

Roughness, Contact Area, and Residual Flow in Unpropped Shale Fractures

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Abstract. Mean fracture opening does not uniquely determine flow through a rough, partially closed surface. The location of contacts and constrictions can matter as much as their total extent. This note uses a two-segment synthetic example to demonstrate how identical mean aperture can produce different effective conductivity. The example is then connected to stress-sensitive preserved-shale experiments and rough-contact models. The contribution is a transparent geometric argument and a measurement checklist, rather than a new universal roughness correlation.

1. Introduction and physical quantities

For smooth parallel plates with laminar single-phase flow, $C = w^3/12$ in consistent SI units [1]. In a rough fracture, an equivalent hydraulic aperture can be defined from measured flow, but it need not match the arithmetic mean separation [2]. The distinction matters most when constrictions and contacts organize into barriers or preferential channels.

Mechanical loading changes the aperture field as well as its average. Non-local closure models account for interactions among surface regions [3], while elastoplastic contact models address persistent deformation [4]. Accordingly, a roughness number measured before loading is not a complete description of the hydraulic geometry after loading.

The thesis summary reports strong stress-related loss in unpropped shale and incomplete recovery after unloading [5]. The 2017 study examines induced unpropped fractures in preserved samples [6], and the related 2019 paper links their response to stress, fluid exposure, and mineralogy [7]. Those data motivate a changing-contact interpretation, but conductivity alone does not reconstruct the aperture map that produced it.

Coupled joint behavior provides a general mechanical context [8]. Barnett tests compare multiple fracture configurations [9], and rock-characterization experiments include surface topography [10]. These approaches suggest pairing flow measurements with surface information instead of fitting a unique roughness-to-conductivity relationship from a small number of scalar descriptors.

The example in Table 1 is intentionally one-dimensional. In a real fracture, flow may bypass a constriction through lateral paths, or a connected contact band may block a broad region. A contact-area fraction without its spatial arrangement is therefore incomplete. The same fraction could describe isolated islands or a barrier spanning the flow direction. Any image-based hydraulic inference should preserve that distinction.

2. Measuring and reconstructing geometry

2.1 Aperture measures and specimen characterization

Distinguish mean mechanical separation, hydraulic aperture, and the distribution of local openings. Mean separation summarizes geometry. Hydraulic aperture is an equivalent value inferred from a chosen flow relation. The aperture distribution describes spatial variability and may include closed contact regions. Equality among these quantities is an idealization, not a definition. Rough-fracture flow theory provides the context for keeping them separate [2].

If an equivalent hydraulic aperture is calculated from conductivity using the parallel-plate law, report the assumptions used in that conversion. The inferred value is a compact hydraulic descriptor even when no physical location in the fracture has exactly that opening. It should not be substituted into a mechanical contact model as though it were a directly measured average separation.

A proposed measurement program retains both geometric observations and hydraulic measurements at matched stress. If their relationship changes after exposure or cycling, the discrepancy is a result to investigate. It may reflect altered connectivity, contacts, or measurement assumptions. The useful question is whether a geometric descriptor predicts flow under the tested conditions, rather than whether one descriptor can be declared the uniquely correct aperture.

Record both fracture surfaces, their relative offset, and the registration method used to construct an aperture map. State instrument resolution and the minimum opening that can be resolved. Measure displacement under the same stress schedule as conductivity, with fixture compliance removed where possible. Preserve sample state [11] and use controlled flow procedures [12] so that the geometric comparison is not confounded by handling or bypass flow.

Fluid exposure can alter wall response and introduce fines [13], making the initial scan insufficient for a post-exposure interpretation. Partially propped fracture models additionally show why support placement affects residual opening [14]. A practical analysis should therefore distinguish initial roughness, loaded aperture, and altered geometry after exposure instead of labeling all three as "roughness effects."

