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Investigation of failure mechanisms around a cylindrical cavity in rock mass under true-triaxial loading

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Abstract

In underground rock engineering applications such as mining, petroleum engineering, and tunnelling, various types of rock mass failure often occur in the vicinity of underground openings. Although a biaxial stress state exists at the tunnel boundary, the surrounding rock mass experiences a true-triaxial state of stress. This study investigates the failure mechanisms around a cylindrical cavity subjected to true-triaxial loading. The sample consists of a 100 mm side cubic block containing a cylindrical cavity with a diameter of 25 mm, while the outer boundary is maintained at three times the cavity radius to minimise boundary effects. The artificial rock mass is prepared in the laboratory using cement-based mortar, and its similarity to natural rock is evaluated based on four criteria: formation morphology, deformability characteristics, modulus ratio, and brittleness index. According to the Deere-Miller classification, the prepared rock mass sample falls under the low-strength, low-modulus-ratio (DL) category. In the present study, cylindrical cavities in isotropic and transversely isotropic rock masses (foliation angles of 0° and 90°) are considered. Furthermore, the cavity orientation is varied to investigate its influence on the failure mechanisms around the cavity. From the experimental results its observed that the failure pattern in case of horizontal and vertical cavities are V-shaped breakout and toroidal shaped failure, respectively.

Keywords

Artificial rock, Isotropic rock, Anisotropic rock, Boreholefailure mode, True triaxial testing.

1 Introduction

Extraction of conventional and unconventional energy resources from deep reservoirs is often carried out from multiple platforms, making the process expensive. This number can be reduced by drilling deviated boreholes, which enlarge the drainage area accessible from a single location and improve reservoir productivity (Saavedra and Reyes 2001; Quy et al. 2009). Non-vertical boreholes are also required to reach targets inaccessible by vertical drilling. However, increasing borehole inclination raises the risk of borehole instability during drilling (Garrouch and Ebrahim 2001; Simangunsong et al. 2006). Although successful drilling of non-vertical wells can reduce operational costs, maintaining borehole stability remains a major challenge. Even vertical boreholes do not necessarily guarantee stability because borehole behaviour is strongly controlled by the in-situ stress state (Al-Ajmi 2006). During drilling, the surrounding rock mass must redistribute the stresses previously carried by the excavated material (Burnwal and Singh 2024), causing stress redistribution around the borehole and stress concentrations near the borehole wall that may exceed rock strength and result in failure.

In many geological settings, boreholes are drilled in anisotropic rocks with direction-dependent mechanical, hydraulic, and thermal properties. Although these boreholes have relatively small diameters, the presence and orientation of natural planes of weakness can significantly influence their stability (Asaka and Holt 2021). Experimental and theoretical studies show that the strength behaviour of anisotropic rocks is governed by the prevailing stress state, intrinsic engineering properties of the rock, and the orientation of bedding planes, β (Singh et al. 2018; Burnwal and Kumar 2022; Liu et al. 2020; Gao et al. 2024; Burnwal and Singh 2026). Therefore, understanding borehole stability in anisotropic rocks is essential for the safe and efficient design of underground excavations and drilling operations. Figure 1 illustrates a typical directionally drilled borehole consisting of vertical sections in isotropic rock (Section I), vertical sections in anisotropic rock (Section II), inclined sections (Section III), and horizontal sections (Section IV).

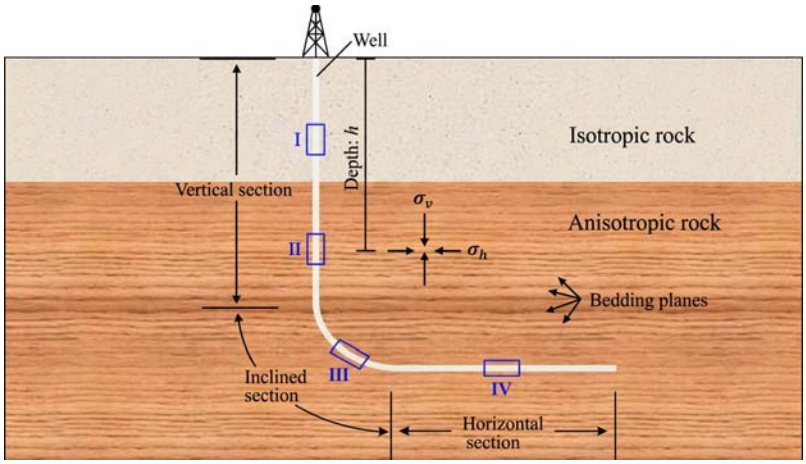


Fig. 1 Schematic of a well trajectory showing vertical, inclined, and horizontal borehole sections passing from isotropic to anisotropic rock (Duan et al. 2018).

