Software for determining the true displacement of faults

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A B S T R A C T

One of the most important parameters of faults is the true (or net) displacement, which is measured by
restoring two originally adjacent points, called “piercing points”, to their original positions. This
measurement is not typically applicable because it is rare to observe piercing points in natural outcrops.
Much more common is the measurement of the apparent displacement of a marker. Methods to calculate
the true displacement of faults using descriptive geometry, trigonometry or vector algebra are common
in the literature, and most of them solve a specific situation from a large amount of possible
combinations of the fault parameters. True displacements are not routinely calculated because it is a
tedious and tiring task, despite their importance and the relatively simple methodology. We believe that
the solution is to develop software capable of performing this work. In a previous publication, our
research group proposed a method to calculate the true displacement of faults by solving most
combinations of fault parameters using simple trigonometric equations. The purpose of this contribution
is to present a computer program for calculating the true displacement of faults. The input data are the
dip of the fault; the pitch angles of the markers, slickenlines and observation lines; and the marker
separation. To prevent the common difficulties involved in switching between operative systems, the
software is developed using the Java programing language. The computer program could be used as a
tool in education and will also be useful for the calculation of the true fault displacement in geological
and engineering works. The application resolves the cases with known direction of net slip, which
commonly is assumed parallel to the slickenlines. This assumption is not always valid and must be used
with caution, because the slickenlines are formed during a step of the incremental displacement on the
fault surface, whereas the net slip is related to the finite slip.

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1. Introduction

Faults are ubiquitous structures in the upper crust of the Earth. Geologists and engineers encounter faults during the construction of roads, buildings, dams and other civil works. Additionally, faults can form zones of fluid transport, permeability barriers or structural traps for ore deposits (e.g., McKinstry, 1948), oil or gas (e.g., Evans et al., 1997). In geological work, it is crucial to determine the true (net) displacements of faults, for example, to intersect veins in mining and drilling, constructing restored sections, and conducting local or regional strain analysis. Thus, geologists study faults in a wide range of environments and scales. Nevertheless, in daily work, geologists seldom determine the true (net) displacement of faults observed during fieldwork.

A common and simple definition of fault is “a fracture in which there has been displacement of the sides relative to one another parallel to the fracture” (e.g., Bates and Jackson, 1984; Jaeger and Cook, 1969, p. 3). Fault-slip data collected in the field typically consist of the strike and dip of the fault plane and the pitch angle of the slickenlines (Fig. 1a). Although, in general, the slickenlines are considered parallel to the slip direction (e.g., Ragan, 2009), it is not valid in many cases because the slickenlines are formed during the steps of incremental fault displacement and not necessarily reflect the finite slip of the fault. Other important data are the true displacement of the fault, which is obtained from the identification of two points (piercing points) that were adjacent before the fault movement. A graphical technique using piercing points for calculating the net slip is presented in Ragan (2009). However, in general, the true displacement of a fault cannot be measured or determined directly in the field because the piercing points cannot be observed. Moreover, most of the faults observed in the field do not have slickenlines.

On the other hand, it is more common to find cut-off markers, such as beds, veins, dikes or other planar structures displaced by...
the fault. The apparent displacements (separations) measured from cut-off markers depend on the geometric relationships between the fault plane, observation plane, slickenlines and markers. The true displacement is estimated from the slickenline orientation and the apparent displacement of a marker or, in the absence of slickenlines, calculated using two non-parallel markers (e.g., Lisle and Walker, 2013; Xu et al., 2009; Yamada and Sakaguchi, 1995).

In daily geological work, the calculation of the true displacement is not performed because it is a tedious and time-consuming task. Although the geometrical problem is not complicated and can be solved using trigonometry, descriptive geometry, stereographic projections or vector algebra, there are a high number of possible combinations among the parameters observed in the field. The solutions for specific cases can be found in numerous publications (e.g., Lisle, 2004; Lisle and Walker, 2013; Ragan, 2009; Ramsay and Huber, 1987; Xu et al., 2007). A general method to find the solutions for all combinations of fault parameters was published in Yamada and Sakaguchi (1995), who used the direction cosines of the fault, observation plane and cut-off marker to find piercing points that permit the true displacement to be calculated.

