# Advanced Fracturing Technology for Tight Gas: Where is the Proppant Going?

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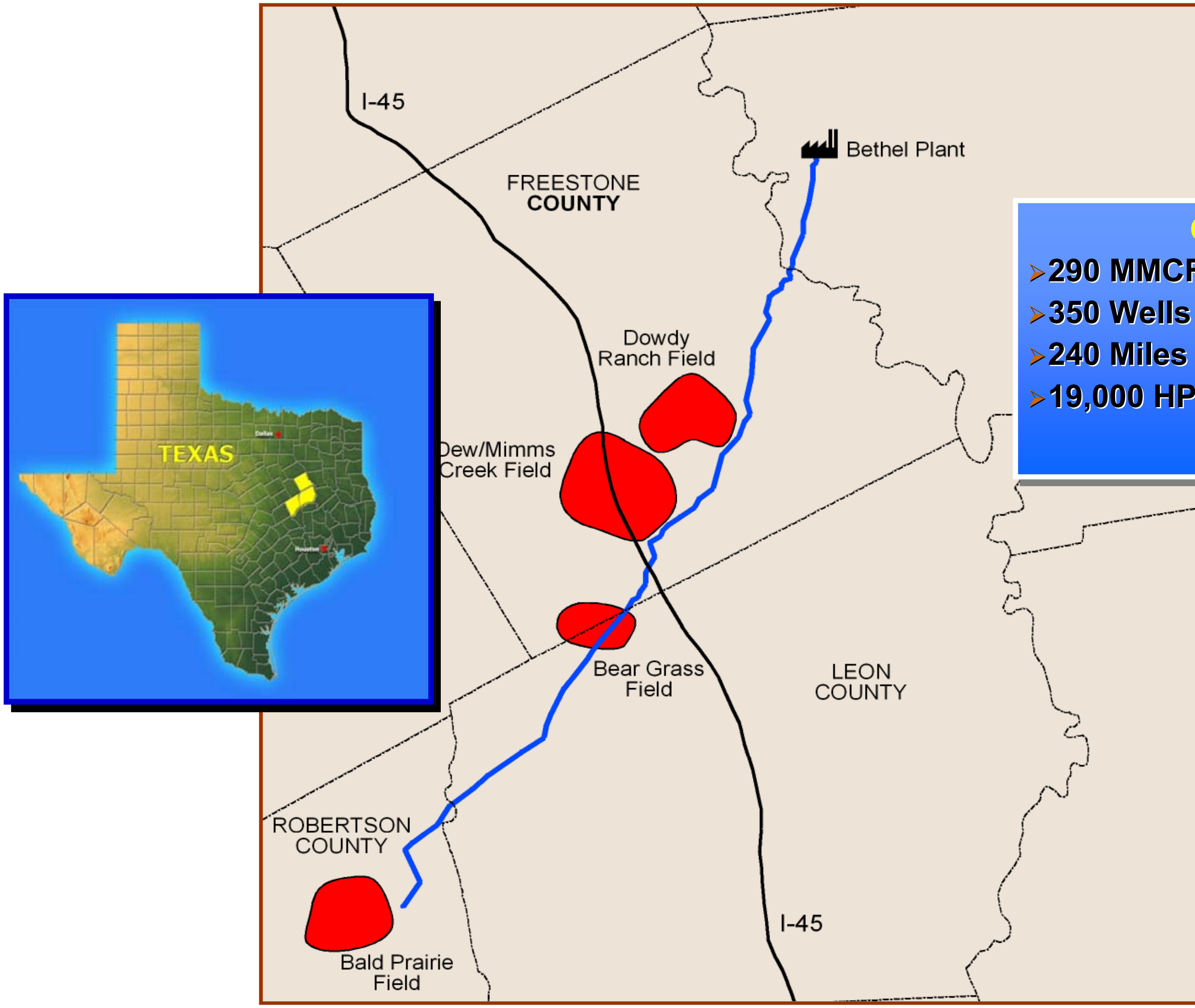
# DOE Research Project

- Task 1. Data analysis and interpretation of current treatments in the Bossier.
- Task 2. Drilling and data collection for wells in the Dowdy Ranch Field.
- Task 3. Fracture diagnostics program.
- Task 4. Enhancing current frac models (proppant transport and leak-off in water fracs).
- Task 5. Fracture cleanup.
- Task 6. Model validation with field data
- Task 7. Technology Transfer

# Texas Bossier Trend




**Current Status**

- 290 MMCFD Gross Production
- 350 Wells
- 240 Miles of Gathering
- 19,000 HP of Compression

# Texas Bossier Properties

- Composition - Sandstone
- Depth ~ 12,500 ft
- Porosity ~ 10%
- Permeability ~ 0.03 md
- Net Pay ~ 150 ft
- Pressure Gradient ~ 0.65 psi/ft
- Fracture Gradient ~ 0.85 psi/ft

# Texas Bossier Post-Frac Analysis

- Post-Frac PBU Tests ($L_f$, $wk_f$,$k_g$)
- Production Matching
- Matching with exisiting frac models
- Microseismic mapping

# Texas Bossier Fracturing Analysis

## Well A

Frac'd w/ 10083 BSW + 170k 40/70, AIR = 80 BPM, ATP 7524.

Net Pay = 159 ft

IP = 10962 MCFD

BHP (calc) = 9237 psi

| | $k_{res}$ md | $X_f$ ft | $wk_f$ mdft | $F_{cd}$ | $C_r$ |
|---|---|---|---|---|---|
| **Microseismic Imaging** | Created $X_f$ = 500 ft to the West & 300 ft to the East | | | | |
| **PBU Results** | 0.0293 | 62 | 17 | 9 | 3 |
| **Production Matching** | 0.0241 | 102 | 10 | 4 | 1 |

# Objectives for Improvement

- Need longer propped fractures
- Need better conductivity
- Must contain height growth

**Better proppant placement!**

# Technical Barriers

- Better models for proppant transport and fluid leakoff with low viscosity fluid in turbulent flow
- Measurement of propped fracture lengths in the Bossier.
- Optimal fracture treatment design (fluids, rates, pumping schedule, proppant size and concentration etc.)
- Inexpensive frac-fluid formulations that allow low pressure, low perm zones to flow back and produce at economic rates.

# Our Strategy to Improve/Optimize TGS Fracs

- Develop accurate estimates of propped and unpropped frac lengths,
  - microseismic data
  - post-frac PBU and production data.
- Develop more accurate models for leakoff and proppant transport.
- Verify the models, develop modified designs, and iteratively optimize in the field.

# Proppant Transport is the Key

Proppant settling depends on

- Fluid viscosity
- Fracture width
- Injection rate
- Fracture extension
- Leakoff
- Proppant size

An accurate model for proppant transport is essential in any water-frac simulation / design.

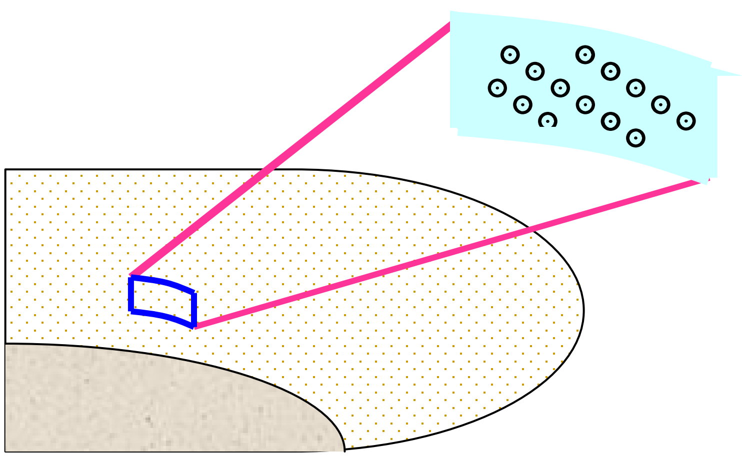
# Proppant Transport Models in Current Frac Simulators

- The fracturing fluid and proppant are grouped together as a slurry.
- Relative motion between fluid and proppant is generally Stokes settling.
- Gravity acts as a body force on the slurry.
- For gels, settling velocity is much less than advective velocity of slurry (and so can be neglected).

# New Proppant Transport Model Coupled with Fully 3-d Frac Model (UTFRAC)

The proppant mass balance equation can be expressed as,

$$w\frac{\partial c}{\partial t}+(1-c)\frac{\partial w}{\partial t}+\frac{\partial}{\partial x}\left[(1-c)q_x\right]+\frac{\partial}{\partial y}\left[(1-c)q_y-cV_t\frac{\rho_p}{\rho_f}\right]=q_l$$

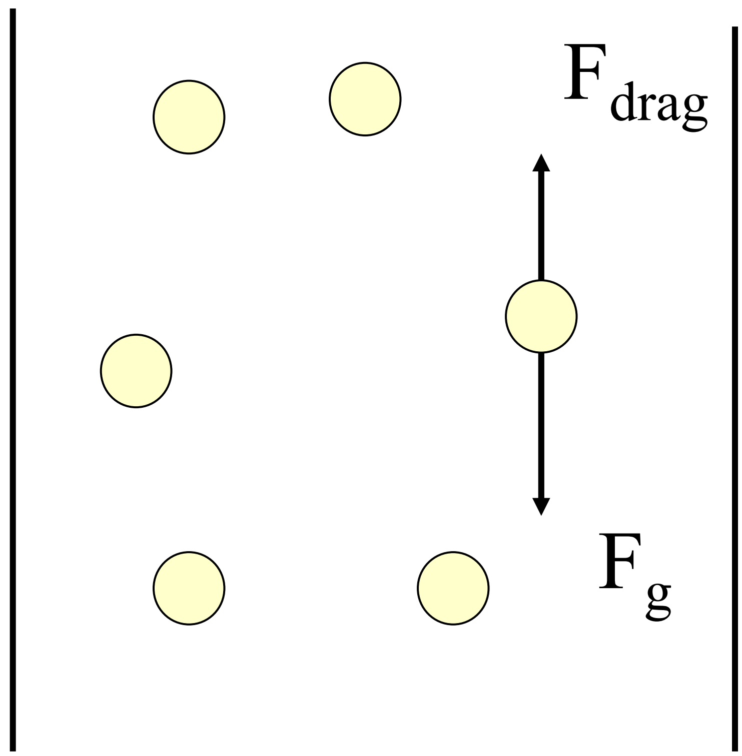


# Fluid Flow Equations (UTFRAC)

- Momentum balance equations for non-Newtonian fluid flow in the fracture.
- Power-law indices k and n are functions of the proppant concentration
- At high proppant concentration the slurry viscosity increases dramatically.
- Allow for relative motion between frac-fluid and the proppant

