Sedimentation Engineering

Pierre Y. Julien

Colorado State University

USBR Lectures – Part II

Denver, Colorado

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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

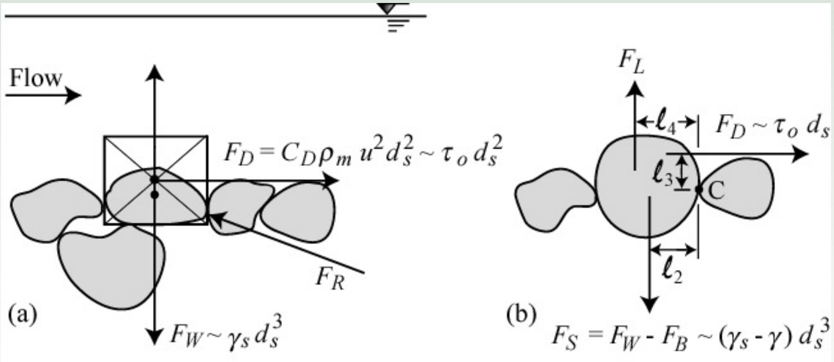
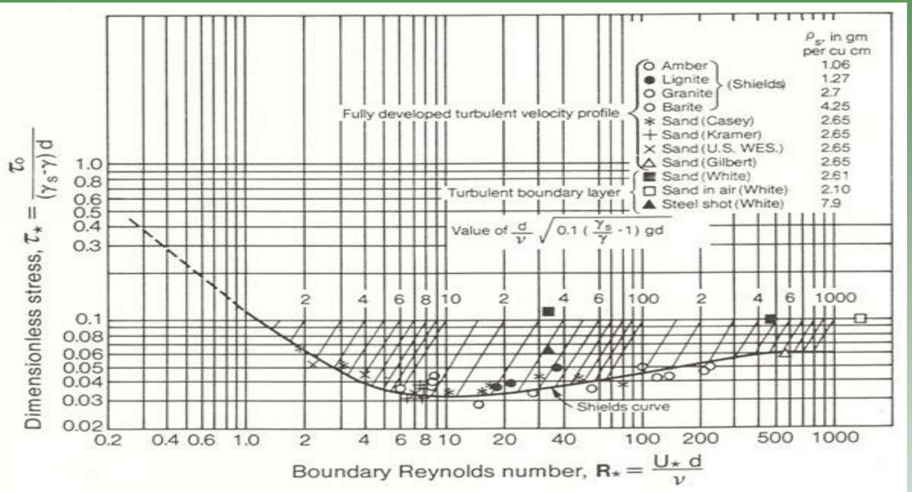


Figure 7.6. Force diagram under steady uniform flow

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



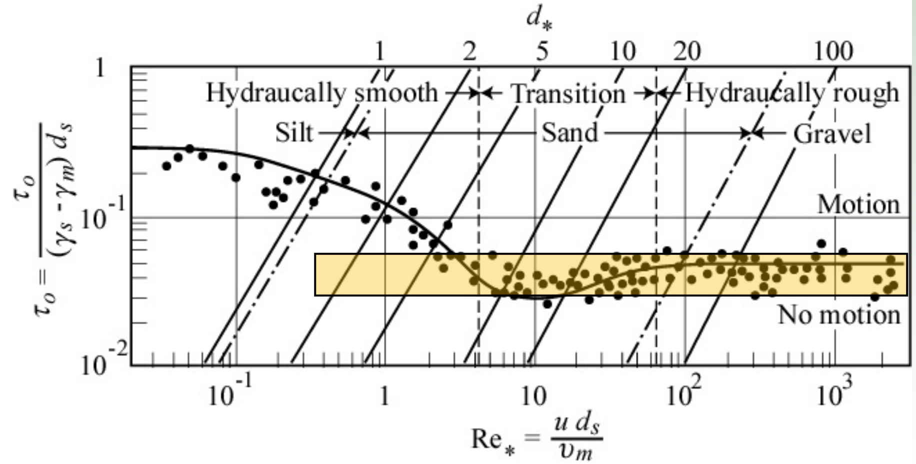
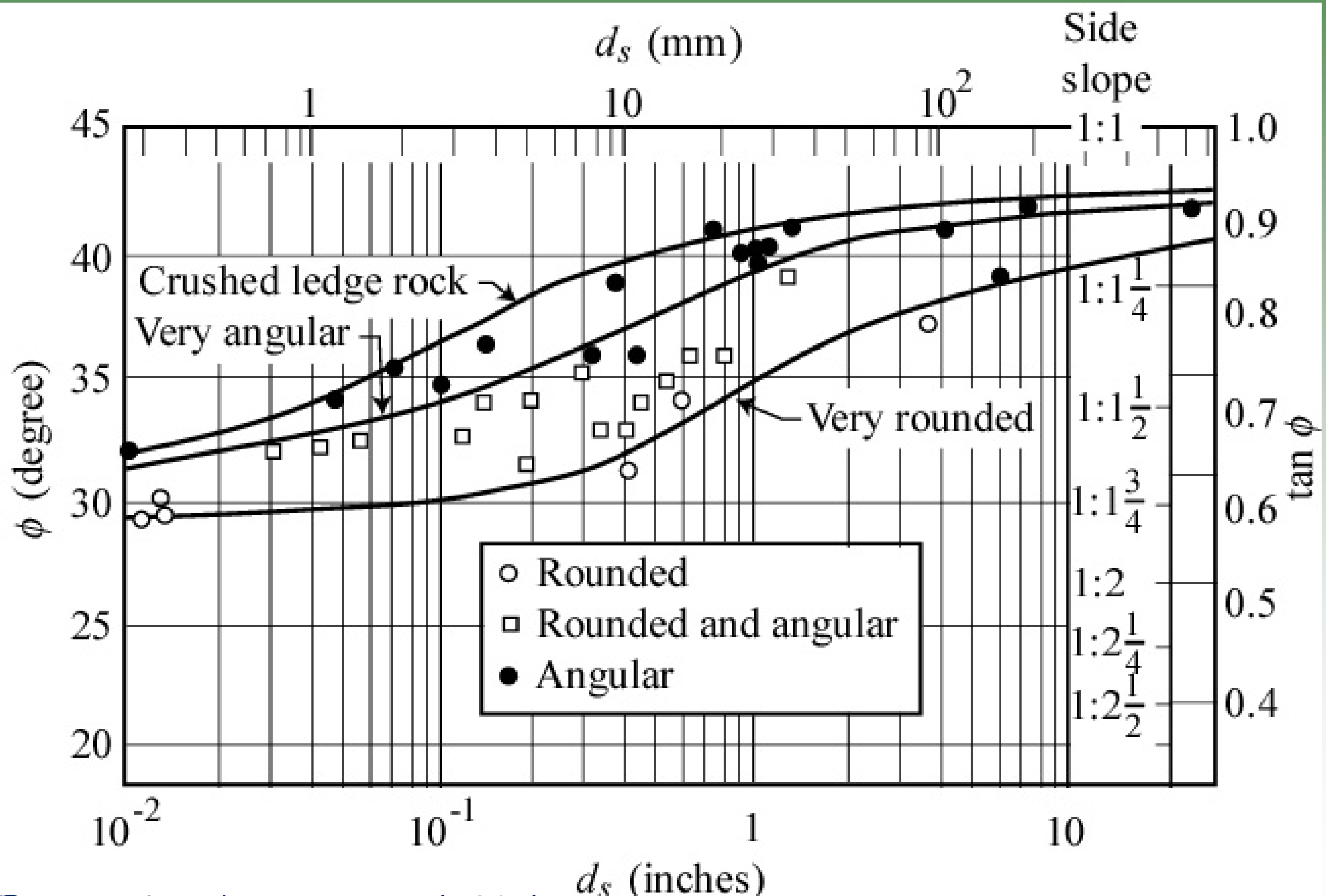


Figure 7.7. Shields diagram for granular material

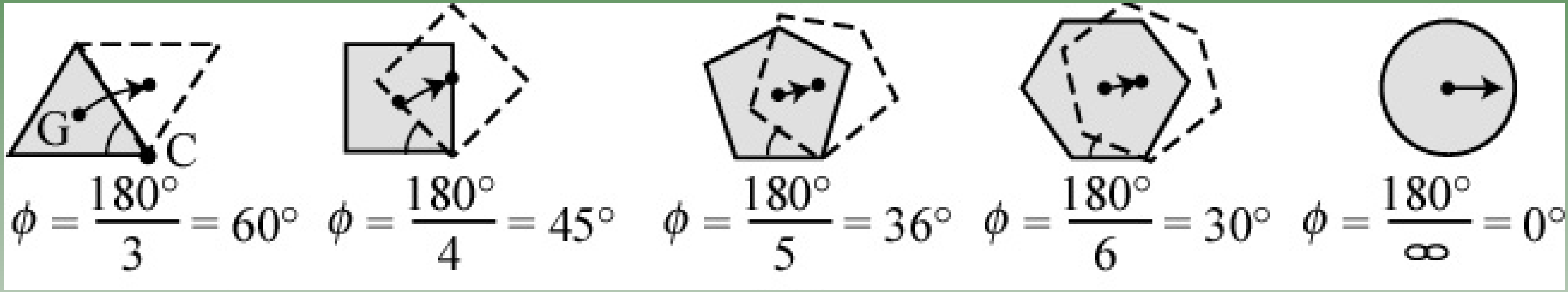
Julien Erosion &Sedimentation (2012)

Angle of Repose
Granular Material

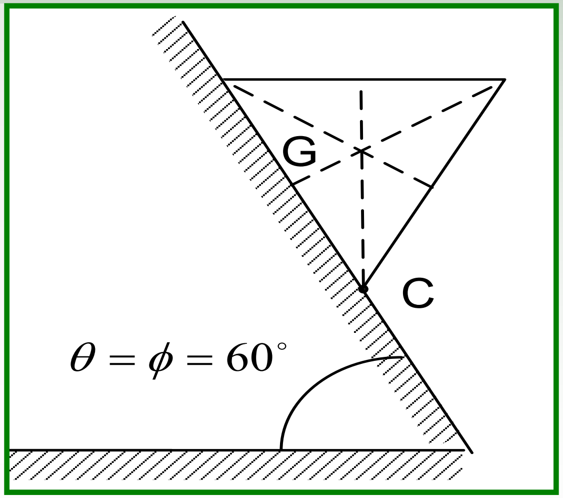


Julien Erosion &Sedimentation (2012)

Angle of Repose
Effects of Angularity

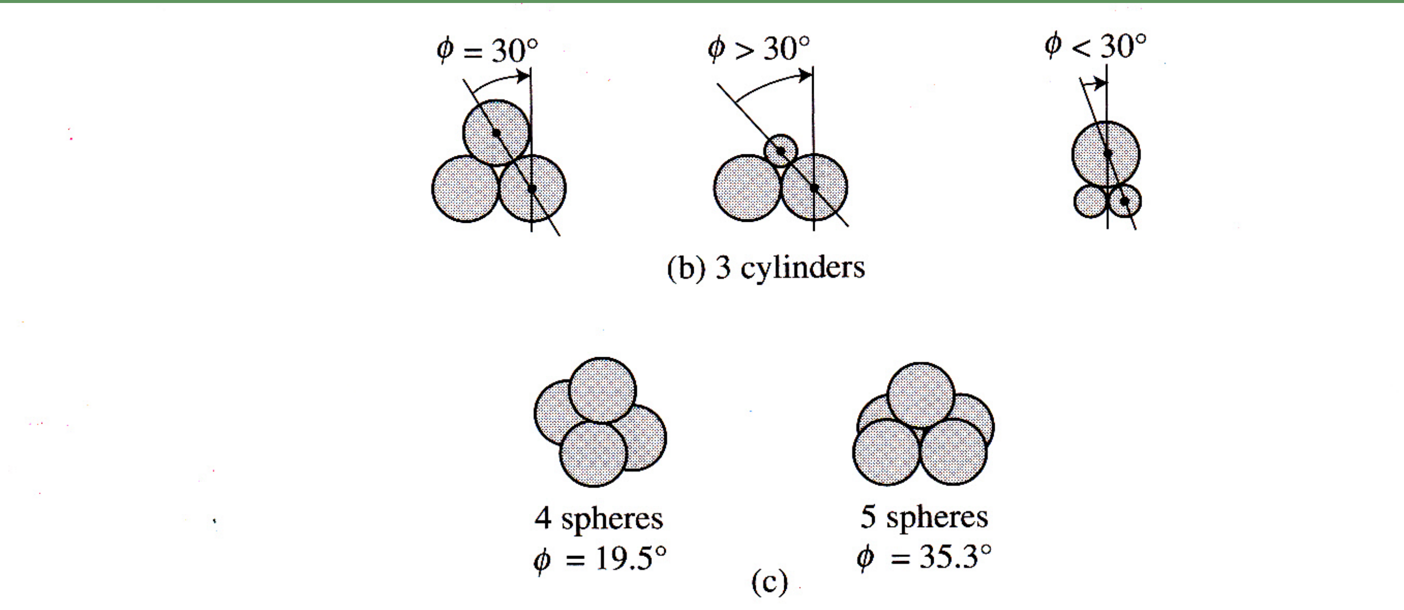


Motion occurs when the center of gravity (G), is above the point of contact (C).



