Lushan $M_s7.0$ earthquake: A special earthquake occurs on curved fault

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Relocation result shows that the aftershocks of the Lushan $M_s7.0$ earthquake spatially distribute in a shape like “half bowl”, indicating that the rupture structure of the mainshock is a highly curved surface. Kinematic analysis reveals that a laterally varied dislocation pattern occurs on this curved fault even though a single relative horizontal movement controls slip on this fault. Reverse slip prevails on curved fault. However, significant normal slip is predicted near the edge of north flank. Moreover, the north flank features left-lateral slip while the south flank contrarily features right-lateral slip. The relative scope of aftershock distribution implies inadequate breaking of the curved fault during the mainshock, calling for the attention to potential earthquake risk on the neighboring portions of the coseismic rupture due to significant increase of the coseismic Coulomb stress. Coseismic stress modeling also reveals that it is unnecessary for the stress on ruptured part to be unloaded following the earthquakes on the curved fault. The coseismic stress loading on ruptured elements unveils the specialty of faulting for the Lushan earthquake and we conclude that this specialty is due to the highly curved fault geometry.

Lushan earthquake, Longmenshan fault belt, curved fault, dislocation pattern, Coulomb stress change

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Focal depth [1,2], inferred geometrical dimension [3], and field investigations [4], all indicate that the Lushan $M7.0$ earthquake occurs on a blind fault. Although distribution of most aftershocks agrees with the horizontal trace of the frontal fault of the Longmenshan fault belt, a low dip angle of source plane from the thrust mechanisms [2,5] (http://www.seis.ac.cn/manage/html/8a9080a125b29b1b0125b2a3-093a0002/_content/13_04/28/1367129118338.html; <http://www.cea-igp.ac.cn/jjxcdsxj/266826.shtml>) suggests that the earthquake probably occurs on the blind Dayi fault [6] to the east of the front-range fault or on a fault under the Dayi fault (Figure 1(a)). Since late Mesozoic, multi-stage deformation of the Longmenshan fold and thrust system developed series of reverse faults with various depths and complex geometries along the Longmen Mountain and also

within its foreland basin [7–13]. Due to the complexity of the regional tectonics and the blindness of source fault, large uncertainties exist about the faulting structure of the Lushan earthquake.

Seismic waveform fitting [14,15] found pure reverse slip in the immediate area around the hypocenter. Comparatively, the slip on the north part of rupture has left-lateral component, while the slip on the south part has right-lateral component. This lateral variation of slip pattern for the Lushan earthquake is obviously different from that during the 2008 Wenchuan earthquake since although the slip varies in rake with distance along strike, no more senses other than reverse slip or right-lateral slip were observed. Furthermore, during the Wenchuan earthquake, the rake varies gradually along the strike [16] (http://earthquake.usgs.gov/eqcenter/eqinthenews/2008/us2008ryan/finite_fault.php). However, for the Lushan earthquake abrupt rake change

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Figure 1 Aftershock distribution of the Lushan earthquake (up to April 27, 2013). In (a), star and circles represent mainshock and aftershocks, respectively; blue curves are the surface trace of major faults near the Lushan earthquake, and black lines denote the positions of profiles shown in (b)–(g). In (b)–(g), black circles represent aftershocks and dashed curves present the characters of aftershock distributions. Half swath width for selection of aftershocks is 3.5 km in (b)–(e), and 4.5 km in (g)–(f).

from left-lateral to right-lateral occurs within relatively limited rupture plane. The different slip patterns for the Lushan earthquake and the Wenchuan earthquake indicate that the deformation styles of faults can be different due to their tectonic positions, even they are sharing the same tectonic background.

Our qualitative analysis on the relocated aftershocks of the Lushan earthquake shows that the distribution of aftershocks differs from common listric geometry being laterally straight for it reveals a feature of three-dimensional curvature. In this paper, we propose a special model of curved fault and we further present preliminary discuss on its characters in kinematics and coseismic mechanics.

