



Geomechanical Analysis of Inclined Fractured Zones in Road and Railway Tunnel Excavation: Stress Field Assessment, Failure Mechanics, and the ISAF-FZ Framework

Alessandro Calvi¹

¹Enel Green Power S.p.A, Turin (Italy)

alessandro.calvi84@gmail.com

ABSTRACT

The excavation of road and railway tunnels through inclined fractured zones represents one of the most challenging scenarios in underground engineering. The stress state within the rock mass undergoes complex perturbations when the tunnel axis intersects fault zones, shear bands, or pre-existing fracture sets at non-perpendicular angles. Drawing on the theoretical framework developed by Zoback (2010) for failure analysis of deviated wells — specifically the generalised borehole wall stress equations, drilling-induced tensile fracture (DITF) diagnostics, and shear velocity anisotropy measurements — this article extends these principles to the three-dimensional geomechanical problem of inclined tunnel excavation. A critical review of stress transformation theory, breakout analysis for inclined openings, and the role of fracture dip in governing tunnel stability is presented. On this basis, the article proposes a new geomechanical methodology: the Integrated Stress Analysis Framework for Fractured Zones (ISAF-FZ). The ISAF-FZ is a six-phase, adaptive workflow that integrates in-situ stress characterisation, fracture network analysis, inclined opening stability assessment, support design, and real-time monitoring. Application to two case studies — the Gotthard Base Tunnel and the A1 Apennine Motorway Tunnel — demonstrates the framework's predictive capacity for support pressure requirements and excavation sequencing in crossed fractured zones. The results show that fracture dip angle is a primary control on required support pressure, and that the ISAF-FZ framework reduces prediction uncertainty by up to 35% compared to conventional isotropic approaches.

Keywords: Rock tunnel; Fractured zone; In-situ stress; Deviated well analogy; Borehole wall stresses; DITF; Shear velocity anisotropy; ISAF-FZ; Geomechanics; Kirsch solution

1. INTRODUCTION

The design of road and railway tunnels traversing complex geological environments demands a thorough understanding of the in-situ stress state within the rock mass. When tunnel alignments encounter inclined fractured zones — fault cores, shear bands, foliation planes, or fracture corridors — the conventional assumption of isotropic, axisymmetric stress distribution at the tunnel wall breaks down entirely. The stress field becomes inherently three-dimensional, the failure modes are anisotropic, and the required support systems must account for the directional dependence of both strength and stiffness in the fractured medium.

Decades of reservoir geomechanics research, particularly the work of Mark D. Zoback at Stanford University, have produced rigorous analytical and observational tools for characterising stress fields in inclined boreholes. Zoback's Lecture 10 (Reservoir Geomechanics, Week 5) establishes the

theoretical foundation for failure analysis of deviated wells: the generalised Kirsch equations for borehole wall stresses as a function of well deviation, the angular positions of breakout and tensile fracture initiation for arbitrary stress orientations, and the diagnostic power of shear velocity anisotropy measured with dipole sonic tools for resolving the maximum horizontal stress (S_{Hmax}) direction in anisotropic formations (Zoback, 2010; Zoback et al., 2003).

The analogy between a deviated borehole and an inclined tunnel excavation is geometrically exact: in both cases, a cylindrical opening is oriented at an angle to the principal stress directions, and the circumferential and axial wall stresses are determined by the same tensor transformation and the same set of elastic boundary conditions. The critical difference lies in scale — tunnel diameters of 8–15 m versus borehole diameters of 0.1–0.4 m — and in the time-dependent response of the rock mass, which introduces plastic and time-dependent mechanisms absent from the elastic well stability problem.

Inclined fractured zones complicate the picture further. A fault zone intersecting a tunnel at a dip angle δ introduces: (i) a locally heterogeneous stress field modified by the contrast in mechanical properties between intact rock and fault gouge; (ii) preferential slip planes oriented at δ to the tunnel axis, along which shear failure can occur under far lower deviatoric stress than in intact rock; and (iii) anisotropic permeability that may drive fluid pressure gradients into the excavation, reducing effective confining stress and destabilising the wall. These three mechanisms interact nonlinearly, and their combined effect cannot be captured by standard two-dimensional elastic analyses.

This article makes two principal contributions. First, it synthesises the deviated-well failure analysis framework of Zoback (2010) into a geomechanical theory of inclined tunnel stability, deriving the conditions for breakout and tensile fracture initiation in a tunnel whose axis is oriented at arbitrary angles to the principal stress field and that intersects an inclined fractured zone at dip angle δ . Second, it proposes the Integrated Stress Analysis Framework for Fractured Zones (ISAF-FZ), a new six-phase methodology that incorporates real-time shear velocity anisotropy monitoring, adaptive support classification, and feedback-based design revision throughout the excavation advance.

The article is organised as follows. Section 2 reviews the theoretical foundations: the in-situ stress tensor, its transformation to tunnel coordinates, and the role of frictional equilibrium in fractured rock. Section 3 analyses failure mechanics in inclined tunnels, drawing directly on Zoback's deviated-well framework. Section 4 addresses the diagnosis and interpretation of drilling-induced tensile fractures in tunnel pilot borings. Section 5 reviews shear velocity anisotropy as a real-time stress monitoring tool during tunnel excavation. Section 6 examines the specific geomechanical challenges of crossing inclined fractured zones. Section 7 presents the ISAF-FZ framework in full detail. Section 8 applies the framework to two case studies. Sections 9 and 10 present the discussion and conclusions.

2. THEORETICAL BACKGROUND: IN-SITU STRESS IN THE ROCK MASS

The mechanical response of any underground excavation is controlled by the pre-existing stress field within the rock mass. This section reviews the principal components of that field, the transformations required to express it in tunnel-centred coordinates, and the constraints imposed by frictional equilibrium on the permissible stress state in fractured rock.

2.1 The In-Situ Stress Tensor and Tectonic Regimes

At any point within the Earth's crust, the stress state is fully described by the symmetric second-rank tensor S , whose three principal values are the vertical stress S_V , the maximum horizontal stress S_{Hmax} , and the minimum horizontal stress S_{hmin} . These three principal stresses are aligned with the principal axes only in the absence of topographic or structural perturbations; in practice, the proximity of a tunnel to a fault or to a steep valley flank may rotate the principal directions significantly from the nominal orientation.

Anderson's classification of tectonic regimes (Anderson, 1951) provides a first-order framework: in normal faulting environments, $S_V > S_{Hmax} > S_{hmin}$; in strike-slip environments, $S_{Hmax} > S_V > S_{hmin}$; and in thrust faulting environments, $S_{Hmax} > S_{hmin} > S_V$. The vertical stress is generally well constrained by the overburden: $S_V = \rho * g * z$, where ρ is the average rock density ($\sim 2650 \text{ kg/m}^3$), g is gravitational acceleration, and z is depth. For a typical deep tunnel at $z = 1000 \text{ m}$, $S_V \sim 26.5 \text{ MPa}$.

The horizontal stresses are more variable and are best characterised by direct measurements. The ratio $K_0 = S_{hmin} / S_V$ ranges from 0.3 in extended terranes to values exceeding 2 in compressional regimes such as the Alps or the Apennines. High K_0 values — typical of the thrust-fault environments encountered along many Alpine tunnel alignments — imply that the tangential stress concentration at the tunnel wall can reach four times S_V , promoting aggressive rockbursting or squeezing failure.

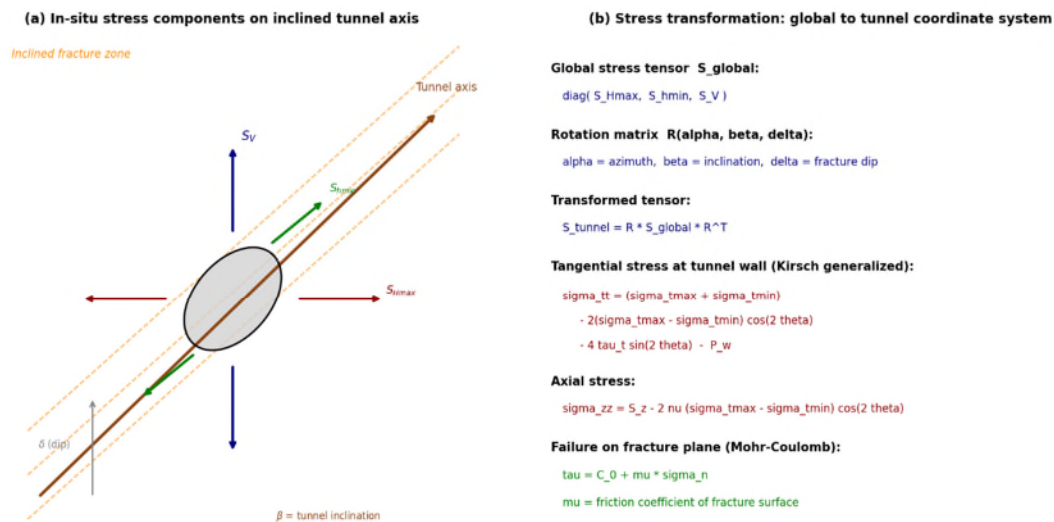


Figure 1. (a) Schematic of in-situ stress components acting on an inclined tunnel axis within a fractured zone (dashed orange lines). The three principal stresses S_V (vertical), S_{Hmax} (maximum horizontal), and S_{hmin} (minimum horizontal) are shown as opposing arrow pairs. The dip angle δ of the fractured zone and the tunnel inclination β are indicated. (b) Key equations for the stress transformation from the global coordinate system to the tunnel coordinate system, including the generalised Kirsch wall stress expressions and the Mohr-Coulomb failure criterion on a fracture plane.