Julien Erosion &Sedimentation (2012)

Angle of Repose
Boundary and Particle Configuration



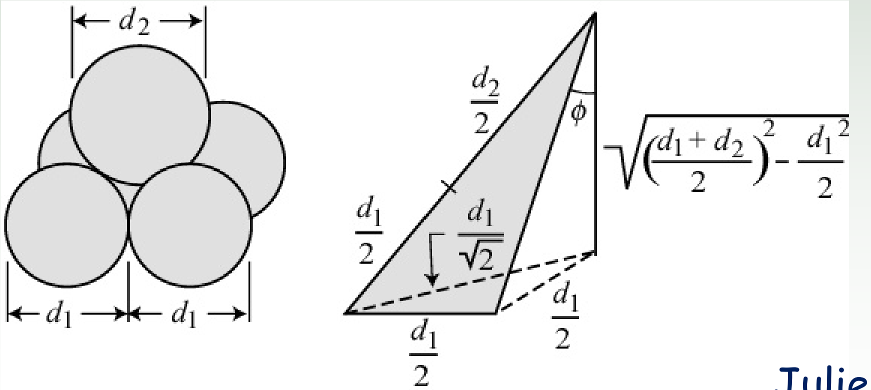


Figure 7.3. Angle of repose for spheres of different diameter

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

Julien Erosion &Sedimentation (2012)

Angle of Repose
Boundary and Particle Size

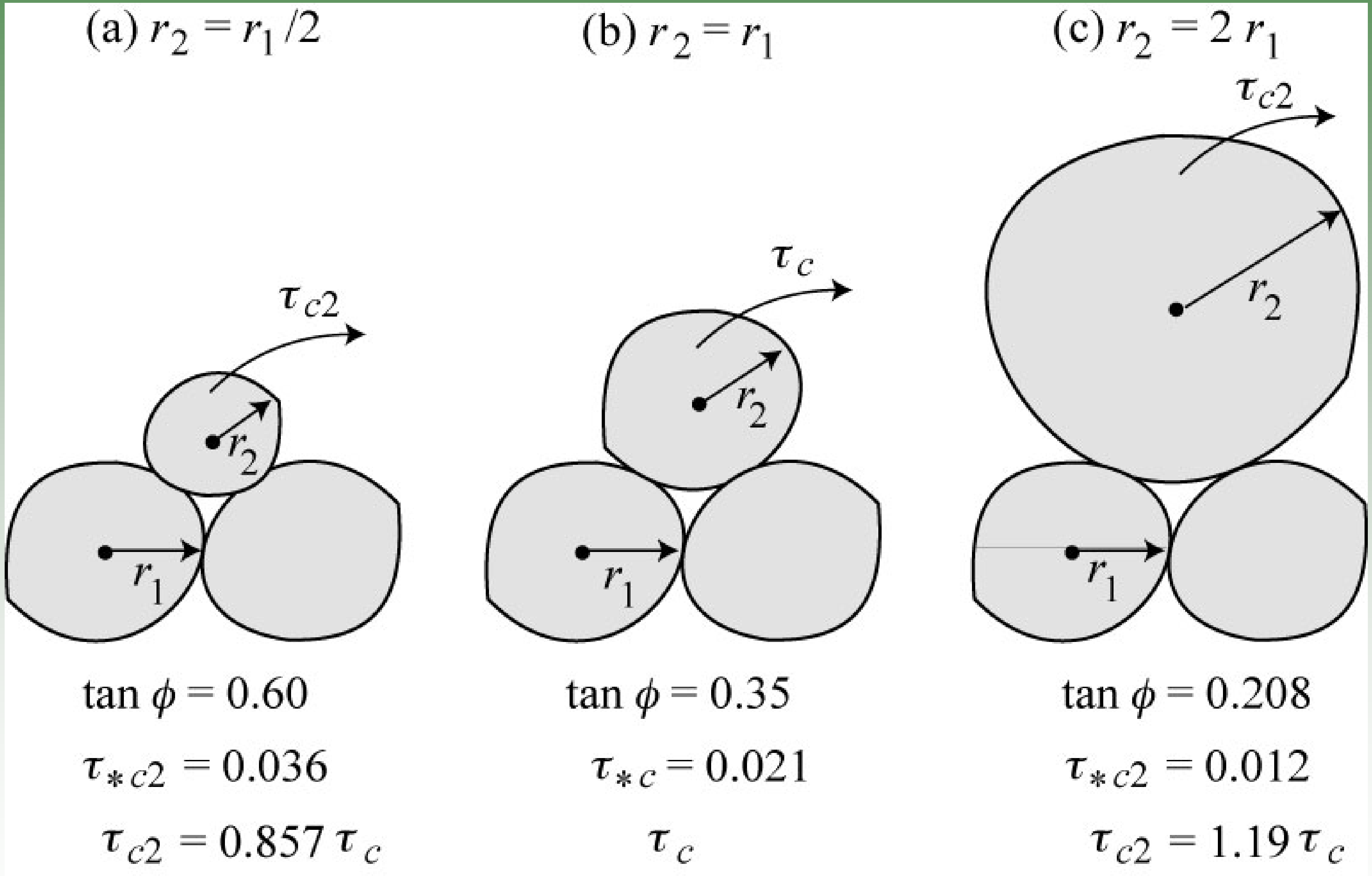
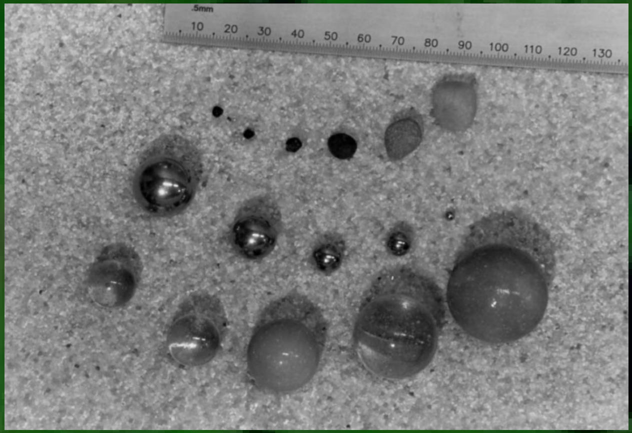
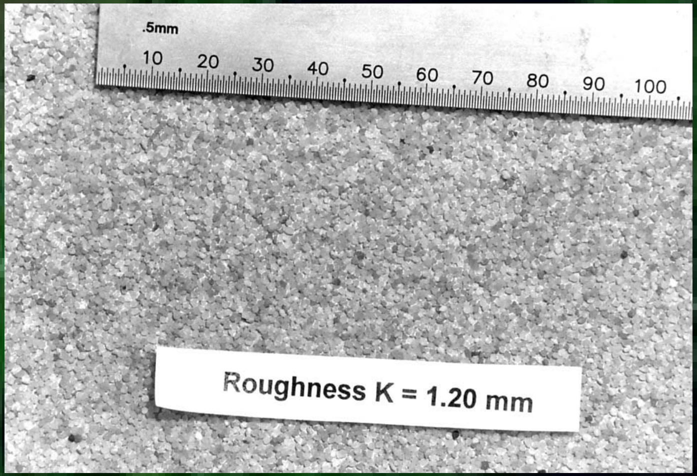


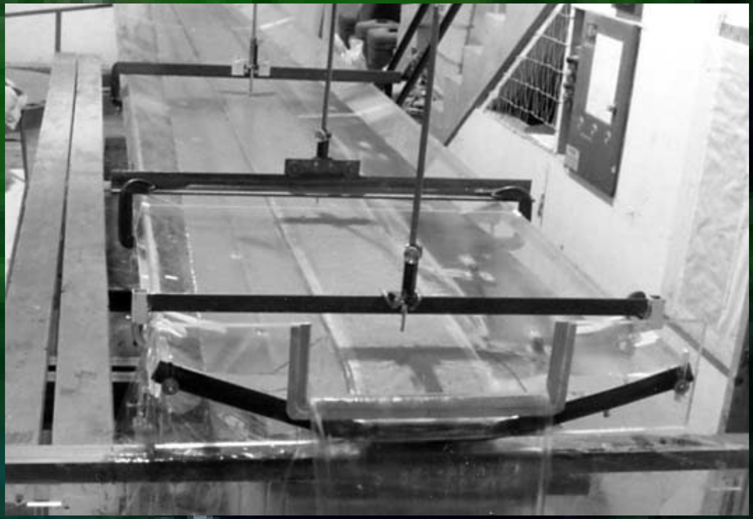
Figure 7.12. Relative stability for different particle sizes

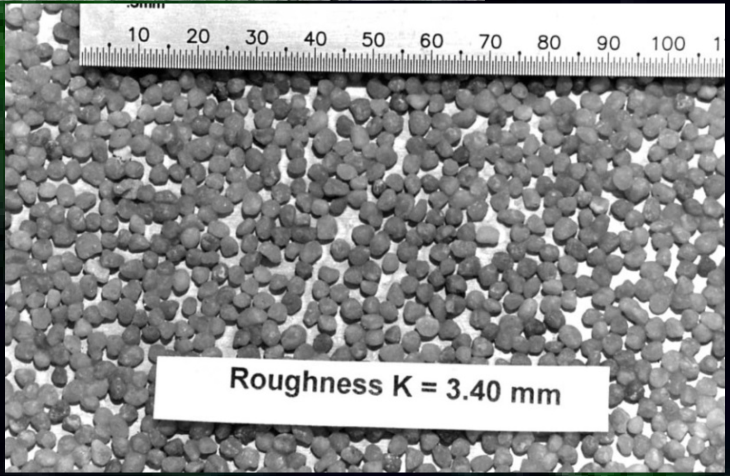
Laboratory experiments at CSU





~10,000 particle velocity measurements





Bounvilay and Julien, ASCE-JHE (2013)