1 Lushan earthquake fault model based on distribution of aftershocks

Seismic relocation shows that the focal depth of mainshock is about 17 km and that the aftershocks are distributed in a depth range between 10–20 km. Studies on seismic waveform fitting show that the large coseismic dislocation occurs at shallower portion next to the hypocenter [5,14,15]. Af-

tershocks on fault plane are usually distributed in neighbor to the portion that experienced coseismic dislocation [17]. The tendency of aftershocks distribution like this could be induced by stress adjustment [18,19]. Preliminary analysis leads to our conjecture that most aftershocks occur along the extending part of main rupture plane (Figure 1(b)–(e)) and consequently the distribution of aftershocks indicate the shape of main rupture plane.

The NW-SE profiles are perpendicular to the main rupture strike indicated by focal mechanism. In these profiles, the front of aftershock distribution appears in a listric shape (Figure 1(b)–(e), red dash line). Particularly, two NW-SE profiles across the south and the north tips of aftershock belt (AA' and DD') show that many aftershocks cluster in a 10 km width range behind the front, in contrast with the narrow belts of aftershocks in two NW-SE profiles (BB' and CC') across the middle part of aftershock belt (Figure 1(c)–(d)). Profile CC' shows that one straight strip of aftershocks (Figure 1(d), blue dash line) extends sub-vertically from 10 to 15 km depth above the rear of listric strip. This straight strip diminishes within a very limited north-to-south length (Figure 1(c),(e)) and appears to be a steep fault, indicating that it is not the main fault plane. The NE-SW profiles are

parallel to the main rupture and show that the shape of the north and the south edges of aftershock belt are also listric (Figure 1(g)–(f)). According to comprehensive features of aftershock distribution shown by profiles in two oblique-crossing directions with big separation angle, it can be inferred that the downward extension of main rupture is a curved fault with a shape like “half bowl”. Near the south and north edges of aftershock cluster, the NW-SE profiles (AA' and DD') just cut through the “edge of the bowl”, which explains why there are clusters of aftershocks above the listric edges and the clusters depict the surface of bowl edges as shown in profiles EE' and FF'.

Using ellipsoidal surface model to simply fit the distribution of aftershocks, we obtain an ellipsoidal equation,

$$z(x, y) = -14.29 + 0.2183x + 0.00015y + 0.003891x^2 - 0.005701y^2 + xy, \quad (1)$$

where x , y and z are horizontal coordinates and depth, the origin of horizontal coordinates corresponds to a geographical point (30.3°N, 103°E). According to eq. (1), a curved fault surface between 0–15 km depth can be created as shown in Figure 2. An assemblage of 225 straight sub-faults is generated to approximately describe the curved fault surface. As shown in Figure 2(b), the dips of sub-faults vary laterally and the trace of fault surface within any NW-SE or NE-SW profile is expected to be listric. The purpose of this study is to discuss the primary kinematic features of curved rather than blind fault. For this reason, the top depth of the fault surface is set to zero despite of the large uncertainty of top depth where the Lushan earthquake fault could be terminated.

2 Characters of dislocation on curved fault under simple kinematic constraints

In this section, the basic characters of dislocation pattern on

curved fault are analyzed and discussed semi-quantitatively under simple assumptions. According to kinematics of block model, the dislocation on fault is determined by relative motion between blocks separated by the fault [20,21]. Assuming relative motion between fault blocks is simple rigid motion in horizontal plane, the horizontal projection of slip on fault plane, i.e. slip vector, should be equal to relative motion. In such case, slip vector can be transferred into slip and rake on fault plane as

