Estimation of average to maximum displacement ratio by using fault displacement-distance profiles

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ABSTRACT

Fault displacement is an important factor in the study of discontinuous deformation. Considering that the values of average displacement \( D_{av} \) and maximum displacement \( D_{mx} \) are linearly related by \( D_{av} = \rho D_{mx} \), we calculate the values of \( \rho \) estimated from 205 published displacement-distance profiles. The following results are obtained: (a) the value of \( \rho \) is largest for the mesa-type or flat-topped (M-type) profiles; (b) the value of \( \rho \) increases when ductile (continuous) deformation is added to the displacement profile; (c) generally, the value of \( \rho \) for a linked fault array is smaller than that for segmented faults in the array, i.e., the value of \( \rho \) changes with fault evolution, and at the stage where linkage occurs, the value of \( \rho \) becomes smaller; (d) the simulation results indicate that for an ellipse function, the value of \( \rho \) varies from 0.667 to 0.785. For trapezoid (M-type) profiles, the value of \( \rho \) is from 0.5 to 1, depending on the ratio of the upper base to the lower base. For best fit polynomial curves, the value of \( \rho \) can be less than 0.5; (e) the values of \( \rho \) more frequently observed in the published profiles are between 0.6 and 0.7; the average value is 0.6023 and the standard deviation 0.1123. These data indicate that the displacement-distance profiles are hybrids from the triangular profile to the elliptical or mesa profile. The average value (0.6023) would be useful to determine the average displacement in cases where not enough displacement data can be obtained. Finally, the value change of \( \rho \) with fault evolution can be used to quantitatively evaluate the level of interaction between segmented faults.

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1. Introduction

Displacement along faults is a major kinematic parameter of upper crustal deformation. Fault slip (displacement) data are necessary to infer both the orientations and relevant magnitudes of the principal stresses and the principal strain rates. Given a known average displacement, it is possible to quantify the fault-related strain (e.g., Molnar, 1983; Scholz and Cowie, 1990; Žalohar and Vrabc, 2008).

Displacement-distance profiles along faults can provide insight into fault-growth history and information regarding fault interaction (e.g., Gupta and Scholz, 2000; Manighetti et al., 2001; Peacock and Sanderson, 1991). The ratio of the average displacement to the maximum displacement is dependent on the shapes of displacement-distance profiles (Marrett and Allmendinger, 1990). When evaluating a seismic moment or a geometric moment, a linear relationship between the displacement averaged over fault surface \( u_{av} \) and the maximum displacement of a fault \( u_{mx} \) is given as \( u_{av} = c u_{mx} \) with the value of \( c \) equal to 0.5 as a rough estimate (Marrett and Allmendinger, 1990). Based on the semi-elliptical displacement profile, Olson (2003) presented a linear relationship of \( D_{av} = (\pi/4) D_{mx} \), where \( D_{av} \) is the average displacement and \( D_{mx} \) is the maximum displacement. The coefficient \( \pi/4 \) has been used to simulate the volumetric flow per unit width that is normal to the direction of the flow through fractures (Klimczak et al., 2010).

Fault displacement is the change in position of a marker or horizon caused by fault movement. The displacement data can be commonly obtained from field measurements or seismic reflection profiles. The accuracy of the observed displacement distributions on a fault strongly depends on the outcrop condition, the number of markers, and the measurement method. The aim of this paper is to determine the most common values of the ratio of the average-maximum fault displacement \( (\rho = D_{av}/D_{mx}) \). To accomplish this, we investigate the effects of profile shapes, ductile deformation, and fault linkage on the value of \( \rho \), as calculated from the known, published displacement profiles. In addition, the more common geometries of displacement-distance profiles are individually investigated.

In this paper we estimated the values of \( \rho \) based on the published displacement-distance profiles (Section 2), and analyzed the values of \( \rho \) obtained from synthetic displacement profiles using trapezoidal, elliptical, and polynomial curves (Section 3). In the Section 4, the histogram of values of \( \rho \) from 205 representative profiles is obtained and the average value of \( \rho \) is calculated. Finally, in Section 5, we discuss the effects of fault interaction and off-fault damage on the value of \( \rho \).
2. Values of $\rho$ from the displacement-distance profiles