$$q_{yp} = q_{yf} + V_t$$

# Settling Velocity of Particles ($V_t$)
# Corrections to Stokes Settling Velocity



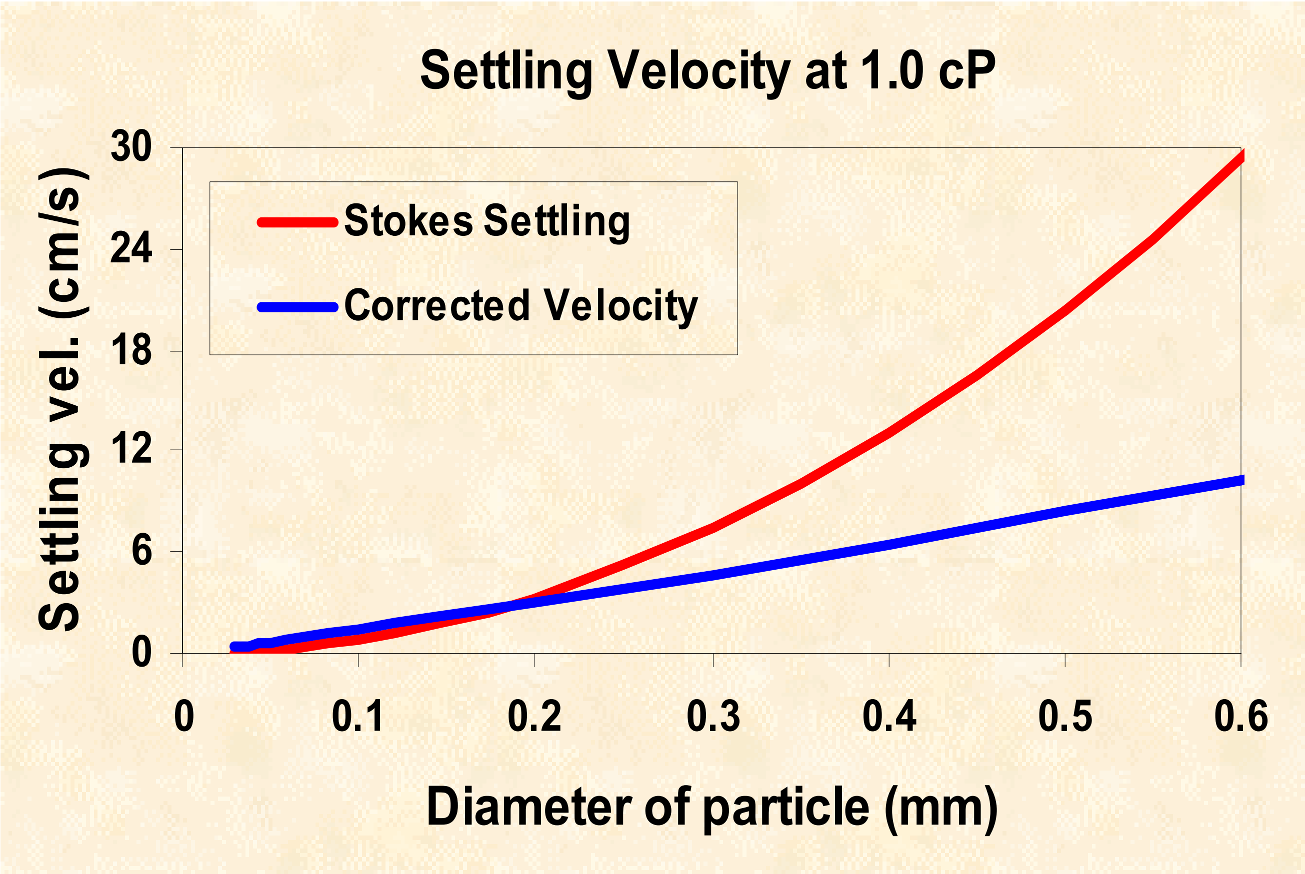

**$F_{drag}$ =**
- **Inertial Effect**
- **Concentration Effect**
- **Wall Effect**
- **Effect of turbulence**

$$Fg = \frac{4\pi a^3}{3}(\rho_p - \rho_f)g$$

# Settling Rate of a Single Particle

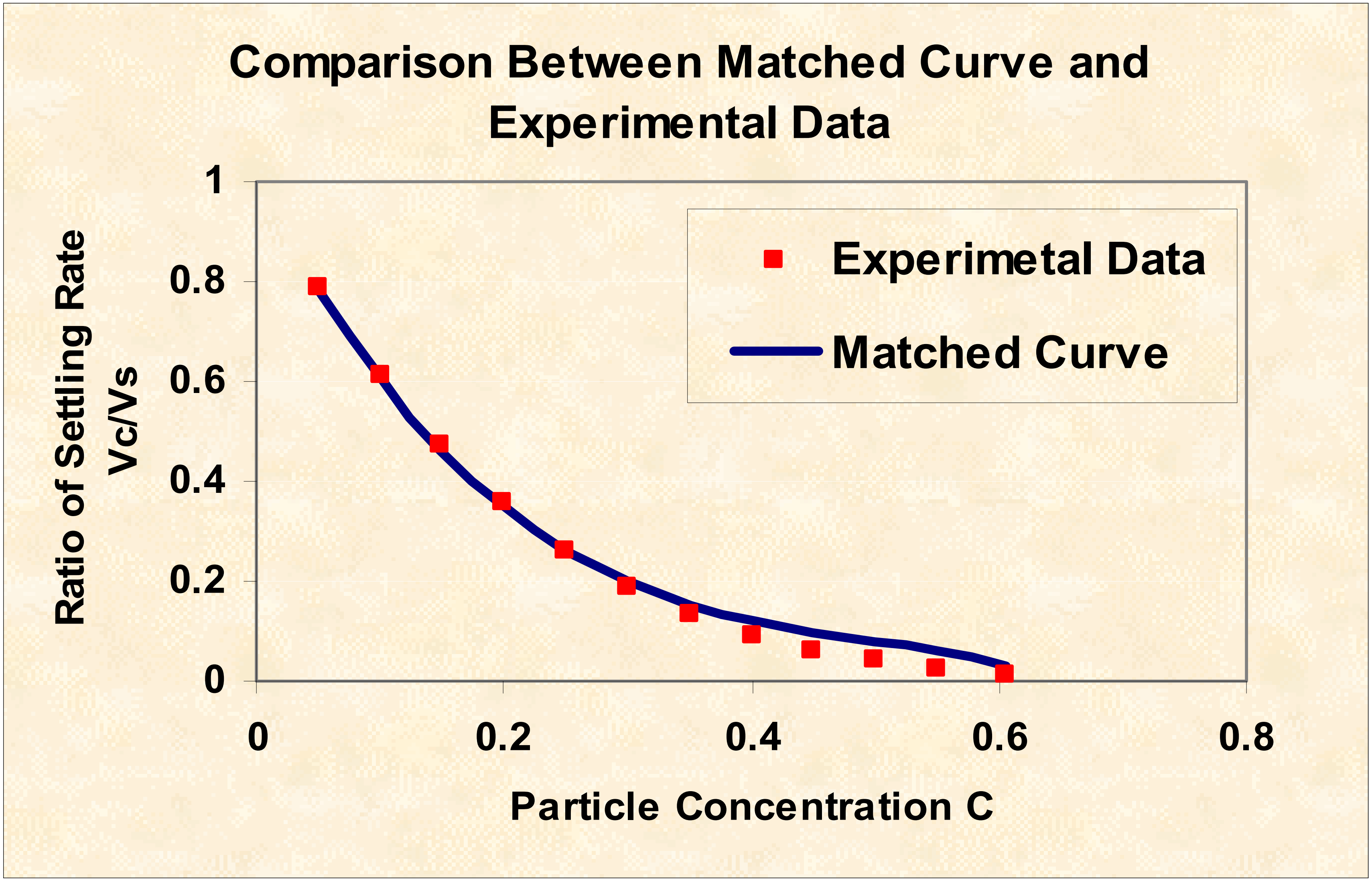
$$V = V_s = \frac{(\rho_p - \rho_f) g d_p^2}{18\mu}, \quad \mathrm{Re_p} < 2$$