2.2 Surface registration and contact thresholds

An aperture map derived from two measured surfaces requires a rule for placing those surfaces in the same coordinate system. Relative translation, rotation, and normal separation determine the calculated gap. A proposed workflow should preserve the original scans, the registration transformation, and the reference used for separation. Without those elements, a derived aperture distribution cannot be reconstructed, and differences between processing choices may be mistaken for physical changes in the fracture.

A useful sensitivity test repeats the hydraulic calculation for a small set of plausible registrations consistent with measurement uncertainty. If a slight lateral shift changes whether a narrow channel connects inlet to outlet, registration uncertainty is hydraulically important. If the predicted conductance changes little, the same uncertainty may be less consequential for that specimen. The goal is to evaluate the consequence of the uncertainty rather than assign a universal acceptable registration error.

The contact and rough-flow literature motivates preserving spatial geometry [2, 8]. A new reconstruction should also state whether the opposing surfaces were measured before or after loading and exposure. Post-test surfaces document the final recovered geometry, which may differ from the geometry under load. Using them to reconstruct an earlier state requires an additional assumption. Keep that assumption visible instead of presenting the resulting aperture map as a direct observation of the loaded flow path.

A numerical aperture field may classify cells as open or closed using a threshold selected by the analyst. That classification is part of the model and should not automatically be described as a direct contact measurement. State how negative reconstructed gaps are treated, whether a minimum positive aperture is imposed, and whether the threshold reflects instrument resolution or a constitutive assumption. These choices can alter connectivity even when their effect on mean aperture is small.

Consider an illustrative map in which most of the pressure drop occurs across a narrow bridge of cells. Assigning those cells an aperture of zero disconnects the path; assigning them a small positive aperture leaves a finite, potentially weak connection. The difference is topological as well as numerical. Report a threshold sensitivity analysis when the result depends on that bridge, and distinguish a resolved closure from an unresolved opening below the measurement scale.

A model should also explain how contact carries load. Setting hydraulic conductance to zero does not by itself define mechanical stiffness, and assigning stiffness does not uniquely define a residual hydraulic gap. Conductivity-compliance models provide a framework for linking these responses [4]. The proposed reporting rule is to state the mechanical and hydraulic treatments separately before describing their coupling. This helps another analyst identify whether a disagreement arises from geometry, contact mechanics, or flow discretization.

3. Connectivity and hydraulic response

3.1 Equal-mean and series-parallel examples

Consider a synthetic path made of two equal-length segments of equal breadth. Let their normalized apertures be u_1 and u_2 , with local normalized conductivity u_i^3 . With the same fluid in both segments, resistances add in series. The effective normalized conductivity is $C_{eq} = 2/(u_1^{-3} + u_2^{-3})$. This idealization neglects entrance effects and exchange with the surrounding matrix.

A uniform path with $u_1 = u_2 = 1$ has $C_{eq} = 1$. A second path with $u_1 = 0.5$ and $u_2 = 1.5$ has the same mean aperture of one, yet $C_{eq} = 0.241$. It therefore has only about 24% of the uniform path's conductivity. The low-aperture segment dominates the resistance; averaging aperture before applying the cube law misses that effect.

Table 1. Synthetic equal-length paths; all apertures and conductivities are normalized.

Path	Segment apertures	Mean aperture	Effective C
Uniform	1.00; 1.00	1.00	1.000
Moderately variable	0.75; 1.25	1.00	0.694
Strongly variable	0.50; 1.50	1.00	0.241

The original worked example places different openings along a common flow path, so resistance adds in series. A complementary synthetic construction places equal-width channels side by side between the same inlet and outlet. Under the ideal parallel-plate assumptions, their conductivities add in proportion to channel width. For normalized apertures 0.5 and 1.5, the equal-width parallel average is $(0.5^3 + 1.5^3)/2 = 1.75$.

