# Sedimentation Engineering

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**USBR Lectures – Part II**
Denver, Colorado
January 17, 2024

# USBR Short Course

1. Watersheds and Climate
2. Sedimentation Engineering
3. Rivers and Dams
4. River Environment

# Sedimentation Engineering

1. Incipient motion
2. SEMEP and SEMEPP
3. Mudflows and Debris Flows

# Shields Parameter

- Shields only defines the ratio of the shear force (no lift) to the particle submerged weight

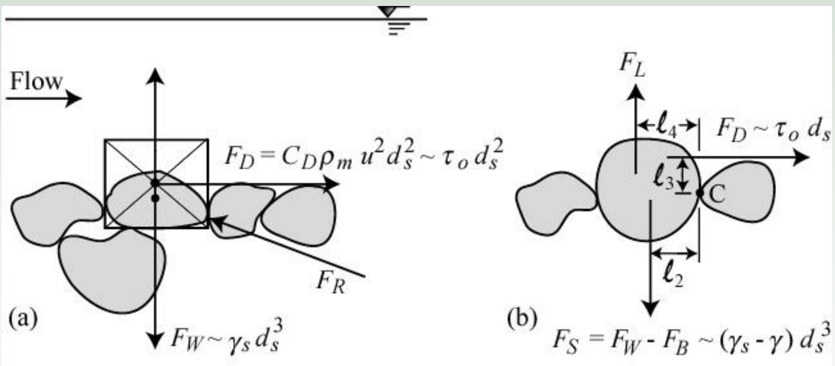
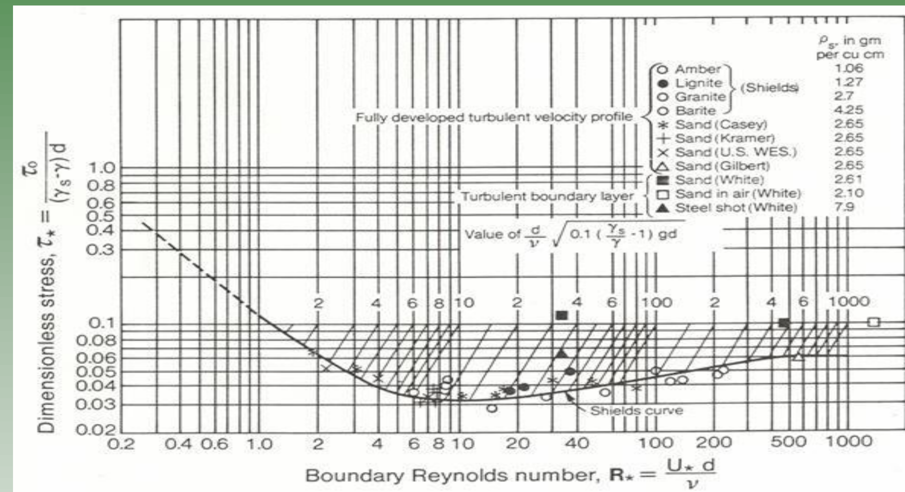


Figure 7.6. Force diagram under steady uniform flow

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma)d_s} = \frac{\rho_m u_*^2}{(\gamma_s - \gamma)d_s}$$



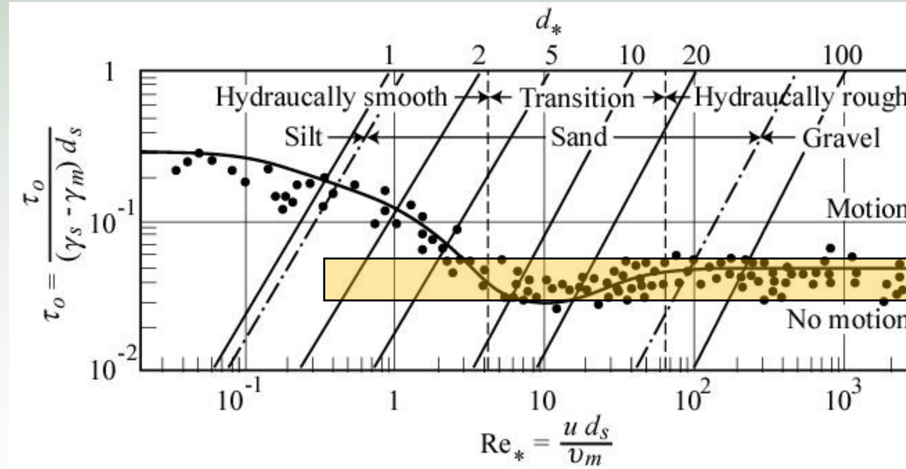
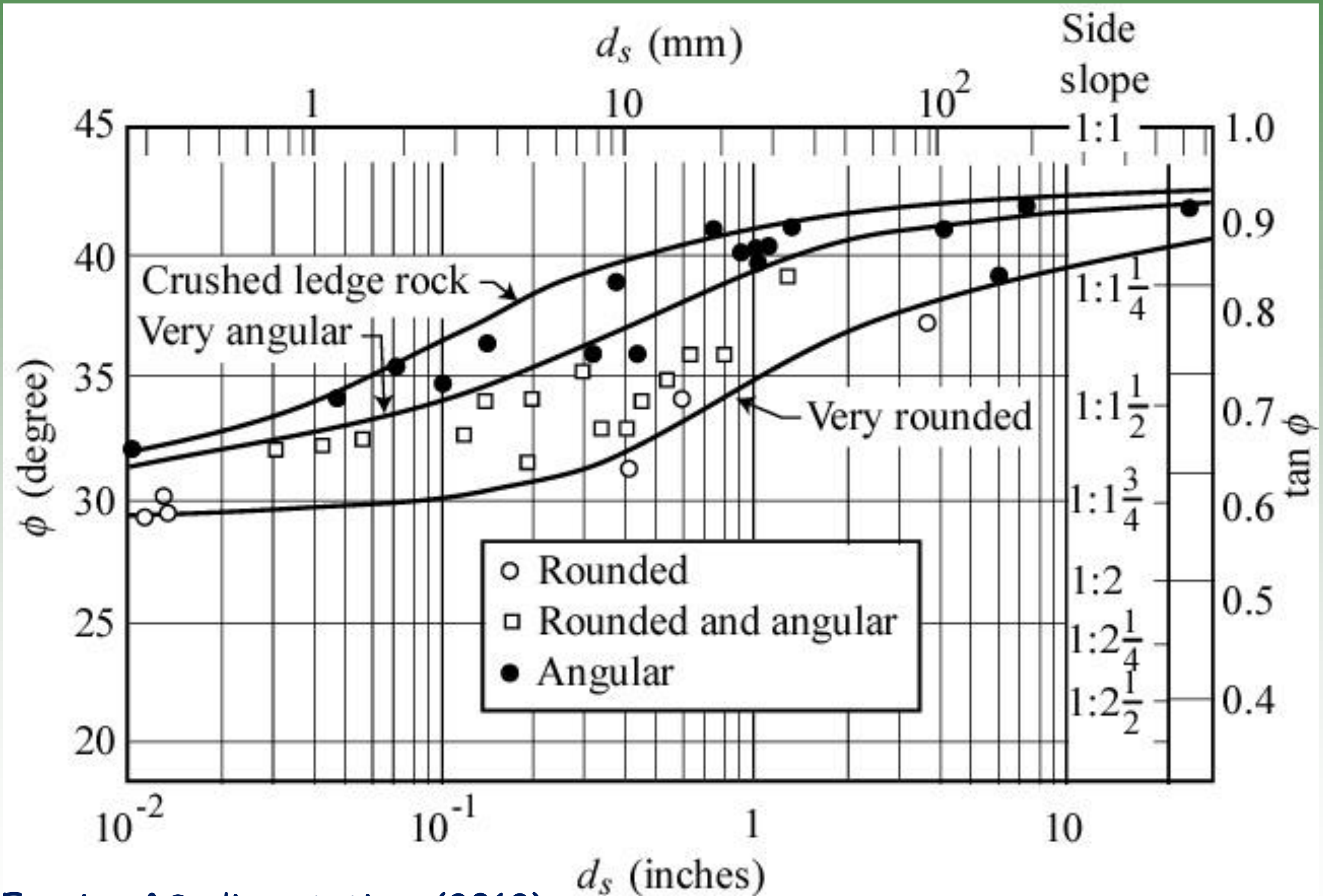



Figure 7.7. Shields diagram for granular material

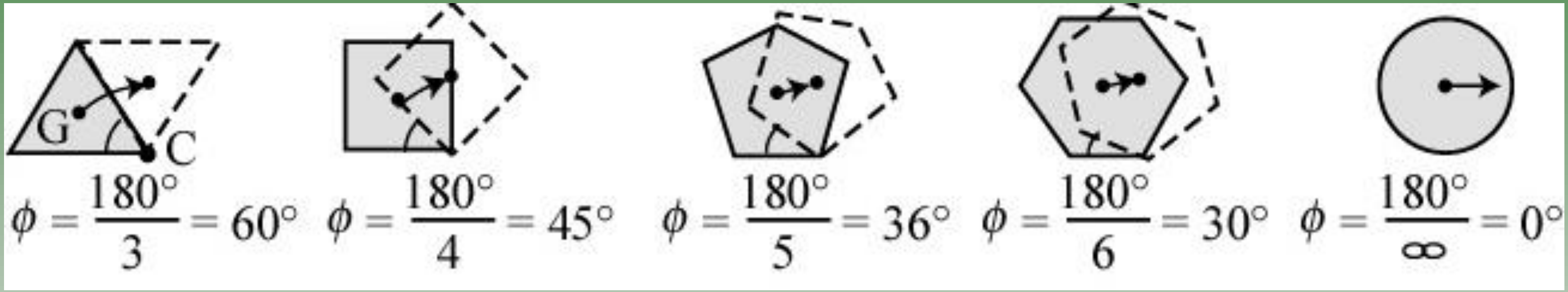
Julien Erosion &Sedimentation (2012)

# Angle of Repose
# Granular Material

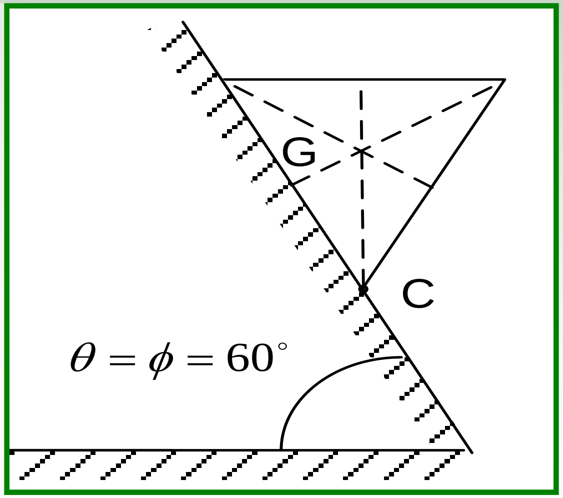



Julien Erosion &Sedimentation (2012)

# Angle of Repose
## Effects of Angularity

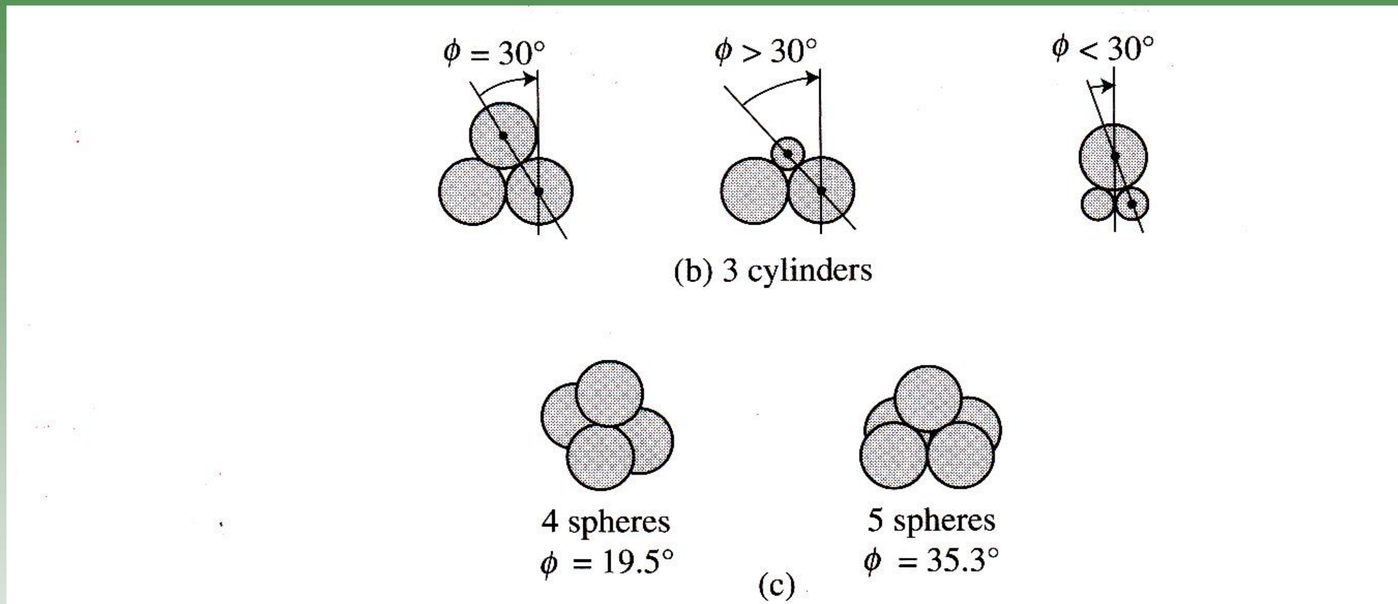



**Motion occurs when the center of gravity (G), is above the point of contact (C).**




Julien Erosion &Sedimentation (2012)