Previous studies have investigated vertical and inclined boreholes under biaxial stress states. For example, rockburst behaviour around horizontal boreholes under biaxial stress conditions, along with associated early warning signals, was reported by Hu et al. (2019) and Zhang et al. (2022), while the influence of lateral loading conditions on rockburst behaviour was examined by Liu et al. (2020) and Liang et al. (2020). The effect of rock type on the failure modes of circular openings under biaxial stress conditions was analysed by Shi et al. (2025) and Xiao et al. (2025), whereas Wang et al. (2025) investigated borehole spallation mechanisms. Kun et al. (2024) further examined the influence of the angle between the principal stresses and the tunnel axis on the failure behaviour of the surrounding rock mass by considering borehole inclinations of 0°, 5°, 10°, 15°, 30°, and 45°. Although these studies provide significant insights into borehole failure under biaxial loading conditions, the stress state surrounding underground openings is generally true-triaxial in nature, except at the tunnel boundary (Singh et al. 2019; Burnwal and Singh 2024a, 2025).

To better represent in-situ stress conditions, several researchers have also investigated borehole failure under true-triaxial stress states. Various studies have reported spalling around the cylindrical opening (Jia et al. 2012; Gong et al. 2018; Luo et al. 2020), rockburst (Si et al. 2022a; Ling et al. 2023), and borehole breakout (Xiang et al. 2024a, b). Observations include breakout orientation, pit formation, severity of borehole damage, dominant failure mode (tensile or shear), fragment characteristics, and

rockburst precursors, together with the influence of borehole orientation relative to principal stresses, loading pattern, loading rate, confinement, and lithology. Inclined cylindrical cavity has been investigated by several researchers. For example, Ma and Zuo (2024) examined the effect of misalignment between the roadway axis and the principal stress direction (0°-20°) on failure mechanisms around cylindrical cavity, although significant boundary effects were observed. Ma et al. (2025) analysed roadways with axes non-coplanar to the in-situ stress field and demonstrated that the spatial angle between the roadway axis and the principal stresses governs stress redistribution, leading to asymmetric spalling and V-shaped failures. Rockburst behaviour in anisotropic rocks has also been reported by Si et al. (2022b) and Liu et al. (2025).

From the brief literature review, it is evident that no study has systematically compared cylindrical cavity failure mechanisms in isotropic and anisotropic rocks under identical stress states. Furthermore, the failure behaviour around vertical cylindrical cavities has not been comparatively investigated under the same loading conditions. To address this gap, the present study examines the failure patterns of horizontal and vertical cylindrical cavities in isotropic and anisotropic rock-type materials subjected to true-triaxial stress conditions. The paper is organised as follows: Section 1 presents introduction; Section 2 describes the preparation of isotropic and anisotropic rock-type specimens; Section 3 presents the true-triaxial testing procedure and discusses the observed borehole failure patterns; and Section 4 summarises the main conclusions.

2 Sample preparation

In the present study, two types of rock-type materials were prepared: an isotropic rock-type material (Fig. 2(a)) and an anisotropic rock-type material (Fig. 2(b)). The specimens were fabricated using self-compacting mortar. Details of the raw materials used in the preparation and their characteristics are reported by Burnwal and Singh (2025, 2026). The mechanical behaviour of the isotropic rock-type material is discussed in Burnwal and Singh (2025), whereas that of the anisotropic rock-type material is presented in Burnwal and Singh (2026). In Fig. 2(b), the red layer represents the same material as the isotropic rock-type material shown in Fig. 2(a), having a uniaxial compressive strength (UCS) of 39.36 MPa, while the grey layer in Fig. 2(b) has a UCS of 29.98 MPa. The materials are classified as DL according to the Deere and Miller rock strength classification (Deere and Miller 1966). After preparation, a cylindrical cavity of 25 mm diameter and 100 mm length was drilled at the centre of cubic samples with a side length of 100 mm, as shown in Fig. (2).