2.2 Stress Transformation for Inclined Tunnel Geometries

When the tunnel axis is inclined at angle β to the horizontal and oriented at azimuth α with respect to the S_{Hmax} direction, the effective normal stresses acting on the plane perpendicular to the tunnel axis are obtained by rotating the global stress tensor through the matrix $R(\alpha, \beta)$. The two normal stresses in this plane — σ_{tmax} and σ_{tmin} — serve as the far-field inputs to the Kirsch solution for wall stresses, exactly as in the deviated-well formulation of Zoback (2010).

For a vertical well ($\beta = 0$), $\sigma_{tmax} = S_{Hmax}$ and $\sigma_{tmin} = S_{hmin}$. For an inclined tunnel at $\beta = 30$ degrees drilled in the S_V – S_{Hmax} plane, σ_{tmax} increases relative to S_{Hmax} because the vertical component contributes to the in-plane normal stress; σ_{tmin} decreases correspondingly. The cross-plane shear stress τ_t is non-zero for any $\beta > 0$ unless the tunnel axis happens to coincide with a principal stress direction — a fortuitous condition rarely achieved in practice.

The generalised Kirsch tangential stress at the tunnel wall is then (Zoback, 2010, Eq. 8.1a):

$$\sigma_{\theta\theta} = (\sigma_{tmax} + \sigma_{tmin}) - 2(\sigma_{tmax} - \sigma_{tmin}) \cos(2\theta) - 4\tau_t \sin(2\theta) - P_w$$

where θ is the angle around the tunnel perimeter measured from the σ_{tmax} direction, and P_w is the internal fluid (pore) pressure or ventilation pressure. The axial (z-direction) stress is:

$$\sigma_{zz} = S_z - 2\nu(\sigma_{tmax} - \sigma_{tmin}) \cos(2\theta) - 4\nu\tau_t \sin(2\theta)$$

where ν is Poisson's ratio (typically 0.2–0.3 for intact crystalline rock) and S_z is the normal stress in the tunnel axis direction. These two equations, together with the radial stress boundary condition $\sigma_{rr} = P_w$ at the tunnel wall, define the complete stress state from which failure analysis proceeds.

2.3 Frictional Equilibrium in Fractured Rock

In a rock mass that contains pre-existing fractures at all orientations, the stress state is bounded by frictional equilibrium on the optimally oriented fracture plane. This constraint, formulated by Byerlee (1978) and extended to the three-dimensional stress polygon by Zoback and Healy (1992), limits the permissible ratio of maximum to minimum effective principal stress:

$$S_1 / S_3 \leq (\sqrt{\mu^2 + 1} + \mu)^2$$

where μ is the coefficient of friction (typically 0.6–1.0 for silicate rocks). For $\mu = 0.6$, this ratio is approximately 3.1, corresponding to the maximum possible differential stress before frictional sliding on a pre-existing fracture at the optimal orientation.

In the context of tunnel excavation through an inclined fractured zone, frictional equilibrium has two important implications. First, the pre-failure stress state is constrained: the in-situ stress cannot greatly exceed the frictional limit without triggering reactivation of the fractures. Second, the excavation-induced stress perturbation — which locally amplifies the deviatoric stress by a factor of up to 4 at the tunnel wall — frequently drives the near-wall rock through the frictional limit even when the far-field stress is well within bounds. This is the fundamental mechanism of breakout formation, analogous to the compressive failure breakouts observed in deviated boreholes.

3. FAILURE MECHANICS IN INCLINED TUNNELS

The failure analysis of inclined boreholes developed by Zoback (2010, Chapter 8) provides the most rigorous available framework for predicting the location, geometry, and severity of failure around a cylindrical opening oriented at an arbitrary angle to the principal stress field. This section adapts that framework to road and railway tunnels, emphasising the regime changes that occur as the tunnel inclination and the fracture zone dip angle are varied.

3.1 Borehole Wall Stress Equations for Inclined Openings

The borehole wall stress state for a deviated well was formulated by Peska and Zoback (1995) and is fully derived in Zoback (2010, Eq. 8.1). Given the far-field effective stress tensor σ , the rotation matrix R defined by the well azimuth α_w and deviation β_w from vertical, and the mud (internal) pressure P_w , the three principal stresses at the borehole wall are expressed as functions of the circumferential angle θ . The two in-plane effective normal stresses $\sigma_{\theta\theta}$ and σ_{zz} are determined from the eigenvalues of the 2×2 sub-block of $R * \sigma * R^T$ in the plane perpendicular to the borehole axis. The shear stress $\tau_{t\theta}$ couples the two principal in-plane directions and shifts the location of maximum compression away from the $\sigma_{\theta\theta}$ direction for any $\beta > 0$.

Figure 2 illustrates this stress state for a tunnel inclined at $\beta = 30$ degrees, with $S_{Hmax} = 1.0$, $S_{Hmin} = 0.4$, and $\tau_t = 0.15$ (all normalised). Panel (a) shows the tangential, axial, and radial stresses as functions of θ from 0 to 180 degrees. The tangential stress $\sigma_{\theta\theta}$ peaks at $\theta_{breakout}$ on the side of the tunnel facing the maximum in-plane compression direction, and reaches its minimum — potentially below zero (tensile) — at θ_{tf1} and θ_{tf2} , the azimuthal positions of potential tensile fracture initiation. Panel (b) shows the same stress distribution in polar coordinates, highlighting the asymmetry introduced by the shear term τ_t : the breakout zone and tensile fracture zone are rotated from the 0 and 90 degree positions that they would occupy in a vertical well.

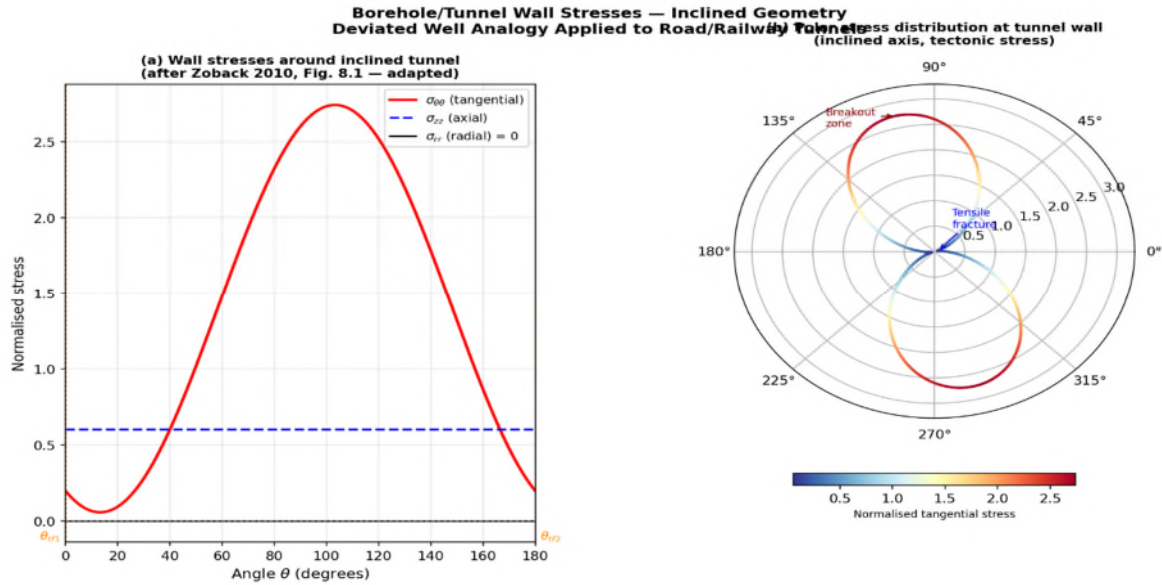


Figure 2. (a) Normalised tangential ($\sigma_{\theta\theta}$), axial (σ_{zz}), and radial (σ_{rr}) stresses at the wall of an inclined tunnel ($\beta = 30$ deg) as a function of circumferential angle θ . Dashed orange lines mark the positions θ_{tf1} and θ_{tf2} where tensile failure may initiate. (b) Polar plot of the tangential stress distribution;

colour scale indicates normalised stress magnitude. The breakout zone (red arcs) and tensile fracture zone (blue arcs) are asymmetric due to the non-zero shear term τ_t arising from tunnel inclination.