The same two aperture values gave approximately 0.241 for equal-length segments in series. Both constructions have mean aperture 1.0, but they represent different spatial arrangements. The contrast is deliberately idealized: it does not imply that a real fracture is either a collection of independent channels or a single one-dimensional path. It demonstrates that an aperture histogram without location information cannot uniquely determine conductivity.

A spatially resolved model must also define boundary conditions and lateral communication between pathways. Contact mechanics supplies a way to evolve geometry under load [3, 4], while a flow model determines how that geometry transmits fluid. Keeping those roles separate helps identify whether disagreement with an experiment arises from the estimated opening field or from the hydraulic approximation applied to it.

3.2 Connected contact and directional flow

A contact-area fraction is useful but incomplete. Contacts concentrated in isolated patches may leave a continuous open route, while a connected band across the flow direction can restrict transmission much more strongly. This is a topological distinction: the locations and connections matter in addition to the total area. A proposed reporting scheme should therefore retain the spatial map or a clearly defined connectivity descriptor.

The measured map also depends on resolution and the criterion used to label a point as open or closed. If a narrow passage falls below the imaging resolution, treating it as fully open or fully closed can change the inferred network. Report that threshold and test the sensitivity of calculated flow to reasonable alternatives. An image-derived model should not imply more geometric certainty than the measurement provides.

For comparison across stress steps, preserve coordinate registration so the same regions can be followed. If registration is unavailable, compare distributions cautiously and avoid asserting that a particular contact grew or disappeared. The proposed approach does not demand a uniquely complete map; it demands a transparent account of the geometry observed, the geometry inferred, and the uncertainty introduced by unresolved features.

A fracture with elongated channels can transmit fluid differently along different in-plane directions. A proposed numerical test applies the same pressure difference across opposite pairs of boundaries while retaining the same aperture field and boundary convention. The resulting directional conductances describe that field under those conditions. They should not be reduced to a single scalar unless the intended model either requires that approximation or has a justified averaging procedure.

For a synthetic example, let conductance be 4 units in one direction and 1 unit in the perpendicular direction. Their arithmetic mean is 2.5 units, but that value reproduces neither directional response. A network whose dominant pressure gradient follows the weak direction would be misrepresented by treating 2.5 as its measured conductance. The selected values demonstrate an averaging issue; they do not establish a typical anisotropy ratio for shale fractures.

Laboratory rotation experiments require additional care because changing the flow direction may also change the fixture or boundary access. Document those changes and compare them with the numerical boundary conditions. A directional result can help distinguish a connectivity effect from a purely average-aperture explanation. It also suggests which surface descriptors are useful: the orientation and continuity of constrictions may matter more for a given flow direction than a single roughness amplitude.

3.3 Locating the pressure drop

A flow solution contains more information than total conductance. Inspect the spatial pressure gradient and identify where the modeled pressure drop is concentrated. These regions are candidates for hydraulic bottlenecks within the assumed geometry and flow law. They are not automatically the locations of greatest mechanical damage. A proposed analysis compares bottleneck locations with contact, surface alteration, and measurement uncertainty before using them to explain the observed response.

In an idealized series path, suppose a short constriction has resistance 8 units and the remaining path has resistance 2 units. The constriction accounts for 80% of the total pressure drop. Halving the resistance of the remaining path changes total resistance from 10 to 9, whereas halving the constriction resistance changes it from 10 to 6. This arithmetic explains why improving a large area away from the controlling restriction can have a modest hydraulic effect.

The example is compatible with rough-fracture flow reasoning [2] but does not identify real bottlenecks without spatial evidence. If a reconstructed high-gradient region lies where the aperture measurement is least reliable, the uncertainty deserves explicit attention. A useful validation target is whether observed local pressure or tracer behavior supports the predicted pathway, where such observations are available. Agreement in total flow alone can leave several different spatial solutions unresolved.

