Modeling and Simulating the Hazardous Flows over Non-Trivial Topography

國立中央大學　　水文與海洋科學研究所

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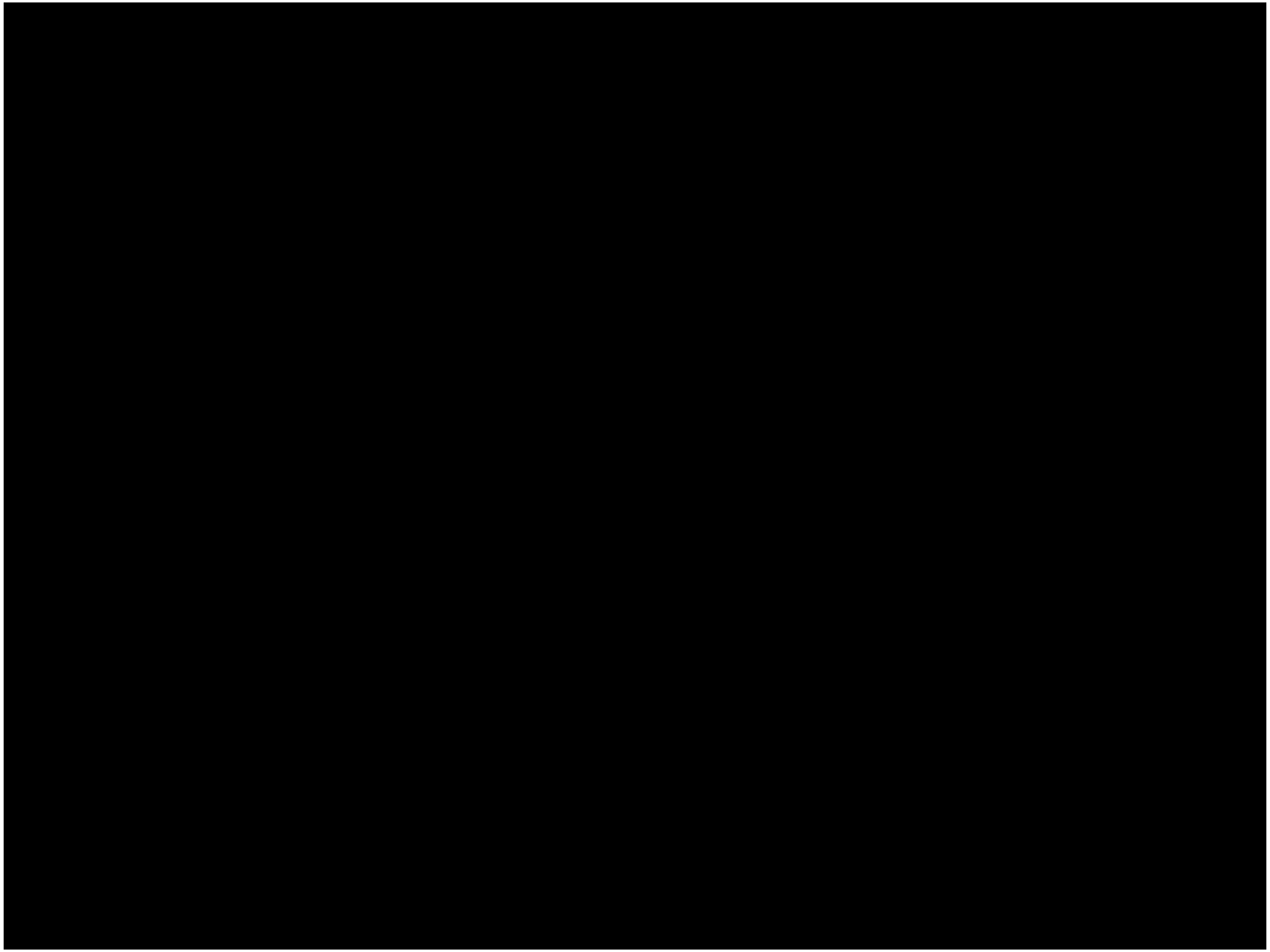
Contents

- Motivation and background
- Coordinate system for general topography
- Model equations and Numerical example
- Reconstruction of the Hsiaolin landslide catastrophe
- Concluding remarks

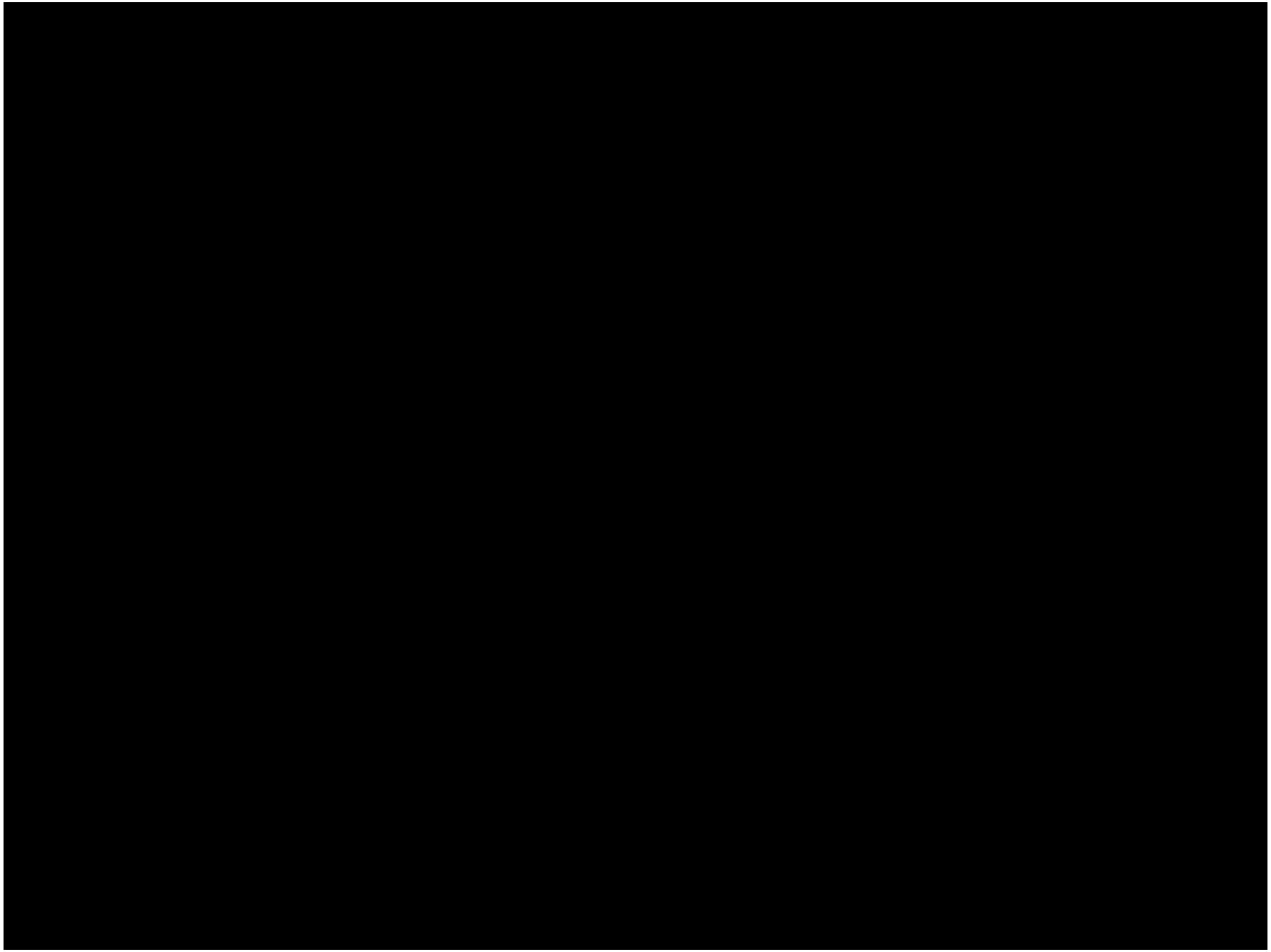
Earthquake induced landslide in middle Taiwan, 2nd June 2013

(Magnitude 6.3, Depth 10 km) (from Youtube)



Heavy rainfall induced landslide in southern Taiwan, 1st September 2013

(after the Typhoon Kong-Rey 康芮) (from Youtube)



[redacted]

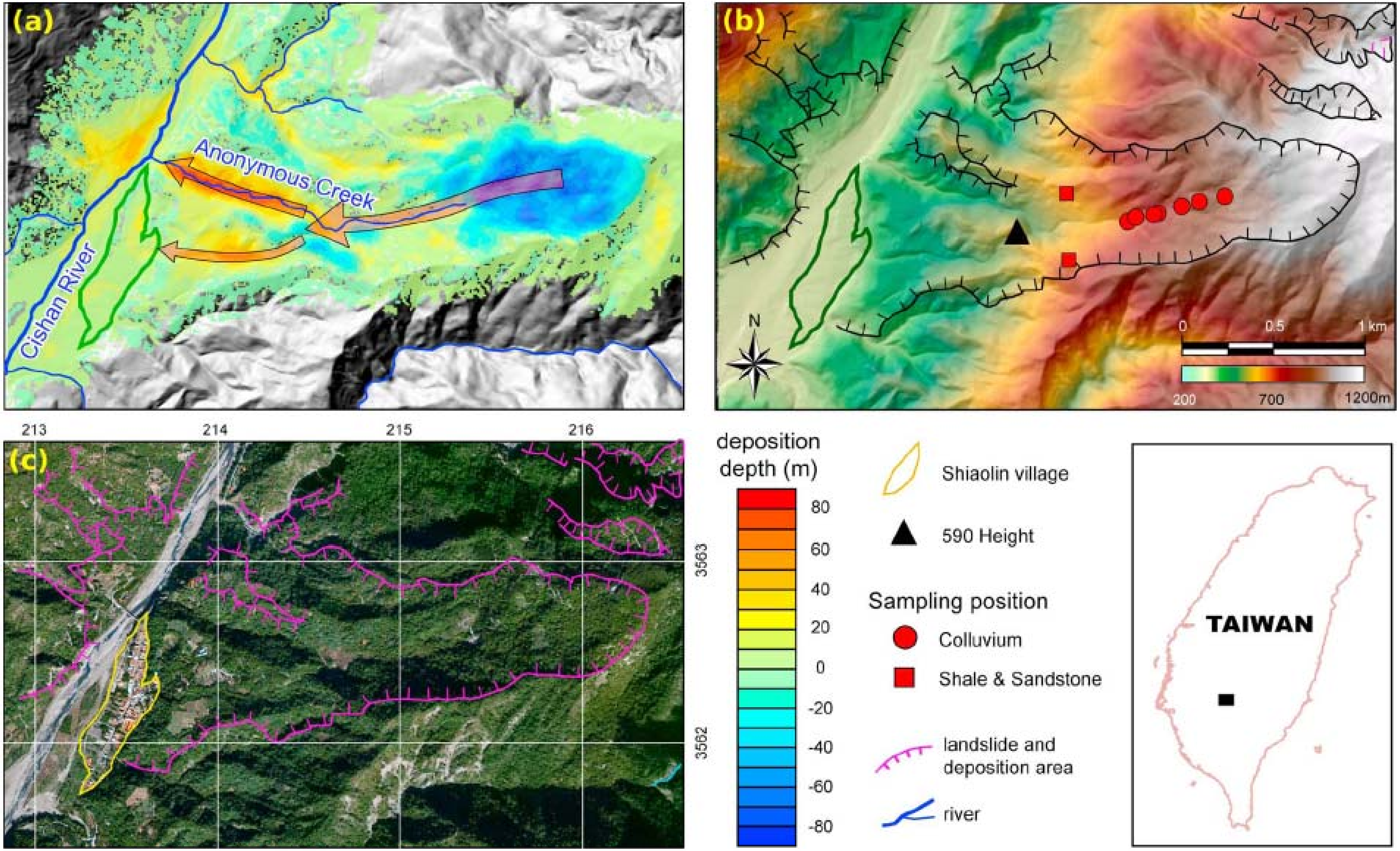
Hsiaolin catastrophe (2009)

- Typhoon Morakot
- Aug. 7^{th}-10^{th} 2009
- > 2,000 mm accumulated precipitation in southern Taiwan
- Total 724 deaths (474 in Hsiaolin catastrophe)

before　　八八水災圖片情報網　　after


Siaolin village
Volume: ca. 24 ±2 Mm³
Run-out distance: c.a. 2,700 m
Descending elevation: c.a. 800 m