# Angle of Repose
## Boundary and Particle Configuration



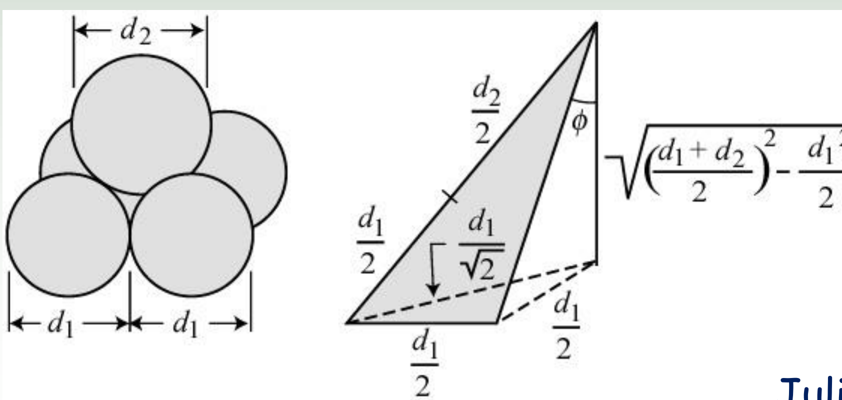




Figure 7.3. Angle of repose for spheres of different diameter

$$\tan\phi = \frac{d_1}{\sqrt{(d_1+d_2)^2 - 2d_1^2}}$$

Julien Erosion &Sedimentation (2012)

# Angle of Repose
## Boundary and Particle Size

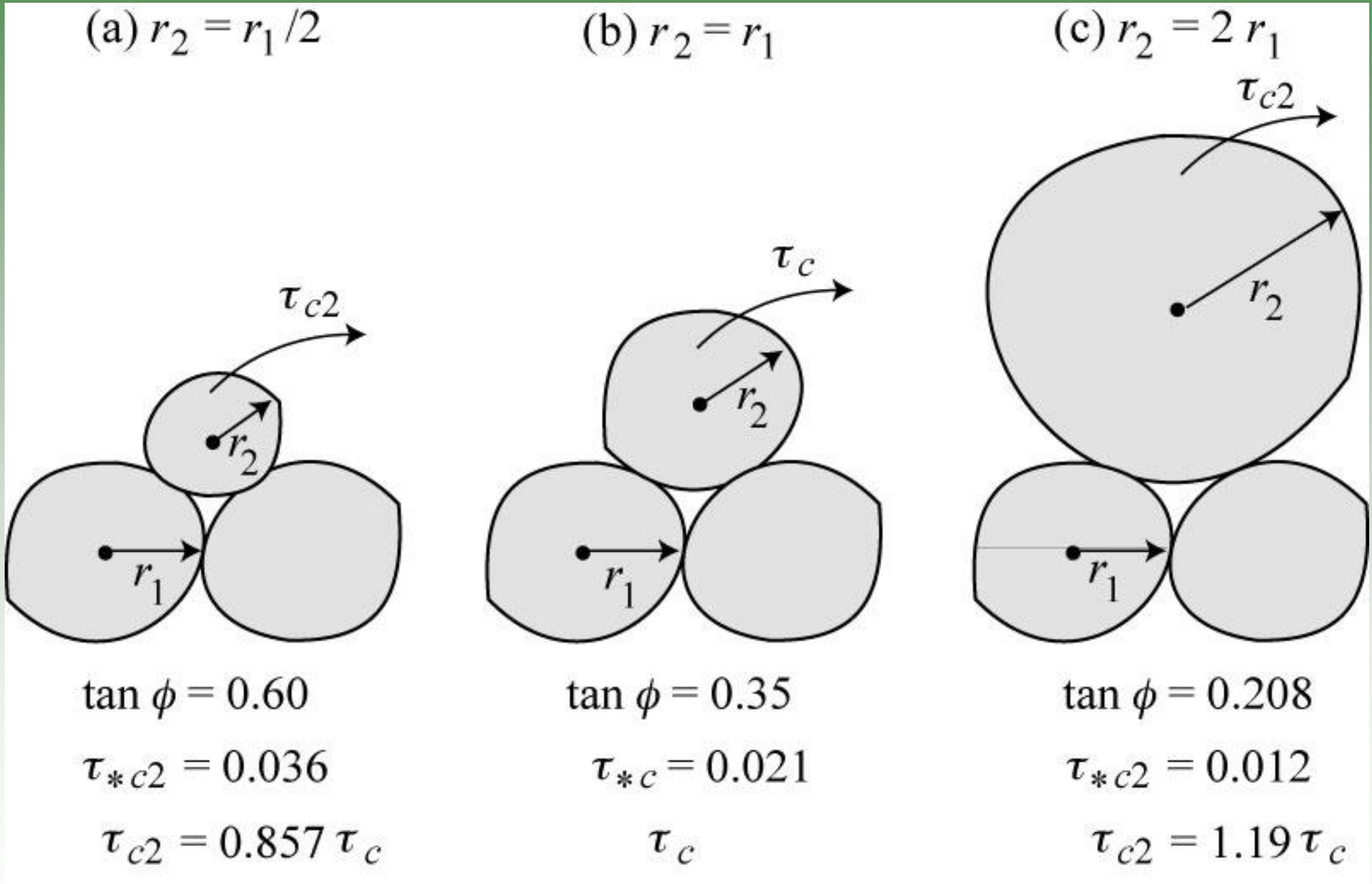
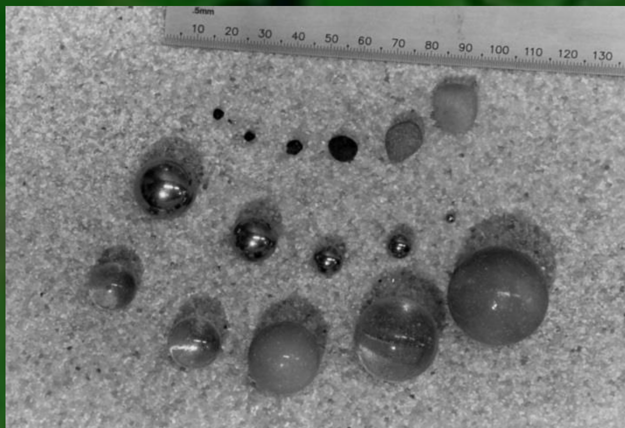
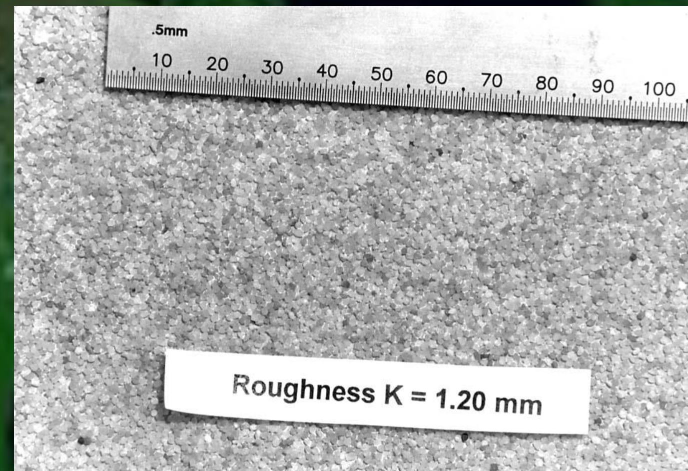


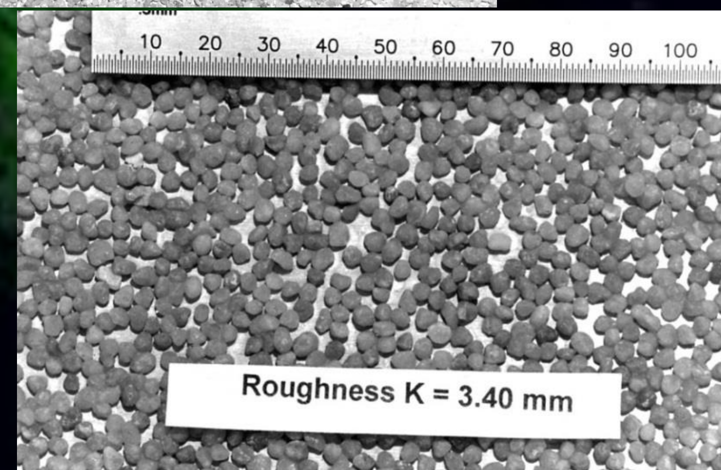

Figure 7.12. Relative stability for different particle sizes

# Laboratory experiments at CSU






~10,000 particle velocity measurements




Bounvilay and Julien, ASCE-JHE (2013)

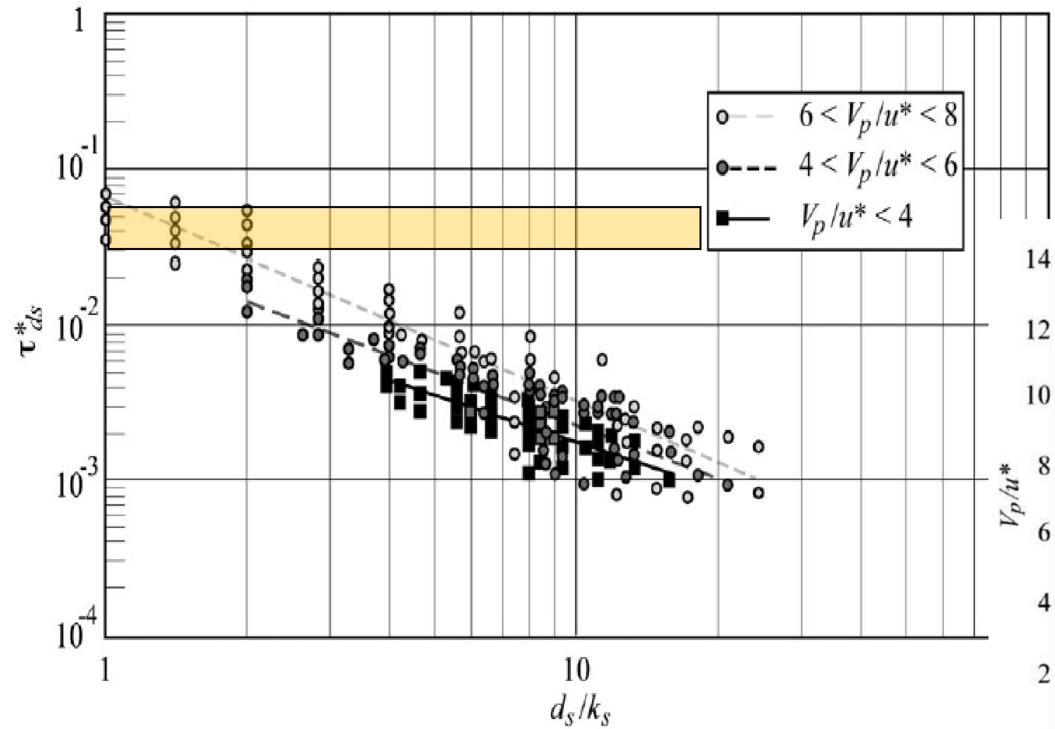
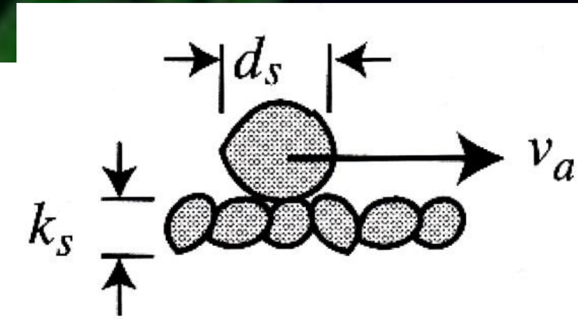
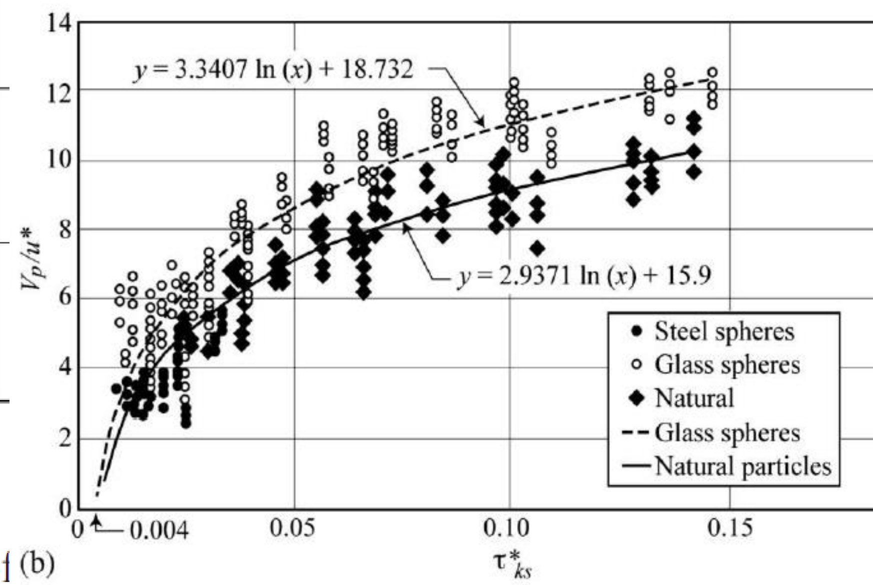



**Fig. 9.** Shields parameter $\tau^*_{ds}$ vs $d_s/k_s$ for different values of $V_p/u_*$




(b)

Bounvilay and Julien
ASCE-JHE (2013)

Lets remember:

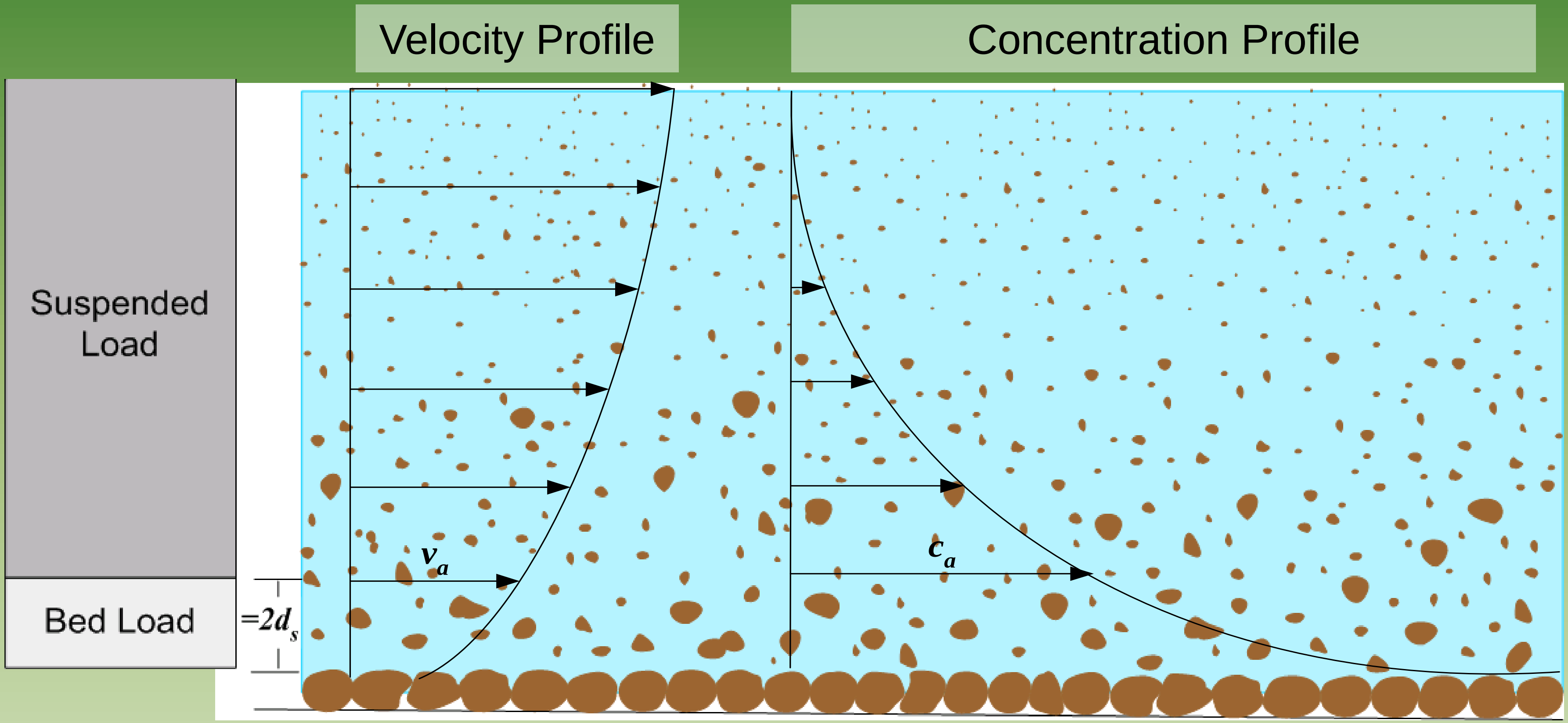
Incipient motion depends on the sum of moments, not forces.

Particles move at Shields values << 0.03 (in shaded box)

# Sedimentation Engineering

1. Incipient motion
2. SEMEP and SEMEPP
3. Mudflows and Debris Flows

# Sediment Transport Mechanism
# Einstein -> bottom up
# Modified Einstein (MEP) -> top down

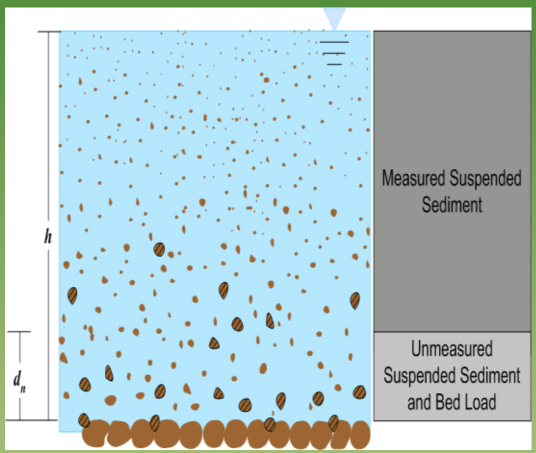


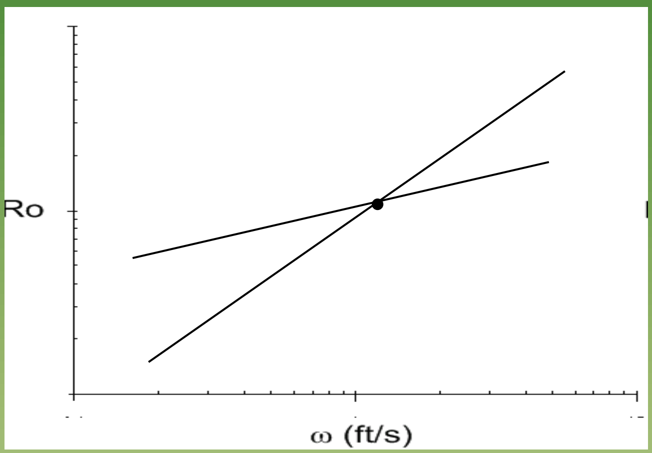

$$v = \frac{u_*}{\kappa} Ln\left(30.2\frac{y}{k_s}\right)$$

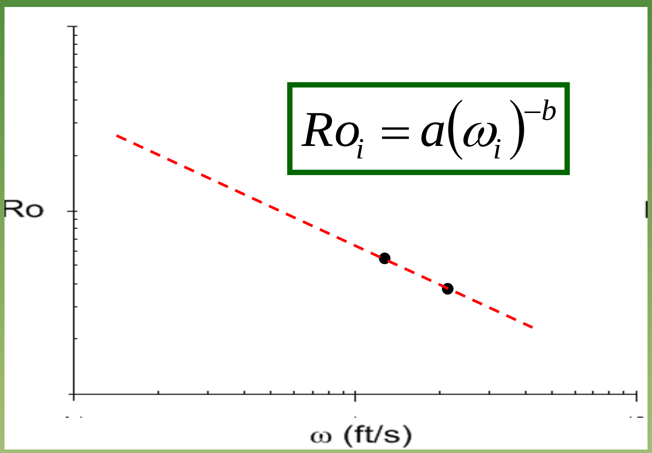
$$c = c_a\left(\frac{h-y}{y}\frac{a}{h-a}\right)^{Ro}$$

$$Ro = \frac{\omega}{\kappa u_*}$$

# Problems with the 'traditional' Modified Einstein Procedure

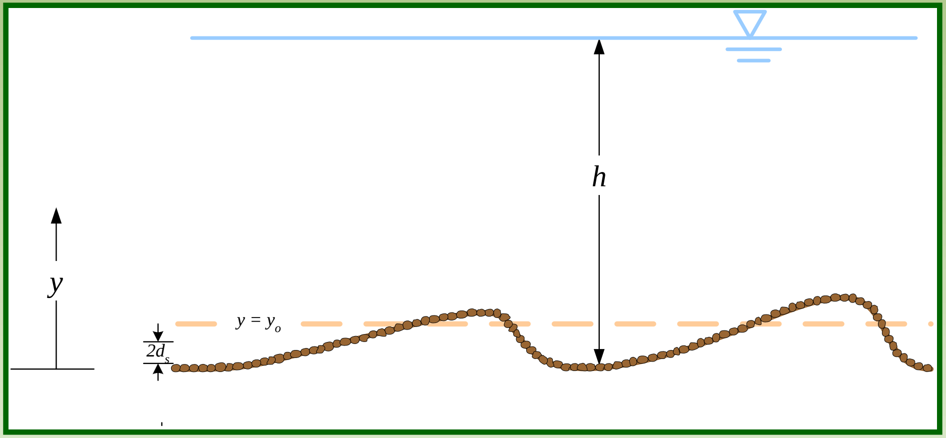



**CASE 1 – Not Enough Overlapping Bins**

**CASE 2 – Negative exponent**




**CASE 3 – Calculate Total Load is less than Suspended Load**

# Series Expansion Modified Einstein Procedure SEMEP

## Efficient Algorithm for Computing Einstein Integrals

Junke Guo[1] and Pierre Y. Julien[2]

### Einstein Algorithm Calculator:

This calculator was made using equations in the following reference:

Junke Guo and Pierre Y. Julien (2004). "Efficient Algorithm for Computing Einstein Integrals." J. Hydraul. Eng., 130(12), 1198-1201.

DOI: 10.1061/(ASCE)0733-9429(2004)130:12(1198)

Procedure:

The cells with red are inputs while the cells with blue are outputs.

To calculate, place mouse on user input cell, type in the desired inputs and press the enter key.

To change the inputs, simply select cell again and type in desired input and press the enter key.

To view the equations used in the calculations select the Einstein Algorithm Calculations tab below.

Also included are graphical solutions for $J_1(z)$ & $J_2(z)$ using E-values of 0.1 and .00001.

### Non-Integer Algorithm Analysis

| | | Value Inputted | Value Used In Analysis |
|---|---|---|---|
| Input: | z= | 1 | 1 |
| | E= | 0.00001 | 0.00001 |

| | | | | |
|---|---|---|---|---|
| Ouput: | $J_1(z)$= | | $J_2(z)$= | |
| | $J_1(0)$= | | $J_2(0)$= | |
| | $J_1(1)$= | 1.051E+01 | $J_2(1)$= | 6.537E+01 |

# Primary Mode of Transport from SEMEP
# Ratio of the suspended to total load $q_s/q_t$

- Calculate the Suspended Load

$$q_s = \int_{2ds}^{h} cv\,dy$$

$$q_s = \int_{2ds}^{h} c_a \left( \frac{h-y}{h} \frac{a}{h-a} \right)^{Ro} \frac{u_*}{\kappa} \ln\left( \frac{30y}{d_s} \right) dy$$