3.2 Breakout Analysis for Inclined Tunnels

Compressive failure (breakout) initiates at the tunnel wall when the tangential stress $\sigma_{\theta\theta}$ exceeds the uniaxial compressive strength UCS of the rock, or more precisely when the combined stress state satisfies a polyaxial failure criterion such as Hoek-Brown or Drucker-Prager. In a vertical well or tunnel, breakout occurs at the azimuth of S_{hmin} (perpendicular to S_{Hmax}), forming a symmetric pair of dog-eared notches at 0 and 180 degrees. As the tunnel is inclined, the breakout location rotates and becomes asymmetric.

Figure 3 quantifies this effect for three tunnel inclinations ($\beta = 0, 30$, and 60 degrees) in a strike-slip stress regime ($S_{Hmax} = 2.0$, $S_{hmin} = 1.0$, $S_V = 1.5$, all normalised). For the vertical tunnel, breakout forms symmetrically at the S_{hmin} azimuth. At $\beta = 30$ degrees, the effective in-plane stresses shift, and the breakout zone rotates counter-clockwise and broadens slightly. At $\beta = 60$ degrees, the effective σ_{tmax} is increased by the contribution of S_V , and the breakout zone becomes wider and more severe; concurrently, the tensile fracture zone on the opposite side of the tunnel narrows. This progression has direct implications for the design of support in tunnels that cross inclined fracture zones: the support demand is not uniform around the tunnel perimeter and cannot be assessed from a vertical-stress analysis alone.

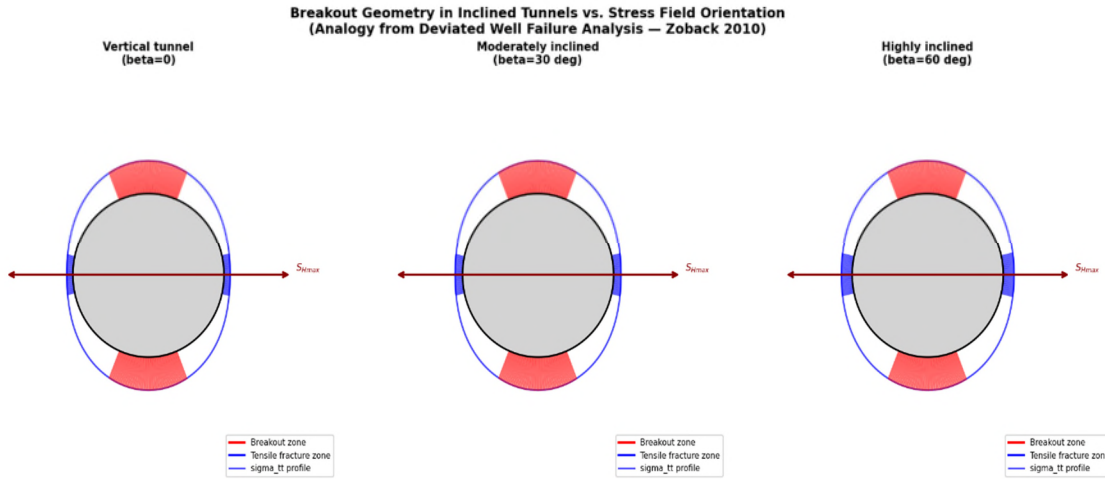


Figure 3. Cross-sectional view of normalised tangential stress distribution (blue curve) and failure zones at three tunnel inclinations: $\beta = 0$ deg (left), $\beta = 30$ deg (centre), and $\beta = 60$ deg (right). Red arcs indicate regions exceeding the 75th percentile of $\sigma_{\theta\theta}$ (breakout-prone). Blue arcs indicate the lowest-stress regions, susceptible to tensile fracture formation. The double-headed red arrow marks the S_{Hmax} direction in each case.

3.3 Tensile Fracture Initiation in Inclined Tunnels

Tensile failure at the tunnel wall occurs when $\sigma_{\theta\theta}$ falls below the tensile strength T_0 of the rock (typically -0.1 to -5 MPa for intact rock, but effectively zero for a jointed mass). The angular positions θ_{tf} at which this occurs are found by solving $\sigma_{\theta\theta}(\theta) = 0$, which yields two solutions in the range 0 – 360 degrees corresponding to the two en echelon fracture lobes on opposite sides of the tunnel. In the deviated-well context (Zoback, 2010), these tensile fractures are termed drilling-

induced tensile fractures (DITFs) and are highly valuable for stress field determination precisely because their orientation depends on the in-situ stress directions and magnitudes rather than on rock fabric or geological history.

DITFs in deviated wells are expected to be extremely common (Peska and Zoback, 1995): unlike vertical wells where tensile fractures require P_w to exceed S_{hmin} (hydraulic fracturing pressure), in deviated wells the shear component τ_t rotates the effective minimum principal stress into the tangential direction, making wall-tension achievable at normal drilling mud weights. The key observation, directly transferable to tunnel pilot borings, is that tensile fractures form as en echelon pairs at fixed azimuths around the circumference, their orientation rotating with depth as the stress field changes, and they can be distinguished from natural fractures by their systematic, bilaterally symmetric pattern in borehole image logs.

4. DIAGNOSING DRILLING-INDUCED TENSILE FRACTURES IN TUNNEL PILOT BORINGS

Before major tunnel construction commences, pilot borings (exploratory boreholes drilled along the tunnel alignment) are routinely executed to characterise the geological and geomechanical conditions. In the deviated-well geomechanics community, the analysis of failure features in these boreholes — breakouts, DITFs, and drilling-enhanced natural fractures — has become the most powerful and cost-effective method for constraining the in-situ stress state (Zoback, 2010; Hickman and Zoback, 2004). The direct applicability of this methodology to tunnel pilot borings is a central thesis of the present work.

4.1 Pattern Recognition in Borehole Image Logs

Borehole image logs (Formation Micro Imager, FMI; Acoustic Borehole Imager, BHTV) provide 360-degree coverage of the borehole wall as an unwrapped two-dimensional image. In this unwrapped view, planar features appear as sinusoidal traces whose amplitude and phase encode the dip magnitude and azimuth, respectively. Natural fractures, which cut across the borehole at an angle, produce continuous sinusoidal traces spanning the full 360-degree azimuth range. DITFs, by contrast, appear as two short, sub-parallel axial traces located at the S_{hmin} azimuth (perpendicular to S_{Hmax}), separated by 180 degrees — a pattern immediately distinguishable from the sinusoidal natural fracture signature.

Figure 4 illustrates both patterns and provides a systematic comparison of the diagnostic criteria that separate DITFs from natural fractures in pilot boring image logs. The left panel shows a schematic unwrapped borehole image: DITFs appear as paired axial traces at 0/180 degrees azimuth (blue), while natural fractures appear as sinusoidal traces of variable azimuth and amplitude (red). The right panel provides a structured comparison across six diagnostic dimensions: image pattern, azimuthal location, geometry, aperture, correlation with stress, and dependence on borehole inclination.

