# Borehole Instabilities in Granular Rocks Revisited: A Multiscale Perspective

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**Abstract** We employ a recently developed hierarchical multiscale approach based on Finite-Discrete Element Method (FEM/DEM) coupling to revisit the borehole stability problem for granular rocks. The progressive failure of the borehole is simulated by gradually reducing the support pressure. A Representative Volume Element (RVE) with dual-porosity structure is adopted to characterize the material response of high-porosity quartz-rich sandstone without considering particle crushing. Compaction bands, or so-called 'fracture-like' breakouts are reproduced which initiate almost from the crossing points of $\sigma_0$ springline and the borehole wall and penetrate into the rock matrix along radial direction. Further development of the borehole is characterized by curved shear bands forming 'V-shaped' patterns.

## 1 Introduction

The stability of borehole is of important relevance to many applications in geotechnical, mining and petroleum engineering. A wide variety of methods have been developed to study this topic, including theoretical analysis based on bifurcation theory [8], numerical simulations using gradient-enhanced models [11] and Discrete Element Method (DEM) [9] and experimental means (e.g., [5]). In particular, miniature drilling experiments have been conducted to examine the failure mechanism of borehole in rock. Frequently, 'V-shaped' or 'dog-eared' breakouts have been observed as a result of progressive extensile or shear failure [5]. Interestingly, fracture-like borehole breakout has more recently been found in the

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drilling experiments of highly porous sandstones, such as high-porosity Berea sandstones (porosity: 25%) and St. Peter sandstone (porosity: 16–22%) [5]. This failure pattern for borehole shares great similarities with the 'compaction band' observed in these sandstones, including their host-rock properties and their shear-free, contractive failure mechanism.

In this study, we re-examine the instability patterns and failure mechanisms of boreholes in granular rocks by employing a hierarchical multiscale modelling approach based on rigorous coupling of Finite Element Method (FEM) and DEM [3, 4]; see also [1, 2, 7]. The multiscale approach adopts FEM to solve a boundary value problem (BVP), and attaches a Representative Volume Element (RVE) to each Gauss point of the FEM mesh to solve by DEM for the local material constitutive responses. It retains the robustness of FEM in handling BVPs, while helping by-pass the necessity of assuming phenomenological constitutive models in conventional continuum approaches. Importantly, this hierarchical approach offers a viable way to directly link the macro observations with their underpinning microstructural mechanisms, a key feature to be employed to revisit the borehole stability problem in highly porous sandstones.

## 2 Multiscale Analysis of Borehole Stability

We simplify the borehole in a highly porous sandstone into to a plane-strain ring with the borehole radius of $r_I = 15\,\text{mm}$ and the outer radius $r_O = 150\,\text{mm}$ (Fig. 1a). The whole domain is discretized by eight-noded serendipity finite element elements (80 layers in the hoop direction and 20 layers in the radial direction). Finer mesh is adopted for near borehole zone to highlight the deformation patterns around it. A similar domain and discretization has been used by Papanastasiou and Vardoulakis [8]. We simulate the progressive failure of the borehole by gradually decreasing the inner support pressure following a scheme illustrated in Fig. 1b. The support pressure is normalized by minimal principal stress ($\sigma_{I0}$), and the time is normalized by the total time used. In the simulation, the maximum principal stress ($\sigma_{I1}$) is reduced at a constant rate, while $\sigma_{I0}$ is kept unchanged until $\sigma_{I1}$ is reduced to be equal to $\sigma_{I0}$. After that, both $\sigma_{I1}$ and $\sigma_{I0}$ are further reduced to zero at the same rate. Detail formulation and solution procedures of the coupled FEM/DEM multiscale approach can be found in Guo and Zhao [3].

