Subaqueous sediment gravity flows undergoing progressive solidification

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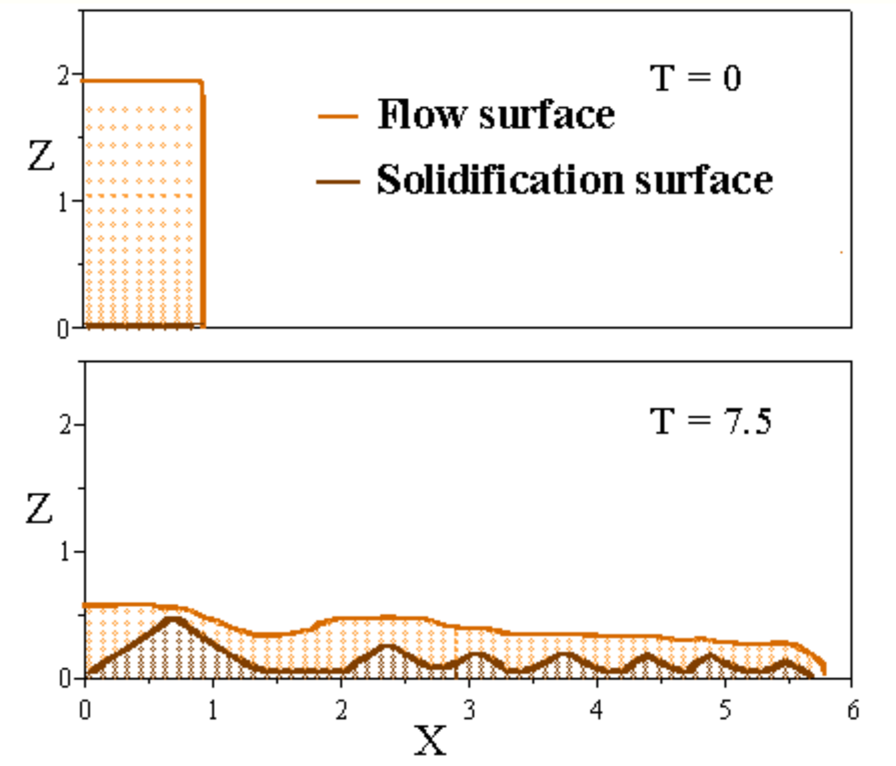
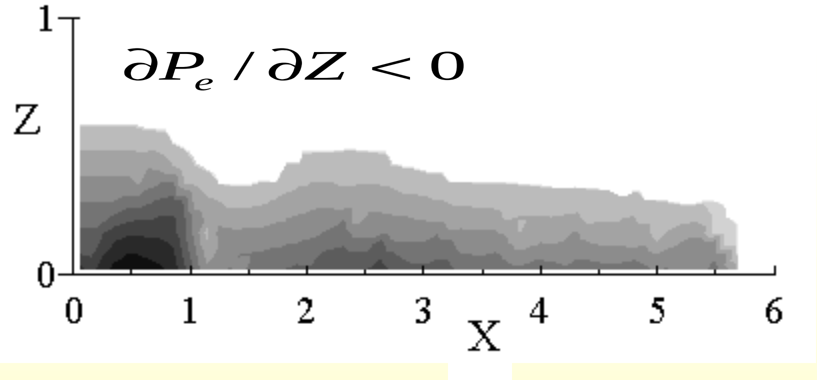
Background: Salient physics of two-phase material as highlighted by a theoretical framework LIQSEDFLOW (2003)

Purpose of present study: To clarify the process of progressive solidification in hyperconcentrated sediment flows by physical modelling



Upward seepage flow during flowage



Development of solidified zones in the course of sediment gravity flow

x, z: Normalized coordinates

Predictions from LIQSEDFLOW (Sassa et al., 2003)

LIQSEDFLOW (Sassa, et al., 2003)

2-D Navier-Stokes Equations:

$$\frac{\partial U}{\partial X} + \frac{\partial W}{\partial Z} = 0$$

$$\frac{\partial U}{\partial T} + U\frac{\partial U}{\partial X} + W\frac{\partial U}{\partial Z} = -\frac{\rho_2 - \rho_1}{\rho_2}\frac{\partial P_e}{\partial X} + \frac{1}{R_e}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Z^2}\right)$$

$$\frac{\partial W}{\partial T} + U\frac{\partial W}{\partial X} + W\frac{\partial W}{\partial Z} = -\frac{\rho_2 - \rho_1}{\rho_2}\frac{\partial P_e}{\partial Z} + \frac{1}{R_e}\left(\frac{\partial^2 W}{\partial X^2} + \frac{\partial^2 W}{\partial Z^2}\right) - \frac{\rho_2 - \rho_1}{\rho_2}$$

2-D Consolidation Equation:

$$\frac{\partial\left(\sigma_m - P_e\right)}{\partial T} = --\frac{\rho_2 - \rho_1}{\rho_2}\ M\left(K_X\frac{\partial^2 P_e}{\partial X^2} + K_Z\frac{\partial^2 P_e}{\partial Z^2}\right)$$

Constrained Modulus of Soil Skeleton:

$$M = \left(Z_s - Z\right)M_r \quad for\ 0 \le Z \le Z_s$$

$$M \propto \frac{1 + e_0}{a_v}$$

LIQSEDFLOW (Sassa, et al., 2003)

A. Assume a thin transition layer, which has zero effective stress but has a marginally discernable stiffness, at the bottom of the liquefied soil

B. Solve N-S equations in the liquefied region above the transition layer. (MAC, Gauss-Jordan, VOF)

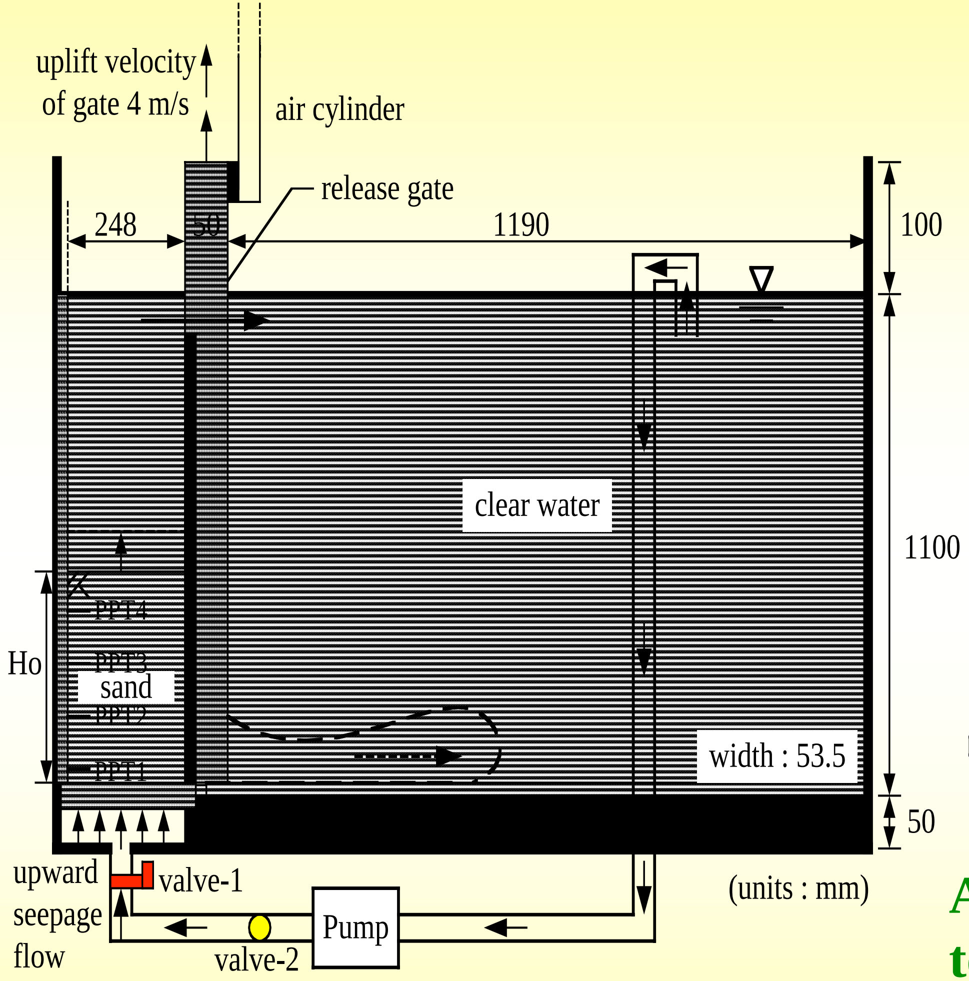
C. Solve the consolidation equation, by using the implicit finite-difference method, in the transition layer under the predicted liquefied flow. (VOF)