C. Y. Kuo, Y. C. Tai, C. C. Chen, K. J. Chang, A. Y. Siau, J. J. Dong, R. H. Han, T. Shimamoto and C. T. Lee, JGR (2011)



Volume: ca. 24 $\pm$2 Mm^3, Run-out distance: c.a. 2,700 m
Descending elevation: c.a. 800 m

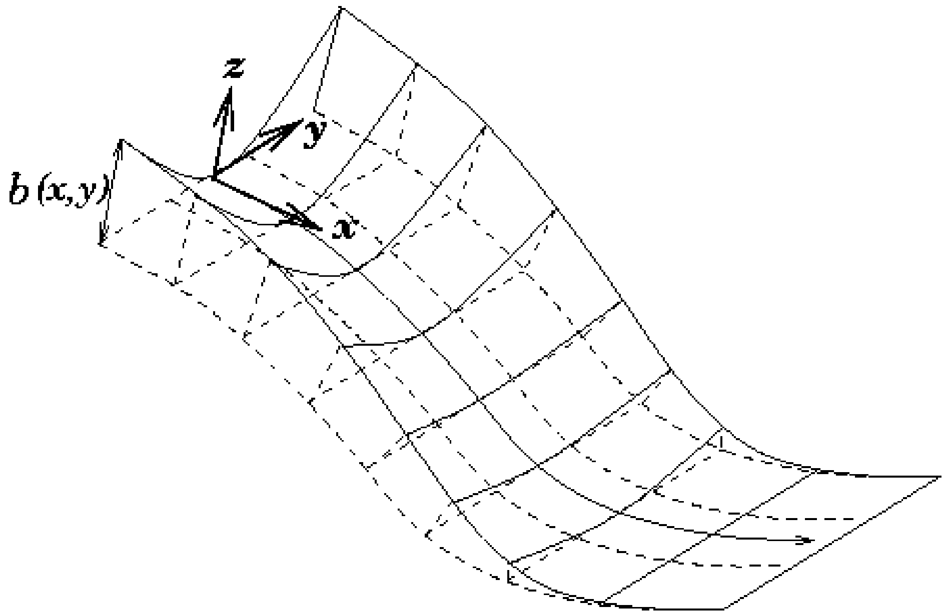
Three main challenges in simulating the behavior:

- Gravity-driven flows over complex topography
  - *an appropriate coordinate system (local curvature)*
  - *an appropriate mesh system for the complex topography (depth-integration or not)*

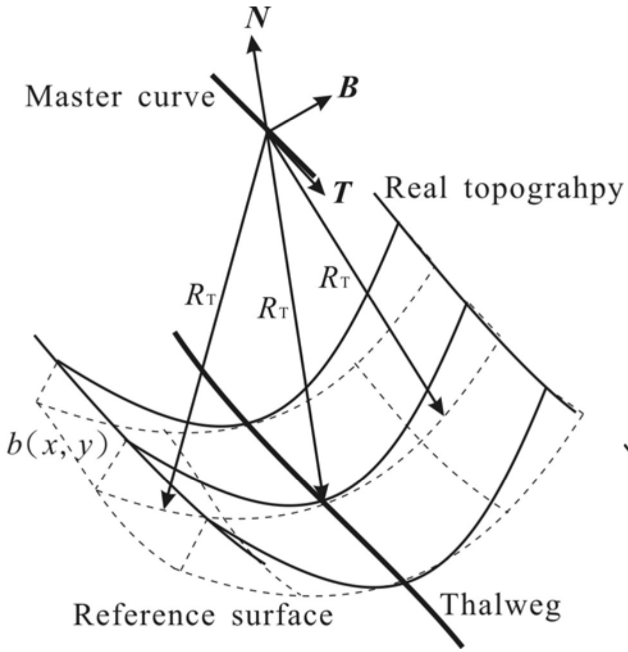
- Characteristics of the flow
  - *constitutive relation (rheology)*
  - *single-phase or mixture theory*

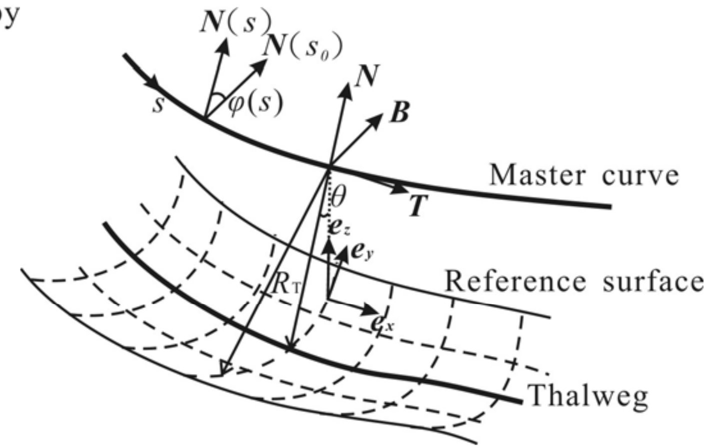
- Deformable basal surface
  - *entrainment and deposition*
  - *non-material surface*
  - *evolution of the basal surface*

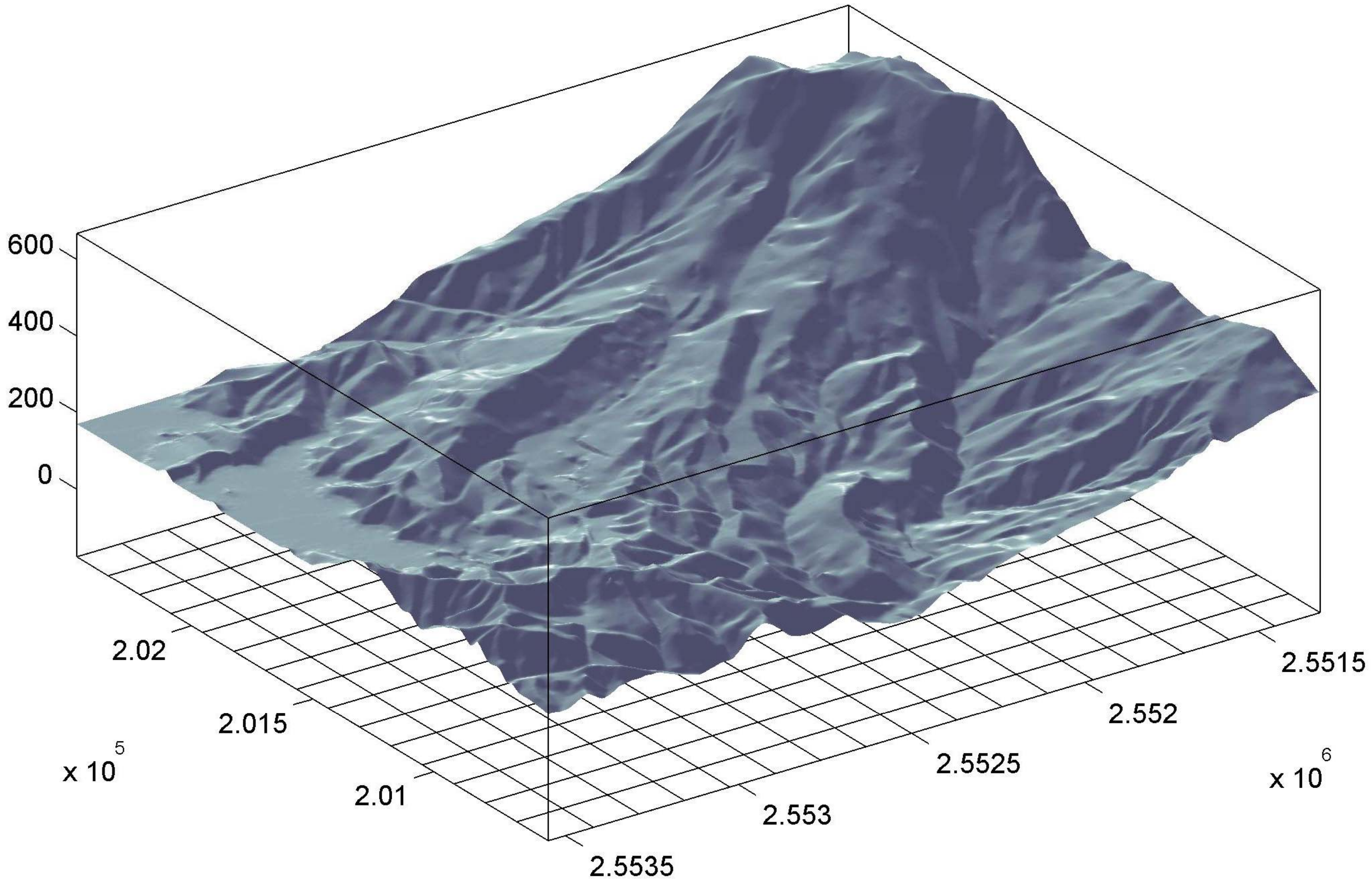
- **Coordinates of SH-Type** (*1989 — 1999*)



- **Curved and Twisted Coordinates** (2003 —)