4. History and model validation

4.1 Reversible and permanent surface change

A decrease in hydraulic aperture under load can arise from a reversible displacement of the surfaces, an irreversible change in their shape, or a combination. A proposed geometry study records the loading sequence and compares surfaces at defined reference states. When imaging under load is unavailable, acknowledge that before-and-after scans constrain permanent recovered changes more directly than they constrain the instantaneous loaded aperture. The distinction matters when a model is intended to predict unloading or repeated cycles.

A hypothetical sequence might show the original surface relief after unloading while conductivity remains lower than initially measured. That result would prompt investigation of relative alignment, unresolved contact changes, particles, and the hydraulic measurement state. Conversely, visible surface alteration without a large conductivity change could indicate that the altered regions did not control the connected flow path. Neither pattern is inconsistent by itself; each narrows the relationship between the measured geometry and the hydraulic endpoint.

The anchor studies report strong stress and exposure sensitivity in preserved shale [5, 6, 7]. Their observations motivate a geometry record that retains both material history and loading history. The

proposed extension is to avoid assigning every aperture reduction to one mechanism. Contact models and proppant-distribution studies further emphasize that support arrangement matters [4, 14], so a surface comparison should include the spatial location of supporting regions whenever those data are available.

4.2 Geometry-to-flow tests and numerical adequacy

A useful validation separates calibration from prediction. Use one stress state to set any unresolved hydraulic parameter, then predict conductivity at another measured state using the independently observed geometry. If every state receives its own fitted correction, agreement does not establish that the geometric representation predicts stress sensitivity. The model may simply be reproducing its calibration targets.

Repeat the exercise after a documented fluid exposure or loading cycle where feasible. The preserved-shale experiments motivate both changes of state [5, 6, 7]. If the same geometric model no longer predicts flow, investigate whether the measurement resolution, wall alteration, particle retention, or fluid-flow convention has changed. The discrepancy should remain visible rather than being hidden by an unexplained recalibration.

Report prediction errors in absolute conductivity and in relative terms, with the measurement limits attached. Where several geometries remain compatible with the images, propagate them as alternative scenarios. This produces a bounded geometry-to-flow inference and identifies which additional observation would be most valuable. It does not claim that roughness, mean aperture, or contact fraction alone provides a universal conductivity predictor.

A reconstructed-flow calculation should be checked for sensitivity to grid resolution and domain treatment. Refining the grid can change how narrow channels and contacts are represented. Compare total flow, mass-balance residual, and the location of the main pressure drops across refinements. If conductance continues to change substantially, report the unresolved numerical dependence rather than tuning a roughness factor until one grid reproduces the measured flow.

A calibration parameter can compensate for several errors at once, including registration, unresolved aperture, and boundary conditions. A good fit therefore does not uniquely validate the inferred geometry. A proposed test calibrates on one state and evaluates a separate stress or flow-direction state while preserving the geometry-processing choices. If the same correction fails elsewhere, investigate which omitted feature changes across states. This is more informative than assigning a different unexplained correction to every measurement.

The final geometry-to-flow statement should identify the measured surfaces, registration, contact rule, flow law, boundaries, and the states used for calibration and evaluation. Include the range of predictions produced by plausible unresolved geometry. Such a record turns a visually persuasive

aperture map into a reproducible hydraulic argument. It also makes clear whether the study has demonstrated a predictive relationship, a conditional reconstruction, or simply one spatial interpretation consistent with the measured total conductivity.

5. Conclusions

Identical average opening can coexist with very different hydraulic capacity. The synthetic calculation demonstrates why connected constrictions deserve explicit attention, while the literature motivates tracking how contact changes under stress and exposure. Report roughness together with registration, contact arrangement, loading state, and hydraulic conditions. This information is more useful for reproducible interpretation than a single surface statistic presented as a universal predictor of unpropped conductivity.

References

Numbered references correspond to the citations in the text. Links lead to DOI records or the identified source record.