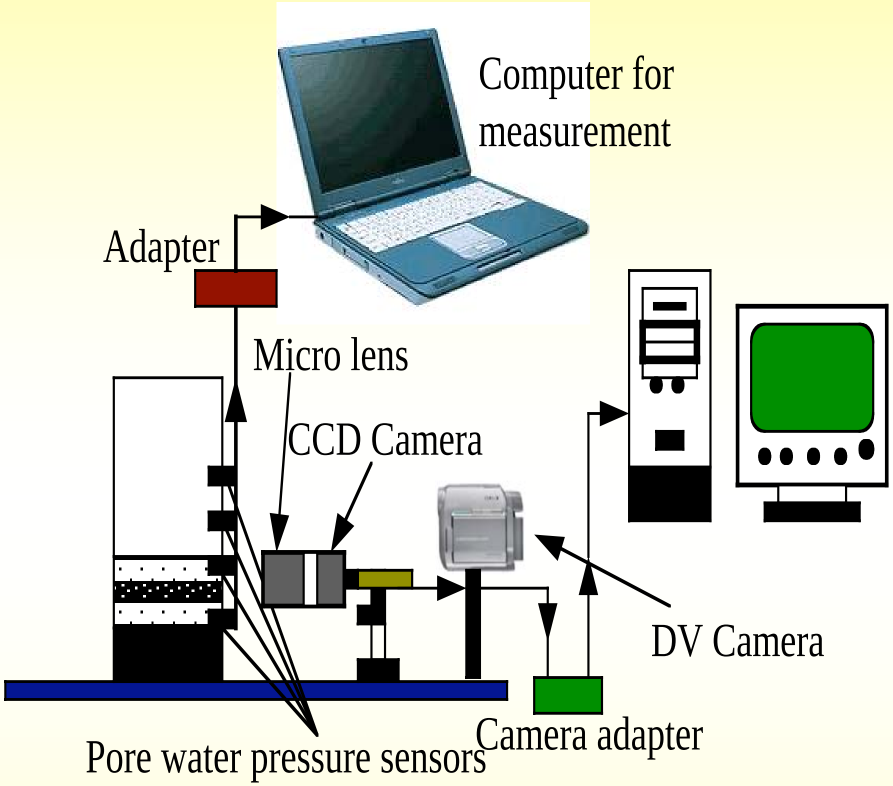
D. If the effective stress increment in the transition layer becomes positive, then identify it to be a consolidated layer and shift a transition layer to the level immediately above the consolidated layer.

E. Correct the slope of the solidification surface if necessary, so as not to exceed the critical friction angle adopted.

F. Continue the steps (B)-(E) until the targeted time. Note that the transition layer in (C) represents now the transition layer as well as the consolidated layer developed.

Experimental setup for fluidization, hindered settling and subaqueous sediment gravity flows





Applications of high-speed CCD and PIV technique

Fluidization of sediment by imposing upward seepage flow

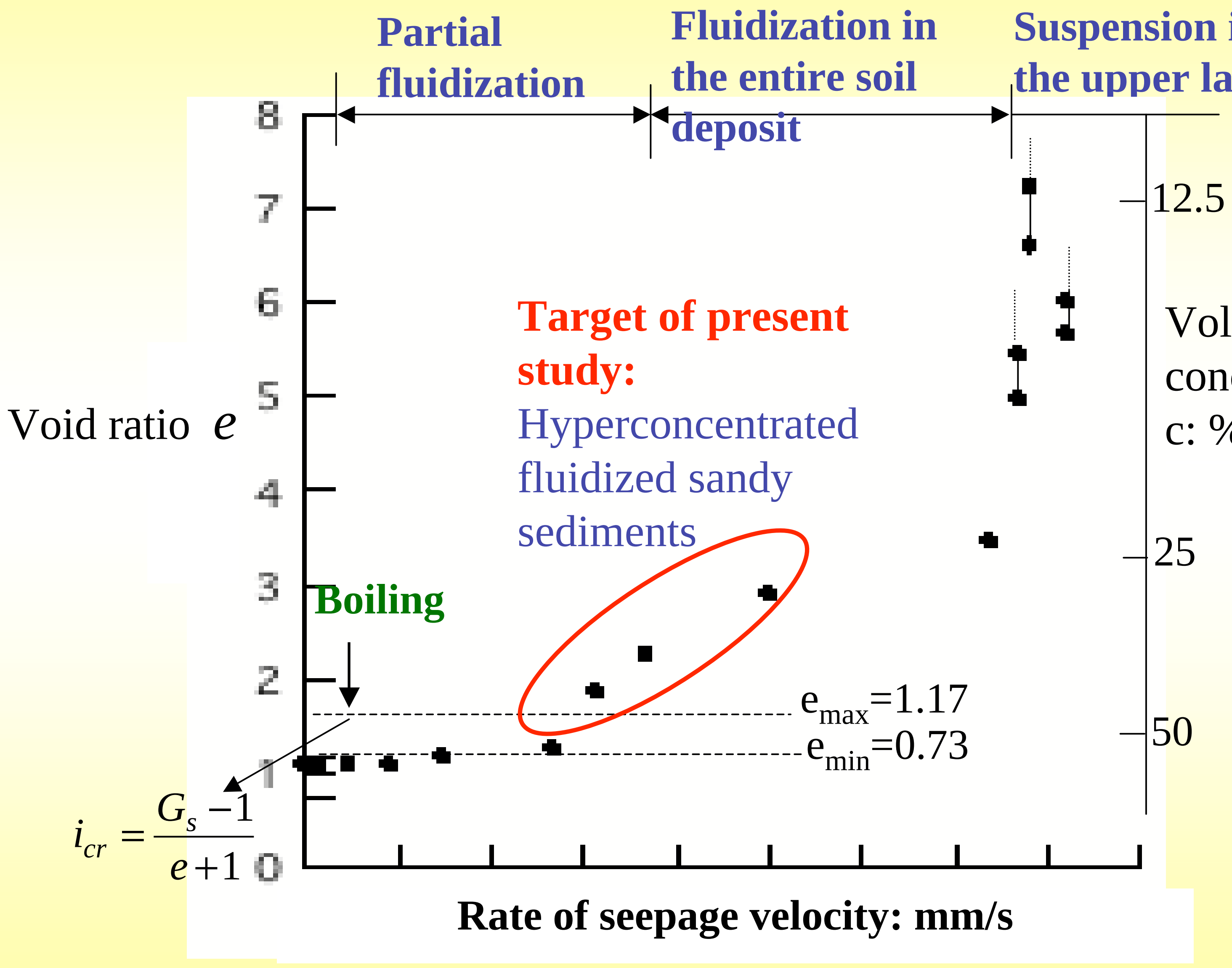
Hindered settling

Subaqueous sediment gravity flows

Release gate

Flow-out, stop

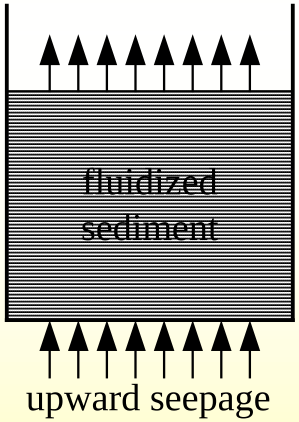
Transformation of the state of sediment



$$i_{cr}=\frac{G_s-1}{e+1}$$

Note:

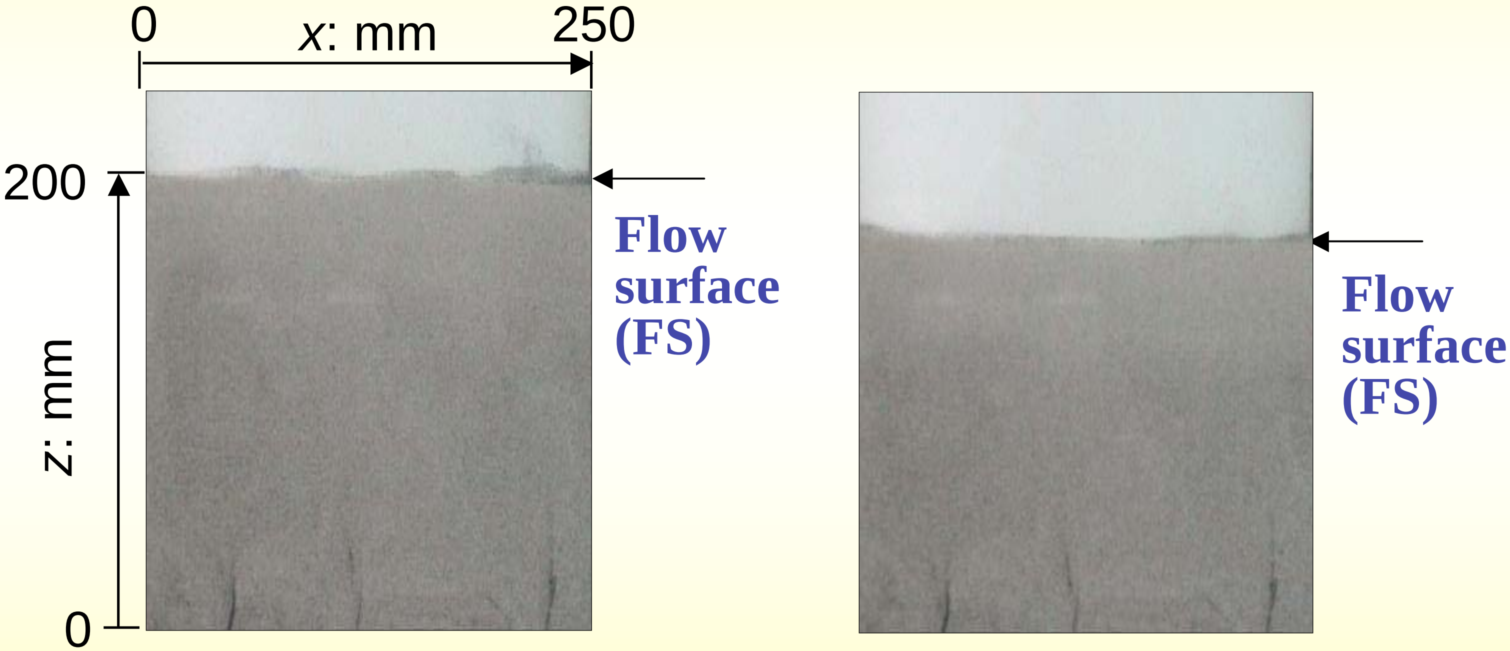
$$C=\frac{1}{1+e}$$



Average grain size of the sand used: 0.32mm

Results from *Hindered settling experiments*

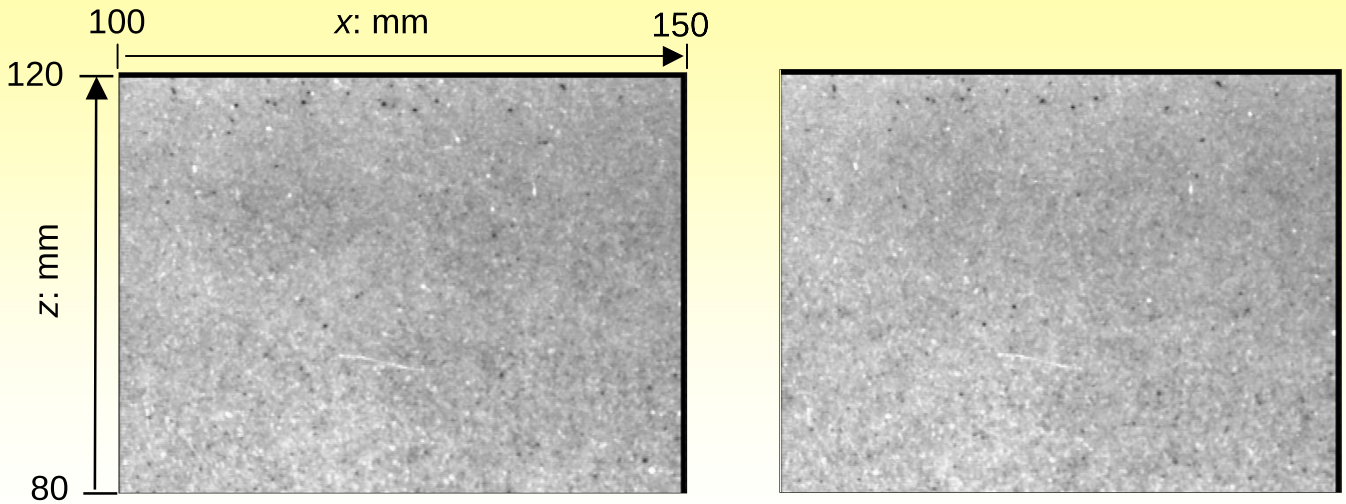
Snapshots of hyperconcentrated sand-water mixture using a digital video camera (frame rate : 1/30 s) in test PPTCCD-1 (c = 38%)



(a) t=1s (b) t=5s

Identification of the downward advancement of the settling surface following the cessation of fluidization

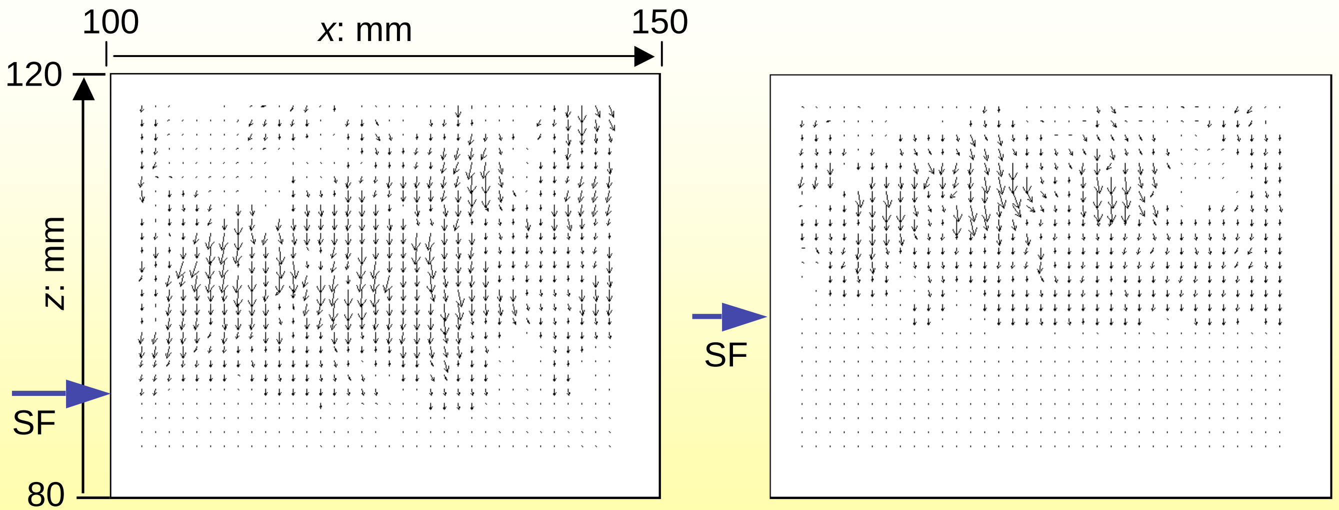
Closer views from a high-speed CCD camera (test PPTCCD-1)