600
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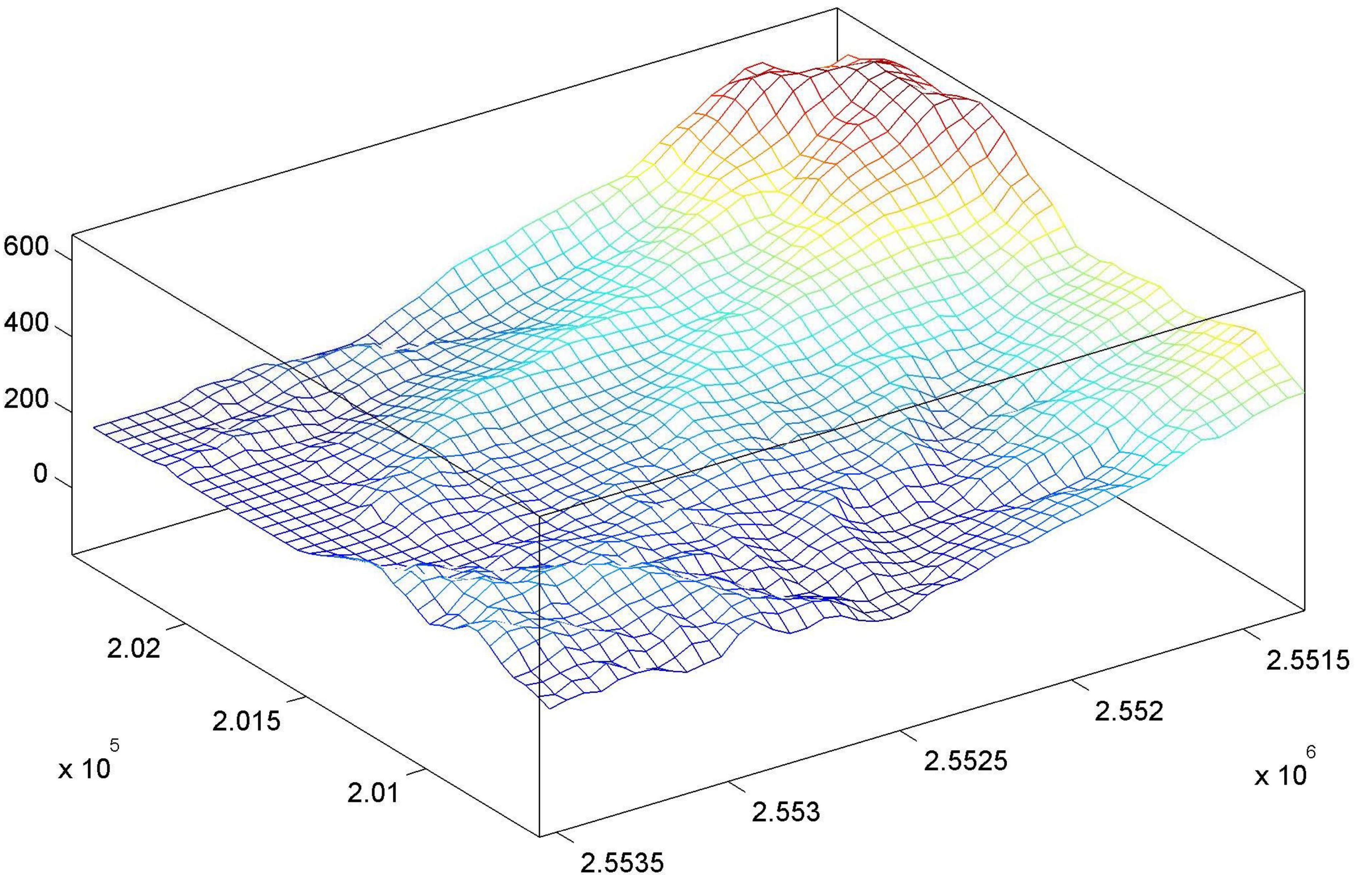
x 10^5
2.5515
2.552
2.5525
2.553
2.5535
x 10^6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x 10^5
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2.552
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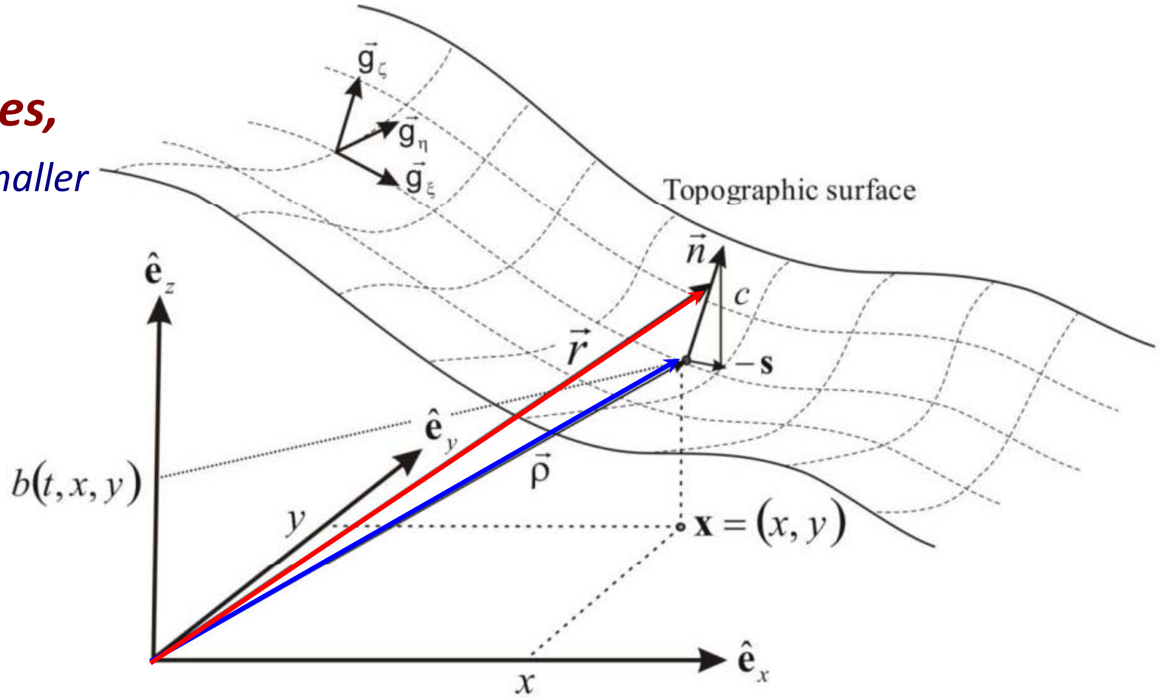
x 10^6

Coordinates for general topography (BW 2004)



- ***Topography-fitted coordinates,***

  where the flow thickness is much smaller than the curvature radius

- ***Basal topography***

$$z - b(x, y, t) = 0$$

- ***Basal normal vector***

$$\vec{n} = n_x \mathbf{e}_x + n_y \mathbf{e}_y + n_z \mathbf{e}_z$$

where $\quad n_x = -c\,\partial_x b, \quad n_y = -c\,\partial_y b, \quad n_z = c = \left(1 + (\partial_x b)^2 + (\partial_y b)^2\right)^{-1/2}$

- ***Position vector in the flow***

$$\vec{r} \equiv r_x \mathbf{e}_x + r_y \mathbf{e}_y + r_z \mathbf{e}_z = \vec{\rho} + \zeta \vec{n}$$

$$= (x + \zeta n_x)\mathbf{e}_x + (y + \zeta n_y)\mathbf{e}_y + (b + \zeta n_z)\mathbf{e}_z$$

Coordinate Transforms

- ***Coordinate Transformation*** (*e.g. Hui 2004, Hui 2007*)

$$d\vec{r} = \partial_\lambda \vec{r}\, d\lambda + \partial_\xi \vec{r}\, d\xi + \partial_\eta \vec{r}\, d\eta + \partial_\zeta \vec{r}\, d\zeta = \vec{Q}\, d\lambda + \tilde{\mathbf{\Omega}}\, d\vec{\xi}$$

$$dt = d\lambda$$

where

$\vec{Q}$ is the local velocity of the coordinate

$\tilde{\mathbf{\Omega}} = \nabla_{\vec{\xi}} \vec{r}$ is the Jacobian matrix

- ***The choice of the coordinate velocity***

$\vec{Q}$ is zero $\Rightarrow$ Eulerian description

$\vec{Q}$ is chosen to the velocity of the fluid particle $\Rightarrow$ Lagrangian description

$\vec{Q}$ is set to the basal entrainment/deposition rate
$\Rightarrow$ **Terrain-following coordinate**

Equations of Conservative Laws

- ***Equations of mass and momentum conservation***

$$\partial_i u^i = 0$$
$$\partial_t u^i + \partial_j \left(u^i u^j - t^{ij}\right) = g^i \quad \text{for} \quad i, j \in \{x, y, z\}$$

$$\vec{v} = u^x \mathbf{e}_x + u^y \mathbf{e}_y + u^z \mathbf{e}_z = u^\xi \boldsymbol{g}_\xi + u^\eta \boldsymbol{g}_\eta + u^\zeta \boldsymbol{g}_\zeta$$

- ***Transformed equations in the topography-fitted coordinates***

$$\partial_\lambda J + \partial_m u^m = 0$$
$$\partial_\lambda \left(J u^i\right) + \partial_m \left(J u^i \left(u^m - Q^m\right) - J\,\Sigma^{im}\right) = J g^i$$

$$J = \det \tilde{\mathbf{\Omega}}$$

$$dt = d\lambda$$

for $i, j \in \{x, y, z\}, \quad m, n \in \{\xi, \eta, \zeta\}$

- ***The stress term***

$$\Sigma^{in} = \Omega^i_m t^{mn}$$

Remark: A similar treatment for Euler equations can be found in *Vinolur (1974) J. Comput. Phys.*

Approximation and Depth Integration

- ***Jacobian matrix***

$$\tilde{\mathbf{\Omega}} = \begin{pmatrix} \left(\mathbf{I} - \zeta \partial_{\mathbf{x}} \mathbf{s}\right) \partial_{\xi} \mathbf{x} & -\mathbf{s} \\ \left(\partial_{\xi} b\right)^{T} + \left(\zeta \partial_{\xi} c\right)^{T} & c \end{pmatrix} = \begin{pmatrix} \partial_{\xi} \mathbf{x} & -\mathbf{s} \\ \left(\partial_{\xi} b\right)^{T} & c \end{pmatrix} + O\left(\varepsilon^{1+\alpha}\right) = \tilde{\mathbf{\Omega}}_{b} + O\left(\varepsilon^{1+\alpha}\right)$$

$$J = \det \tilde{\mathbf{\Omega}} = J_{b} + O\left(\varepsilon^{1+\alpha}\right)$$

where

$$\mathbf{s} = \begin{pmatrix} s_x \\ s_y \end{pmatrix} = \begin{pmatrix} c \partial_x b \\ c \partial_y b \end{pmatrix}, \quad \partial_{\xi} b = \begin{pmatrix} \partial_{\xi} b \\ \partial_{\eta} b \end{pmatrix}, \quad \partial_{\xi} c = \begin{pmatrix} \partial_{\xi} c \\ \partial_{\eta} c \end{pmatrix},$$

$$\partial_{\mathbf{x}} \mathbf{s} = \begin{pmatrix} \partial_x s_x & \partial_y s_x \\ \partial_x s_y & \partial_y s_y \end{pmatrix}, \quad \partial_{\xi} \mathbf{x} = \begin{pmatrix} \partial_{\xi} x & \partial_{\eta} x \\ \partial_{\xi} y & \partial_{\eta} y \end{pmatrix}.$$

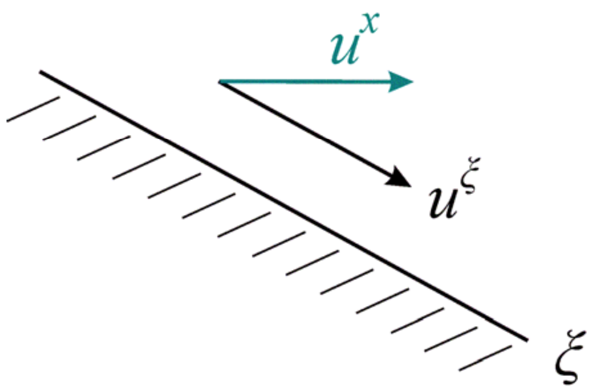
Depth-integrated equations

$$\frac{\partial}{\partial \lambda}\left(J_b h\right)+\frac{\partial}{\partial \xi}\left(J_b h\,\overline{u}^{\xi}\right)+\frac{\partial}{\partial \eta}\left(J_b h\,\overline{u}^{\eta}\right)=-J_b E$$

$$\frac{\partial}{\partial \lambda}\begin{pmatrix} J_b h\overline{u}^{x} \\ J_b h\overline{u}^{y}\end{pmatrix}+\frac{\partial}{\partial \xi}\begin{pmatrix} J_b\varpi_{\parallel} h\overline{u}^{x}\overline{u}^{\xi}+J_b h\,\overline{p}M_{11} \\ J_b\varpi_{\parallel} h\,\overline{u}^{y}\overline{u}^{\xi}+J_b h\,\overline{p}M_{21}\end{pmatrix}$$
$$+\frac{\partial}{\partial \eta}\begin{pmatrix} J_b\varpi_{\parallel} h\overline{u}^{x}\overline{u}^{\eta}+J_b h\,\overline{p}M_{12} \\ J_b\varpi_{\parallel} h\overline{u}^{y}\overline{u}^{\eta}+J_b h\,\overline{p}M_{22}\end{pmatrix}=-J_b E\begin{pmatrix} u_b^{x} \\ u_b^{y}\end{pmatrix}+\mathbf{s}^{\xi}$$

- ***Material equation***
- ***Boundary conditions***
  - *Drag free at flow surface.*
  - *Coulomb friction at basal surface (or Voellmy's law).*
  - *Non-material surface condition at basal surface due to entrainment/deposition.*

- ***basic concept***



Erosion-deposition rate

- *BCRE-Model (1994), Tai & Kuo (Acta Mech., 2008), Tai & Lin (Phys. Fluids, 2008)*

