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SHORT NOTES

Geometric relations of dip slip to a faulted ground surface: new nomograms for estimating components of fault displacement

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Abstract—The throw, heave, and dip-slip components of displacement on a fault scarp can be estimated from two easily collected field measurements when fault dip is known or assumed: the vertical separation and slope angle of the original ground surface displaced across the fault. Nomograms allow graphical determination of slip components for cases where fault dip is in the same or in an opposite direction as the slope of the ground surface. The technique has several advantages over a previous method that requires three field measurements; those of scarp height, scarp slope angle, and the slope of the original ground surface. The geometric relations of a fault scarp illustrate that although differences between throw and vertical separation of the ground surface are small in the cases of steep fault dips or flat ground surfaces, these differences can be greater than commonly assumed.

INTRODUCTION

Subsequent to large earthquakes that produce surface ruptures, it is now standard for investigators to collect field measurements describing the amount and sense of offset on the causative fault. This information is basic to efforts in seismic hazard analyses to characterize the seismic behavior of faults (e.g. fault slip, seismic moments and slip rates) and to predict the future behavior of similar faults. Optimally, geologists want to measure the direction and magnitude of the three-dimensional net slip vector at the surface (e.g. Jackson *et al.* 1982, Beanland *et al.* 1989), but this is usually only possible immediately following earthquakes when net slip indicators such as striations on fault planes are well preserved. In lieu of direct observations of the net slip vector, data bearing on the amount of dip slip (or lateral slip) are critical to constraining the minimum amount of net slip on a fault.

Estimations of fault slip from surface ruptures produced by dip-slip displacement are problematic because fault dips are often unknown and surface ruptures are commonly accompanied by near fault warping, formation of grabens, and fault scarp degradation. A previous method for estimating the amount of dip slip (the down-dip component of displacement), throw, and heave (the vertical and horizontal components of dip slip, respectively) generally required assumptions of fault dip and field measurements of three variables: scarp height, the vertical distance between the crest and toe of a fault scarp; the scarp slope angle, the vertical angle between the crest and toe of the scarp; and the slope angle of the original ground surface displaced by the fault (Wallace 1980).

This short note shows that components of displacement can be estimated from only two variables: the sope angle of the original ground surface and the vertical separation of the ground surface across the fault, which is defined as the vertical distance between projections of the natural (unwarped) ground surface in the hanging-wall and footwall of a fault (Fig. 1). The approach has an advantage over the previous method of Wallace (1980) because fewer field measurements are required and the measurement of vertical separation is generally considered more straightforward than that of apparent scarp height (discussed further below).

GEOMETRY OF A FAULTED SURFACE AND NOMOGRAMS

The amount of dip slip (DS), throw (T), and heave (H) across an idealized fault scarp can be described in terms of fault dip (θ), the slope angle of the original ground surface (α), and the vertical separation (VS) of the ground surface. Figures 1(a) & (b) show these geometric relations for cases where the slope of the ground surface is both in the same and the opposite direction as fault dip. When fault dip is known or assumed, the components of dip-slip displacement can

