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Compaction bands in porous rocks: localization analysis using breakage mechanics

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It has been observed in fields and laboratory studies that compaction bands are formed within porous rocks and crushable granular materials (Mollema and Antonellini, 1996; Wong et al., 2001). These localization zones are oriented at high angles to the compressive maximum principal stress direction. Grain crushing and pore collapse are the integral parts of the compaction band formation; the lower porosity and increased tortuosity within such bands tend to reduce their permeability compared to the outer rock mass. Compaction bands may thereafter act as flow barriers, which can hamper the extraction or injection of fluid into the rocks. The study of compaction bands is therefore not only interesting from a geological viewpoint but has great economic importance to the extraction of oil or natural gas in the industry.

In this paper, we study the formation of pure compaction bands (i.e. purely perpendicular to the principal stress direction) or shear-enhanced compaction bands (i.e. with angles close to the perpendicular) in high-porosity rocks using both numerical and analytical methods. A model based on the breakage mechanics theory (Einav, 2007a, b) is employed for the present analysis. The main aspect of this theory is that it enables to take into account the effect that changes in grain size distribution has on the constitutive stress-strain behaviour of granular materials at the microscopic level due to grain crushing. This microscopic phenomenon of grain crushing is explicitly linked with a macroscopic internal variable, called Breakage, so that the evolving grain size distribution can be continuously monitored at macro scale during the process of deformation. Through the inclusion of an appropriate parameter the model is also able to capture the effects of pore collapse on the macroscopic response. Its possession of few physically identifiable parameters is another important feature which minimises the effort of their recalibration, since those become less sensitive to the state of the matter (e.g. the initial porosity and grain size distribution).

In our previous work (Nguyen and Einav, 2009) we showed that the breakage mechanics model is capable of capturing the experimentally observed stress-strain behaviour of sandstones under conventional triaxial loading, along with the associated evolving grain size distribution. Here, these predictions are further improved through the inclusion of the additional pore-collapse parameter. Furthermore, localization analysis that is based on the loss of positive definiteness of the determinant of the acoustic tensor (Issen and Rudnicki, 2000) is performed to determine the onset of compaction localization, as an indication of material failure. This analysis results in the prediction of the possible range of compaction band orientations. The behaviour and onset of compaction localization of different sandstones are numerically predicted in well accordance with published experimental observations. A parametric study is also carried out to emphasize the complementary effects of grain crushing and pore-collapse on the formation of compaction bands.

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