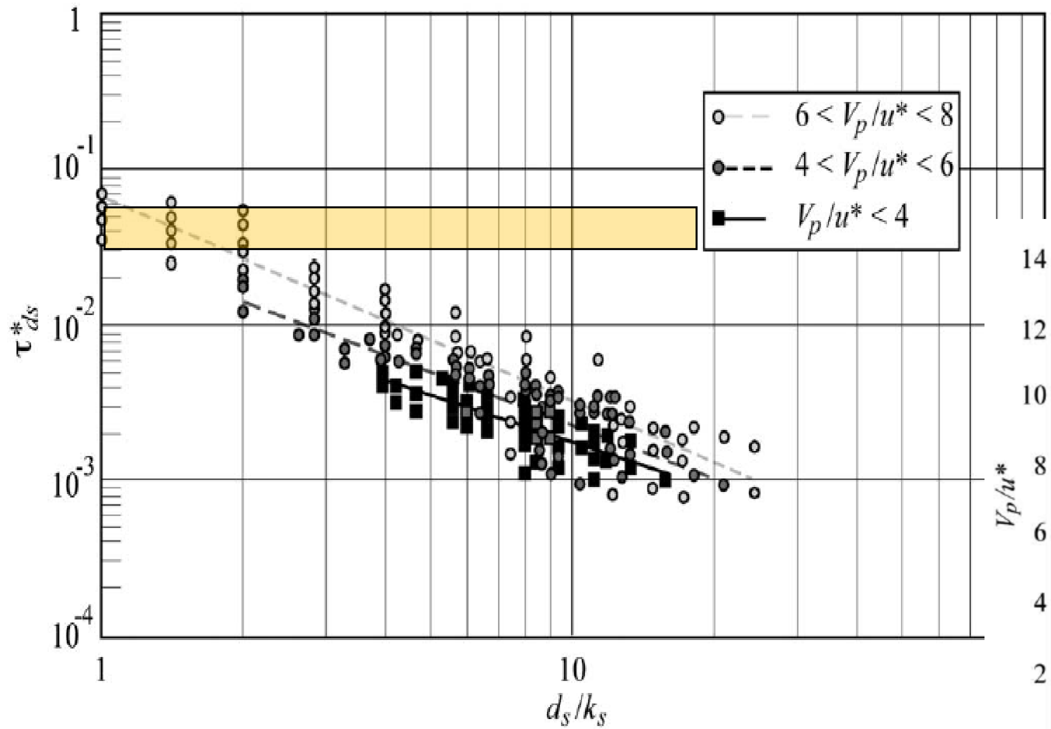
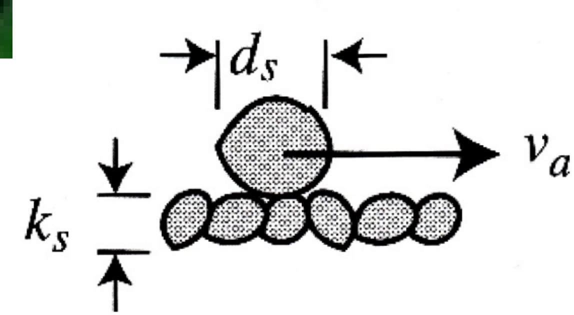
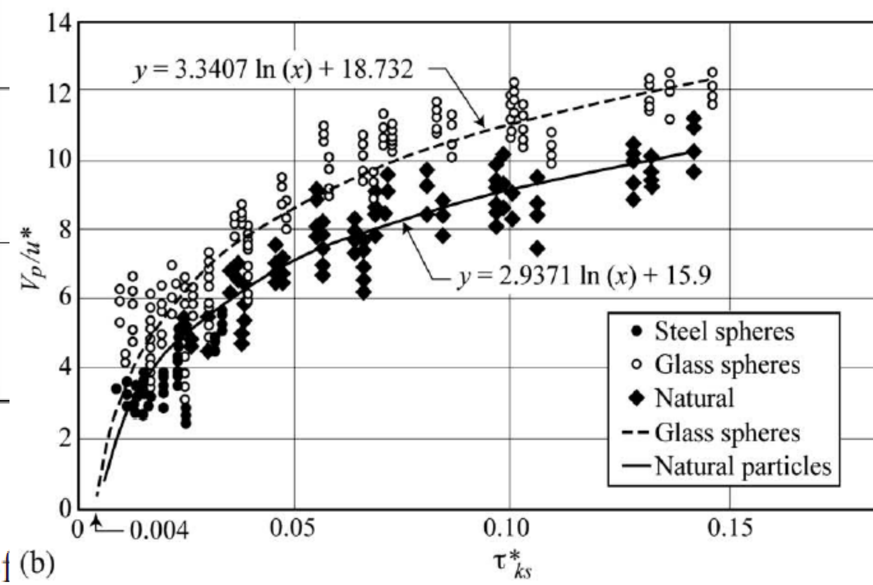


Fig. 9. Shields parameter τ^*_{ds} vs d_s/k_s for different values of V_p/u_*





Bounvilay and Julien
ASCE-JHE (2013)

Lets remember:

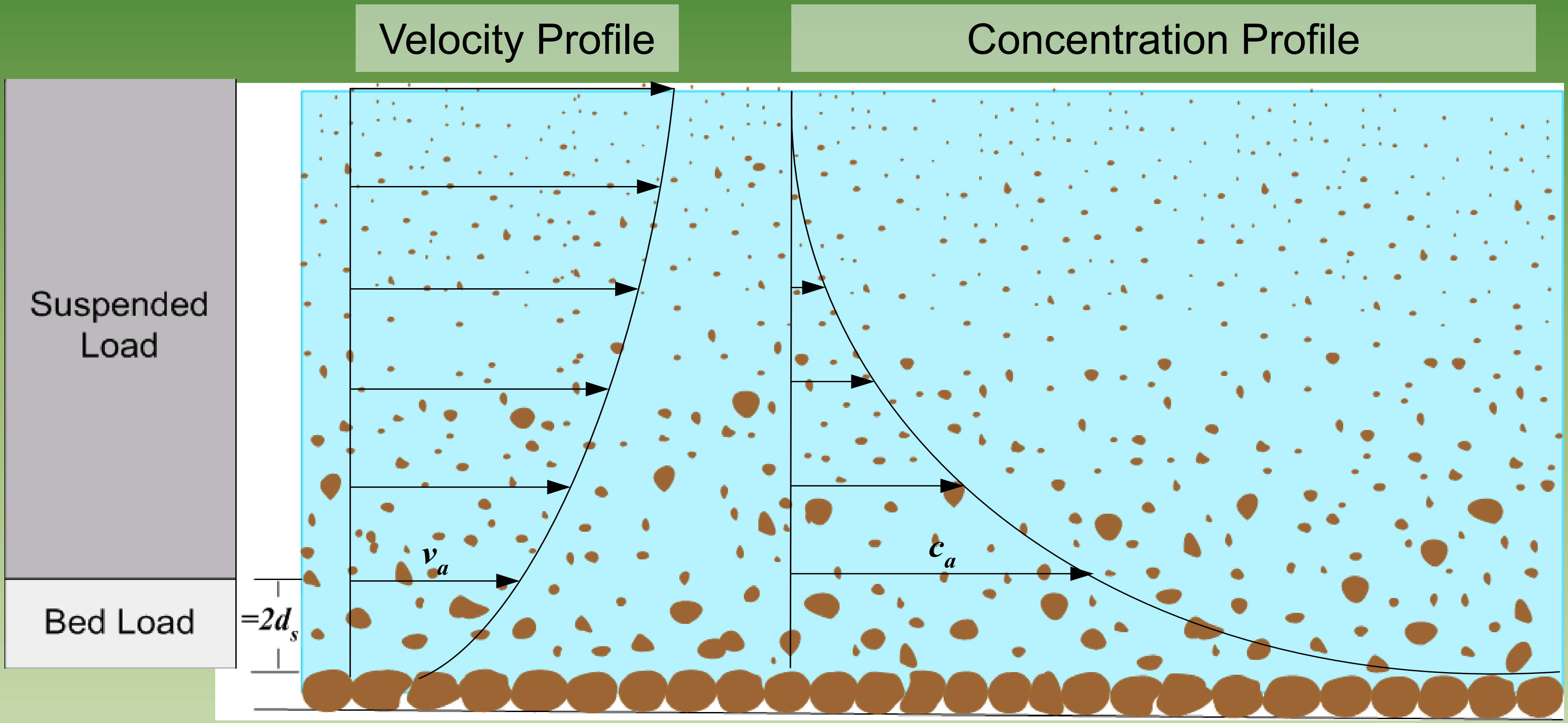
Incipient motion depends on the sum of moments, not forces.

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

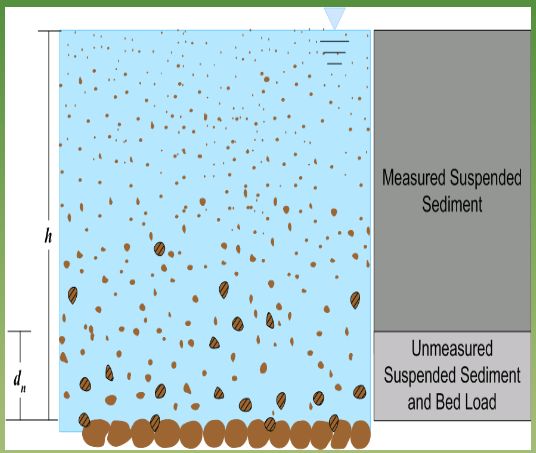


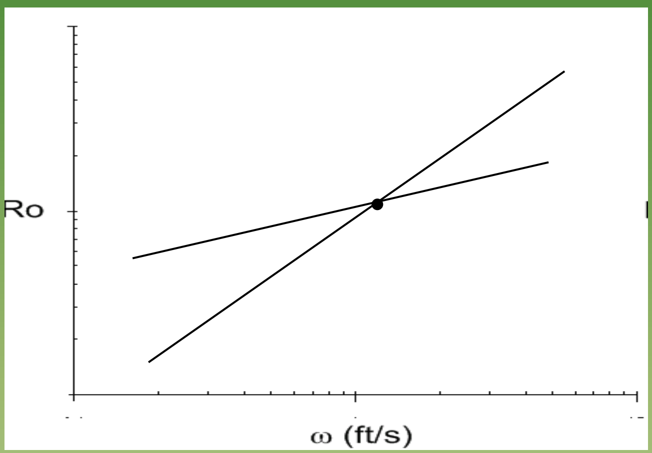
$$v = \frac{u_*}{\kappa} Ln\left(30.2\frac{y}{k_s}\right)$$

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

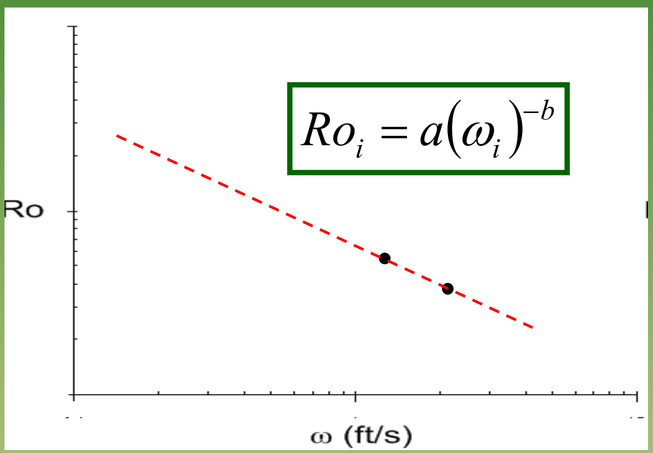
$$Ro = \frac{\omega}{\kappa u_*}$$

Problems with the 'traditional' Modified Einstein Procedure

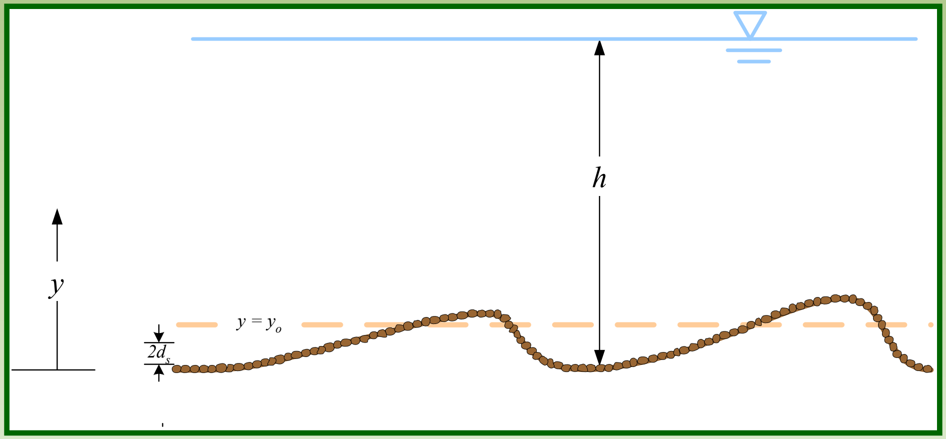




CASE 1 – Not Enough Overlapping Bins



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	$J_2(1)=$	6.527E+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