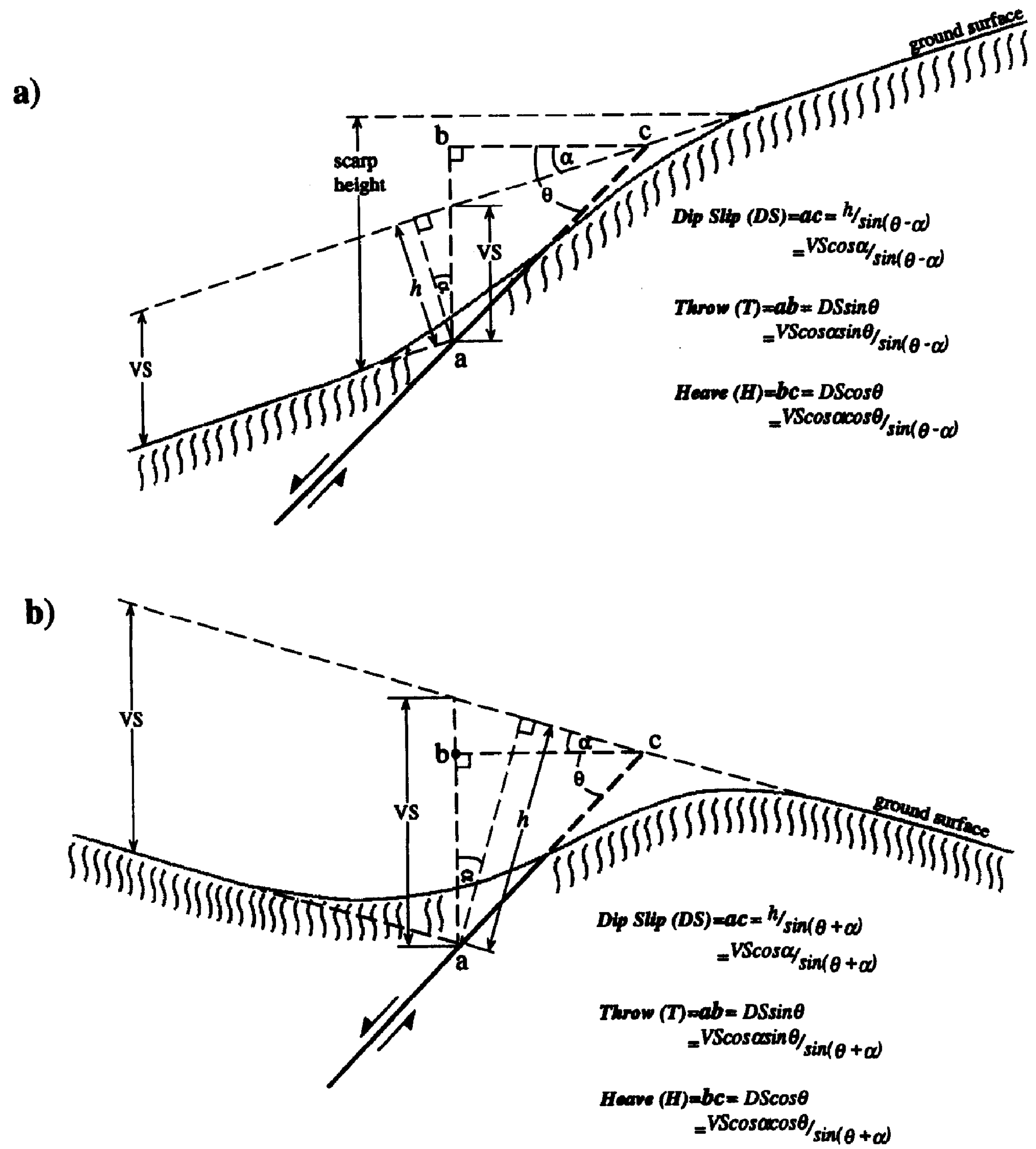


Fig. 1. Diagrams showing the geometric relations between the stratigraphic separation of the ground surface (h), the vertical separation of the ground surface (VS), ground surface slope angle (α), fault dip (θ), dip slip (DS = ac), throw (T = ab), and heave (H = bc) for two cases: (a) when fault dip is in the same direction as the slope of the ground surface; and (b) when fault-dip direction is opposed to the slope of the ground surface. The respective trigonometric equations describing DS, T, and H in terms of α, θ, and VS are shown at the lower right in the figures. Profiles of the scarps in a degraded form are shown by wavy lines.

be determined from field measurements of the slope angle (α) and vertical separation (VS) of the ground surface. The two general cases in Figs. 1(a) & (b) apply to both normal and reverse faults as well as to the dip-slip components of oblique slip faults, but only the geometry for normal faults is shown in Fig. 1 for simplicity. When a significant component of lateral displacement is involved, extra care in the field is warranted to insure that apparent vertical separation well represents the true vertical separation. It is also useful to note that the geometric relations also hold true for estimating cumulative displacements on compound (i.e. multiple event) scarps when geomorphic surfaces can be correlated across the fault.

Using the equations in Fig. 1, slope angle (α) is plotted against the ratios of dip slip, throw, and heave to vertical separation for varying fault dip angles in Fig. 2. Figures 2(a)–(c) and (d)–(f) correspond respectively to the two general cases in Figs. 1(a) & (b). The nomograms provide a convenient tool for graphically estimating components of fault displacement from easily made field measurements of vertical separation and ground slope angle(s).

