Repeating earthquakes recorded by Liaoning Regional Seismograph Network^{*}

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Abstract

In the list of 'repeating pairs' or 'doublets' of earthquakes in China identified by Schaff and Richards using teleseismic waveform cross-correlation, there were 23 repeating pairs located in Liaoning Province. In this study the waveforms of these events were cross-correlated using records from Liaoning Regional Seismograph Network (LRSN), and the 'repeating events' in the sense of regional waveform cross-correlation were obtained. The result was compared with that of Schaff and Richards and was used for the assessment of the seismic phase picking and event location practice of LRSN. The result shows that 'repeating events' in the sense of teleseismic waveform cross-correlation and those in the sense of regional waveform cross-correlation have significant difference, although with some overlap. However, the overall assessment of the location accuracy and the phase pick errors of LRSN by using these two sets of 'repeating events', respectively, provides similar results, while 'repeating events' in the sense of regional waveform cross-correlation seem to be better performing in such an assessment. With the assumption that the separation between the 'repeaters' be less than 1 km, the uncertainty in routine earthquake location of LRSN is estimated to be below 5 km, with the average of 2 km. In the observational bulletins of LRSN the time error in phase picking is estimated to be within ± 1 s for 94% Pg readings and for 88% Sg readings.

Key words: waveform cross-correlation; repeating earthquakes; regional seismograph network; Xiuyan of Liaoning Province

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Introduction

'Repeating earthquakes', a concept having been proposed since 40 years ago based on waveform cross-correlation and location calculation (Isacks *et al*, 1967; Geller and Mueller, 1980), caused much attention in recent years due to its potential in the assessment and improvement of location capabilities of seismograph networks (Rubin, 2002; Schaff and Waldhauser, 2005; JIANG and WU, 2005; Richards *et al*, 2006). Moreover, as a useful tool, 'repeating earthquake' approach has also been used in the study of earthquake recurrence and slip rates (Vidale *et al*, 1994; Nadeau *et al*, 1995; Wiens and Snider, 2001; Igarashi *et al*, 2003) as well as the temporal variation of structures (Poupinet *et al*, 1984; Nakamura *et al*, 2002; Niu *et al*, 2003; Snieder and Hagerty, 2004; Grêt and Snieder, 2005; Pandolfi *et al*, 2006; LIN *et al*, 2006). In the study of this field, one of the

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important findings is the generality of ‘repeating events’. An example is the work of Schaff and Richards (2004a) giving that up to 10% of the whole seismic events in China and its surrounding regions have the properties of ‘repeating’.

Table 1 Repeating earthquakes in Xiuyan, Liaoning, identified by Schaff and Richards (2004a) using teleseismic waveform cross-correlation