(a) *t*=1.28s (b) *t*=5.12s

Velocity fields obtained using PIV technique (test PPTCCD-1)

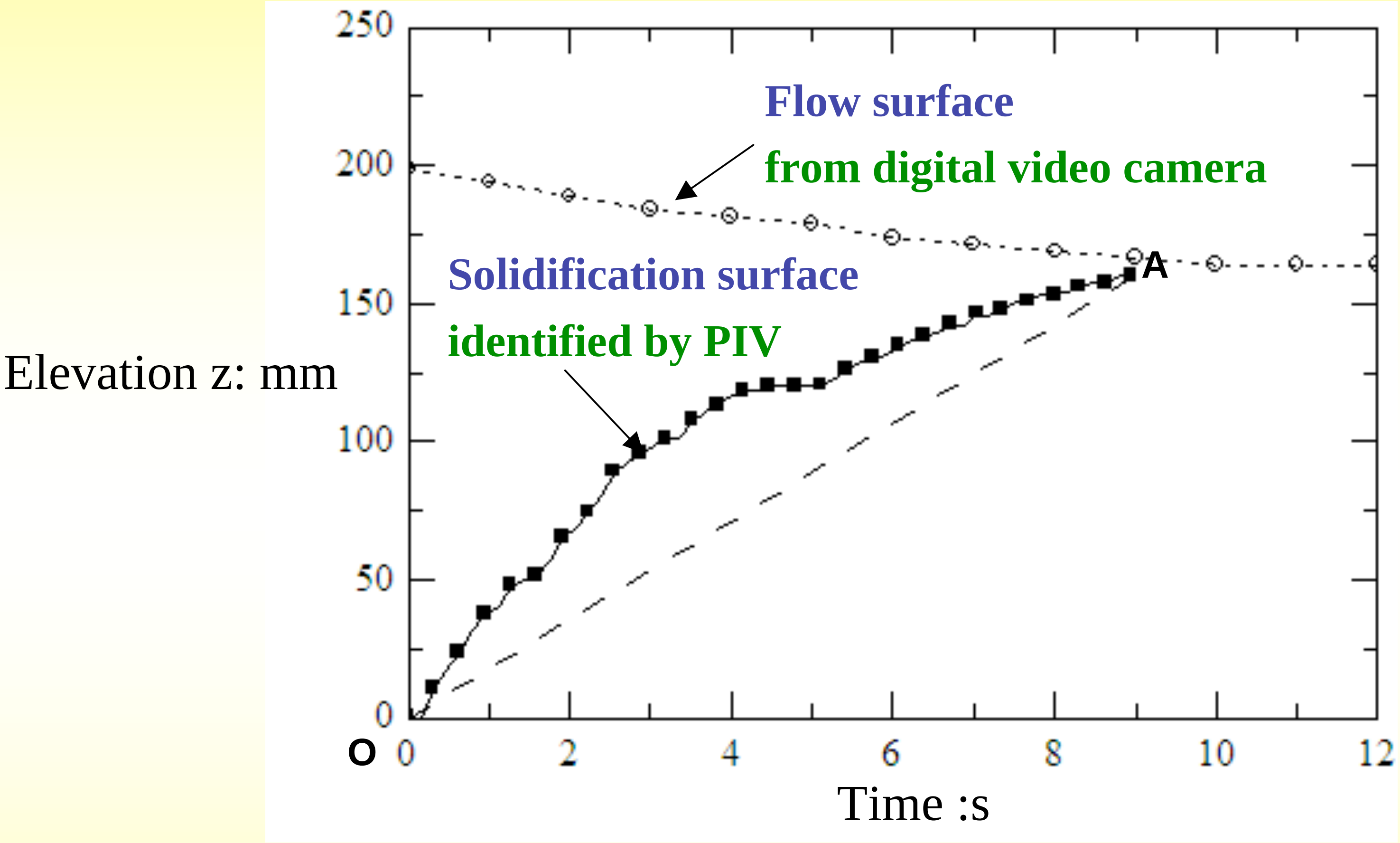
Identification of the solidification front (SF)



(a) *t*=1.28s (b) *t*=5.12s

Below SF, zero velocities

Evolutions of flow and solidification surfaces in test FEB05-2

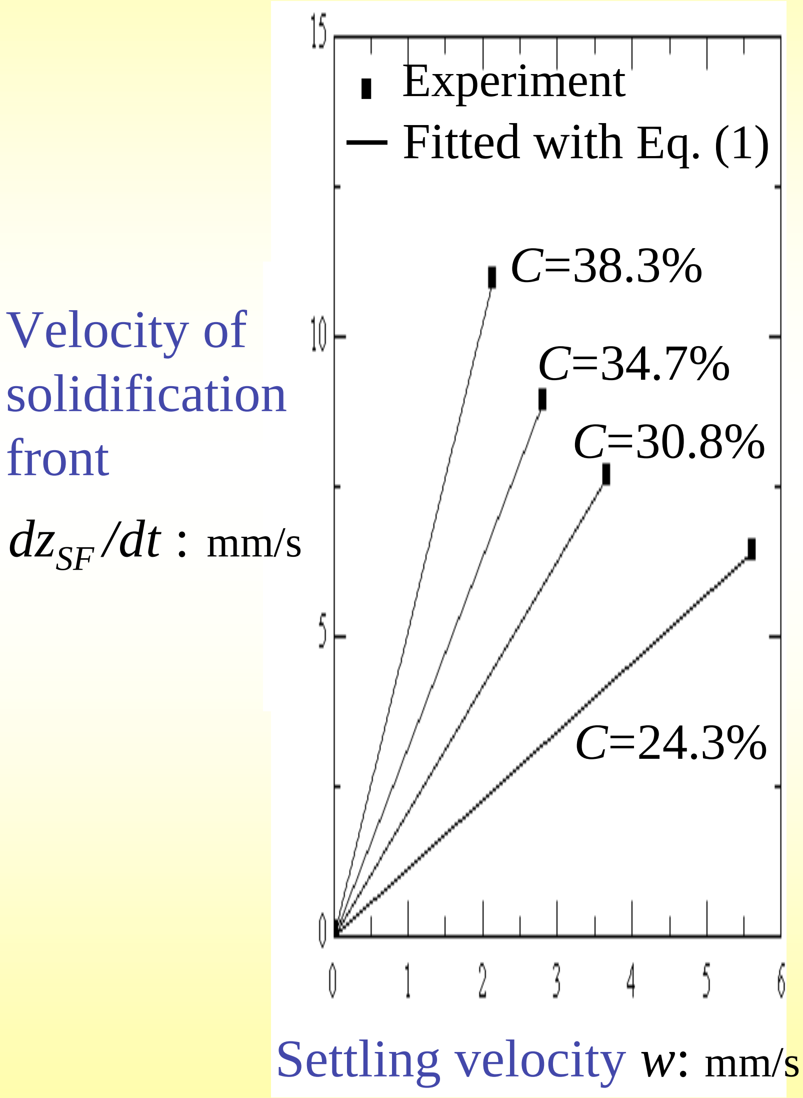


Average downward velocity of the flow surface $dz_{FS}/dt = 2.6$ **mm/s**

$$\ll$$

Average upward velocity of the solidification front $dz_{SF}/dt = 17.8$ **mm/s**

Relationships between upward velocity of solidification front and settling velocity



Mass conservations for hindered settling and solidification

⇩

Velocity of solidification front

$$\frac{dz_{SF}}{dt} = \frac{C}{C_{gf} - C} \bullet w$$

w; Settling velocity

Eq. (1)