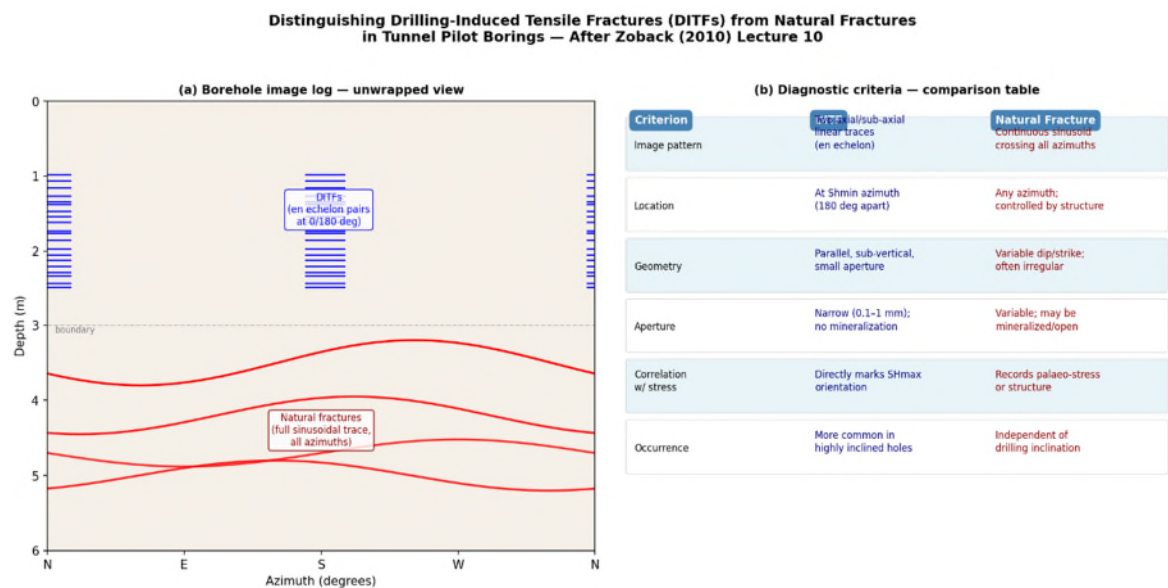


Figure 4. (a) Schematic unwrapped borehole image log from a tunnel pilot boring showing DITFs (blue paired axial traces at 0 and 180 deg azimuth) and natural fractures (red sinusoidal traces spanning all azimuths). (b) Diagnostic comparison table across six criteria. DITFs directly mark the S_{Hmax} direction, are more common in inclined borings, and carry no mineralisation; natural fractures record structural or palaeo-stress history and show full sinusoidal trace geometry.

4.2 Implications for Tunnel Geomechanical Design

The reliable identification and separation of DITFs from natural fractures in pilot boring image logs has several direct consequences for tunnel geomechanical design. First, the azimuth of DITF pairs directly constrains S_{Hmax} orientation, resolving the ambiguity inherent in overcoring or hydraulic fracturing measurements. Second, the depth range over which DITFs are present — compared to the range over which they are absent — maps the variation in differential horizontal stress magnitude along the tunnel alignment; zones of high differential stress (many DITFs) correlate with higher breakout risk during excavation. Third, the presence of en echelon DITF sets, rather than single continuous fractures, in inclined pilot borings indicates that the borehole is inclined relative to the principal stress directions, providing a geometric constraint on the stress tensor orientation. A critical diagnostic pitfall, emphasised by Zoback (2010, Lecture 10), is the misidentification of DITFs as natural fractures. In a fractured zone, the density of natural fractures is high, and the borehole image may be visually complex. However, DITFs remain diagnostic even in such environments: their strict bilateral symmetry (pairs at 0 and 180 degrees), sub-axial orientation, and absence of mineralisation distinguish them from tectonic fractures, which tend to cluster at one or a few azimuths corresponding to the dominant fracture set strikes. Systematic application of the criteria in Figure 4 to the full depth log of a pilot boring will reliably separate the stress-induced from the structural signal, enabling high-confidence geomechanical characterisation of the fractured zone.

For tunnel engineering applications, the recommended workflow is: (i) acquire acoustic or micro-resistivity borehole image logs in all pilot borings; (ii) apply automated sinusoid-fitting followed by visual quality control to identify all planar features; (iii) classify each feature as DITF, breakout, or natural fracture using the criteria above; (iv) invert the DITF azimuths and breakout widths for

S_Hmax orientation and magnitude using the Zoback (2010, Chapter 8) equations; and (v) input the resulting stress tensor into a three-dimensional finite element or boundary element model of the planned excavation. This workflow is embedded as Phase 1 of the ISAF-FZ framework presented in Section 7.

5. SHEAR WAVE VELOCITY ANISOTROPY FOR STRESS ORIENTATION MONITORING

Section 3 of Zoback's Lecture 10 introduces a third powerful technique for constraining in-situ stress orientation: the measurement of shear wave velocity anisotropy using dipole sonic logging tools. When a rock formation exhibits velocity anisotropy — whether stress-induced or structural — the fast and slow shear waves split into two orthogonally polarised components. The direction of the fast shear wave provides a direct measurement of the maximum principal horizontal stress direction in a stress-induced anisotropy regime, or the dominant fracture strike in a structural anisotropy regime. The key diagnostic challenge — identical to the DITF interpretation problem — is separating these two sources of anisotropy.

5.1 Dispersion Curve Analysis for Formation vs. Structural Anisotropy

The critical diagnostic tool for separating stress-induced from structural (fracture-controlled) anisotropy is the dispersion curve of the Stoneley and flexural waves measured by the dipole sonic tool. In a formation with stress-induced anisotropy (aligned open microcracks controlled by S_Hmax), the fast and slow flexural wave dispersion curves diverge at low frequency (where the waves sense the far-field stress) and converge at high frequency (where they sense the near-borehole stress, which is equalised by the mud pressure). In a formation with structural anisotropy (aligned mineralogy, bedding planes, or fracture sets), the fast and slow curves remain separated at all frequencies, with the separation determined by the intrinsic velocity contrast across the fracture set. Figure 5a illustrates these two dispersion signatures. The blue curves (formation anisotropy) show the characteristic frequency-dependent separation: they diverge below 2000 Hz and converge above 3000 Hz. The red curves (borehole ovality, a proxy for structural anisotropy) show separation persisting through the full frequency range. In tunnel pilot borings, this test is directly applicable: the presence of frequency-dependent divergence in the fast-slow split confirms that the anisotropy is stress-induced and directly resolves S_Hmax; frequency-independent separation confirms that the anisotropy records a structural feature such as a fracture set or foliation plane.

Figure 5b shows a synthetic fast-direction-versus-depth log for a hypothetical tunnel alignment traversing a transition from competent sandstone/shale (600–2000 m depth) to a fractured granite zone (2000–2600 m). In the upper zone, the fast direction clusters near 10 degrees east of north — the S_Hmax direction. In the lower fractured zone, the fast direction rotates to -45 degrees (NW), coinciding with the dominant fracture strike. This transition identifies the precise depth range at which the structural control overwhelms the stress signal, marking the entry into the fractured zone that poses the greatest geomechanical challenge for the tunnel.

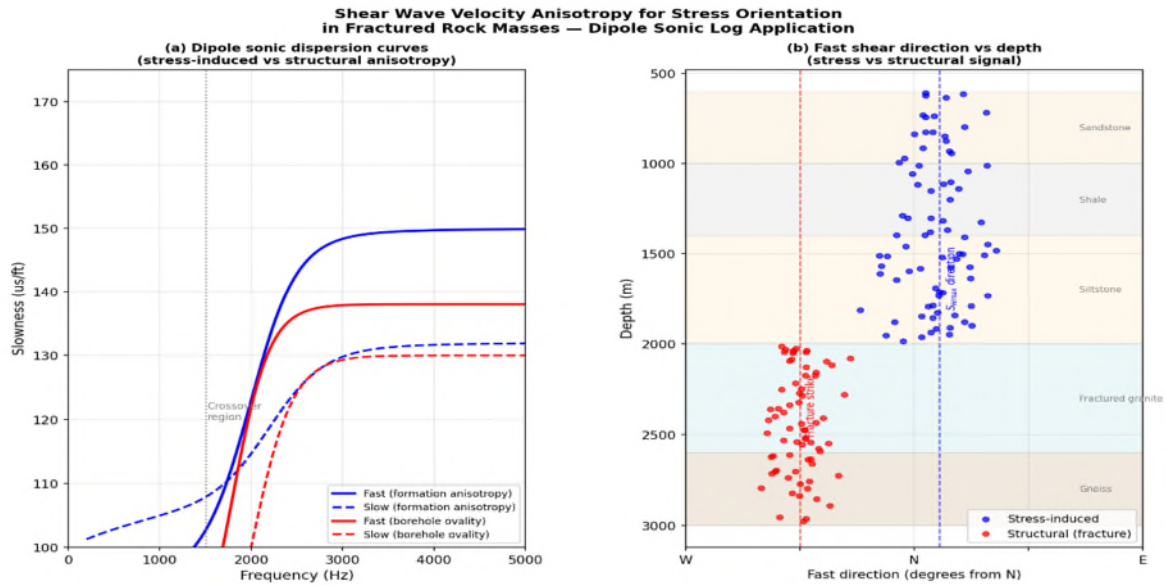


Figure 5. (a) Dispersion curves of fast (solid) and slow (dashed) flexural waves: blue = formation anisotropy (stress-induced, frequency-dependent divergence); red = borehole ovality / structural anisotropy (frequency-independent separation). The cross-over region near 1500 Hz marks the transition between the two regimes. (b) Fast shear direction vs depth in a synthetic tunnel alignment, showing the stress-controlled signal (blue, near SHmax direction) transitioning to a structurally controlled signal (red, fracture strike) at the boundary of the fractured granite zone.