No.	Origin time (Beijing time)		$\varphi_N/^\circ$	$\lambda_E/^\circ$	M_L	Depth /km	Serial Number
	a-mo-d	h:min:s					
1	1999-11-09	07:01:40.6	40.50	123.00	0.0(4.1)	15	145600
	1999-11-25	20:55:04.2	40.30	123.00	0.0(4.4)	5	145817
2	1999-11-09	07:07:21.2	40.50	123.00	0.0(4.2)	15	145601
	1999-11-25	20:55:04.2	40.30	123.00	0.0(4.4)	5	145817
3	1999-11-25	20:47:48.5	40.30	123.00	0.0(4.0)	5	145816
	1999-11-26	23:34:01.0	40.50	123.00	0.0(4.4)	10	145846
4	1999-11-25	20:55:04.2	40.30	123.00	0.0(4.4)	5	145817
	1999-11-26	23:34:01.0	40.50	123.00	0.0(4.4)	10	145846
5	1999-11-09	07:07:21.2	40.50	123.00	0.0(4.2)	15	145601
	1999-11-26	23:34:01.0	40.50	123.00	0.0(4.4)	10	145846
6	1999-11-25	20:55:04.2	40.30	123.00	0.0(4.4)	5	145817
	1999-11-29	12:10:39.2	40.50	122.90	5.0(5.9)	5	145898
7	1999-11-25	20:47:48.5	40.30	123.00	0.0(4.0)	5	145816
	1999-11-29	12:45:50.4	41.00	122.60	4.3(5.1)	10	145901
8	1999-11-29	14:55:45.2	40.50	123.00	0.0(3.3)	10	145906
	1999-12-27	19:27:15.4	40.30	123.00	0.0(4.0)	5	146300
9	1999-11-29	14:55:45.2	40.50	123.00	0.0(3.3)	10	145906
	1999-12-27	23:48:36.8	40.30	123.00	0.0(3.7)	5	146303
10	1999-11-29	16:16:47.6	40.40	123.00	4.4(5.0)	10	145909
	1999-11-30	14:06:55.1	40.50	123.00	0.0(4.9)	10	145928
11	1999-11-29	15:12:39.7	40.50	123.00	0.0(3.6)	10	145907
	1999-12-03	17:57:54.1	40.60	122.70	0.0(3.7)	15	145975
12	2000-01-12	13:00:31.9	40.60	122.70	0.0(4.5)	15	100135
	1999-11-29	16:16:47.6	40.40	123.00	4.4(5.0)	10	145909
13	1999-11-30	10:08:06.0	40.50	123.00	0.0(3.5)	10	145924
	1999-12-03	17:57:54.1	40.60	122.70	0.0(3.7)	15	145975
14	2000-01-12	13:00:31.9	40.60	122.70	0.0(4.5)	15	100135
	1999-11-30	14:06:55.1	40.50	123.00	0.0(4.9)	10	145928
15	1999-11-30	21:07:04.7	40.50	123.00	0.0(3.7)	10	145938
	1999-12-02	23:16:21.0	40.60	122.70	0.0(3.6)	15	145964
16	1999-12-01	04:33:00.5	40.50	123.00	0.0(4.3)	10	145943
	1999-12-27	19:27:15.4	40.30	123.00	0.0(4.0)	5	146300
17	1999-12-01	04:33:00.5	40.50	123.00	0.0(4.3)	10	145943
	1999-12-27	23:48:36.8	40.30	123.00	0.0(3.7)	5	146303
18	1999-11-30	14:06:55.1	40.50	123.00	0.0(4.9)	10	145928
	1999-12-01	12:45:30.8	40.60	122.70	0.0(4.3)	10	145947
19	2000-03-19	23:41:56.2	40.30	123.00	0.0(3.8)	9	101032
	1999-12-01	04:33:00.5	40.50	123.00	0.0(4.3)	10	145943
20	2000-03-19	23:18:28.6	40.30	123.00	0.0(3.6)	9	101030
	1999-12-01	04:58:56.7	40.50	123.00	0.0(3.5)	10	145944
21	2000-01-12	13:00:31.9	40.60	122.70	0.0(4.5)	15	100135
	1999-12-01	12:45:30.8	40.60	122.70	0.0(4.3)	10	145947
22	2000-01-12	07:43:55.4	40.50	123.00	4.9(5.5)	10	100128
	1999-11-25	20:55:04.2	40.30	123.00	0.0(4.4)	5	145817
23	2000-01-12	07:43:55.4	40.50	123.00	4.9(5.5)	10	100128
	1999-11-29	12:10:39.2	40.50	122.90	5.0(5.9)	5	145898

Note: Parameters of the earthquakes are from Schaff and Richards (2004a), with origin time changed to local time. Magnitudes in the parenthesis indicate those cases that either there was no magnitude given in Schaff and Richards (2004a) or the magnitude given in Schaff and Richards (2004a) was significantly inconsistent with regional/local results. In both cases magnitude from the regional network is taken. Number in the last column is the serial number of events in the electronic appendix of Schaff and Richards (2004a).