C : Volume concentration of fluidized sediment

C_{gf} : Volume concentration of solidified soil

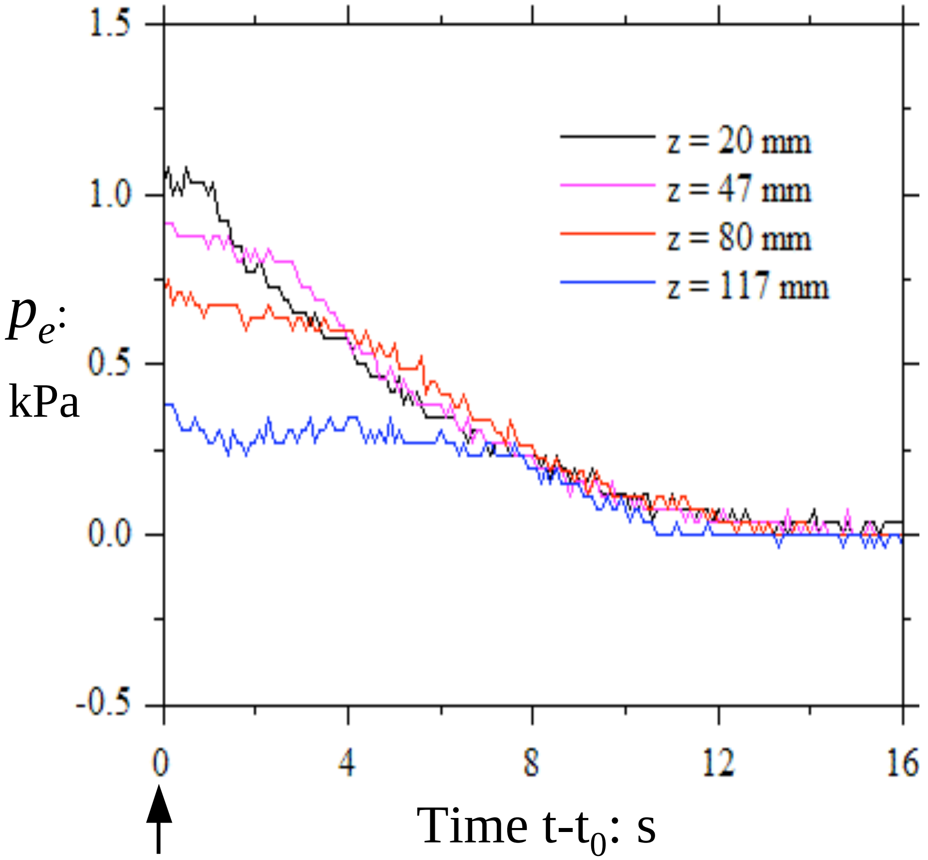
C_{gf} value (best fit) = 45.9%

⇩

Corresponding to **e_{max} -state**
with C_{gf} = 46.1%

Dissipation characteristics of excess pore pressure in the processes of hindered settling/sedimentation following fluidization

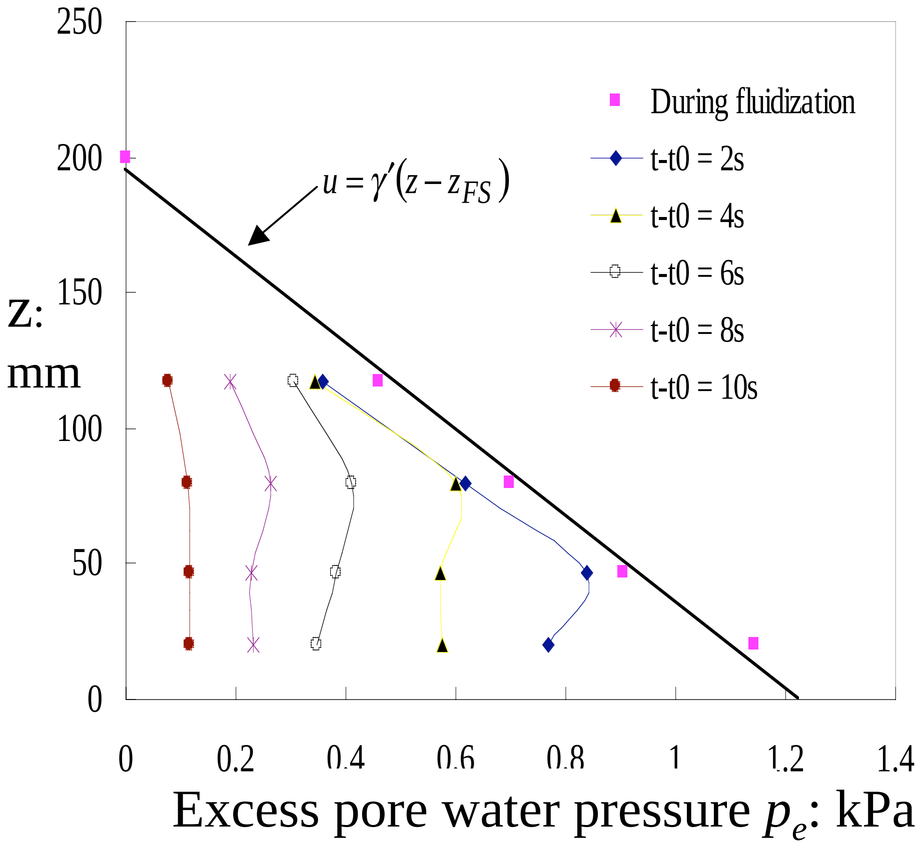
Measured time histories of excess pore water pressure p_e in test FEB05-2-3



Start of sedimentation

Valve closed

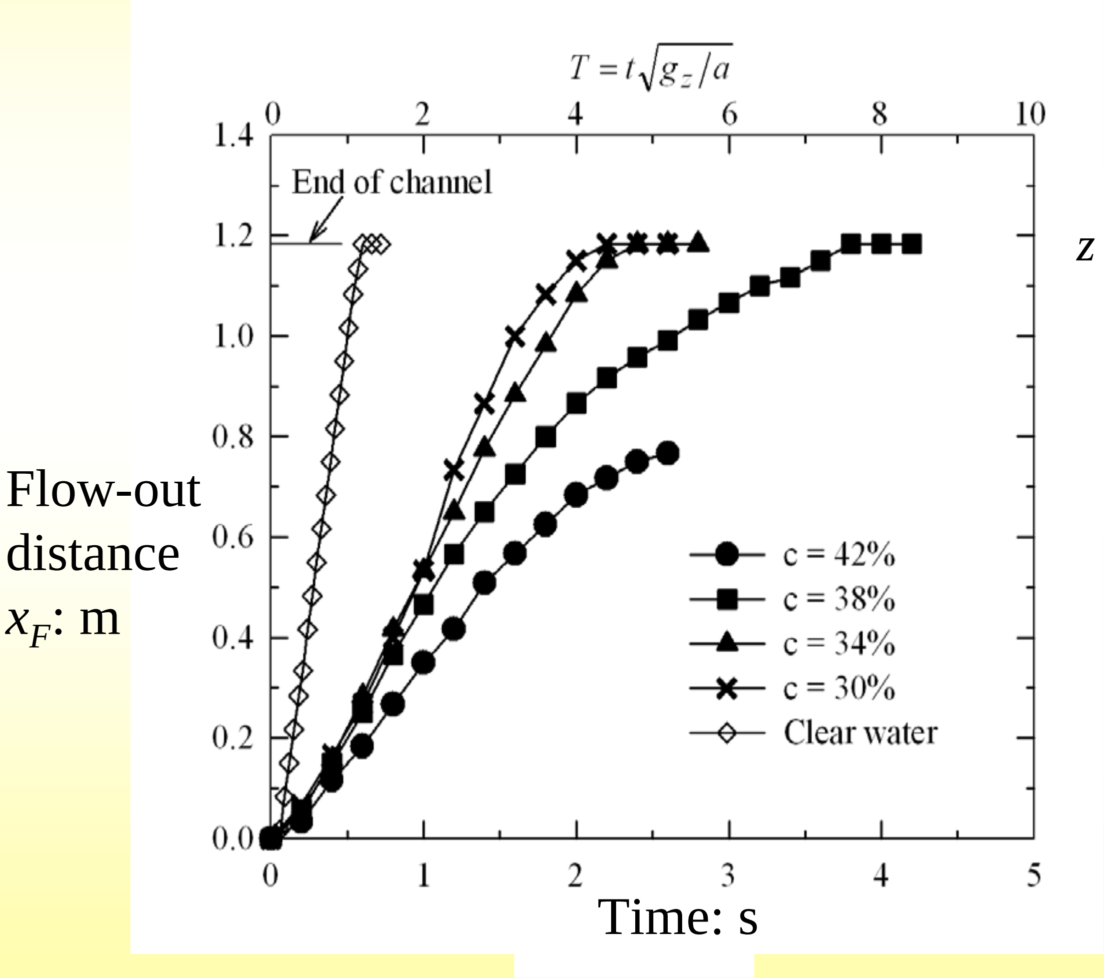
Temporal changes in the profile of u against z for case FEB05-2-3