$$c_a = \frac{q_b}{v_a a}$$

$$v_a = 11.6 u_*$$

$$q_s = 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}$$

- Calculate the Total Load

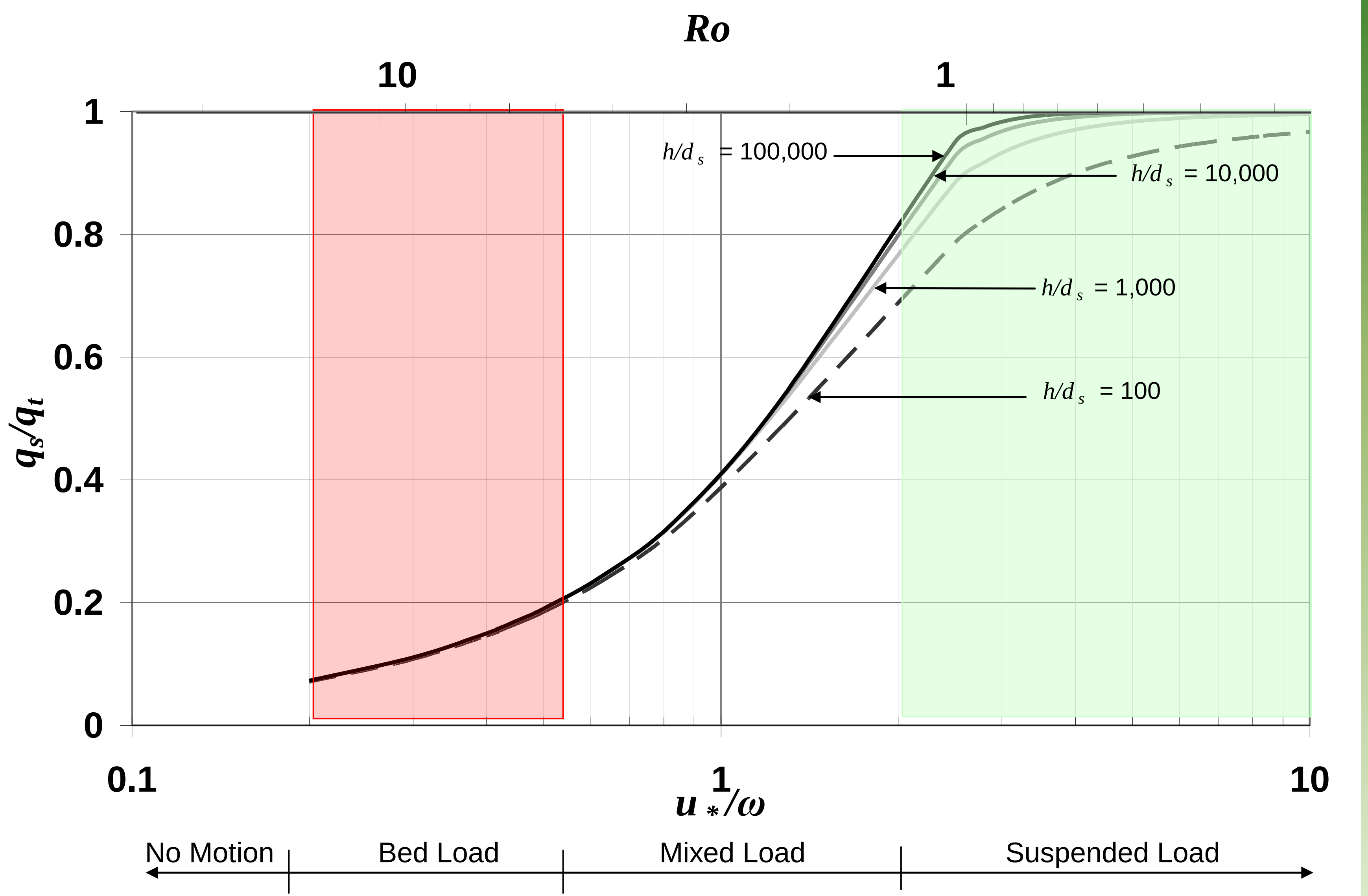
$$q_t = q_b + q_s$$

$$q_t = q_b + 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}$$

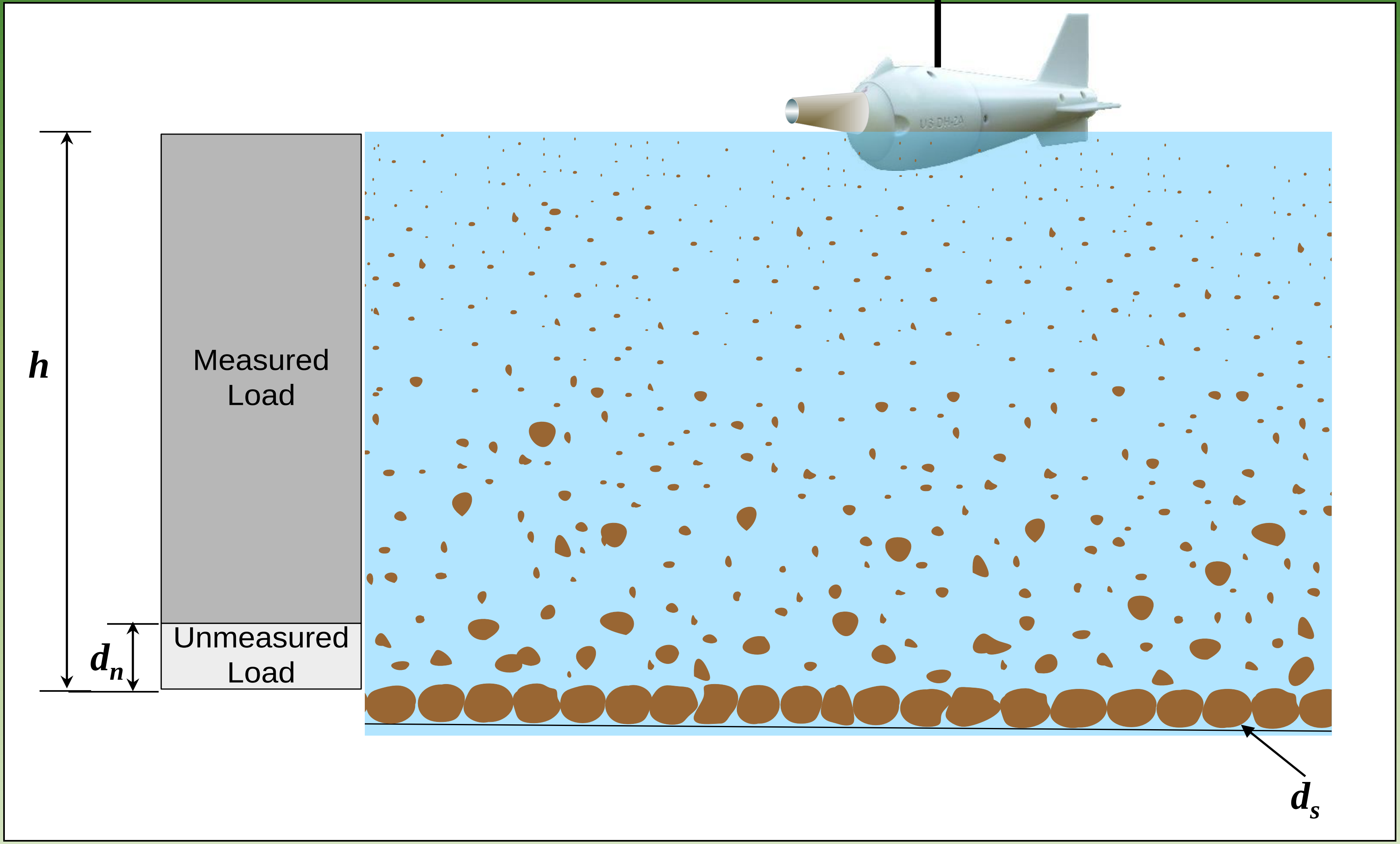
- Ratio of qs/qt

$$\frac{q_s}{q_t} = \frac{0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}}{1 + 0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}}$$

# Primary Mode of Transport



# Ratio of Measured to Total Load from SEMEP



# Total Sediment Load from SEMEP Using Depth-Integrated Concentration Measurements

Seema C. Shah-Fairbank, M.ASCE[1]; Pierre Y. Julien, M.ASCE[2]; and Drew C. Baird, M.ASCE[3]

**Abstract:** This study improves total sediment load calculations on the basis of depth-integrated sediment concentration measurements for channels with significant sediment transport in suspension. The series expansion of the modified Einstein procedure (SEMEP) removes most of the empiricism found in the existing modified Einstein procedures (MEP). SEMEP calculations require field measurements of flow discharge, depth-integrated suspended sediment (SS) concentration, and suspended particle sizes. SEMEP calculates the Rouse number, Ro, from the median particle size measured in suspension $d_{50ss}$. On the basis of the sediment discharge measurements collected from 14 rivers, the accuracy of sediment discharge calculations depend on the ratio of the shear velocity $u_*$ to the settling velocity $\omega$. SEMEP performs accurately (error less than 25%) and without bias when $u_*/\omega > 5$. Calculations are also acceptable, but less accurate when $u_*/\omega$ is between two and five. Both SEMEP and MEP should not be used when the value of $u_*/\omega < 2$, and a simplified formulation on the basis of bed sediment discharge is recommended when $u_*/\omega < 2$. **DOI: 10.1061/(ASCE)HY.1943-7900.0000466.** 

INTERNATIONAL JOURNAL OF SEDIMENT RESEARCH

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International Journal of Sediment Research 30 (2015) 1-12

## Sediment load calculations from point measurements in sand-bed rivers

Seema C. SHAH-FAIRBANK[1] and Pierre Y. JULIEN[2]

**Abstract**

Point velocity and suspended sediment concentration measurements are used to calculate the total sediment discharge in sand-bed rivers. Calculations with the Series Expansion of the Modified Einstein Point Procedure (SEMEPP) depend on grain diameter $d_s$ and settling velocity $\omega$, flow depth $h$, shear velocity $u_*$, and sampling depth $h_p$. This procedure extends the applicability of the Modified Einstein Procedure (MEP) by using point sediment concentration and velocity measurements. This procedure is tested using the laboratory data from Coleman, and field measurements from the Enoree, Middle Rio Grande and Mississippi Rivers. Based on 801 point measurements over 124 verticals at flow depths ranging from 0.17 m to 33.5 m and sediment concentrations less than 0.1 kg L$^{-1}$, the accuracy of the calculations depends on $u_*/\omega$ and $h_p/d_s$. Point measurement techniques like SEMEPP are well-suited when $u_*/\omega > 5$ where at least 60% of the total sediment load is measured when 90% of the flow depth is sampled. The determination of sediment discharge from point measurements is most accurate in deep rivers when $h_p/d_s > 10{,}000$, and $u_*/\omega > 10$. Point measurements are not well-suited for shallow rivers and laboratory flumes where $h < 0.5$ m and when $u_*/\omega < 2$.

International Journal of Sediment Research 34

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Original Research

## The ratio of measured to total sediment discharge

Chun-Yao Yang*, Pierre Y. Julien

*Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523, USA*

# Zone of Applicability
# $q_m/q_t$

- Calculate the Measured Load

$$q_m = \int_{dn}^{h} cv\,dy$$

$$q_m = \int_{dn}^{h} c_a \left( \frac{h-y}{h} \frac{a}{h-a} \right)^{Ro} \frac{u_*}{\kappa} \ln\left( \frac{30y}{d_s} \right) dy$$

$$c_a = \frac{q_b}{v_a a}$$

$$v_a = 11.6 u_*$$

$$q_m = 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_{1A} + J_{2A} \right\}$$

- Calculated Total Load

$$q_t = q_b + q_s$$

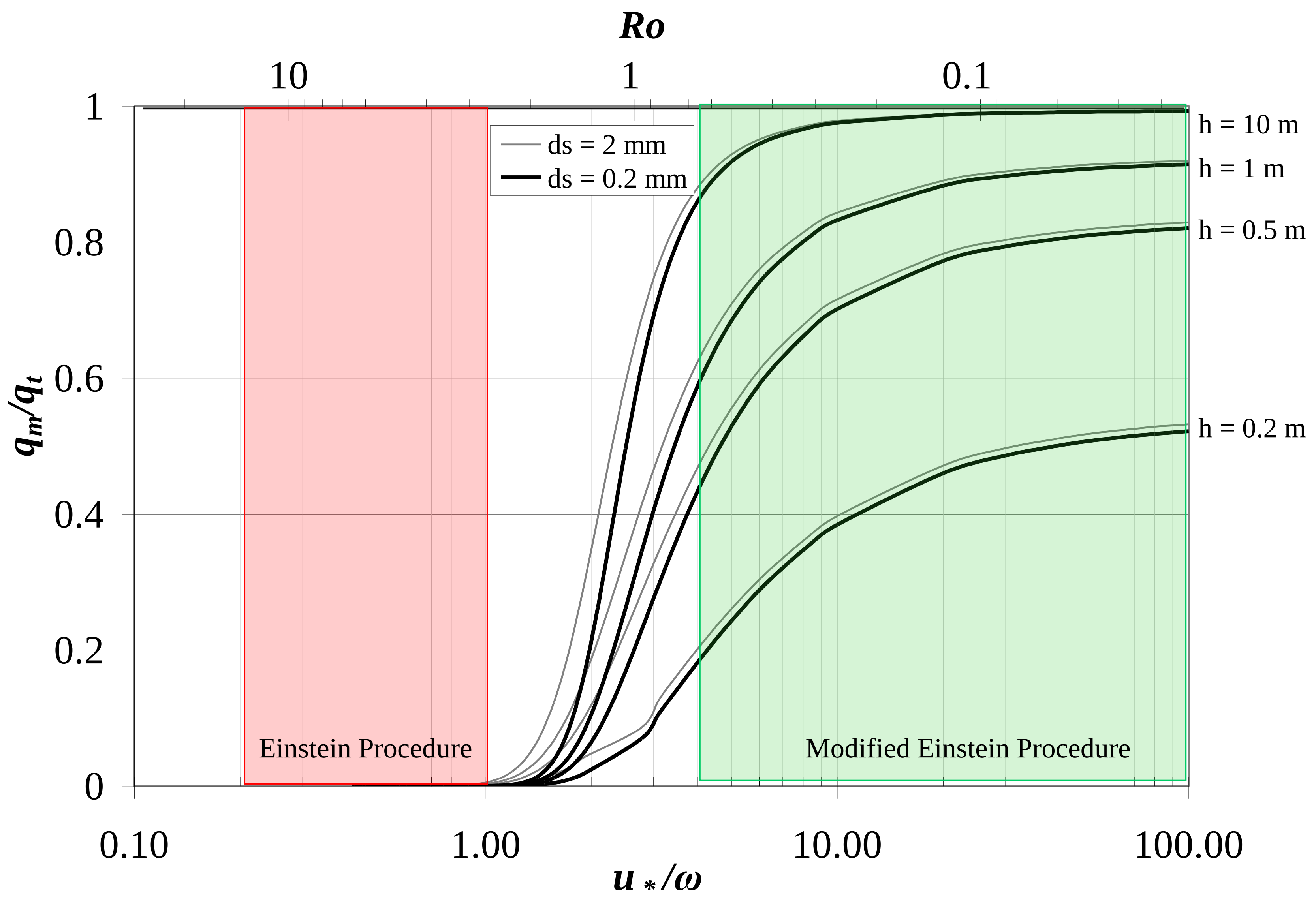
$$q_t = q_b + 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}$$

- Ratio of qm/qt

$$\frac{q_m}{q_t} = \frac{0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_{1A} + J_{2A} \right\}}{1 + 0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left( \frac{30h}{d_s} \right) J_1 + J_2 \right\}}$$

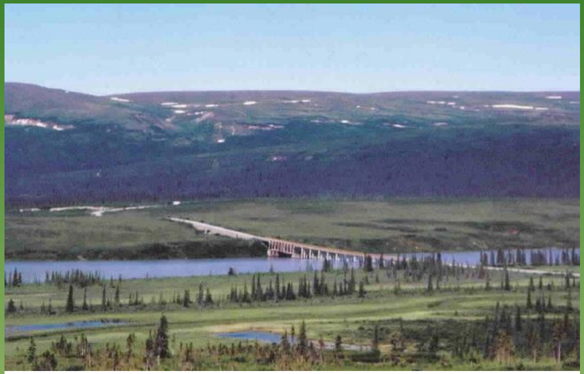
# Measured to Total Sediment Load

## from a standard suspended sediment sampler dn = 10 cm



# Field Testing by Seema Shah-Fairbank

Enoree River, SC



Susitna River, AK

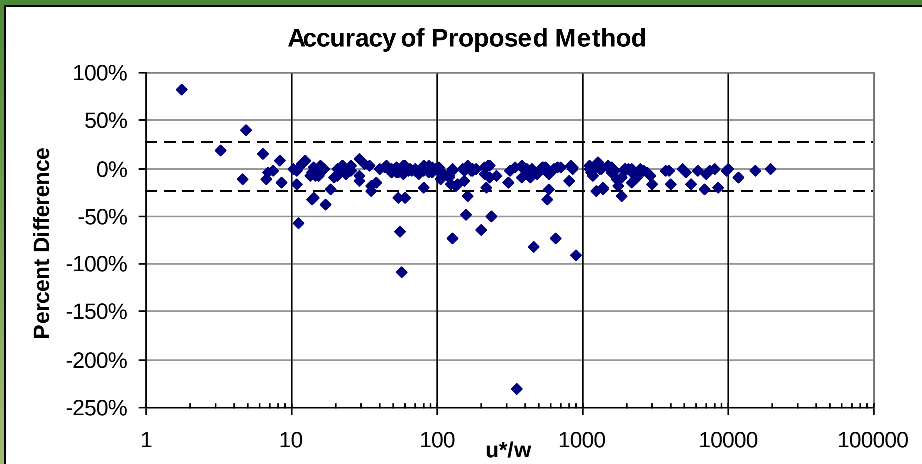
Snake River, WA

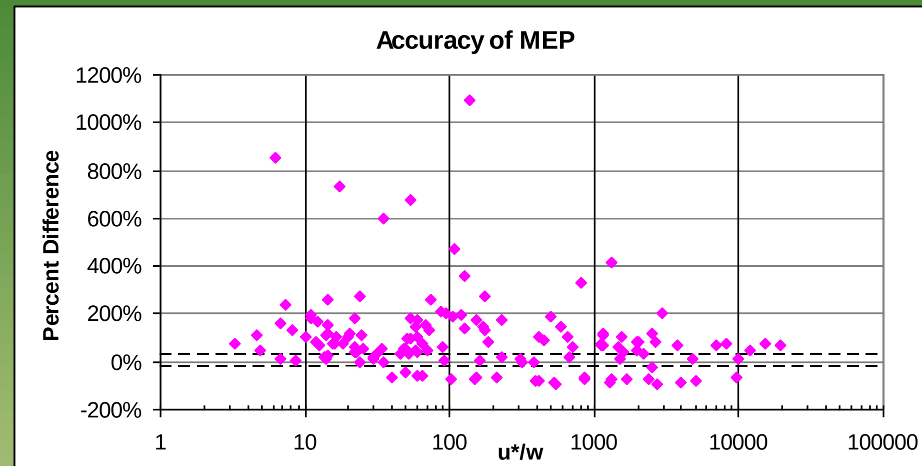

Middle Rio Grande, NM

Clearwater River, ID

Mississippi River, MS

# Results from Depth Integrated Sampler




| River | Hydraulic Data | | | | | Median Particle Size (mm) | | Total Number of Samplers | Number of Samples with Calculated Total Load within 25% of measured Total Load | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Q (cms) | V (m/s) | h (m) | W (m) | S | Bed | Suspension | | Proposed Method | BORAMEP |
| Susitna River near Talkeetna Alaska | 238 to 1,300 | 1.2 to 2.7 | 1.1 to 2.4 | 165 to 202 | 0.0011 to 0.0018 | 0.392 to 41.465 | 0.004 to 0.227 | 37 | 37 | 3 |
| Chulitna River below Canyon near Talkeetna, Alaska | 212 to 1,350 | 1.2 to 2.7 | 1.7 to 3.6 | 98.5 to 136 | 0.00039 to 0.011 | 0.744 to 11.273 | 0.006 to 0.500 | 43 | 33 | 0 |
| Susitna River at Sunshine, Alaska | 504 to 2,740 | 1.4 to 2.6 | 0.8 to 4.4 | 174 to 311 | 0.0012 to 0.0024 | 0.436 to 29.440 | 0.006 to 0.175 | 37 | 36 | 3 |
| Snake River near Anatone, Washington | 1180 to 37,770 | 1.9 to 3.3 | 3.9 to 5.8 | 169 to 197 | 0.000087 to 0.00124 | 0.412 to 43.077 | 0.0075 to 0.079 | 31 | 27 | 1 |
| Toutle River at Tower Road near Silver Lake, Washington | 29.2 to 592 | 1.2 to 3.1 | 0.46 to 2.3 | 20 to 70 | 0.0013 to 0.0055 | 0.583 to 20.766 | 0.025 to 0.220 | 19 | 16 | 9 |
| North Fork Toutle River near Kid Valley, Washington | 26.1 to 171 | 1.7 to 2.8 | 0.74 to 1.1 | 20.5 to 59 | 0.0032 to 0.0038 | 3.161 to 9.290 | 0.047 to 0.158 | 5 | 5 | 2 |
| Clearwater River at Spalding, Idaho | 677 to 2,740 | 1.2 to 3.4 | 4.1 to 5.5 | 128 to 146 | 0.000183 to 0.00056 | 0.390 to 27.636 | 0.005 to 0.291 | 35 | 32 | 1 |