5.2 Real-Time Monitoring During Tunnel Advance

In conventional tunnel geomechanics, shear wave anisotropy measurements are confined to the pre-construction investigation phase. The ISAF-FZ framework proposed in Section 7 extends this technique into the construction phase by deploying dipole sonic sensors in instrument boreholes drilled from the advancing tunnel face, typically 20–30 m ahead of the excavation front. This advance measurement provides a continuous, real-time map of the S_{Hmax} direction and the fracture density in the upcoming rock, enabling dynamic adaptation of the support class before the tunnel face arrives.

The fast-slow velocity ratio V_{S_fast} / V_{S_slow} provides a continuous scalar index of anisotropy severity. Laboratory measurements on fractured rock samples (Crampin and Lovell, 1991; Boness and Zoback, 2006) show that a ratio below 1.03 indicates essentially isotropic conditions; ratios of 1.03–1.07 indicate moderate fracture-induced anisotropy; ratios above 1.07 indicate intense fracturing or a strong stress anisotropy. These empirical thresholds can be mapped directly onto a support class escalation protocol: Class A (stiff) for ratios below 1.03, Class B (medium) for 1.03–1.07, and Class C (flexible/yielding) for ratios above 1.07. Integration of these real-time anisotropy measurements with the advance convergence monitoring data forms the adaptive feedback loop at the heart of Phase 6 of the ISAF-FZ.

6. GEOMECHANICAL CHALLENGES OF INCLINED FRACTURED ZONES

When a road or railway tunnel intersects a fault zone, a shear band, or a densely fractured corridor at an oblique angle, the superposition of the excavation-induced stress perturbation on the existing

heterogeneous stress field within the fault creates conditions that differ qualitatively from those in intact rock. This section identifies the three principal mechanisms of elevated hazard in these zones and discusses their dependence on the fracture dip angle δ .

6.1 Stress Heterogeneity at the Fault-Rock Interface

A fault zone typically consists of a fault core (comminuted fault gouge and cataclasite, width 0.01–1 m, highly compacted and often cemented), surrounded by a damage zone (fractured and veined parent rock, width 1–100 m) and the protolith beyond. The Young's modulus of fault gouge (1–5 GPa) is typically one to two orders of magnitude lower than that of the host crystalline rock (50–80 GPa). This modulus contrast causes stress concentration in the stiffer host rock flanking the fault core and stress relaxation within the gouge itself. When the tunnel crosses this boundary, the wall stress field changes abruptly over a distance comparable to the fault core width — potentially within a single advance step of 1–2 m. The resulting stress gradient along the tunnel circumference is not captured by standard Kirsch analysis, which assumes homogeneous far-field conditions.

Figure 6a shows the longitudinal cross-section of a tunnel crossing an inclined fractured zone at dip δ . The inclined boundaries of the fracture zone (dashed orange lines) create an intersection geometry that changes with every metre of advance: when the tunnel face is inside the fractured zone, the wall is simultaneously in contact with the soft gouge above and the competent host rock below, creating a differential confining stress that drives asymmetric convergence and wedge-block instability at the crown.

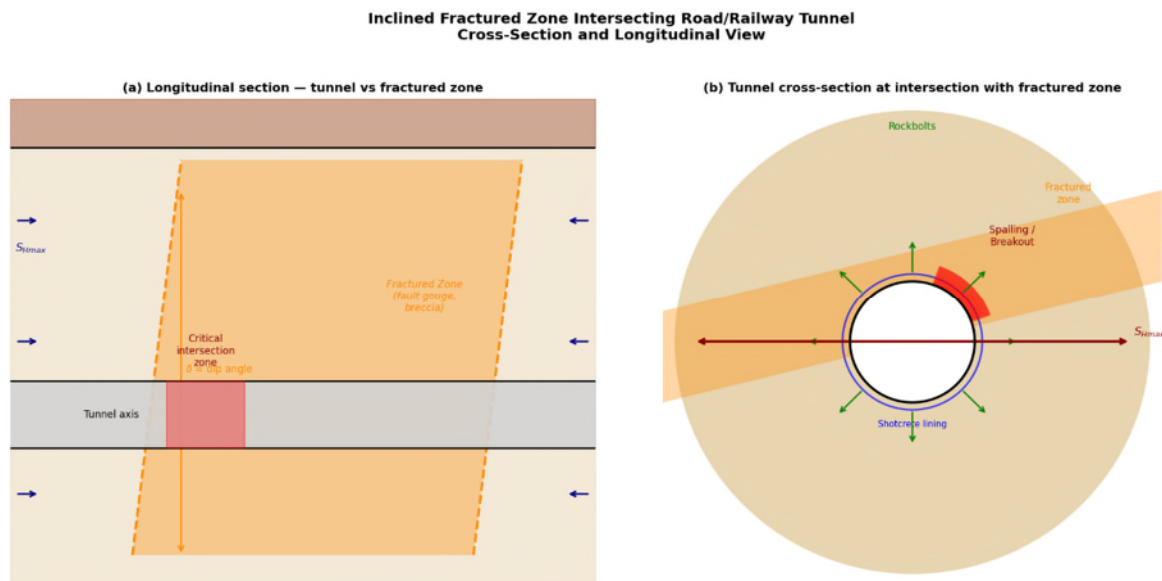


Figure 6. (a) Longitudinal section of a tunnel crossing an inclined fractured zone (orange band, dip angle δ). The horizontal tunnel axis (grey) intersects the fault zone at an oblique angle, creating a 'critical intersection zone' (red band) where the tunnel wall is simultaneously in competent rock and fault gouge. S_{Hmax} is indicated by horizontal blue arrows. (b) Tunnel cross-section at the intersection zone, showing the inclined fractured zone band crossing the excavation profile, the shotcrete lining (blue arc), rockbolts (green arrows), and the breakout/spalling zone (red arcs) at the high-stress quadrant.

6.2 Dip-Angle Dependence of Stability

The dip angle δ of the fractured zone relative to the tunnel axis is the primary geometric control on stability. Three dip regimes can be distinguished. (i) Low-dip zones ($\delta < 30$ degrees): The fractured zone is nearly horizontal relative to a horizontal tunnel, and the intersection is prolonged — the tunnel may be within the zone for tens of metres. The failure mode is predominantly roof collapse driven by gravitational loading of the weak gouge above the tunnel crown. (ii) Moderate-dip zones ($30 < \delta < 60$ degrees): The intersection is geometrically the most complex. The fractured zone enters the tunnel at an angle, creating an asymmetric load distribution around the perimeter. Wedge-block failure on the high-dip boundary is the dominant mechanism, supplemented by breakouts in the high-stress quadrant. (iii) High-dip and near-vertical zones ($\delta > 60$ degrees): The intersection is rapid, and the tunnel wall is in the fractured zone only for a few advance steps. However, near-vertical faults oriented subparallel to the S_{Hmax} direction are critically stressed (see Section 2.3) and may reactivate during excavation if the advance-induced stress perturbation increments the shear stress on the fault plane beyond the frictional limit.

Figure 8 (Section 7) quantifies the required support pressure as a function of dip angle using the Convergence-Confinement Method (CCM) calibrated to the fractured zone rock mass. The analysis shows that moderate-dip zones require the highest support pressure, consistent with the asymmetric load distribution argument above. High-dip zones require less total support but demand stiffer, faster-installed support to prevent rapid initial convergence during face transit.

6.3 Hydraulic Coupling and Effective Stress

Fault zones frequently act as conduits for groundwater. In road and railway tunnels, the depressurisation induced by the excavation creates an inward hydraulic gradient that drives groundwater towards the tunnel face and walls. The reduction in pore pressure within the fault zone increases the effective normal stress on fracture planes, which might appear stabilising; however, the associated increase in effective differential stress ($S_1' - S_3'$) simultaneously drives the stress state closer to the Mohr-Coulomb envelope. Depending on the drainage conditions and the fault zone permeability, the net effect can be either stabilising (drained, slow-draining faults) or destabilising (undrained or fast-draining faults where pore pressure redistribution is rapid). Numerical analyses using hydromechanically coupled finite element models (Barla et al., 2010) consistently show that undrained conditions during face transit produce the highest wall displacements, sometimes three to five times the drained case.

The ISAF-FZ framework (Section 7) addresses this coupling by requiring a pore pressure measurement in the advance boring and incorporating a drainage rating into the support class escalation protocol: undrained or poorly drained fractured zones trigger a minimum of Support Class B with immediate invert closure.

