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Ductile shear zones as counterflow boundaries in pseudoplastic fluids: Discussion

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The model for a shear zone proposed in Talbot (1999), which appeals to the behavior of a uniform power-law, or pseudoplastic, fluid, may provide adequate fits to the kinematics or strain distribution in natural or experimentally-produced shear zones. However, it is invalid as a *possible* description of shear zone behavior, since a fundamental principle of mechanics is violated. Briefly, since the model shear zone is constructed by combining two halves of a pressure-gradient driven flow in a straight-sided channel, the linear pressure gradients in each half of the constructed zone will have opposite signs. This implies that, except for a single point along the zone, the normal stress across its central plane will be discontinuous. This violates Newton's Third Law of Motion, often stated as: "action equals reaction." Although the model has other features that do not jibe with mechanical intuition, it suffices to establish a *single* violation of mechanical principles to discount it as a valid model for the phenomenon of interest.

It will be sufficient to consider only the simplest case, that for the Newtonian viscous fluid. According to the conditions stipulated by the author, a shear zone of width 2 h in a uniform Newtonian viscous fluid may be described by the velocity field (Fig. 1)

$$u = C^{(u)}\left(y^2 - 2hy\right) \qquad 0 \le y \le h \tag{1a}$$

$$u = C^{(1)}\left(y^2 + 2hy\right) \qquad -h \le y \le 0 \tag{1b}$$

where the constants are

$$C^{(u)} = -V/(2h^2) \tag{2a}$$

$$C^{(1)} = V/(2h^2) \tag{2b}$$

The relative tangential motion between the two bounding blocks is V, in a right-lateral sense. The velocity component u, is in the tangential, x-direction, and the component v, which vanishes, is in the normal, y-direction. This velocity field, as the author states, yields displacement and strain distributions that look like those in a shear zone and might quantitatively approximate those observed in some natural shear zones.

We may then ask what the distribution of stress in the zone is. Since it is stipulated that the zone is in a uniform viscous fluid, the velocity field must correspond to a unique[1] stress distribution derivable through the kinematic, constitutive, and stress equilibrium equations. For an incompressible, isotropic viscous fluid in plane flow in the x,y-plane

$$\begin{aligned} \sigma_{xx}\sigma_{yy} &= 4\eta\partial u/\partial x \\ \sigma_{xy} &= \eta\left(\partial v/\partial x + \partial u/\partial y\right) \end{aligned} \tag{3a}$$

and further,

$$\begin{aligned} \sigma_{zz} &= \tfrac{1}{2}(\sigma_{xx} + \sigma_{yy}) \\ \sigma_{xz} &= \sigma_{yz} = 0 \end{aligned} \tag{3b}$$

where η is the viscosity. From the first relations in (3a) and (3b),

$$\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -p \tag{4}$$

where p is the pressure. From the second relation in (3a) and the expressions for the velocity, (1) and (2),

$$\sigma_{xy} = \eta\partial u/\partial y$$

and

$$\begin{aligned} \sigma_{xy} &= 2\eta C^{(u)}(y - h) \qquad 0 \le y \le h \\ \sigma_{xy} &= 2\eta C^{(1)}(y + h) \qquad -h \le y \le 0. \end{aligned} \tag{5}$$

The shear stress must be continuous at the boundary between the two halves of the model, $y = 0$, requiring

$$-C^{(u)} = C^{(1)} \tag{6}$$

[1] The stress distribution is only determined to within an arbitary uniform pressure.

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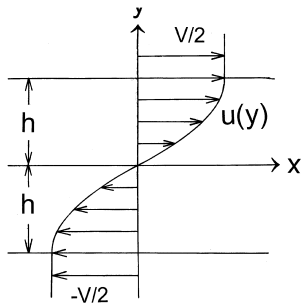

Fig. 1. Shear zone model, with velocity profile drawn for the case of a Newtonian viscous fluid, identifying symbols used here.

From (2), this is the case, and the condition is satisfied.

Now, complete the derivation of the pressure, p. From Eq. (4), and the equilibrium equation

$$\partial\sigma_{xx}/\partial x + \partial\sigma_{xy}/\partial y = 0.$$

or

$$\partial p/\partial x = \partial\sigma_{xy}/\partial y \tag{7}$$

Then, from the two equations in (5), and from (2)

$$\begin{aligned} (\partial p/\partial x)^{(u)} &= 2\eta C^{(u)} = -\eta V/h^2 \qquad 0 \le y \le h \\ (\partial p/\partial x)^{(1)} &= 2\eta C^{(1)} = \eta V/h^2 \qquad -h \le y \le 0. \end{aligned} \tag{8}$$

The pressure gradients in the upper and lower half of the “shear zone”, for this case, are equal in magnitude, but opposite in sign. Then, integrating (8), and from (4), we have, in particular,

$$\begin{aligned} \sigma_{yy}^{(u)} &= -p^{(u)} = -p_0^{(u)} + \left(\eta V/h^2\right)x \\ \sigma_{yy}^{(1)} &= -p^{(1)} = -p_0^{(1)} - \left(\eta V/h^2\right)x. \end{aligned} \tag{9}$$

But a necessary condition at the boundary surface between the two halves of the putative shear zone, $y = 0$, is

$$\sigma_{yy}^{(u)}(x,0) = \sigma_{yy}^{(1)}(x,0) \tag{10a}$$

or

$$-p_0^{(u)} + \left(\eta V/h^2\right)x = -p_0^{(1)} - \left(\eta V/h^2\right)x. \tag{10b}$$

This condition may only be satisfied at a single point, by fixing one of the constants of integration. (The other constant of integration remains arbitrary.) Hence, the required condition (10a) cannot be satisfied on the interface for any $V \neq 0$. Thus, on this ground, the model is invalid, and any conclusions drawn from it are unfounded.

Since the channel flow in the case of an arbitrary pseudo-plastic fluid with stress exponent n is also driven by a linear pressure gradient, the same violation will arise in the general case.

Talbot’s (1999) model, like others in structural geology, is constructed chiefly on the basis of kinematic reasoning. What has been left out of its derivation is a check of all conditions that must be satisfied, notably those in the stress. In this case, the velocity distribution in a channel flow is adapted, by a cutting and splicing operation, to provide a shear zone look-alike. Since we already know what a shear zone looks like, and may have some notion of its evolution, the appeal of the model is in providing a potential *mechanical basis* for understanding its behavior. It is this possibility that the above argument negates: there is no possibility of producing the desired flow by the considered loading.

References

Talbot, C.L., 1999. Ductile shear zones as counterflow boundaries in pseudoplastic fluids. Journal of Structural Geology 21, 1535–1551.