SPE-210013-MS: A Systematic Approach to Evaluate the Sanding Potential Caused by Formation Shear Failure in Unconsolidated Oil and Gas Reservoirs

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Sand Production in Unconsolidated Reservoirs

"Should we gravel-pack or frac-pack our completion or opt for a natural completion?"

- **Microscopic Shear Failure**
  - Friable formations likely to produce sand grains.

- **Macroscopic Shear Failure**
  - Fines migration.
  - Relationship between formation compressibility and elasto-plastic hysteresis.
  - Recognizing symptoms leading to catastrophic shear failure.

- The above two are tangentially related but can occur simultaneously.

Microscopic and Macroscopic Shear Failure

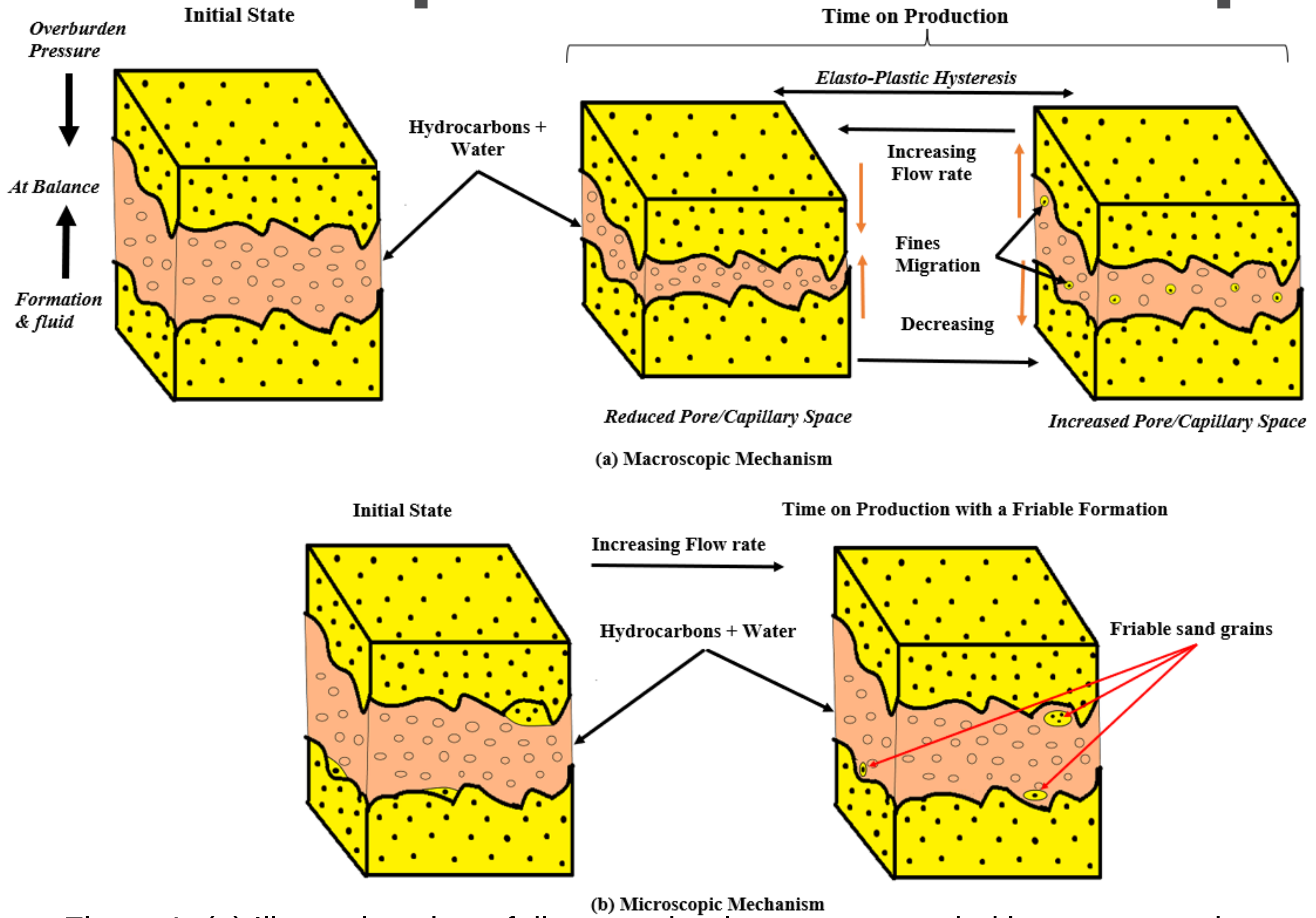


Figure 1: (a) Illustrating shear failure mechanisms accompanied by macroscopic plastic hysteresis and fines migration. (b) Illustrating shear failure with microscopic friability of the sand grains with an existing sanding potential.