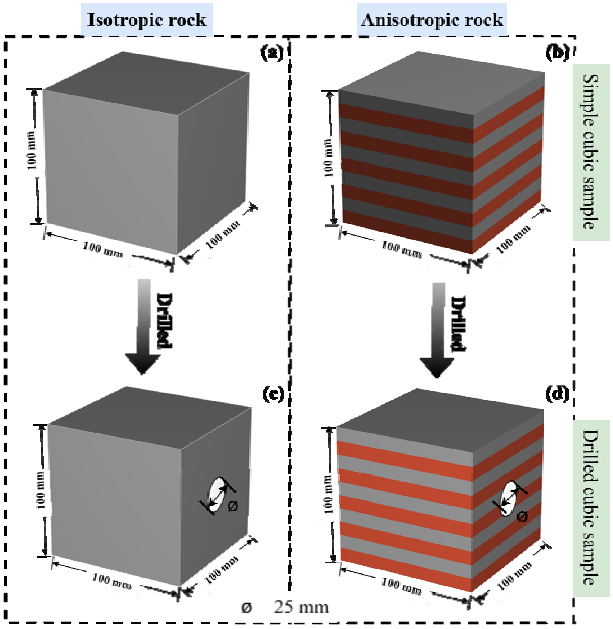


Fig. 2 Cubic samples of isotropic (a) and transversely isotropic rock (b), and corresponding drilled samples (c, d).

3 Borehole Failure Patterns under True-Triaxial Stress

This section describes the stress state adopted in the experiments and the orientation of the borehole with respect to the principal stresses for isotropic rock-type specimens and the foliation plane for anisotropic specimens. The details of the true-triaxial testing apparatus and loading procedure are

available in Burnwal and Singh (2025). In the present study, two borehole orientations were considered: a vertical borehole, where the borehole axis is parallel to the major principal stress (σ_1), and a horizontal borehole, where the borehole axis is perpendicular to σ_1 and parallel to the minor principal stress (σ_3). During all tests, the intermediate and minor principal stresses (σ_2 and σ_3) were maintained constant at 4 MPa and 2.5 MPa, respectively.

3.1 Horizontal borehole

True-triaxial compression tests were conducted on 100 mm side cubic specimens of isotropic and transversely isotropic rock containing a centrally drilled borehole of 25 mm diameter, with the borehole axis aligned with the minor principal stress (σ_3). Under the applied stress state (σ_2 = 4 MPa and σ_3 = 2.5 MPa), failure around the cylindrical cavity typically exhibits V-shaped breakouts in isotropic rock (Fig. 3(a)) as well as in transversely isotropic rock (Fig. 3c)with a slight offset between the left and right breakout tips (Figs. 3(b) and (d), which may be due to imperfect platen-specimen contact between steel loading platen and specimen surface). Similar failure patterns have been reported in previous studies for the case of cylindrical cavity in isotropic (Si et al. 2022a;Ling et al. 2023; Burnwal and Singh 2024b; Xiang et al. 2024a; Xiang et al. 2024b; Li et al. 2025; Zuo et al. 2025) and transversely isotropic rocks (Liu et al. 2025).

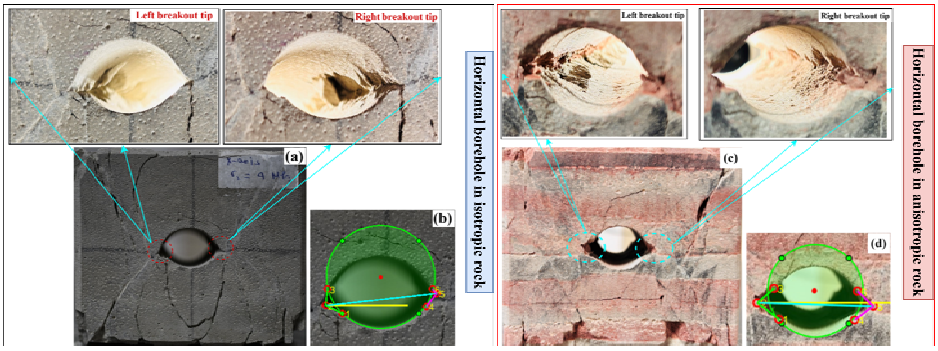


Fig. 3 Development of V-shaped breakout around a horizontal borehole under true-triaxial loading in isotropic (a, b) and transversely isotropic (c, d) rock-type specimens.

The fragments recovered from the tested horizontal cylindrical borehole in isotropic and anisotropic rocks are shown in Figs. 4(a) and 4(b), respectively. Visual inspection suggests that the fragments obtained in both cases are similar, i.e., they consist of angular chips along with crushed particles. Furthermore, the left and right breakout tips in both cases in Fig. 3 show rough shear surfaces on either side along the borehole length.