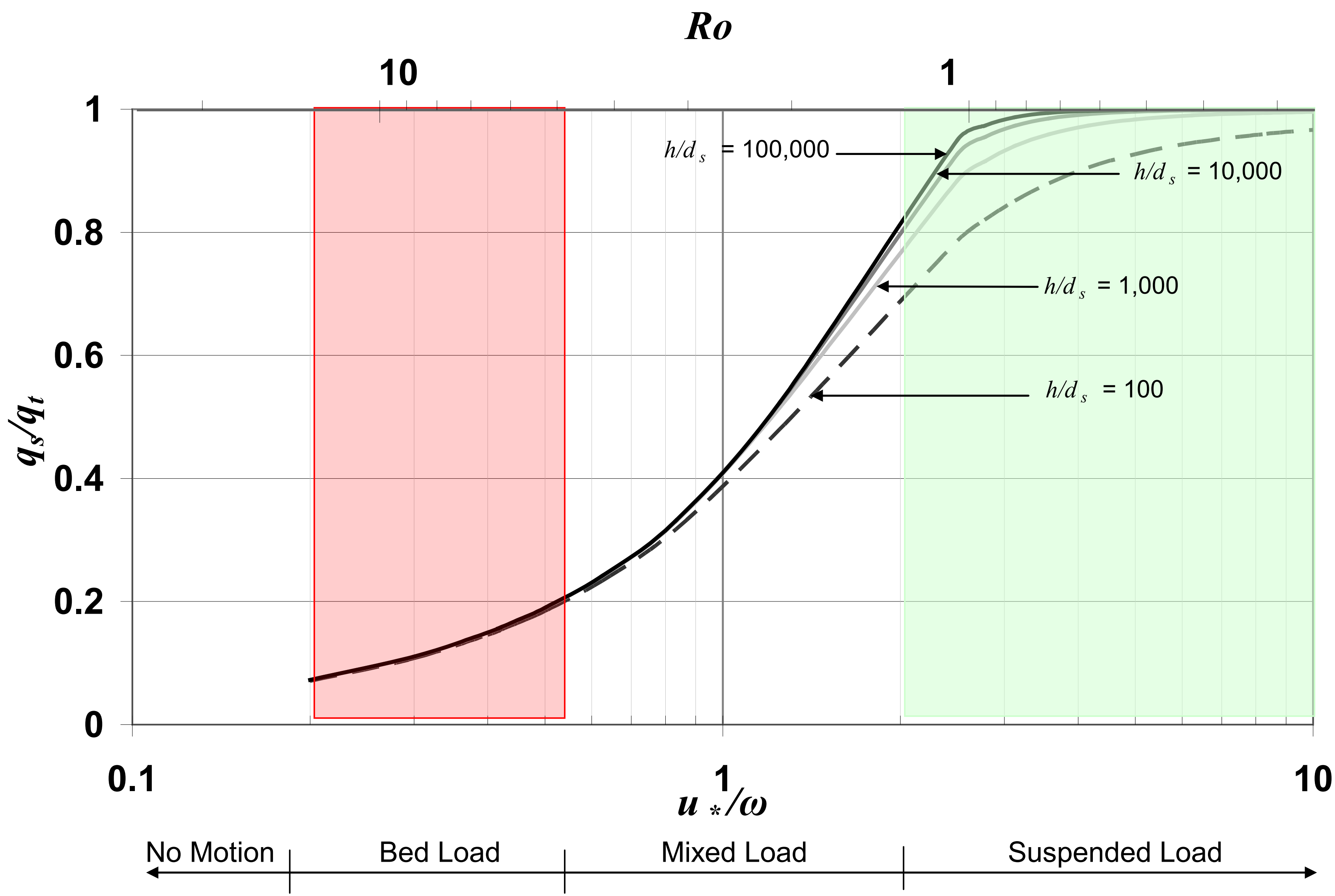
$$q_t = q_b + q_s$$

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

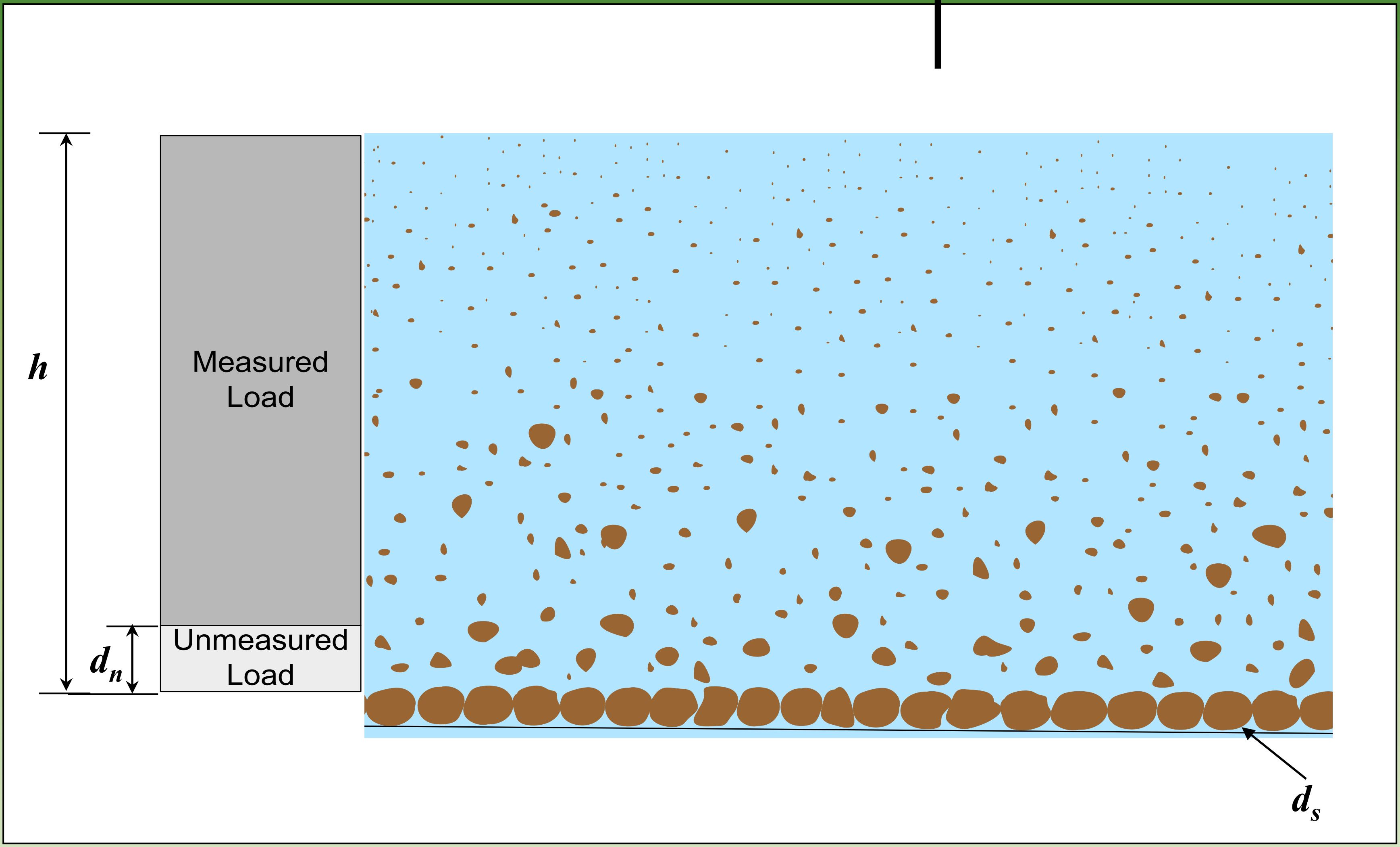
- Ratio of qs/qt

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

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 ω. SEMEP performs accurately (error less than 25%) and without bias when $u_*/\omega > 5$. Calculations are also acceptable, but less accurate when u_*/ω 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 ω, 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_*/ω 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

$$q_t = q_b + q_s$$

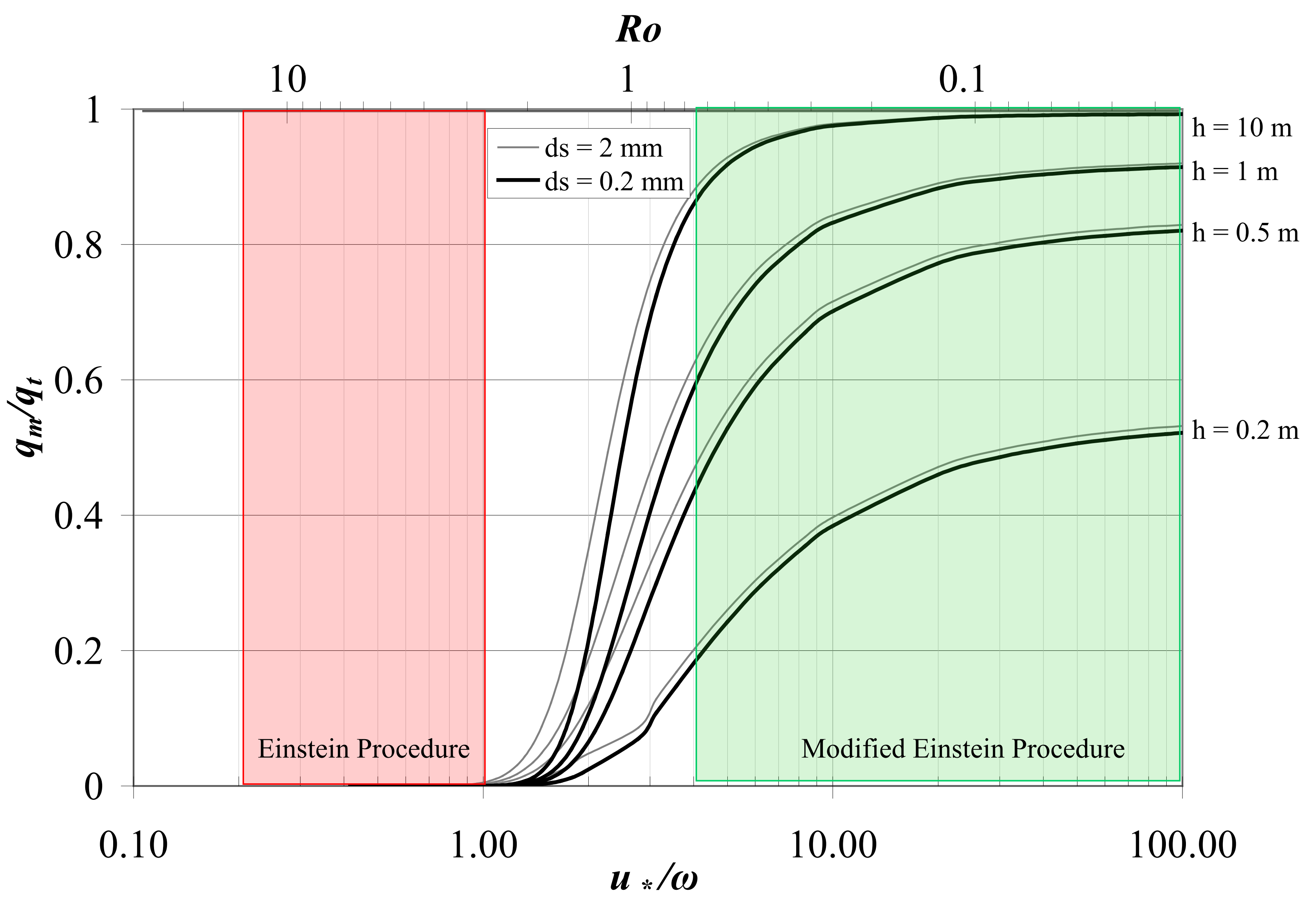
$$q_t = q_b + 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left(\frac{30h}{d_s} \right) J_1 + J_2 \right\}$$