- [1] Witherspoon, P. A.; Wang, J. S. Y.; Iwai, K.; Gale, J. E. (1980). Validity of cubic law for fluid flow in a deformable rock fracture. *Water Resources Research*, 16(6), 1016-1024. <https://doi.org/10.1029/WR016i006p01016>
- [2] Zimmerman, R. W.; Bodvarsson, G. S. (1996). Hydraulic conductivity of rock fractures. *Transport in Porous Media*, 23, 1-30. <https://doi.org/10.1007/BF00145263>
- [3] Wang, H.; Sharma, M. M. (2017). A non-local model for fracture closure on rough fracture faces and asperities. *Journal of Petroleum Science and Engineering*, 154, 425-437. <https://doi.org/10.1016/j.petrol.2017.04.024>
- [4] Wu, W.; Sharma, M. M. (2017). A model for the conductivity and compliance of unpropped and natural fractures. *SPE Journal*, 22(6), 1893-1914. <https://doi.org/10.2118/184852-PA>
- [5] Kakkar, P. (2016). Experimental study of the effect of stress and fluid sensitivity on propped and un-propped fracture conductivity in preserved reservoir shale. *Thesis, The University of Texas at Austin*. <https://www.pge.utexas.edu/pge-research/2016/>
- [6] Wu, W.; Kakkar, P.; Zhou, J.; Russell, R.; Sharma, M. M. (2017). An experimental investigation of the conductivity of unpropped fractures in shales. *SPE Hydraulic Fracturing Technology Conference and Exhibition, SPE-184858-MS*. <https://doi.org/10.2118/184858-MS>
- [7] Wu, W.; Zhou, J.; Kakkar, P.; Russell, R.; Sharma, M. M. (2019). An experimental study on conductivity of unpropped fractures in preserved shales. *SPE Production & Operations*, 34(2), 280-296. <https://doi.org/10.2118/184858-PA>
- [8] Barton, N.; Bandis, S.; Bakhtar, K. (1985). Strength, deformation and conductivity coupling of rock joints. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 22(3), 121-140. [https://doi.org/10.1016/0148-9062\(85\)93227-9](https://doi.org/10.1016/0148-9062(85)93227-9)
- [9] Zhang, J.; Kamenov, A.; Zhu, D.; Hill, A. D. (2014). Laboratory measurement of hydraulic-fracture conductivities in the Barnett Shale. *SPE Production & Operations*, 29(3), 216-227. <https://doi.org/10.2118/163839-PA>
- [10] Jansen, T. A.; Zhu, D.; Hill, A. D. (2015). The effect of rock mechanical properties on fracture conductivity for shale formations. *SPE Hydraulic Fracturing Technology Conference, SPE-173347-MS*. <https://doi.org/10.2118/173347-MS>
- [11] Jung, C. M.; Zhou, J.; Chenevert, M. E.; Sharma, M. M. (2013). The impact of shale preservation on the petrophysical properties of organic-rich shales. *SPE Annual Technical Conference and Exhibition, SPE-166419-MS*. <https://doi.org/10.2118/166419-MS>
- [12] Zhang, J.; Kamenov, A.; Zhu, D.; Hill, A. D. (2015). Development of new testing procedures to measure propped fracture conductivity considering water damage in clay-rich shale reservoirs: An example of the Barnett Shale. *Journal of Petroleum Science and Engineering*, 135, 352-359. <https://doi.org/10.1016/j.petrol.2015.09.025>
- [13] Zhang, J.; Zhu, D.; Hill, A. D. (2016). Water-induced damage to propped-fracture conductivity in shale formations. *SPE Production & Operations*, 31(2), 147-156. <https://doi.org/10.2118/173346-PA>
- [14] Wang, J.; Elsworth, D. (2018). Role of proppant distribution on the evolution of hydraulic fracture conductivity. *Journal of Petroleum Science and Engineering*, 166, 249-262. <https://doi.org/10.1016/j.petrol.2018.03.040>