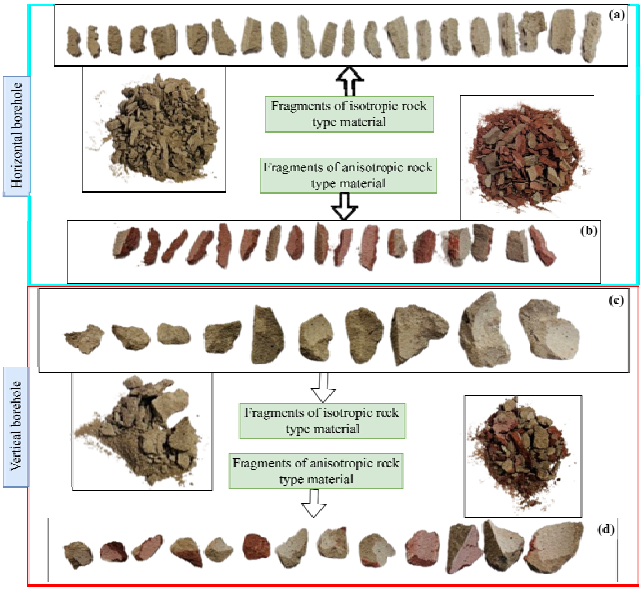


Fig. 4 Fragments from tested borehole: horizontal borehole in (a) isotropic rock-type material and (b) anisotropic rock-type material, and vertical borehole in (c) isotropic rock-type material and (d) anisotropic rock-type material.

3.2 Vertical borehole

This section presents a comparison of the failure patterns developed around vertical cylindrical cavity in isotropic and transversely isotropic rock specimens, where, in the latter, the foliation planes are oriented parallel to the major principal stress (σ_1). The failure morphology observed around the circular opening is broadly similar for both isotropic (Figs. 5(a) and 5(b)) and transversely isotropic specimens (Figs. 5(c) and 5(d)). In both cases, the fragments recovered from the tested vertical specimens exhibit a distinct toroidal (ring-shaped) failure geometry, as evident from Figs. 4(c) and 4(d). This failure pattern indicates the development of a circumferential damage zone around the borehole wall under the prevailing stress configuration. Similar failure pattern for vertical borehole is reported by previous researchers for an example Fjaer et al. (2008), Maury and Sauzay (1987). However, in the transversely isotropic specimens, failure was also observed along the foliation planes. The relatively lower strength of these planes facilitates preferential crack initiation and propagation along the inherent planes of weakness.

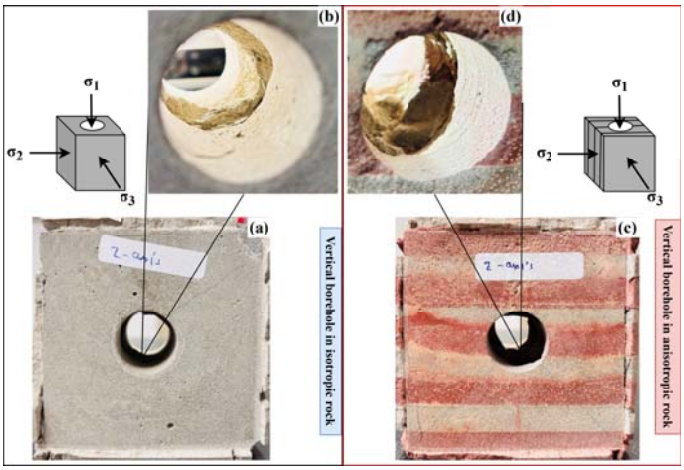


Fig. 5 Observed toroidal shaped failure pattern around vertical borehole under a true-triaxial stress state in isotropic rock-type specimen (a, b) and 0°transversely isotropic rock-type specimen (c, d).

4 Conclusions

The following conclusions are drawn from the experimental investigation of failure patterns around horizontal and vertical borehole in isotropic and anisotropic rock-type specimens subjected to true triaxial stress conditions:

- Failure around horizontal borehole in isotropic and transversely isotropic rocks exhibit a shear breakout type failure.
- Failure around vertical borehole in isotropic and transversely isotropic rocks shows toroidal shaped (ring-shaped) failure.
- In transversely isotropic rocks, the orientation of foliation planes relative to the major principal stress (σ_1) significantly influences the failure morphology around the borehole. The presence of foliation planes promotes preferential fracture propagation along these inherent planes of weakness, thereby modifying the local failure pattern.

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