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Fault motion and curved slickenlines: a theoretical analysis

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Abstract—Slickenlines record on a fault surface the nature of relative movement of the faulted blocks. An assemblage of straight slickenlines indicates linear-translational fault motion. Curved slickenlines, on the other hand, may arise either due to rotational-translational fault motion or due to fault motions where the translation direction changes continuously (curvilinear-translational fault motion). The analysis of roto-translational fault motion involves the ratio of relative rate of rotation vs translation whereas that of curvilinear-translational fault motion involves the ratio of rate of change of translation direction to the rate of translation. The analyses reveal that an assemblage of curved slickenlines where each slickenline differs in shape from the other is indicative of roto-translational fault motion, whereas an assemblage where the slickenlines are of similar shape is the consequence of curvilinear-translational fault motion.

INTRODUCTION

SURFACES, along which there were sliding movements, are often characterized by linear features termed slickenlines (Fleuty 1975). Fault surfaces are by far the most common locales of such features. There are several types of slickenlines which differ in their characters and modes of origin (Means 1987). However, in all cases their geometries are related to the nature of relative movement of the rigid blocks along the discontinuity surface. Any slickenline among a set of slickenlines, marked either by simple striations or by displacement-controlled fibre growth, characteristically records on the fault surface the locus of movement, on that surface, of a point fixed on the sliding surface of the opposite block (Ramsay & Huber 1983, Means 1987). Thus, assuming the blocks to be rigid the nature of relative movement of the blocks can be deciphered from the shapes of slickenlines.

A set of straight slickenlines indicates linear-translational motion of the faulted blocks. Curved slickenlines, on the other hand, represent either rotational-translational (roto-translational) fault motion or curvilinear-translational fault motion, a fault motion where the translation direction of the relatively moving block changes continuously owing to re-orientation of the stress system or change in relative magnitudes of the principal stresses (Bott 1959). This note presents quantitative analyses of the shapes of curved slickenlines resulting from both kinds of fault motion and enumerates the distinguishing features of each type in order to decipher the nature of fault motion from natural curved slickenlines.

ANALYSES OF CURVED SLICKENLINES

In order to depict the shapes of curved slickenlines we shall find the loci of migration, on the fault surface, of points fixed on the sliding surface of the relatively moving block and to do so we choose two reference frames, viz., a frame lying on the fault plane ($X_1 0_1 Y_1$) and the other on the sliding surface of the relatively moving block ($X_2 0_2 Y_2$) (Fig. 1). The reference frame on the moving block is considered to be fixed with respect to the block itself, but moving with respect to the fault plane. The movement of the $X_2 0_2 Y_2$ frame with respect to the $X_1 0_1 Y_1$ frame would, thus, essentially represent the locomotion of the relatively moving block (Fig. 1). The axes of the $X_1 0_1 Y_1$ frame may be chosen to coincide with the strike and down-dip directions of the fault plane. At the onset of fault motion the two reference frames may be considered to coincide with each other; however, subsequently the $X_2 0_2 Y_2$ frame would be displaced with respect to the $X_1 0_1 Y_1$ frame and different points fixed on the sliding surface of the moving block would remain fixed with respect to the $X_2 0_2 Y_2$ frame but would travel along different paths in the $X_1 0_1 Y_1$ frame producing a set of slickenlines on the fault plane (Fig. 1, P paths). In order to analyse the shapes of slickenlines we shall find the pathline of a point fixed on the sliding surface of the moving block (i.e. on the $X_2 0_2 Y_2$ frame) with respect to the $X_1 0_1 Y_1$ frame for two different kinds of fault motion.