$$V = V_{\mathrm{Re}} = V_s f(\mathrm{Re}_p), \qquad 2 < \mathrm{Re_p} < 500$$

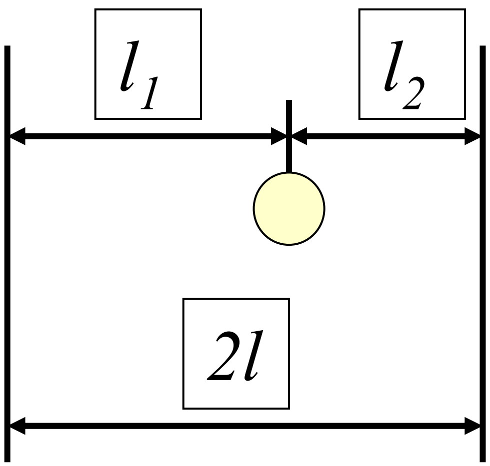


# Effect of Particle Concentration

$$V = V_c = V_s f(c)$$

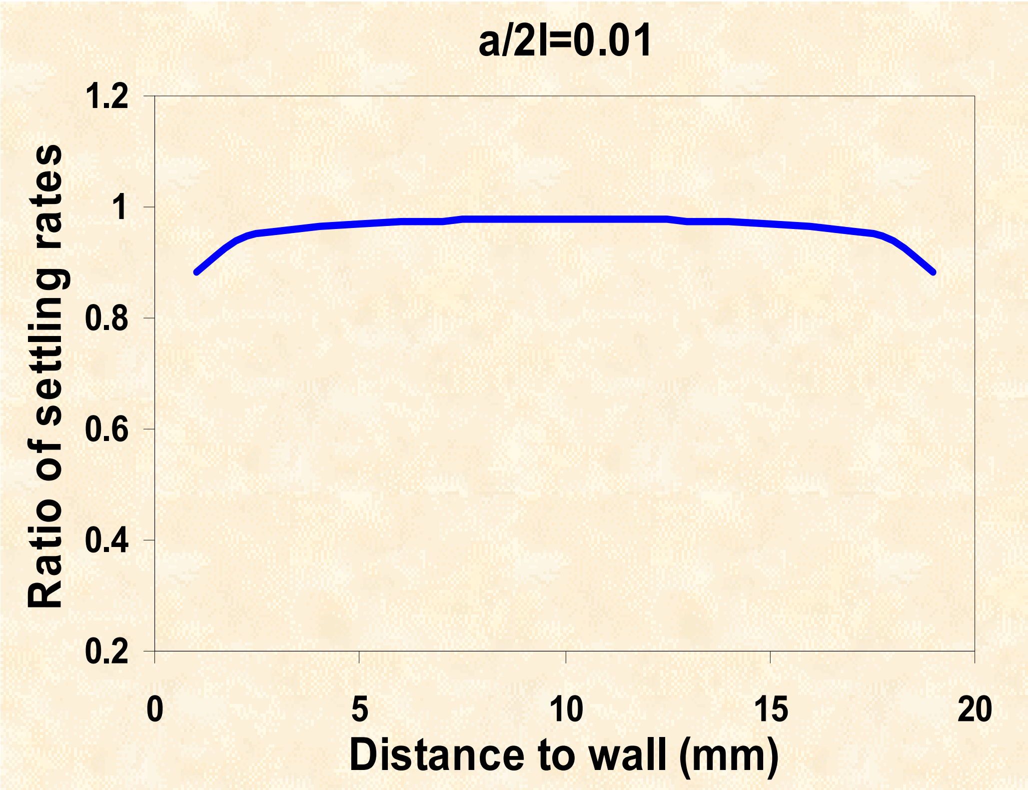


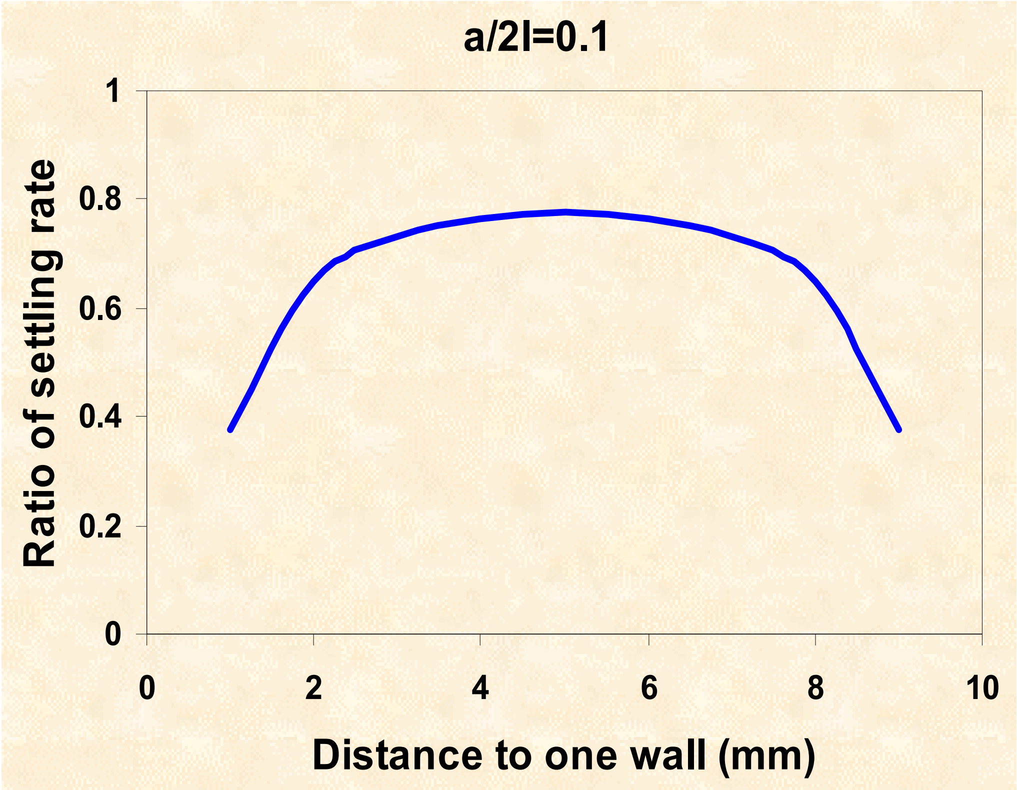
# Effect of Fracture Walls



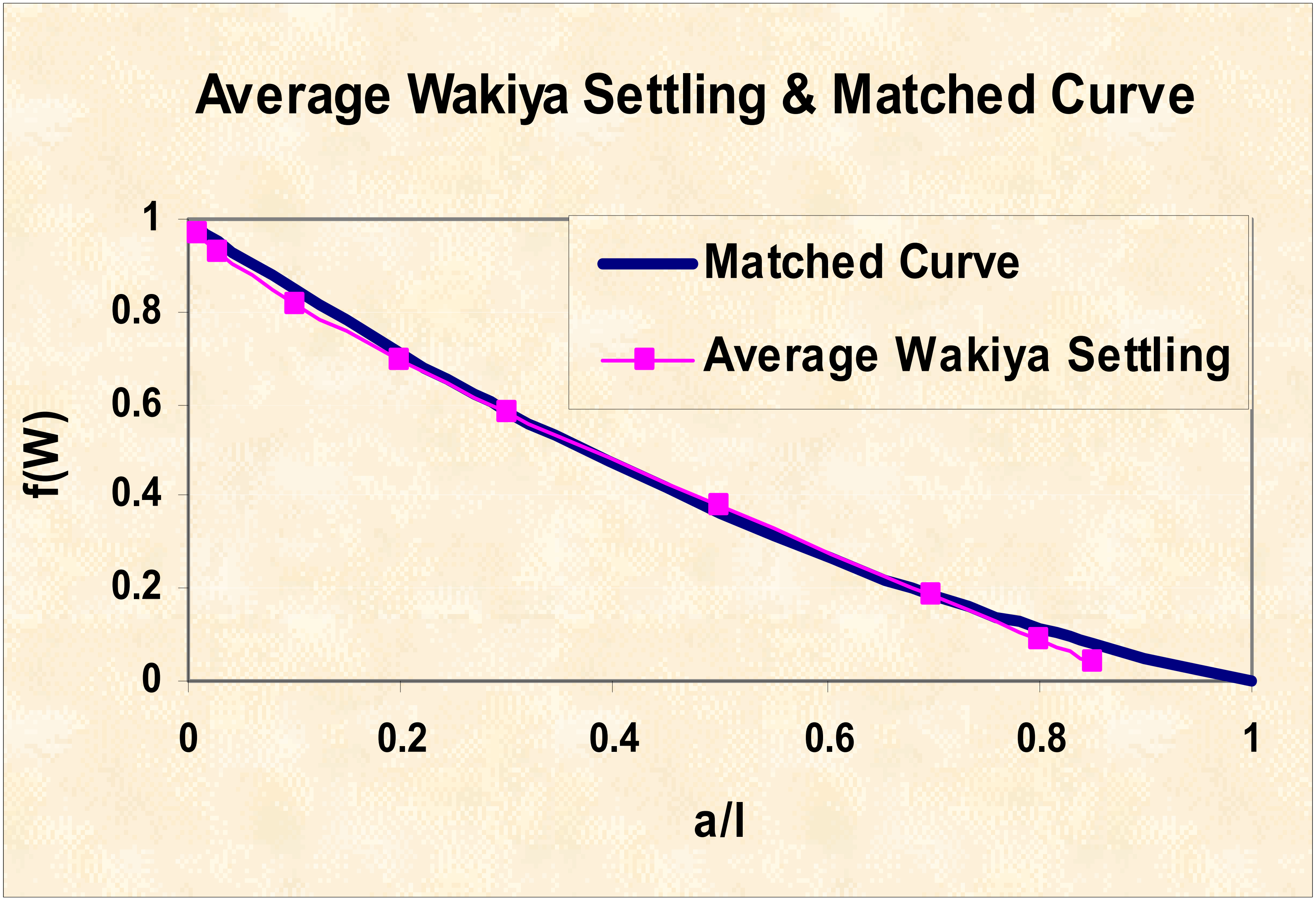

a is the particle radius

$$V_w = V_s[1 - \frac{9a}{16}(\frac{1}{l_1} + \frac{1}{l_2})]^{-1}$$

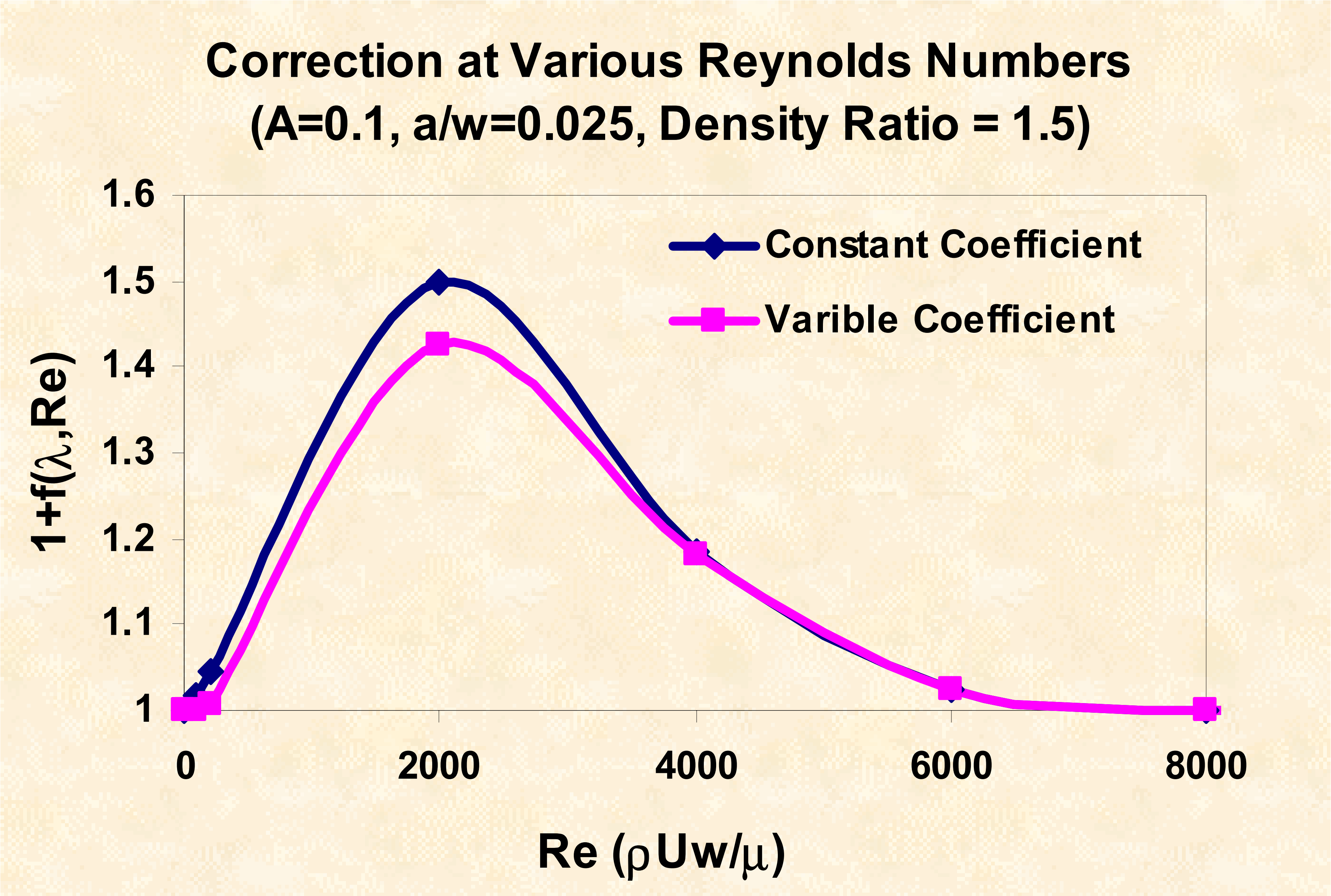


# Settling Velocity, Wall Effect



# Effect of Turbulence



# Example

**Properties:**

- Fluid density: 1 gm/cc
- Particle density: 2.5 gm/cc
- Fluid viscosity: 0.01 poise
- Radius of particle: 0.05cm
- Width of cell: 2cm
- Particle concentration: 20%
- Fluid horizontal velocity: 0.2 m/s