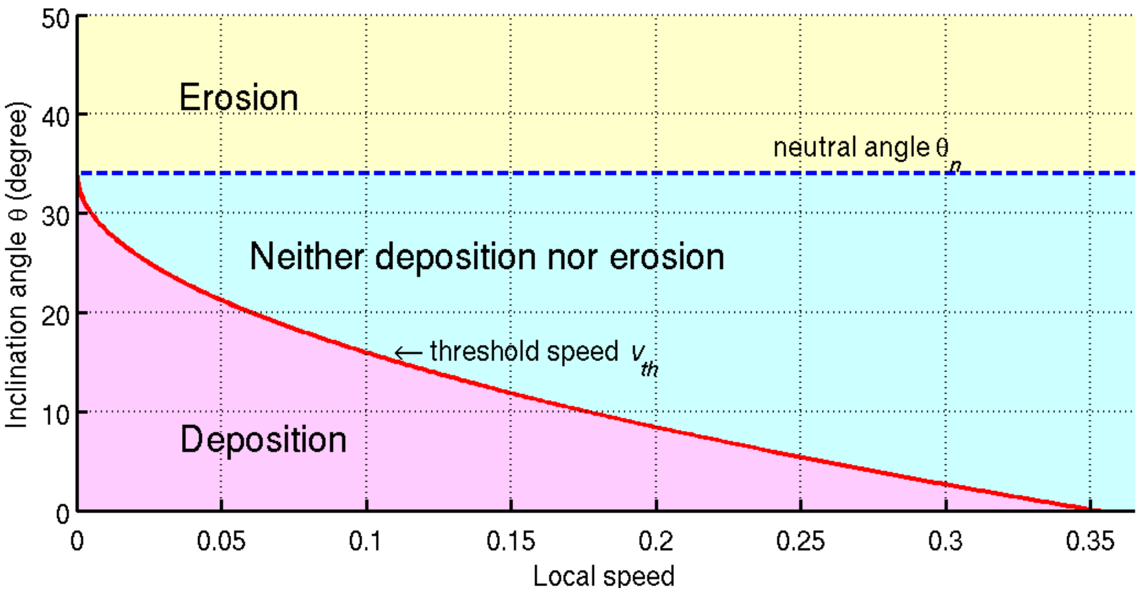
Three states for basal surface:

$$\begin{cases} \theta < \theta_n \text{ and } \|\mathbf{q}_\parallel\| > v_{\text{th}} \Rightarrow \mathcal{E}_+ = 0 : \text{immobile basal surface,} \\ \theta < \theta_n \text{ and } \|\mathbf{q}_\parallel\| < v_{\text{th}} \Rightarrow \mathcal{E}_+ > 0 : \text{deposition,} \\ \theta > \theta_n \qquad\qquad\qquad\qquad \Rightarrow \mathcal{E}_+ < 0 : \text{erosion.} \end{cases}$$

where

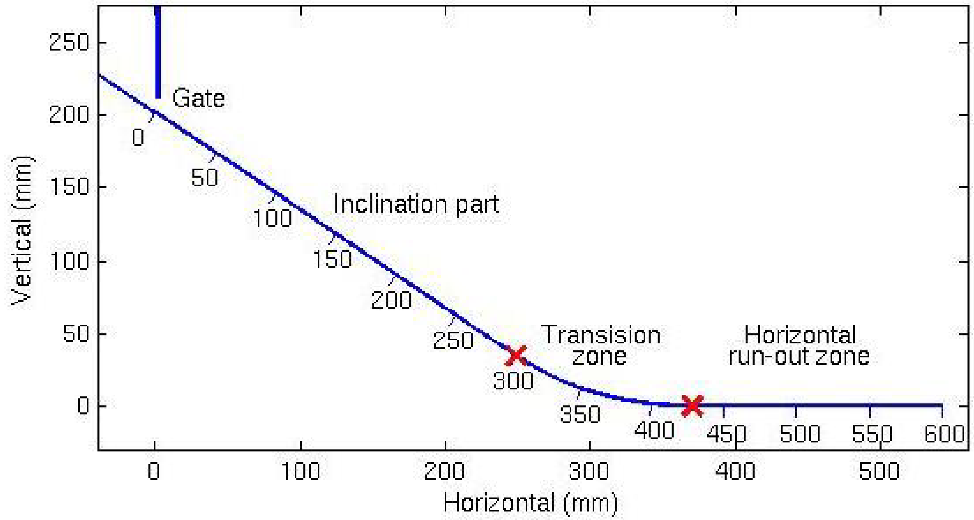
$$\theta = \sin^{-1}\left(\frac{-w}{\|\mathbf{q}_\parallel\|}\right)$$

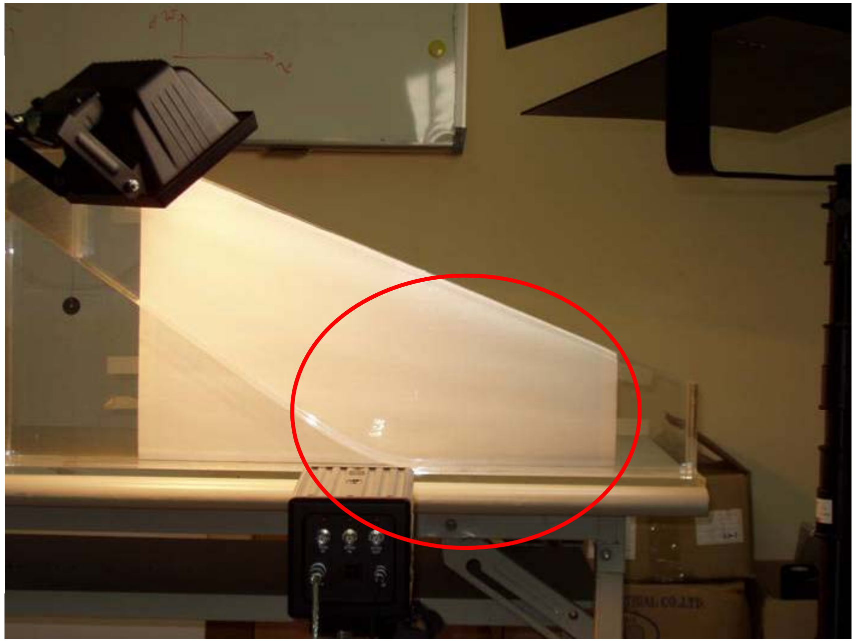
Remark:
***any reasonable erosion rate** can be applied to this proposed formulation.*



Is the temporally variable coordinates necessary?

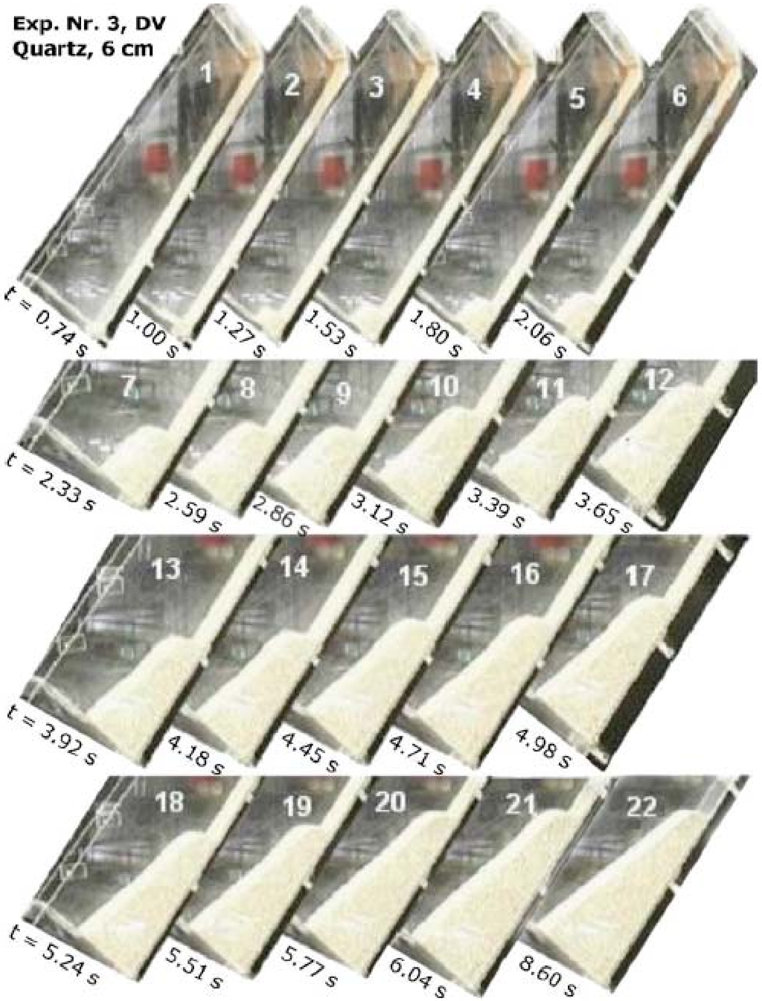
- Material：Ottawa sand（ϕ: 0.3~0.6 mm）
- Width of channel: 38 mm,   Inclination angle: 34° to horizontal
- Gate opening at the top: 10, 15, 20 mm

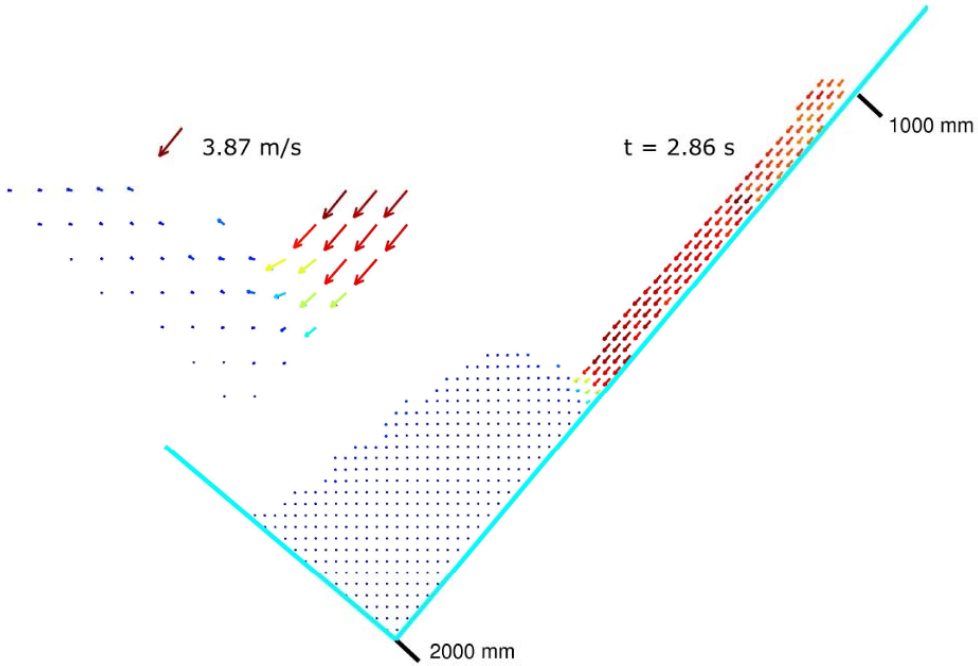


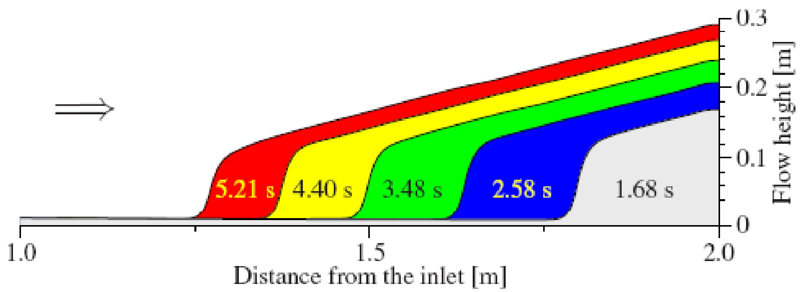


Tai & Lin (Phys. Fluids, 2008)