- Ratio of qm/qt

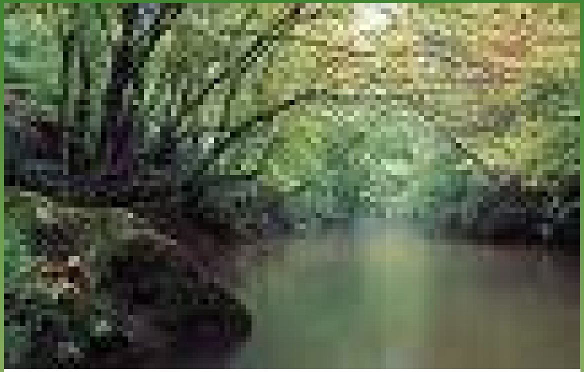
$$\frac{q_m}{q_t} = \frac{0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left(\frac{30h}{d_s} \right) J_{1A} + J_{2A} \right\}}{1 + 0.216 \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left(\frac{30h}{d_s} \right) J_1 + J_2 \right\}}$$

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

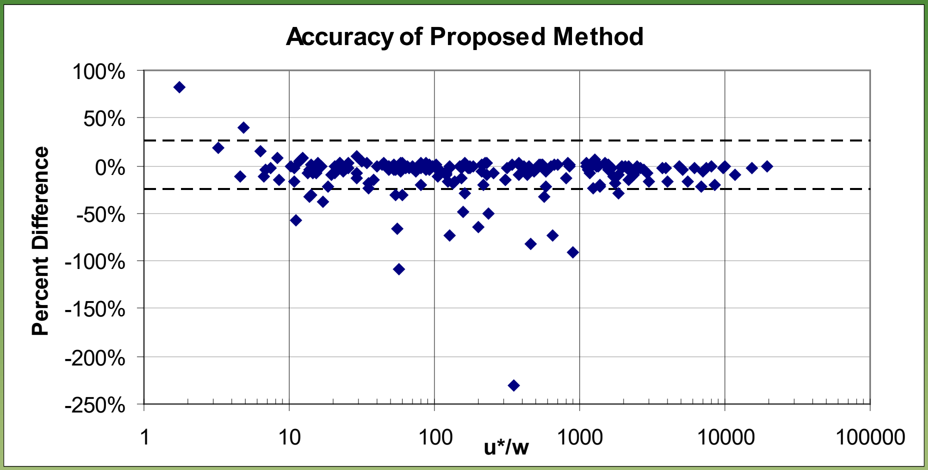
Snake River, WA

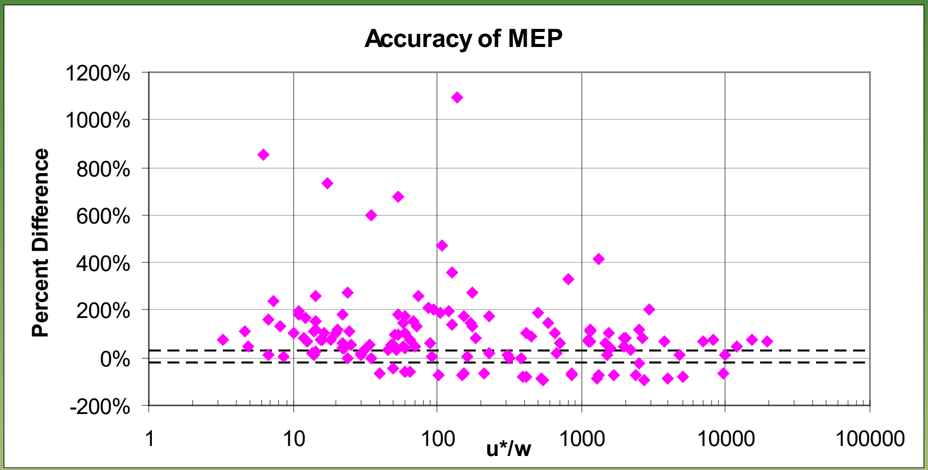
Middle Rio Grande, NM

Clearwater River, ID

Mississippi River, MS

Results from Depth Integrated Sampler

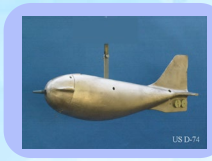


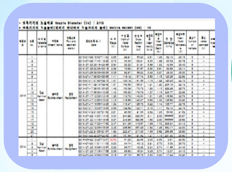


River	Hydraulic Data					Median Particle Size (mm)		Total Number of Samplers	Number of Samples with Calculated Total Load within 25% of measured Total Load	
	Q (cms)	V (m/s)	h (m)	W (m)	S	Bed	Suspension		Proposed Method	BORAMEP
Susitna River near Talkeetna Alaska	238 to 1,300	1.2 to 2.7	1.1 to 2.4	165 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

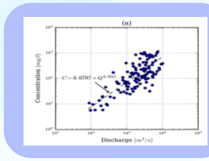


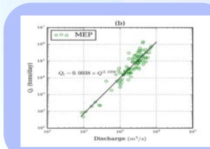


(Korean team)

Field Measurement Data

Sediment Rating Curve

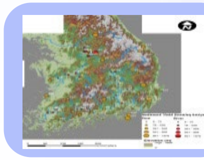


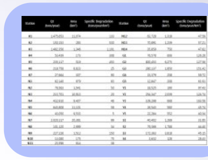


- Q – C relationship
- Q – Q_T relationship

Sediment Yield

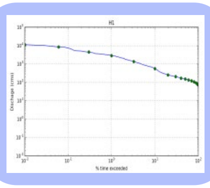
- Suspended sediment
- Total sediment

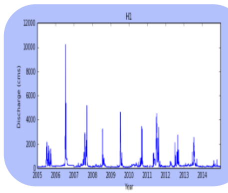




Flow Duration Curve

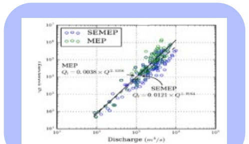
- 10 years data
- Daily discharge





- MEP vs SEMEP

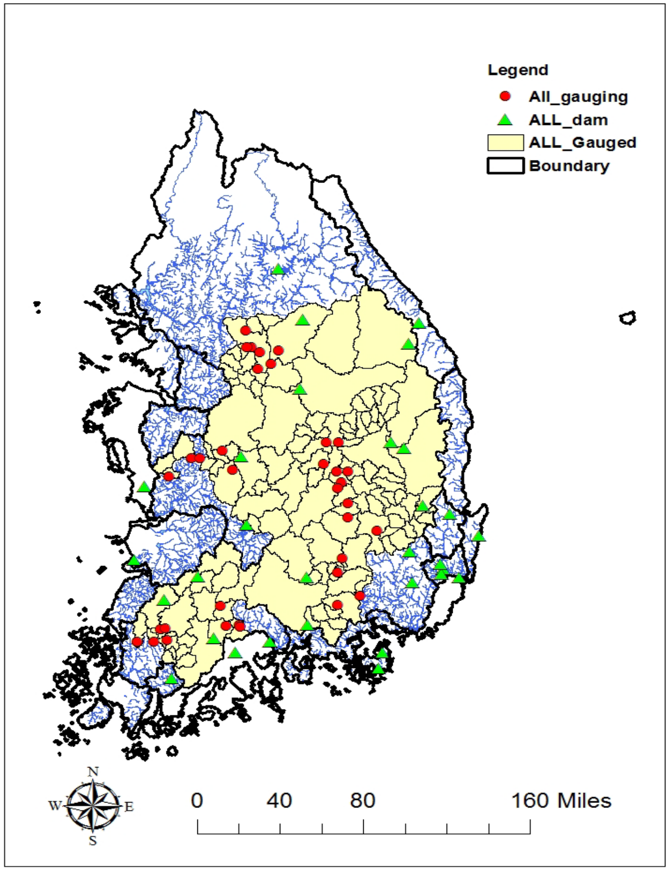
: U_*/ω, Q_s/Q_t (Q_m/Q_t), h_m/h



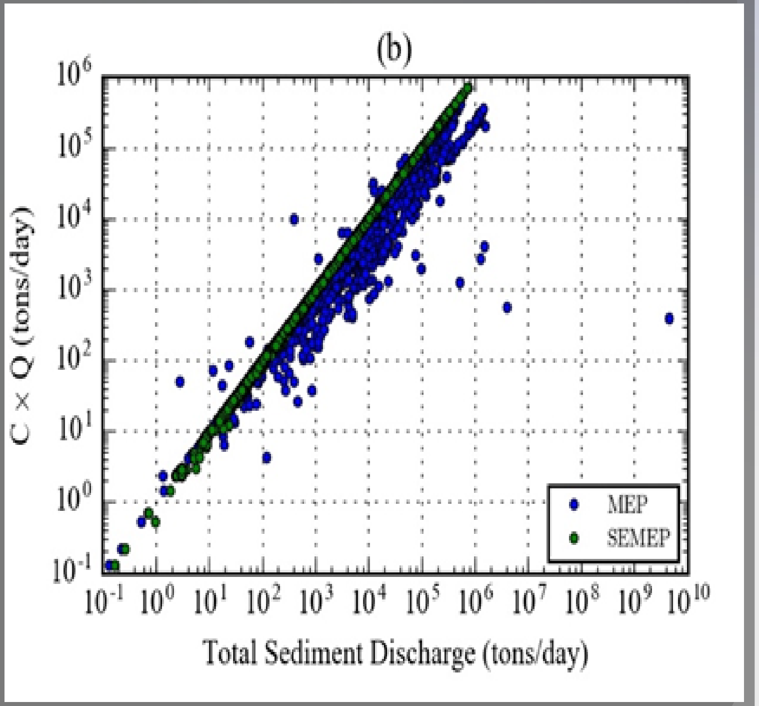
Total Sediment Discharge

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	ρ_{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

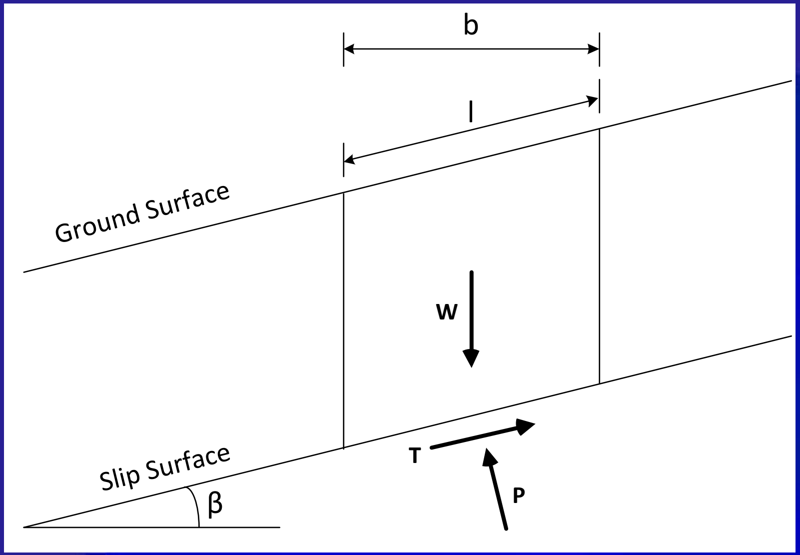
Classification and Rheology

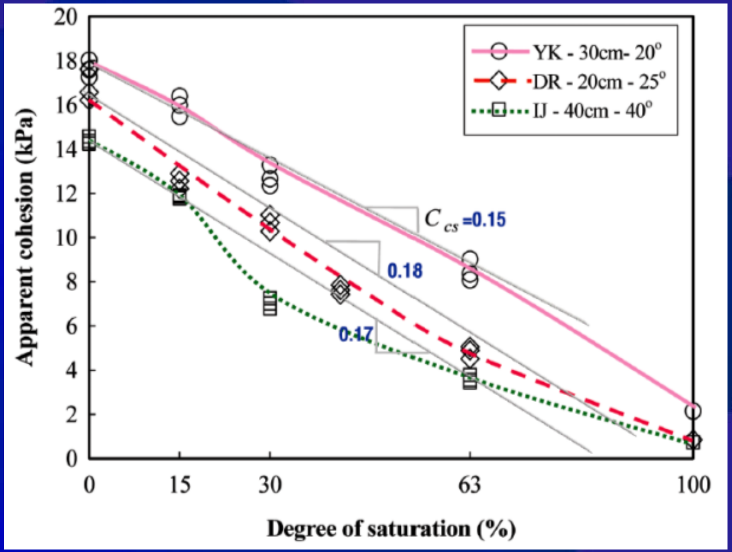
Total shear stress :