DISCUSSION

Comparisons to previous methods

Wallace (1980) previously put forth a similar technique for estimating components of fault displacement (previously discussed). Wallace's (1980) approach is viable though less practical than the technique outlined here because: (1) three rather than two measurements are required. This results in equations that are more complex and, in turn, means that many more nomograms are necessary to fully illustrate the relations between displacement and field measurements. The additional measurement also introduces an added source for error, and (2) measurement of apparant scarp height is less straightforward than measurement of vertical separation. Scarp height can be difficult to uniquely measure, especially in the case of highly degraded scarps when scarp crests and toes become difficult to precisely define. Also, as scarp degradation occurs, scarp height can change appreciably because the crests and toes of scarps change in elevation when scarps retreat and advance along a sloping ground. Furthermore, in many cases, scarp height can greatly exaggerate the displacement on a fault, such as when warping of the ground surface occurs adjacent to fault scarps (see Fig. 3c). Such near-fault warping (along normal faults) occurs because of volume problems created when faults become more steep near the surface due to a lack of confining pressure, particularly in weak unconsolidated sediments (e.g. Cole & Lade 1984). Although scarp heights and scarp

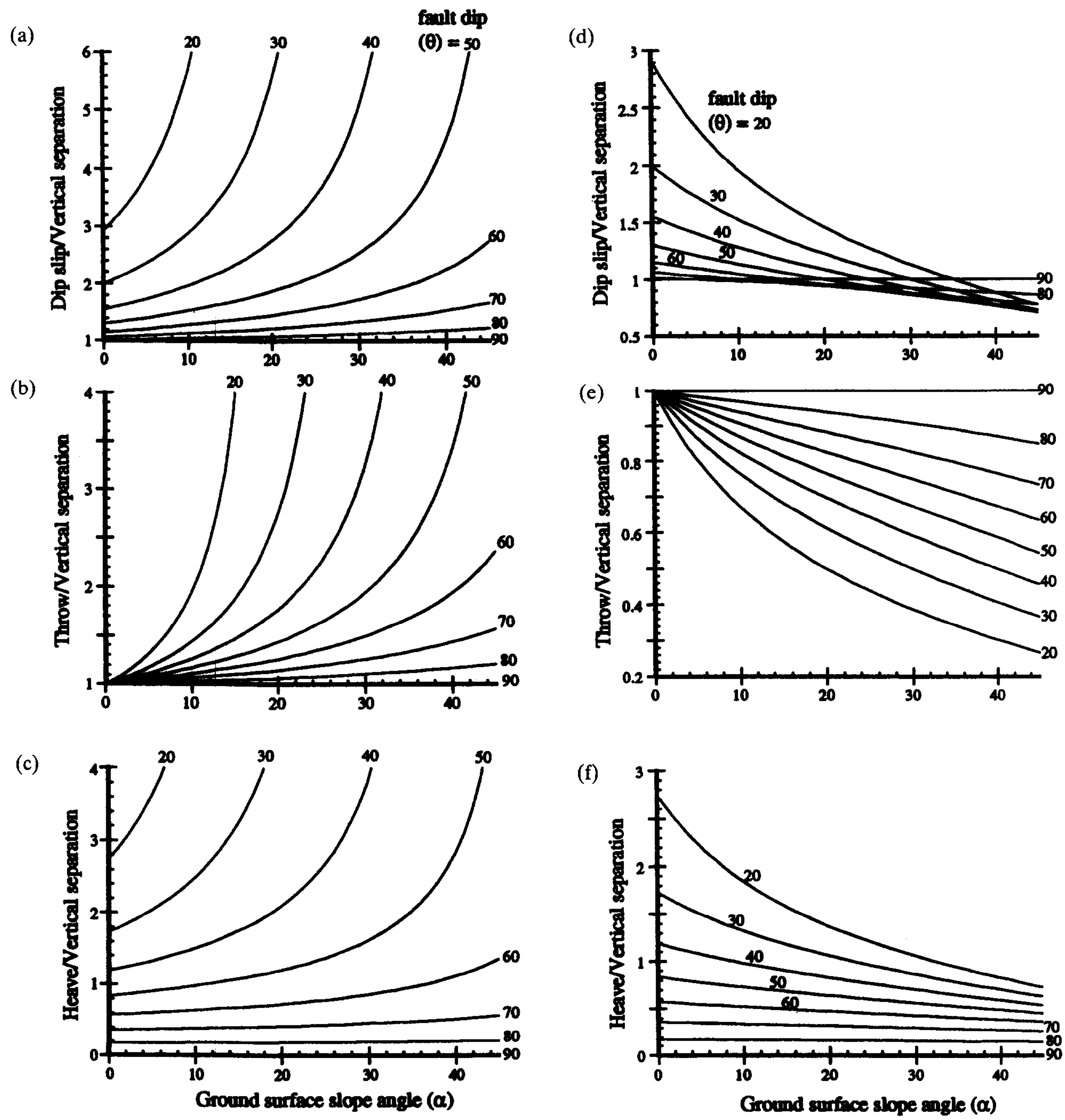


Fig. 2. Nomograms for estimating components of dip-slip displacement for the case when fault dip is in the same direction as the slope of the ground surface (a)–(c) and the case when fault dip is in the opposite direction as the slope of the ground surface (d)–(e) (refer to Figs. 1a & b, respectively). Slope angle (α) is plotted against the ratios of dip slip (a) & (d), throw (b) & (e), and heave (c) & (f) to vertical separation for various fault dip angles (θ). Fault dips are shown along their respective curves.