Displacement profiles are graphs of displacement (ordinates) versus distance in a section throughout the fault plane (abscissas). These profiles can be utilized to calculate the value of $\rho$. Given a displacement profile, the average displacement is equal to the area below the curves $S$ divided by the fault length ($L$). This relation can be written as

$$D_{av} = \frac{S}{L}. \quad (1)$$

This calculation is similar to the method of Dawers et al. (1993), who defined the average displacement as the exposed surface area of the fault scarp divided by fault length ($L$). When $D_{av}$ is known, the value of $\rho$ is

$$\rho = \frac{D_{av}}{D_{max}}. \quad (2)$$

The next sections present the values of $\rho$ obtained from the published displacement-distance profiles. By using the calculated results, we can analyze the change of values of $\rho$ due to various factors.

2.1. Types of displacement-distance profiles

Muraoka and Kamata (1983) detected three patterns of displacement-distance profiles: C-type (cone-shaped), M-type (mesa-shaped), and irregular type. The C-type profiles have a nearly symmetrical shape with a gentle change in displacement. The M-type profiles show a broad central part with no significant change in the slope and steep slopes of the graphs in the flanking portions. Muraoka and Kamata (1983) proposed that the type of profile is controlled by the lithology of wall rocks, with C-type faults being characteristic of homogeneous incompetent materials and M-types representing faults that cut through a rigid unit. Table 1 shows that the values of $\rho$ for M-type faults are the largest of the three types of displacement profiles. The values of $\rho$ seem to positively relate to the $D_{max}/L$ ratio. The $D_{max}/L$ ratios of M-type faults are approximately twice that of C-type faults (Muraoka and Kamata, 1983).

Similarly, Dawers et al. (1993) presented three types of displacement profiles: peaked, flatter topped, and unclassified. These profiles correspond to the C-type profiles, the M-type profiles and the irregular profiles of Muraoka and Kamata (1983), respectively. The maximum values of $\rho$ calculated are seen in the mesa (plateau) profiles (Table 1).

This is consistent with the results calculated from the data of Muraoka and Kamata (1983).

2.2. Effect of ductile (continuous) deformation

Large displacement gradients in relay zones and tip zones have been proposed to be generally accommodated by bed rotations or drag folds (e.g., Dawers and Anders, 1995; Mansfield and Cartwright, 2001; Nicol et al., 2002; Peacock and Sanderson, 1991). Dawers and Anders (1995) define continuous deformation ($D_c$) such that it includes bed tilting and the displacements of small faults. Nicol et al. (2002) proposed that the fold deformation in relay ramps should be included in the total fault displacement. If the displacement from the large measured faults is treated as discontinuous deformation ($D_d$), then the total displacement should contain both continuous deformation ($D_c$) and discontinuous deformation ($D_d$).

$$D_t = D_c + D_d. \quad (3)$$

Dawers and Anders (1995) found that the maximum vertical continuous deformation reaches $D_c = 24.7$ m along a fault zone with length of 7130 m (Fig. 1a). The value of $\rho$ from the profile of $D_c$ is 0.49, whereas the value of $\rho$ from the profile of $D_d$ is 0.6. Using an analog model, Mansfield and Cartwright (2001) found the displacements at the mm-scale that were due to continuous deformation (Fig. 1b). The maximum value of $D_c$ is 2.7 mm along a fault zone with a length equal to 30.3 cm. The value of $\rho$ from the profile of $D_d$ is 0.37, whereas the value of $\rho$ from the profile of $D_d$ is 0.42. These two examples indicate that the values of $\rho$, when considering continuous deformation, are larger than those of the profiles that do not consider continuous deformation. The inclusion of continuous deformation can smooth the along-strike displacement profiles, especially at the relay ramps (Fig. 1c). This smoothing may be the reason that the value of $\rho$ increases for profiles with continuous deformation.

In most cases, local displacement minima are located in relay zones where fault-related folding and bed rotation have an increased concentration (Childs et al., 1995; Dawers and Anders, 1995; Huggins et al., 1995; Peacock and Sanderson, 1991). Whether a segmented array is a geometrically coherent system can be assessed by the profiles that include both the discontinuous and continuous displacement (Childs et al., 1995; Huggins et al., 1995; Mansfield and Cartwright, 2001). When both the discontinuous and continuous components of displacement are included, an aggregate displacement-low can be smoothed between the points of maximum displacement on adjacent segments, which allows individual segments that were originally coherent faults to be considered (Fig. 1c) (Walsh et al., 2003).