- Sand production through **Macroscopic Shear Failure** is caused due to production related to formation compressibility and elasto-plastic hysteresis (fines migration).
- Sand production through **Microscopic Shear Failure** is caused due to the friability of the formation.

Strength of Materials: A Qualitative Approach to Microscopic Shear Failure – Sanding Potential

- Sanding potential can be interpreted using the following petrophysical logs:
  - Acoustic/Sonic Logs
  - Bulk Density Logs
  - Neutron-Porosity Logs

- **Concept:** Less compact zones are prone to sanding. Compaction can be evaluated qualitatively using the following relation:

$$Pwave\ or\ compressional\ waves\ (transit\ time) \propto \frac{Density}{Strength} \quad (1)$$

Quantifying Sanding Potential – Microscopic Shear Failure

- The calculation of the mechanical properties of the rock or the **Mechanical Properties Log (MPL)** is possible from:
  - Acoustic Logs – Compressional and Shear Waves
  - Density Logs

- This provides a means to validate previously flagged zones quantitatively.
- **MPL Key Properties:**
  - Shear Modulus (G) , Psi
  - Bulk compressibility (C_b) , sq in./lb
  - Bulk modulus (K) , Psi

Approaches to Quantifying Sanding Potential

- **Tixier Approach – Tixier et al. (1975)**

If Shear Modulus, G > 0.6 x 10^6 psi and Bulk compressibility (C_b) < 0.75 x 10^{-6} sq in./lb,

Indicates a compact formation not prone to sanding.

- **Sharma Approach – Sharma and Arya (2006)**

Formation Strength Index, $(FSI) =$ Shear Modulus$(G) *$ Bulk modulus (K)

If 'fsi' < 2.4 x 10^{12} psi^2 it is a candidate for possible sand cut.

If 'fsi' > 2.9 x 10^{12} psi^2, it will be a sand free gas producer.

- **Schlumberger Sanding Index - Dong et al. (2013)**

Sanding Index (SR) = Shear Modulus(G)* Bulk modulus (K)

Sand production is likely if the SR < 1.2411 Mpsi^2.

- **B-Index (Sand Production Index) - Dong et al. (2013)**

B-Index = Bulk modulus (K) + (4/3)* Shear Modulus(G)

Sand production is likely if the B < 2.9 Mpsi.

Case Study 1: Assessment of Microscopic Shear Failure

$$Pwave\ or\ compressional\ waves\ (transit\ time) \propto \frac{Density}{Strength}$$

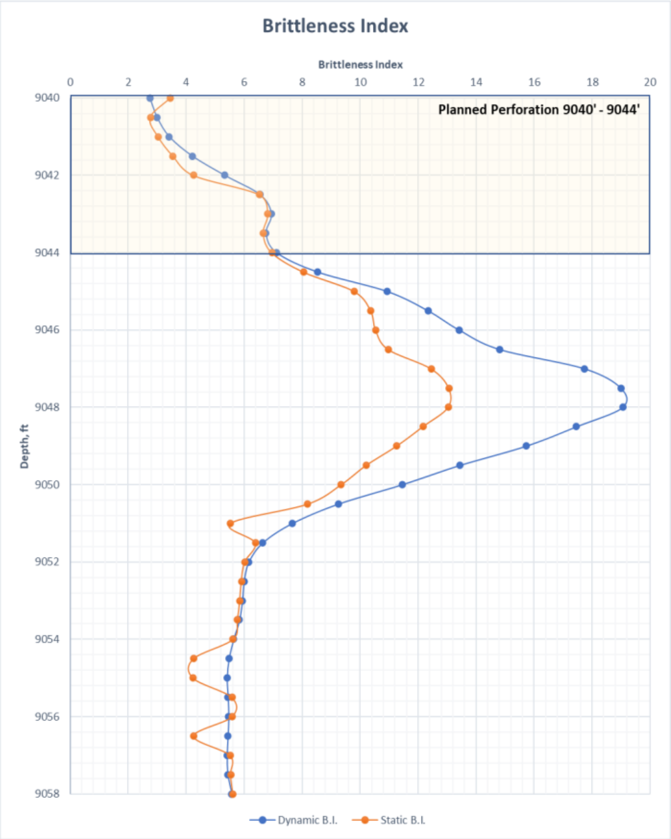


Figure 4 – Brittleness index data gathered every half foot. Note the box at the top of the graphic indicating the planned perforation interval.