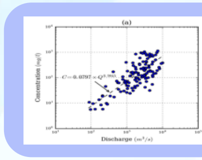
# Sediment Calculations (All Korean Rivers)

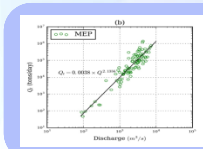
## Process for River Sediment

(Korean team)

Field Measurement Data

Sediment Rating Curve

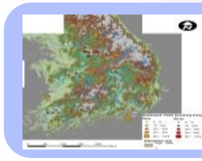


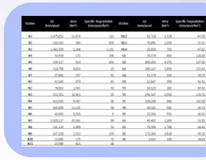


- Q – C relationship
- Q – $Q_T$ relationship

Sediment Yield

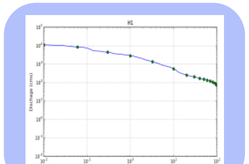
- Suspended sediment
- Total sediment

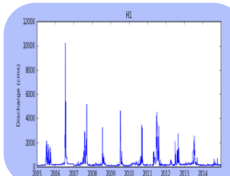




Flow Duration Curve

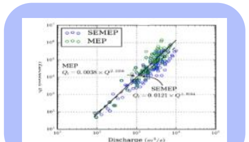
- 10 years data
- Daily discharge





- MEP vs SEMEP

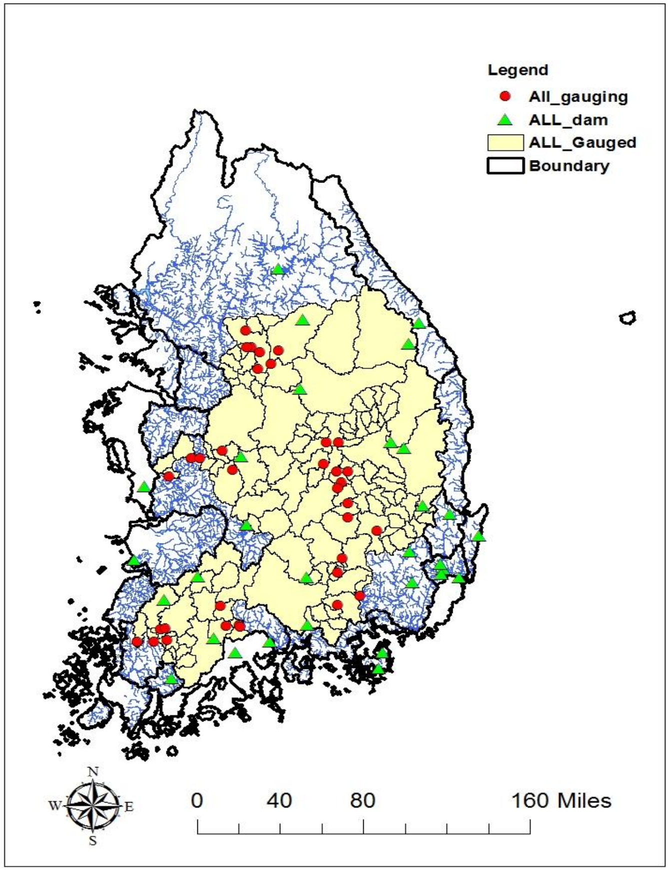
: $U_*/\omega$, $Q_s/Q_t$ ($Q_m/Q_t$), $h_m/h$



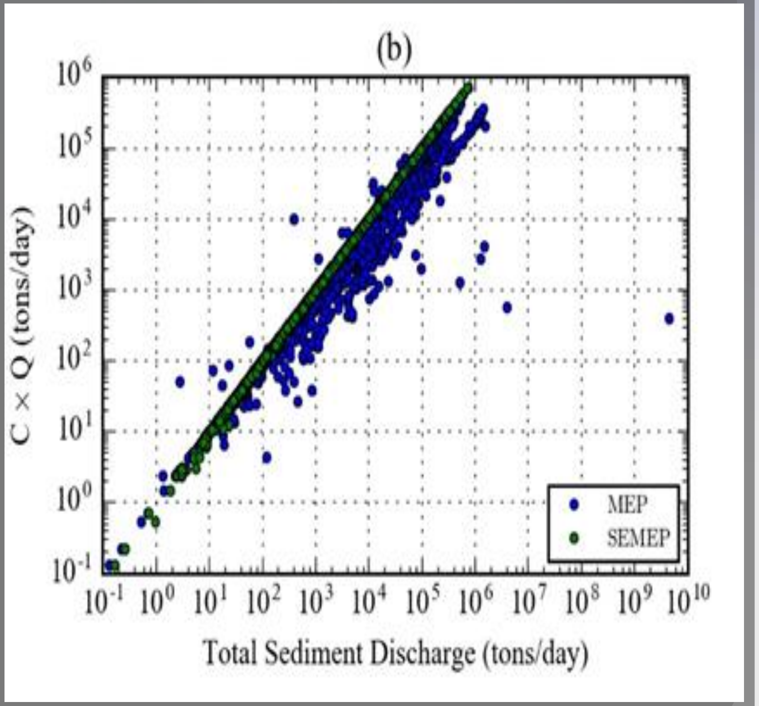
Total Sediment Discharge

# SEMEP vs MEP testing in South Korea

- **35 Gaging stations in South Korea**




**MEP vs SEMEP**



# Sedimentation Engineering

1. Incipient motion
2. SEMEP and SEMEPP
3. Mudflows and Debris Flows

# Physical Properties

Table 10.3. *Physical properties of mudflows and debris flows*

| $C_v$ | $C_w$ | $C_{ppm}$ | $C_{mg/l}$ mg/l | $\rho_m{}^a$ kg/m$^3$ | $\rho_{md}$ kg/m$^3$ | $p_o$ |
|---|---|---|---|---|---|---|
| 0.05 | 0.122 | 122,401 | 132,500 | 1,082 | 132 | 0.95 |
| 0.10 | 0.227 | 227,468 | 265,000 | 1,165 | 265 | 0.9 |
| 0.20 | 0.4 | 398,496 | 530,000 | 1,330 | 530 | 0.8 |
| 0.30 | 0.53 | 531,773 | 795,000 | 1,495 | 795 | 0.7 |
| 0.40 | 0.64 | 638,554 | 1,060,000 | 1,660 | 1,060 | 0.6 |
| 0.50 | 0.73 | 726,027 | 1,325,000 | 1,825 | 1,325 | 0.5 |
| 0.60 | 0.8 | 798,994 | 1,590,000 | 1,990 | 1,590 | 0.4 |
| 0.70 | 0.86 | 860,789 | 1,855,000 | 2,155 | 1,855 | 0.3 |

[a] Calculations assuming $G = \rho_s/\rho = 2.65$

# 1. Rheology

# Classification and Rheology

Total shear stress :