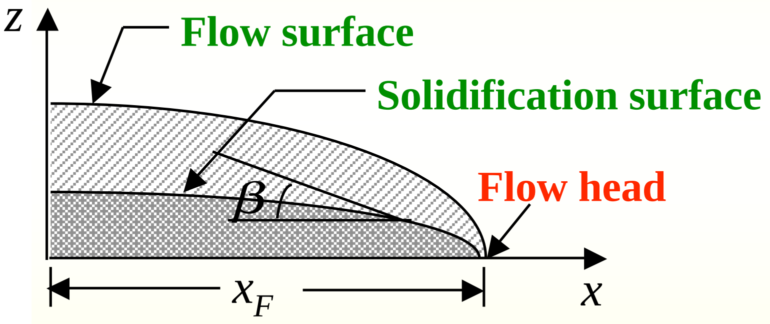


Volumetric concentration of fluidized sand: c = 38%

Results from subaqueous sediment gravity flows experiment series

Measured time histories of locations of gravity flow heads with four different solids concentrations



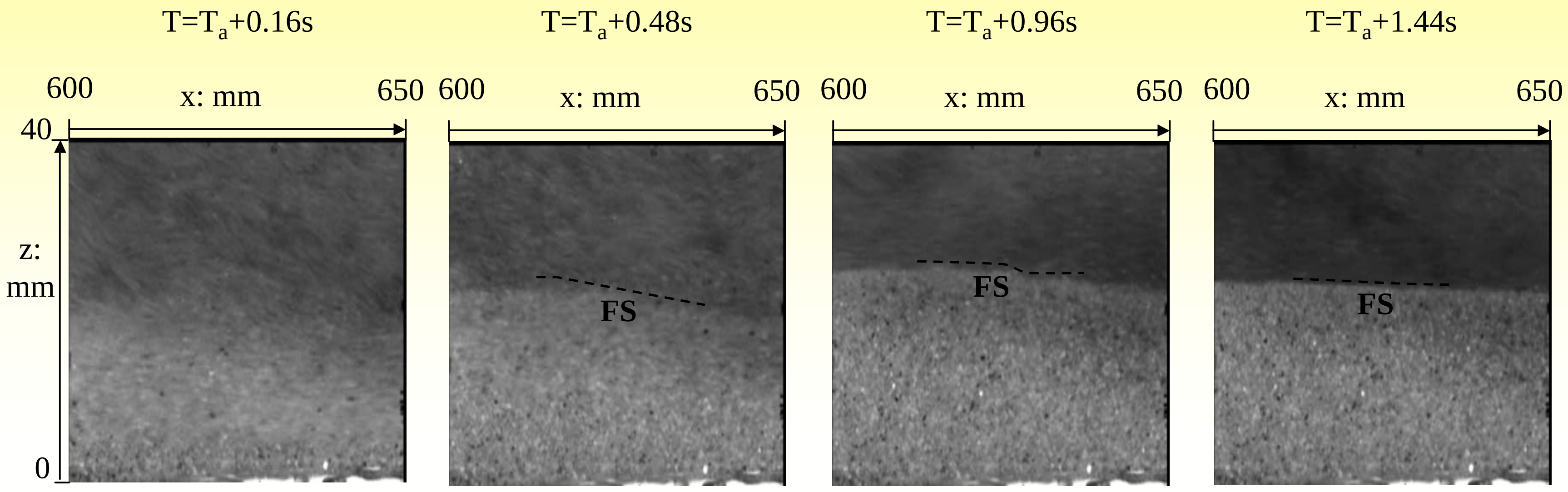


$\beta \leq \beta_{cr}$ = critical angle in view of frictional resistance of the soil

x_F = flow-out distance

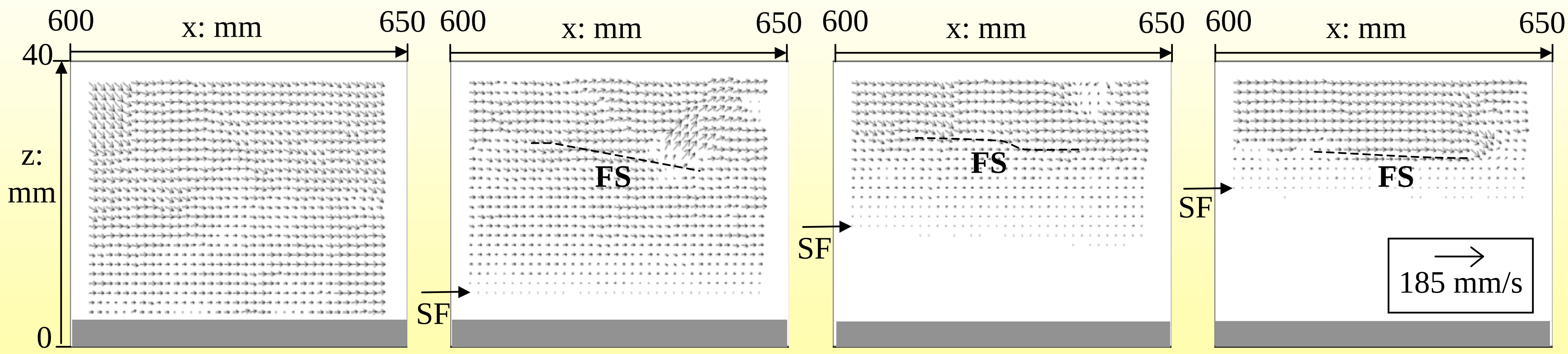
The effect of solids concentration upon flow-out potential

Snapshots of fluidized sediment gravity flow (test PPTCCD-11) from a fixed station using the high-speed CCD camera