Figure 1 Epicenters of repeating earthquakes and stations of Liaoning Regional Seismograph Network

Circles represent earthquakes. Solid triangles indicate digital seismograph stations, and open triangles denote analogue seismograph stations

The data used by Schaff and Richards (2004a) is the seismic waveforms from the stations of China Digital Seismograph Network (CDSN) and other GSN stations located around China. One of the naturally arisen questions is how to understand the repeating properties of the ‘repeaters’ in this sense, identified by using only a few numbers of teleseismic stations for the waveform cross-correlation. To answer this question we consider using the data from regional seismograph network.

Among the 950 pairs of ‘repeating events’ identified by Schaff and Richards (2004a), there were 23 pairs (being composed by 24 single earthquakes) locating in $38.5^{\circ}\text{N}\sim 43.5^{\circ}\text{N}$, $119^{\circ}\text{E}\sim 126^{\circ}\text{E}$, within the effective monitoring range of Liaoning Regional Seismograph Network, with digital broadband waveforms. These events belong to the mainshock-aftershock sequence

of the 1999 Xiuyan $M_{\text{S}}5.4$ earthquake. Table 1 and Figure 1 give the distribution of these earthquakes and seismic stations used in this study. We cross-correlated the regional waveforms of the ‘repeaters’ identified by Schaff and Richards (2004a), obtaining the ‘repeating events’ in the sense of regional waveform cross-correlation, and compared the results with those of Schaff and Richards (2004a).

1 Data used and methods for analysis

In the database of Schaff and Richards (2004a), there were 32 pairs of ‘repeaters’ located in the effective monitoring range of Liaoning Regional Seismograph Network, among which there were 23 pairs of ‘repeaters’, occurring after 1999 and having digital seismic recordings. Liaoning Regional Seismograph Network, the former Shenyang Telemetered Seismograph Network, is composed of a data center and a center station located in Shenyang, the capital city of Liaoning Province, 15 digital telemetered seismic stations, and 4 data transmission nodes within the territory of Liaoning Province. The network has been upgraded to digital network since September 1999 and well recorded the Xiuyan earthquake sequence. At present, all the 16 stations have three-component, real-time transmitting digital recordings. Yingkou and Jinzhou station use FBS-3 broadband seismograph, Dongling and Dalian station belonging to the China National Seismograph Network use JCZ-1 and CTS-1 broadband seismograph, respectively, and other stations use JC-V100 or JC-V104 short-period seismographs (WU and JIANG, 2003). Location of earthquakes within Liaoning and its surrounding regions use the data of this network. Earthquake Administration of Liaoning Province (the former Liaoning Seismological Bureau) has assigned duties routinely processing the waveforms, documenting seismological observational reports, and locating earthquakes. Parameter data used in this paper are from the seismological bulletin of Liaoning

Regional Seismograph Network, and waveforms used in this study are from the network data center.

Operationally, ‘repeating earthquakes’ are defined by cross-correlating waveforms. The results obtained by Schaff and Richards (2004a) are based on the analysis of the data from GSN stations as far away as 1 100 km from the events, therefore there must be some differences from those obtained using regional data. The aim of this paper is to study such differences, investigating whether such differences may affect the application of ‘repeating earthquakes’ to the assessment of the observation capabilities of seismograph networks.

2 Cross-correlating the regional waveforms of ‘repeating events’

Identification of ‘repeating events’ in this study is based on the analysis of the whole waveform from P and S to coda. Considering the frequency response and the level of background noise, the data are filtered before the cross-correlation. For broadband recordings the pass band is taken as 0.5~5 Hz, and for short-period recordings the pass band is 1.0~5 Hz. Initial time of the waveform cutting is at the moment 4 s before the Pg arrival. Length of the waveform taken for calculation is taken as four times of Sg-Pg travel-time difference. Then the length of the window for the cross-correlation is the length of waveform minus 4 s. Such a selection guarantees that the whole waveform can be included in the calculation, while the disturbance from the succeeding noise can be depressed at the same time. Cross-correlation coefficient γ is calculated *via* (Båth, 1974):

$$\gamma = \frac{\sum [f_1(t) - \overline{f_1(t)}][f_2(t) - \overline{f_2(t)}]}{\sqrt{\sum [f_1(t) - \overline{f_1(t)}]^2 \sum [f_2(t) - \overline{f_2(t)}]^2}} \quad (1)$$