Shapes of slickenlines resulting from roto-translational fault motion

In roto-translational fault motion the relatively moving block performs rotational as well as translational motion. Figure 1(a) depicts such fault motion showing the movement of the $X_2 0_2 Y_2$ frame in the $X_1 0_1 Y_1$ space. The center of rotation of the moving block is taken to coincide with the origin of the $X_2 0_2 Y_2$ frame and is assumed to be fixed for a finite interval of time. Naturally, the point on the sliding surface about which the moving block rotates would move in a straight line in the $X_1 0_1 Y_1$ space defining the translation direction of the

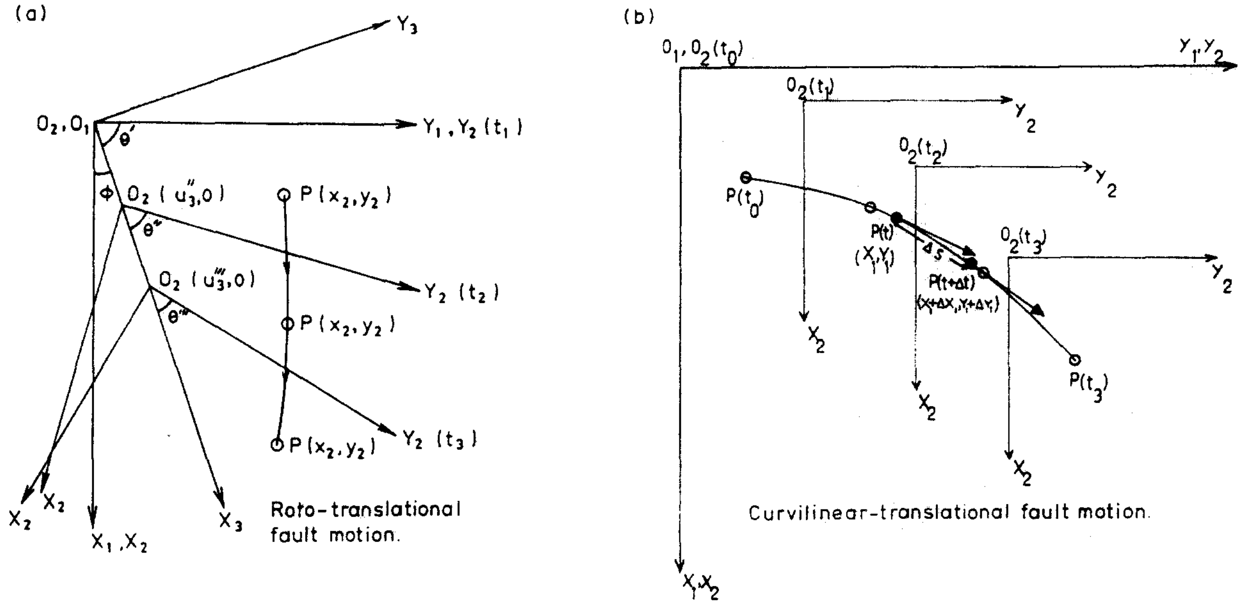

Fig. 1. Diagram showing movement of the $X_20_2Y_2$ frame and of a point fixed on that frame with respect to the $X_10_1Y_1$ frame in roto-translational fault motion (a) and in curvilinear-translational fault motion (b). In (a) 0_2, the centre of rotation of the moving block (see text), translates along 0_1X_3 making an angle ϕ with 0_1X_1. In (b) points on the curve marked by open circles denote the positions of the moving particle (P) at different instants ($t_0, \ldots, t_3$). $P(t)$ and $P(t + \Delta t)$ are any two positions in time interval Δt, Δs being curvilinear distance travelled in this interval.

fault. We now choose another reference frame $X_30_1Y_3$ on the fault plane whose X_3-axis coincides with the locus of movement of the center of rotation of the moving block (Fig. 1a).