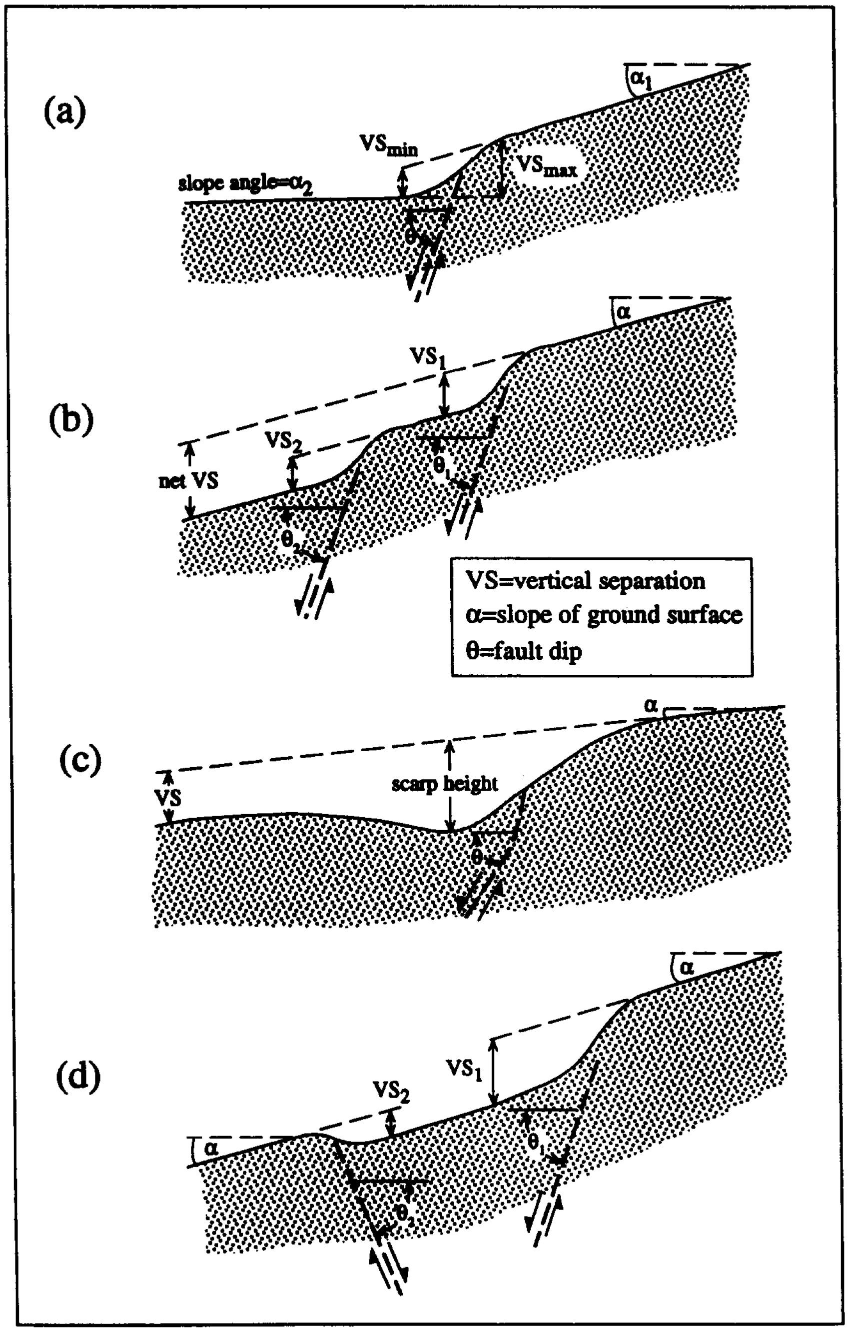


Fig. 3. Schematic profiles showing examples of complex fault scarps: (a) case where the original ground slope differs across the fault trace; (b) fault zone where multiple similar-facing scarps overlap along strike; (c) fault zone charcterized by near-fault warping; (d) fault zone characterized by the presence of a graben. Details for estimating fault displacements in these cases are discussed in text.

slope angles provide useful information, it is more reasonable to make field measurements of vertical separation for studies of fault displacements because: (1) vertical separation, in many cases, represents a good approximation of throw (discussed below); and (2) vertical separation is overall less subjective than scarp height since it is more easily defined and more constant throughout the process of scarp degradation.

Vertical displacement (throw) vs vertical separation of the ground surface

The ratios of throw (vertical component of displacement) to vertical separation of the ground surface (Fig. 2) for the two geometric cases depicted in Figs. 1(a) & (b) serve to illustrate an application of the nomograms and also a point on terminology. When fault dip is in the same direction as slope angle (α) (Fig. 1a) vertical separation (VS) underestimates throw. When fault dip is in an opposite direction as slope angle VS overestimates throw. In either case, VS is only equal to throw when fault dip is vertical ($\theta = 90°$) or when slope angle is horizontal ($\alpha = 0°$). As examples of these relations, when fault dip and slope angle are in the same direction (Figs. 1a and 2b), VS of a ground surface sloping 20° broken by a fault dipping 50° underestimates throw by about 31%. For a surface sloping 10° broken by a 70° dipping fault, VS underestimates throw by only about