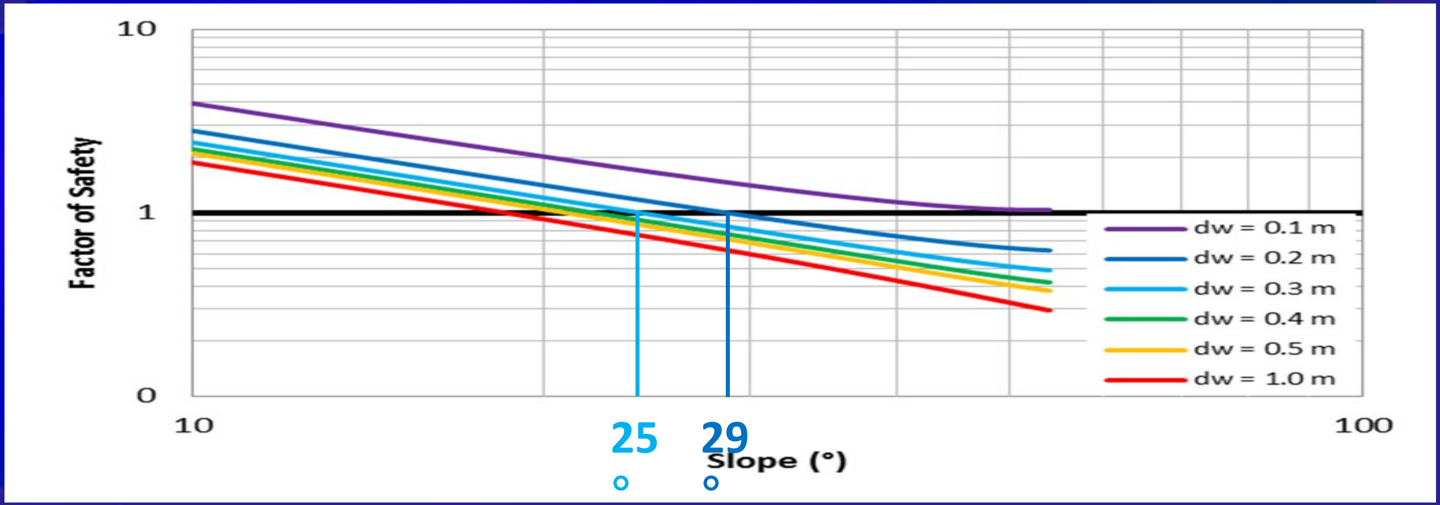
$$\tau = \tau_y + \tau_v + \tau_t + \tau_d$$

- τ_y → Yield stress
- τ_v → Viscous stress
- τ_t → Turbulent stress
- τ_d → Dispersive stress