$$u = s \cdot \cos(\alpha - \beta), \quad (2)$$

$$v = s \cdot \sin(\alpha - \beta) / \cos \delta, \quad (3)$$

$$\text{slip} = \sqrt{u^2 + v^2}, \quad (4)$$

$$\text{rake} = \arctan(v, u), \quad (5)$$

where α is strike and δ is dip angle of fault plane [22], s is size and β is azimuth of slip vector (Figure 3(a)). If direction of slip vector on fault plane remains constant at different points, for straight fault its rake will be constant because the strike of straight fault is unique, while for curved fault its strike varies at different points on the fault and consequently the rake will change along with the variation of strike. In the case of the Lushan earthquake, the focal mechanism indicates that the hanging wall moved in azimuth around 130° with respect to the footwall. With slip vector in this azimuth, the variation of rake versus strike for curved fault is shown in Figure 3(b). It can be found out that the rake varies monotonously with respect to the change of strike. When dip angle is relatively small, the variation of rake is linear with little vibration. However, the magnitude of vibration becomes significantly large when dip angle is relatively large. Given the pattern of how rake varies under different strikes and dip angles, and assuming the magnitude of slip vector is 1 m, the dip slip and the strike slip on the curved fault surface can be obtained (Figure 3(c)–(d)). As a result, the dip slips on most sub-faults are reverse slips

Figure 2 Geometric model of the curved fault for the Lushan earthquake. Blue curves are the surface traces of the Back-range fault (BRF), the Middle-range fault (MRF) and the Front-range fault (FRF) within the Longmen Shan fault belt, and the Dayi fault (DYF) lying further east. Abbreviations are the same for the following figures. Depth given in (a) is the depth of the top edge of each sub-fault. For absence of constraints on fault shape above 10 km, the shape of shallow part is an inferred result. Owing to this kind of uncertainty in shape of shallow part, the correspondence between the Lushan earthquake fault and the neighboring faults is not clear yet. Colors in (b) represent the dips of sub-faults.

Figure 3 Typical slip distribution on curved fault. A cartoon is shown in (a) to illustrate geometric relation between dislocation and slip vector. Assuming the azimuth of slip vector is 130°, (b) shows variation of rake (slip type) versus fault strike. Shadows highlight the rake ranges for right-lateral strike slip (RL), left-lateral strike slip (LL), reverse slip (RS) and normal slip (NS). Curves show that the variation differs in trend for different fault dips. (c) and (d) present the distributions of dip-slip and strike-slip on curved fault, respectively.

but significant normal slips occur near the north edge of the curved surface (Figure 3(c)). Furthermore, it is conspicuous that strike slips are left-lateral on the north flank while right-lateral on the south flank (Figure 3(d)). It needs to be pointed out that the rupture of the Lushan earthquake may not extend to shallow crust [4], therefore distributed deformation or folding would come about in the shallow part above the rupture [23], which is not controlled by whether or not fault is curved and so will not be addressed here.

3 Characters of coseismic stress change on curved fault

Coseismic slip could not only trigger seismicity on neighboring fault but also induce stress adjustment on ruptured fault and consequently result in intensive aftershocks [18,19]. According to elastic rebound theory, stress will be unloaded and energy will be released on the ruptured part of fault plane during an earthquake. After the earthquake, it needs a period of time for the ruptured part to be locked again and continue to accumulate stress and energy until the occurrence of next earthquake [24]. Therefore, aftershocks

generally do not take place in the coseismically ruptured area on fault plane [17,19]. Under above circumstances, the aftershocks of the Lushan earthquake concentrate in a depth range of 10–20 km, which suggests that the major slip of this earthquake occurs above the depth of 10 km and thus is apparently shallower than the results from rupture process inversion [5,14,15]. This discrepancy poses a question that whether the distribution of aftershocks is also complementary to the distribution of coseismic slip for the Lushan earthquake. Given the geometry and slip pattern of curved fault, a static dislocation model [25] in elastic half-space is created to derive relation between the distribution of Coulomb stress change [26,27] on fault surface and the position of coseismic slip. In this way, the question can be addressed on the basis of stress adjustment on source fault.

Following common cases, the elastic module, the Poisson's ratio, and the apparent friction coefficient are assumed to be 8×10^4 MPa, 0.25, and 0.4, respectively. The rake and slip size on each element of fault surface is constrained by a single slip vector (azimuth 130°, magnitude 1 m). Sub-faults have no slip in the model except those belonging to ruptured part.