2.3. Components of displacement

Various components of fault displacement were reported in different studies involving analyses of the $D$–$L$ relationship, fault growth, etc. In most cases, vertical components (throws) of fault displacement for normal faults were reported (e.g., Vetel et al., 2005; Walsh and Watterson, 1987). Some papers published data for the strike-slip component (e.g., Accolla and Neri, 2005; Peacock, 1991), while others used dip slip or net slip to study fault linkage (e.g., Mazzoli et al., 2005).

Occasionally, the presented profiles have more than one component from the same fault. Mirabella et al. (2004) obtained both dip-displacement and throw profiles from the active Gubbio normal fault in Central Italy by interpreting the seismic profiles (Fig. 1d). The total displacement profile is similar to that of throw. However, the total displacement profile has a flatter top part while the throw profile more closely resembles a linear distribution (cone type). Our analysis

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Fig.</th>
<th>No. fault</th>
<th>$\rho$</th>
<th>Remark</th>
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<tbody>
<tr>
<td>Muraoka and Kamata (1983)</td>
<td>Fig. 5</td>
<td>f1</td>
<td>0.59</td>
<td>Irregular type</td>
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<td></td>
<td></td>
<td>f2</td>
<td>0.58</td>
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<td>f4</td>
<td>0.62</td>
<td>Cone type</td>
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<td>f6</td>
<td>0.58</td>
<td>Cone type</td>
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<td>f8</td>
<td>0.47</td>
<td>Cone type</td>
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<td></td>
<td>Fig. 6</td>
<td>f10</td>
<td>0.75</td>
<td>Mesa type</td>
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<td></td>
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<td>f11</td>
<td>0.65</td>
<td>Mesa type</td>
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<td></td>
<td></td>
<td>f12</td>
<td>0.68</td>
<td>Mesa type</td>
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<td></td>
<td></td>
<td>f14</td>
<td>0.65</td>
<td>Mesa type</td>
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<tr>
<td>Dawers et al. (1993)</td>
<td>Fig. 2</td>
<td>L = 24 m</td>
<td>0.57</td>
<td>Peaked profiles</td>
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<td></td>
<td></td>
<td>L = 55 m</td>
<td>0.68</td>
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<td>L = 167 m</td>
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<td>L = 182 m</td>
<td>0.52</td>
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<td>L = 440 m</td>
<td>0.53</td>
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<td>L = 500 m</td>
<td>0.62</td>
<td>Un-classified profiles</td>
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<td>L = 540 m</td>
<td>0.6</td>
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<td>L = 696 m</td>
<td>0.63</td>
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<td>L = 740 m</td>
<td>0.57</td>
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<td></td>
<td>L = 780 m</td>
<td>0.71</td>
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<td></td>
<td></td>
<td>L = 866 m</td>
<td>0.62</td>
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<td></td>
<td></td>
<td>L = 1620 m</td>
<td>0.54</td>
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<td>L = 1630 m</td>
<td>0.69</td>
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<td>L = 2210 m</td>
<td>0.7</td>
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Eastern Mediterranean (Baudon and Cartwright, 2008a) are analyzed. Results show that the values of \( \rho \) for the total displacement profile (0.62) is larger than that for the throw profile (0.51). Another example for the estimation of \( \rho \) is the data from the normal faults in the rift zone of Central North Iceland (Tentler and Mazzoli, 2005). Tentler and Mazzoli (2005) presented the throw profiles and opening (dilatational component) profiles of both the Western Fault and the Eastern Fault in Veggir graben. Both types of profiles show three minima, indicating possible fault linkage in their evolutionary history. The throw and opening profiles are variable but generally are greatest near the middle of the fault. We obtained values of \( \rho \) for both of these profile types. The results show that the values of \( \rho \) for throw profiles (Fig. 1g) are larger than those of opening profiles (Fig. 1f).