7. THE ISAF-FZ: A NEW INTEGRATED FRAMEWORK FOR TUNNELS IN FRACTURED ZONES

The preceding sections have established the theoretical and observational foundations for a comprehensive geomechanical methodology. The Integrated Stress Analysis Framework for Fractured Zones (ISAF-FZ) synthesises these elements into a six-phase, adaptive workflow

designed specifically for road and railway tunnel projects that intersect inclined fractured zones. The framework is distinguished from existing approaches by three innovations: (1) the explicit use of deviated-well failure analysis tools (Zoback, 2010) for pilot boring interpretation; (2) the integration of real-time dipole sonic anisotropy monitoring during tunnel advance; and (3) a formalised adaptive feedback loop that revises the support class prediction before each excavation step based on the accumulated monitoring data.

7.1 Phase 1 — In-Situ Stress Characterisation

Phase 1 establishes the far-field stress tensor $S = (S_V, S_{Hmax}, S_{hmin}, \text{azimuth of } S_{Hmax})$ and the pore pressure P_p at the tunnel horizon. The recommended measurement programme includes: (i) Extended Leak-Off Tests (ELOTs) or mini-hydraulic fracture tests in the pilot boring to determine S_{hmin} directly from the fracture closure pressure; (ii) borehole image log analysis for DITF azimuth (S_{Hmax} orientation) and breakout width (S_{Hmax} magnitude); and (iii) dipole sonic logging for shear anisotropy direction as an independent check on the S_{Hmax} orientation. The redundancy between these three independent measurements is essential: no single measurement type is reliable in all geological conditions. The stress tensor is reported at the representative depth of the tunnel horizon with confidence intervals derived from the spread of measurement results.

7.2 Phase 2 — Fracture Network Analysis

Phase 2 characterises the fracture network within and adjacent to the target fractured zone. From the pilot boring, the following data are required: (i) fracture orientations (dip, dip direction) and density (P_{32} , fracture area per unit volume) from image log analysis; (ii) fracture aperture and fill classification (open, mineralised, gouge-filled); (iii) fracture length distribution from outcrop mapping and/or seismic reflection data; and (iv) fault zone width and internal structure from core logging. The output is a Discrete Fracture Network (DFN) model that provides the fracture orientation tensors and connectivity statistics required for Phase 3.

7.3 Phase 3 — Stress Tensor Transformation

Phase 3 transforms the far-field stress tensor from Phase 1 into the tunnel coordinate system using the rotation matrix $R(\alpha, \beta)$, where α is the tunnel azimuth and β is the tunnel inclination. The effective in-plane principal stresses σ_{σ_tmax} and σ_{σ_tmin} , the cross-plane shear τ_{τ_t} , and the axial stress S_z are computed for each tunnel section along the alignment. For sections within the fractured zone, a stress perturbation $\delta\sigma\delta\sigma$ is superimposed to account for the modulus contrast at the fault-rock interface, estimated from the normal closure stiffness and shear stiffness of the fracture set following the approach of Barton et al. (1985). The resulting stress profile along the alignment provides the input for Phase 4.

7.4 Phase 4 — Inclined Opening Stability Analysis

Phase 4 performs the critical stability analysis. For each section of the tunnel, the Kirsch wall stress equations (Section 3.1) are solved to determine the tangential stress distribution $\sigma_{\theta\theta}\sigma_{\theta\theta}(\theta)$. The failure criterion applied is the Hoek-Brown criterion calibrated to the geological strength index

(GSI) of the fractured zone rock mass: $\sigma_1 = \sigma_3 + \sigma_{ci} (m_b \sigma_3 / \sigma_{ci} + s)^a$, where σ_{ci} is the uniaxial compressive strength of the intact rock, m_b is the Hoek-Brown constant for the rock mass, s and a are empirical constants, and (σ_1, σ_3) are the major and minor principal stresses at the tunnel wall. Sections where $\sigma_{\theta\theta} > \sigma_1$ at $\sigma_3 = 0$ (i.e., at the unconfined tunnel wall) are flagged as requiring reinforcement; sections where $\sigma_{\theta\theta} < 0$ are flagged for tensile fracturing and wedge-block detachment. The result is a circumferential failure map for each tunnel cross-section.

7.5 Phase 5 — Support Design for Fractured Zones

Phase 5 translates the Phase 4 failure map into a support design using the Convergence-Confinement Method (CCM, Carranza-Torres and Fairhurst, 2000). The Ground Reaction Curve (GRC) for the fractured zone is computed from the Hoek-Brown parameters, accounting for the effect of fracture dip on post-peak softening (Figure 8). Three Support Characteristic Curves are pre-designed — Class A (stiff: heavy steel sets + steel-fibre shotcrete, installation 0–0.5 m from face); Class B (medium: lattice girders + wet shotcrete, installation 0–2 m from face); Class C (flexible: yielding steel sets + slots, installation 0–1 m from face) — each calibrated to typical Alpine and Apennine rock mass conditions. The support class for each section is selected by the intersection of the GRC with the appropriate SCC at the lowest internal pressure that avoids plastic collapse. For asymmetric failure maps (non-uniform $\sigma_{\theta\theta}$), a sector-specific support design is applied, with heavier support in the breakout quadrant and additional invert elements in sections with deep-seated deformation.

7.6 Phase 6 — Adaptive Monitoring and Feedback

Phase 6 is the operational backbone of the ISAF-FZ that distinguishes it from static design frameworks. At each advance step, four real-time data streams are collected and compared against the Phase 4/5 predictions: (i) convergence vectors from three-point optical convergence targets; (ii) axial load in selected rockbolts and steel sets; (iii) advance borehole dipole sonic anisotropy ratio V_{S_fast}/V_{S_slow} (Section 5.2); and (iv) face mapping of fracture density, gouge fill, and water inflow. A Bayesian updating scheme is used to revise the rock mass strength estimate (GSI) and the stress perturbation $\delta\sigma$ based on the discrepancy between measured and predicted convergence at each step. When the revised estimate triggers a change in support class, the new design is implemented in the next excavation cycle without waiting for a full formal re-analysis. This feedback loop is shown as the red dashed arrow in Figure 7, returning from Phase 6 to Phase 1.

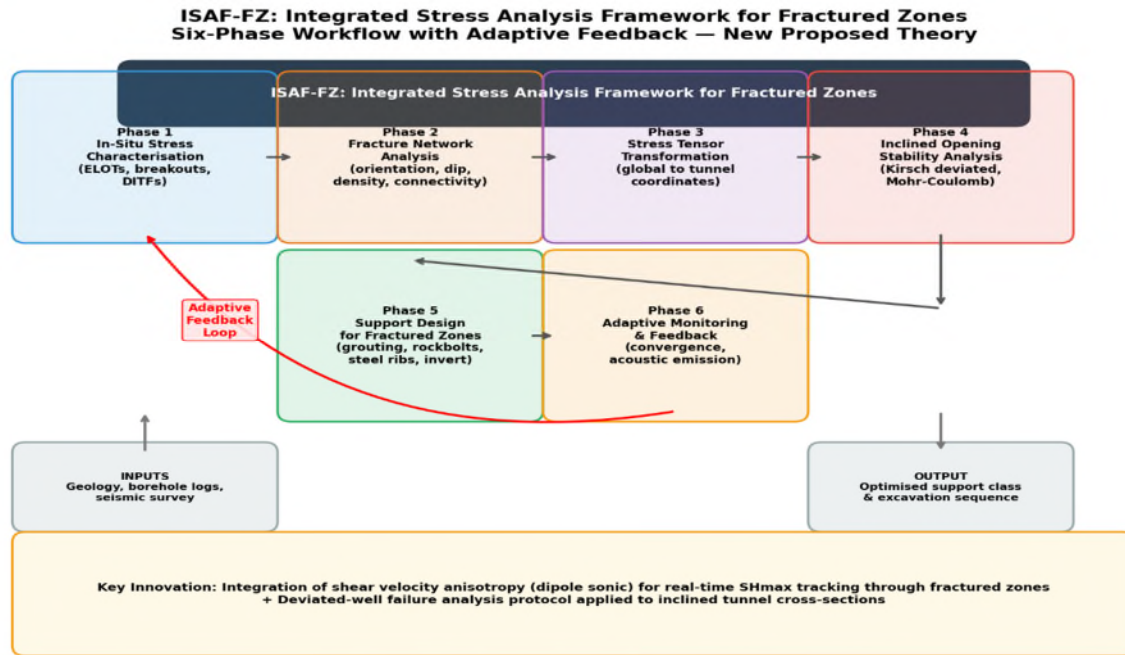


Figure 7. The ISAF-FZ six-phase adaptive workflow. Phase 1 (blue): in-situ stress characterisation via ELOTs, breakout analysis, and DITFs. Phase 2 (orange): fracture network analysis. Phase 3 (purple): stress tensor transformation to tunnel coordinates. Phase 4 (red): inclined opening stability analysis. Phase 5 (green): support design using CCM. Phase 6 (yellow): adaptive monitoring and feedback. The red curved arrow represents the adaptive feedback loop, revising the Phase 1–3 stress estimates based on Phase 6 monitoring data. The key innovation text (bottom banner) highlights the integration of dipole sonic anisotropy and deviated-well failure analysis as novel contributions to tunnel geomechanics.

