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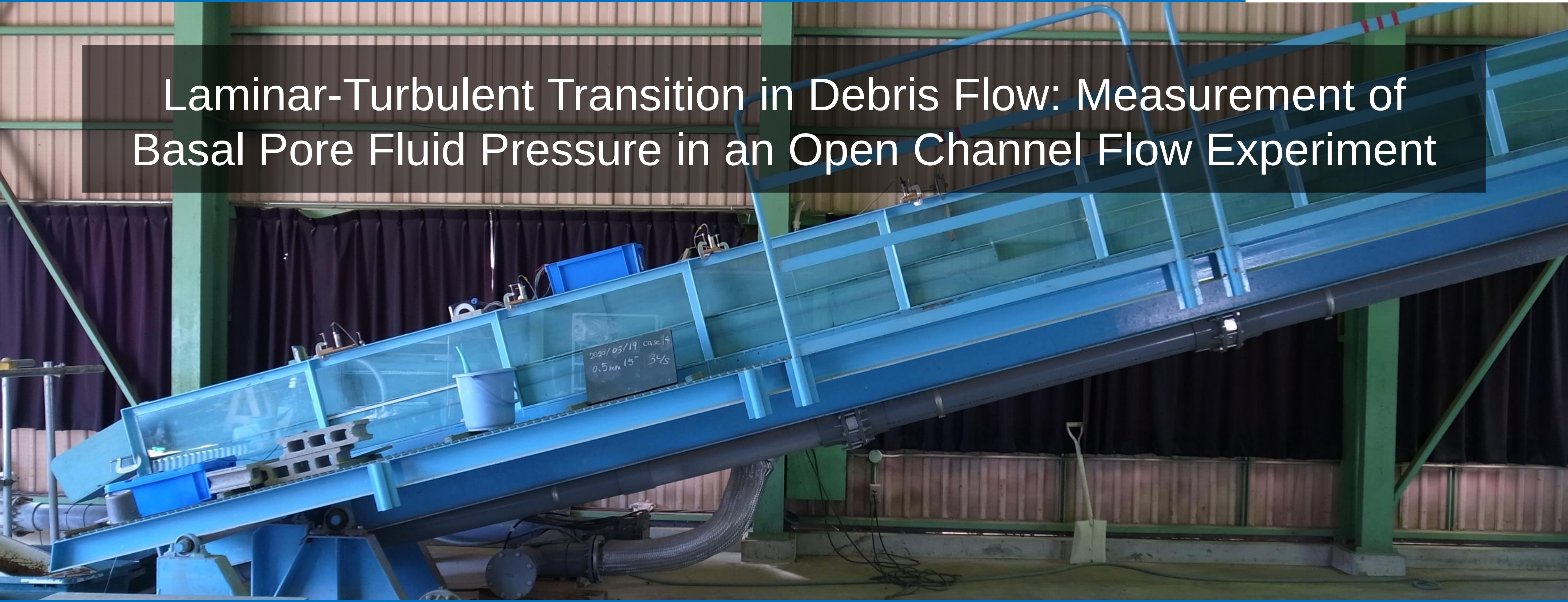
東京大学 THE UNIVERSITY OF TOKYO

Laminar-Turbulent Transition in Debris Flow: Measurement of Basal Pore Fluid Pressure in an Open Channel Flow Experiment



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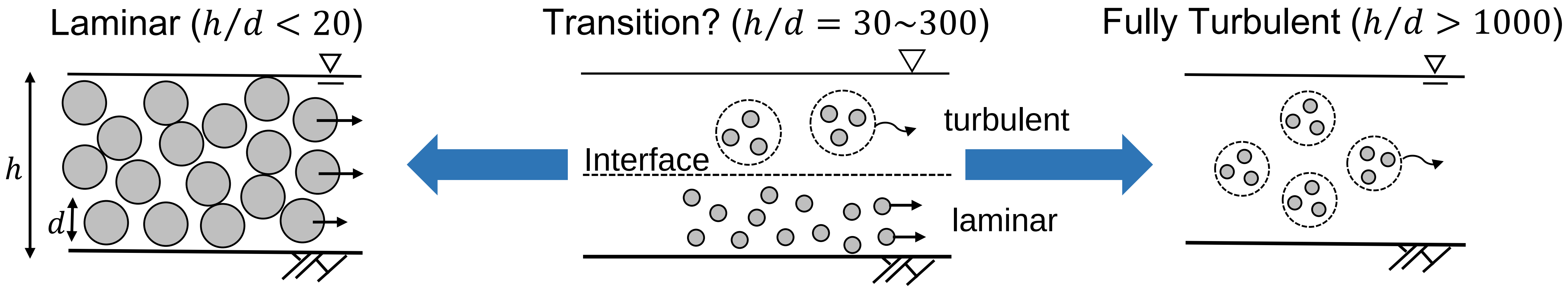
Introduction

- Flow characteristics of a debris flow varies by its grain size composition.
  - --Coarse-grained → grains supported by grain-grain interactions, laminar motion
  - --Fine-grained (incohesive) → grains suspended by turbulence
- Investigations on velocity profiles & flow resistance have indicated that laminar-turbulent transition depends on the relative flow depth to grain size, h/d
  - -- entirely laminar for $h/d < 20$; fully turbulent for $h/d > 1000$; transitional flow with two-layered structure suggested for $h/d = 30\sim300$ (Hotta & Miyamoto, 2008)
- However, modeling the transition remains incomplete given the lack of data on the internal stresses.