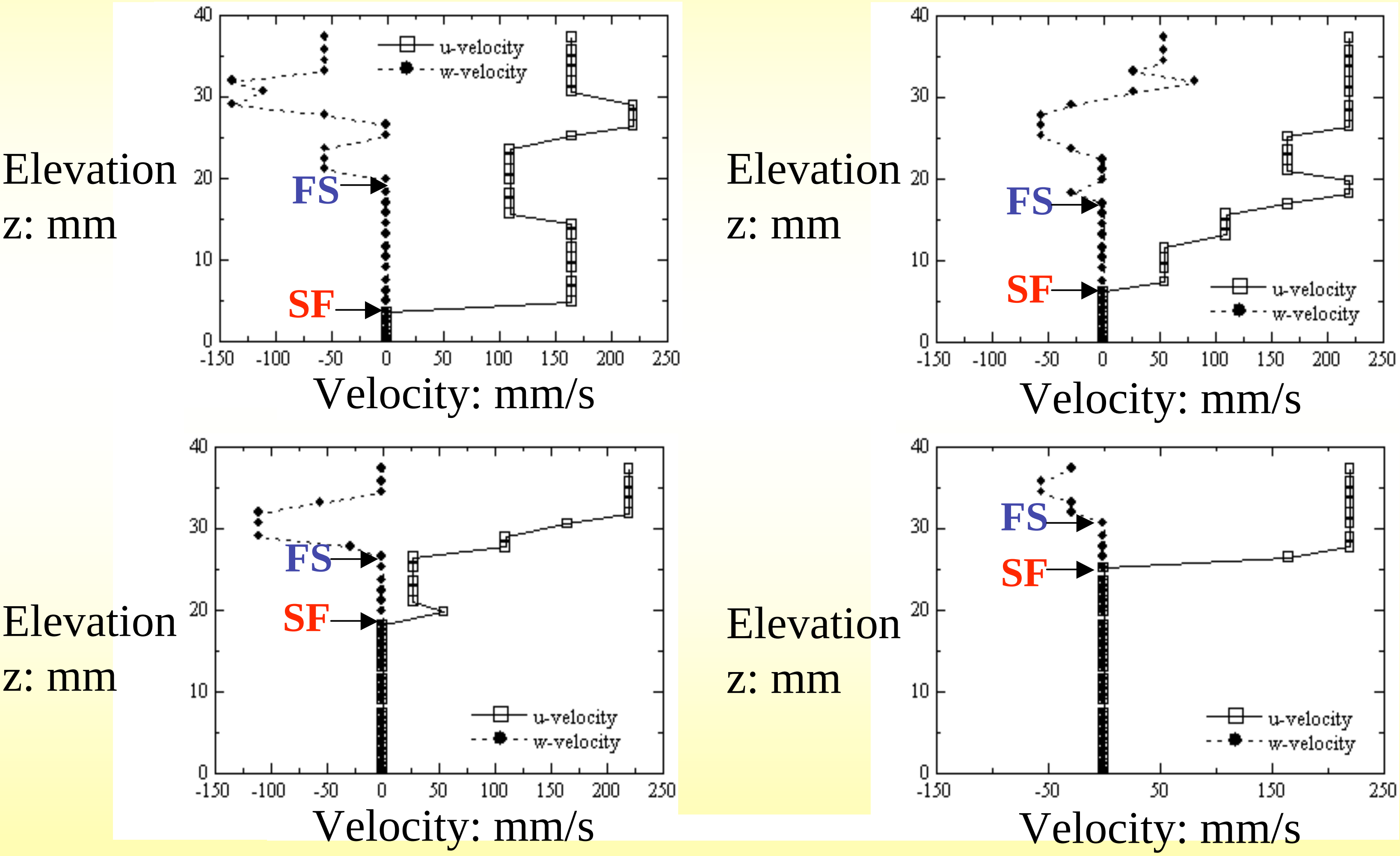
T_a: **Instant of time when the flow head arrived at the station of observation (x=650mm)**

Velocity fields of sediment gravity flow in test PPTCCD-11 obtained through PIV technique, showing upward advance of solidification front



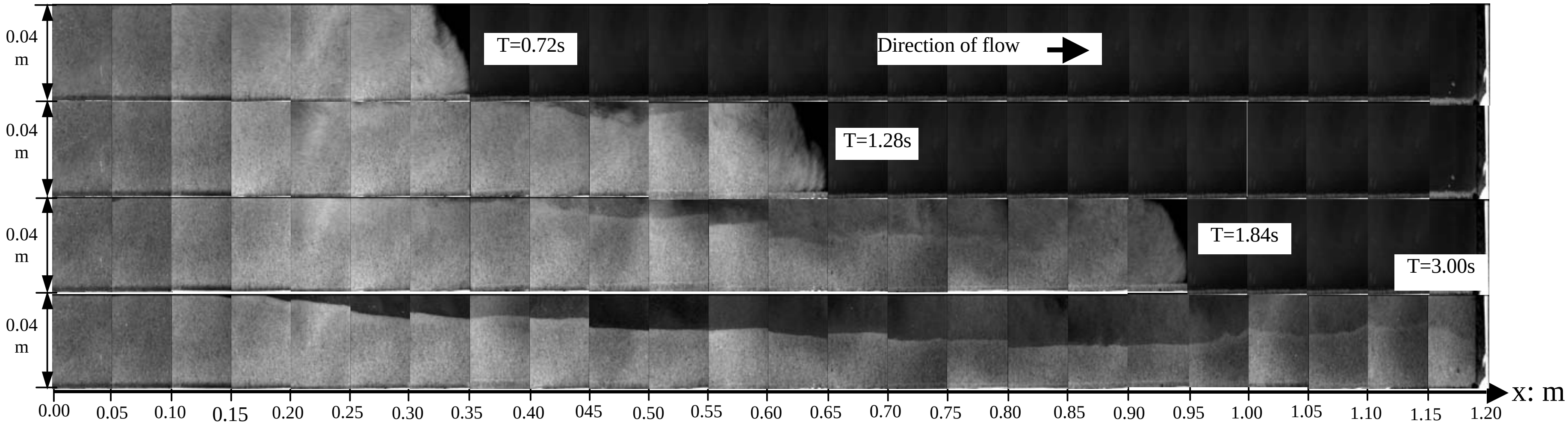
■ **Initially placed sand**

Profiles of flow velocities with elevation, at x=624mm, at four different instants of time

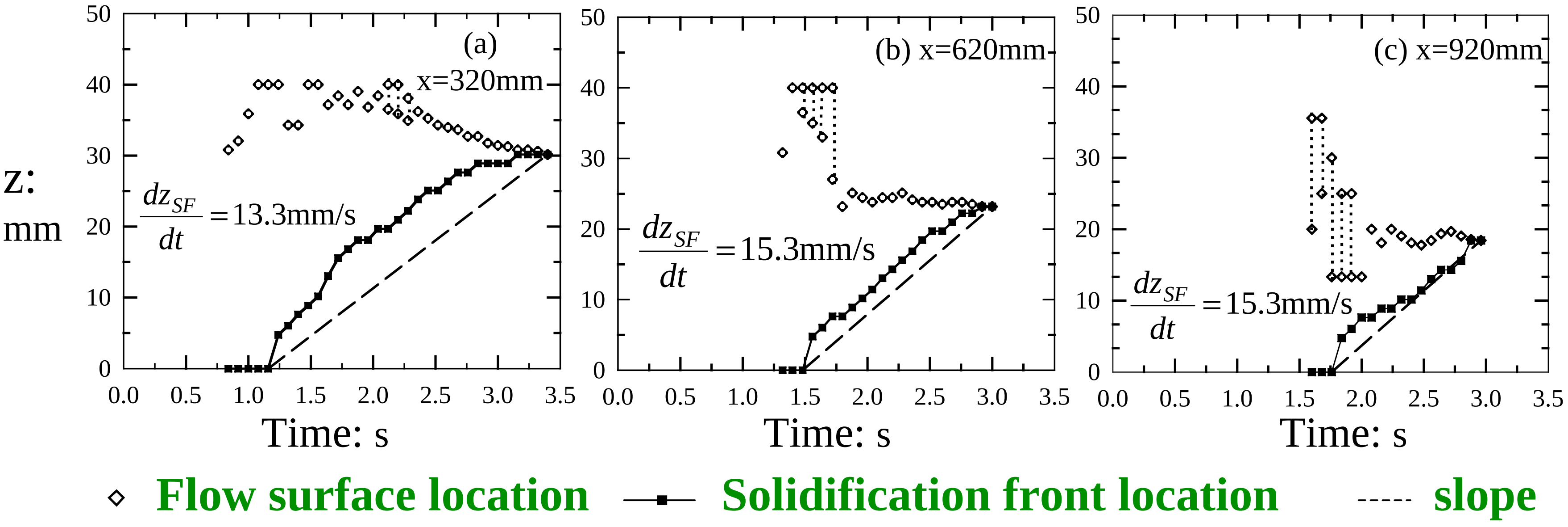


Concurrent evolutions of flow and solidification surfaces !