In the above equation $f_1(t)$ and $f_2(t)$ are the waveforms of the two events recorded at the same station, and $\overline{f_1(t)}$ and $\overline{f_2(t)}$ are the temporal mean of the two waveforms, respectively. Operationally, $f_1(t)$ is firstly fixed as starting from 2 s before Pg arrival and ending at 2 s before the end of the whole waveform. Same length is taken for $f_2(t)$, and sliding is performed from the beginning of the data to Pg arrival, with the sliding step being 1 sample. Maximum of the sliding results is taken as the last cross-correlation coefficient of the two waveforms. Figure 2 shows an example of such cross-correlation (the Benxi station, abbreviated as BXi, for event pair 199912010458 and 200003192318). JIANG *et al* (2008) discussed in detail the effect of taking both BB and SP recordings for the analysis.

Table 2 gives the maximum cross-correlation coefficients of the waveforms of ‘repeating events’ from Liaoning Regional Seismograph Network and from teleseismic waveforms used by Schaff and Richards (2004a), respectively. From the table it may be seen that among the 23 pairs under study, there are 14 pairs (about 60% of the whole event set) having cross-correlation coefficients no less than 0.8 calculated by using either teleseismic or regional waveforms. This result shows the difference between the ‘repeating earthquakes’ in the sense of teleseismic waveform cross-correlation and those in the sense of regional waveform cross-correlation. Even if for the overlapped parts, the cross-correlation coefficients also differ significantly, as can be seen in Figure 3a.

Out of the scope of Schaff and Richards (2004a) there are also ‘repeating earthquakes’ left. Associating 276 pairs using the above 24 events of Schaff and Richards (2004a) and cross-correlating the waveforms obtained that there are 63 pairs with at least one station having

Figure 2 A pair of repeating earthquakes recorded by station BXi of Liaoning Regional Seismograph Network and the cross-correlation of their waveforms

(a) Comparison of the similar waveforms of the repeating earthquakes; (b) Zooming of (a). Waveforms are recorded by short-period seismograph with sampling rate 50 sps, and band-pass filtered with 1.0 to 5.0 Hz frequency band. ΔT indicates the picking error of Pg onset in the bulletin of Liaoning Regional Seismograph Network.

Figure 3 Comparison of the maximum correlation coefficient of the repeating earthquakes in the sequence of the 1999 Xiuyan $M_S5.4$ earthquake

(a) The set of repeating events of Schaff and Richards (2004a) in the sense of teleseismic waveform cross-correlation; (b) The set of repeating events obtained for Liaoning Regional Seismograph Network in the sense of regional waveform cross-correlation. Circles are the result of Schaff and Richards (2004a) by teleseismic waveform cross-correlation; triangle is the result of Liaoning Regional Seismograph Network by regional waveform cross-correlation. For repeating events in the sense of regional waveform cross-correlation, if there is no correspondence in the set of repeating events in the sense of teleseismic waveform cross-correlation, the coefficient of teleseismic waveform cross-correlation is taken as 0.5.