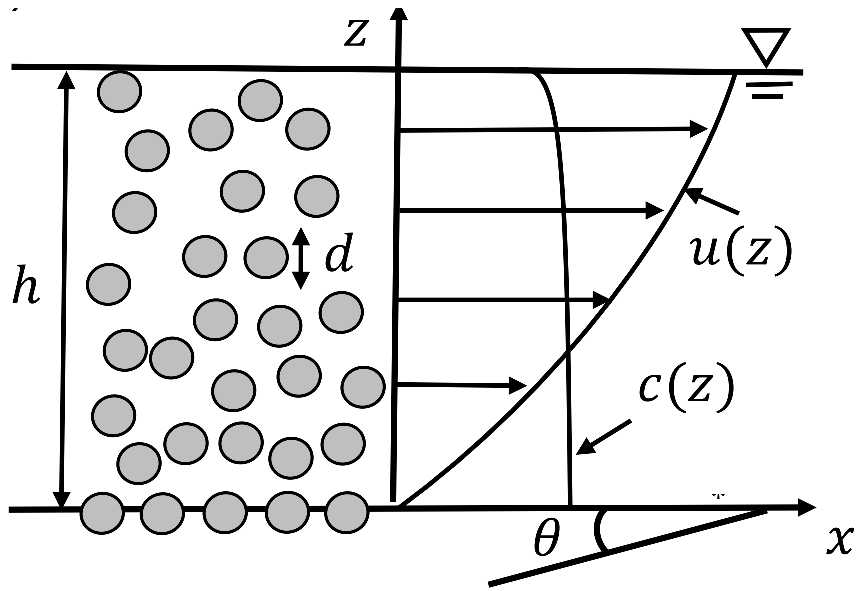


Objectives

- Here we studied the laminar-turbulent transitions of debris flows by measuring basal pore fluid pressures using flume tests.

- Coarse-grained debris flows exhibit non-Newtonian rheology, which are composed of static (shear rate independent) and dynamic (shear rate dependent) stress. By analogy with Newtonian fluid, we investigated the transition based on Reynolds number for debris flows, defined as ratio of inertial stress to dynamic stress of debris flows.

Constitutive eqs. of coarse-grained debris flow (Egashira et al., 1997)



u = local velocity, c = local sediment concentration, c_* = sediment concentration of static deposited layer, ϕ_s = internal friction angle, ρ_w = density of water , g = acceleration of gravity, σ = density of sediment particles, e = coefficient of restitution, k_d & k_f = empirical constants

Inelastic particle-particle collision | Hydrostatic pressure

Normal stress (Pressure) $p = p_s + p_d + p_f + p_w$

Shear stress $\tau = \tau_s + \tau_d + \tau_f$

Interparticle friction | Reynolds stress due to turbulence in pore fluid

$$p_s = (c/c_*)^{0.2}(p_s + p_d) \qquad \tau_s = p_s \tan\phi_s$$

$$p_d = \rho_w K_{pd} d^2 (\partial u/\partial z)^2 \qquad \tau_d = \rho_w K_d d^2 (\partial u/\partial z)^2$$

$$p_f = \rho_w K_f d^2 (\partial u/\partial z)^2 \qquad \tau_f = \rho_w K_f d^2 (\partial u/\partial z)^2$$