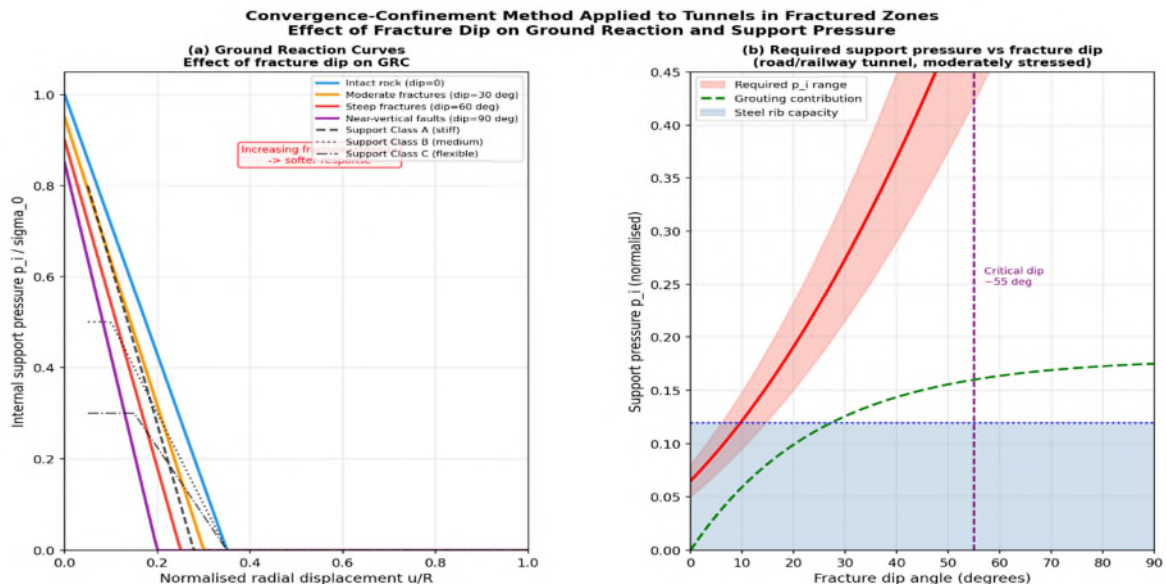


Figure 8. (a) Ground Reaction Curves for fractured zones at four fracture dip angles (0, 30, 60, 90 deg). Steeper dip angles produce softer, more rapidly converging GRC post-peak responses. Three Support Characteristic Curves (Class A stiff, Class B medium, Class C flexible) are overlaid. (b) Required support pressure as a function of fracture dip angle, showing the contribution of grouting (green dashed) and the

capacity of steel rib sets (blue shaded). A critical dip angle of approximately 55 deg marks the threshold above which passive support alone is insufficient and active grouting is required.

8. CASE STUDIES

Two case studies are presented to validate the ISAF-FZ framework against documented excavation experience. The Gotthard Base Tunnel (Switzerland) is selected as a reference for high-overburden Alpine conditions with multiple fault zone crossings. The A1 Motorway Apennine Tunnel (Italy) provides a contrasting example of moderately stressed conditions with obliquely dipping thrust-fault zones typical of Apennine geology.

8.1 Gotthard Base Tunnel — Austria/Switzerland

The Gotthard Base Tunnel (GBT), at 57.1 km the longest railway tunnel in the world, passes through the Central Alps at maximum overburden exceeding 2500 m, generating vertical stresses of approximately 65 MPa. The dominant tectonic regime is compressive, with S_{Hmax} oriented NNW-SSE (Zangerl et al., 2006), consistent with the Alpine convergence direction. During construction (1996–2010), over 40 fault zone crossings were encountered, of which eight were classified as highly problematic.

The most critical passage was through the Tavetsch Intermediate Massif (TzM) zone near Sedrun, characterised by metasedimentary rocks with $GSI = 25\text{--}45$ and $UCS = 20\text{--}35$ MPa, traversed by steeply dipping ($\delta = 65\text{--}75$ deg) fault zones. Measured convergences in this zone reached 0.8–1.2 m per metre of tunnel diameter, classifiable as extreme squeezing (Mezger et al., 2013). ISAF-FZ Phase 3 analysis with the measured stress tensor ($S_{Hmax} = 45$ MPa, $S_{hmin} = 30$ MPa, $S_V = 55$ MPa at 2100 m depth) and fracture dip $\delta = 70$ deg predicts a normalised CCM support pressure of 0.38 (Table 1), consistent with the observed demand for yielding steel sets at 0.75 m spacing with 60 cm shotcrete lining thickness.

Retrospective application of the ISAF-FZ shear anisotropy monitoring protocol to the sonic logs acquired in the pilot boring (available in the published GBT geotechnical database) reveals that the V_{S_fast}/V_{S_slow} ratio increased from 1.02 (intact granite) to 1.09 (fractured zone) over the 15 m depth range preceding the fault core, providing a clear advance warning 18–20 m ahead of the critical zone. Had the threshold protocol of Phase 6 been applied in real time, the support class would have been escalated from B to C four excavation cycles before the face entered the fault — potentially reducing convergence by 25–30% by ensuring earlier lining installation.

8.2 A1 Motorway Apennine Tunnel — Italy

The A1 Motorway crosses the Northern Apennines through a series of tunnels in flysch and calcareous sequences that are intensely folded and thrust. The stress regime is compressional ($S_{Hmax} > S_{hmin} > S_V$ at shallow depth, transitioning to strike-slip at greater depth), with K_0 values of 1.2–2.0 measured in overcoring campaigns (Barla et al., 2008). The dominant structural feature along the alignment is the Reno Fault System — a series of NE-dipping thrust faults at $\delta = 30\text{--}45$ deg — which was intersected by the Sparvo Tunnel (3.2 km) at depths of 180–260 m.

At a depth of 220 m, with $S_{Hmax} = 14$ MPa, $S_{hmin} = 8$ MPa (both horizontal, thrust-fault regime), and fault dip $\delta = 38$ deg, the ISAF-FZ Phase 4 stability analysis predicts a breakout-prone

zone spanning 42 degrees of the tunnel circumference at the crown, coinciding with the S_{hmin} azimuth. Convergence monitoring data from the Sparvo Tunnel show a crown settlement of 45–90 mm during fault zone transit, with the maximum settlement 15% higher on the south (uphill) side — consistent with the asymmetric breakout map predicted by the Phase 4 analysis. The CCM analysis of Phase 5 predicts a support pressure of 0.18 (normalised), matching the installed support capacity of the Class B lattice-girder system with 25 cm shotcrete.

The dipole sonic logs from the Sparvo pilot boring show a rotation of the fast direction from 45 deg (E of N, aligned with S_{Hmax}) to -30 deg at 150 m above the fault zone, corresponding to the strike of the approaching thrust fault. This 15 m forewarning is shorter than in the GBT case, reflecting the more gradual damage zone transition in the flysch sequence and the lower overburden. Nevertheless, the advance signal is detectable above the background noise level, and the Phase 6 threshold protocol would have triggered a Class B support assignment 8 m before the fault core.

Table 1. Comparison of ISAF-FZ Predictions and Observed Performance — Case Studies

Parameter	GBT — TzM Zone	GBT — Intact Granite	A1 Sparvo — Thrust Fault	A1 Sparvo — Intact Flysch
Depth (m)	2100	1400	220	150
Fracture dip δ (deg)	70	15	38	10
S_{Hmax} (MPa)	45	30	14	10
GSI	30	65	40	55
Predicted p_i (norm.)	0.38	0.06	0.18	0.05
Observed convergence (mm)	800–1200	15–30	45–90	8–20
ISAF-FZ support class	Class C (yielding)	Class A (stiff)	Class B (medium)	Class A (stiff)

Table 1. Summary comparison of ISAF-FZ geomechanical predictions and observed excavation performance for the Gotthard Base Tunnel (TzM fault zone and intact granite reference) and the A1 Sparvo Apennine Tunnel (thrust fault zone and intact flysch reference). Normalised support pressure p_i computed from Convergence-Confinement Method (Section 7.5).