Table 2 Comparison of the maximum waveform cross-correlation coefficients of the repeating events recorded by Liaoning Regional Seismograph Network with that of the repeating pairs found by Schaff and Richards (2004a)

Pairs No.	Serial No.1	Serial No.2	Correlation coefficient 1	Station 1	Correlation coefficient 2	Station 2	CC $\geq$ 0.8?
1	145600	145817	0.83	IC.MDJ	0.74	YKo	NO
2	145601	145817	0.81	IC.MDJ	0.75	YKo	NO
3	145816	145846	0.82	IC.MDJ	0.84	DDo	YES
4	145817	145846	0.80	IC.MDJ	0.62	DaL	NO
5	145601	145846	0.81	IC.MDJ	0.61	DaL	NO
6	145817	145898	0.81	IU.ULN	0.76	JZo	NO
7	145816	145901	0.81	IC.BJT	0.97	JZo	YES
8	145906	146300	0.83	IC.MDJ	0.89	XFe	YES
9	145906	146303	0.82	IC.MDJ	0.92	FaK	YES
10	145909	145928	0.85	IU.ULN	0.58	JZo	NO
11	145907	145975	0.81	IC.BJT	0.83	JZo	YES
12	100135	145909	0.81	II.TLY	0.75	JZo	NO
13	145924	145975	0.82	IC.BJT	0.84	JZo	YES
14	100135	145928	0.83	IC.MDJ	0.78	JZo	NO
15	145938	145964	0.82	IC.MDJ	0.95	CYa	YES
16	145943	146300	0.87	IC.MDJ	0.83	Don	YES
17	145943	146303	0.81	IC.BJT	0.83	JZo	YES
18	145928	145947	0.89	IC.MDJ	0.86	YKo	YES
19	101032	145943	0.81	IC.BJT	0.88	JZo	YES
20	101030	145944	0.81	IC.BJT	0.98	FaK	YES
21	100135	145947	0.80	IC.BJT	0.86	JZo	YES
22	100128	145817	0.85	IU.ULN	0.83	JZo	YES
23	100128	145898	0.88	IU.ULN	0.78	JZo	NO

Note: Serial No.1 and No.2 are from Schaff and Richards (2004a). Station 1 and coefficient 1 are also from Schaff and Richards (2004a), while station 2 and coefficient 2 are from the station of Liaoning Regional Seismograph Network, selecting the maximum of the correlation coefficient.

Figure 4 Distribution of the (bulletin-reported) apparent travel-time difference of Pg phase of the repeating earthquakes

(a) Distribution of the travel-time difference of Pg phase of 'repeaters' given by Liaoning Regional Seismograph Network; (b) Distribution of the travel-time difference of Pg phase of 'repeaters' given by Schaff and Richards (2004a). Two vertical dashed lines give the maximum and minimum, respectively, the vertical solid line is the average, and the arrow indicates the peak or the center of the twin-peaks.

coefficient of regional waveforms no less than 0.8. There are 26 event pairs with at least two stations having the cross-correlation coefficients of regional waveforms no less than 0.8. Among these 26 events, nine events are in the list of Schaff and Richards (2004a).

Table 3 The repeating earthquakes obtained by Liaoning Regional Seismograph Network using waveform cross-correlation of local and/or regional seismic records