$$p_w = \rho_w g (h - z)\cos\theta$$

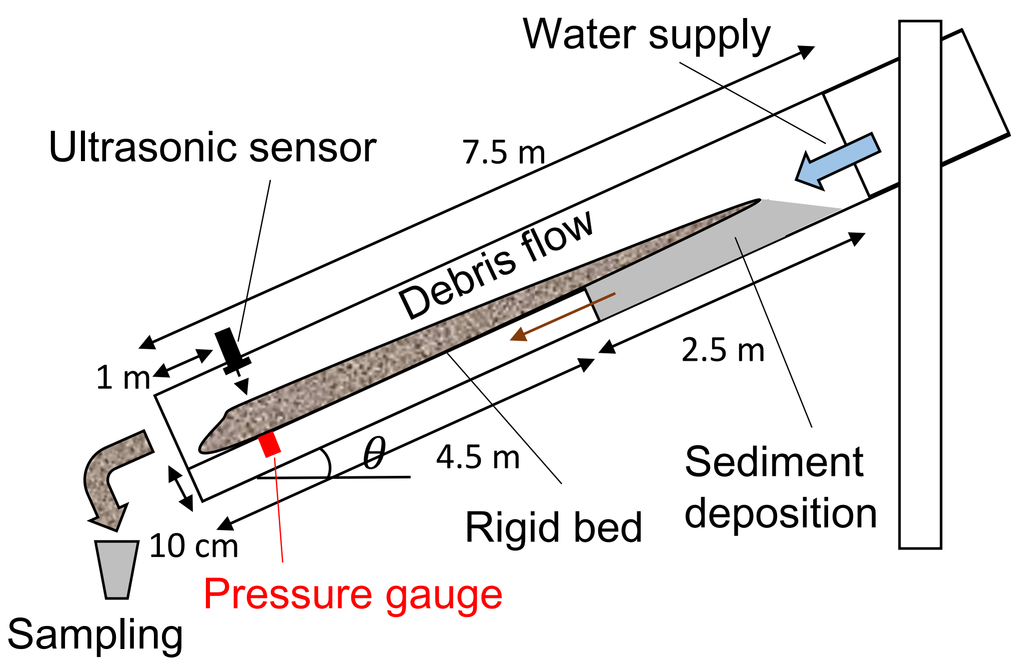
$$K_{pd} = k_d\, \sigma/\rho_w\, e^2 c^{1/3} \qquad K_d = k_d\, \sigma/\rho_w\, (1 - e^2) c^{1/3}$$

$$K_{pf} = k_f((1 - c)/c)^{2/3} \qquad K_f = k_f\, (1 - c)^{5/3}/c^{2/3}$$

- Pore fluid of coarse-grained debris flow is turbulent due to strong shear by coarse grains
- Reynolds stress having mixing length of interparticle length scale takes place
- Pore fluid pressure is expressed as $p_f + p_w$, and generally assumed to be $p_f + p_w \approx p_w$

Flume tests

Debris flow flume



Experimental conditions

(Total case number was 112, pore pressure measurement succeeded in 32 cases)

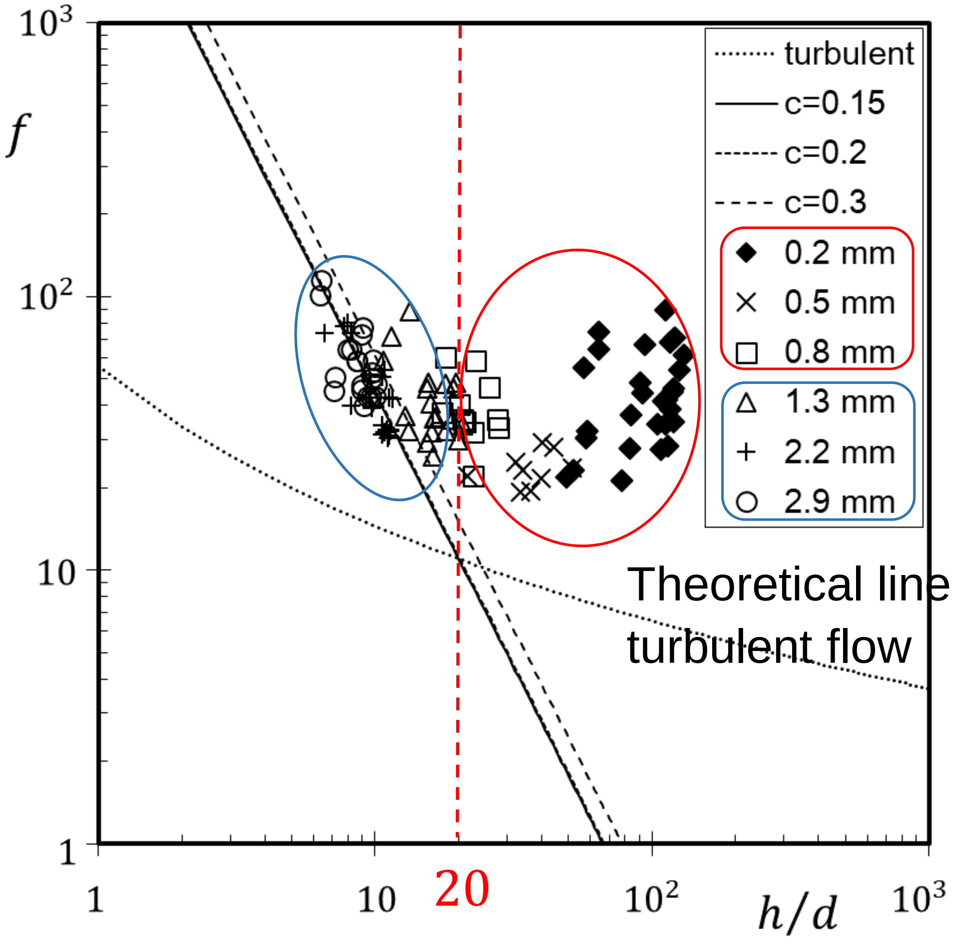
d (mm)		θ (deg.)		Water supply (L/s)
0.2				
0.5		13		1
0.8	×	15	×	2
1.3		17		3
2.2				3.5
2.9				