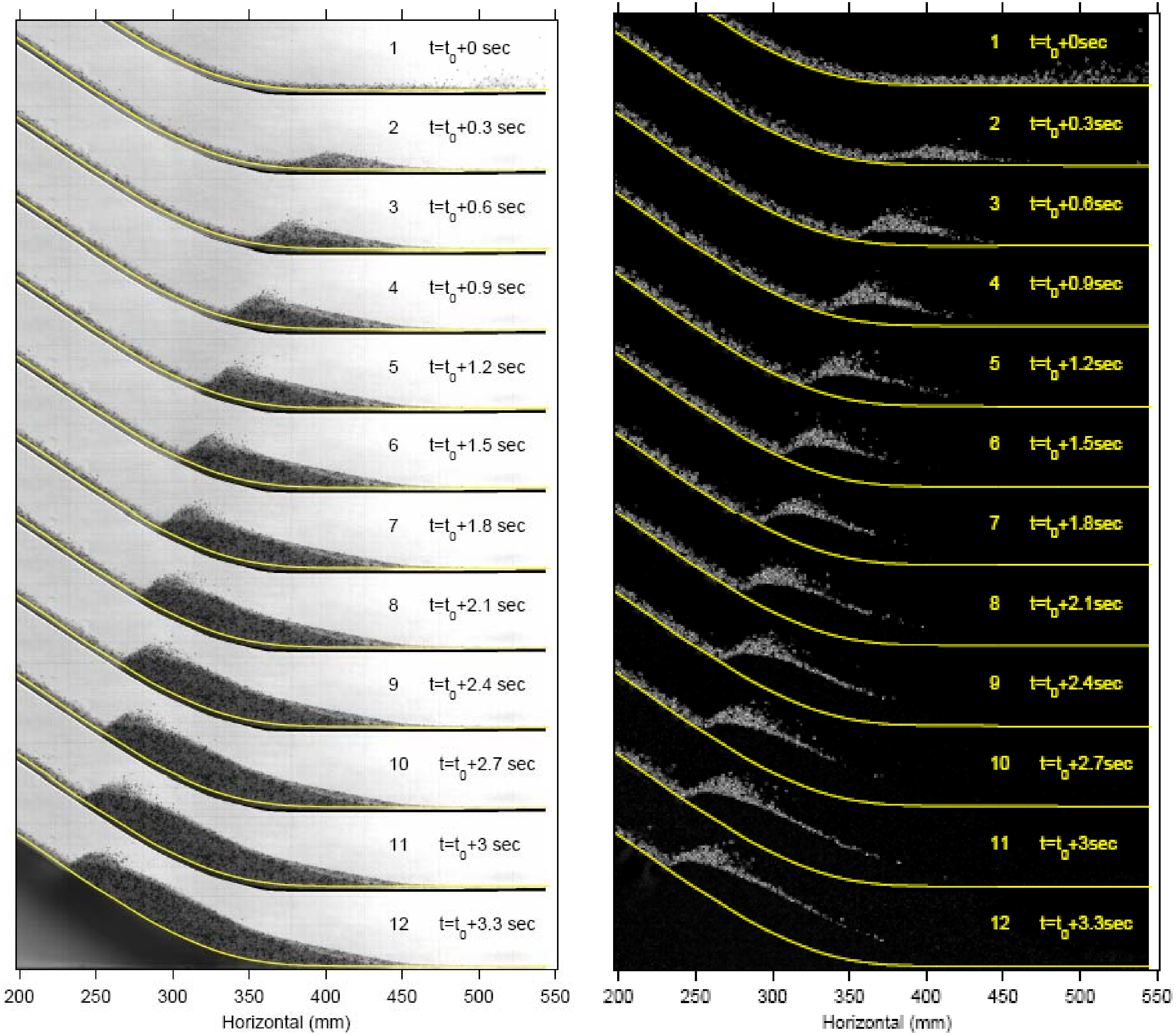
Traveling shock wave: *Pudasaini et al, Phys. Fluids (2007)*



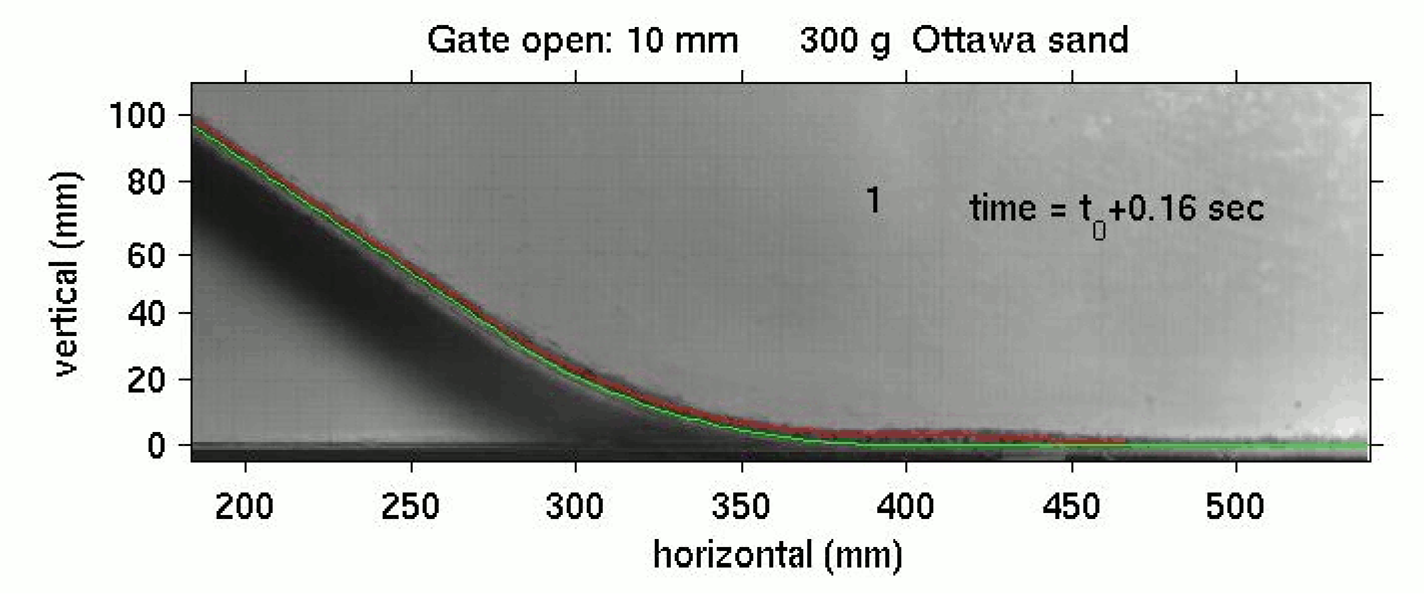




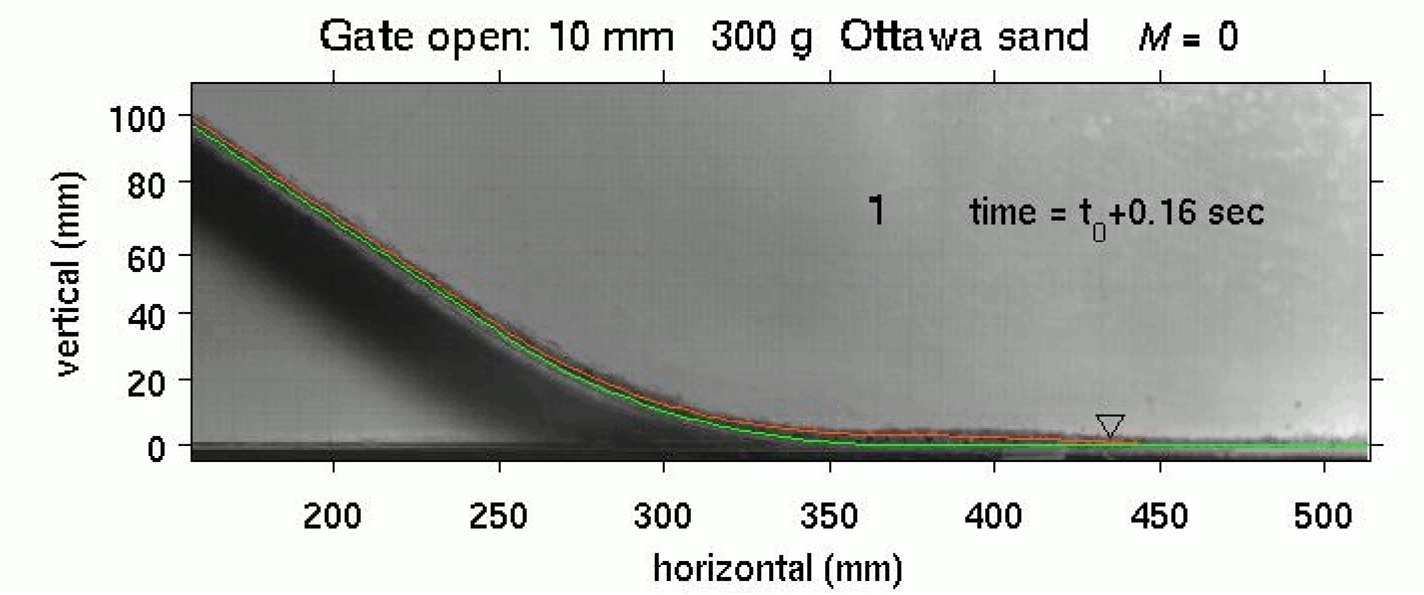
Pudasaini and Kröner, Phy. Rev. E (2008)


1 t=t0+0 sec
2 t=t0+0.3 sec
3 t=t0+0.6 sec
4 t=t0+0.9 sec
5 t=t0+1.2 sec
6 t=t0+1.5 sec
7 t=t0+1.8 sec
8 t=t0+2.1 sec
9 t=t0+2.4 sec
10 t=t0+2.7 sec
11 t=t0+3 sec
12 t=t0+3.3 sec
200 250 300 350 400 450 500 550
Horizontal (mm)
1 t=t0+0sec
2 t=t0+0.3sec
3 t=t0+0.6sec
4 t=t0+0.9sec
5 t=t0+1.2sec
6 t=t0+1.5sec
7 t=t0+1.8sec
8 t=t0+2.1sec
9 t=t0+2.4sec
10 t=t0+2.7sec
11 t=t0+3sec
12 t=t0+3.3sec
200 250 300 350 400 450 500 550
Horizontal (mm)

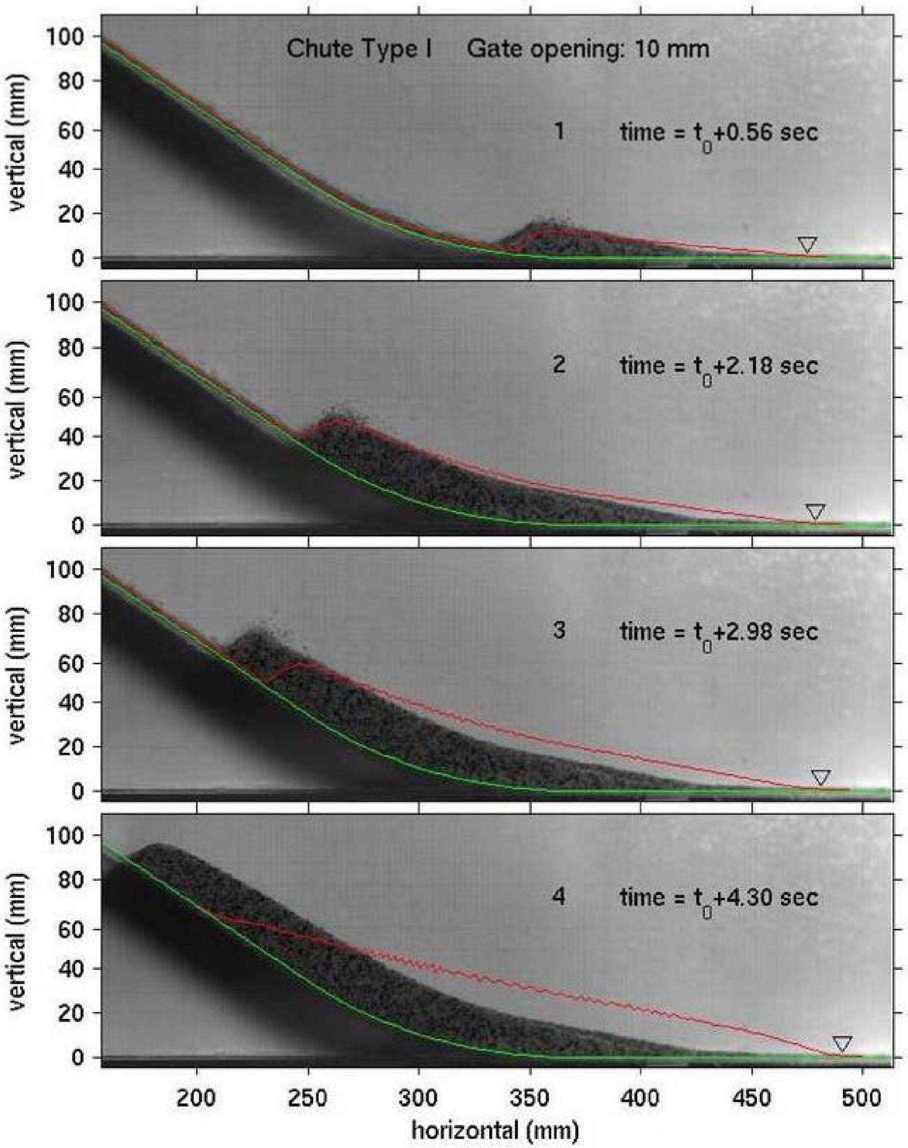
- Comparison with experimental data (*with deposition*)