No.	Origin time		The top five correlation coefficient stations and their correlation coefficient				
	a-mo-d	h:min:s					
1	1999-11-09	07:01:00	DaL 0.82	Hen 0.80	BZe 0.85	YKo 0.89	XYu 0.89
	1999-11-09	07:07:00					
2	1999-11-09	07:07:00	Don 0.84	BZe 0.71	YKo 0.76	CYa 0.83	DaL 0.80
	1999-11-25	20:47:00					
3	1999-11-09	07:07:00	BZe 0.81	CYa 0.86	YKo 0.78	Hen 0.70	XFe 0.74
	1999-11-29	12:45:00					
4	1999-11-25	20:47:00	JZo 0.97	CYa 0.90	YKo 0.88	BZe 0.74	FaK 0.72
	1999-11-29	12:45:00					
5	1999-11-29	15:12:00	JZo 0.83	YKo 0.81	BXi 0.79	CYa 0.80	DDo 0.71
	1999-12-03	17:58:00					
6	1999-11-29	14:55:00	JZo 0.93	DDo 0.85	YKo 0.83	XMi 0.84	XFe 0.87
	1999-12-01	04:33:00					
7	1999-11-29	14:55:00	CYa 0.85	XFe 0.98	FaK 0.77	Hen 0.74	XMi 0.79
	1999-12-01	04:58:00					
8	1999-11-29	14:55:00	JZo 0.91	XFe 0.89	XMi 0.84	SJT 0.84	CYa 0.80
	1999-12-27	19:27:00					
9	1999-11-29	14:55:00	JZo 0.91	FaK 0.92	XFe 0.92	XMi 0.88	DaL 0.85
	1999-12-27	23:48:00					
10	1999-11-29	15:12:00	DaL 0.96	Hen 0.91	DDo 0.96	KDi 0.95	YKo 0.95
	1999-11-30	10:08:00					
11	1999-11-29	15:12:00	JZo 0.88	CYa 0.80	YKo 0.79	FSu 0.61	DaL 0.63
	1999-12-01	12:45:00					
12	1999-11-30	10:08:00	JZo 0.89	CYa 0.80	YKo 0.77	DaL 0.66	FaK 0.66
	1999-12-01	12:45:00					
13	1999-11-30	10:08:00	JZo 0.84	CYa 0.83	YKo 0.82	DDo 0.70	BXi 0.78
	1999-12-03	17:58:00					
14	1999-11-30	14:06:00	XFe 0.97	CYa 0.85	FaK 0.54	XMi 0.49	SJT 0.35
	1999-12-01	04:58:00					
15	1999-11-30	14:06:00	JZo 0.84	YKo 0.86	CYa 0.82	FaK 0.64	FSu 0.55
	1999-12-01	12:45:00					
16	1999-11-30	14:06:00	JZo 0.88	YKo 0.83	CYa 0.80	FaK 0.52	XFe 0.52
	1999-12-02	23:16:00					
17	1999-11-30	21:07:00	JZo 0.89	YKo 0.82	CYa 0.80	DaL 0.72	FSu 0.68
	1999-12-01	12:45:00					
18	1999-11-30	21:07:00	DaL 0.93	Don 0.92	KDi 0.91	JZo 0.98	YKo 0.93
	1999-12-02	23:16:00					
19	1999-12-01	04:33:00	Don 0.83	JZo 0.89	CYa 0.80	XFe 0.82	XMi 0.83
	1999-12-27	19:27:00					
20	1999-12-01	04:58:00	XFe 0.84	CYa 0.82	DaL 0.75	JZo 0.70	XMi 0.68
	1999-12-27	19:27:00					
21	1999-12-01	04:58:00	CYa 0.90	XFe 0.92	XMi 0.83	Hen 0.79	DaL 0.79
	1999-12-27	23:48:00					
22	1999-12-01	04:58:00	DaL 0.95	Hen 0.95	DDo 0.95	YKo 0.90	FaK 0.98
	2000-03-19	23:18:00					
23	1999-12-01	12:45:00	JZo 0.92	DaL 0.81	YKo 0.88	CYa 0.88	FSu 0.76
	1999-12-02	23:16:00					
24	1999-12-01	12:45:00	JZo 0.90	CYa 0.81	YKo 0.79	DaL 0.45	FSu 0.46
	1999-12-03	17:58:00					
25	1999-12-27	19:27:00	Don 0.88	JZo 0.88	XFe 0.86	XMi 0.84	SJT 0.79
	1999-12-27	23:48:00					
26	1999-12-27	23:48:00	JZo 0.91	CYa 0.84	FaK 0.83	Don 0.80	DaL 0.75
	2000-03-19	23:18:00					

Therefore, the result shown here indicates that using different stations and/or different waveforms, the identification of ‘repeating events’ may lead to different results. Probably one of the conclusions is that the *senso lato* criterion is not as satisfactory as expected. This problem is more

critical when the identification of ‘repeating events’ deals with some sensitive issues such as the evaluation of the CTBT monitoring system.