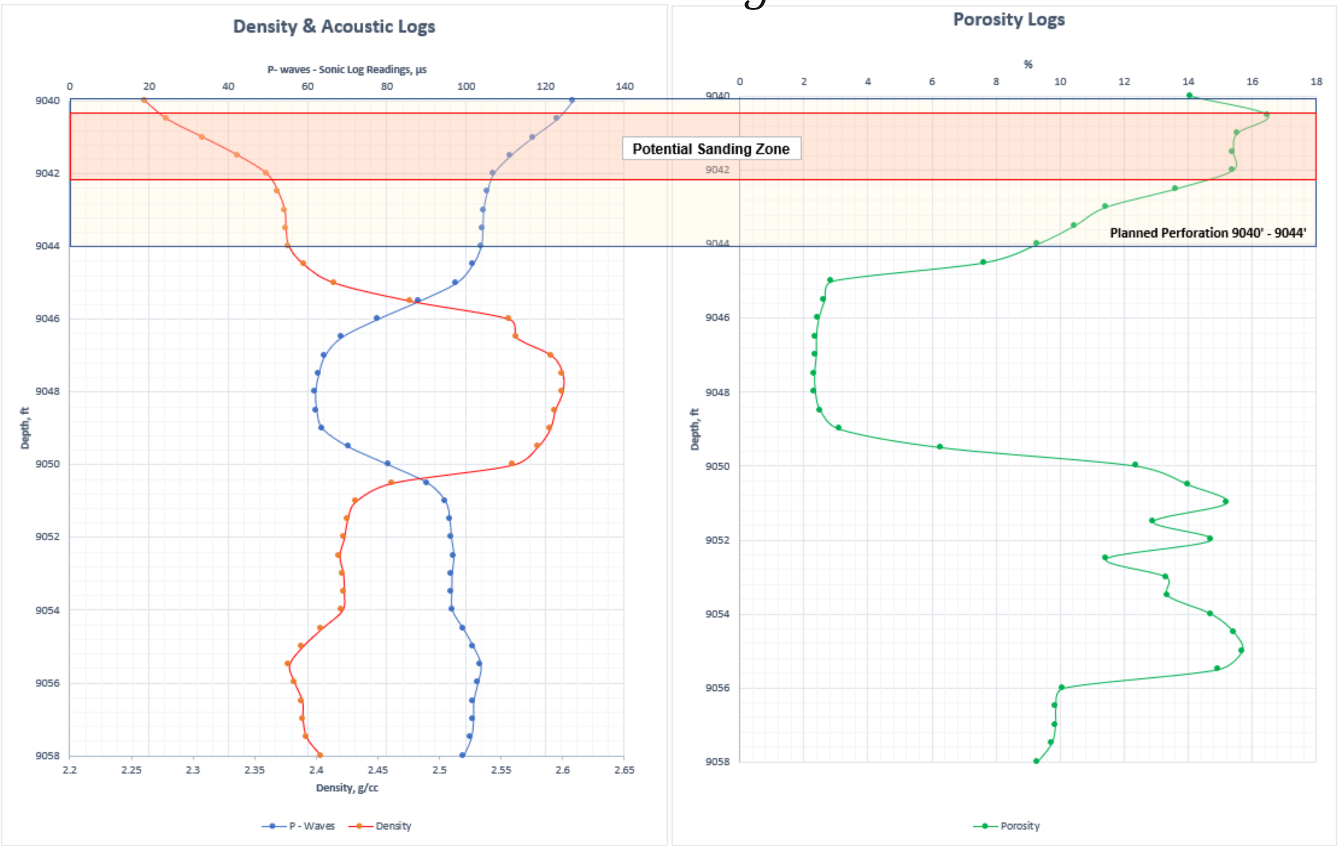


Figure 5 – Density/acoustic and porosity logs for the same formation as Figure 4. Note the orange box indicating a potential sanding zone in the upper planned perforation zone.