6%. For the case when fault dip and slope angle are in opposite directions (Figs. 1b and 2e), the same conditions of ground slope and fault dip yield measurements of VS that overestimate throw by approximately 31% and 6%, respectively. There is therefore an obvious advantage to selecting measurement sites where the ground surface has a shallow slope when uncertainties in fault dip exist.

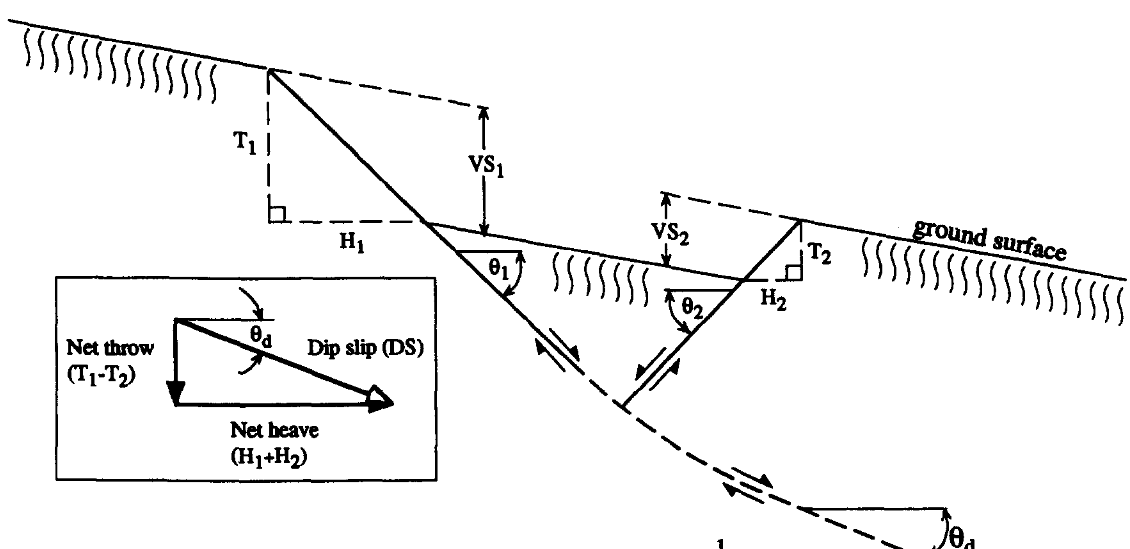
In extensional environments such as the Basin and Range province, measurements of vertical separation are often made on gently sloping piedmonts where the dips of normal faults commonly project up steeply at the surface (70–90°). In such environments, vertical separation may closely approximate or even equal throw across a fault. As a result, this has led to reporting field measurements of vertical separation variously as "true throw" (Gilbert 1890), "corrected surface displacement" (Witkind 1964), "cumulative vertical tectonic displacement" (Swan *et al.* 1980), and "vertical displacement of the ground surface" (Crone *et al.* 1987) to list a few examples. Although differences in throw and vertical separation of the ground surface are very small in the cases of steep fault dips and gently sloping ground surfaces, it should be kept in mind that these differences can be greater than commonly assumed and that it is generally inaccurate to refer to separation as throw or displacement.