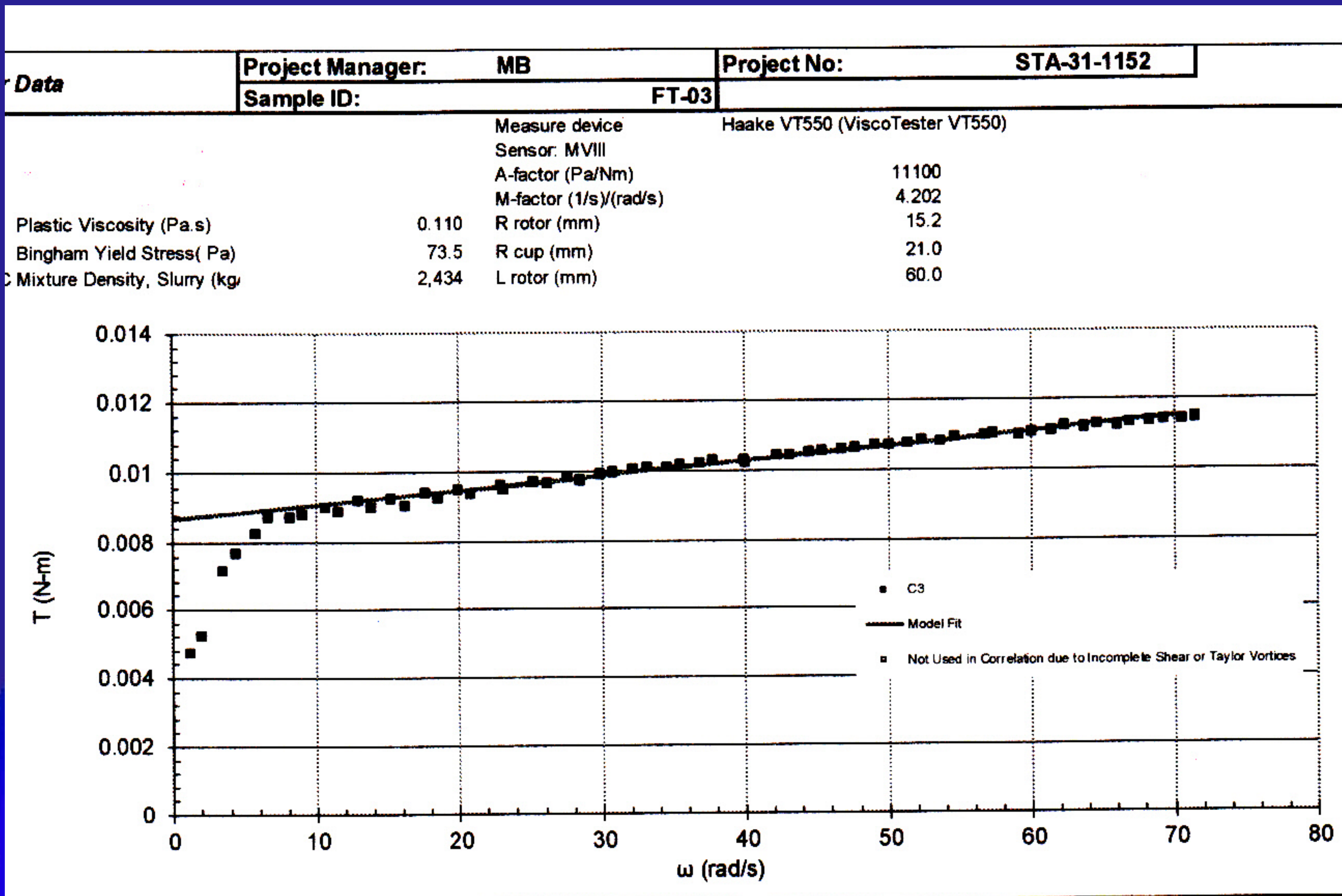
Yield Strength for Landslides







Viscometer Test



Rheogram

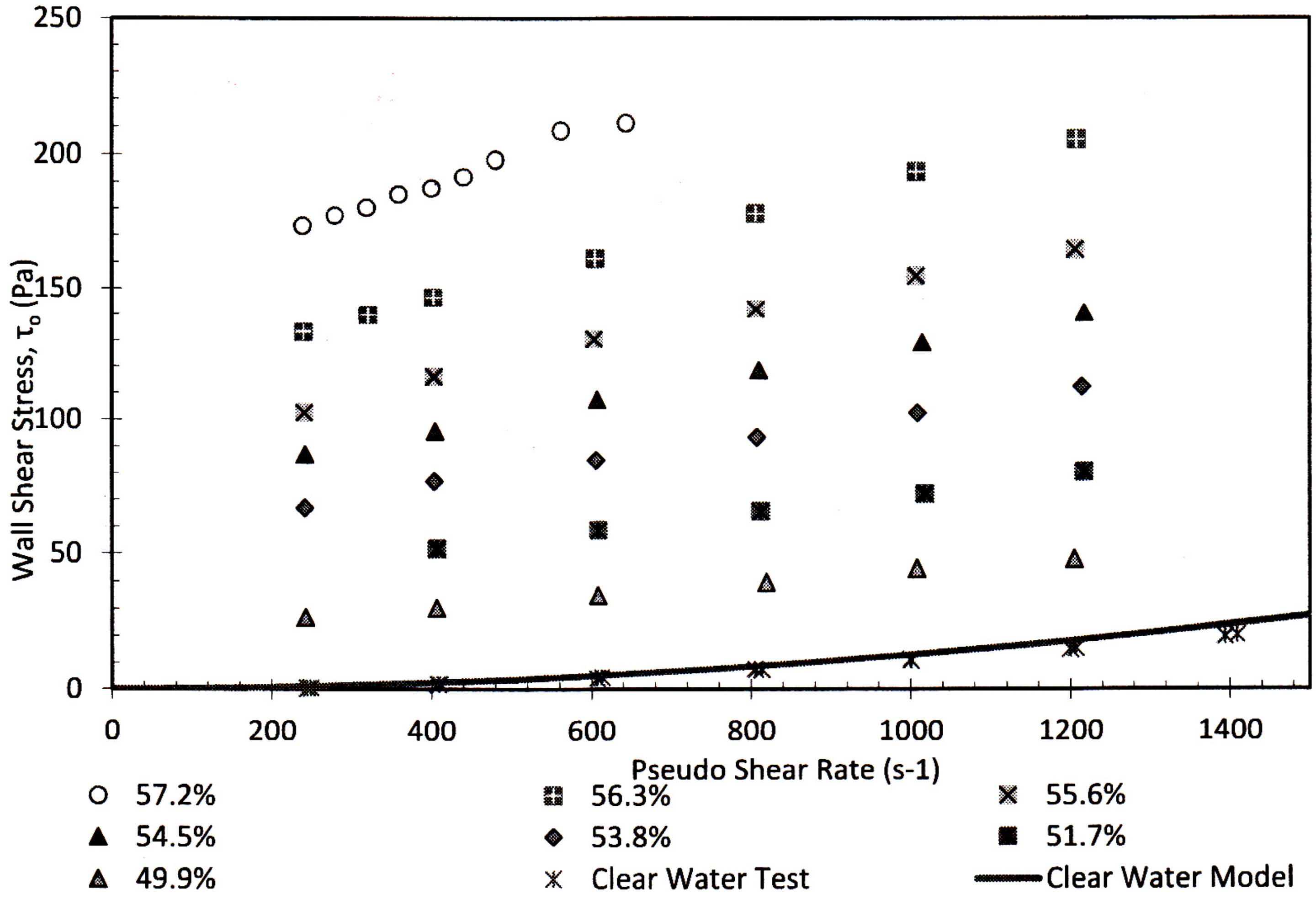


Figure 11: FT-02 Pseudo-Shear Diagram

Yield and Viscosity of Mudflows

Mudflow Rheology

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

τ_y *is the yield stress*

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

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

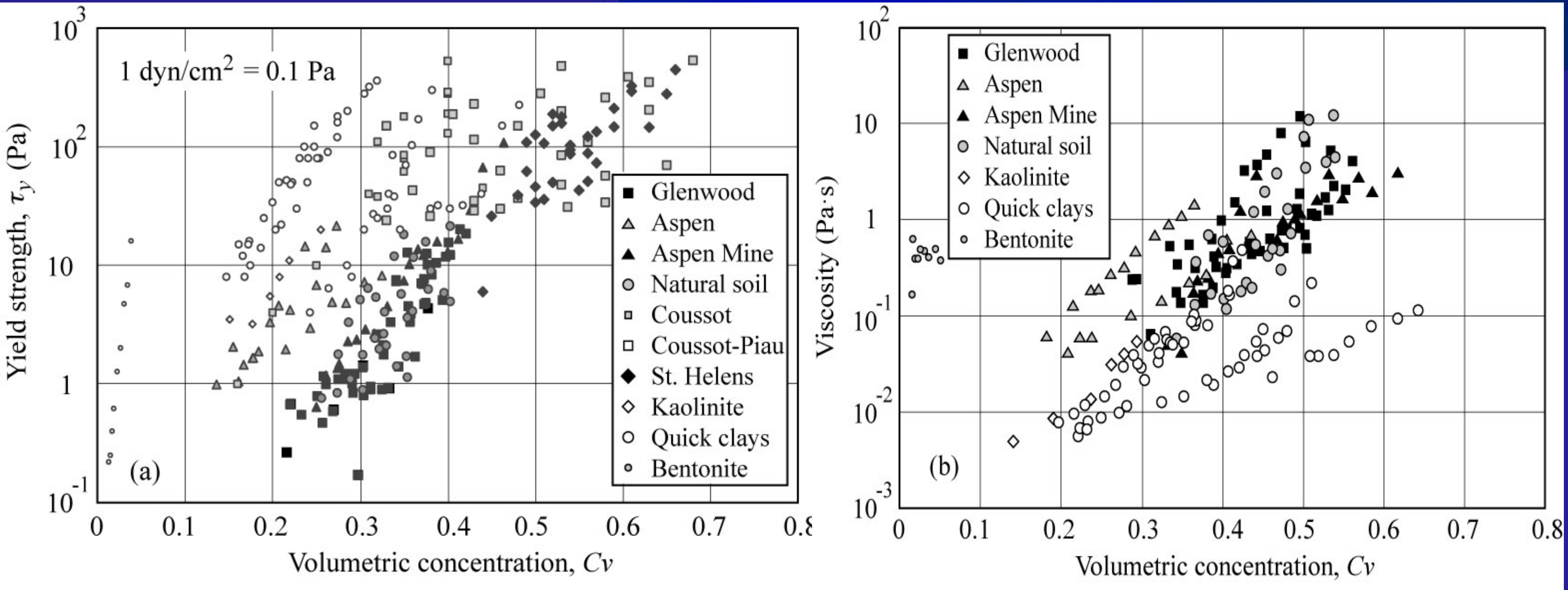


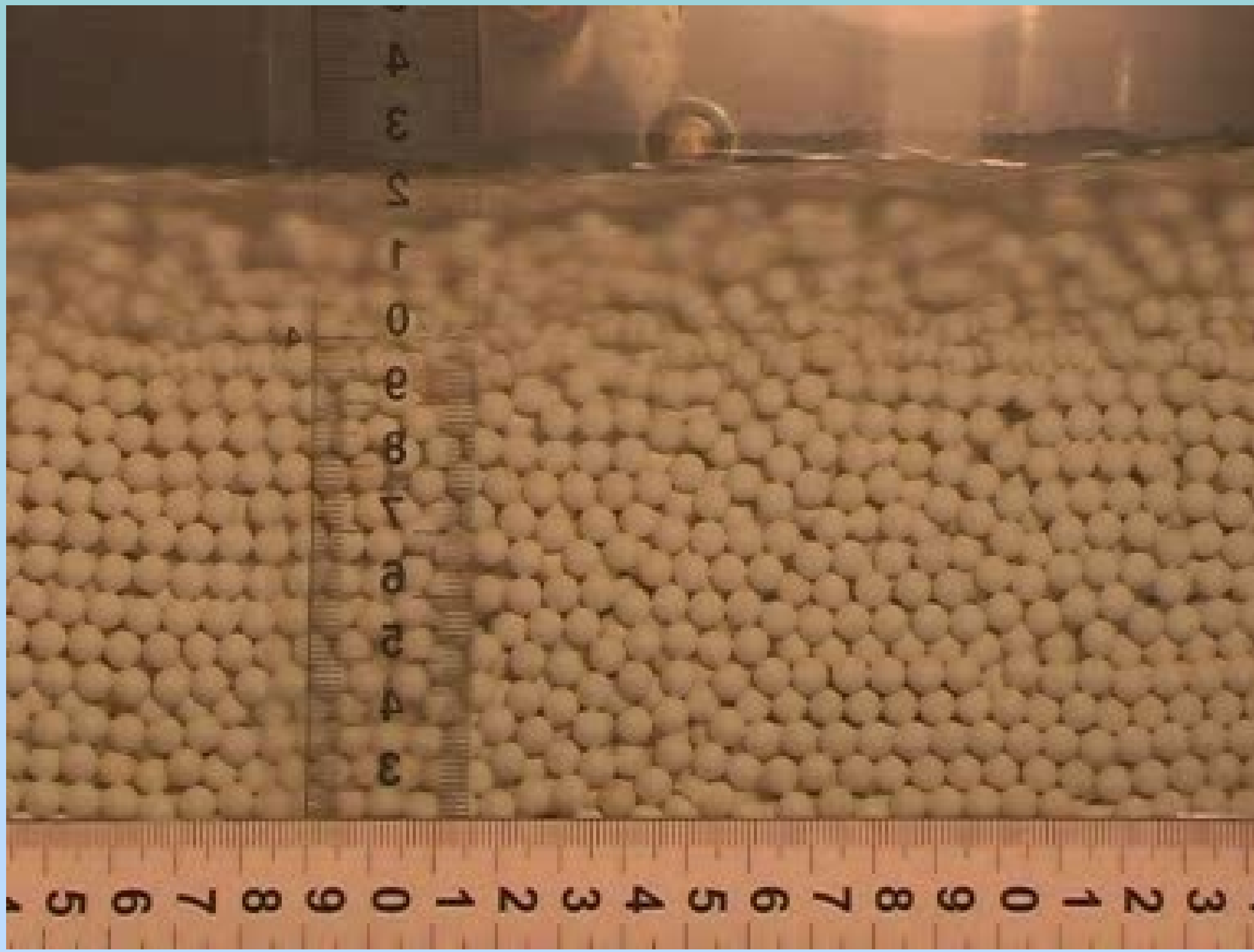
Figure 10.13a. Yield strength versus volumetric concentration

Figure 10.13b. Dynamic viscosity versus volumetric concentration

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

ρ_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} □ 0.01*)*

ρ_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?

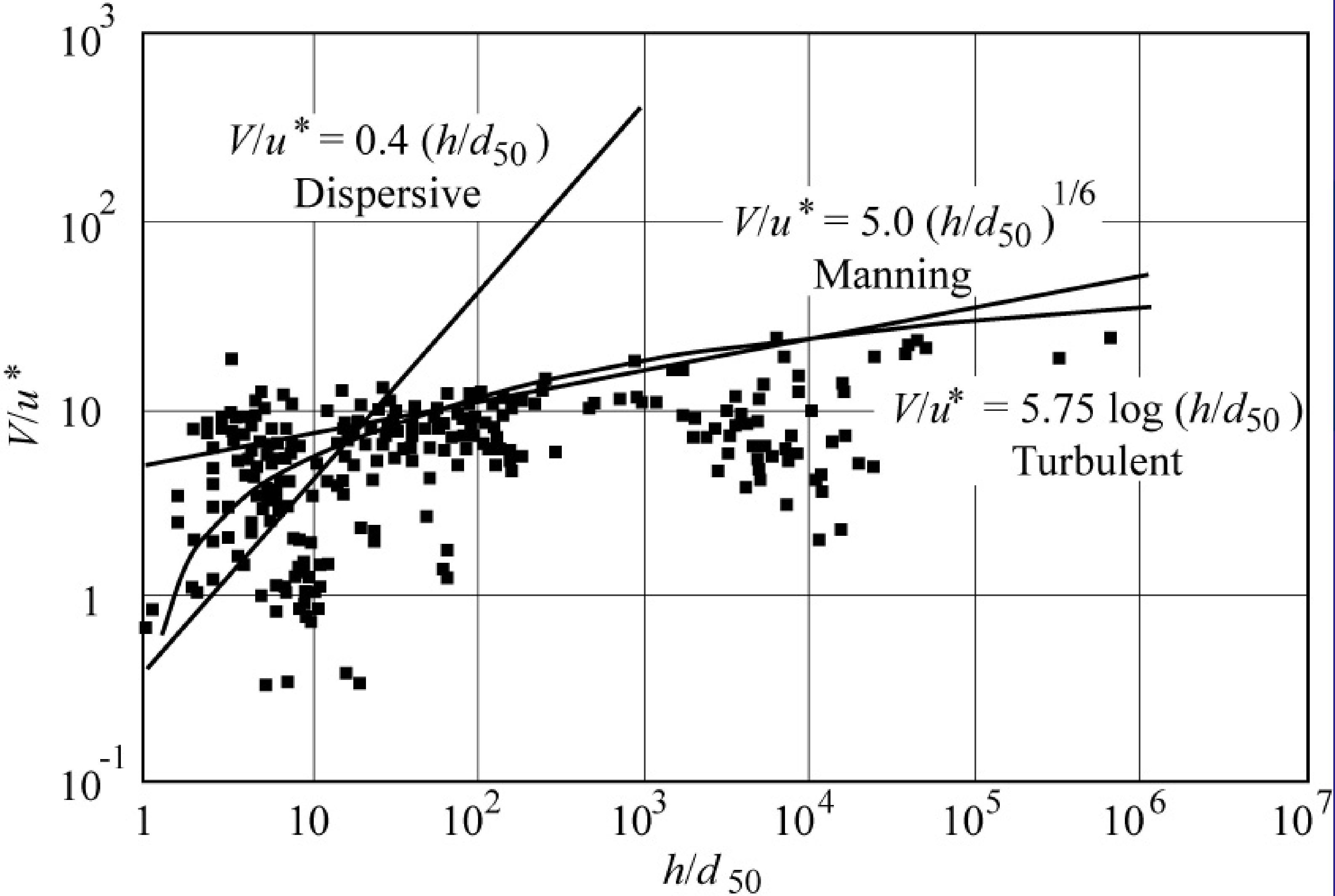


Figure 10.16. Resistance diagram for hyperconcentrated flows.