Case Study 1: Quantitative Assessment of Microscopic Shear Failure

	II - Tixier's et al's Method (i)		II - Formation Strength Index (ii)		III - Schlumberger Index		IV - Sand Production Index	
Depth	Ratio of G/Cb	G/Cb < 0.8 $Mpsi^2$, will cut sand	G*K	G*K < 2.4 $Mpsi^2$, will sand cut	SR Index	SR < 1.2411 $Mpsi^2$, will cut sand	B Index	B Index < 2.9 Mpsi, will cut sand
ft.	$Mpsi^2$	Sand Cut/ No Sand Cut	$Mpsi^2$	Sand Cut/ No Sand Cut	$Mpsi^2$	Sand Cut/ No Sand Cut	Mpsi	Sand Cut/ No Sand Cut
9040	0.520	Sand Cut	0.520	Sand Cut	0.520	Sand Cut	1.888	Sand Cut
9040.5	0.606	Sand Cut	0.606	Sand Cut	0.606	Sand Cut	2.030	Sand Cut
9041	0.768	Sand Cut	0.768	Sand Cut	0.768	Sand Cut	2.276	Sand Cut
9041.5	1.003	No Sand Cut	1.003	Sand Cut	1.003	Sand Cut	2.543	Sand Cut
9042	1.268	No Sand Cut	1.268	Sand Cut	1.268	No Sand Cut	2.777	Sand Cut
9042.5	1.433	No Sand Cut	1.433	Sand Cut	1.433	No Sand Cut	2.876	Sand Cut
9043	1.506	No Sand Cut	1.506	Sand Cut	1.506	No Sand Cut	2.934	No Sand Cut
9043.5	1.505	No Sand Cut	1.505	Sand Cut	1.505	No Sand Cut	2.945	No Sand Cut
9044	1.551	No Sand Cut	1.551	Sand Cut	1.551	No Sand Cut	2.973	No Sand Cut

Table 1 – Analysis of the planned interval using the four different MPL methodologies.

- **Result:** At least 1 ft out of 4ft or 25% of the net pay will sand.
- **Field Outcome:** Wellbore full of sand!

Macroscopic Shear Failure

- A petroleum system as a **Total System of Energy**:

$$C_t = (S_o * C_o) + (S_w * C_w) + (S_g * C_g) + \boldsymbol{C_f}$$

- **Elasto-Plastic Hysteresis**: Oil and gas reservoirs tend to undergo cycles of elongation (drawdowns) and relaxation (build-ups), depending on degree of compressibility. This results in permanent deformation over time. This is then followed by shear failure (the inability of the formation and the fluids to support the overburden).

C_f (µsip)	*1 µsip = 1 x 10^{-6} /psi* **Potential to Fail due to Macroscopic Shearing**
< 5	Unlikely to fail
5-10	Unlikely to fail until the pore pressure is below one-thirds of the normal pressure
10-20	Will likely fail when the pore pressure is in between one-thirds to half the normal pressure
20-35	Will likely fail when the pore pressure is in between half to the normal pressure
35-50	Will likely fail at or above normal pressure
50+	Failure imminent upon production without significant pressure support, i.e., strong water drive

Table 2 – Formation Compressibility and Macroscopic Shear Failure in the Gulf of Mexico.

Macroscopic Shear Failure and the Four Horsemen

The **“The Four Horsemen”**, otherwise known as *omens of the apocalypse*:

- **1st Horseman:** First sign of non-aquifer water production or liberated bound water production.
- **2nd Horseman:** Decrease in permeability (near wellbore) due to pressure depletion with time.
- **3rd Horseman:** First sign of sand production. Typically observed by an increase in skin due to increased fines migration or **sand grain production that is not caused by friability of the formation.**
- **4th Horseman: Catastrophic shear failure**, or the well apocalypse, resulting in failure of the completion, casing and/or well bore.

Macroscopic Shear Failure or the Fourth Horsemen

- Macroscopic shear failure is due the inability of the formation and the fluids to support the overburden.

- Sand production observed as fines migration that is not caused by friability (microscopic shear failure) is a precursor sign prior to macroscopic shear failure.

- **We can avoid the 4th Horseman - Catastrophic shear failure by:**
  - Monitoring for precursor signs.
  - Tracking the changes in permeability due to formation compressibility/compaction.
  - Monitoring skin accretion mechanisms coincident with reduced permeability.

Increasing Skin due to fines but no change in Permeability.

Monitor Permeability Vs. Skin

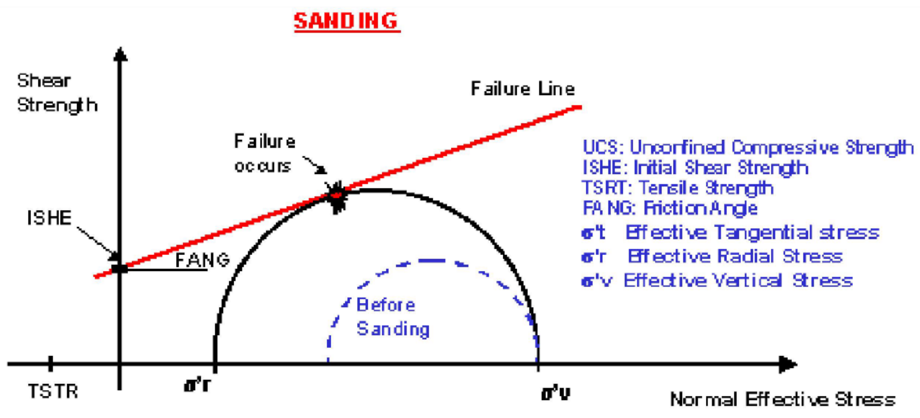
→

If Permeability is decreasing,

Monitor Permeability Vs. FBHP
or
Monitor Mobility Thickness Vs. FBHP

→

Predict and Monitor Changes to Shear Failure Point



- *Alternate methods include 'Mohr's Circle' to predict point of failure.*
- Macroscopic shear failure can be reduced or mitigated if the reservoir has sufficient pressure support, i.e. strong water drive.

