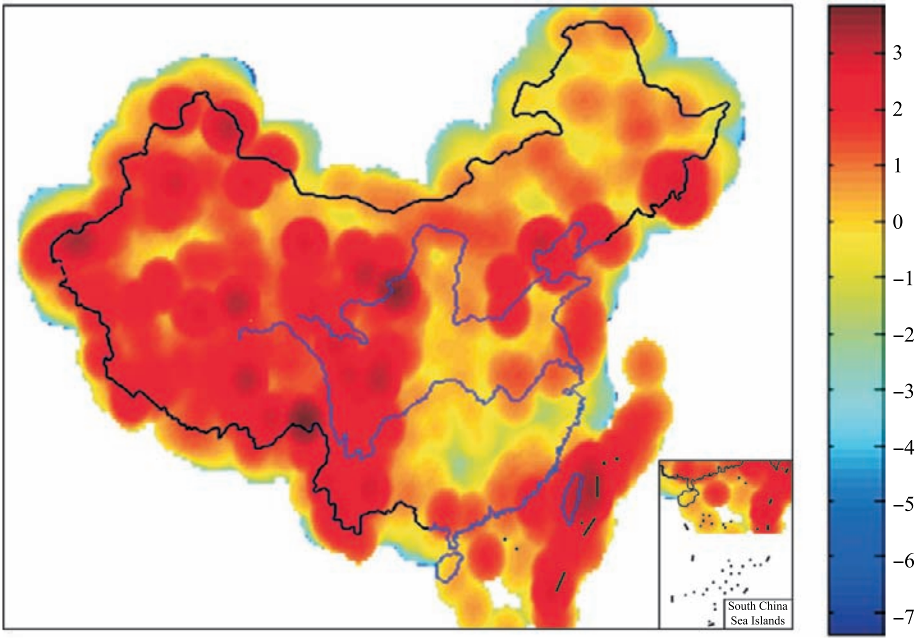


Fig. 6.6 The distribution of E_a in the mainland of China. The color scale indicates the equivalent magnitude for E_a

Then $E_s \propto E_a/\gamma_r \cdot J_{PP}^{2/3} \cdot (\beta \cdot A^{1/2})^{2/3} = \beta^{2/3} \cdot E_a \cdot J_{PP}/\gamma_r$, and $E_s \cdot \gamma_r/E_a \cdot J_{PP} \propto \beta^{2/3}$ $E_s \cdot \gamma_r/(E_a \cdot J_{PP})$ is a nondimensional quantity. According to the tradition of dimensional analysis, it is denoted with π_1.

$$\pi_1 = E_s \cdot \gamma_r/(E_a \cdot J_{PP}), \tag{6.11}$$

and $\pi_1 \propto \beta^{2/3}$. Obviously β is related to magnitude M, So that,

$$\pi_1 = f_1(M) \tag{6.12}$$

Furthermore, we rewrite $\pi_1 = E_s \cdot \gamma_r/(E_a \cdot J_{PP}) = E_s/E_d$, here

$$E_d = E_a \cdot J_{PP}/\gamma_r \tag{6.13}$$

Fitting the data of about 50 earthquake cases in the mainland of China (Figure 6.7), it is obtained that

$$\pi_1 = 1\mathrm{E} - 17\mathrm{e}^{3.006Ms} \quad (R^2 = 0.96), \tag{6.14}$$

and then

$$M_s = 5.14\lg E_d - 112.08. \tag{6.15}$$

The magnitude of the predicted future earthquake can be calculated from fomula (6.15) as long as we get the value of E_d.

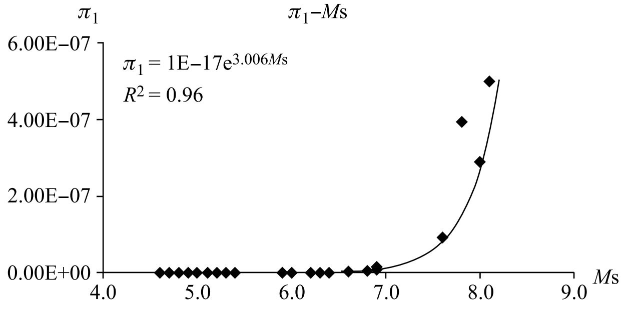


Fig. 6.7 The curve of π_1 *vs*. magnitude M.

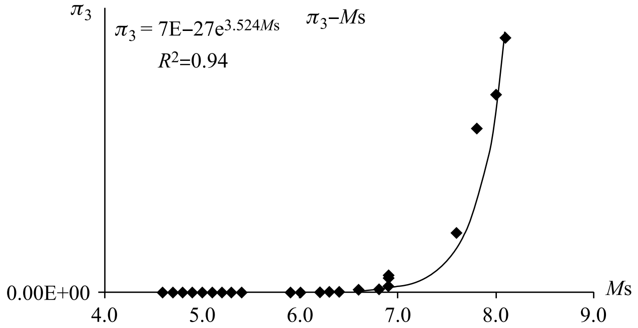


Fig. 6.8 The curve of π_2/π_1 *vs*. magnitude M.

