

A study of compaction bands originating from cracks, notches, and compacted defects

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Abstract

Compaction bands are zones of localized grain crushing and porosity reduction, which form spontaneously in high porosity rock under certain compressive stress conditions. Recent experiments show that compaction bands may nucleate at the edges of notches, holes and cracks subjected to compressive stress. We present an elasto-plastic model, used to investigate compaction band formation under a variety of boundary conditions. When simulating a notched specimen and a specimen with a central hole, compaction initiated at the macroscopic void's tips, and propagated in a step-wise manner, in agreement with experimental results. This step-wise manner of propagation is different from the compaction band run-away observed when compaction bands nucleate from pre-existing compaction bands. In addition, heterogeneity in rock properties, such as heterogeneity in local compressive strength, was found to control the morphology of compaction features initiating from voids.

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1. Introduction

Compaction bands (CBs) were recently identified in the field and in laboratory experiments (e.g. Mollema and Antonellini, 1996; Wong et al., 1997, 2001; Rudnicki and Olsson, 1998; Issen and Rudnicki, 2000, 2001), as discrete localized deformation zones, occurring in initially high porosity rocks subjected to high mean and low differential compressive stress. These naturally occurring compaction zones appear perpendicular to the maximum compressive direction, and are formed by grain crushing and porosity reduction.

CBs may play an important role in determining fluid flow, and stress and strain distribution in sedimentary basins. In addition, their importance in controlling borehole stability was recently noted (Haimson, 2001, 2003; Klaetsch and Haimson, 2002; Haimson and Kovachich, 2003). Despite their importance, they are a recently discovered feature and their formation under a variety of boundary conditions is still not well understood.

We recently proposed a new model to investigate CB formation and localization (Katsman et al., 2005). By modeling

an elasto-plastic media where localized compression-induced volume reduction is allowed to occur, it was found that locations of compressive stress concentration may act as nucleation sites for compaction bands. The model thus explains how a stiff sample boundary causes CBs to originate at its corners, as in the experiments of Rudnicki and Olsson (1998), Issen and Rudnicki (2000, 2001), Klein et al. (2001), Wong et al. (1997, 2001), and Baud et al. (2004). Then, the CB tip itself operates as a stress concentrator, inducing band growth perpendicular to the maximum compressive stress, and nucleation of other bands downstream, resulting in a CB front propagation.

Moreover, recent field observations and experiments show that CBs may nucleate not only at the edges of the previously-created CBs, but also at the edges of notches, holes, cracks, and other geological structures. Mollema and Antonellini (1996) observed thick CBs specifically in the compressional quadrant near the tip of a shear band. Haimson et al. (citation of 'Haimson et al.' refers to Haimson (2001, 2003), Klaetsch and Haimson (2002), Haimson and Kovachich (2003), and Haimson and Lee (2004)) experimentally observed long and narrow, stress-induced breakouts in the vicinity of boreholes in high-porosity sandstones. Vajdova et al. (2003) and Vajdova and Wong (2003) experimented with aspects of CB nucleation and propagation at the edges of notches cut into a high-porosity sandstone. These field and laboratory observations suggest that in high-porosity rock, the enhanced compressive stress

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expected at a breakout or a shear band tip may result in localized grain de-bonding, grain crushing, and formation of a CB. Moreover, both macro- and micro-scale heterogeneities and defects in the real rocks, even sometimes small voids, may initiate CBs, probably due to the stress concentration induced by these defects (Sternlof and Pollard, 2002; Vajdova et al., 2003; Vajdova and Wong, 2003; Tembe et al., in press; Haimson et al.).

To understand the physical mechanism of CB nucleation and propagation in the vicinity of various defects, i.e. preexisting compacted regions and macroscopic voids, the dependence on elastic properties, and the role of disorder in the development of compaction features, we conducted the theoretical investigation presented here. Results indicate that disturbances and defects in elastic matter (preexisting CBs, holes, heterogeneous material properties, and boundary incompatibility) all act as local stress concentrators. In this way, features of one kind, such as open holes, may cause nucleation and propagation of stress-induced features of a completely different nature, in this case CBs. However, since CB propagation depends on the specific features of the stress field, different defects may cause a different propagation pattern.

2. The physical basis for the model

The compaction process usually occurs in rocks with high initial porosity $\phi_{\text{init}} > 20\%$ (Olsson, 2001). After compaction, the porosity within the band is measured to be reduced to

values of $\phi_{\text{comp}} = 10\text{--}20\%$ (Mollema and Antonellini, 1996; Issen and Rudnicki, 2000; Olsson, 2001). The compaction process in high-porosity sedimentary rock can be mechanically described as follows: when a compactive yield stress is exceeded, the sutures and cement between grains break down; the mobility of de-bonded grains in a fabric containing significant porosity allows them to re-pack (Klaetsch and Haimson, 2002), with possible (Mollema and Antonellini, 1996; Vajdova et al., 2003; Vajdova and Wong, 2003; Haimson et al.) intra-granular microcracking (Fig. 1a).