Case Study 2: Monitoring Macroscopic Shear Failure

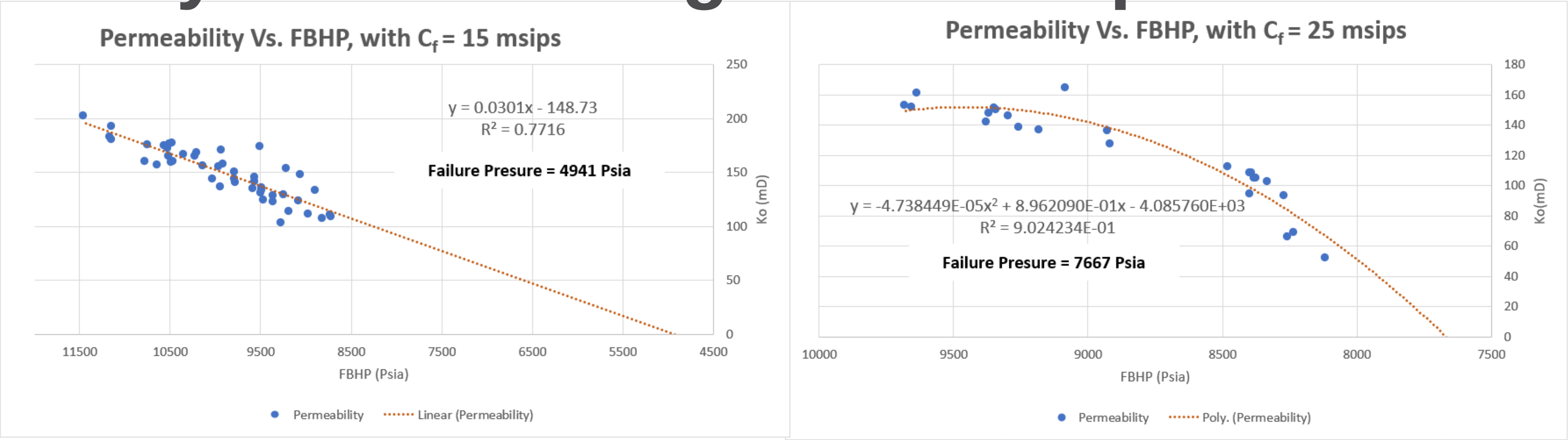


Figure 6 – Impact of the permeability curve and flowing bottomhole pressure on shear failure prediction

- Track **Permeability** with flowing bottom hole pressure for **single phase fluids.**
- Track **Mobility-thickness** with flowing bottom hole pressure for **multi-phase fluids.**
- Shear Failure trend line is linear with C_f of 1-15 μsip and tends to be geometric with C_f of 15-50+ μsip.
- Catastrophic shear failure (*'Fourth Horsemen'*) depends on the formation compressibility. **Higher the formation compressibility, higher the shear failure point!**

Shear Failure – Methodology Review

- **Microscopic Shear Failure:**
  - Use the bulk density, acoustic/sonic, and neutron porosity logs to ***qualitatively*** identify sanding potential zones.
  - If P-waves (compressional) and S-waves (shear) are available, calculate the mechanical properties log to ***quantitatively*** confirm zones prone to sand.

- **Macroscopic Shear Failure:**
  - Use Table 2 to determine the potential to fail.
  - Use permeability or mobility thickness plots and curve fits to determine the point of macroscopic shear failure.
  - Monitor this with production.

Shear Failure – Conclusions

- The decision to gravel-pack or frac-pack your completion should be based on friability of the formation or microscopic shear failure
  - This should be based on a qualitative and/or quantitative assessment (initially).
  - Microscopic Shear Failure is a static interpretation.
- The four horsemen should be monitored for macroscopic shear failure.
- Sand production that is not due to friability is a pre-cursor sign to macroscopic shear failure.
- An effective drawdown management plan should be focused on managing the macroscopic shear failure to maximize recovery and return on investment.

Final Comments

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