$$\tau = \tau_y + \tau_v + \tau_t + \tau_d$$

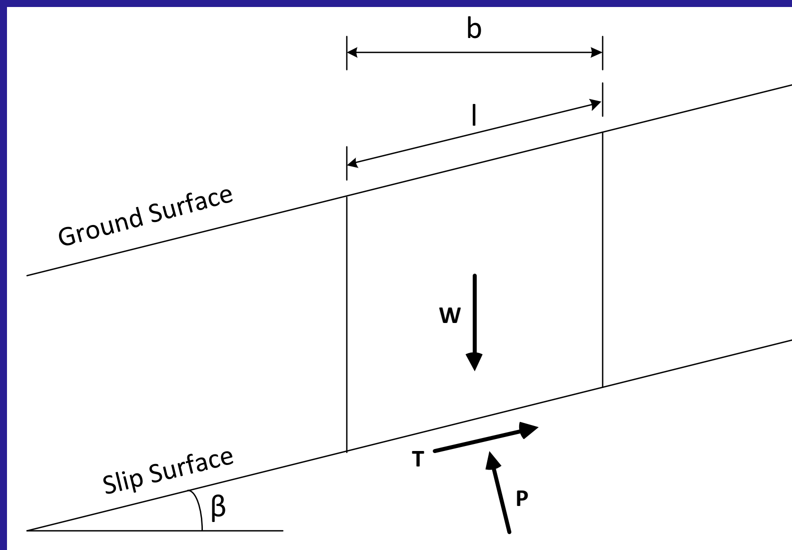
Yield stress

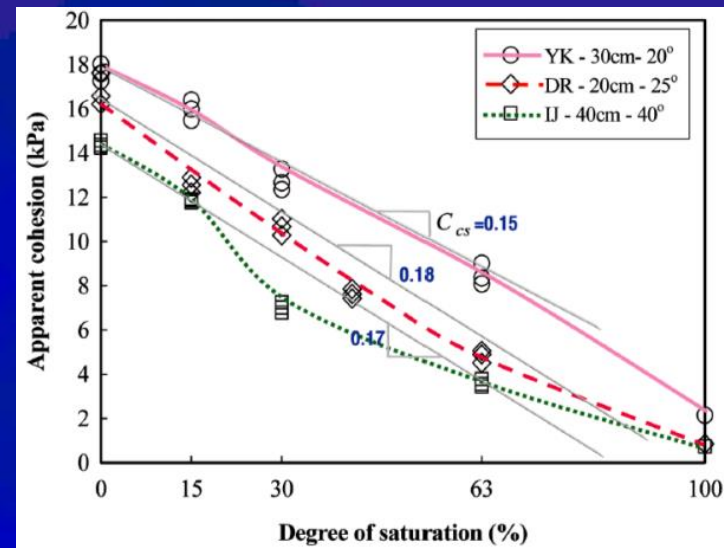
Viscous stress

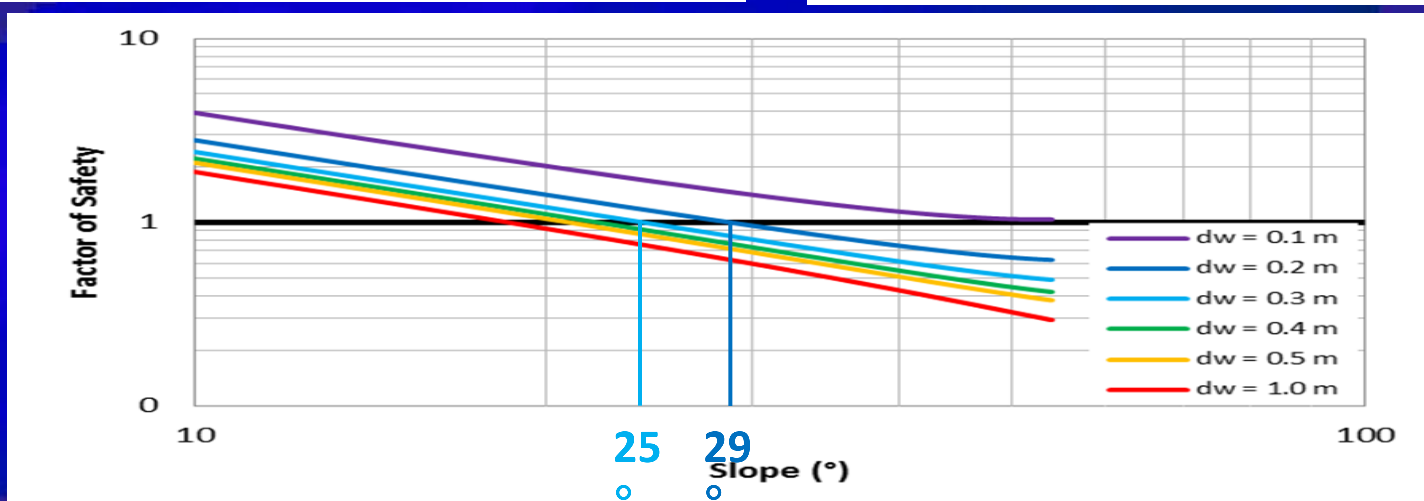
Turbulent stress

Dispersive stress

# Yield Strength for Landslides



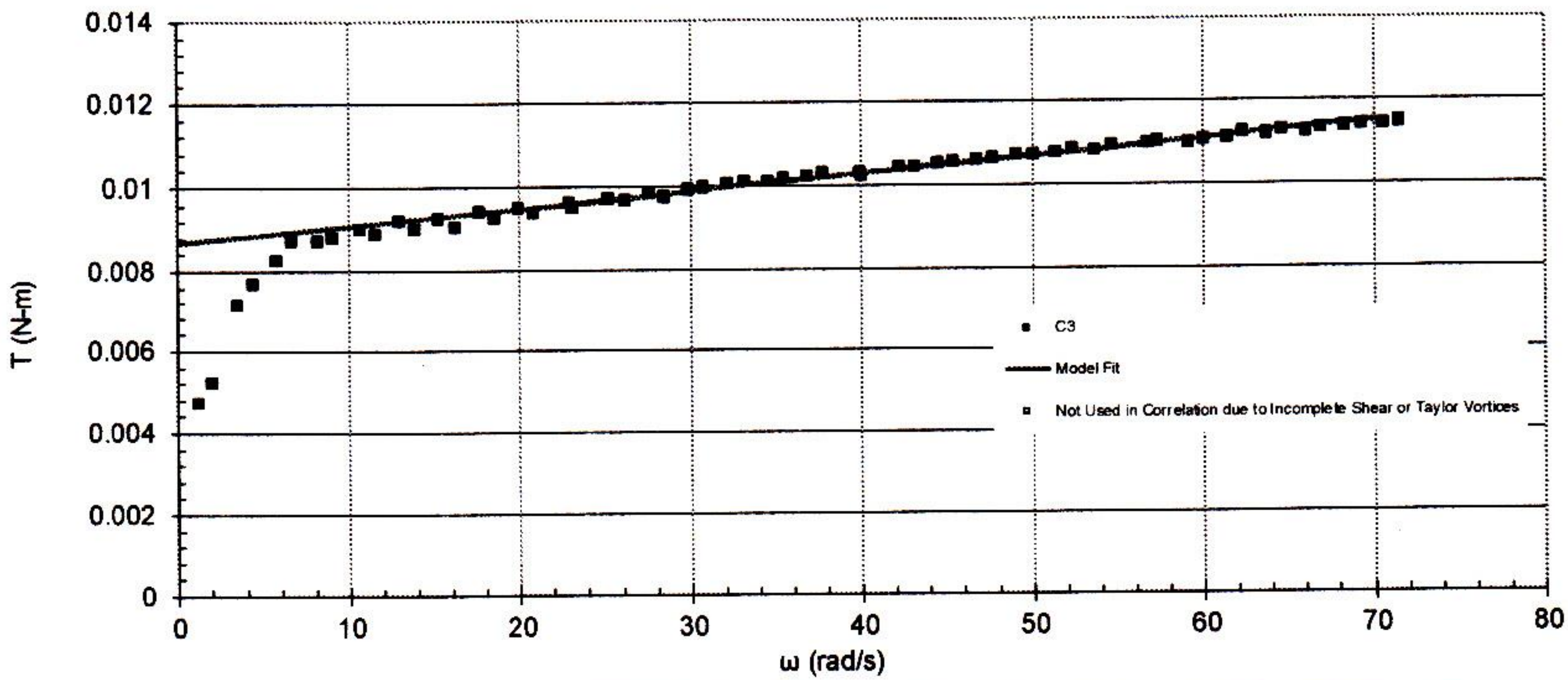



# Viscometer Test

| r Data | Project Manager: MB | | Project No: STA-31-1152 |
|---|---|---|---|
| | Sample ID: | FT-03 | |

| | | | |
|---|---|---|---|
| | | Measure device | Haake VT550 (ViscoTester VT550) |
| | | Sensor: MVIII | |
| | | A-factor (Pa/Nm) | 11100 |
| | | M-factor (1/s)/(rad/s) | 4.202 |
| Plastic Viscosity (Pa.s) | 0.110 | R rotor (mm) | 15.2 |
| Bingham Yield Stress( Pa) | 73.5 | R cup (mm) | 21.0 |
| C Mixture Density, Slurry (kg/ | 2,434 | L rotor (mm) | 60.0 |



# Rheogram

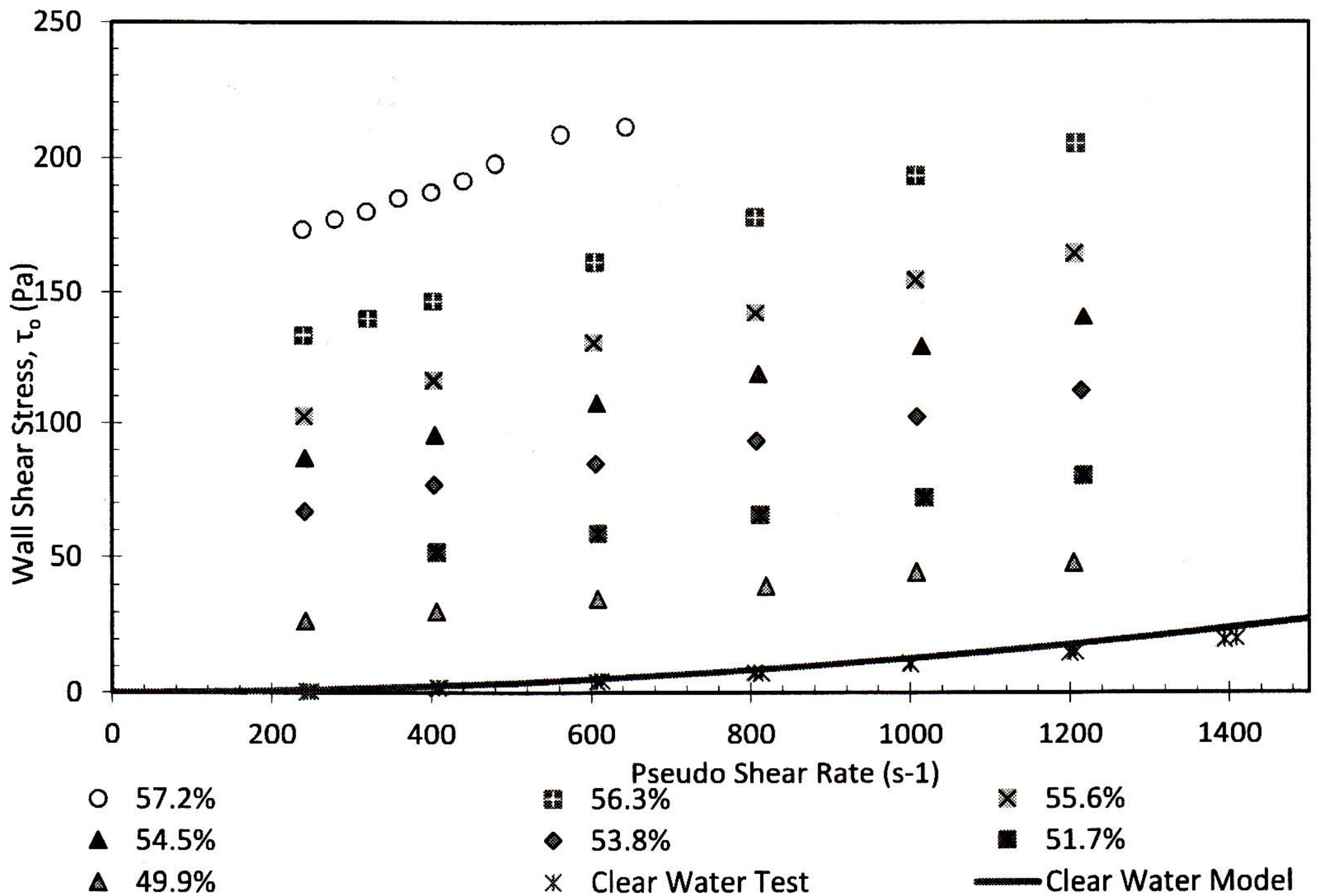



*Figure 11: FT-02 Pseudo-Shear Diagram*

# Yield and Viscosity of Mudflows

## Mudflow Rheology

$$\tau = \tau_y + \mu_m \frac{dv}{dy}$$

$\tau_y$ *is the yield stress*

$\mu_m$ *is the dynamic viscosity (water at* $0.001\ Pa.s$*)*

$dv/dy$ *is the velocity gradient (typically* $1-10\ s^{-1}$*)*

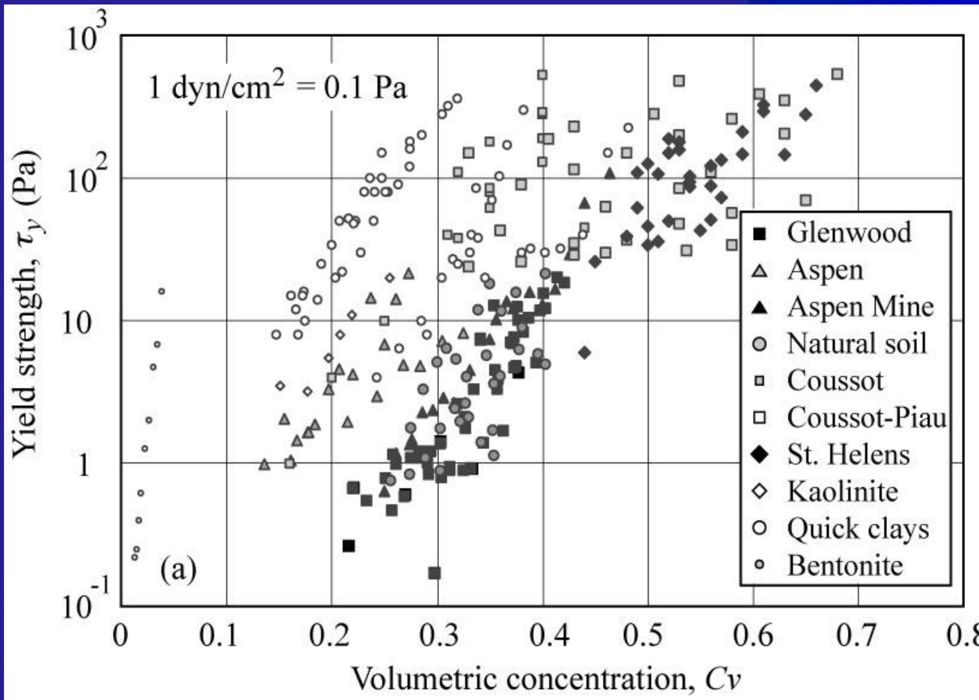



Figure 10.13a. Yield strength versus volumetric concentration

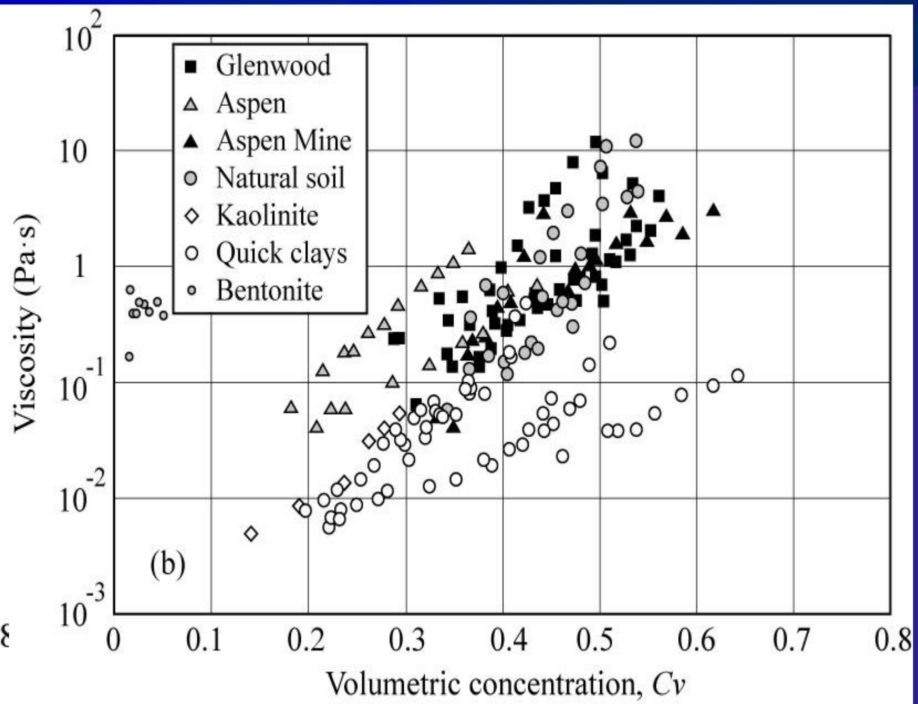


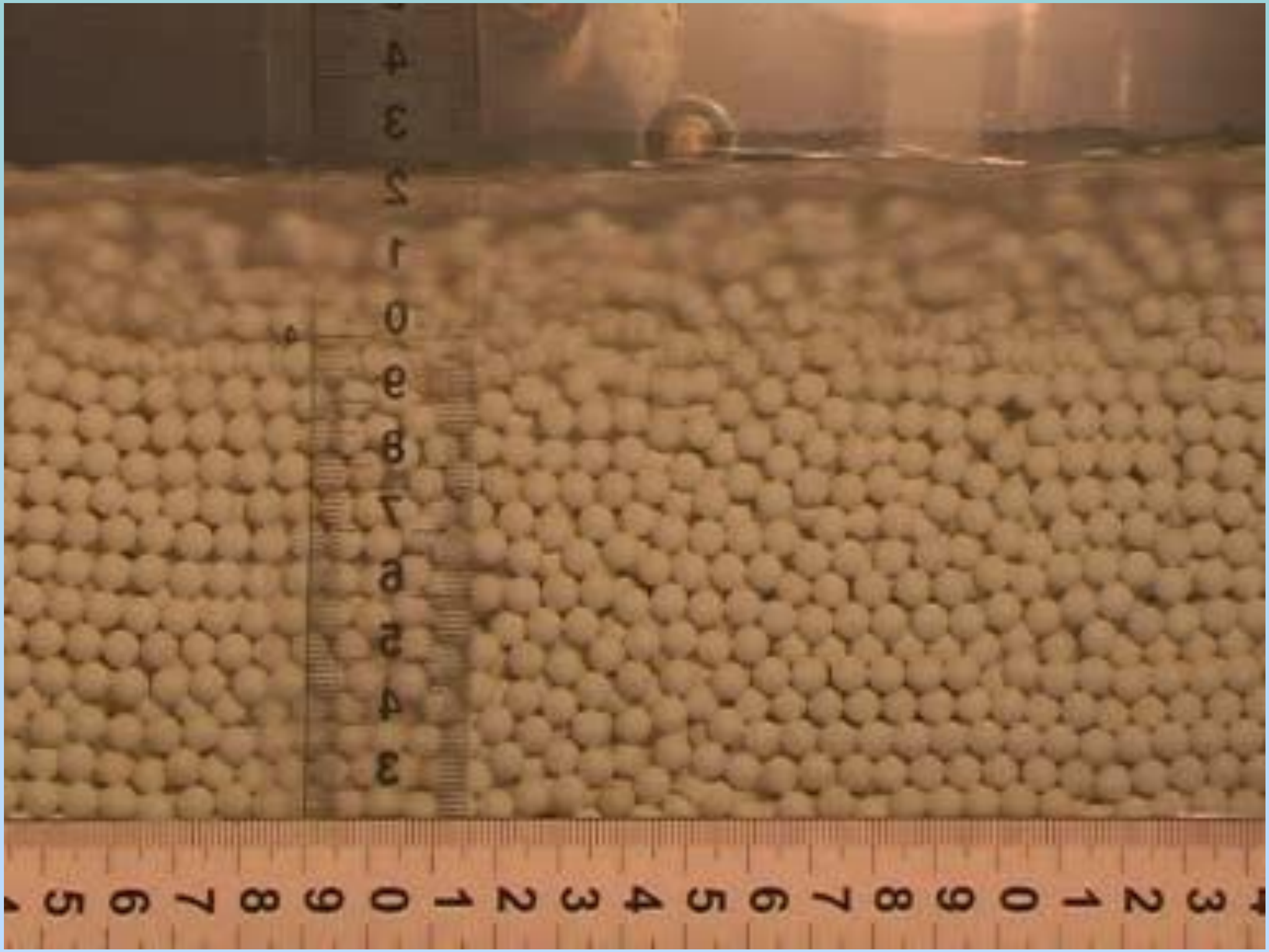

Figure 10.13b. Dynamic viscosity versus volumetric concentration


Veja o momento exato do rompimento da barragem da Vale
Jornal Hoje
25/01/2019 12:28:32
ST-01
00:13 / 02:17