Coseismic stress change on fault plane consists of two

parts. One is the stress unloading, i.e. stress decrease due to slip on the sub-fault itself. Another one is stress change due to slip on the other sub-faults. Calculation shows that Coulomb stress significantly increases (larger than 0.5 MPa) in the immediate area around where coseismic slip happened (Figure 4(a)–(d)). When slip occurred on sub-faults is located at moderate depth, the stress on deeper neighboring sub-faults increases no matter whether ruptured area is on the north, the middle or the south flank of fault surface (Figure 4(a)–(c)). When slip occurred on sub-faults near the bottom of fault surface, stress also increases (0.2–0.5 MPa) in large area where has been dislocated (Figure 4(d)). Such stress rise in ruptured area also exists when slip occurred at moderate depth, but it is very limited in extent (Figure 4(a)–(c)). When whole fault surface is ruptured, the Coulomb stress does not decrease but increase instead in large area except the bottom and the edges of two flanks. The increase of Coulomb stress on ruptured area can also occur during earthquake on straight fault, in which case stress loading concentrates within outer regions along the edges of ruptured area (It is similar to the examples shown in Figure 4(a)–(c)). For rupture in such magnitude, the curvature of fault plane can be neglected, i.e. the curved fault can be treated as a straight fault. Results show that stress increases in regions surrounding the major ruptured area). The regions next to the edges of ruptured area were not dislocated sufficiently and become prone to aftershocks due to stress increase.

The correspondence between the distribution of coseismic Coulomb stress change and the position of rupture, to some degree, explains the phenomenon that aftershocks cluster in the depth range of 10–20 km for the case of the Lushan earthquake: (1) Provided that slip occurs below moderate depth, stress on sub-faults near bottom will increase and subsequently accelerate further rupture on sub-faults on which coseismic dislocation is zero or non-

sufficient during earthquake. (2) Even if major slip occurs near the bottom of fault surface, stress loading would also happen. Nevertheless, because elastic strain energy accumulated before an earthquake has been released during the earthquake, aftershocks with low magnitude would be likely in the ruptured area.

4 Discussion

To derive the geometry of coseismic rupture through fitting the distribution of aftershocks, the precondition is that the aftershocks occur along the seismogenic fault of mainshock. However, no direct evidence has been reported to support the precondition for the case of the Lushan earthquake. On the other hand, it can be partially confirmed that the ruptured fault of mainshock is in curved shape if some qualitative judgments on the earthquake sequence and the tectonic background are considered. First, seismic relocation displays very clear belts of aftershocks (Figure 1(c)–(d)). Second, the fault surface based on geometrical fitting also agrees with the stretching pattern of reverse faults within the Longmenshan fault belt and its foreland area. Third, the dominant dip angles of sub-faults are close to the comprehensive character reflected by focal mechanisms [2,5] (http://www.seis.ac.cn/manage/html/8a9080a125b29b1b0125b2a3093a0002/_content/13_04/28/1367129118338.html; <http://www.cea-igp.ac.cn/jjxcdsxj/266826.shtml>). It needs to be pointed out that the “half bowl” model just describes the primary geometrical features of the Lushan earthquake fault. This model is an idealized geometrical model representing the shape of a class of curved faults. For real fault, it is possible that the fault surface is rugged to some extent. Moreover, the temporal and spatial distribution of rupture could be heterogeneous due to the heterogeneity of material properties and stress condition. Rupture process of the Lushan

Figure 4 Position of rupture and correspondent coseismic Coulomb stress change on fault. Fault models in (a)–(e) are the same except that the ruptures occur at different positions.

earthquake reveals a secondary rupture took place around 20 s at deeper part south to major rupture area [14]. This secondary rupture is governed by reverse slip with right-lateral component, which is consistent to the prediction of slip pattern based on “half bowl” model and hence suggests this secondary rupture occurred on a part of the “half bowl” fault. With regard to geometric characters, the Lushan earthquake fault differs from the three major faults of the Longmenshan fault belt (i.e. the front-range, central-range and back-range faults). Furthermore, the corresponding surface position where the Lushan earthquake fault extends toward obviously differs from the trace of Dayi fault. For the uncertainties of fault structures in deep place, the relation between the Lushan earthquake fault and the other faults in vicinity is still unknown.