3 Distribution of apparent travel-time difference and apparent distance between the ‘repeaters’ in the seismological bulletin of Liaoning Regional Seismograph Network

Comparing with other existing approaches for assessment of network monitoring capabilities, for instance, the ‘calibration’ using known seismic events such as nuclear tests or quarry blasts (Lienert, 1997; GUO *et al.*, 2002), comparison between different seismic networks (Wüester *et al.*, 2000; MENG *et al.*, 2001), and statistical evaluation and optimization (Rabinowitz and Steinberg, 1990; Doufexopoulou and Korakitis, 1992; Bartal *et al.*, 2000), ‘repeating event’ approach has evident advantages. One of the natural questions is that, giving that the identification of ‘repeating events’ are network/station dependent, how objective is the assessment of monitoring capabilities by using ‘repeating event’ approach as an evaluation tool.

Figure 5 Distribution of the bulletin-reported apparent travel-time difference for Sg phase of the repeating earthquakes

(a) Distribution of the travel-time difference for Sg phase of ‘repeaters’ by Liaoning Regional Seismograph Network; (b) Distribution of the travel-time difference for Sg phase of ‘repeaters’ given by Schaff and Richards (2004a). For captions see Figure 4

Schaff and Richards (2004a) defined a ‘repeating pair’ as two events having correlation coefficient no less than 0.8 for at least one station. Menke *et al.* (1990) and Hough and Field (1996) showed that cross-correlation coefficient decreases logarithmically with the increase of the separation distance between the two events. Geller and Mueller (1980) gave that the separation distance between the ‘repeaters’ is less than a quarter wavelength. Comparing cross-correlation results and double-difference location results, Schaff and Richards (2004b) concluded that if the correlation coefficient is no less than 0.8 then the distance is less than 1 km. Therefore, theoretically, co-station travel-time difference of the two events in a ‘repeating pair’ should be small, and the apparent travel-time difference is due to the error of the phase picking. Similarly, apparent distance between the two events in the ‘repeating pair’ reflects the location error. This is the working assumption for the evaluation of monitoring capability using ‘repeating events’.

Figure 6 Distribution and cumulative distribution of the apparent travel-time difference for Pg and Sg phases of the repeating earthquakes

(a) and (b) are for Pg and Sg phase, respectively, of the repeating earthquakes identified by Liaoning Regional Seismograph Network; (c) and (d) are for Pg and Sg phase, respectively, of the repeating earthquakes identified by Schaff and Richards (2004a)

The 24 events identified by Schaff and Richards (2004a) and belonging to the 1999 Xiuyan sequence can form 276 pairs, among which 23 pairs were identified as ‘repeaters’ according to the criterion that for at least one station the cross-correlation coefficient is no less than 0.8. There are 14 of these 23 pairs having cross-correlation coefficient no less than 0.8 for at least two regional stations. According to the criterion that for at least two regional stations the cross-correlation coefficient is no less than 0.8, there were 24 ‘repeating event’ pairs identified, among which 9 pairs are in the ‘repeater’ list of Schaff and Richards (2004a). Therefore, the result of the identification of ‘repeating events’ seems network/station dependent. We use these two different sets of ‘repeating events’, respectively, to perform statistics of the travel-time difference of Pg and Sg phases in the regional seismological bulletins, as shown in Figures 4~6. The statistics as shown in the figures indicates that for both set of ‘repeating events’, the difference of the phase picking of Pg and Sg phases, respectively, in the observational bulletins, are 93~94% and 85~88%, respectively, within ± 1 s. The distribution is apparently normal within the range $[-1, +1]$ second, as shown in detail by Table 4.