# Turbulence

# EXPERIMENTAL ANALYSIS

VIDEO FOOTAGE from Anna Paris and Aronne Armanini (U. Trento)



# Rheology of Debris Flows

## Debris flow Rheology

$$\tau = \tau_y + \mu_m \frac{dv}{dy} + \varsigma \left(\frac{dv}{dy}\right)^2 \quad \textit{quadratic model}$$

$$\varsigma = \rho_m l_m^2 + c_{Bd} \rho_s \lambda^2 d_s^2 \quad \textit{turbulent-dispersive parameter}$$

where

$\rho_m$ *is the mass density of the hyper-concentration*

$l_m$ *is the mixing length, (*$l_m = \kappa y$ *from elevation y and von Karman constant* $\kappa \cong 0.4$*). Note that the mixing length is scaled to the flow depth*

$c_{Bd}$ *is the Bagnold coefficient (*$c_{Bd} \simeq 0.01$*)*

$\rho_s$ *is the mass density of solids*

$$\lambda = \left(\left(\frac{0.615}{C_v}\right)^{1/3} - 1\right)^{-1}$$ *is Bagnold's linear concentration given the volumetric concentration* $C_v$*, and*

$d_s$ *is the grain size.*

*The dispersive term requires three condition: (1) very high concentration, i.e.* $C_v > 0.5$*; (2) very large sediment where h is the flow depth; and (3)high rates of deformation, i.e. large* $dv/dy$*.*

*As a result, the turbulent term is dominant unless ds>h/20.*

# Turbulent or Dispersive?

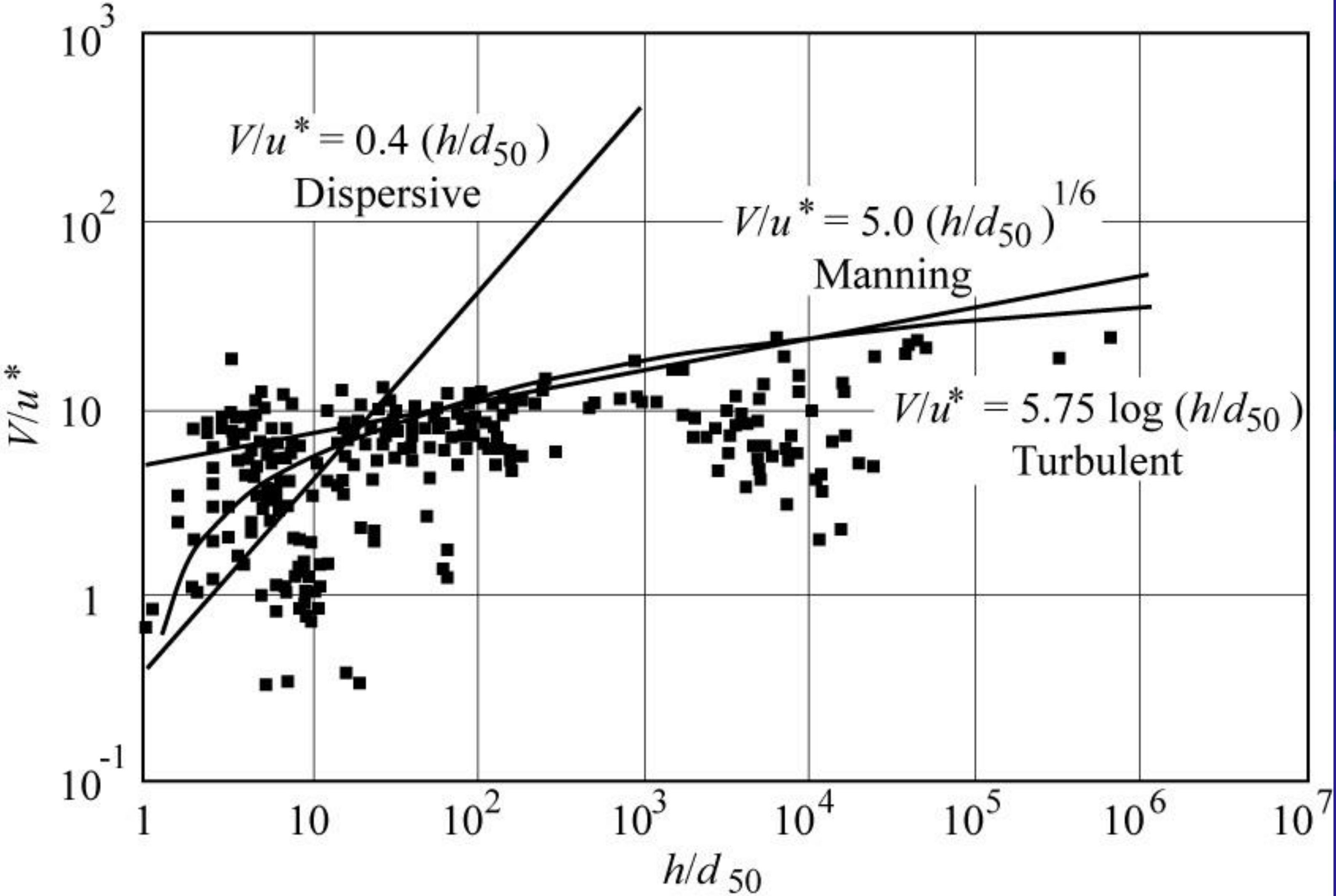



Figure 10.16. Resistance diagram for hyperconcentrated flows.

# Mitigation Countermeasures

Guidelines for designing mitigation countermeasures based on the type of hyperconcentrated flow

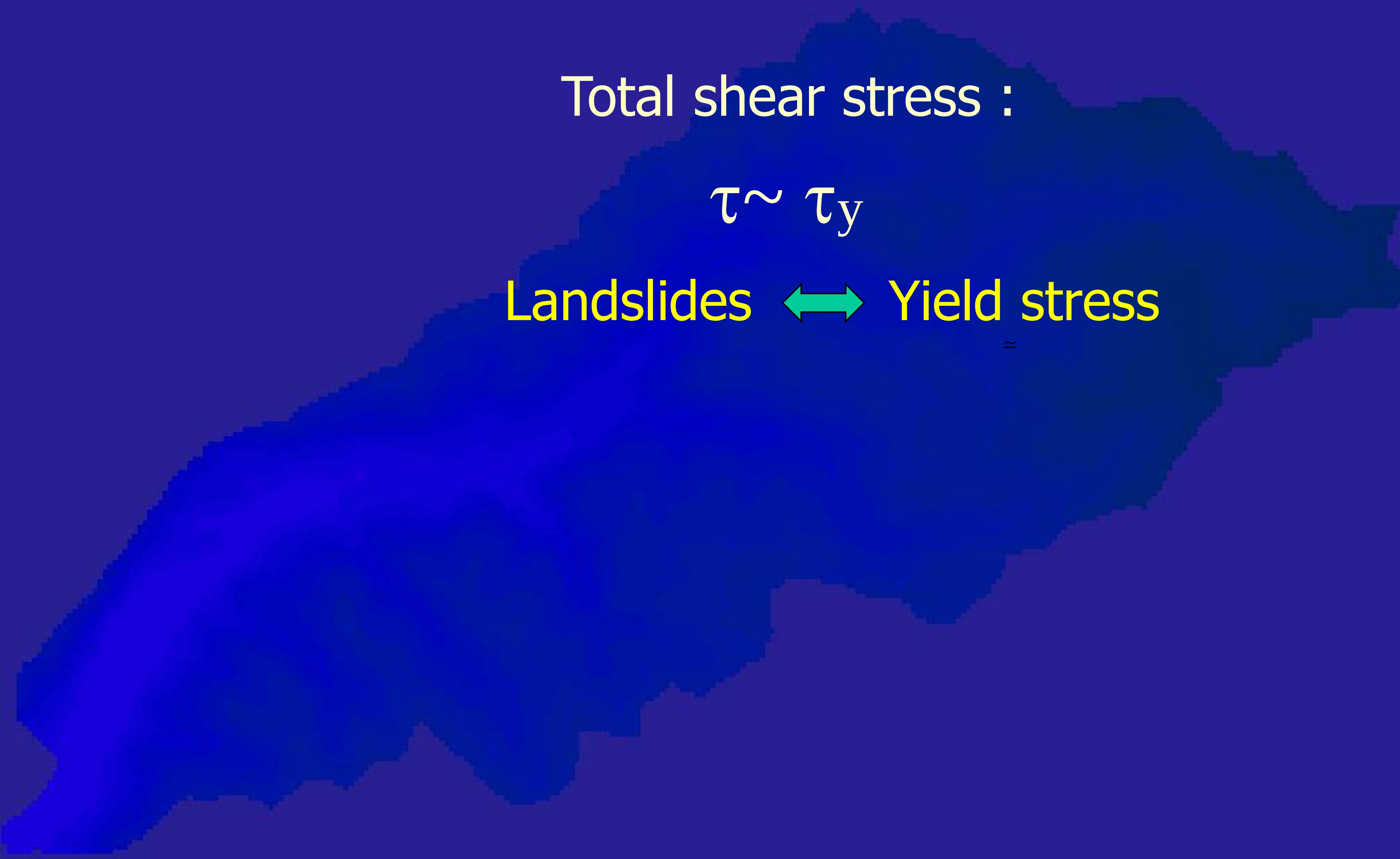
# 2. Landslides

# Yield Stress -> Landslides

Total shear stress :

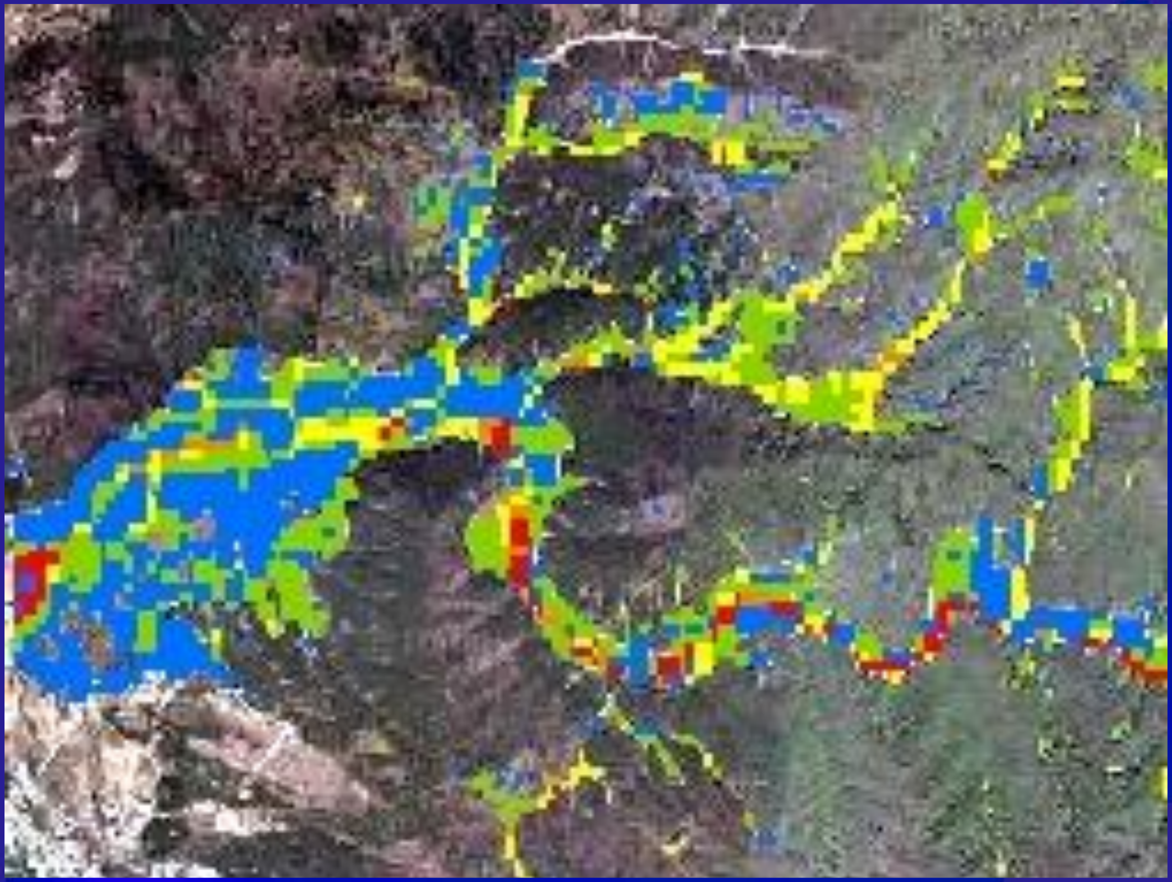
$$\tau \sim \tau_y$$

Landslides ⟺ Yield stress



# Mangun mountain, South Korea

# Landslides



- Steep hillslopes
- High rainfall precipitation
- High Infiltration
- Saturated yield strength ~ 1kPa