6.5.3 Occurrence time (T_2)

Obviously, T_2 times γ_r is also a non-dimensional quantity, which denoted as π_2

$$\pi_2 = T_2 \cdot \gamma_r. \tag{6.16}$$

Of course,

$$\pi_1 \cdot \pi_2 = \pi_3, \tag{6.17}$$

π_3 is another non-dimensional quantity. Fitting the same data of Figure 6.7, it is obtained that

$$\pi_3 = 7E - 27e^{3.524Ms} \quad (R^2 = 0.94), \tag{6.18}$$

and then

$$T_2 = 8.5E_d \cdot 10^{0.03M} \cdot 10^{-30.8}/\gamma_r \cdot \pi_1. \tag{6.19}$$

The unit of T_2 is day and the unit of γ_r is 10^{-9} rad/yr (Figure 6.8).

As examples of this methodology, the magnitude of the forthcoming earthquake in Kaifeng-Heze region will be probably $M5.7$ and with regard to the expansive south-western region (including Tibet, Qinghai and Yunnan) the magnitude of the future earthquake even will be above $M8$.

6.6 Conclusions

Since the proposal of LURR, more than 2 decades have elapsed (Yin et al., 2006). A lot of achievements have been made on LURR in such a long period, but there still exist many problems and also enough improving room, e.g. evolution law of LURR after PP which may be related to its application to short-term earthquake prediction.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (Grant No. 11021262, 19732060 and 40004002) and Informalization Construction Project of Chinese Academy of Sciences during the 11th Five-Year Plan Period (No.INFO-115-B01). The earthquake catalog used in this chapter is provided by CENC (China Earthquake Networks Center), China Earthquake Administration. The calculation in the chapter was conducted partly in Supercomputing Center of Computer Network information Center, Chinese Academy of Sciences.

References

Bai Y.L., Lu C.S., Ke F.J. et al. 1994, Evolution induced catastrophe, Physics Letters A, 185, 196-201.

Buckingham E. 1914, On physically similar systems: illustrations of the use of dimensional analysis, Physical Review, 4, 345-376.

Gu G.H., Shen X.H., Wang M., Zheng G.M., Fang Y., Li P. 2001, General characteristics of the recent horizontal crustal movement in Chinese mainland, Acta Seismologica Sinica, 23 (4): 362-369.

Institute of Earthquake Science, China Earthquake Administration. 2008, The researches on prediction of the strong earthquake tendency for Chinese mainland in 2009, in The Research on Prediction of the Strong Earthquake Tendency in Chinese Mainland for 2009, Seismological Press, Beijing (in Chinese).

Jaeger J.C., Cook N.G.W. 1979, Fundamentals of Rock Mechanics, Chapman and Hall, London

Kanamori H., Anderson D.L. 1975, Theoretical basis of some empirical relation in seismology, Bull. Seism. Soc. Am., 65, 1073-1096.

Krajcinnovic D. 1996, Damage Mechanics, Elsevier, Amsterdam.

Li Y.X., Li Z., Zhang J.H. et al. 2004, Horizontal strain field in the Chinese mainland and its surrounding areas, Chinese Journal of Geophysics, 47 (2): 222-231 (in Chinese).

Liang N.G., Liu H.Q., Wang T.C. 1998, A meso elastoplastic constitutive model for polycrystalline metals based on equivalent slip systems with latent hardening, Science in China, Ser. A 41, 887-896.

Lyakhovsky V., Ben-Zion Y., Agnon A. 1997, Distributed damage faulting and friction, Journal of Geophysical Research, 102, 27635-27649.

Lyakhovsky V., Ben-Zion Y., Agnon A. 2001, Earthquake cycle, fault zones, and seismicity patterns in a rheologically layered lithosphere, Journal of Geophysical Research, 106, 4103-4120.

Maruyama T. 1995, Earthquake prediction in China, *Zisin*, 19, 69-75 (in Japanese).

Meakin P. 1991, Model for material failure and deformation, Science, 252, 226-234.

Mora P., Wang Y., Yin C., Place D., Yin X.C. 2002, Simulation of load-unload response ratio and critical sensitivity in the Lattice Solid Model, Pure and Applied Geophysics, 159, 2525-2536.

Oda M. 1983, A method for evaluating the effect of crack geometry on the mechanical behavior of cracked rock mass, Mech Mater, 2, 163-171.