# Example

## Single unbounded particle:

$$V = V_s f(\mathrm{Re}_p) = 14.1\,(cm/s)$$

## Terminal settling rate:

$$V_t = V_s f(\mathrm{Re}_p) * f(\phi) f(W) f(c)$$

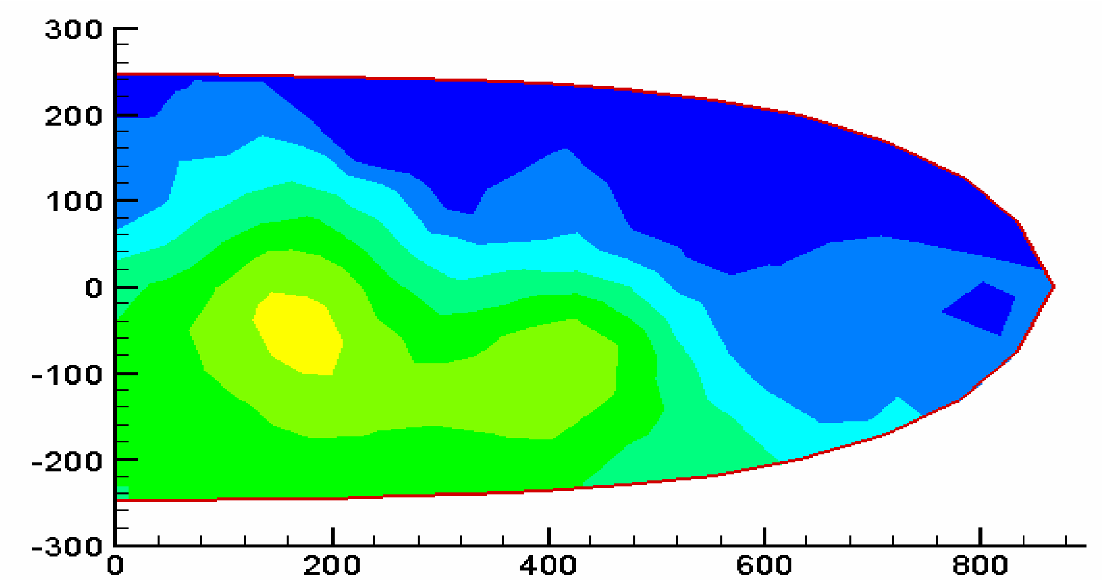
$$f(c) = 0.349$$

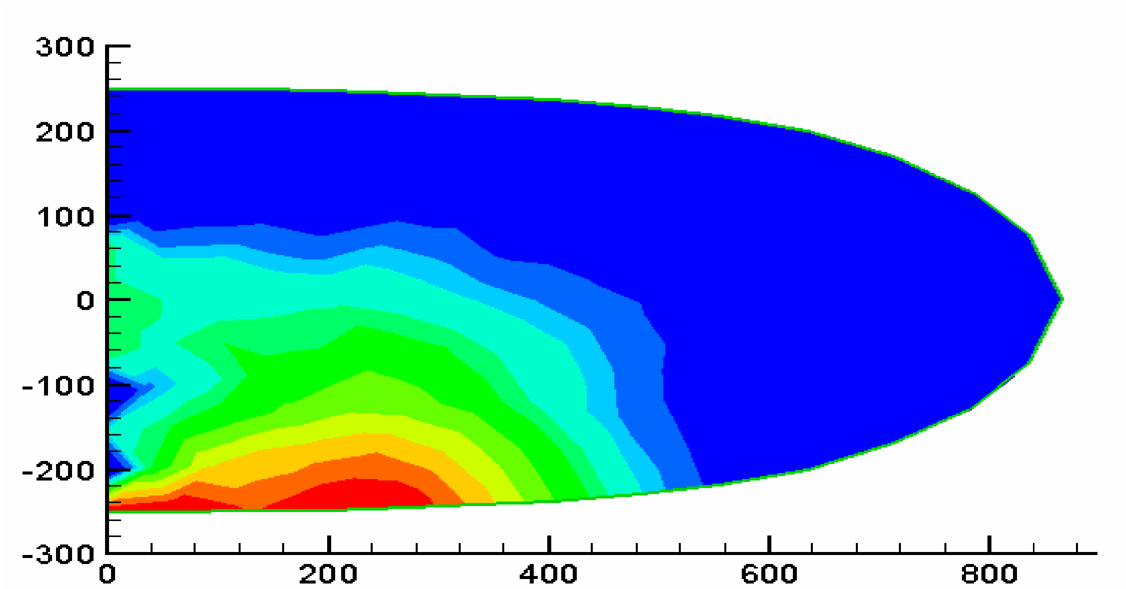
$$f(W) = 0.923$$

$$f(T) = 1.004$$

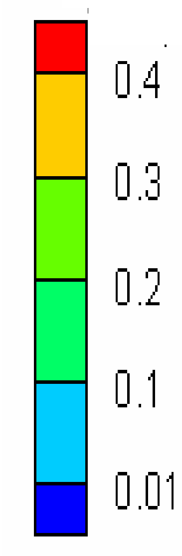
$$V_t = 4.55\ (cm/s)$$

# Effect of Settling



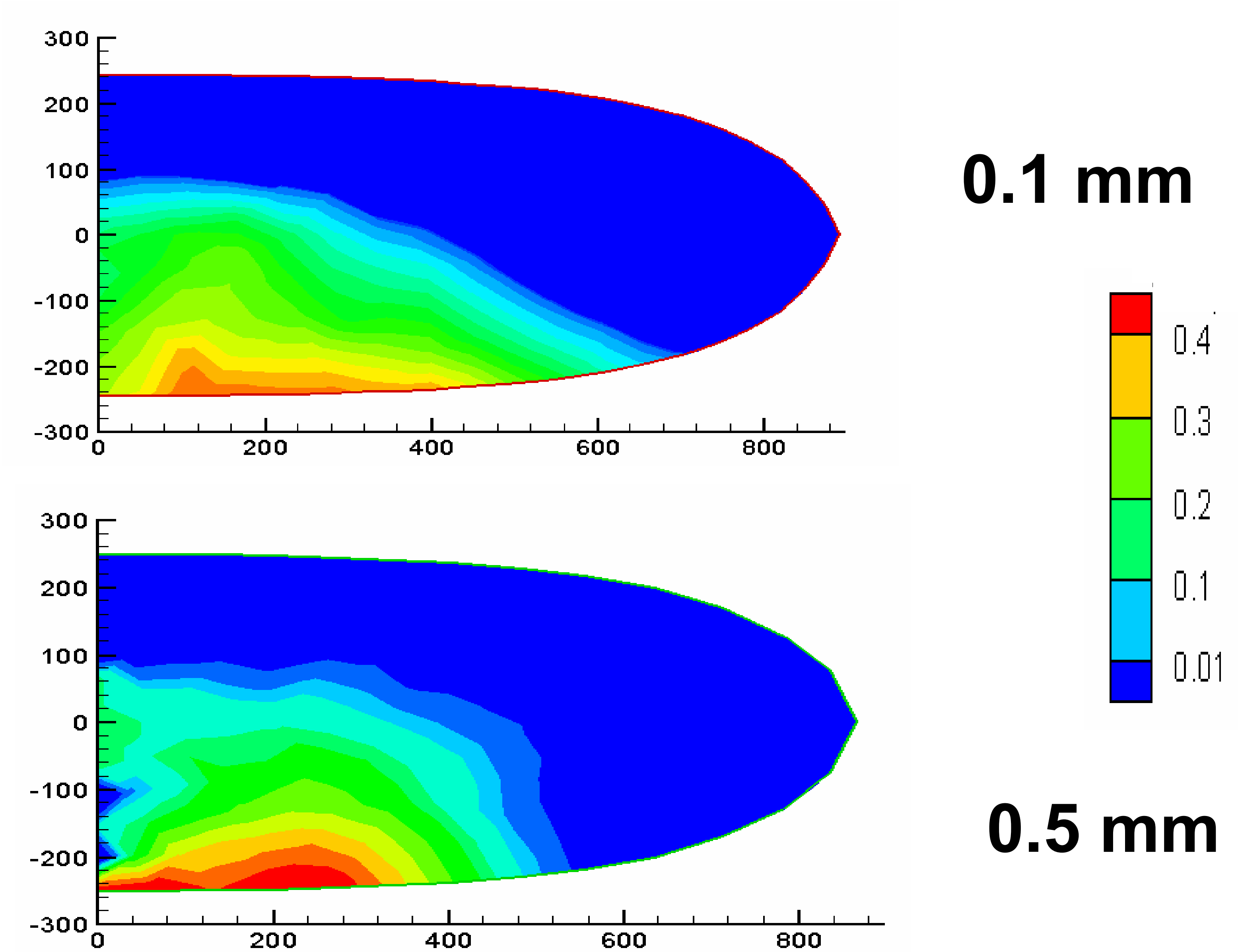




**Without Settling**

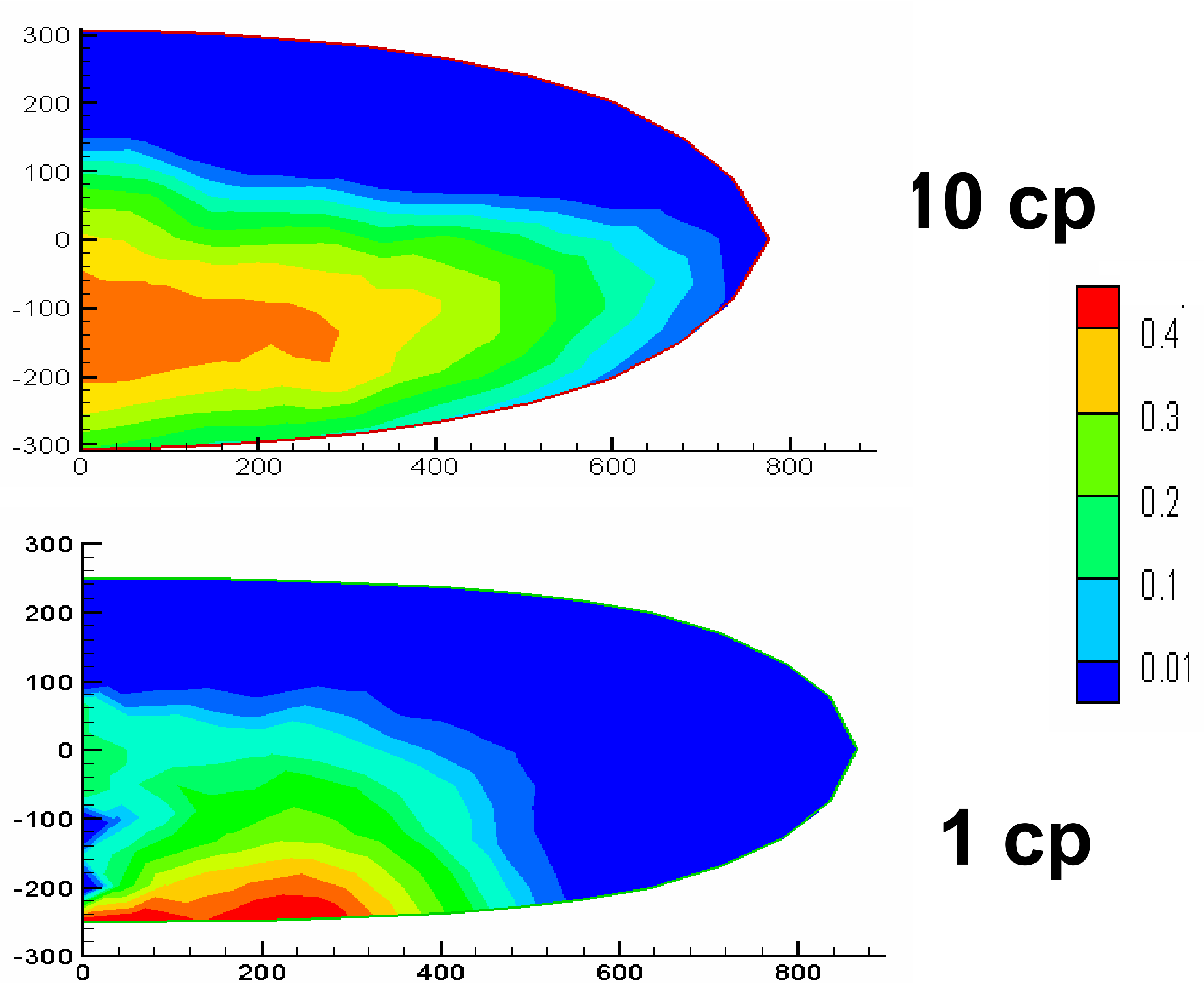



**With Settling**

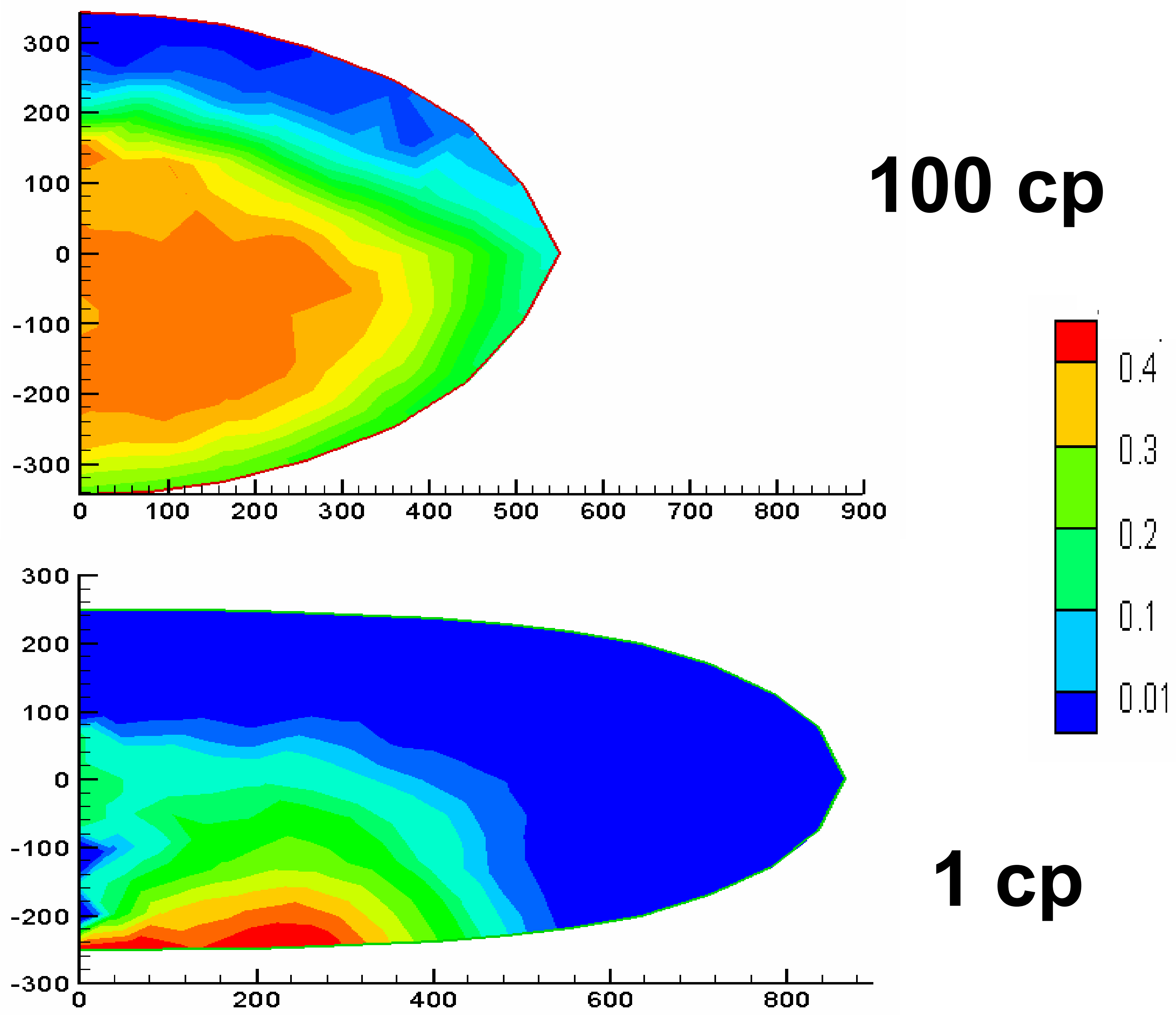