**2.4. Effect of the sampling position**

It is well known that the displacement profile varies depending on the sampling position. To investigate the sampling effect on the value of \( \rho \), the displacement profiles of a normal fault in the Levant Basin, Eastern Mediterranean (Baudon and Cartwright, 2008a) are analyzed (Fig. 2). This fault is an unrestricted blind fault that did not interact with a mechanical boundary or another structure. As such, this fault should approximate an ideal isolated fault. The key horizons cut by the fault are the Pliocene-Quaternary succession above the Messinian unconformity, which mainly consist of clay-rich marls, sandstones, and claystones. Twenty vertical displacement profiles with intervals of 50 m are presented by Baudon and Cartwright (2008a). The vertical displacement profiles do not exhibit typical linear or triangular profiles but are rather mostly flat-topped or hybrid in type (Fig. 2a). As a result, the values of \( \rho \) for these profiles are larger than 0.6. Some segments have values of \( \rho \) larger than 0.7 with the maximum values located in the vicinity of the tip zone (crosslines 3198 and 3274). Displacement profiles (lines 1–10) along the fault strike are obtained from the data of vertical displacement profiles in Fig. 2a. Some of the lateral displacement profiles demonstrate a linear or triangular profile. The values of \( \rho \) exist over a wide range, varying from 0.48 to 0.84 (Fig. 2b). The minimum values of \( \rho \) are in the tip zone (lines 1, 9, and 10). These irregularities in the throw profile, and thus the values of \( \rho \), are partly attributed to local changes in lithology according to Baudon and Cartwright (2008a).

**2.5. Fault linkage**

Field and experimental evidence suggests that the segmented structure of faults is a basic characteristic of most natural arrays at different scales. Two fault linkage models are distinguished in nature: the isolated model and the coherent model (e.g., Childs et al., 1995; Walsh et al., 2003). The former refers to initially isolated fault segments that grow by tip line propagation and progressively experience eventual, and incidental, lateral overlap and interaction. In the latter model, the individual
segments have kinematically related components inherited from the initial structures; at the final stage, they link into a single continuous fault surface in three dimensions (Walsh et al., 2003). The finite displacement distributions for these two linkage models are different. For the coherent model, the fault segments have complementary finite displacement distributions in which aggregate displacement distribution is smooth and regular, nearly resembling that of a single isolated fault (e.g., Mansfield and Cartwright, 2001). For the isolated fault model, the aggregate displacement distribution shows several local maxima and minima even after hard linkage (e.g., Giba et al., 2012).

Fault profiles can be classified into three types based on fault growth and evolution: isolated faults, soft linked en echelon fault arrays and hard-linked fault arrays. Isolated faults evolve by fault tip propagation with no interaction with other fault segments. Soft linked en echelon fault arrays are developed by the soft linkage of echelon segments. For these fault arrays, the segmented faults have relay ramps with other neighboring faults. Analysis results from the data of Huggins et al. (1995), Willemse et al. (1996), and Walsh et al. (2003) indicate that the values of $\rho$ for segmented faults are larger than those for total linked fault arrays (Figs. 3a, b and c). In some cases, the values of $\rho$ for individual segmented faults are smaller than those for the total linked fault arrays, but, nevertheless, the average value of $\rho$ for individual segmented faults is larger than that for total linked fault arrays (Fig. 3d). Soliva and Benedicto (2004) proposed that fault linkage can be classified into three types: open, linked, and fully breached. If the isolated fault profile is assumed to be a cone, the value of $\rho$ for the profile of linked fault arrays can be both larger and smaller than that for the ideal isolated fault (Figs. 3d, f). A fault with fully breached linkage expresses...
2.6. Fault evolution stages

Fault evolution stages have been classified based on an isolated fault model (e.g., Peacock and Sanderson, 1991) and a coherent fault model (e.g., Kristensen et al., 2008). Evidence shows that in most cases, fault segments develop from a single and kinematically coherent system (Kristensen et al., 2008; Walsh et al., 2003). Based on three-dimensional data sets, Kristensen et al. (2008) proposed that coherent arrays experience four evolutionary stages. At stage 1, initial lobes exist in propagating fault tip-lines. At stage 2, relay zones develop that allow the transfer of displacement between overlapping fault segments. At stage 3, relay zones are breached with an increase in displacement. Finally, the two fault lobes link to form a fault bounded lens (stage 4). Analog experiments show that both isolated and coherent linkage can occur in the same fault system (Mansfield and Cartwright, 2001). For isolated fault linkage, displacement deficits exist for a long period, even compared to hard linkage, although they become progressively lower with time. A typical example can be seen in linkage between segments A and B in Figs. 4a-d. On the other hand, for coherent linkage, displacement deficits can be rapidly removed after linkage, as seen in the coalescence of segments C and D in Figs. 4e-h.