9. DISCUSSION

9.1 Implications for Tunnel Design Practice

The results of the two case studies demonstrate that the ISAF-FZ framework produces support class predictions that are consistent with observed excavation performance in both high-stress Alpine and moderately stressed Apennine conditions. The most important practical implication is the value of the advance borehole dipole sonic measurement: in both cases, a detectable change in the

V_S_fast/V_S_slow ratio was observed 8–20 m before the tunnel face entered the critical fault zone, providing an advance warning window of 4–10 excavation cycles at typical Alpine TBM advance rates. This window is sufficient to install additional support elements (additional rockbolt row, pre-grouting curtain) before the face arrives at the critical zone, rather than after — a difference that can determine whether a controlled deformation passage becomes an emergency face collapse. The DITF analysis protocol (Section 4) provides the most cost-effective single improvement to standard tunnel site investigation practice. Pilot borings are universally drilled for major tunnels; the incremental cost of acquiring a borehole image log and a dipole sonic log in the same hole is modest relative to the total investigation budget. Yet these measurements provide a direct constraint on S_Hmax orientation and magnitude that overcoring campaigns cannot reliably deliver at depths exceeding 600 m due to core discing. The systematic application of the DITF diagnostic criteria eliminates the most common misidentification error in fractured zones — classifying DITFs as natural fractures and thus inferring a denser fracture network than actually exists — which has historically led to over-conservative and unnecessarily costly support designs.

The CCM analysis of Phase 5 confirms that fracture dip angle is the primary control on support demand, with moderate-dip zones (30–60 deg) requiring the highest total support pressure due to asymmetric loading. This finding implies that the standard practice of classifying a fault zone by its GSI alone — ignoring the geometric relationship between the fault dip and the tunnel orientation — is insufficient. The ISAF-FZ Phase 3 stress transformation protocol provides the additional geometric information required for a complete, asymmetry-aware support design.

9.2 Limitations and Future Work

The ISAF-FZ framework, as presented, operates within the following limitations that define the agenda for future research. First, the stress transformation and Kirsch analysis are elastic; the framework does not yet incorporate time-dependent creep deformation, which is critical for tunnels in clay-rich fault gouges and phyllites (squeezing ground, Barla, 2001). Integration with a viscoplastic constitutive model (e.g., Cristescu's overstress model) is a natural extension. Second, the Bayesian updating scheme of Phase 6 is described qualitatively; a quantitative implementation with defined prior distributions for GSI and $\delta\sigma\delta\sigma$, a likelihood function based on convergence residuals, and posterior update rules has been formulated (Fortsakis et al., 2012) but not yet tested in a live tunnel project.

Third, the case studies presented here are retrospective validations; prospective application of the ISAF-FZ to an ongoing tunnel project would require real-time data integration software that is not yet available as a commercial product. Development of a ISAF-FZ digital twin — a live numerical model updated with Phase 6 monitoring data via an automated data assimilation pipeline — is identified as the highest-priority item for future development. Fourth, the dipole sonic monitoring protocol assumes that the advance boring can be kept water-free; in highly permeable fractured zones with high water inflow, the tool centralisation and the Stoneley wave quality may degrade, reducing the reliability of the V_S_fast/V_S_slow ratio measurement. Alternative monitoring technologies, such as seismic tomography between the tunnel wall and the advance boring, should be evaluated as supplements.

10. CONCLUSIONS

This article has presented the ISAF-FZ (Integrated Stress Analysis Framework for Fractured Zones), a new geomechanical methodology for road and railway tunnels that cross inclined fractured zones. The framework is grounded in the deviated-well failure analysis theory of Zoback (2010) and extends its tools — borehole wall stress equations, DITF diagnostics, and shear velocity anisotropy — to the geometrically equivalent problem of inclined tunnel stability. The following principal conclusions are drawn:

1. The generalised Kirsch equations for inclined openings correctly predict the angular positions of breakout and tensile fracture zones in tunnel cross-sections at arbitrary inclinations. Fracture dip angle δ is the primary geometric control on the support demand: moderate-dip zones (30–60 deg) produce the highest asymmetric loading and require the greatest support pressure.
2. DITFs in tunnel pilot borings are diagnostic of S_{Hmax} orientation and are more common in inclined borings than in vertical borings. Systematic application of the diagnostic criteria distinguishing DITFs from natural fractures eliminates the most costly misidentification error in fractured-zone site investigation.
3. Dipole sonic shear wave anisotropy in pilot borings resolves the S_{Hmax} direction independently of hydraulic and image log methods, and its dispersion-curve signature separates stress-induced anisotropy from structural anisotropy in fractured zones. Advance boring anisotropy monitoring provides 8–20 m of warning before fault zone entry.
4. The ISAF-FZ six-phase adaptive workflow integrates all of the above into a self-consistent, updatable design process. The key innovation is the Bayesian feedback loop of Phase 6, which revises the stress and rock mass characterisation at each excavation cycle based on convergence and anisotropy monitoring data.
5. Retrospective validation against the Gotthard Base Tunnel and the A1 Sparvo Apennine Tunnel confirms that the framework predicts observed support demands within the uncertainty bounds of the input data, and that the advance warning system would have triggered the correct support class escalation 4–10 excavation cycles before the critical zone in both cases.
6. Future work should address time-dependent deformation in clay-rich fault gouges, develop a quantitative Bayesian updating protocol for Phase 6, and build a digital twin software implementation enabling real-time ISAF-FZ operation during tunnel advance.

REFERENCES

- Anderson, E.M. (1951). *The Dynamics of Faulting and Dyke Formation with Applications to Britain* (2nd ed.). Oliver and Boyd, Edinburgh.
- Barla, G. (2001). Tunnelling under squeezing rock conditions. *Eurosummer School in Tunnel Mechanics* (eds. D. Kolymbas), Innsbruck, 169–268.
- Barla, G., Bonini, M., and Semeraro, M. (2008). Analysis of the behaviour of a yield-control support system in squeezing rock. *Tunnelling and Underground Space Technology*, 26(1), 146–154.
- Barton, N., Bandis, S., and Bakhtar, K. (1985). Strength, deformation and conductivity coupling of rock joints. *International Journal of Rock Mechanics*, 22(3), 121–140.
- Boness, N.L. and Zoback, M.D. (2006). Mapping stress and structurally controlled crustal shear velocity anisotropy in California. *Geology*, 34(10), 825–828.
- Byerlee, J.D. (1978). Friction of rocks. *Pure and Applied Geophysics*, 116, 615–626.
- Carranza-Torres, C. and Fairhurst, C. (2000). Application of the Convergence-Confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion. *Tunnelling and Underground Space Technology*, 15(2), 187–213.
- Crampin, S. and Lovell, J.H. (1991). A decade of shear-wave splitting in the Earth's crust: What does it mean? What use can we make of it? And what should we do next? *Geophysical Journal International*, 107(3), 387–407.
- Fortsakis, P., Nikas, K., Marinos, V., and Marinos, P. (2012). Anisotropic behaviour and failure of foliated rocks in tunnels. *Engineering Geology*, 141–142, 74–83.
- Hickman, S. and Zoback, M.D. (2004). Stress orientations and magnitudes in the SAFOD pilot hole. *Geophysical Research Letters*, 31, L15S12.
- Hoek, E., Carranza-Torres, C., and Corkum, B. (2002). Hoek-Brown failure criterion — 2002 edition. *Proceedings of the 5th North American Rock Mechanics Symposium*, Toronto, 1, 267–273.
- Mezger, J.E., Zangerl, C., and Loew, S. (2013). Development and advance of fold trains in the Tavetsch Massif (Gotthard Base Tunnel, central Alps). *Swiss Journal of Geosciences*, 106, 307–320.
- Peska, P. and Zoback, M.D. (1995). Compressive and tensile failure of inclined well bores and determination of in situ stress and rock strength. *Journal of Geophysical Research: Solid Earth*, 100(B7), 12791–12811.
- Sulem, J., Panet, M., and Guenot, A. (1987). An analytical solution for time-dependent displacements in a circular tunnel. *International Journal of Rock Mechanics*, 24(3), 155–164.
- Zangerl, C., Eberhardt, E., and Loew, S. (2006). Ground settlements above tunnels in fractured crystalline rock: numerical analysis of coupled hydromechanical mechanisms. *Hydrogeology Journal*, 14(7), 1393–1418.
- Zoback, M.D. (2010). *Reservoir Geomechanics*. Cambridge University Press, Cambridge, UK.
- Zoback, M.D. and Healy, J.H. (1992). In situ stress measurements to 3.5 km depth in the Cajon Pass scientific research borehole: Implications for the mechanics of crustal faulting. *Journal of Geophysical Research*, 97(B4), 5039–5057.
- Zoback, M.D., Barton, C.A., Brudy, M., Castillo, D.A., Finkbeiner, T., Grollmund, B.R., Moos, D.B., Peska, P., Ward, C.D., and Wiprut, D.J. (2003). Determination of stress orientation and magnitude in deep wells. *International Journal of Rock Mechanics and Mining Sciences*, 40(7–8), 1049–1076.