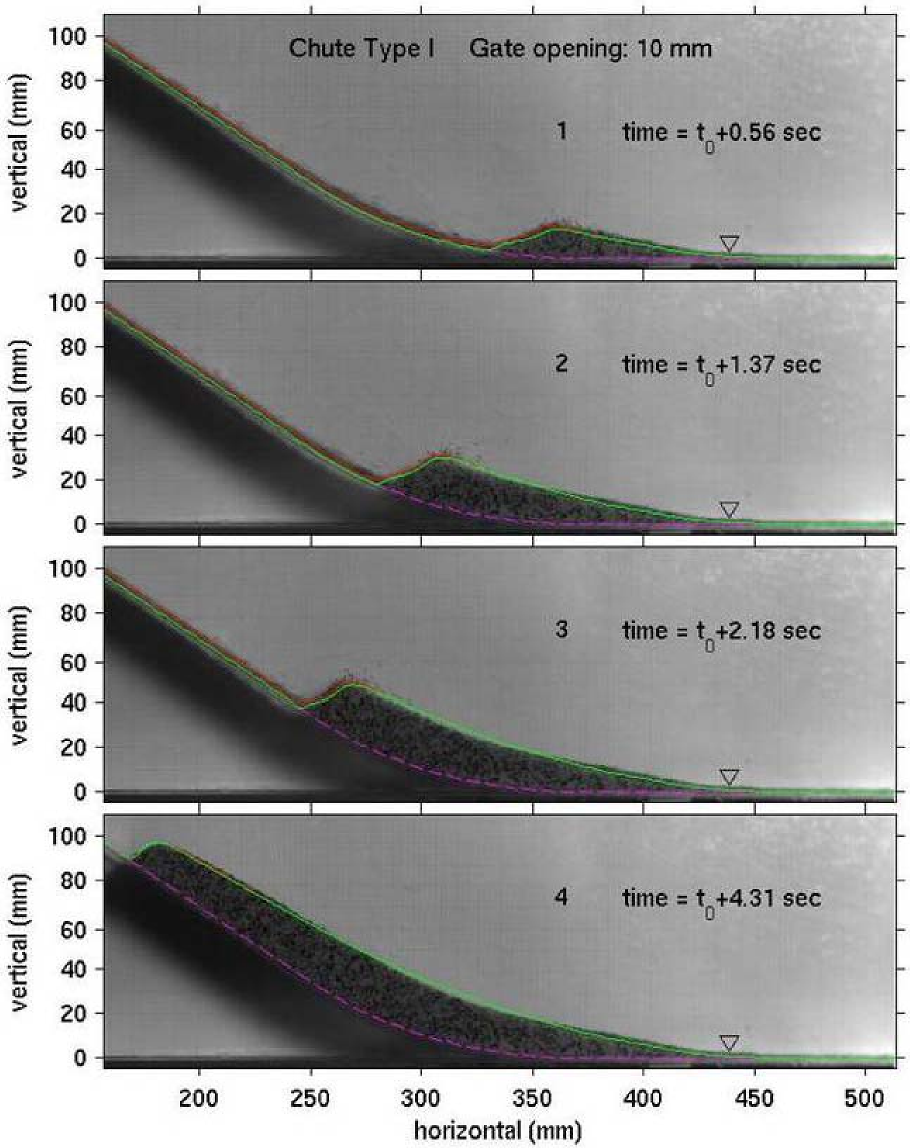
- Comparison with experimental data (*without deposition*)



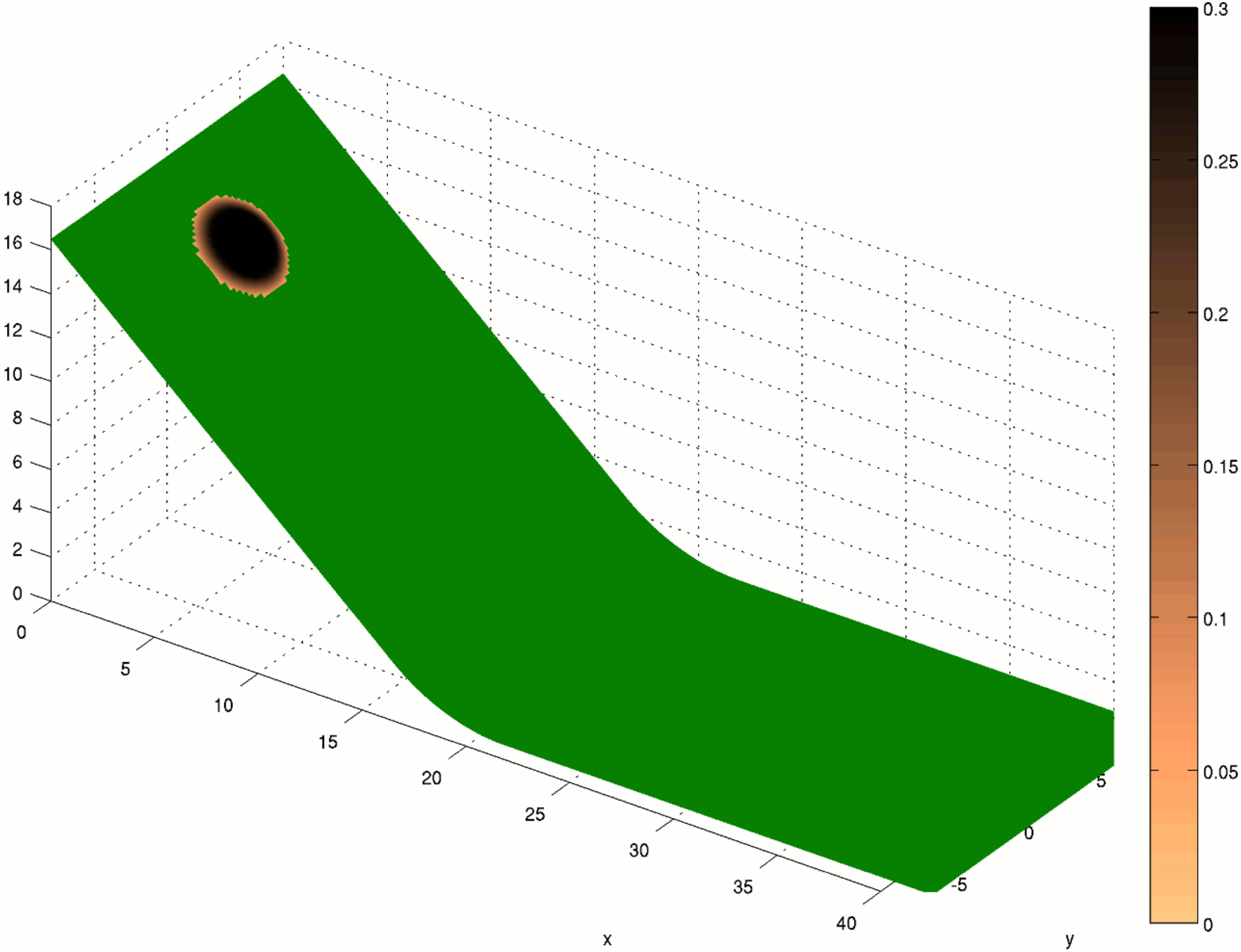
Without Deposition



With deposition



Tai & Lin (Phys. Fluids, 2008)



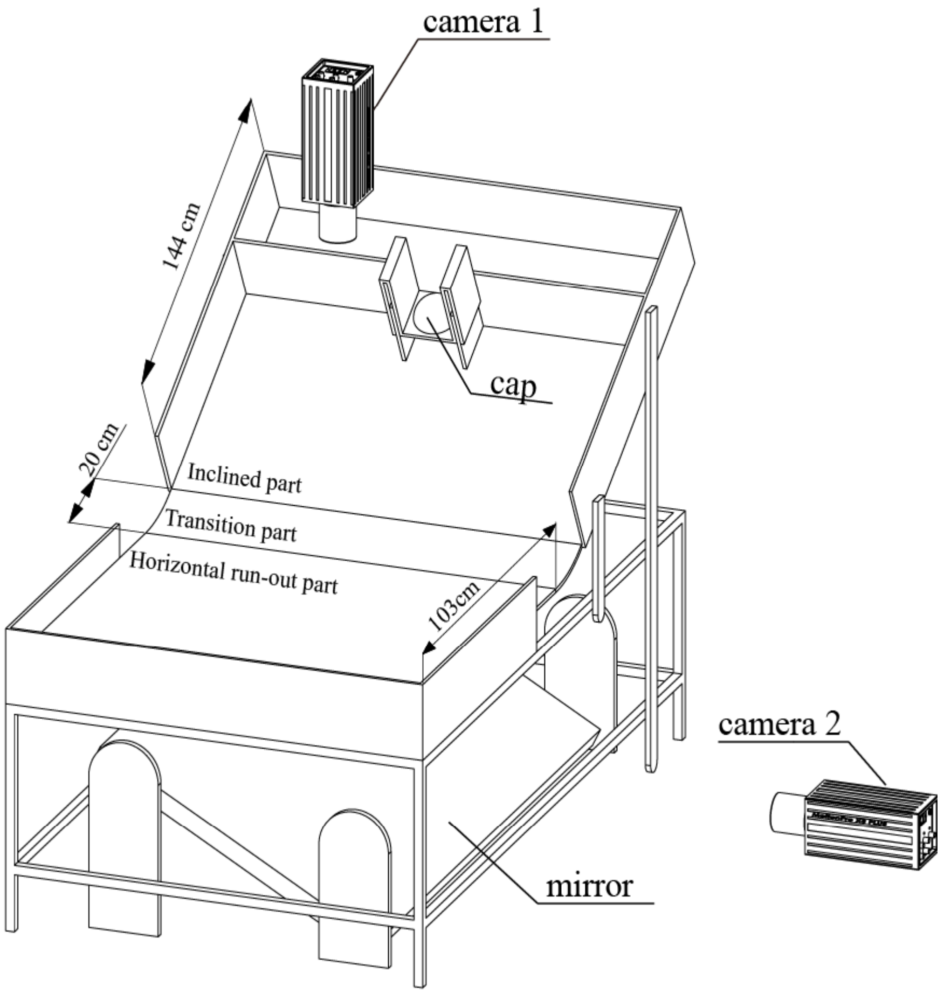
0.3
0.25
0.2
0.15
0.1
0.05
0
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
x
-5
0
5
y