# Effect of Size



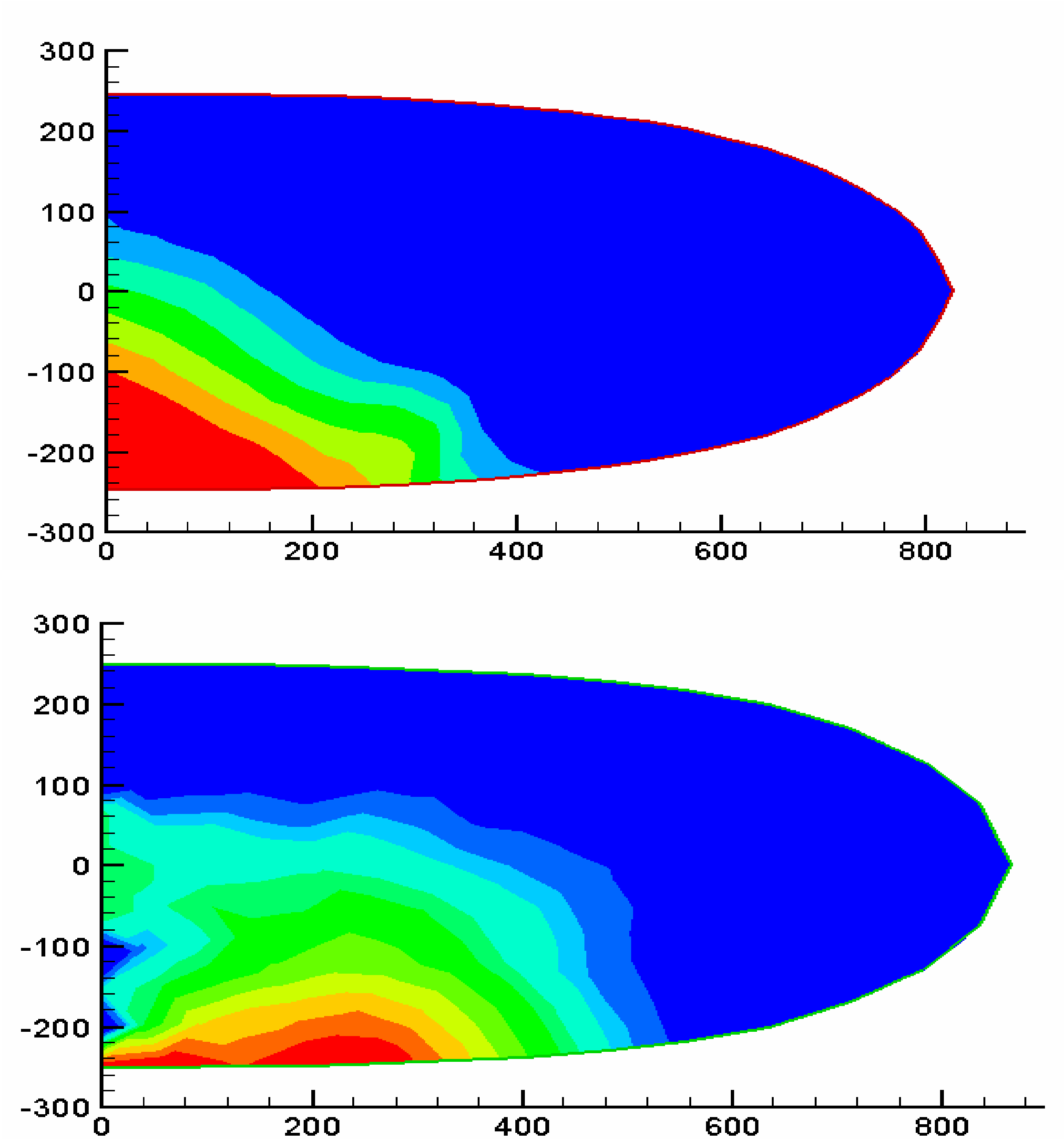
# Effect of Viscosity



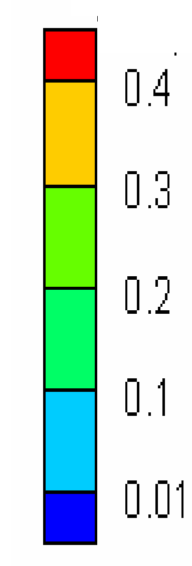
# Effect of Viscosity



# Effect of Inertia Correction on Proppant Settling

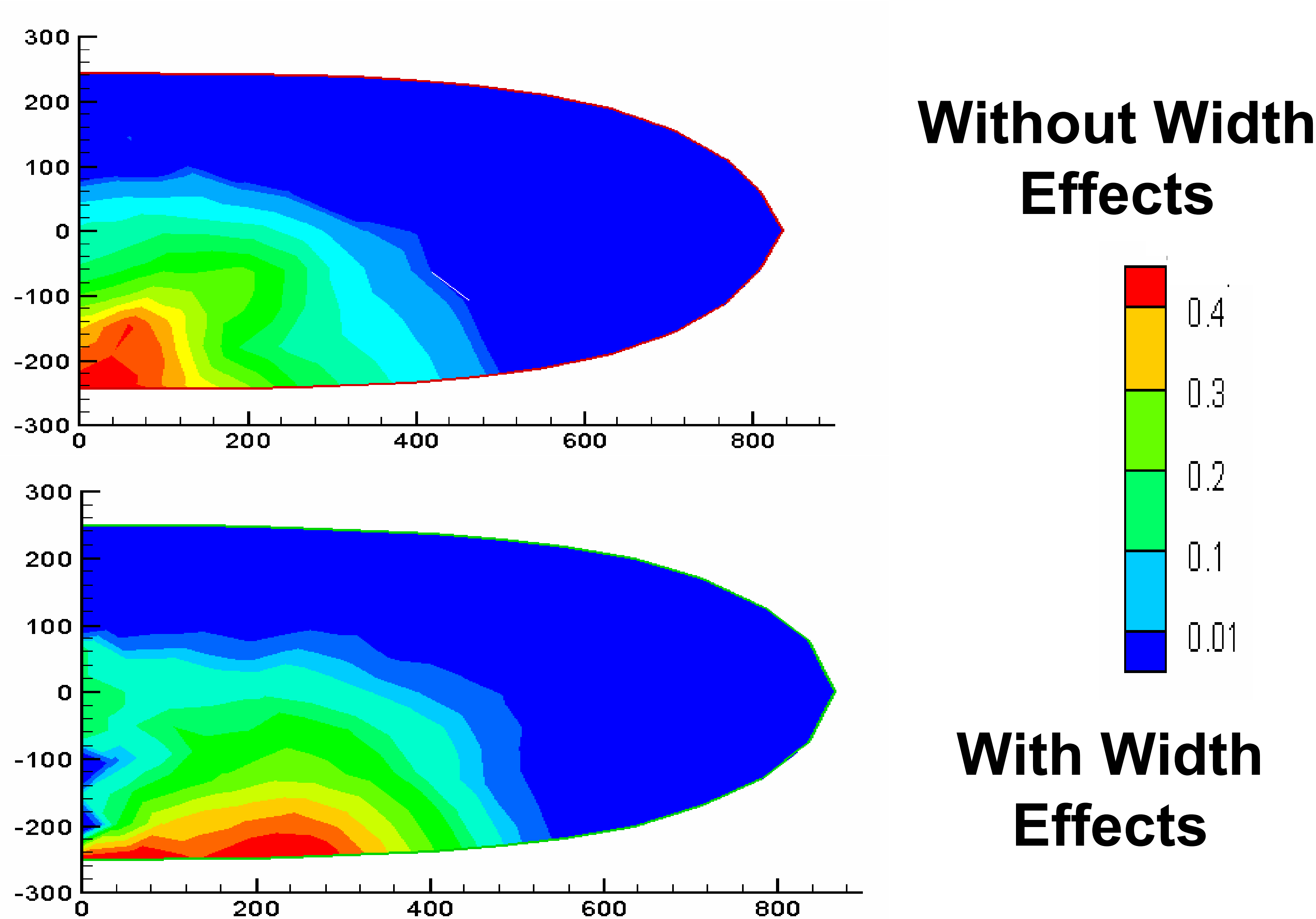



**Without Inertial Effects**

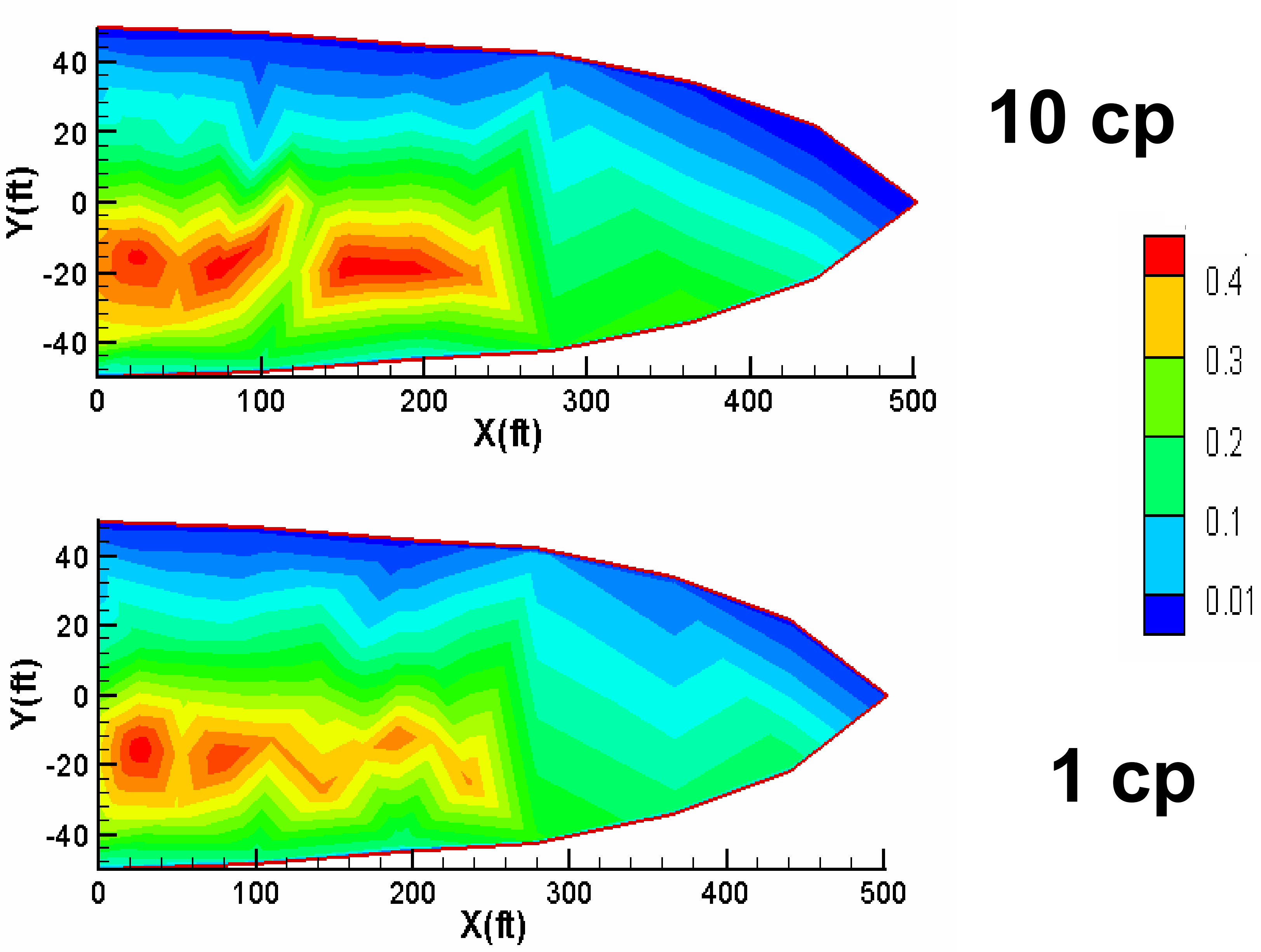



**With Inertial Effects**

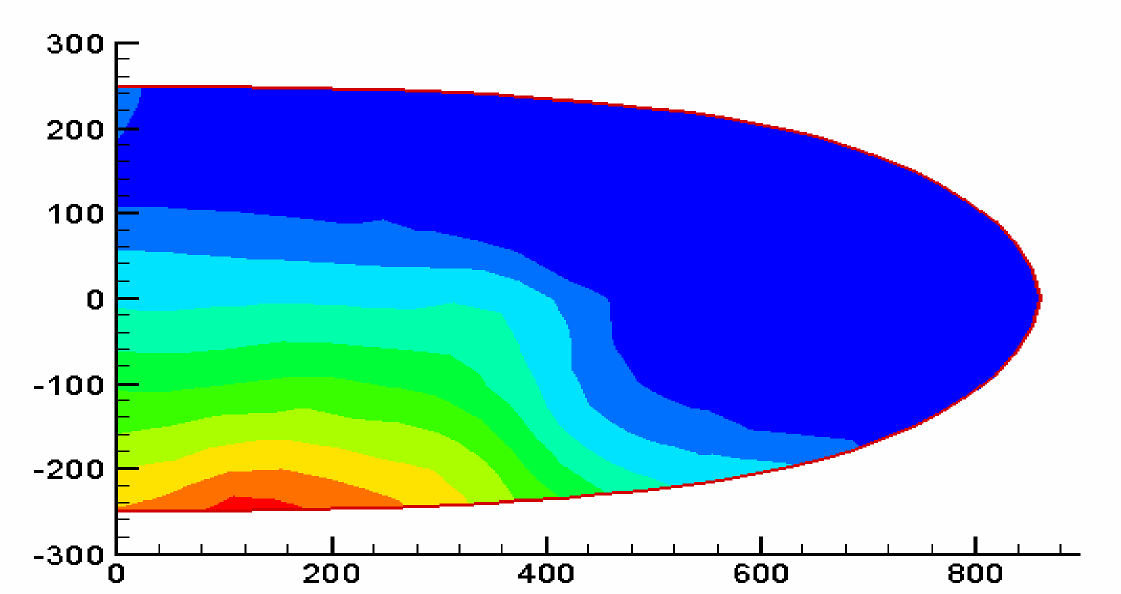
# Effect of Fracture Walls on Proppant Settling



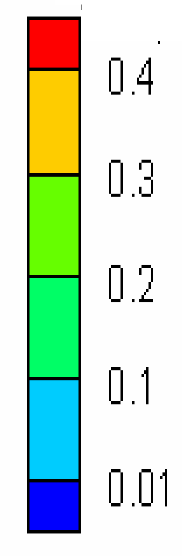
# Effect of Viscosity (Narrow Fracture)