A recent study by the authors shows compaction bands can be reproduced in biaxial compression tests on highly porous sandstone with no particle crushing [10]. Considering the great similarities between the fracture-like breakout and 'compaction band', we employ a similar dual-porosity structure to generate the RVE for the multiscale analysis in this study. The typical RVE at an initial state of $\sigma_0 = 30\,\text{MPa}, \sigma_1 = 45\,\text{MPa}$ is depicted in Fig. 2. Each RVE contains 749 sphere particles, with an initial porosity of 0.326. A bonded contact model is employed

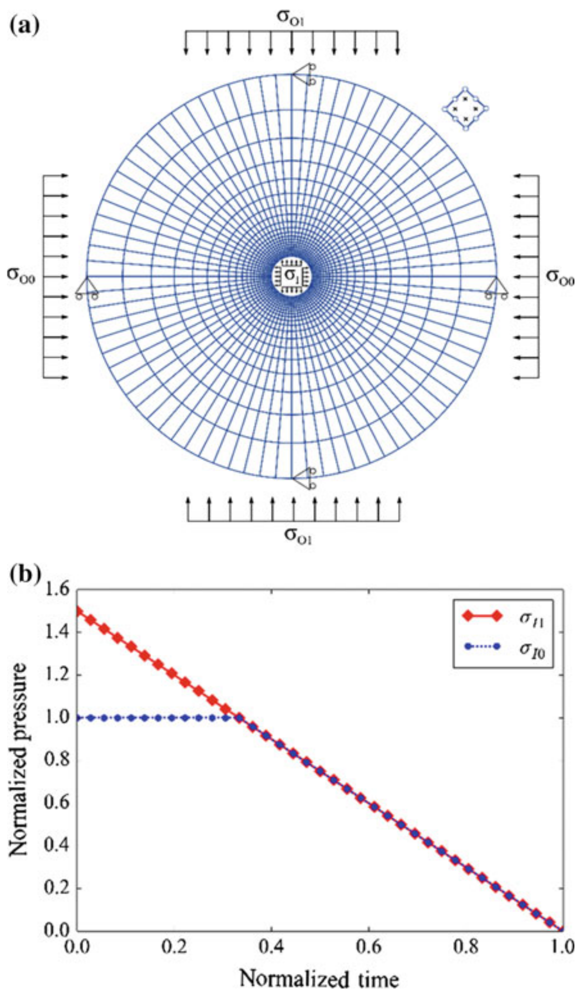


**Fig. 1** **a** FE discretization by eight-noded serendipity elements of four Gauss points (reduced integration) and the prescribed boundary conditions for 2D borehole stability analysis and **b** Illustration of the simulating scheme by reducing the inner support pressure ($\sigma_{I1}$ is reduced at a constant rate with $\sigma_{I0}$ being kept constant until the two are equal, after which both are reduced to zero at the same constant rate)

with linear force-displacement contact law and a Coulomb-type friction criterion. The normal and tangential contact stiffness are expressed as $k_n = E_c r^*$ (where $r^* = 2r_1 r_2/(r_1 + r_2)$, $r_1$ and $r_2$ are the radii of the two contacted particles) and $\mathbf{k_t} = \boldsymbol{\nu}_\mathbf{c} \mathbf{k_n}$. Normal and tangential bonds are assigned to each contact as $a_n = C_n \min(r_1, r_2)^2$ and $a_t = C_t \min(r_1, r_2)^2$. If the tensile force exceeds the threshold $F_n^{max} = a_n$ or tangential force exceeds the bond strength $F_t^{max} = a_t + F_n \tan\phi$, the bond will be eliminated, leaving the contact a pure frictional one. The typical micro parameters adopted for multiscale modeling of Berea sandstone of 25% porosity (BS25) are summarized in Table 1.