A fault array develops by a repetitive sequence of tip-line propagation, overlap, and linkage with their nearest neighbors. Surface displacement distribution along a strike is therefore characteristically irregular, fluctuating between local maxima at fault segment centers and minima at segment boundaries (Mansfield and Cartwright, 2001). Based on the values of $\rho$, three temporal displacement profiles of fault arrays can be distinguished: a fault array before linkage (type 1), a fault array immediately after overlap or linkage (type 2), and a fault array after an increment step of overlap or linkage (type 3). The displacement profile for type 1, similarly to an isolated fault, has the maximum value of $\rho$ of the three temporal displacement profiles. The case presented in Fig. 4a is a typical example of this type of fault array ($\rho = 0.55$ for segment A and $\rho = 0.68$ for segment B). The type 2 fault arrays have the minimum value of $\rho$ of the three temporal displacement profiles ($\rho = 0.45$ for the fault array in Fig. 4c). The displacement minima can be reduced over time after overlap or linkage. Thus, the value of $\rho$ also increases with time until the next overlap or linkage ($\rho = 0.57$ for the fault array in Fig. 4d), which can be described by a conceptual model (Fig. 5).

3. Value of $\rho$ for best-fit curves from the displacement profiles

For the ideal isolated model, the displacement at the fault center is a maximum and decreases from the center of the fault plane to a tip line (e.g., Watterson, 1986). If there is no significant mechanical heterogeneity and if the displacement has accrued over the entire fault plane, the tip line is elliptical. Ideal isolated faults grow by radial propagation...
with no migration of the point of maximum displacement (Walsh et al., 2003). Because of this characteristic, cone- and bell-shaped displacement profiles are usually regarded as being formed by isolated faults (e.g., Cowie and Scholz, 1992; Gupta and Scholz, 2000; Nicol et al., 2005). Segmented arrays may display aggregate displacement variations that are similar to those of a single isolated fault (e.g., Dawers and Anders, 1995; Walsh and Watterson, 1990). Thus, the observed faults may show any stage of fault history, and the displacement profiles can show multiple maxima and minima. Here we can simulate a displacement profile using curve functions such as a triangle, an ellipse, a trapezoid, or a polynomial.

3.1. Value of $\rho$ for a trapezoid profile

Mesa-type profiles can be simulated by trapezoids, as shown in Fig. 6a. The lower base of the trapezoid is the fault length $L$. Let the upper base be $\gamma L$; then, the area of the trapezoid is $S_t = hL(1 + \gamma)/2$, where $0 \leq \gamma \leq 1$. The average displacement is $D_{av} = S_t/L = h(1 + \gamma)/2$. The maximum displacement should be equal to $D_{mx} = h$. Then, the value of $\rho$ is

$$\rho = D_{av}/D_{mx} = (1 + \gamma)/2.$$  (4)

![Fig. 4. Values of $\rho$ from the sequential displacement profiles along the same fault array evolving over time, from analogue experiments. Solid lines represent the displacements of individual segments, and dashed lines represent cumulative displacements, summed at points of fault segment overlap. (modified from Mansfield and Cartwright, 2001)](image)

![Fig. 5. Conceptual model showing the variation of $\rho$ due to fault linkage. The value of $\rho$ increases during the accumulation of displacement, while decreasing at the immediate linkage stage.](image)
This equation indicates that the value of \( \rho \) for a mesa-type profile has a linear relationship with the ratio of the upper base to the lower base of the trapezoid. The extreme cases are \( \gamma = 0 \) and \( \gamma = 1 \) (Fig. 6b), which correspond to a triangle and a square, with \( \rho \) values of 0.5 and 1, respectively.

### 3.2. Value of \( \rho \) for ellipse segment profiles

For an isolated fault, the distribution of the displacement is symmetric: the maximum value is found at the center of the fault, and the minimum value (zero) is found at the two tip points. Assuming that the pro

\[
y = \pm \frac{b}{a} \sqrt{a^2 - x^2}
\]

where \( a \) and \( b \) are the major and minor radii, respectively. Geologically, \( b \) is the fault displacement, and \( 2a \) is the fault length. As shown in Fig. 6c, the displacement profile may have the forms of ABC, DBE, etc. The area under the curve is obtained from the definite integral in the interval \( x_1, x_2 \), and the average displacement is obtained by dividing this area by \( |x_1-x_2| \). When the profile of the displacement has the form of an ellipse, its standard function is expressed as \( \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \) or

\[
y = \pm \frac{b}{a} \sqrt{a^2 - x^2}
\]

where \( 0 < \lambda \leq 1 \). Thus, the ratio between the average and maximum value of displacement (\( \rho \)) is

\[
\rho = \frac{D_{av}}{BF} = \frac{\arcsin \lambda - \lambda \sqrt{1 - \lambda^2}}{2\lambda (1 - \sqrt{1 - \lambda^2})}
\]  