Saturated debris flows over rigid bed were triggered by surface water eroding the sediment deposition composed of monogranular materials

- Flow depth, h, and basal pore fluid pressure, p_{exp}, were measured using an ultrasonic sensor and a pressure gage respectively.
- At quasi-steady state, sediment concentration, C, was estimated by the bulk density of the debris flow, ρ_m, measured by direct sampling (C ranged from 0.1 to 0.3). Total normal stress, p_{total}, were assessed by $p_{total} = \rho_m g h$.

h/d vs friction coefficient

Theoretical line for coarse-grained debris flow



Theoretical line for turbulent flow

- Theoretical friction coefficient for coarse-grained debris flow derived from constitutive eqs.

$$f_{cal} = \frac{25}{2} K(C) \left(\frac{h}{d}\right)^{-2}$$

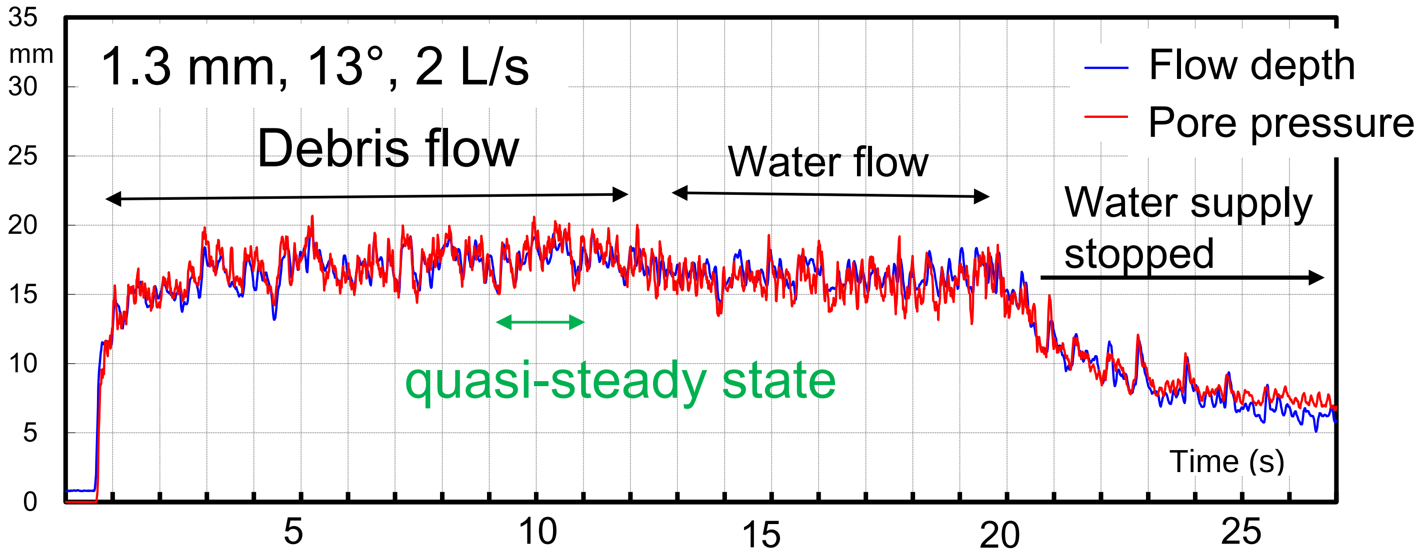
$$K(C) = \frac{K_d + K_f}{\rho_m/\rho_w - (c/c_*)^{0.2}(\sigma/\rho_w - 1)\tan\phi_s/\tan\theta}$$