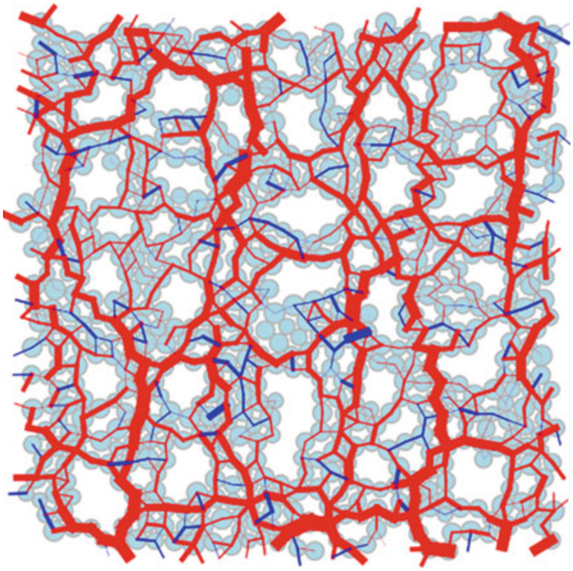

**Fig. 2** Initial structure of the typical RVE prepared for the subsequent borehole study. The figure is an augmented illustration of bonded particles and macro pores with the interparticle contact force network (online: *red lines*—compressive contact forces; *blue lines* tensile forces) after consolidation at the confining pressures

**Table 1** Micro parameters for the RVE

| Radii (mm) | Density (kg/m$^3$) | $E_c$ (GPa) | $\nu_c$ | $\phi$ (°) | $C_n$, $C_t$ (GPa) |
|---|---|---|---|---|---|
| 0.2–0.3 | 2,650 | 950 | 1.0 | 35 | 6.8 |

# 3 Results and Discussion

To highlight the failure mechanism, a typical case with an initial stress state at $\sigma_{I0} = \sigma_{O0} = 30\,\text{MPa}$ and $\sigma_{I1} = \sigma_{O1} = 45\,\text{MPa}$ is demonstrated. The RVE shown in Fig. 2 is adopted to simulate the material behavior of Berea sandstone of 25% porosity (BS25). The inner support pressure is reduced following the scheme illustrated in Fig. 1b at a rate of 1.25 MPa/S (S is the abbreviation for Step, not second). The whole simulation is terminated when $T = 36$ s. The initiation and development of the failure is presented in Fig. 3. The deviatoric strain is defined as $\epsilon_q = \sqrt{2\boldsymbol{e}\colon\boldsymbol{e}}$, where $\boldsymbol{e}$ is the deviatoric strain tensor. The particle rotation is defined as $\theta = \sum_{N_p} \theta_p / N_p$, where $N_p$ is the number of particles within the packing; $\theta_p$ is the accumulated rotation of individual particles. Anti-clockwise rotation is taken as positive.

## 3.1 Initiation of Fracture-Like Breakout

Localized failure of the borehole incepts from $T = 15$ s when $\sigma_{I0} = \sigma_{I1} = 26.25\,\text{MPa}$. The contours of $N, n, \epsilon_q$ and $\theta$ are illustrated in Fig. 3 (I). The failure starts almost