Let the co-ordinate of any point P on the sliding surface of the moving block, at any instant be (x_2, y_2) with respect to the $X_20_2Y_2$ frame and that of the origin of the $X_20_2Y_2$ frame at that instant be $(u_3, 0)$ with respect to the $X_30_1Y_3$ frame (Fig. 1a). The co-ordinate of the point P with respect to the $X_30_1Y_3$ frame can be expressed as

$$x_3 = u_3 + y_2 \cos\theta + x_2 \sin\theta \tag{1}$$

$$y_3 = y_2 \sin\theta - x_2 \cos\theta, \tag{2}$$

where θ is the angle between the X_3-axis and the Y_2-axis at the instant under consideration (Fig. 1a). In response to the movement of the block (and thus the $X_20_2Y_2$ frame) the point P, fixed on the moving block, would change its position with respect to the $X_30_1Y_3$ frame. Thus,

$$\mathrm{d}x_3/\mathrm{d}t = \mathrm{d}u_3/\mathrm{d}t - y_2 \sin\theta \frac{\mathrm{d}\theta}{\mathrm{d}t} + x_2 \cos\theta\, \mathrm{d}\theta/\mathrm{d}t \tag{3}$$

$$\mathrm{d}y_3/\mathrm{d}t = y_2 \cos\theta\, \mathrm{d}\theta/\mathrm{d}t + x_2 \sin\theta\, \mathrm{d}\theta/\mathrm{d}t. \tag{4}$$

Evidently, $\mathrm{d}u_3/\mathrm{d}t$ (say ψ) represents the rate of translation of the center of rotation (i.e. the translational component of the moving block), whereas $\mathrm{d}\theta/\mathrm{d}t$ (say w) represents the rate of rotation of the moving block. Thus,

$$\mathrm{d}y_3/\mathrm{d}x_3 = \frac{y_2 \cos\theta + x_2 \sin\theta}{\delta - y_3}, \tag{5}$$

where $\delta = \psi/w$, a measure of relative rate of translation vs rotation of the moving block, which can be considered to be the controlling parameter of the shape of the pathline of the point $P(x_2, y_2)$. Substituting the values of $\cos\theta$ and $\sin\theta$ as functions of y_3 from equation (2) and using $r^2 = x_2^2 + y_2^2$ (where r is the linear distance of the point P from the origin of the $X_20_2Y_2$ frame) we get,

$$\mathrm{d}y_3/\mathrm{d}x_3 = \frac{\sqrt{r^2 - y_3^2}}{\delta - y_3}. \tag{6}$$

Solution of equation (6) gives,

$$\delta \sin^{-1} y_3/r + \sqrt{r^2 - y_3^2} = x_3 + \text{constant}. \tag{7}$$

Equation (7) can be transformed into the $X_10_1Y_1$ frame as follows,

$$\delta \sin^{-1}\left(\frac{y_1 \cos\phi - x_1 \sin\phi}{r}\right) + \sqrt{r^2 - (y_1 \cos\phi - x_1 \sin\phi)^2} = x_1 \cos\phi + y_1 \sin\phi + \text{constant}, \tag{8}$$

where ϕ is the angle between the X_1-axis and the X_3-axis.

Equations (7) and (8) essentially represent the locus of migration, on the fault plane, of any point fixed on the sliding surface of the relatively moving block and thus describe the geometry of the slickenline produced by that point. Equation (7) shows that for a purely translational fault motion (i.e. $w = 0$ and $\delta = \alpha$) the slickenlines will be straight, whereas for a purely rotational fault motion (i.e. $\psi = 0$ and $\delta = 0$) the slickenlines will be arcs of concentric circles. For all intermediate values of δ, the slickenlines will be curved.

Figure 2 shows assemblages of slickenlines generated by different points fixed on the sliding surface of the relatively moving block for different δ values. The significant feature of the slickenlines of roto-translational faults, as revealed in the figure, is that the shape of individual slickenlines in an assemblage is different.