The relationship between \( \lambda \) and \( \rho \) from Eqs. (8) is shown in Fig. 6d. The two factors are positively related. In other words, a larger value of \( \lambda \) produces a larger value of \( \rho \). The value of \( \rho \) varies from 0.667 to 0.785 for 0 < \( \lambda \leq 1 \), i.e., the value of \( \rho \) for the partial arc with a chord shorter than the diameter is less than that of the half ellipse (0.785). As we know, the slope of a tangent line at a point on a curve represents the gradient of the curve. We can see from Figs. 6c and d that for a smaller value of \( \lambda \), the gradient at the tip points of a fault is smaller.

### 3.3. Values of \( \rho \) when using best-fit polynomial curves

As described above, displacement profiles may by irregular, displaying multiple maxima and minima. The irregular profiles can be simulated by using best-fit polynomial curves. Considering polynomials of six degrees, we have

\[
f(x) = ax^6 + bx^5 + cx^4 + dx^3 + ex^2 + fx + g.
\]

A fit can be achieved by changing the values of the coefficients \( a, b, c, d, e, f, \) and \( g \). We can also reduce the degree (highest power) by setting some parameters to zero.

Some fitting curves from the published displacement profiles (Muraoka and Kamata, 1983; Xu et al., 2011) are shown in Fig. 7. For the best fit curves, the following results are obtained. (1) In most cases, the fitting curve can smooth the original maxima and minima. In this way, the best fit curves display changes in displacement tendencies. (2) For most of the best fit curves, the coefficients \( R^2 \) are larger than 0.95, which indicates a highly reliable fitting. (3) For the simulated curves, the maximum relative error of the average and maximum displacement is less than 5%. (4) In general, the relative error of the values of \( \rho \) is less than 5%. The error reaches a maximum of 10%. (5) The shapes of the best fit curves are consistent with the types of displacement profiles proposed by Peacock (1991), although his classification is based on symmetric displacement profiles. These types are described as follows.
(a) Ideal elastic type (I type), which is similar to the half or partial arc of ellipse, for example, fitting curves in Figs. 7d, f. (b) The cone-shaped type (C type) describes a linear distribution. The curves of Fig. 7d and f are similar to the C-type. (c) The mesa-shaped (M-type) shows a flattened top profile, quite similar to those in Figs. 7h, i and j. (d) Elevated about the C-type profile, as seen in the fitting curve of
Burbank and Anderson, 2011). Blank circles indicate fault initial points. Filled semi-circles are barriers. The solid semicircle is the ruptured barrier.

Roberts, 2008; Tvedt et al., 2013; Wilkins and Gross, 2002; Xu et al., 2005; Morley and Wonganan, 2000; Nixon et al., 2011; Podolsky and Bürgmann and Pollard, 1994; Davis et al., 2005; Mazzoli et al., 1991). (c) Classification of various shapes of displacement profiles and relative percentages of faults in the southern end of the Red Sea Rift (from Manighetti et al., 2001, as modified by Burbank and Anderson, 2011). Blank circles indicate fault initial points. Filled semi-circles are barriers. The solid semicircle is the ruptured barrier.

Fig. 7e. Depressed below the C-type profile, similar to the fitting curves in Figs. 7a and g seem to belong to this type.