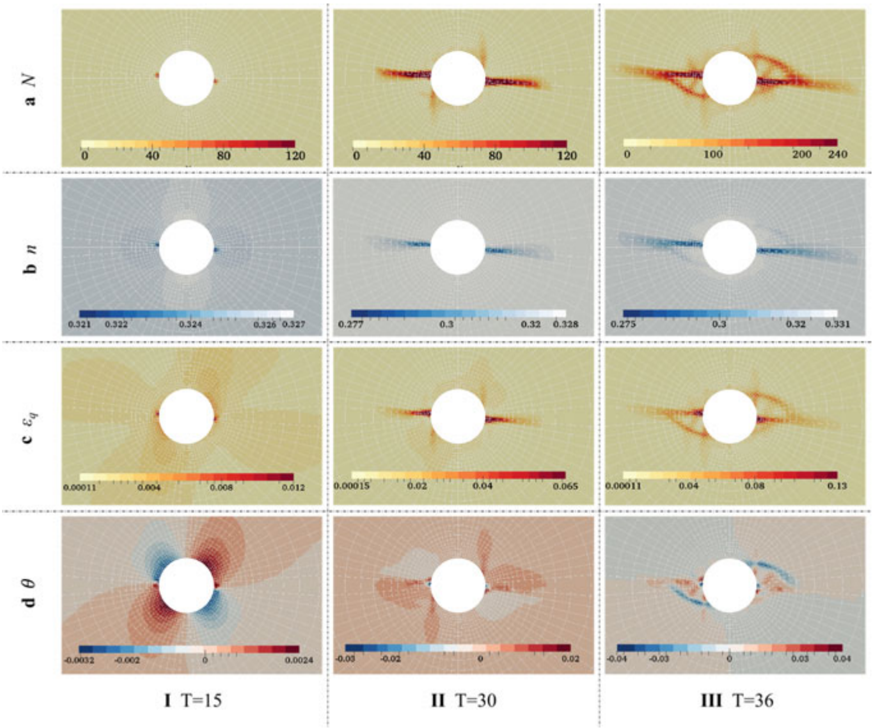


**Fig. 3** Contours of *N* (debonding number), *n* (porosity), $\epsilon_q$ (deviatoric strain), $\theta$ (particle rotation) at different time step demonstrating the development of localization

from the crossing point of $\sigma_0$ springline and the borehole wall. The porosity of the failure zone is reduced to a minimum of 0.317 from the original 0.326 (the minimum of the color bar is adjusted in the figure to make the failure zone more obvious). The contour of $\theta$ also shows a typical compaction failure pattern that the rock mass outside rotates towards the band. A clearer pattern could be observed in Fig. 3 (II) (d) along the x-axis showing a mature compaction band. With further decrease of the support pressure, the fracture-like failure zone penetrates into the rock mass along the radial direction. As inter-particle debonding happens, debonded particles are compacted into a much denser state, resulting in significant porosity reduction without even considering particle crushing. Figure 3 (II) (b) shows the reduction of porosity from the maximum of 0.328 in the matrix (slightly larger than the initial value due to unloading) to a minimum of 0.277 within the mature compaction band.

### 3.2 Shear Failure in the Continuing Simulation

Following the compaction bands, shear failure is observed initiating from the borehole wall and penetrating into the rock mass since $T = 25\,\mathrm{s}$ when $\sigma_{I0} = \sigma_{I1} = 13.75\,\mathrm{MPa}$. The failure pattern at $T = 30\,\mathrm{s}$ when $\sigma_{I0} = \sigma_{I1} = 7.5\,\mathrm{MPa}$ is illustrated in Fig. 3 (II). The shear failure is easily identifiable in contours of $N, \epsilon_q$, and $\theta$. As the support pressure further reduces, the shear failure becomes more evident. The failure pattern at the final stage is illustrated in Fig. 3 (III), showing clearly several curved shear bands around the borehole wall. One major issue in the study of 'fracture-like' breakout is the lack of field observation. All the reported 'fracture-like' breakouts have been found in miniature drilling tests in the laboratory. While possible explanations may include the inadequate accuracy of logging technologies [6], the present multiscale simulation results suggest that the formation of breakouts could be induced by interparticle debonding and pore collapse without removing rock flakes. Compaction bands may appear as a premier failure pattern followed subsequently by shear bands. If the rock flakes between the shear bands and the borehole wall are removed, 'V-shaped' breakouts can be recorded as the eventual failure pattern although compaction bands may have appeared at first.

## 4 Conclusions

Compaction bands, or so-called 'fracture-like' breakouts have been reproduced in borehole stability analysis in highly-porosity sandstone based on a coupled FEM/DEM multiscale modeling approach. Under progressive reduction of the support pressure, compaction bands have been found initiating almost from the crossing points of $\sigma_0$ springline and the borehole wall and penetrating into the rock matrix along radial direction. Further reduction of the support pressure triggers curved shear bands starting from the borehole wall and penetrating into the matrix to form a 'V-shaped' pattern. If the rock flakes between the shear bands and the borehole wall are removed, 'V-shaped breakouts' can eventually be formed, which offers a possible explanation on the lack of field report of 'fracture-like' breakouts.

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