The shape of curved fault that we proposed is only an inference and approximation. The elaborate details of after-shock distribution are also not considered sufficiently during fitting procedure. It is no doubt that the real shape and size of the Lushan earthquake fault would be more complex. Using the method mentioned above, the rake and magnitude of slip on curved fault can be simply assigned to forward models. Through inverse calculation technique, the real distribution of slip on the Lushan earthquake fault can be obtained by fitting coseismic surface deformation and seismic waveform. As a whole, if only the curved degree of fault surface is adequately high, the slip features would vary laterally because the strike of the sub-fault at different positions varies, which qualitatively explains slip distribution from seismic waveform fitting [14,15].

According to the analysis about stress change on fault surface, stress on shallow part will increase when rupture occurred at moderate depth (Figure 4(a)–(d)) (5–10 km). Consequently, the possibility of seismic risk along shallow part would increase if the fault surface extends to near-surface depth. If so, the “aftershock gap” might reflect the asperity [28] that has not been broken by coseismic rupture. It is also possible that the Lushan earthquake fault does not extend to near-surface depth, like the other blind reverse faulting systems within foreland area along the Longmen Shan Mountains [4,12,13]. Rupture process inversion shows that slip larger than 0.2 m concentrates in relatively limited area (about $20 \times 20 \text{ km}^2$) accounting up to about 50% of the lateral scope of aftershock distribution. In contrast, the length of ground rupture of the Wenchuan earthquake is nearly 240–260 km [29,30], while the studies on rupture process and dislocation distribution indicate the total length of the rupture may reach 300 km [16,31], which on the whole agrees with statistical relation between surface rupture length and total rupture length [32]. Seismic relocation shows that the length of aftershock distribution is 330–350 km [33,34]. As a simple estimation, the length of the coseismic rupture of the Wenchuan earthquake accounts 86%–90% of the length of aftershock distribution. Compared to the ratio of the rupture length to the lateral scope of the af-

tershock distribution in the case of the Wenchuan earthquake, the ratio for the Lushan earthquake suggests that the fault surface laterally adjacent to the coseismic rupture is suspected to be not fully ruptured and potentially becomes high seismic risk area due to increased stress on it.

Our curved fault model predicts that the slip with normal component occurs at the edge of the north flank of the Lushan earthquake fault, which agrees with a preliminary result from ground motion and coseismic displacement given by high frequency GPS observation that the ground depressed at a location where is close to the front-range fault and ~50 km north to the epicenter of the Lushan earthquake (Gan Weijun, personal communication). This agreement is still doubtful because the observation error is relatively large at present. On the other hand, the dislocation on fault plane based on the simulation of coseismic GPS displacement suggests that significant left-lateral component is required in addition to reverse slip to better fit observation data (Wang Min, personal communication), which is supposed to be consistent to predicted pattern regarding left-lateral slip. Semi-quantitatively, the azimuth at which the hanging wall moves as a whole with respect to the footwall is about 130° , pointing further into the azimuthal range of the south flank; therefore the boundary between the parts with left-lateral and right-lateral components deviates to the south flank. This deviation further leads to unequal areas for two types of slip patterns, that is, the area for the north flank with left-lateral component is bigger and the slip amount is larger than those for the south flank. On the hanging wall, the horizontal deformation in near-field based on GPS observation also shows clockwise rotation around epicenter [35], which also agrees with left-lateral movement striking east-northeast to southeast on the north flank.