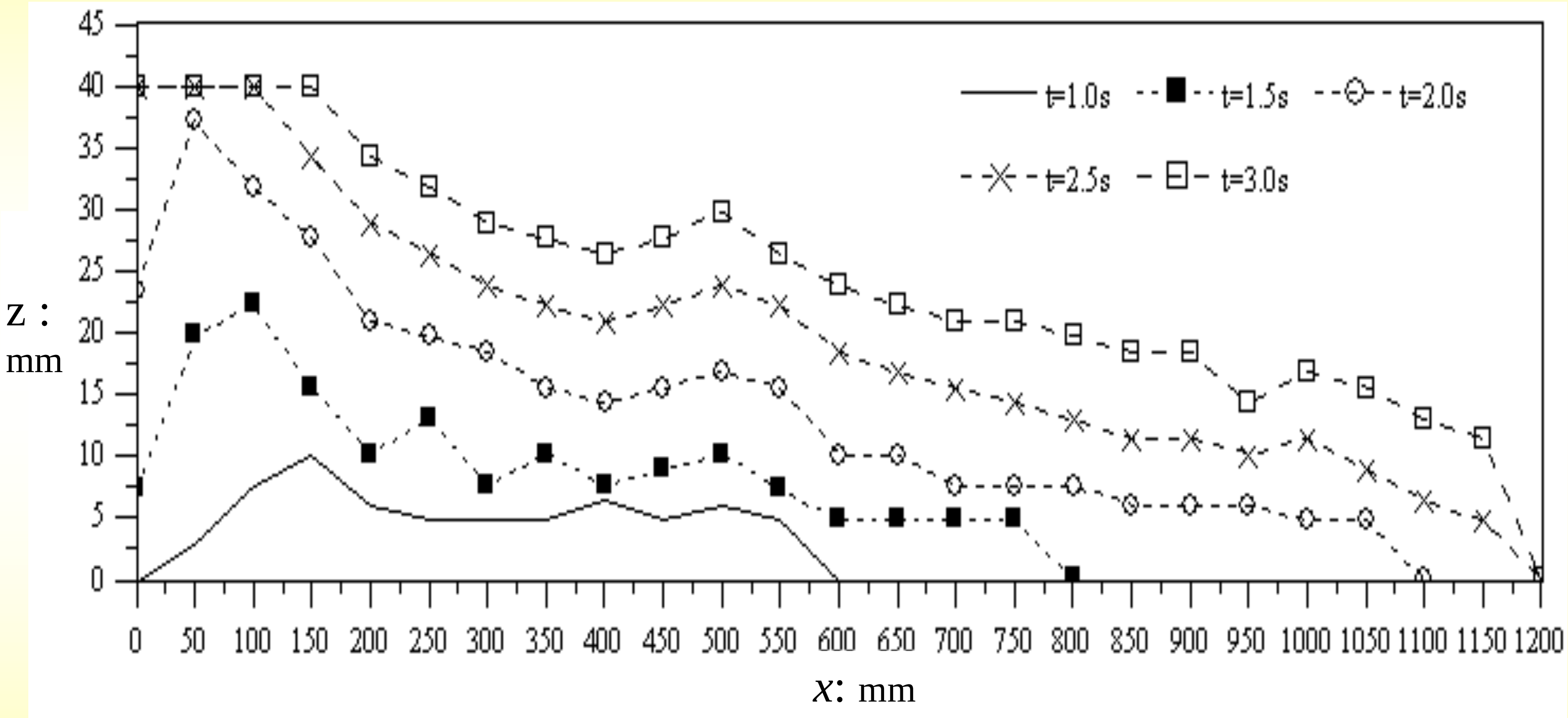
A total of 24 pictures showing flow configurations of initially fluidized sediment with c=38% at four elapsed times indicated



Evolutions of flow surface and solidification front at three different stations c=38%



Results of 24 identical flume tests (c = 38%) obtained through PIV technique



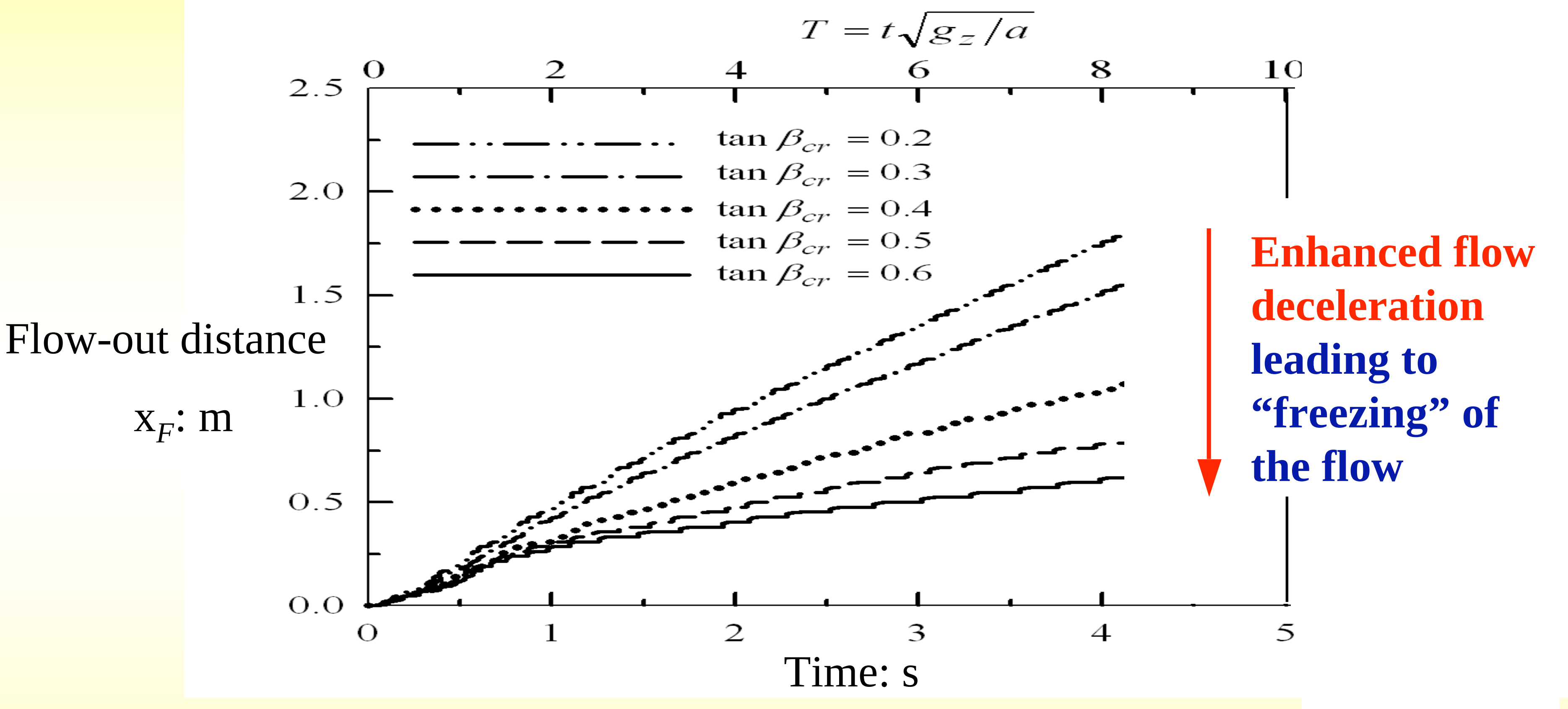
Verification of the 2003 predictions from LIQSEDFLOW !

◎ Very mild slope ◎ Void ratio of redeposited sand: 1.11

◎ Speed of development of solidification front： 16-12mm/s

The effect of progressive solidification upon flowage:

Predicted results from LIQSEDFLOW



Enhanced flow deceleration leading to “freezing” of the flow

β_{cr} : Concentration-dependent friction angle of solidified soil

Predictable based on two-phase physics !

without introducing any artificial viscosity or yield stress

Summary

a. Through physical modelling of subaqueous gravity flows of hyperconcentrated fluidized sandy sediments, we were able to clarify the way in which a grain-supported framework was reestablished during flowage.

b. The observed characteristics of flow stratification/ deceleration involving progressive solidification in the fluidized sediment gravity flows generally support the theoretical framework of a computational code LIQSEDFLOW(Sassa, et al., 2003).

c. The observed complete “freezing” of the sediment gravity flow calls for more development in numerical modelling, in view of the measured effects of hindered settling upon the development of solidification during flowage.