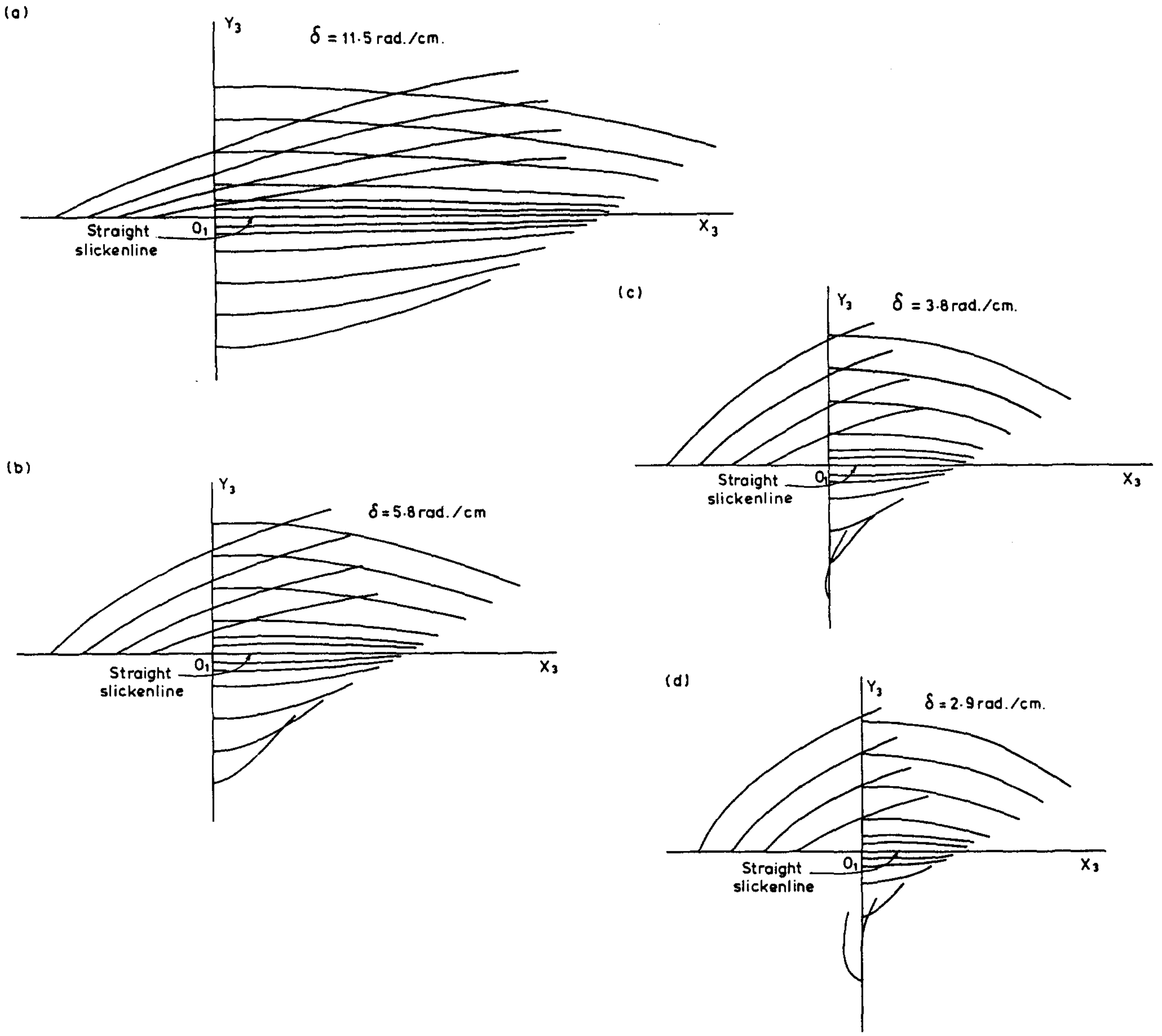

Fig. 2. Shapes of slickenlines for different δ values in roto-translational fault motion.