# Countermeasures

## Landslide Features:

- High precipitations and infiltration
- Steep terrain
- Saturated yield strength ~ 1kPa

## Effective Solution → Drain, Slope Reduction, Vegetation

- Terraces
- Improved drainage

# Landslide Countermeasures

**Effective Solution** ➡ **Slope reduction, drain, vegetation**

- Terraces
- Drainage

# 3. Mudflows

# Yield + Viscous -> Mudflows

Total shear stress :

$$\tau = \tau_y + \tau_v$$

Mudflow ⟺ Yield stress

Viscous stress

# Mudflow

- High viscosity and yield stress
- High concentration of silts and clays
- 45% < Cv < 55%
- Low velocity
- Low Froude Number
- No abrasion
- Large flow depths
- High pressure

# Countermeasures

## Mudflow Features:

- High viscosity and yield stress
- High concentration of silt and clay
- $45\% < C_v < 55\%$
- Low Froude Number
- No abrasion

Effective Solution → Store, Deflect, Spread

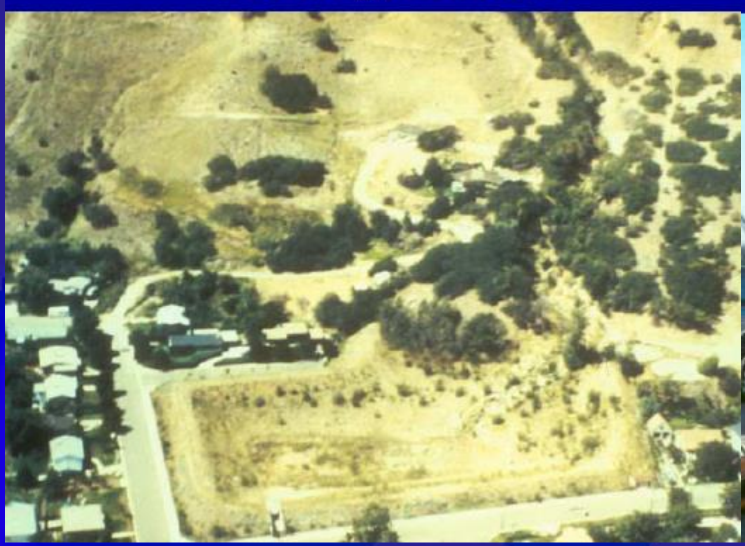
- Storage basins
- Deflection walls

# Mudflow Countermeasures

**Effective Solution** ➡ **Store, Deflect, Spread**

- Storage basins
- Deflection walls

Storage Basin



Deflection Wall

# 4. Mudfloods

# Turbulence -> Mudfloods

Total shear stress :

$$\tau = \tau_y + \tau_v + \tau_t$$

Yield stress

Viscous stress

Mudfloods ⟺ Turbulent stress

# Mud Flood

- Turbulent
- Non-cohesive particles
- Small particles
- Cv as high as 40%
- High velocity
- High Froude Number
- Abrasive

# Straight Channel

# Countermeasures

## Mud Flood Features:

- Turbulent
- Non cohesive particles
- Cv as high as 40%
- High Froude Number
- Abrasive

## Effective Solution ➡ Convey

- Straight channels
- Lined canals, berm and levee channels
- Drop structures, energy dissipators

# Mudflood Countermeasures

**Effective Solution** ➡ **Increased conveyance**

- Straight channel
- Lined canal
- Berm and levee
- Drop structure

Lined canal with drop structures

Straight Channel

# 5. Debris Flows

# Dispersive -> Debris Flows

Total shear stress :

$$\tau = \tau_y + \tau_v + \tau_t + \tau_d$$

Landslides ⟺ Yield stress

Mudflows ⟺ Viscous stress

Mudfloods ⟺ Turbulent stress

Debris flows ⟺ Dispersive stress

# Los Corales

# Los Corales

# Los Corales

# Debris Flow

- Dispersive
- Large clastic particles
- Non cohesive
- Low viscosity
- High velocity
- Destructive impact force

# Countermeasures

Debris Flow Features:

- Dispersive
- Large clastic particles
- Low viscosity
- Large velocity
- High impact

Effective Solution $\Rightarrow$ Retain large clasts
Drain fluid matrix

- Concrete Sabo dams
- Steel frames and debris rakes

# Debris flow Countermeasures

**Effective Solution** ➡ **Retain large rocks**
**Drain water**

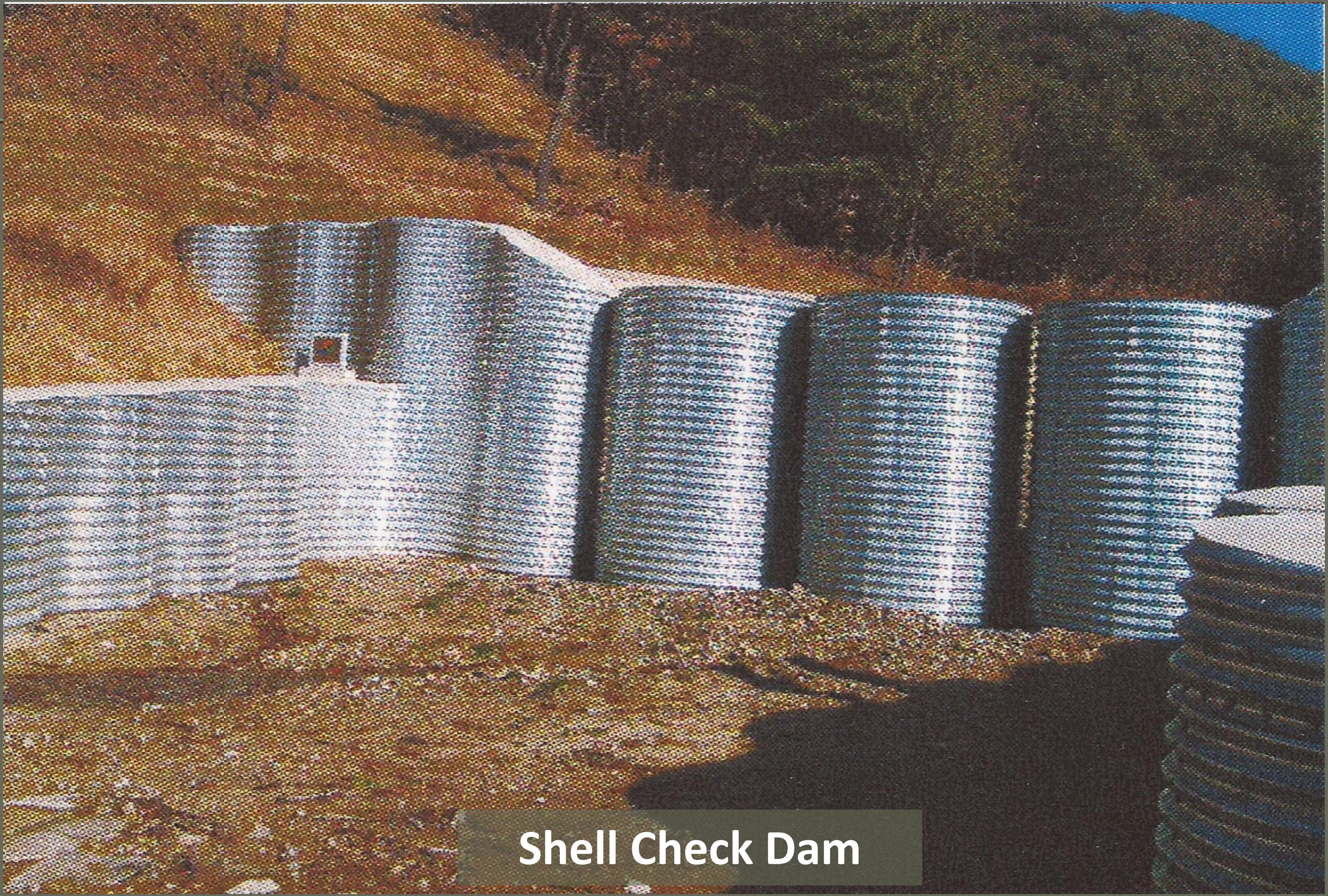
- Concrete sabo dams
- Steel Frames
- Debris Racks

Sabo Dam and Steel Frames

Sabo Dam Construction

Debris Rakes

# Sabo Dam and Steel Frames


Shell Check Dam

# Classification and Rheology

Total shear stress :

$$\tau = \tau_y + \tau_v + \tau_t + \tau_d$$

Landslides ⟺ Yield stress

Mudflows ⟺ Viscous stress

Mudfloods ⟺ Turbulent stress

Debris flows ⟺ Dispersive stress

# Conclusions

- Mitigation structures for mudflows
  - » Detention basins
  - » Deflection walls
- Mitigation structures for mud floods
  - » Straight channels
  - » Lined canals, berm and levee channels
  - » Drop structures, energy dissipators
- Mitigation structures for debris flows
  - » Concrete Sabo dams
  - » Steel frames and debris rakes

# 6. Example (Quiz?)
# Mt Umyeon


특집 뉴스라인
집중호우 강타


Sovico

# Summary and Conclusions

## 1. Incipient Motion

*Incipient motion depends on ratio of moments, not forces.*

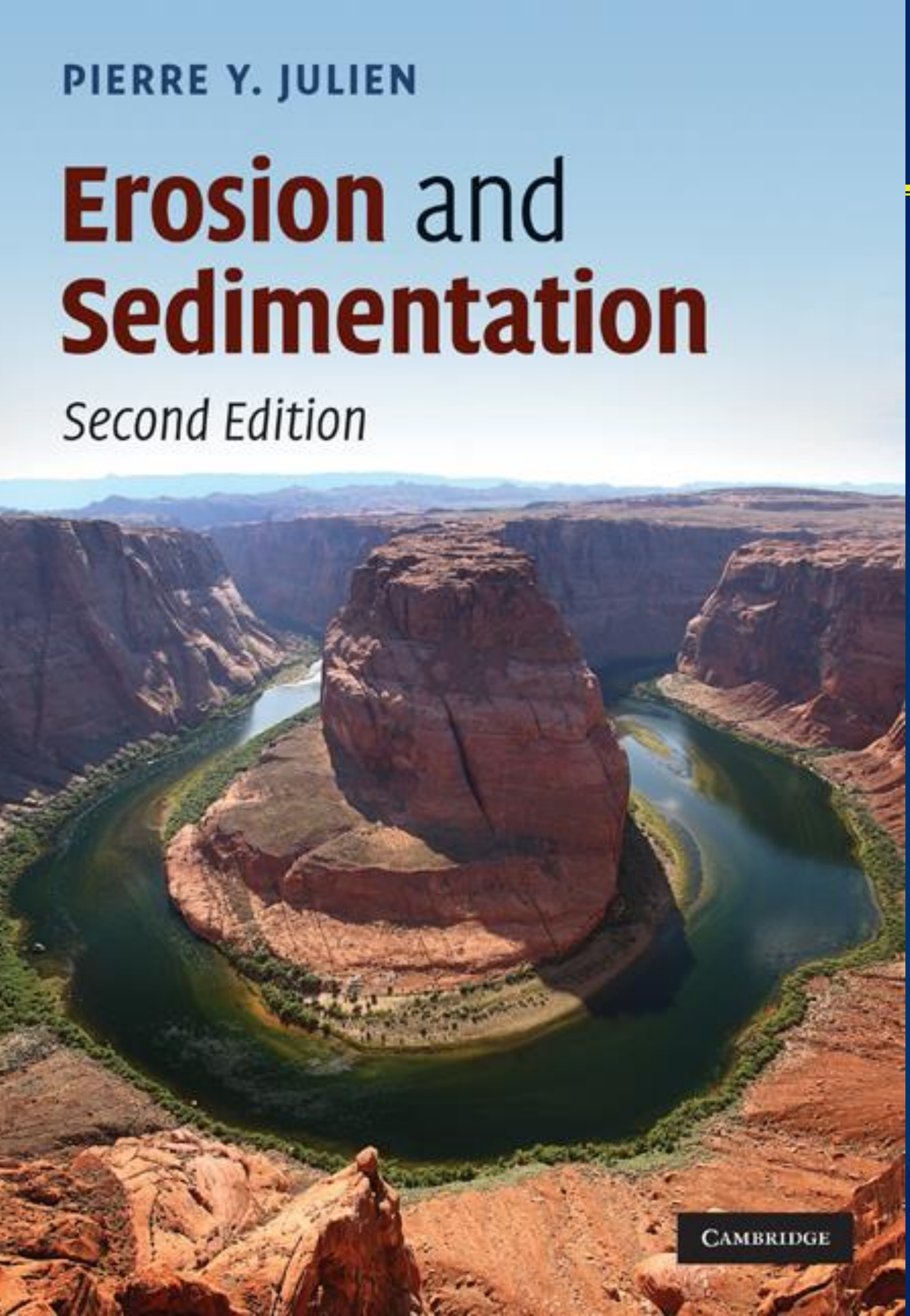
## 2. SEMEP and SEMEPP

*The Einstein integrals are accurately solved numerically.*

## 3. Mudflows and Debris Flows

*The flow type depends on flow rheology.*

*Effective countermeasures depend on the rheology.*




# Thank You!

***ACKNOWLEDGMENTS***

Dr. Bounthanh Bounvilay, Laos
Dr. Claudio Meier, Chile
Dr. Junke Guo, UNO, USA
Dr. Seema Shah-Fairbank, CalPoly
Dr. Chunyao Yang, HydroTech, USA
Dr. Jimmy O'Brien, FLO, USA
Carmen Bernedo, Stantec, Peru
Anna Paris, Maccaferri, USA
Dr. Jaihong Lee, SCSU, USA
Dr. Jose B. Anderson, Brasil
Dr. Neil Andika, Indonesia
Dr. Claudia Leon, USBR
Anna Paris, Maccaferi, Italy
Dr. Jaehoon Kim, KFRI, S. Korea

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