Sedov L.I. 1959, Similarity and Dimensional Methods in Mechanics, Infosearch Ltd., London.

Shen Z.K., Wang M., Gan W.J., Zhang Z.S. 2003, Contemporary tectonic strain rate field of Chinese Continent and its geodynamic implications, Earth Science Frontiers, Vol.10 suppl., 93-100.

Shi X.J., Xu H.M., Wan Y.Z., Lu Z.G., Chen X.Z. 1994, The characteristic of rock fracture under simulated tide force: laboratory study on the theory of loading and unloading response ratio, Chinese Journal of Geophysics, 37, 437-442.

Wang Y., Mora P., Yin C., Place D. 2004, Statistic tests of load-unload response ratio signals by lattice solid model: implication to tidal triggering and earthquake prediction, Pure and Applied Geophysics, 161, 1829-1839.

Wei Y.J., Xia M.F., Ke F.J., Yin X.C., Bai Y.L. 2000, Evolution induced catastrophe and its predictability, Pure and Applied Geophysics, 157, 1929-1943.

Xia M.F., Wei Y.J., Ke J.F., Bai Y.L. 2002, Critical sensitivity and trans-scale fluctuations in catastrophic rupture, Pure and Applied Geophysics, 159, 2491-2509.

Yin X.C. 1987, A new approach to earthquake prediction, Earthquake Research in China, 3, 1-7 (in Chinese with English abstract).

Yin X.C. 1993, A new approach to earthquake prediction, Russia's "Nature", 1, 21-27 (in Russian).

Yin X.C., Chen X.Z., Song Z.P., Yin C. 1994b, The load-unload response ratio theory and its application to earthquake prediction, Journal of Earthquake Prediction Research, 3, 325-333.

Yin X.C., Chen X.Z., Song Z.P., Yin C. 1995, A new approach to earthquake prediction: the load/unload response ratio (LURR) theory, Pure and Applied Geophysics, 145, 701-715.

Yin X.C., WANG Y.C., Peng K.Y., Bai Y.L., Wang H.T., Yin X.F. 2000, Development of a new approach to earthquake prediction—load/unload response ratio (LURR) theory, Pure and Applied Geophysics, 157, 2365-2383.

Yin X.C., Yin C. 1991, The precursor of instability for nonlinear system and its application to earthquake prediction, Science in China, 34, 977-986.

Yin X.C., Yin C., Chen X.Z. 1994a, The precursor of instability for nonlinear system and its application to earthquake prediction—the load-unload response ratio theory, in Non-linear Dynamics and Predictability of Geophysical Phenomena (eds. Newman

W.I., Gabrelov A., Turcotte D.L.), Geophysical Monograph 83, Iugg Volume 18, 55-60.

Yin X.C., Yu H.Z., Kukshenko V., Xu Z.Y., Wu Z.S., Li M., Peng K.Y., Elizarov S., Li Q. 2004, Load-unload response ratio (LURR), accelerating energy release (AER) and state vector evolution as precursors to failure of rock specimens, Pure and Applied Geophysics, 161 (11-12): 2405-2416.

Yin X.C., Zhang H.H., Yu H.Z., Zhang Y.X., Peng K.Y. 2004, Prediction of seismic tendency of Chinese mainland in 2004 in terms of LURR, in The research on seismic tendency of China in 2005, 282-285 (edited by Center for Analysis and Prediction, CSB), Seismological Press, Beijing (in Chinese).

Yin X.C., Zhang L.P., Zhang, H.H., YIN C., Wang Y.C., Zhang Y.X., Peng K. Y., Wang, H.T., Song Z.P., Yu H.Z., Zhuang J.C. 2006, LURR's Twenty Years ans Its Perspective. Pure and Applied Geophysics 163(11-12), 2317-2341.

Zhang H.H., Yin X.C., Liang N.G., Yu H.Z., Li S.Y., Wang Y.C., Yin C., Kukshenko V., Tomiline N., Elizarovs S. 2006, Acoustic emission experiments of rock failure under load simulating the hypocenter condition, Pure and Applied Geophysics, 163 (11-12), 2389-2406.

Zhang L.P. 2009, Study on damage evolution of heterogeneous brittle media in seismogenic conditions and earthquake prediction, PhD Thesis of The Graduate University of the Chinese Academy of Sciences (in Chinese).

Author Information

Xiang-chu Yin

Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China.

State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy Sciences, Beijing 100190, China.

Institute of Geophysics, China Earthquake Administration, Beijing 100081, China.

E-mail: xcyin@public.bta.net.cn

Yue Liu, Shuai Yuan

State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy Sciences, Beijing 100190, China.

Lang-ping Zhang

Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China.

State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy Sciences, Beijing 100190, China.