- Theoretical friction coefficient for rough turbulent flow

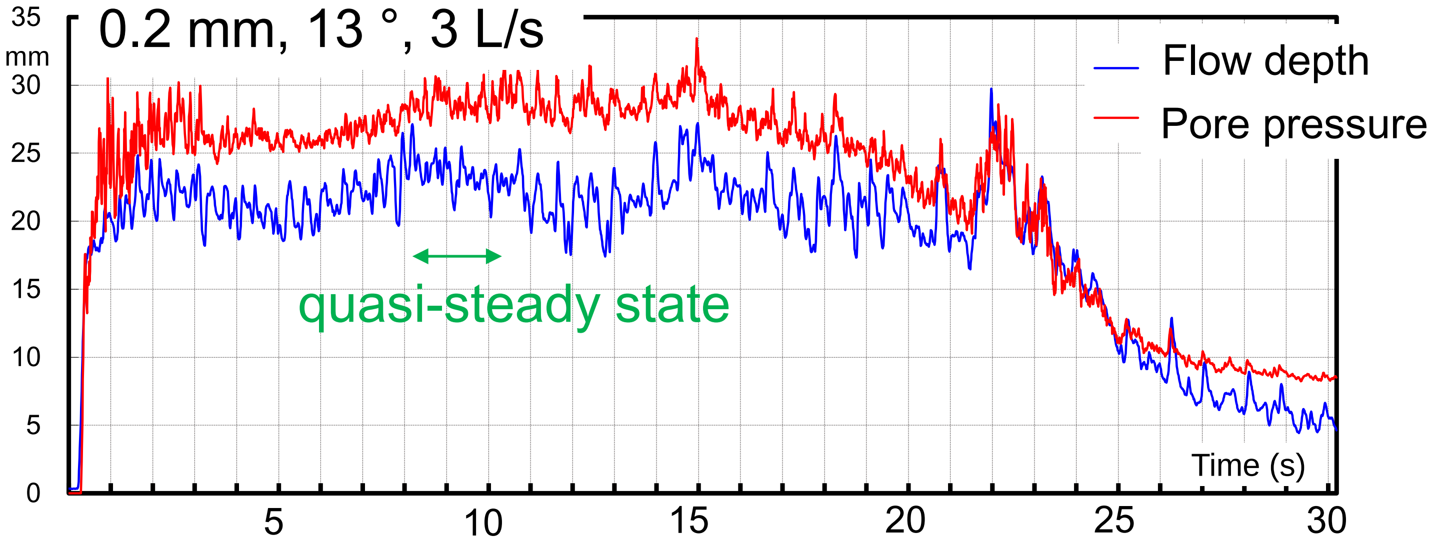
$$f_{cal} = 2\left(A_r - \frac{1}{\kappa} + \frac{1}{\kappa}\ln\frac{h}{d}\right)^{-2}$$

Cases of 2.9, 2.2 and 1.3 mm showed $h/d < 20$ and were described well by the theoretical line for coarse-grained debris flow; cases of 0.8, 0.5 and 0.2 mm showed $h/d > 20$ and were plotted apart from the theoretical lines.

Successful examples of pore pressure measurement



Pore fluid pressure
≈ hydrostatic pressure



Pore fluid pressure
> hydrostatic pressure

→excess pore pressure

Results of pore pressure measurement

Three mechanisms are possible for excess pore pressure in debris flows.

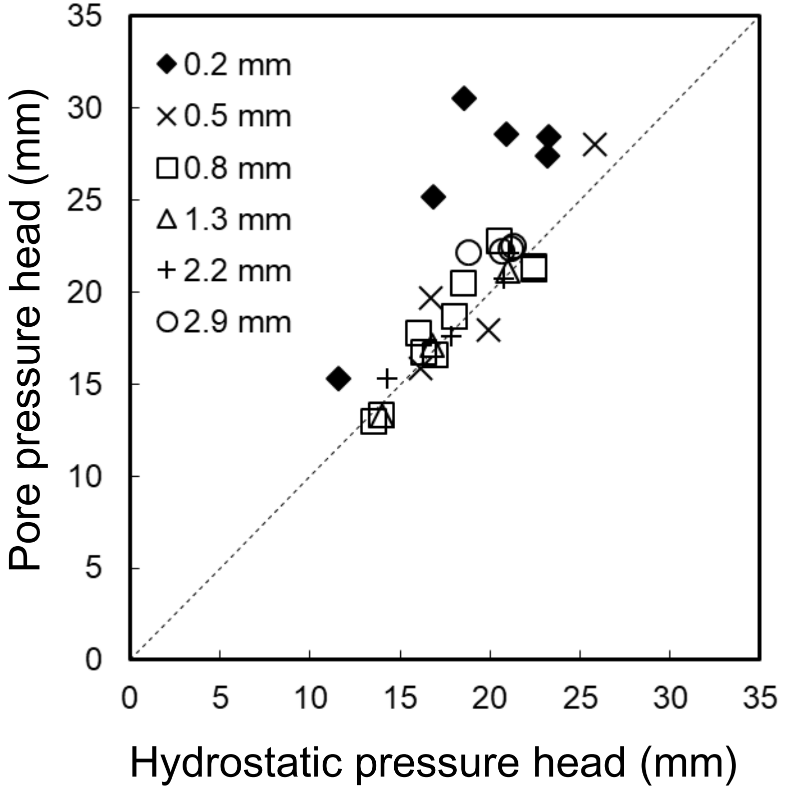
(i) Reynolds stress due to turbulence in pore fluid

(ii) Turbulent suspension

(iii) Pressure gradient due to internal water flow different from the track of grains