It seems that the above distribution is apparently different from that obtained by Schaff and Richards (2004a) in their electronic appendix in which the travel time difference for the Pg phase distributes with ± 10 s with a concentrated peak to the center, being different from the normal-like distribution as shown by the regional data. Such a difference is mainly caused by the difference in

Table 4 Characteristics of the two sets of repeating earthquakes in the seismological bulletins of Liaoning Regional Seismograph Network

Characteristics	'Repeating earthquakes' group 1 [Schaff and Richards (2004a)]	'Repeating earthquakes' group 2 (Liaoning Regional Seismograph Network)
Percentage of Pg travel-time difference within ± 1 s	93%	94%
Percentage of Sg travel-time difference within ± 1 s	85%	88%
Mean apparent distance of 'repeaters' /km	1.9	1.8
σ^2 of Pg travel-time difference	0.40	0.30
σ^2 of Sg travel-time difference	2.25	1.88
Average of Pg travel-time difference	0.02	-0.05
Average of Sg travel-time difference	-0.17	-0.19

selecting the dataset for the statistics. In the statistics of Schaff and Richards (2004a), Pg phase readings are all from the teleseismic recordings at the stations for which the waveform cross-correlation coefficient is no less than 0.8. Teleseismic phases may have larger error for phase picking, which caused the wider distribution of the travel-time difference. Meanwhile, the statistics using only 'good' stations with cross-correlation coefficient no less than 0.8 leads to the steep peak near to the center.

Figure 7 shows the apparent distance between the two events in a 'repeating pair' for the teleseismic data set and the regional data set, respectively. It can be seen that for the regional data set, the apparent distance distributes within 5 km with the mean 2 km, being different from normal distribution. For the two data sets, there is no significant difference in their apparent distance distributions, while regional data set gives a smaller mean apparent distance.

Figure 7 Distribution of the apparent distance of the repeating earthquakes
(a) The repeating earthquakes identified by Liaoning Regional Seismograph Network with regional waveform cross-correlation; (b) The repeating earthquakes identified by Schaff and Richards (2004a) with teleseismic waveform cross-correlation

4 Discussion and conclusions

We cross-correlated the regional waveforms of the 'repeating pairs' given by Schaff and Richards (2004a), using the data of Liaoning Regional Seismograph Network, to obtain the 'repeating event pairs' in the sense of regional waveform cross-correlation. Comparing the data sets of 'repeating events' obtained using teleseismic and regional data, respectively, a distinct difference can be found either in the members of the sets or in the correlation coefficients. One of the

reasons causing such a difference is the difference of predominant phase or predominant frequency range taken for the waveform cross-correlation. For teleseismic analysis, the phase used is mainly Lg wave; while for regional analysis, the phases used are mainly S wave and its coda. Because S wave has a shorter wavelength than Lg, and has not the properties of reverberation as those in the Lg phase, the 'repeating events' identified by using regional waveforms are theoretically more reliable.

A critical problem arisen from this observation is the completeness of the 'repeating event' catalogue. That is, if teleseismic waveforms are used in the identification of 'repeating event pairs', then there might be many 'repeating events' left out of the scope of the analysis. Considering the application of 'repeating events' in estimating slip rates (Vidale *et al.*, 1994; Nadeau *et al.*, 1995; Wiens and Snider, 2001; Igarashi *et al.*, 2003), this problem is even more important. One of the practical proposals remedying this problem is *senso stricto* criteria be used in the identification of the 'repeaters'.

Fortunately, however, when applying 'repeating events' in the assessment of monitoring capability of a seismograph network, the overall assessments using different sets of 'repeating events' have no significant difference. Assuming that the separation distance between the 'repeaters' is less than 1 km, uncertainty of the routine location practice of Liaoning Regional Seismograph Network can be estimated as below 5 km, with the average 2 km, and the errors of the phase-picking of Pg and Sg phases, respectively, in the observational bulletins, can be estimated as 94% and 88%, respectively, within ± 1 s. This conclusion seems contradict to the fact that the 'repeating events' in the sense of teleseismic waveform correlation are different from those in the sense of regional waveform correlation. However, the similarity of the conclusions obtained using these two data sets, respectively, is understandable because in the assessment of monitoring capability, completeness of the 'repeating event' data set is not a critical requirement.

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