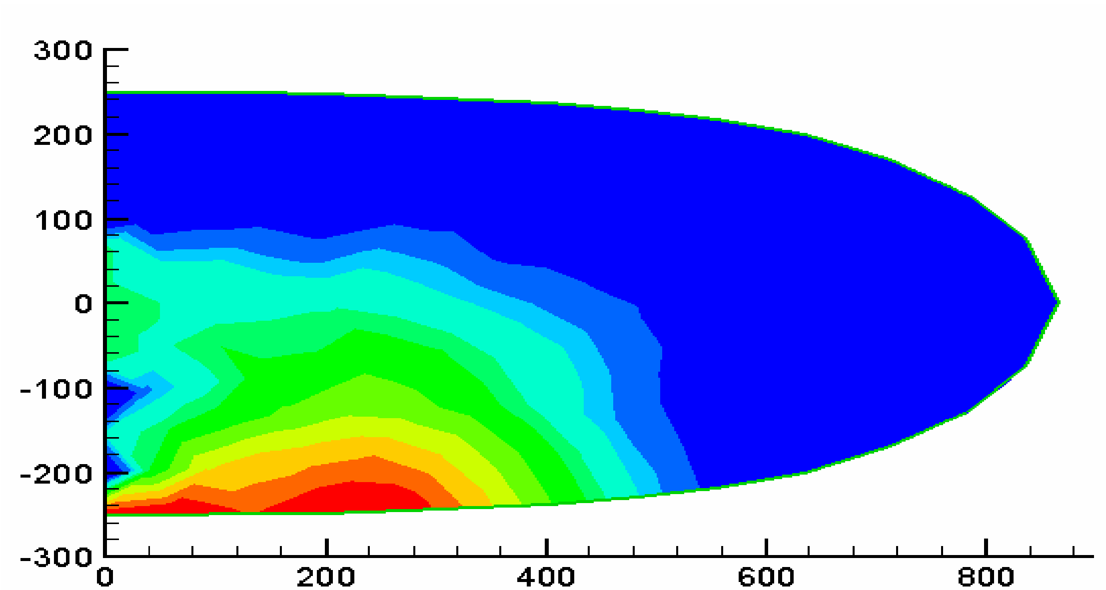


# Effect of Turbulence



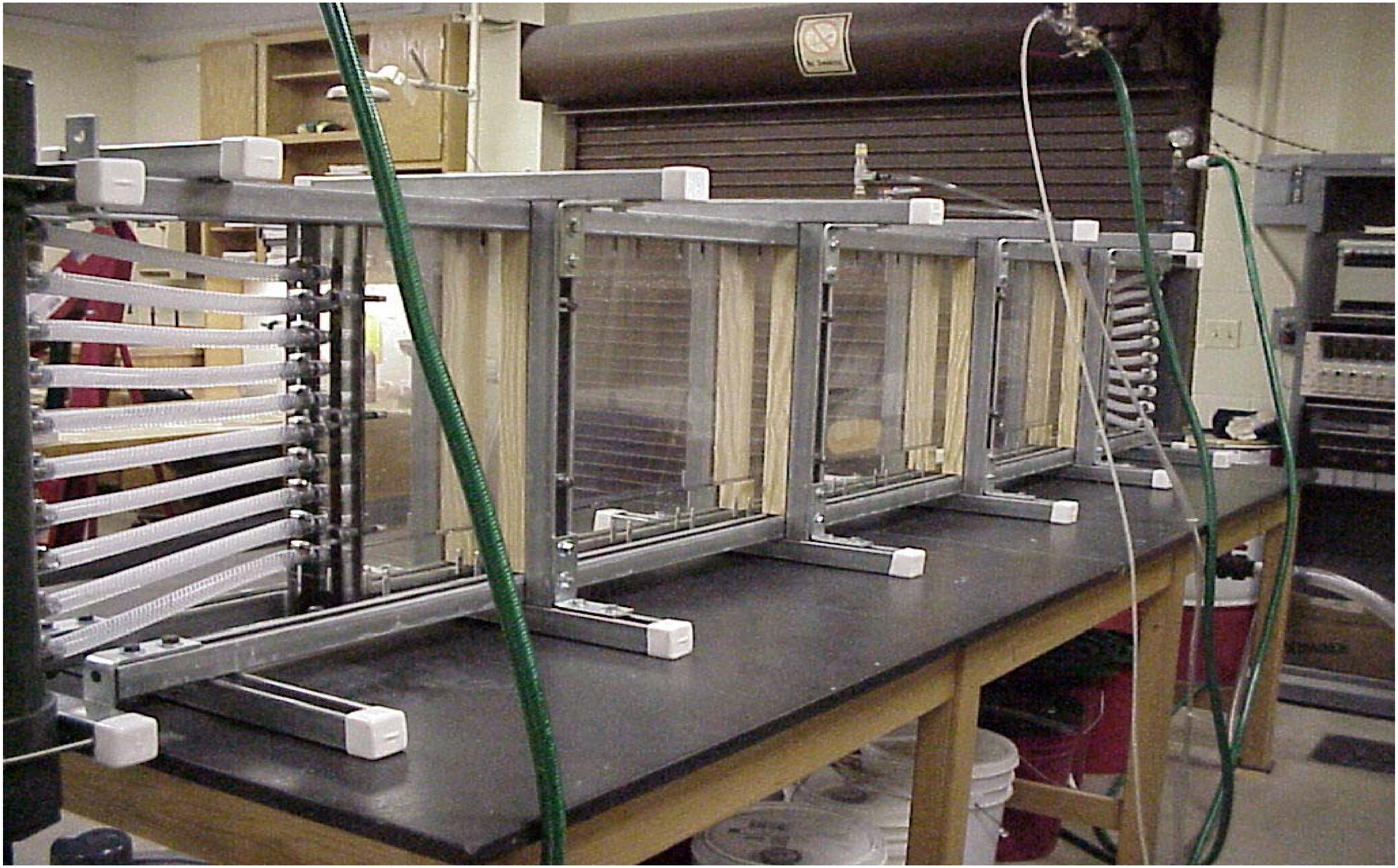

**Without Turbulence Effects**



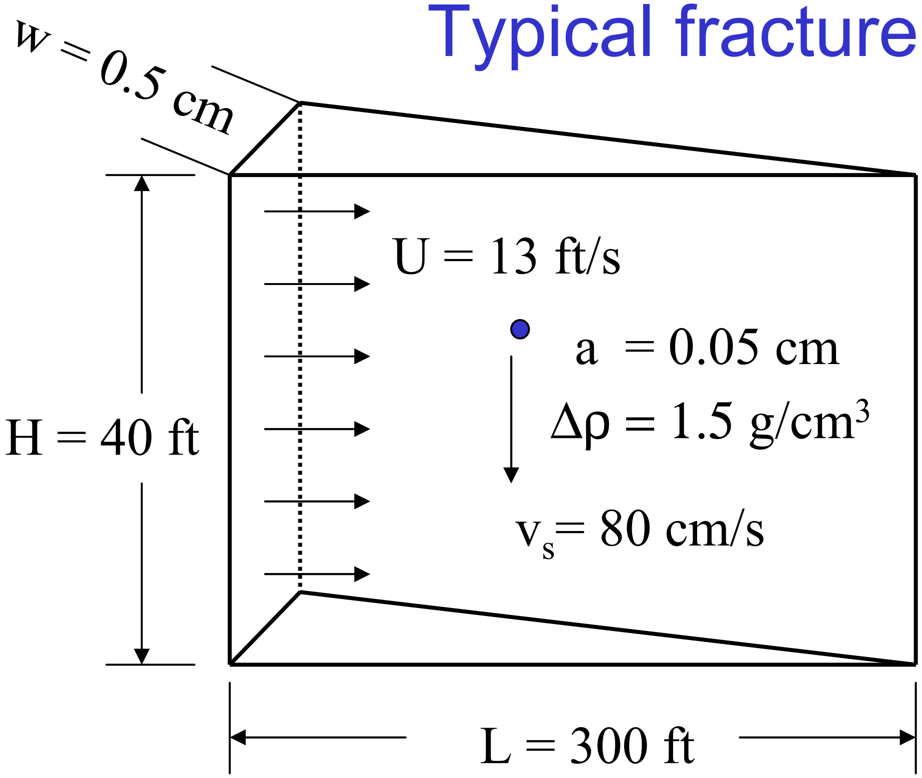

**With Turbulence Effects**

# Proppant Transport Cell



# Proppant Transport Dimensional Analysis

## Typical fracture




- Flow ranges from turbulent to laminar along fracture
- Particle settling and inertia are important
- Particle resuspension occurs