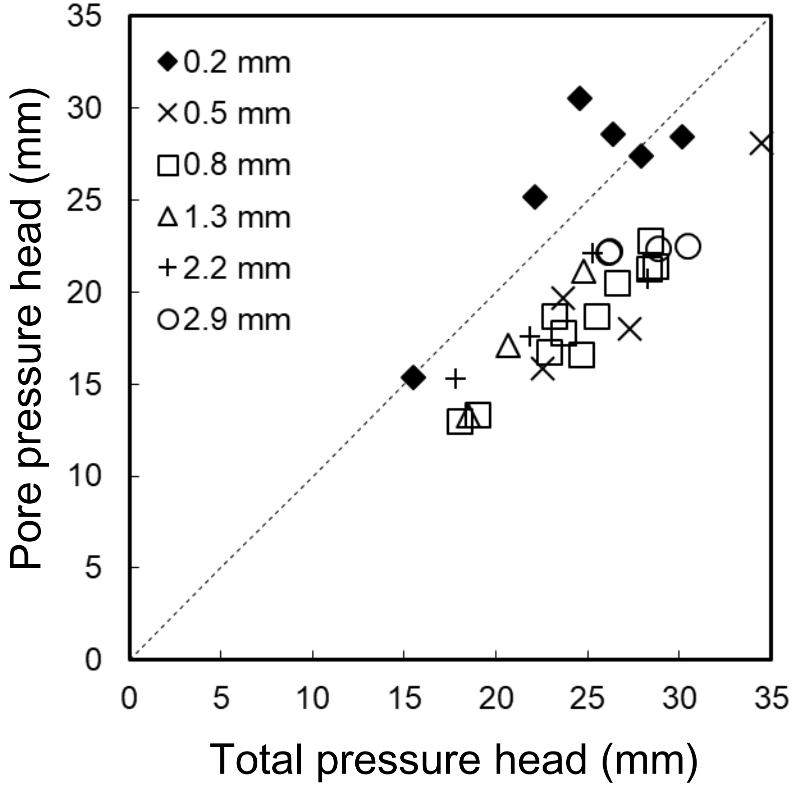
Since flows at quasi-steady, uniform state are investigated, (i) & (ii) are possible mechanism for excess pore pressure in this work.

$\frac{p_{exp}}{\rho_w g}$



$\frac{p_{static}}{\rho_w g} = h$

$\frac{p_{exp}}{\rho_w g}$



$\frac{p_{total}}{\rho_w g} = \frac{\rho_m h}{\rho_w}$

Reynolds number for debris flow

Reynolds number for debris flow was defined as ratio of inertial stress, $\rho_m U^2$, to dispersive stress, $\rho_w (K_d + K_f) d^2 (U/L)^2$, instead of viscous stress for Newtonian fluid (Miyamoto & Itoh, 2003)

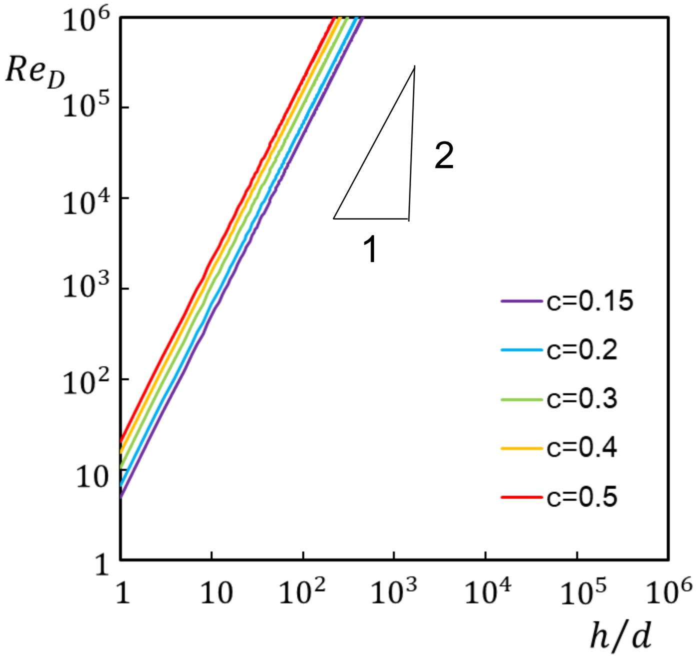
ρ_m : density of debris flow
ρ_w : density of water
L : length, U : velocity
d : grain size

$$\mathrm{Re_D} = \frac{\rho_m U^2}{\rho_w (K_d + K_f) d^2 (U/L)^2} = \frac{\rho_m/\rho_w}{K_d + K_f} \left(\frac{L}{d}\right)^2$$

cf.) Newtonian fluid $\quad \mathrm{Re} = \frac{inertial}{viscous} = \frac{\rho U L}{\mu}$