Mitigation Countermeasures

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

2. Landslides

Yield Stress -> Landslides

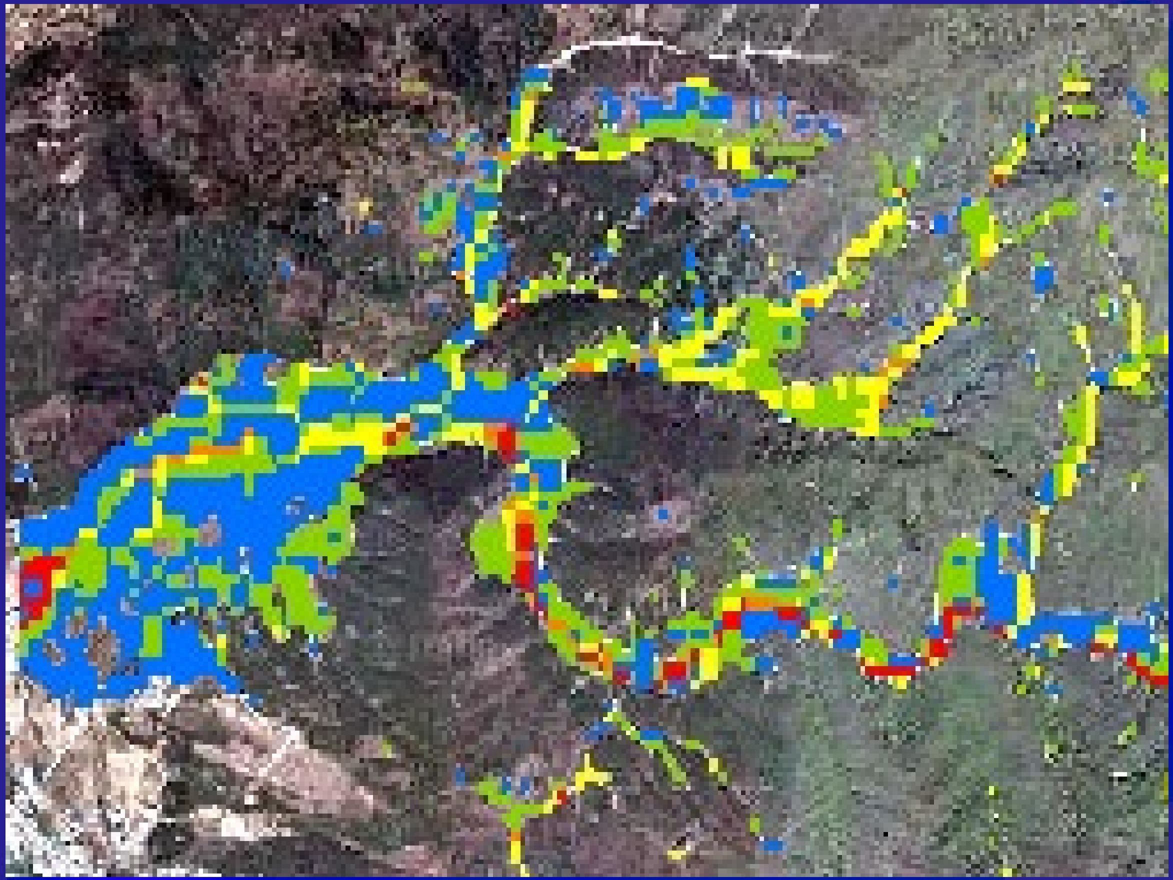
Total shear stress :

$$\tau \sim \tau_y$$

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% < Cv < 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

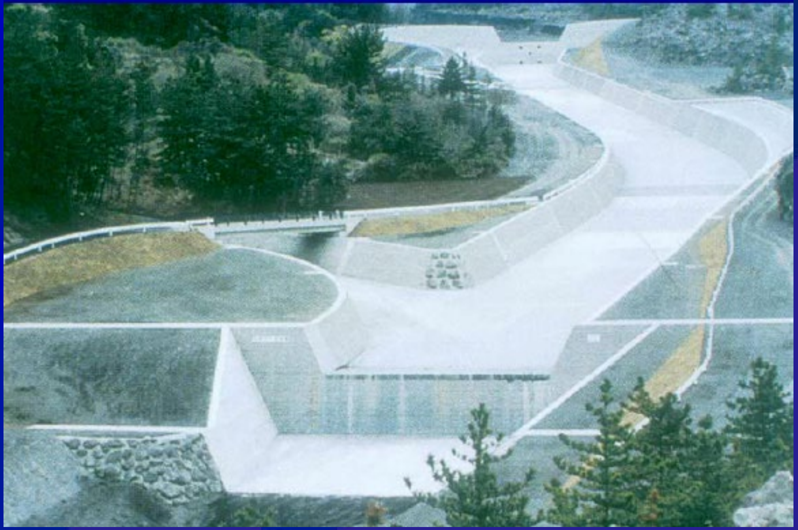
- Straight channels
- Lined canals, berm and levee channels
- Drop structures, energy dissipators

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 ➡ Retain large clasts
Drain fluid matrix

- Concrete Sabo dams
- Steel frames and debris rakes

Debris flow Countermeasures

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

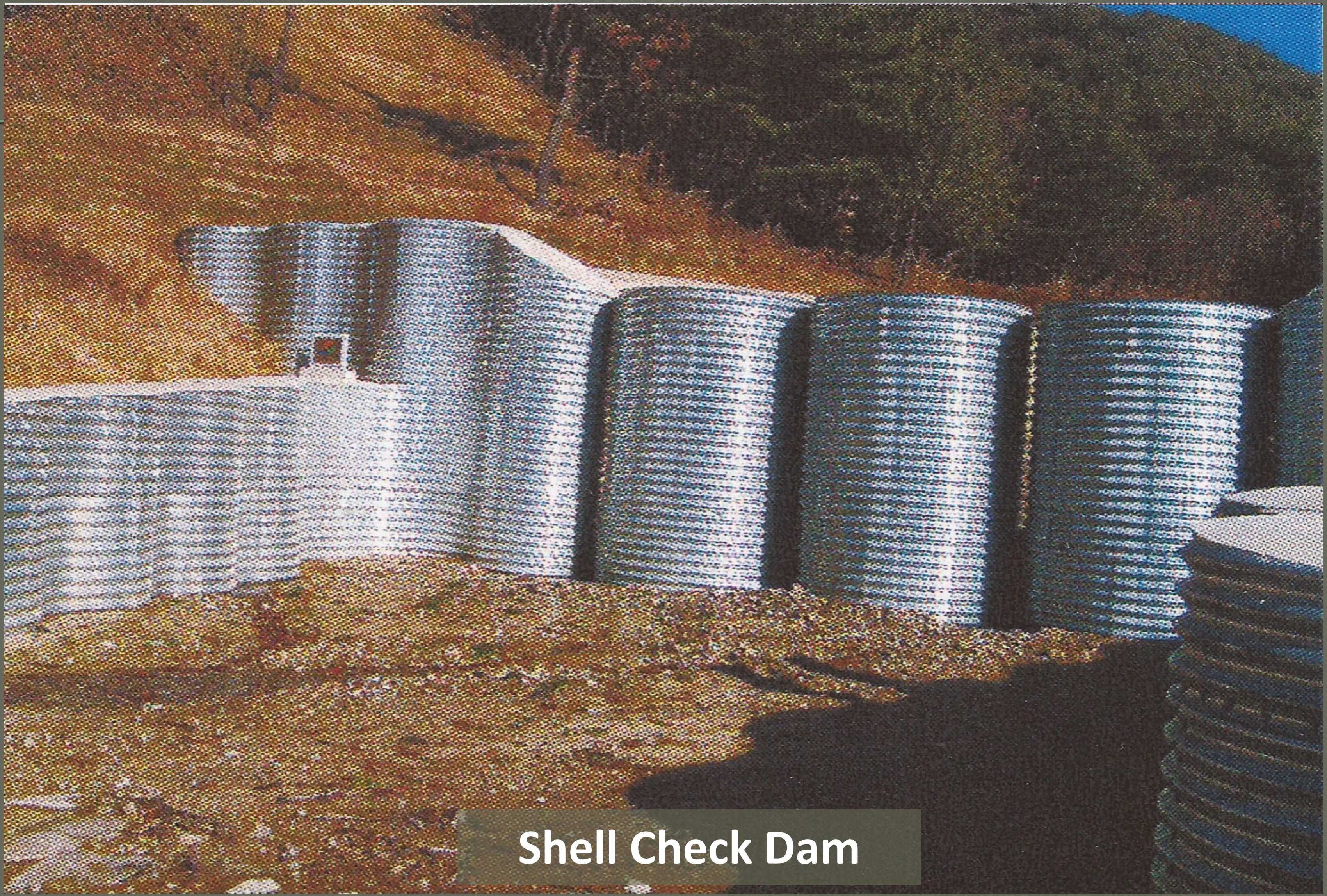
- Concrete sabo dams
- Steel Frames
- Debris Racks

Sabo Dam Construction

Sabo Dam and Steel Frames

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


Sovico

Summary and Conclusions

1. Incipient Motion

Incipient motion depends on ratio of moments, not forces.

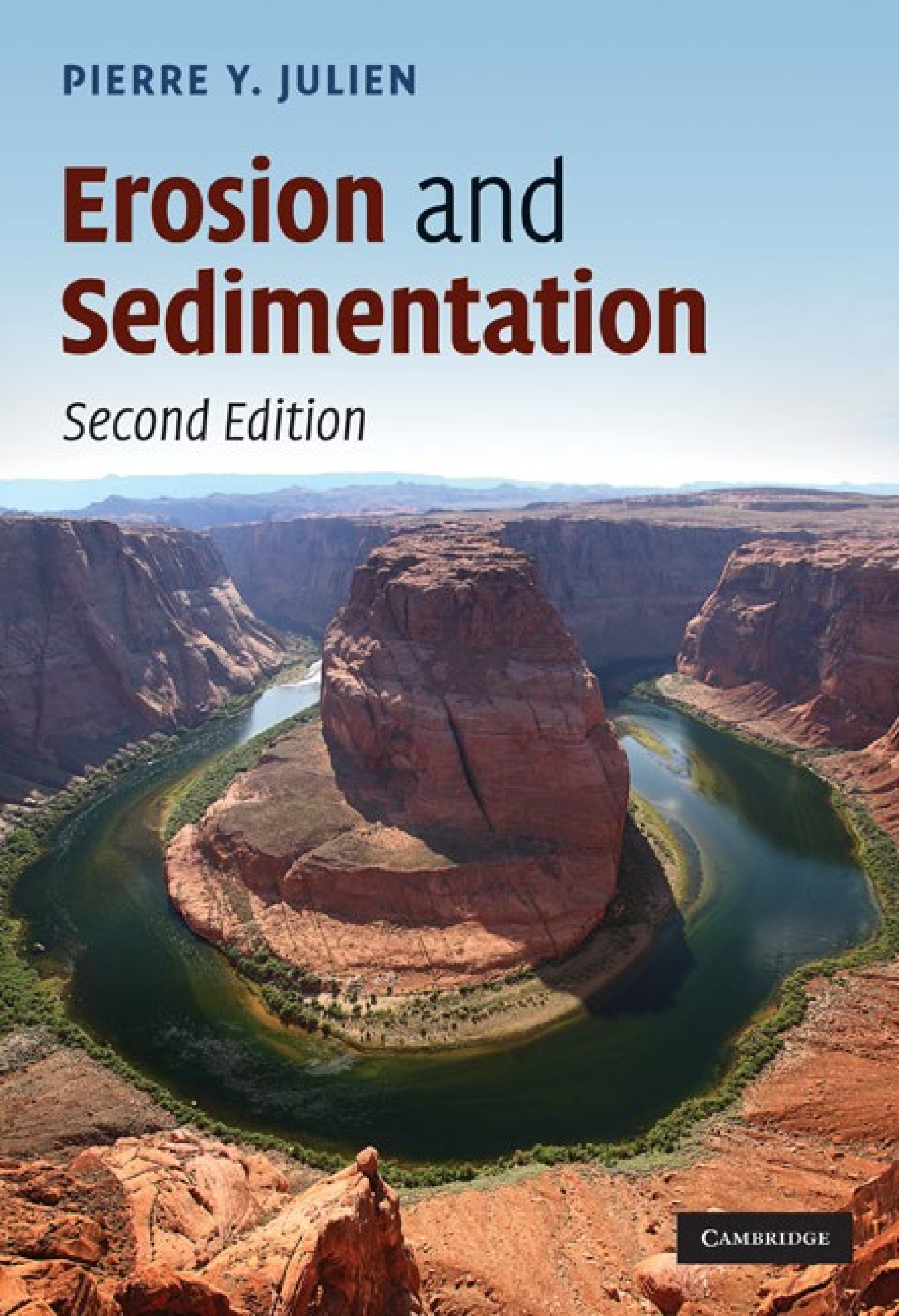
2. SEMEP and SEMEPP

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!

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pierre@engr.colostate.edu