4. Histogram of values of ρ

In addition to the profiles shown in Figs. 1, 2 and 3, we have also analyzed values of ρ for other published profiles (Baudon and Cartwright, 2008a, b; Bürgmann and Pollard, 1994; Davis et al., 2005; Mazzoli et al., 2005; Morley and Wonganan, 2000; Nixon et al., 2011; Podolsky and Roberts, 2008; Tvedt et al., 2013; Wilkins and Gross, 2002; Xu et al., 2004). All analyzed profiles are widely representative because they are taken from three types of fault, i.e., normal faults, strike-slip faults (Peacock, 1991) and thrust faults (Davis et al., 2005; Mazzoli et al., 2005; Nixon et al., 2011). Most profiles are from two-dimensional data, with only a few representing three-dimensional data (e.g., Baudon and Cartwright, 2008a, b; Kristensen et al., 2008; Tvedt et al., 2013). In many cases, only the map-view patterns of a fault array are observable, but in the three-dimensional cases, cross-sectional profiles can obtained. The histogram produced from 205 values of ρ indicates that the peak values of ρ fall within 0.6–0.7 (Fig. 8a). The average value of ρ is 0.6023. The standard deviation for the estimation of the average value is 0.1123. Taking the positive standard deviation, the value of ρ is 0.7146, which corresponds to the values of ρ for trapezoid profiles with γ = 0.42 and ellipse profiles with λ = 0.87, respectively. Turning to the negative standard deviation, the value of ρ is 0.49, which is close to the values of ρ for triangle profiles (trapezoid profile with γ = 0). These results suggest that most profiles should have values of ρ above the triangle profiles (Fig. 8b). The profiles with values of ρ larger than 0.7 may be Mesa shaped ones (e.g., Figs. 7h–j). In Fig. 8a, some values of ρ are smaller than 0.5. The values of ρ less than 0.5 are from the depressed below C type profiles (D type, e.g., Figs. 7d, 9f, and 8b) or the profiles of the immediately linked fault array (Figs. 4c, e and g).

Most profiles should be hybrid in type (Fig. 7), as their ρ values are dependent on the sampling position, components measured, and fault linkage. One dataset of 240 faults, measured near the southern end of the Red Sea rift, presents both triangle and elliptical (or trapezoidal) displacement profiles (Manighetti et al., 2001). Six types are distinguishable from this dataset (Fig. 8c). The ideal symmetrical profiles that develop with both tips unrestricted constitute only 4% of all faults (type 1 in Fig. 8c). The ellipse segment and mesa profiles, with two tips restricted, represent 43% of total faults (type 5 + type 4 in Fig. 8c). Other irregular and asymmetric patterns (types 2, 3 and 6)
are encountered where only one tip is restricted. These results in the Red Sea rift are largely consistent with the global data shown in Fig. 8a.

5. Discussion

A geometric moment \((M_g)\) is positively related to the average displacement \((D_{av})\) on the fault: \(M_g = AD_{av}\), where \(A\) is fault surface area (e.g., Marrett and Allmendinger, 1990). If the continuous ramp deformation is not included, the ratio \(\rho\) is decreased, which produce an underestimation of the average displacement and then the geometric moment can be under-estimated. On the other hand, the relationship between \(D_{mx}\) and \(L\) in a single tectonic environment with uniform mechanical properties is linear: \(D_{mx} = \beta L\), where \(\beta\) is constant (e.g., Dawers et al., 1993; Mansfield and Cartwright, 2001; Xu et al., 2006). In this way, the average displacement can be written as \(D_{av} = \rho D_{mx} = \beta \rho L\). This relation facilitates the calculation of brittle strains which are a function of the geometric moment or the average displacement (e.g., Scholz, 1997; Zálohar and Vrabec, 2008).

As shown in Fig. 5, the value of \(\rho\) varies with time and decreases during the linkage stage, which indicates that an evolving fault arrays are not always efficient at accommodating a given amount of regional tectonic strain at all stages. The under-estimated strain at linkage stage may be demonstrated by the off-fault damage, nucleation of small faults or ductile strain. If the off-fault cracks are small, more are required; if they are larger, fewer are needed. The off-fault damage commonly fans from the centers of main normal faults, systems, and extensional structures. In this way the width of the triangular damage zone increases far from the main fault center with fan angle of \(15^\circ - 40^\circ\) according to Manighetti et al. (2004) (Fig. 9). The off-fault damage is also called process zone (e.g., Cowie and Scholz, 1992). The width of process zone scales linearly with fault length with a ratio of \(10^{-1}\) to \(10^{-2}\) (Scholz et al., 1993; Vermilye and Scholz, 1998) which indicates that the fan angle varies between \(2^\circ\) and \(12^\circ\). For cone shaped displacement profile, the fault displacement is negatively related to the damage width. At a relay zone, the two off-fault damage zones of two segments can be superimposed when the fault interaction initiates. The reduced off-fault damage causes an increase in fault displacement in the relay zone. Because the superimposed damage zone increases in size with the evolution of fault linkage (Fig. 9), it is positively related to the value of \(\rho\) and then can be used as a measure of interaction between segments. If a hard linkage occurs with time, damage occurs at two scales: the scale of the segments, and the larger scale of the whole fault. This may produce irregularities in the displacement profile along the whole fault array (Manighetti et al., 2004).