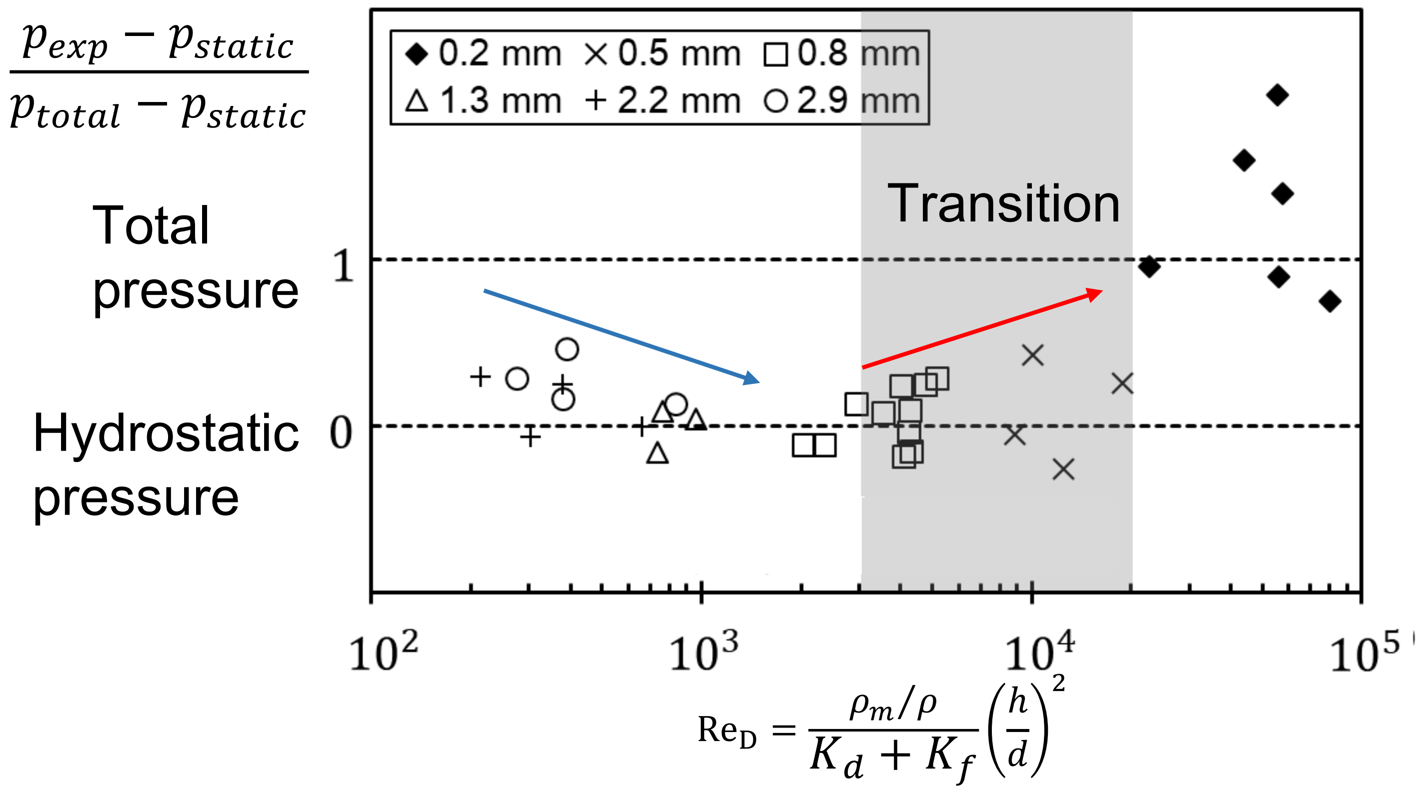
Applying flow depth h for L,

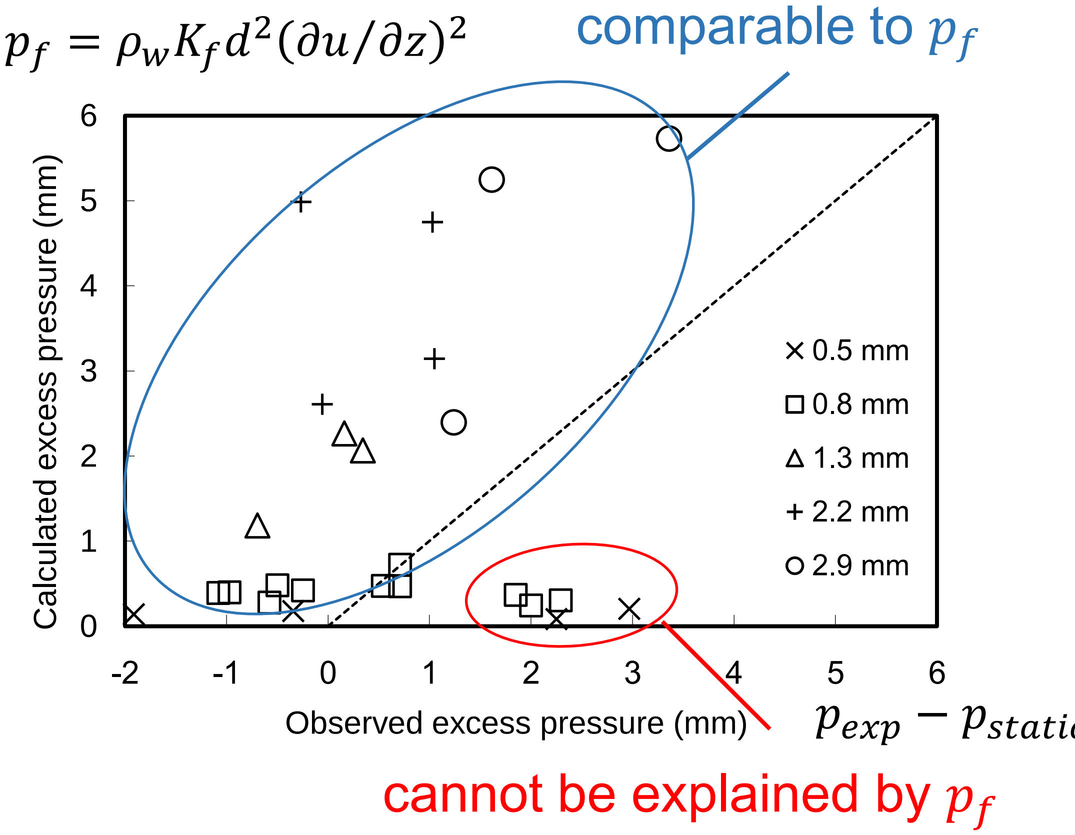
$$\mathrm{Re_D} = \frac{\rho_m/\rho_w}{K_d + K_f} \left(\frac{h}{d}\right)^2$$