Another distinctive feature of these slickenlines is their gradual straightening towards the central part of the assemblage and reversal of the sense of curvature of the slickenlines across the straight slickenline.

Shapes of slickenlines resulting from curvilinear-translational fault motion

In this type of fault motion the relatively moving block does not rotate but changes its translation direction continuously. Figure 1(b) depicts such fault motion showing the movement of the $X_2 0_2 Y_2$ frame in the $X_1 0_1 Y_1$ space. The points fixed on the sliding surface of the moving block, as a consequence, move in curvilinear paths on the fault plane defining the slickenlines (Fig. 1b). It is evident from the figure that the rate of change of translation direction (W) can be expressed as the rate of change of slope of the tangents of the pathline (and thus the slickenline). Therefore,

$$d/dt\,(dy_1/dx_1) = W \tag{9}$$

or

$$d/ds\,(dy_1/dx_1)\,ds/dt = W$$

or

$$d/ds\,(dy_1/dx_1) = W/S = K, \tag{10}$$

where $S = ds/dt$ and $K = W/S$. K is assumed to be constant for a finite interval of time. Now,

$$d/dx_1\,(dy_1/dx_1)\,dx_1/ds = K$$

or

$$\begin{aligned} d^2y_1/dx_1^2 &= K\,ds/dx_1 \\ &= K\sqrt{1 + (dy_1/dx_1)^2} \end{aligned}$$