Complex fault scarps

Fault scarps are commonly not as simple as those portrayed in the idealized models (Fig. 1), however, the method for estimating components of fault displacement is still equally viable. For example, when faults rupture along preexisting fault lines, slope angles of the ground surface commonly differ on either side of a fault trace (Fig. 3a). In such cases, limits can be placed on estimates of fault displacement (e.g. Buchun *et al.* 1986). For example, in the profile shown in Fig. 3(a) the break in slope on the original ground surface must have existed somewhere between the crest and the toe of the scarp. Therefore, the minimum vertical separation (VS_{min}) is determined at the point where the upper surface projects above the toe of scarp. The maximum vertical separation (VS_{max}) is determined where the lower surface projects beneath the crest of the scarp. In this example, maximum estimates of displacements will result by using VS_{max} and the slope angle of the upper surface. Likewise, minimum estimates of displacements will result by using VS_{min} and the slope angle of the lower surface.

When the ground surface is ruptured by multiple strands that overlap along strike components on all strands (both synthetic and antithetic) must be taken into account. In the case of multiple scarps which all face in the same direction (e.g. Fig. 3b) the net vertical separation can be measured by projecting the ground surface across the entire zone of ruptures providing that ground slope angles are same across the zone and the dips of all faults are assumed to be equal. Otherwise, measurements of vertical separation and slope angle across each fault are required.

When warping of the ground surface occurs adjacent to fault scarps (e.g. Fig. 3c), vertical separation is determined where decidedly unwarped portions of the ground surfaces project out beyond the zone of warping where slope angles are preferably equal.



$$DS = \left(\left(T_1 - T_2 \right)^2 + \left(H_1 + H_2 \right)^2 \right)^{\frac{1}{2}}$$

$$\theta_d = \tan^{-1} \left(\frac{\left(T_1 - T_2 \right)}{\left(H_1 + H_2 \right)} \right)$$

Fig. 4. Schematic diagram of the geometric relations across the graben. The amount of dip slip is determined by vector addition of net throw ($T_1 - T_2$) and net heave vector ($H_1 + H_2$). In special cases (discussed in text) the fault-dip angle at a structural level beneath the graben (θ_d) can be estimated from the inclination of the dip-slip vector.

In extensional environments, grabens often develop along normal fault ruptures (Fig. 3d). Similar to ground warping, grabens (on the scale of a fault zone) commonly develop as a result of volume problems created from fault planes that steepen in less consolidated material near the ground surface (previously discussed) (Gilbert 1890, Cole & Lade 1984). In the case of grabens, the synthetic and antithetic scarps must be considered independently to accurately assess components of fault displacement because the causative faults dip in opposite directions and because both faults contribute a component of extension (heave), some of which would be unaccounted for by simply projecting a surface across the graben. Estimates of net throw across the graben are determined by the difference in the throw across the synthetic and antithetic scarps (Fig. 4). Although, if the original ground surface is flat, the net vertical separation projected across the graben will equal the net throw. Estimates of net heave are determined by the sum of the heave across the synthetic and antithetic scarps. Net dip slip must be determined by vector addition of net throw and net heave (Fig. 4). In a special case, where the opposing fault dip angles can be accurately determined at the surface (such as in exploratory trenches or stream cut exposures), net throw net heave can be well constrained. In this case, an estimation of fault dip (θ_d) at a structural level beneath the graben (where the fault dip presumably shallows) can also be attained by determining the inclination of the dip-slip vector (Fig. 4). However, any estimations of fault dip at depth should be met with caution because some deformation may be lost between deeper levels and the ground surface. Such uncertainties are generally impossible to quantify.

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