➢Investigate relationship between pore fluid pressure & $\mathrm{Re_D}$

Relationship between $\mathrm{Re_D}$ and pore fluid pressure

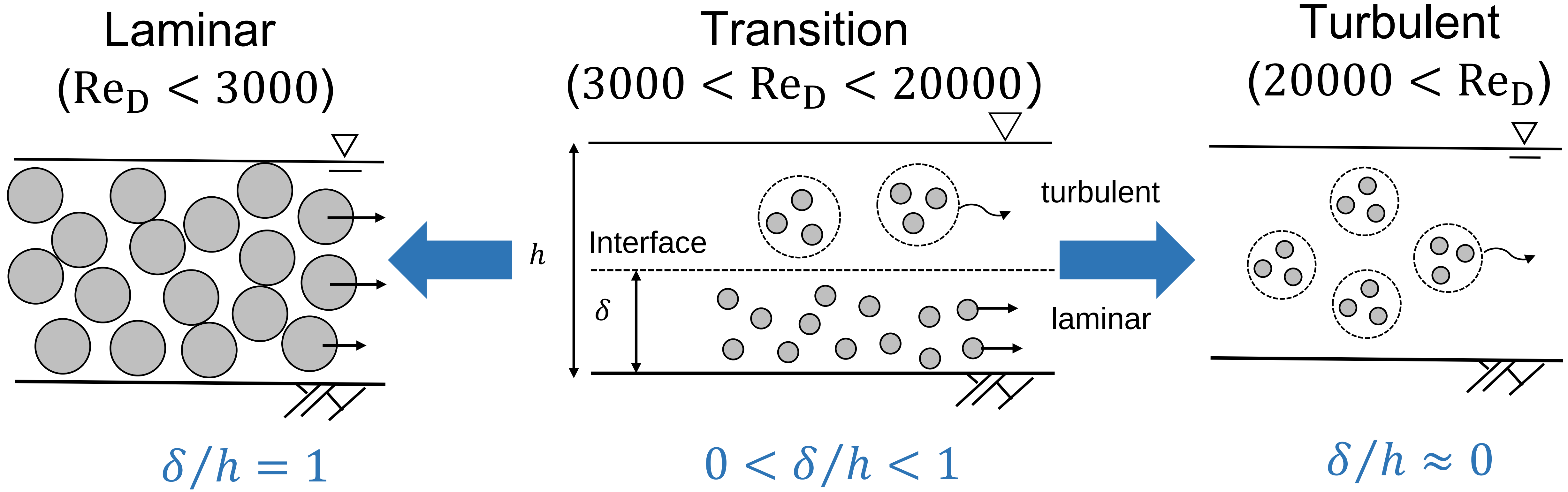




- $20000 < \mathrm{Re_D}$: ~ the total normal stress, indicating fully suspended by turbulence
- $\mathrm{Re_D} < 3000$: excess pressure corresponds to Reynolds stress, p_f; entirely laminar
- $3000 < \mathrm{Re_D} < 20000$: intermediate between hydrostatic and total normal stresses, indicating the transition from fully laminar to partially turbulent flow

→Critical Reynolds number is determined as $\mathrm{Re_{Dc}} = 3000$

Two-layered model for laminar-turbulent transition in debris flow



The laminar-turbulent transition in debris flow may be described in a unified view, using a two-layered model in which the position of the between-layer interface is varied depending on Re_D

Summary

♣ We studied the laminar-turbulent transitions of debris flows by measuring basal pore fluid pressures and compiled the result by Reynolds number for debris flow, $\mathrm{Re_D}$.

♠ When $\mathrm{Re_D} < 3000$, pore fluid pressures were comparable to hydrostatic pressure, while those equaled total pressure for $20000 < \mathrm{Re_D}$. The transition was observed when $3000 < \mathrm{Re_D} < 2000$, showing intermediate value between hydrostatic and total pressure.

♥ $\mathrm{Re_{Dc}} = 3000$ is determined as critical value, in which the transition from laminar to turbulent starts.

◆ We describe the transitional flow behavior of monodisperse granular debris flows using a two-layered model in which the position of the between-layer interface is varied depending on $\mathrm{Re_D}$.