or

$$dy_1/dx_1 = 1/2[e^{Kx_1+c_1} - e^{-(Kx_1+c_1)}], \tag{11}$$

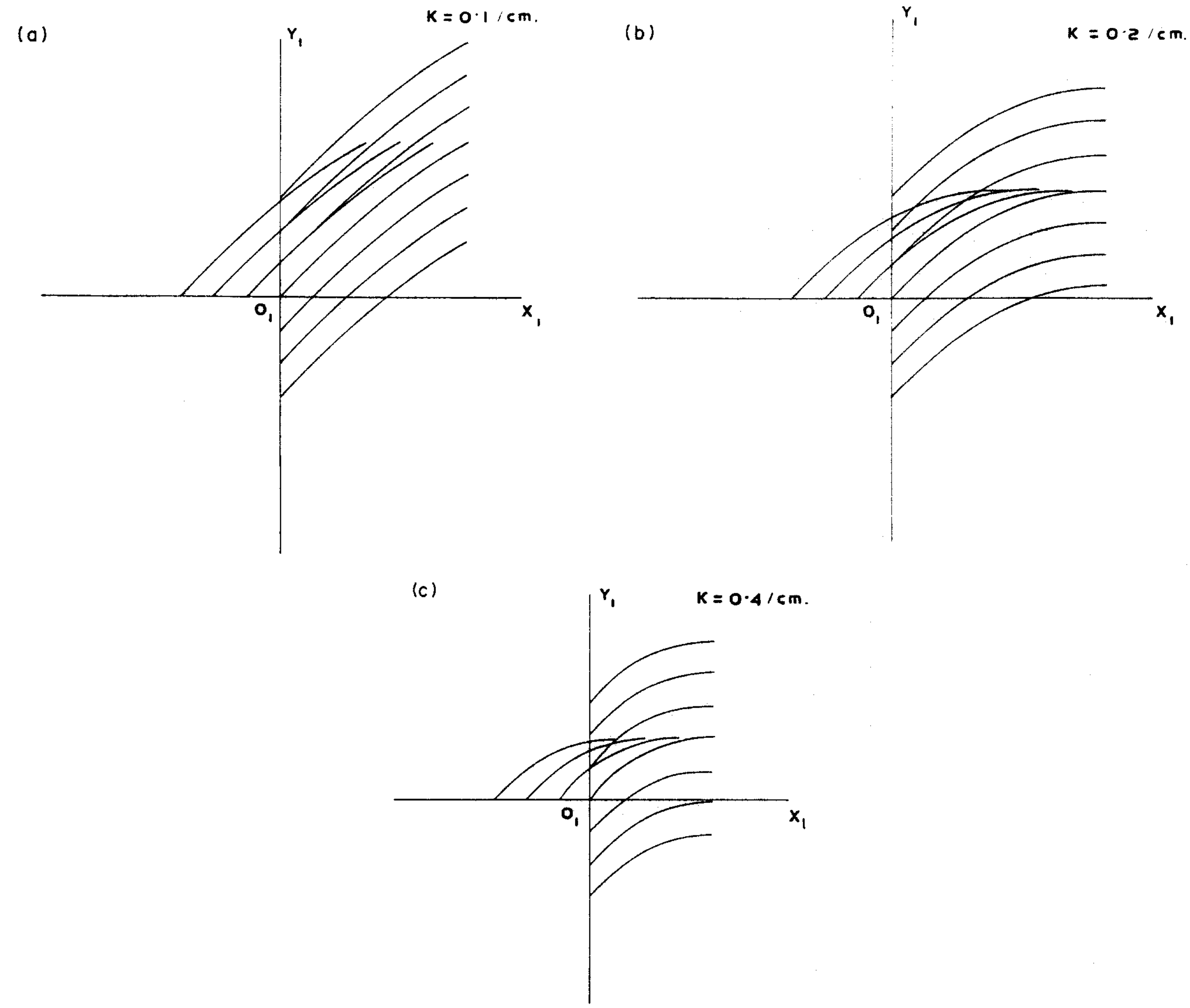

Fig. 3. Shapes of slickenlines for different K values in curvilinear fault motion.

where c_1 is the integration constant. Solution of equation (11) for $K = 0$ gives dy_1/dx_1 = constant.

This means that for linear-translational fault motion (i.e. when $W = 0$ and $K = 0$) the slickenlines will be straight. Solution of equation (11) for $K \neq 0$ gives,

$$y_1 = 1/2K\left[\frac{1 + e^{2(c_1 + Kx_1)}}{e^{(c_1 + Kx_1)}}\right] + c_2, \qquad (12)$$

where c_2 is the integration constant. Equation (12) essentially represents the pathlines of the points fixed on the sliding surface of the moving block and thus the shapes of slickenlines resulting from curvilinear-translational fault motion.

Figure 3 shows assemblages of slickenlines resulting from curvilinear fault motion for different K values. The characteristic feature of these slickenlines, as shown in the figure, is that all the slickenlines in the assemblage are of identical shape. Moreover, these slickenlines, in contradiction to that of the roto-translational fault motion, do not show any reversal of sense of curvature, nor do they straighten towards the central part of the assemblage.

DISCUSSION

The above analyses have shown that curved slickenlines may arise due either to roto-translational fault motion or to fault motions where the translation direction changes continuously during the fault movement. These analyses reveal that the two kinds of fault action can be deciphered from the shapes of their slickenlines. An assemblage of curved slickenlines in which each slickenline differs from the other in shape indicates roto-translational fault motion, whereas an assemblage where the shape of every slickenline is similar suggests curvilinear-translational fault motion. Thus, the dip-isogons between any two slickenlines in the latter type of assemblage will be parallel. Furthermore, the slickenlines of roto-translational faults are characterized by their tendency to straighten towards the central part of the assemblage and a reversal of sense of curvature of the slickenlines across the straight slickenline.

The analysis of slickenlines of roto-translational fault motion can be applied to natural slickenlines to estimate the relative rate of translation vs rotation (i.e. δ value) in natural faults. The δ value can be calculated from natural slickenlines using equation (8). However, application of the equation in natural situations requires fortuitous exposures exhibiting an assemblage of well-developed slickenlines with a straight slickenline so that the ϕ value can be obtained.

The analysis of curvilinear-translational fault motion can also be applied to natural situations to estimate the relative rate of change of translation direction with respect to the rate of translation.

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