## Dimensionless Parameters

$Re = Uw/\nu = 20{,}000$

$Re_p = Re(a/w) = 2000$

$t_{adv}/ t_{set} = Lv_s/UH = 1.6$

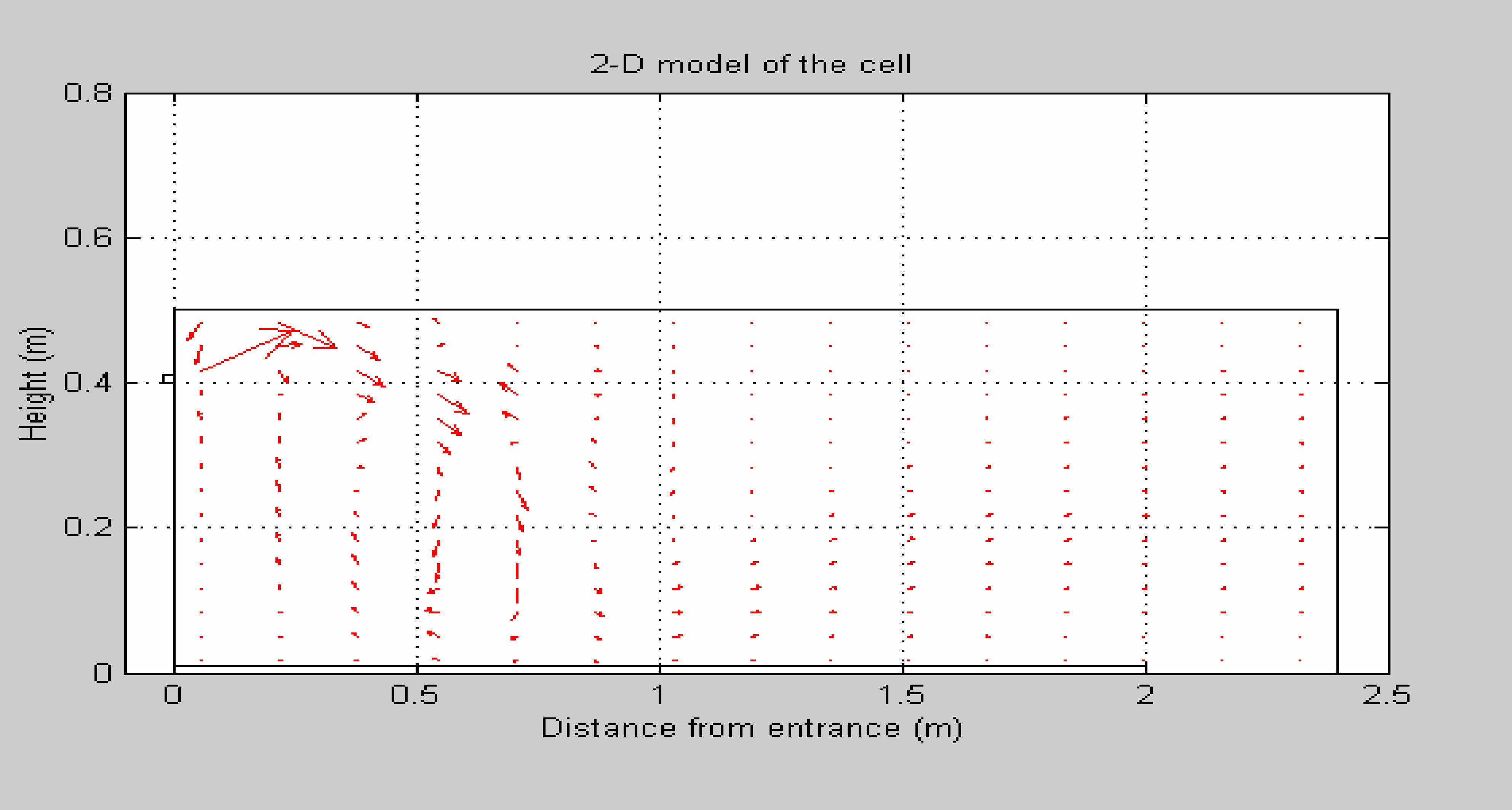
$S = \Delta\rho g a/\rho U^2 = 0.2$

$c = 0.01 – 0.6$

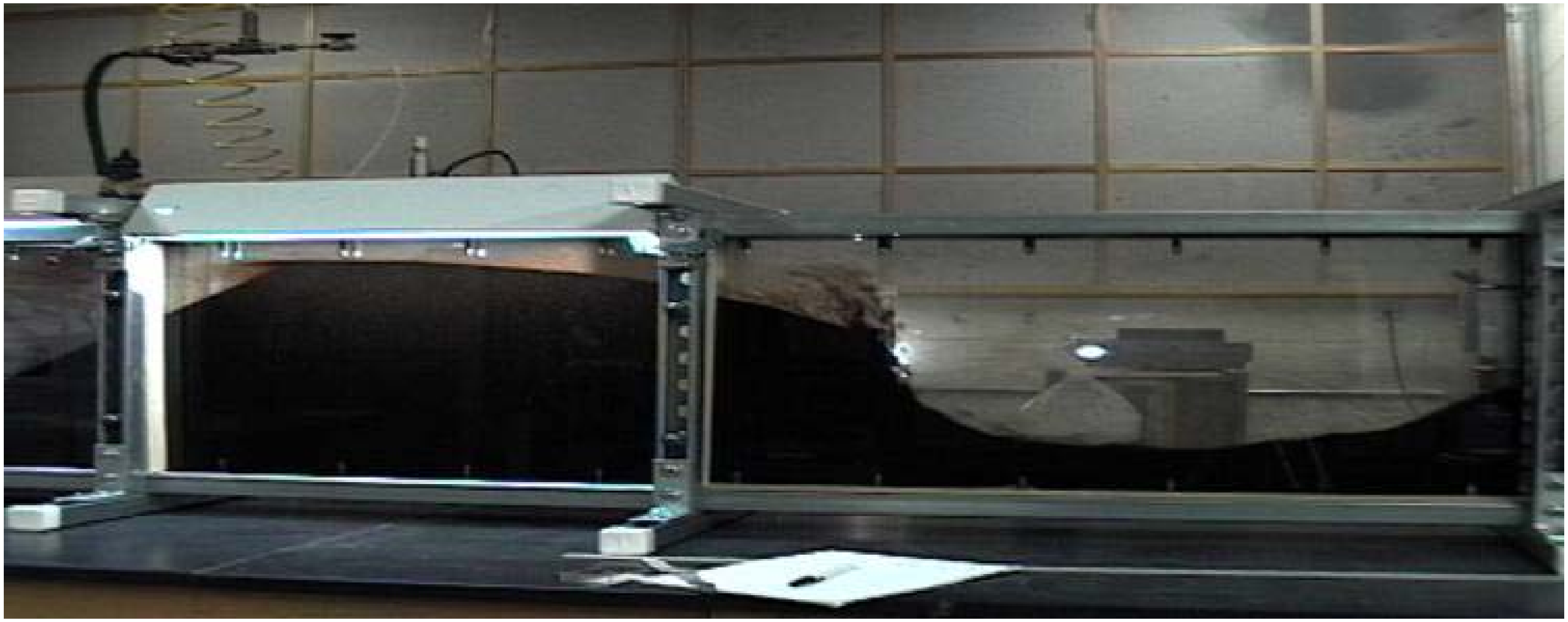
# Stages of Proppant Transport

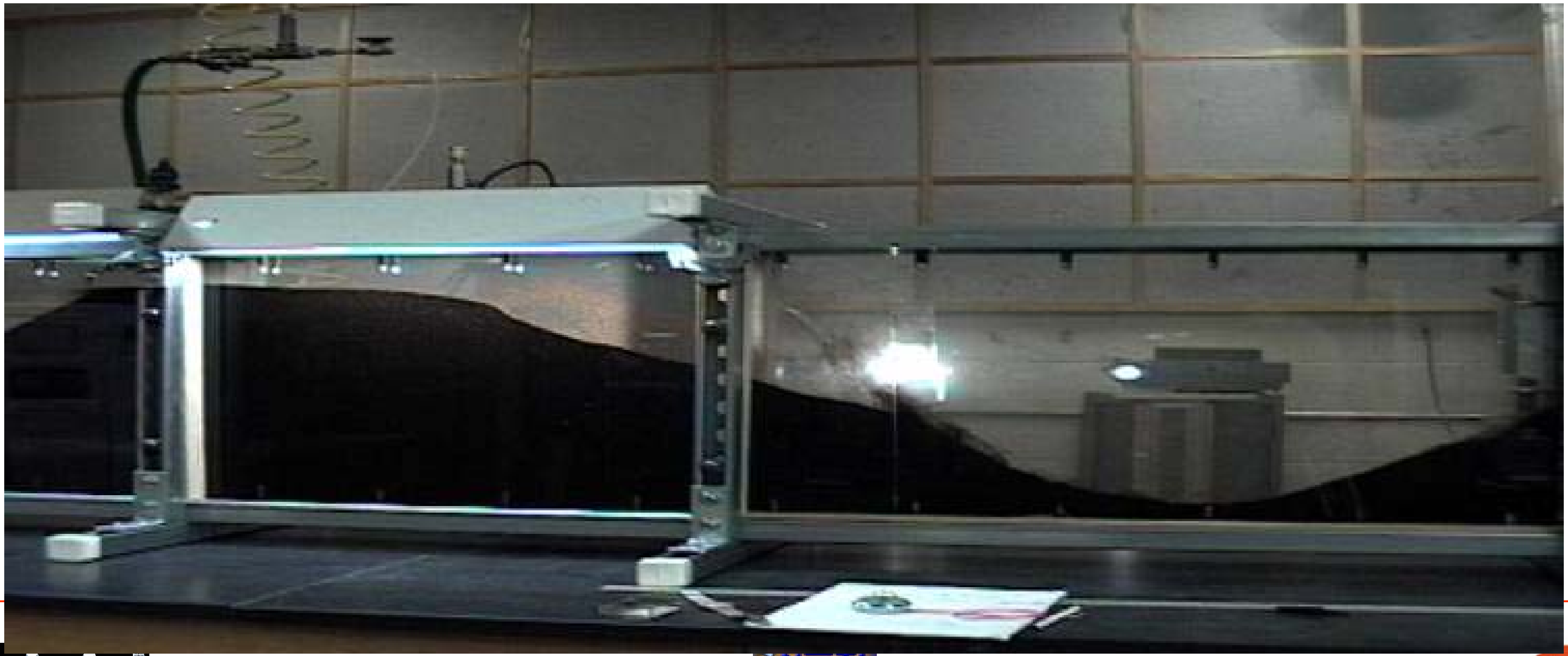
- Stage 1: Convection / settling dominated.
- Stage 2: Buildup of a proppant bed.
- Stage 3: Steady state saltation over bed.
- Stage 4: Final settling after flow shutoff.

# Complex Flow Patterns can Arise

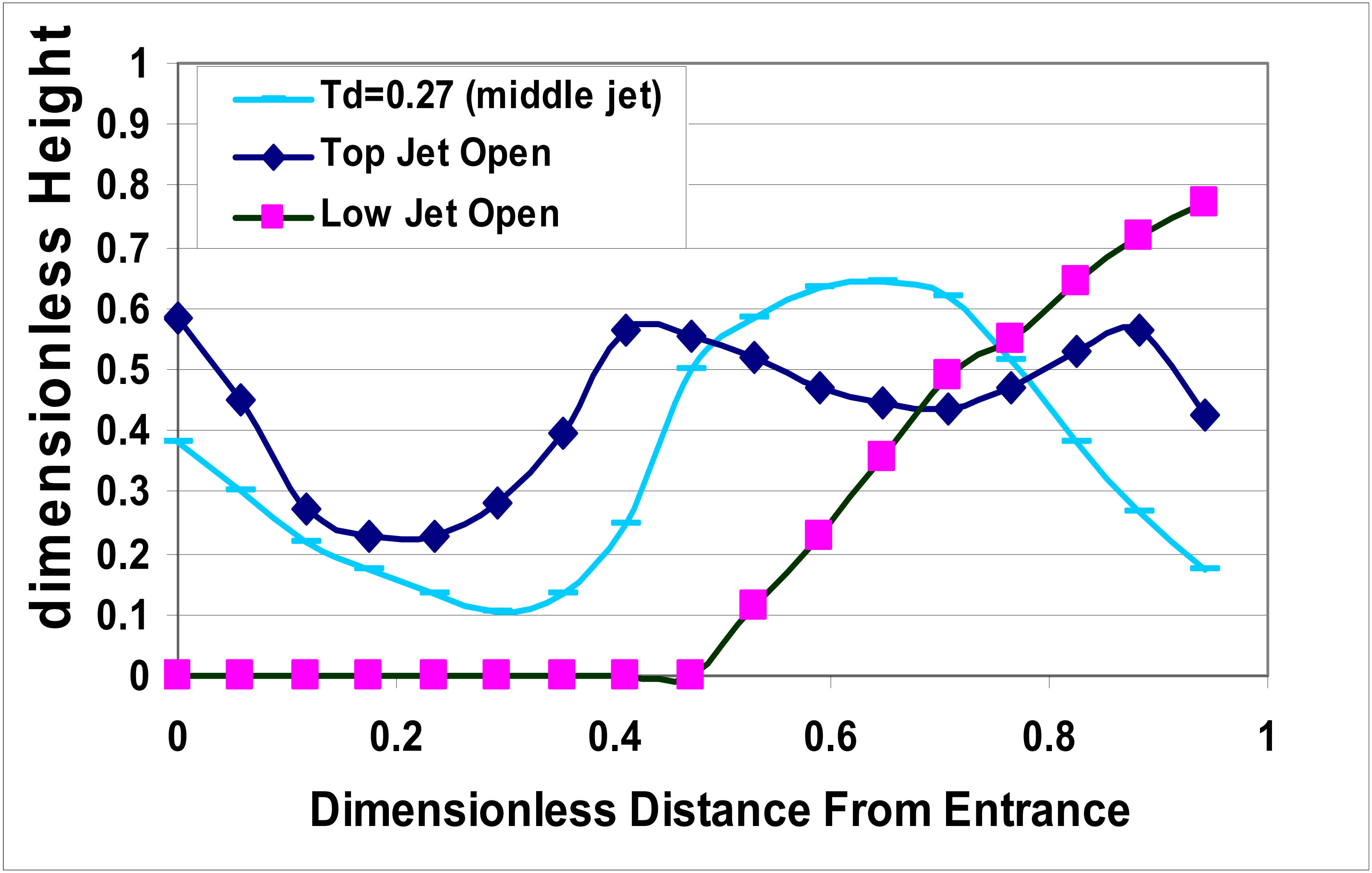


# Example of Stage 2: Bed Buildup

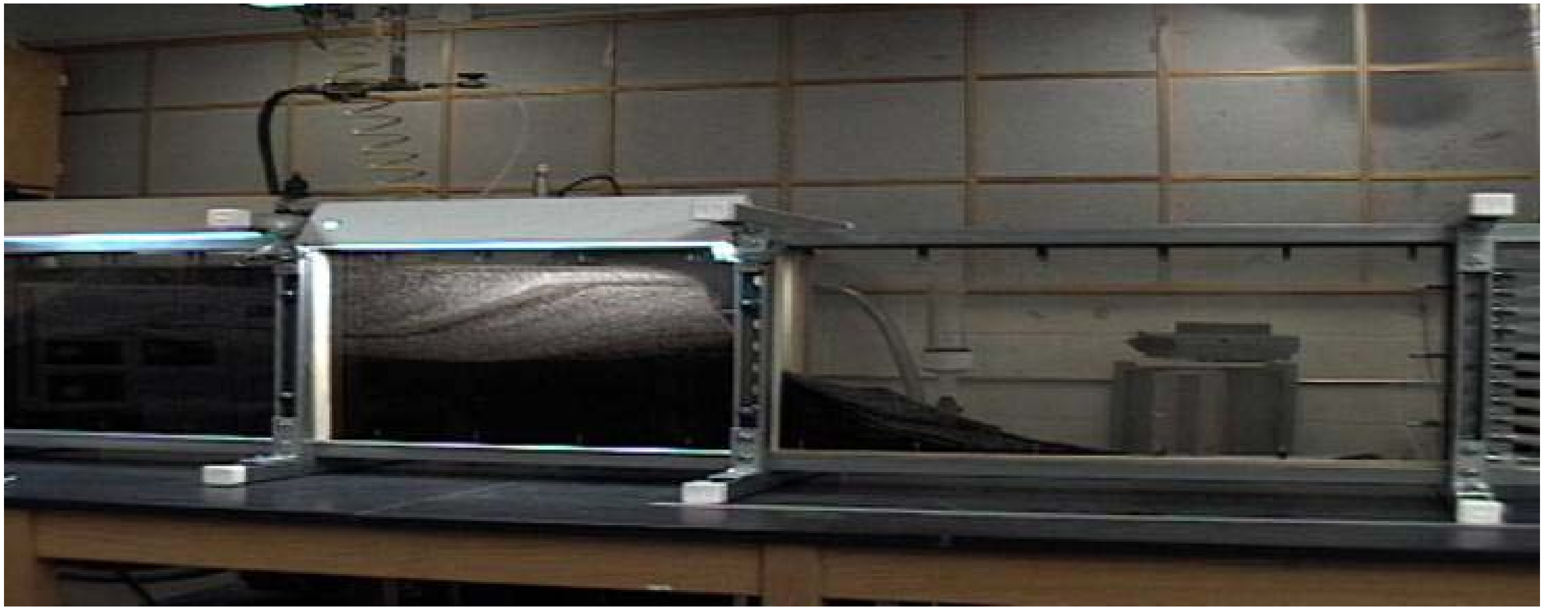




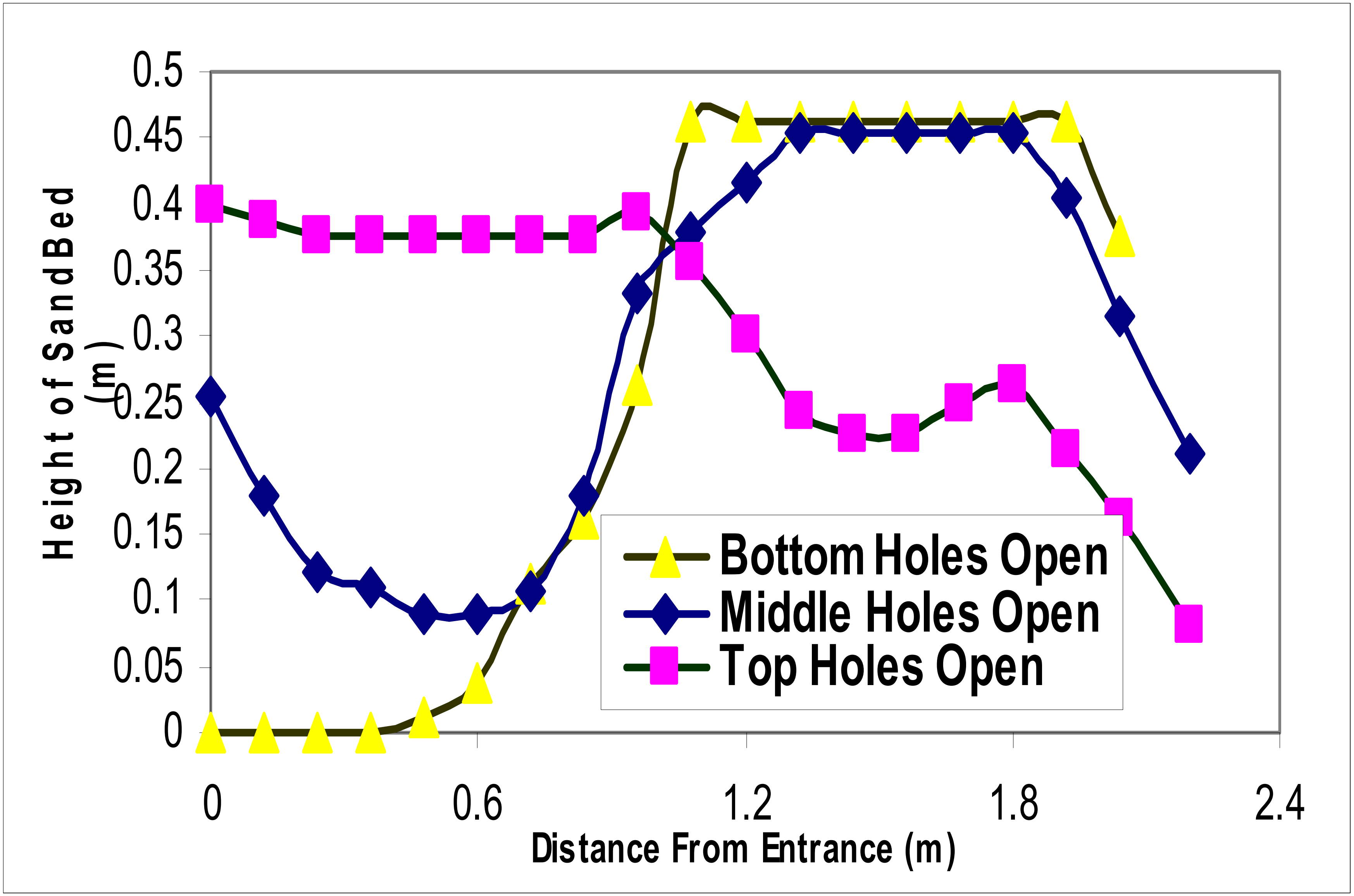
# Effect of Perf Positions (Stage 2)



# Stage 3: Formation of Equilibrium Bed



# Effect of Jet Position On Sandbed Profile (Stage 3)



# Stage 4: Final Proppant Bed

# Effect of Unpropped Portion On Fracture Conductivity

If 1% of fracture near the wellbore is unfilled

Stimulation ratio of partially filled fracture to fully filled fracture is:

$$\frac{J_s}{J_0} = \frac{\ln(R_e/L)}{\ln(0.01L/R_w) + \ln(R_e/L)} = \frac{\ln(2)}{\ln(0.01*5000)} = 0.18$$

# Experimental Observations

- In water fracturing, proppant settling is very different from that in gel fracturing: settling dominates.
- Flowing water forms eddies near the entrance. The distance between the stagnation point and entrance could be very large.
- Most of the early proppant forms a dune around the stagnation point. The remaining proppant is placed by saltation flow over this dune.
- The location of the dune is controlled by the flow rate and the location of the perforations.