Several years ago, our research group published two papers in which we compiled the most common cases of geometrical arrangements of fault parameters (Xu et al., 2007, 2009) and solved each one using simple trigonometric equations. Unlike the model presented by Yamada and Sakaguchi (1995), our solutions are presented in terms of the pitch angles and the separation of a marker along an observation line. Our idea was that a geologist could directly input the measured data into an equation and use an electronic calculator to solve it.

Notwithstanding the critical importance of knowing the true displacement of faults, we have failed to find freeware, or shareware software, that helps geologists and engineers in their daily work. In response to these circumstances, we present in this study an application that makes it easy and amenable to calculate true and apparent (heave and throw) fault displacements from field or map data. The application solves 18 different combinations of parameters, which we hope covers most of the common cases observed in fieldwork.

2. Model assumptions and geometry

The geometrical model assumes that, at the scale of observation (1) the faults are planar, (2) slickensides are straight and are parallel to the net displacement vector, (3) there is no displacement perpendicular to the fault plane, and (4) the host rock is a rigid body. In general, these conditions hold depending on the scale of analysis; competent rocks most likely fulfill the requirements of the geometric models in scales from decimeters to several hundred meters at shallow crustal levels.

The basic geometry of the model is shown in Fig. 1. The fault plane is divided into two halves by the line of maximum dip; one half is located on the side towards the northerly strike direction, labeled “northern half”, and the other is labeled “southern half” (Fig. 1b). The “observation line” is formed by the intersection of the fault and the plane (section) at which the observation is made. The observation plane could have any direction, including map and section views. The model considers a pitch from 0° to 90° and is thus located in one of the two halves of the fault plane, for example, 65°N or 40°S. There are some special cases: (a) cases with a cut-off marker line (β) parallel to the strike or dip of the fault plane (pitches 0° and 90°), in which case the orientation of the line is undetermined and the program will change the values to 0.1 and 89.9, respectively; (b) cases with an observation line parallel to the cut-off marker line (φ = β), called a “null line” (Redmond, 1972; Xu et al., 2009), for which it is not possible to calculate the displacement (S); and (c) cases with slickenlines parallel to the cut-off marker line (φ = γ). For cases b and c, the program adds 1% to the pitch of the marker line (β) to avoid division by zero.

3. Algorithm

The algorithm is illustrated in Fig. 2. The input data are the dip of the fault plane (α), an apparent displacement of a marker (Sm, Smd or Smh), the pitch angle of the cut-off line (β) and the pitch of the slickenline (γ). There are two cases, depending on whether the data are derived (a) from maps or sections perpendicular to the fault plane or (b) from an arbitrary oriented section, in which case the pitch of the observation line (φ) is introduced as well (Fig. 1b). For clarity, the program presents an illustration of these angles and their definitions. The program evaluates the introduced data according to the decision tree shown in Figs. 2 and 3 in the case of the map and perpendicular sections (case a) and that shown in Figs. 2 and 4 in the case of an arbitrary oriented section line (case b). In both cases, the program calculates the true displacement of the fault (S), heave (Sh), throw (Sv), dip displacement (Sd) and strike displacement (Ss).

The results are displayed, and the user can save the input data for later analysis. For example, consider the situation of one
marker and a slickenline having opposite orientations (Fig. 1b). The following relations are established: the angle $\angle CAB = 90^\circ / \gamma$ and $\angle CBA = 90^\circ / \gamma$; then, $\angle ACB = \gamma + \beta$. The angles $\angle DBA = 90^\circ / \varphi$, $\angle CBD = \angle DBA = \gamma - \varphi$ and $\angle CDB = 180^\circ - (\varphi + \beta)$. We now consider the triangle (DCB), where $DB = SM$ and $CB = S$. Using the law of sines, the following equation is obtained: $S = SM \cdot \sin(180^\circ - (\varphi + \beta)) / \sin(\gamma + \beta) = SM \cdot \sin(\varphi + \beta) / \sin(\gamma + \beta)$, which is the equation in the third branch of Fig. 4. The program contains 18 equations shown in Figs. 3 and 4, and all of which were similarly obtained.

4. Computer program

TruDisp 1.0 is a tool for applied geologists, students and academics. Because it is programmed in Java SE 6.0, it runs on most operating systems with the corresponding Java VM. The application is designed for data obtained in the field or from maps and sections, where a compass or a protractor is used as a measuring tool. For the angular input and for displaying data, the decimal degree format is used. The installation process is simple: the compressed TruDisp 1.0 file is copied into a folder and expanded, after which the TruDisp.jar file is run.