Experiments and comparison with theoretical prediction

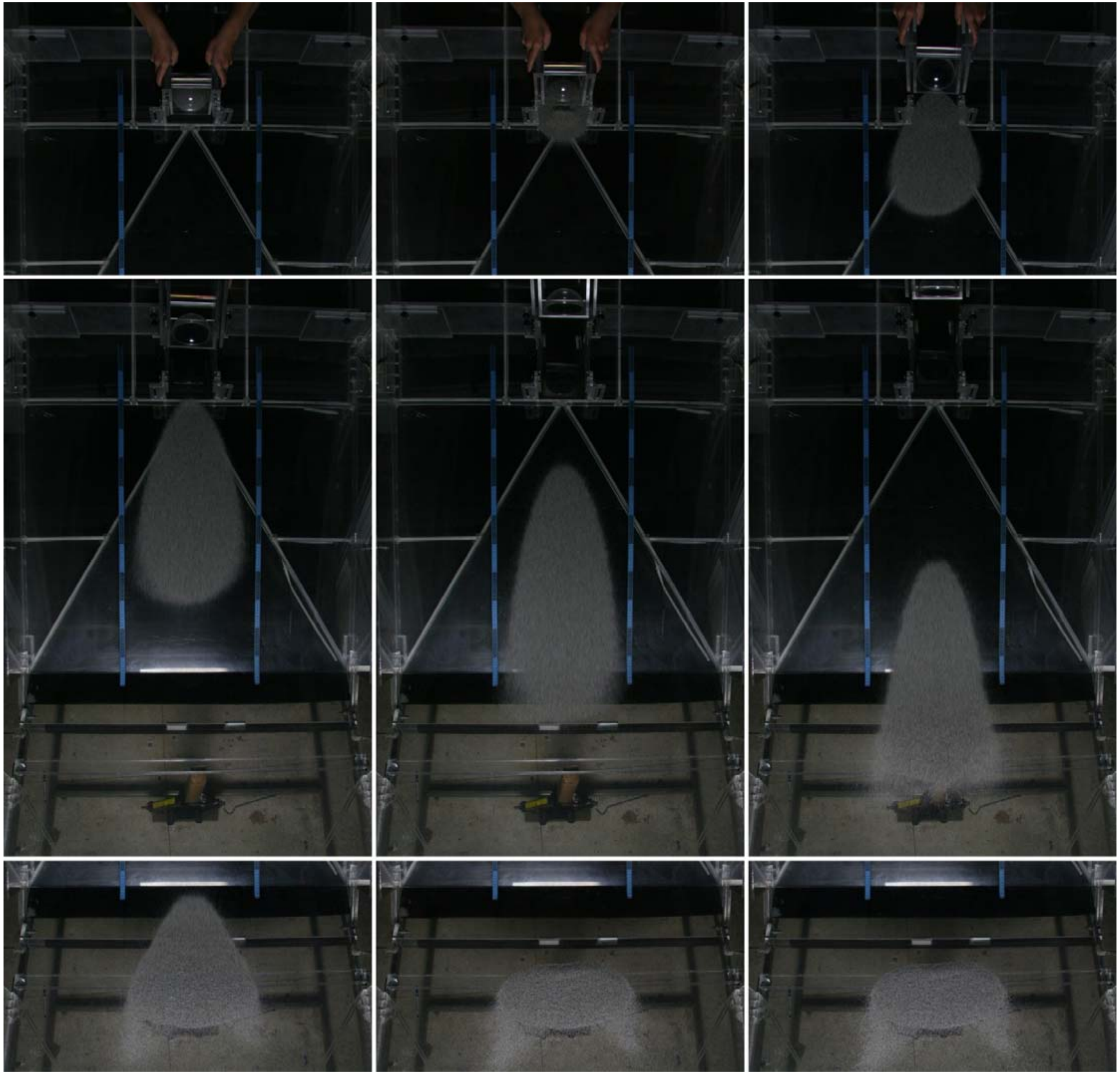
by

L.T. Sheng, Y.C. Tai, C. Y. Kuo and S.S. Hsiau

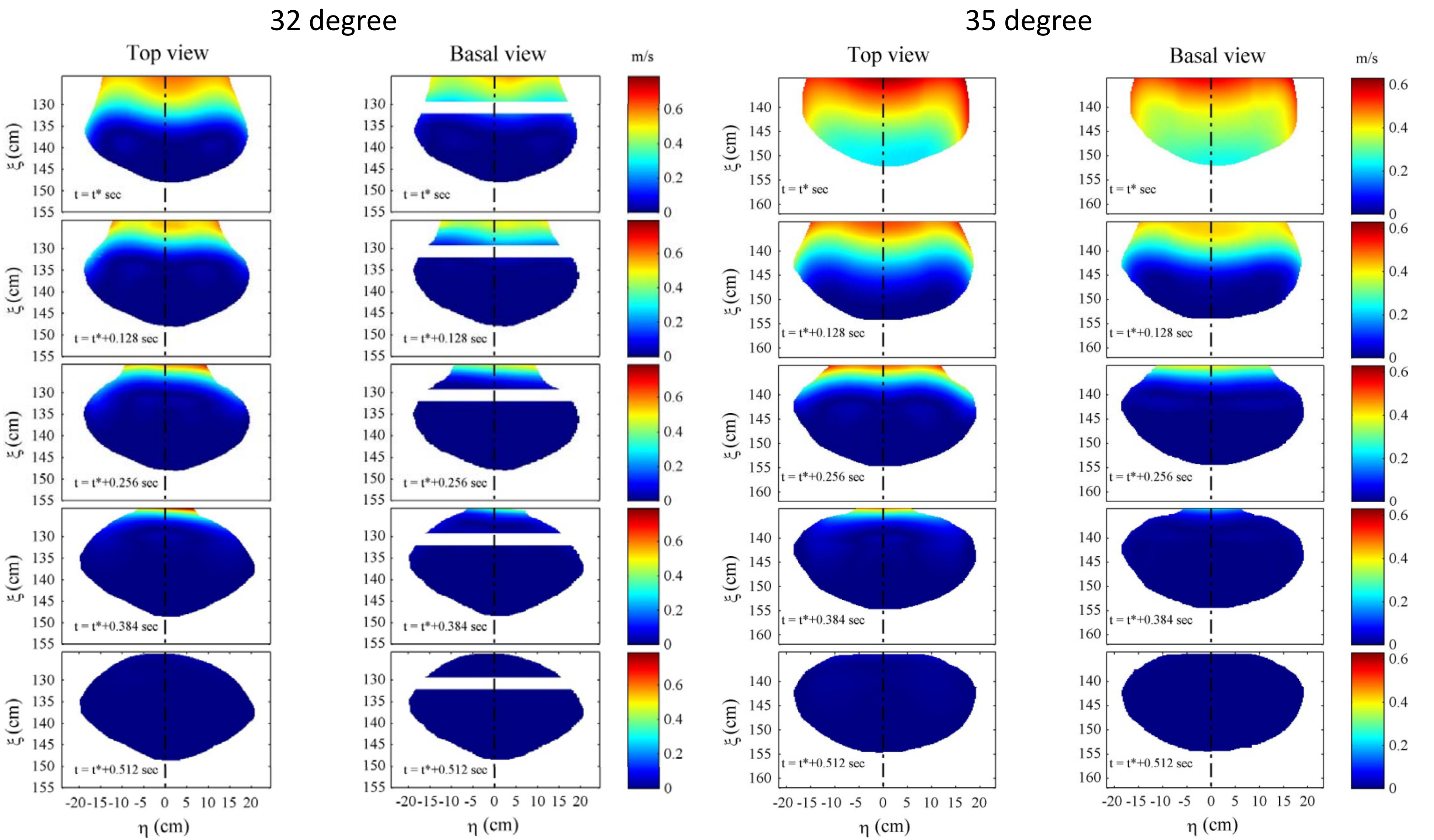
Experimental setup



Three inclination angles: 32, 35 and 38 degree

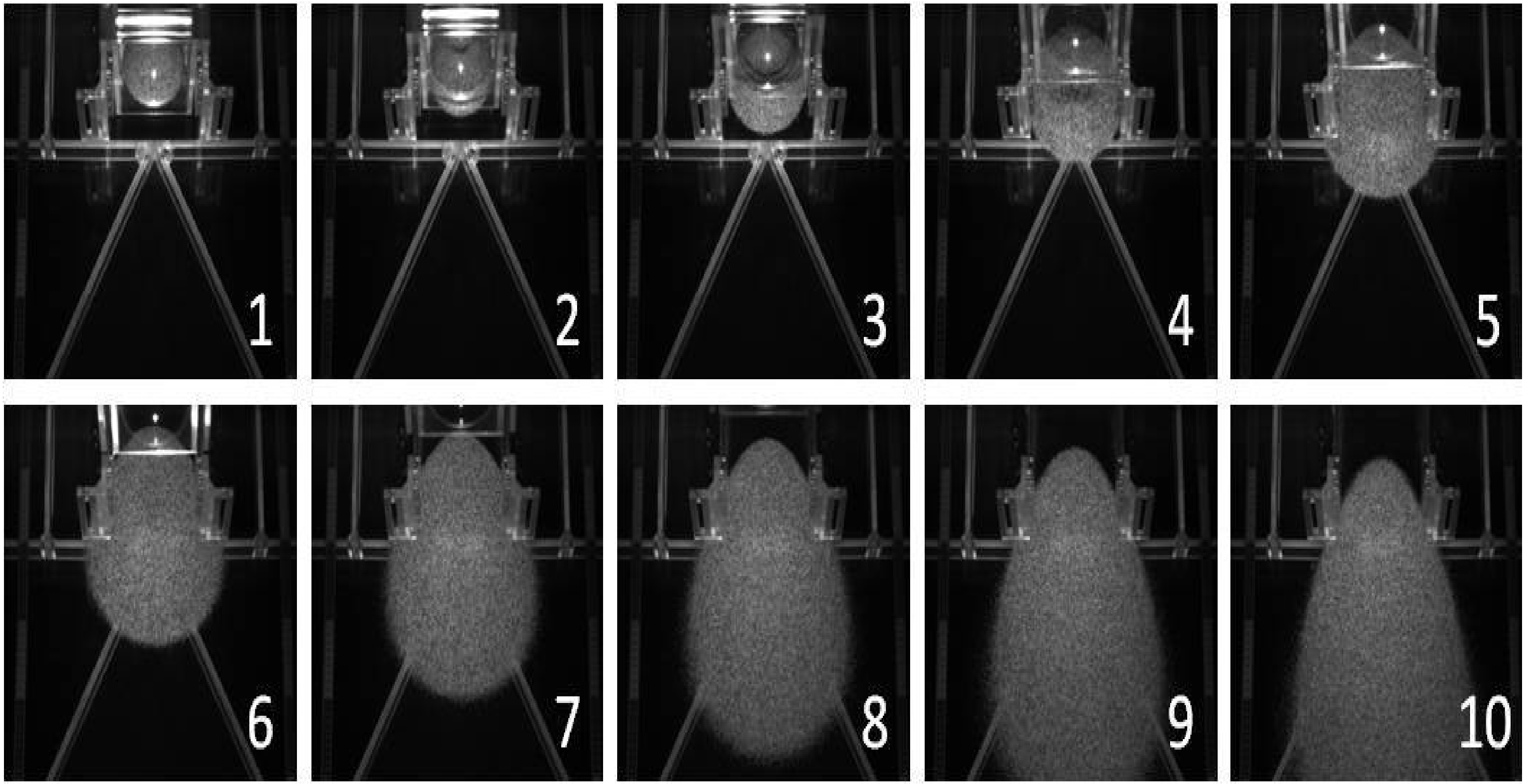


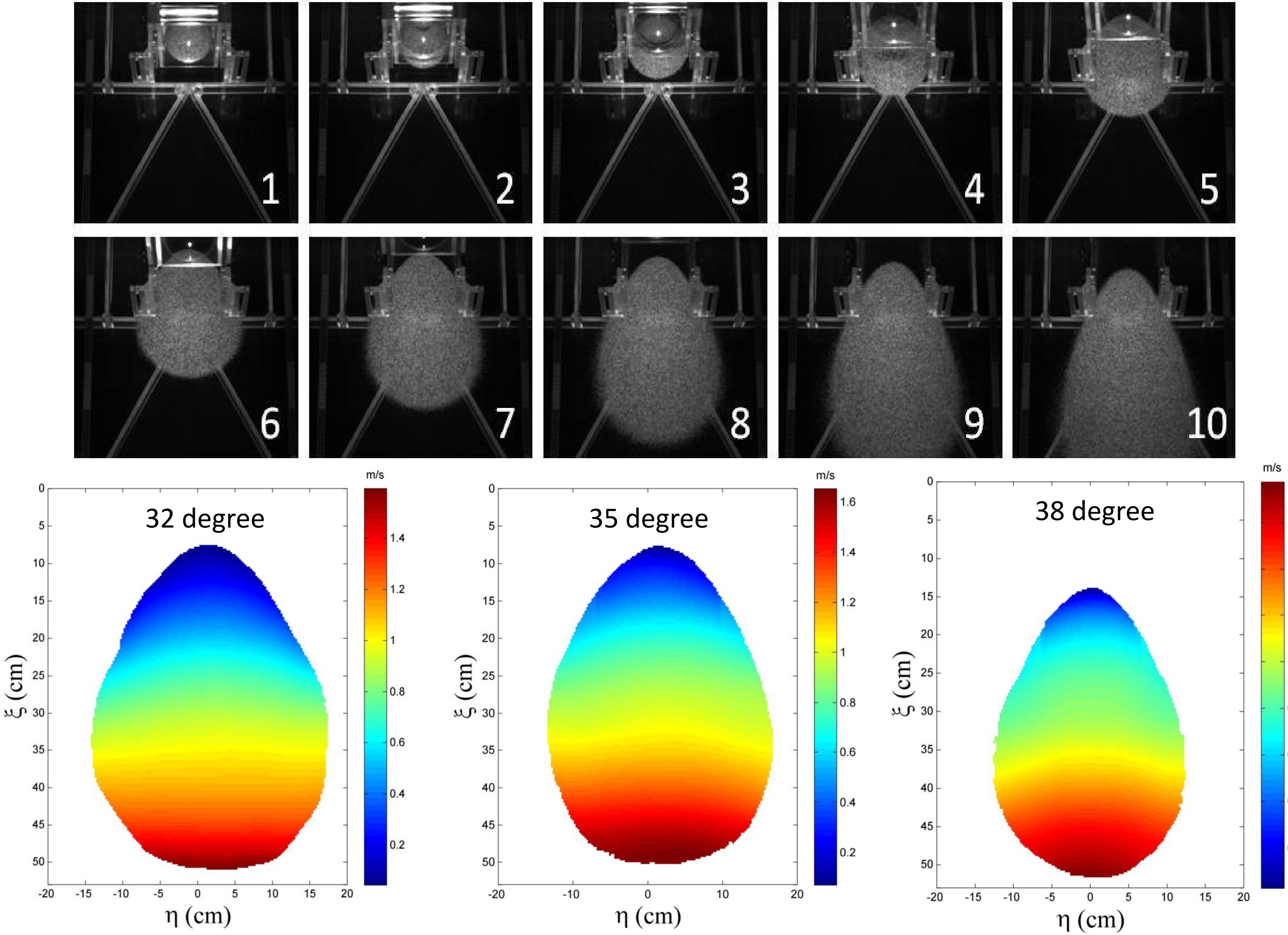
Experimental results



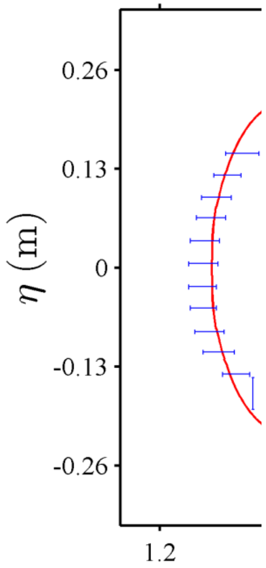
Experimental results

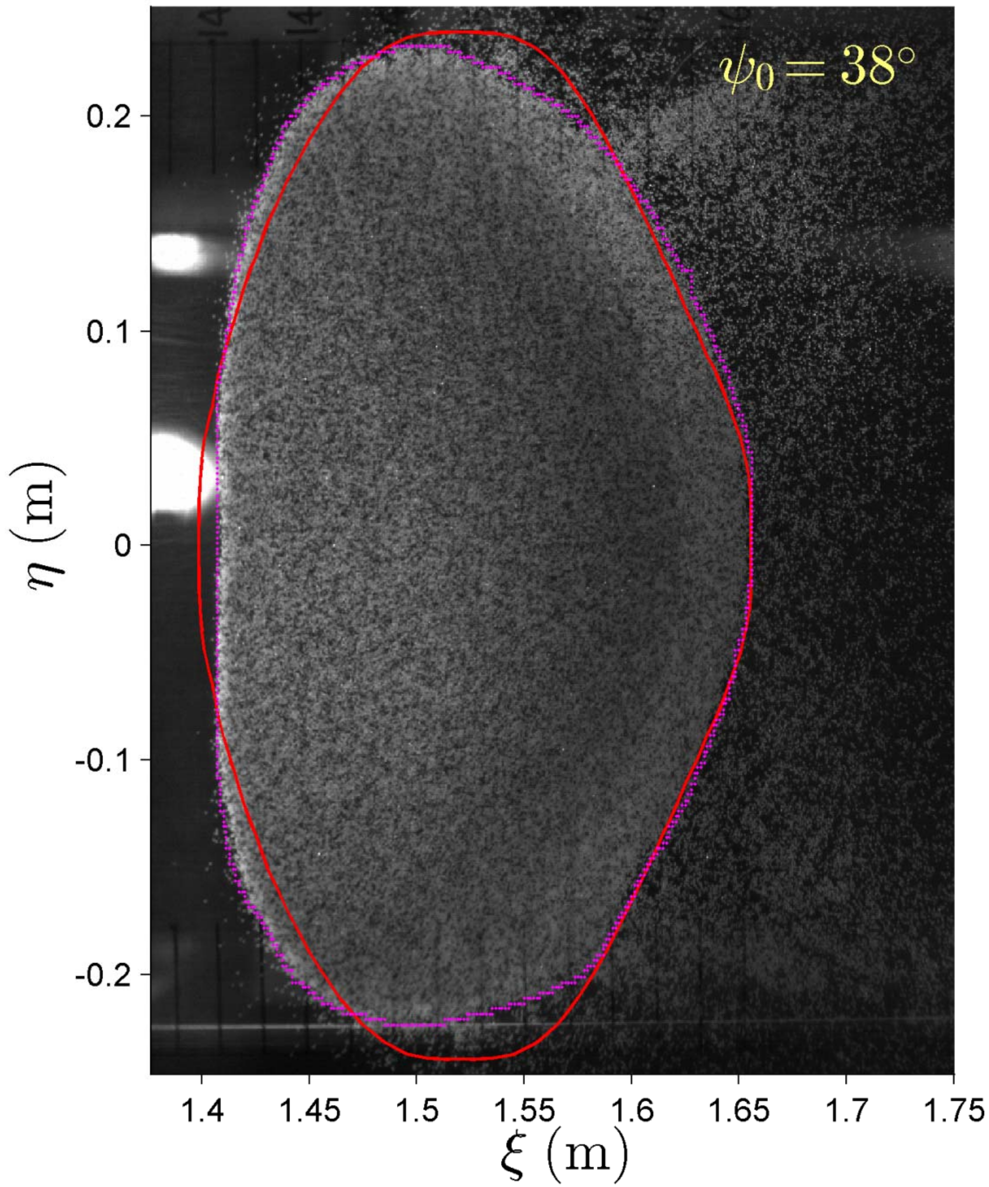
- Initial condition for theoretical prediction

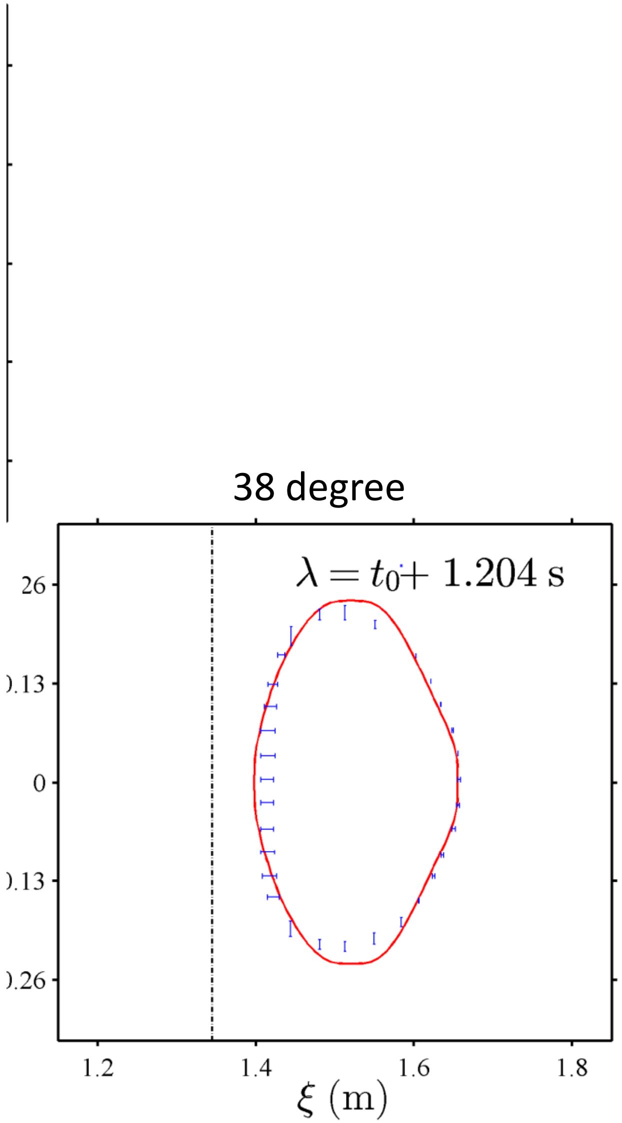



1
2
3
4
5
6
7
8
9
10
32 degree
35 degree
38 degree
m/s
ξ (cm)
η (cm)

Deposition position







Further applications

- **Coulomb-Mixture Theory (with deposition)**

by

Y. C. Tai, and C. Y. Kuo, Nat. Hazards Earth Syst. Sci. (2012)

Coulomb-mixture theory *(Iverson & Denlinger, JGR 2001)*

- **Conservation of mass and momentum**

$$\frac{\partial \rho_s}{\partial t} + \mathrm{div}\,(\rho_s \vec{q}_s) = 0\,, \qquad \frac{\partial \rho_s \vec{q}_s}{\partial t} + \mathrm{div}\,(\,\rho_s \vec{q}_s \otimes \vec{q}_s \,-\, \tilde{\mathbf{T}}_s\,) = \rho_s \vec{g} + \vec{m}\,,$$

$$\frac{\partial \rho_f}{\partial t} + \mathrm{div}\,(\rho_f \vec{q}_f) = 0\,, \qquad \frac{\partial \rho_f \vec{q}_f}{\partial t} + \mathrm{div}\,(\rho_f \vec{q}_f \otimes \vec{q}_f - \tilde{\mathbf{T}}_f) = \rho_f \vec{g} - \vec{m}\,,$$

- **Transformation into UC system**

$$\partial_\lambda(J\nu_s) + \partial_m\Big[J\nu_s(q_s^m - Q^m)\Big] = 0\,, \qquad \partial_\lambda(J\nu_f) + \partial_m\Big[J\nu_f(q_f^m - Q^m)\Big] = 0\,,$$

$$\partial_\lambda(J\nu_s u_s^i) + \partial_m\Big[J\nu_s u_s^i(q_s^m - Q^m) \,-\, J\Sigma_s^{im}\Big] = J\nu_s g^i + \frac{1}{\hat{\rho}_s} m^i\,,$$

$$\partial_\lambda(J\nu_f u_f^i) + \partial_m\Big[J\nu_f u_f^i(q_f^m - Q^m) - J\Sigma_f^{im}\Big] = J\nu_f g^i - \frac{1}{\hat{\rho}_f} m^i\,,$$

where