# Experimental Observations

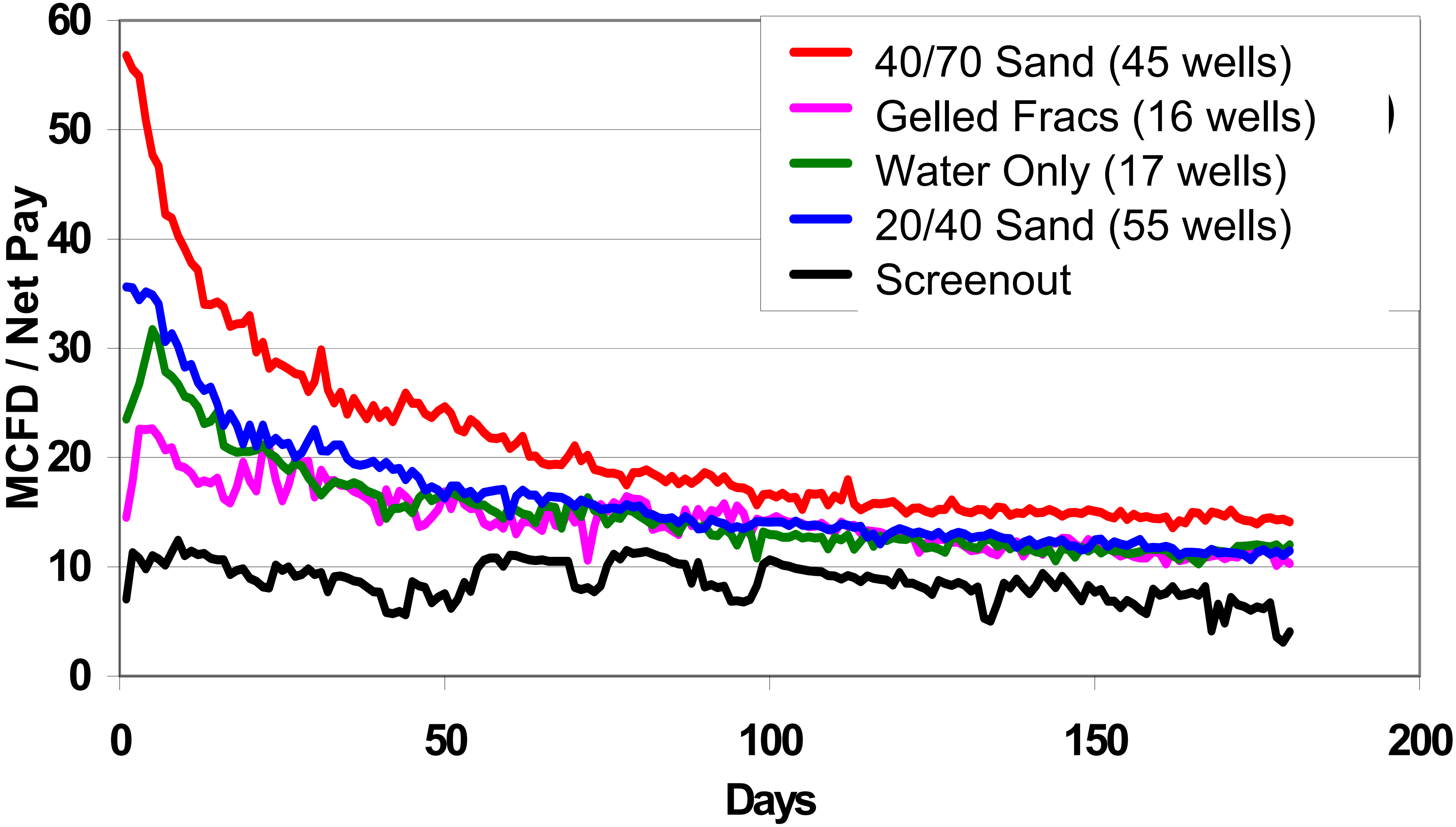
- Proppant transport far into the fracture occurs by saltation type flow and is very much dependent on the shape of the sand dune formed.
- High velocities, small proppant size and high viscosity promote saltation.
- Packing proppant near the perforations is critical to frac conductivity. Location of perfs in the pay zone, the injection rates, rheology and proppant concentration control whether proppant remains packed around the perf tunnels.

# Field Implications?

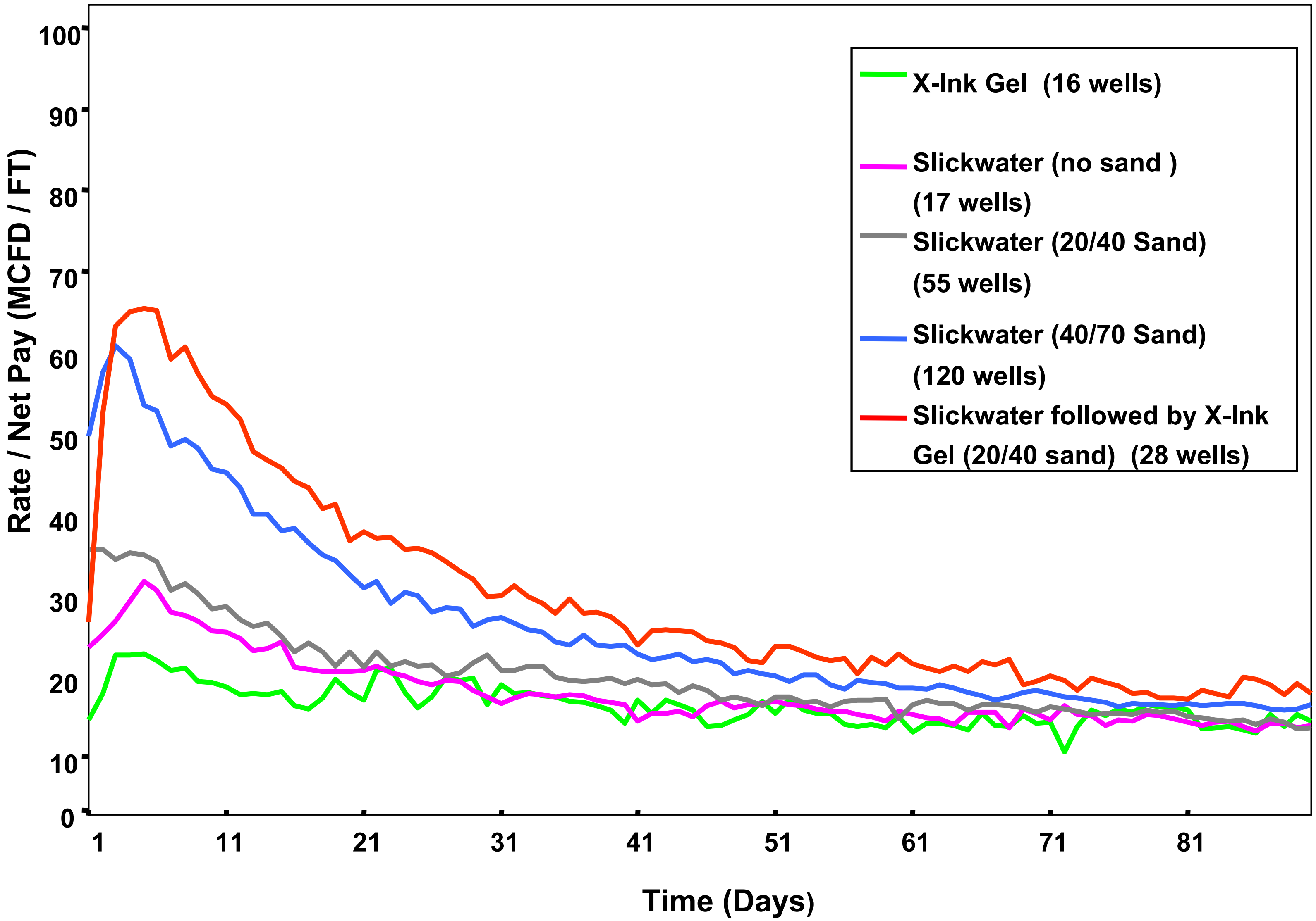
- Where should you perf within the zone? We must ensure:
  - proppant is packed around the perfs
  - promote saltation type flow deep into the fracture
- Proppant concentration ramp-up?
- Injection rates?
- Is there an optimal rheology?

- **Our experiments suggest some preliminary answers that need to be verified in the field.**

# Performance of Fracture Treatments in Tight Gas Sands



# Playing with Fluid Rheology Texas Bossier Fracturing

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# Conclusions

- An accurate model for proppant settling has been incorporated into a fully 3-d frac model.
- The model allows us to evaluate the impact of proppant size, fluid rheology and pump rates on proppant placement.
- Experiments have been conducted to develop additional insight into the process.
- Model is currently being tested and verified against Bossier data.

# Conclusions

- One can design for maximum propped frac lengths based on model developed.
- Optimum values of the following need to be selected,
  - Fluid rheology,
  - Proppant size
  - Rates
  - Location of perfs
- We have a better idea of where the proppant is going and it really does help!

# Acknowledgement


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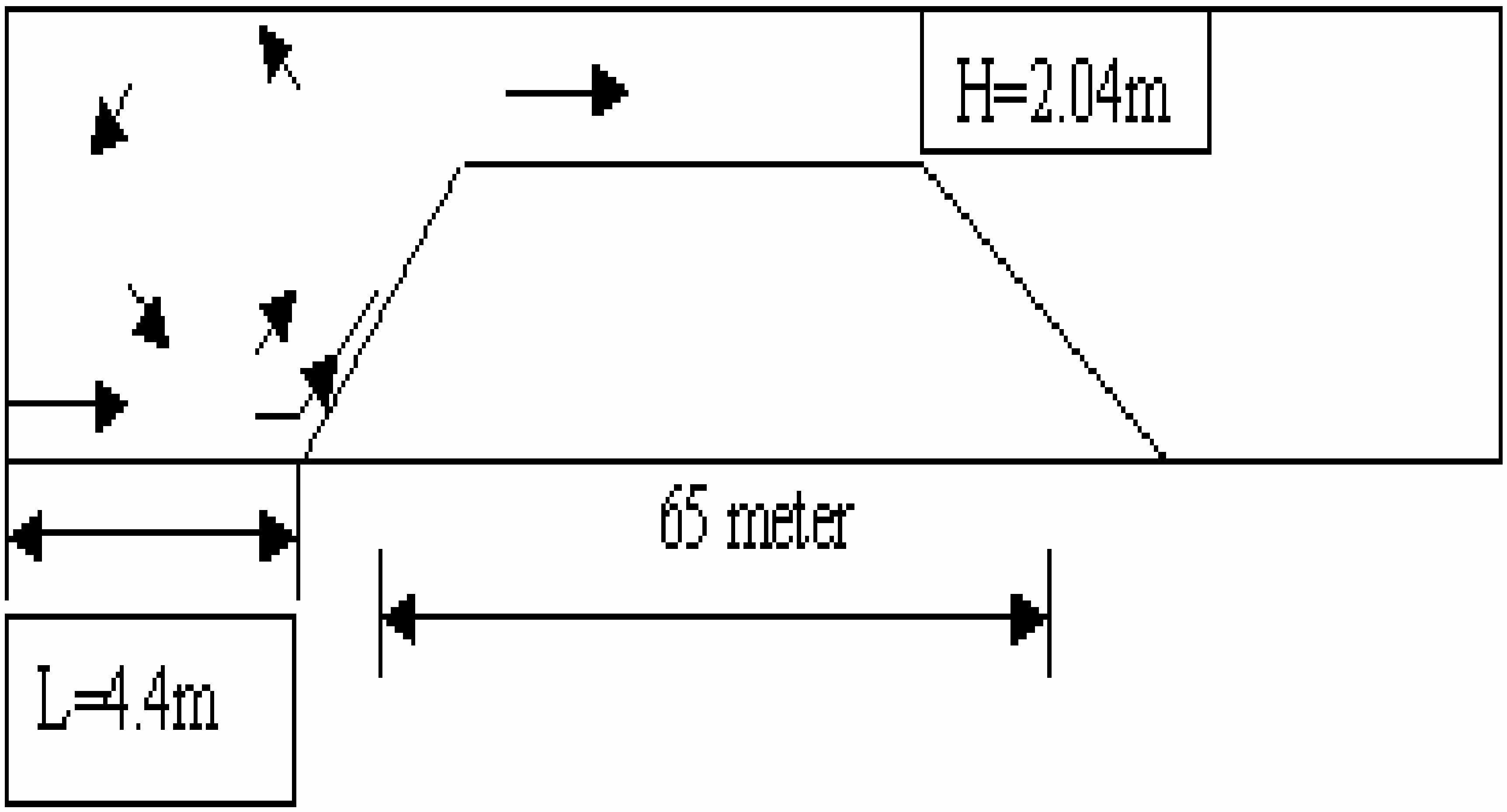
- Cost sharing was provided by Anadarko Petroleum Corporation and the University of Texas at Austin.

# Location of Perforations Impacts Location of the Proppant Bed



# Size of Proppant-Empty-Zone (Bottom Holes Open)