The graphical user interface (GUI) has two windows (Fig. 5). The main window includes the input data area with two buttons: one for the data obtained from maps and perpendicular sections and the other for an arbitrary line of observation. If the user introduces data that approximate the null line, or with angle $\theta < 20^\circ$ (Fig. 1), a warning pop-up is displayed. The calculated (output) data are displayed in the Results panel (Fig. 5).

The secondary window has three tabs: the Input tab, which displays a figure with the input parameters; the Output tab, which displays a figure with the output parameters with color codes for identification; and the history tab, which shows all the analyses conducted during the session. All input and calculated data can be saved or loaded in a file for future revision or re-calculation (Fig. 5).

The program handles each calculation as an object and stores it in the RAM of the computer. In this way, the program can manipulate tens of thousands of fault-slip data, depending on the memory of the host computer. For a common user, this setup means that there is essentially no limitation to the amount of data that can be processed.

5. Some remarks for using TruDisp

The measuring of pitches and separations inevitably has errors. The use of a protractor in the field, maps or sections likely introduces angular errors of approximately $\pm 2^\circ$, depending on the diameter of the protractor and the thickness of the measured lines (striae and contacts on the fault plane or lines drawn on the map and sections). Additionally, errors in measuring the apparent displacements (separations) are most
likely on the order of centimeters or even decimeters for measurements in the field. The reason for this error is that the contacts are not straight, tiny lines; they are irregular, have a thickness and may even be a transitional zone. The errors in angular measurements are not significant for large values of $\theta$ (the angle between $\gamma$ and $\beta$), but for small $\theta$, the errors can be very large. For example, consider the case of a normal fault with dip $\alpha=65^\circ$, a line of observation with pitch $\varphi=80^\circ$, a slickenline with pitch $\gamma=60^\circ$ S and a separation $Sm=20$. Fig. 6 shows the error of the calculated displacement (in percentage) when a deviation of $2^\circ$ is introduced in the pitch of the marker. There are two zones in which errors grow abruptly. The first is near the null line, in which it is not possible to calculate $S$. The other is when the cut-off marker line is near the slickenline. The increase in the error depends on the parameter values.

We recommend not calculating displacements for orientations in which $\beta$ is approximately $10^\circ$ greater or lesser than $\varphi$ and $20^\circ$ greater or lesser than $\gamma$ (Fig. 6).

For compute errors in the $S$ estimation, TruDisp 1.0 introduces an error of $\pm 2^\circ$ in angular input data and 0 for distances. Using these values the program propagates the error in $S$ by solving the equation (e.g., Chapra and Canale, 2010, p. 96)

$$\Delta S = (\partial S / \partial \beta) \Delta \beta + (\partial S / \partial \gamma) \Delta \gamma + (\partial S / \partial Sm) \Delta Sm$$

where $\Delta$ is the error in $S$, $Sm$, $\beta$, $\gamma$, and $\varphi$ respectively.

The partial derivatives are calculated numerically as centered difference approximation of the first derivative: $f'(S) \approx (f(S_0 + h) - f(S_0 - h))/2h$, a value of $h=0.0001$ was the increment used for evaluating the derivative at the point $S_0$. The obtained errors are displayed in the Result panel, and the input errors can be changed by the user in the error panel ($\Delta$ panel).

Fig. 4. Decision tree for the arbitrary observation line case. There are 12 equations for calculating $S$. Note that the values with $\beta=\gamma$ and $\beta=\varphi$ are not included. In those cases the program adds 1% to $\beta$, but the result much probably will be largely deviated from the real $S$. See the text for further discussion.
6. Conclusions

Many methods for calculating the true displacement of faults have been published in the literature. However, these methods are not routinely used because there are many particular cases and performing the calculations is tedious and difficult. The solution presented here is a computer program that automatically calculates net fault displacements, for the cases with known slickenlines. The input data are fault measurements obtained from the field or maps and sections and the output data includes an estimation of errors. The program will be useful for geoscience students, geologists and engineers and will help resolve a longstanding deficiency in geologic mapping and structural geology analysis.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2013.11.010.

References