As the examples for reverse fault, the rupture processes of the 1999 $M_w 7.6$ Chi-Chi earthquake and its strong after-shock ($M_w 6.8$) [36,37] indicate that it is not universal for bi-laterally rupturing reverse fault that the senses of lateral slip on two flanks are opposite. However, the opposite senses appeared in the cases of the 2010 Chile great earthquake and the 2011 Tohoku-Oki great earthquake in Japan [38,39]. Furthermore, as shown by coseismic GPS observation, the shortening sub-parallel to east-west direction is a dominant component of the horizontal deformation in near-field of the Tohoku-Oki earthquake; meanwhile, significant southward component occurred on the north flank of hanging wall and significant northward component occurred on the south flank [39]. The characters of surface rupture distribution and the seismic reflection profiles indicate that the Chi-Chi earthquake occurred on a thrust nappe structure with a straight fault plane [40]. However, for those great earthquakes taking place on subducting interplate boundary like the 2010 Chile earthquake and the 2011 Japan earthquake, the ruptured surface on subduction fault usually has significant curvature regarding the characteristic rupture length (≥ 200 –300 km) of great earthquakes [41].

Comprehensive comparison of above phenomena suggests that the opposite senses on the two flanks of bilaterally ruptured reverse fault may be induced by high-degree curvature of fault surface.

It appears somewhat contrary to the elastic rebound theory that the stress on ruptured part could be increased due to coseismic slip when the rupture occurred on whole curved fault or on the bottom part. However, the coseismic state of fault differs from the inter-seismic state. During inter-seismic period, the fault material can be approximately treated as elastic object and the fault is locked, consequently the elastic stress and elastic strain energy can be accumulated constantly to sufficiently high level to generate earthquake [24]. During coseismic process, stress loading may occur on curved fault. However, the ruptured fault surface, where local melting [42] occurs subsequently, has experienced inelastic damage due to dislocation during earthquake and needs certain time to be locked again [43]. Under this condition, high stress state does not necessarily lead to high elastic strain energy and the stress increased by coseismic process could be released through creeping of materials. On the other hand, the main part of elastic strain energy has been released during earthquake; therefore the recurrence of similar earthquake in short time is not likely though stress loading could happen on the ruptured surface. Nevertheless, the stress loading may lead to a plenty of low magnitude aftershocks breaking some small structures.

In consideration of tectonic background, that the Lushan earthquake fault is a curved fault also accords with the characters of regional stress. Stress measurement shows that the maximum and the second principal components of stress field are almost horizontal within the region east to the southern segment of the Longmenshan fault belt. The strike of maximum component is southeasternward [44,45], which is the main contribution to the formation of reverse faulting earthquake like the Lushan earthquake (Figure 5(a)). As to the southern segment of the Longmenshan fault belt, southeast-trending primary principal stress controls earthquake activity on southwest-striking reverse faults. The second principal stress is sub-parallel to the strikes of the reverse faults, thus contributes very little to the shear deformation along fault plane. However, it could make the region where develops significantly-curved fault receive northeast-trending shortening through slow rheological process and consequently make the fault be more curving (Figure 5(b)). This demonstration of geomorphic process implicates a possible connection between the seismogenic structure and the deformation due to folding in the area near the south segment of the Longmenshan fault belt.

5 Conclusions

The seismogenic fault of the Lushan $M_s7.0$ earthquake is a special curved fault. Under the control of southeast-trending

Figure 5 (a) Schematic three-dimensional map showing structure of curved fault and principal components' orientations of regional tectonic stress; (b) Cartoons separately demonstrating how curved fault deforms in coseismic process and during inter-seismic period. In (a), the upper part is stereoscopic topography, and the colored curved surface in lower part describes curved fault, on which colors indicate depths.

shortening of crust, the curved fault manifests reverse faulting on the whole. However, normal faulting occurs on the edge of the north flank; meanwhile the left-lateral and the right-lateral components are found on the north and the south flanks, respectively. The aftershocks of the Lushan earthquake mainly take place along the downward extending part of coseismic structure. Coseismic fault slip led to Coulomb stress increase on fault surface, and the rise of stress may be the major reason for the concentration of aftershocks in depth range of 10–20 km. It is unlikely that the fault surface of the Lushan earthquake extends to shallow part (above 5 km). At present, the fault surface may be broken incompletely and the seismic risks along the parts next to ruptured area probably become higher. Coseismic stress responses on curved fault surface indicate that curved fault is a type of special faulting structure on which a relevant earthquake may not simply result in stress unloading on ruptured parts.

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