The volume loss associated with observed porosity reduction may be calculated as follows: consider in 3D a unit of rock of length $2c$, height $2H$, and thickness L (perpendicular to the X – Y plane), undergoing compaction, as in Fig. 1a. Before compaction, the unit of porous rock has volume:

$$V_{\text{init}} = V_s + V_p = 2c \cdot 2H \cdot L \quad (1)$$

The total initial volume of the unit, V_{init} , is composed of the volume that the solid grains occupy within the rock matrix, $V_s = (1 - \phi_{\text{init}})V_{\text{init}}$, and the volume that the pores occupy $V_p = \phi_{\text{init}} \cdot V_{\text{init}}$. During compaction, the porosity is reduced from its pre-compacted value, ϕ_{init} , to a post-compacted one, ϕ_{comp} . Since no solid is removed from the unit, V_s remains constant, but the pore volume is reduced to a new value, $V_p^{\text{new}} = \phi_{\text{comp}} \cdot V_{\text{comp}}$. Where V_{comp} is the new total volume of the unit:

$$V_{\text{comp}} = \frac{1 - \phi_{\text{init}}}{1 - \phi_{\text{comp}}} V_{\text{init}} \quad (2)$$

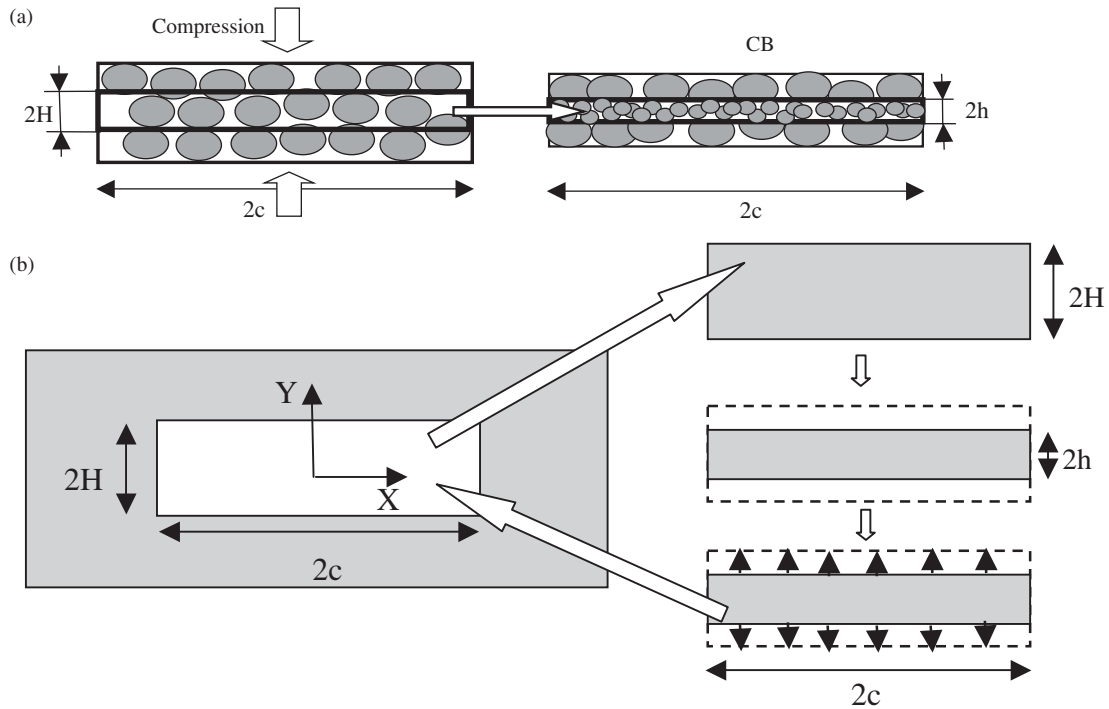


Fig. 1. (a) Compaction band, characterized by vertical dimension shortening ($2H$: before compaction, $2h$: after compaction), and no lateral dimensional changes ($2c$: length of CB before and after compaction process). (b) The transformation problem introduced by Eshelby (1957), applied for the CB studied in the paper. A rectangular region of size $2H \times 2c$ is removed from an elastic body. Then an unconstrained transformation, decreasing the height $2H$ by a value $2(H-h)$ (i.e. volume reduction), took place (CB formation). Its length $2c$ remained unchanged. Vertical surface traction was applied in order to restore the region to its original form. Then the region was glued back into the hole in the matrix. This procedure creates a state of internal stress, which persists even in the absence of external load.

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