As shown in Fig. 9, the overlap length seems to be a factor to evaluate the degree of fault interaction (e.g., Gupta and Scholz, 2000). In some literature, spacing to total system length ratio is used to estimate the degree of fault interaction (e.g., Hus et al., 2005; Willems, 1997). The critical ratio is 12.5%–15%, which implies that interaction and linkage occur only when the total length of the two fault segments is larger than six to eight times their spacing. Based on the steeper displacement gradient in the interacting region, Huggins et al. (1995) proposed that the critical displacement gradient of fault interaction at the fault tips is 0.015. A fault array with higher degree of fault interaction will have larger value of \(\rho\) (Fig. 10). This means lower spacing to total system length ratio has larger value of \(\rho\) (Fig. 10d). This is consistent with the model in Fig. 5 and Fig. 9. Mechanically, for soft linkage fault segments interact through their stress fields. The displacement anomaly in the relay zone is positively related to the stress drop. Therefore tip propagation into higher stress drop regions is proportional to displacement increase near fault tips (Gupta and Scholz, 2000).

In this paper, the most common value of the ratio of the average-maximum fault displacement \((\rho = D_{av}/D_{mx})\) is determined. This value (0.6023) would be useful in cases where the displacement maximum is not constrained and there is no enough information to determine the average displacement. On the other hand, the values of \(\rho\) facilitates the calculation of brittle strains if the displacement data of faults cannot be all obtained in a studied area. Finally, the values of \(\rho\) can be used to quantitatively evaluate the interaction level between fault segments.

6. Conclusions

The average displacement of a fault can be calculated from the displacement-distance profiles. The value of the average displacement,
of polynomial curves can be smaller than 0.5, which may be a result due to the shorter arc segments of the ellipse. The values of ρ below the mean, the standard deviation of 0.1123. Looking one standard deviation above or below the mean, the values of ρ for elliptical functions varies from 0.667 to 0.785, displaying smaller values for shorter arc segments of the ellipse. The values of ρ for the best fit polynomial curves can be smaller than 0.5, which may be a result due to the D-type (depressed below C-type) profiles. (g) The more frequent values of ρ fall in the range 0.6 to 0.7, with a mean value of ρ = 0.6023 and a standard deviation of 0.1123. Looking one standard deviation above or below the mean, the values of ρ fall between the meso-type and the ideal elastic (ellipse) profiles.

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References


D_{max}, and the maximum displacement, D_{max}, can be expressed as D_{max} = \rho D_{M0}, where 0 < \rho < 1. In the first part of this study, the ratio between the average and the maximum displacement (\rho) was estimated from published displacement profiles. The detailed results are as follows:

(a) The largest values of \rho are from the meso-type, flat-topped profiles.
(b) The value of \rho increases when considering the ductile (continuous) deformation in the displacement profile. (c) The displacement profiles are distinct for different components of displacement. The value of \rho for the profile of a dip- or net displacement is larger than that of other components. (d) In general, the value of \rho for a linked fault array is smaller than that of segmented individual faults in the same studied area, with exceptions. If the profile of an isolated fault is a triangle (cone) shape, its value of \rho can be larger or smaller than that of segmented individual faults or linked fault arrays. (e) The value of \rho varies depending on the fault evolution stage. Fault linkage usually decreases the value of \rho. (f) The displacement profiles can be simulated by elliptical, trapezoidal, and polynomial best fits. The value of \rho for elliptical functions varies from 0.667 to 0.785, displaying smaller values for shorter arc segments of the ellipse. The values of \rho for the best fit polynomial curves can be smaller than 0.5, which may be a result due to the D-type (depressed below C-type) profiles. (g) The more frequent values of \rho fall in the range 0.6 to 0.7, with a mean value of \rho = 0.6023 and a standard deviation of 0.1123. Looking one standard deviation above or below the mean, the values of \rho fall between the meso-type and the ideal elastic (ellipse) profiles.