$i \in \{x, y, z\}$ and $m \in \{\xi, \eta, \zeta\}$ $\qquad \rho_f = \nu_f \hat{\rho}_f \qquad \rho_s = \nu_s \hat{\rho}_s$

$\tilde{\mathbf{T}}_{s,f} = T_{s,f}^{ij}\, \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_i = \Sigma_{s,f}^{im}\, \hat{\mathbf{e}}_i \otimes \vec{\boldsymbol{g}}_m$ $\qquad \hat{\rho}_s = \mathrm{const.}$ and $\hat{\rho}_f = \mathrm{const.}$

Coulomb-mixture theory (*Tai & Kuo, Nat. Hazards Earth Syst. Sci., 2012*)

- **Assumptions in Coulomb mixture theory**

  (a) Shallowness of the flowing layer and *the curvature*

  (b) Saturation: $\nu_s + \nu_f = 1$

  (c) Small relative velocity: $|\vec{q}_f - \vec{q}_s| << |\vec{q}_s| \Rightarrow \vec{m} = 0$

  (d) Erosion/deposition rates of both solid and fluid constituents are equal

  (e) Total stress: $\tilde{\mathbf{T}} = \tilde{\mathbf{T}}_s + \tilde{\mathbf{T}}_f$ with $\tilde{\mathbf{T}}_s = \tilde{\mathbf{T}}_{eff}$ and $\tilde{\mathbf{T}}_f = -\mathbf{I}p + \nu_f \tilde{\mathbf{T}}_{vis}$

  (f) Solid constituent: Coulomb friction at the basal surface

  (g) Fluid constituent: Newtonian fluid

  (h) Earth pressure coefficient: $K_{act/pas} = 1$

- *Depth-integration with boundary conditions (BCs)*

Coulomb-mixture theory *(Tai & Kuo, Nat. Hazards Earth Syst. Sci., 2012)*

- **The leading-order governing equations of Coulomb mixture theory in UC system**

$$\frac{\partial}{\partial\lambda}(J_b h) + \frac{\partial}{\partial\xi}(J_b h q_0^\xi) + \frac{\partial}{\partial\eta}(J_b h q_0^\eta) = -J_b\,\mathcal{E}_- + \mathcal{O}(\epsilon^{1+\gamma})\,.$$

$$\frac{\partial}{\partial\lambda}\left(J_b h u_0^i\right) + \frac{\partial}{\partial\xi}\left(J_b h u_0^i q_0^\xi\right) + \frac{\partial}{\partial\eta}\left(J_b h u_0^i q_0^\eta\right) - \frac{\partial}{\partial\xi}\left((1-\Lambda_f)\epsilon J_b h\overline{\Sigma^{i\xi}}\right) - \frac{\partial}{\partial\eta}\left((1-\Lambda_f)\epsilon J_b h\overline{\Sigma^{i\eta}}\right)$$
$$= -J_b\,\mathcal{E}_- u_b^i - \epsilon^\alpha J_b\,h\,A_c\,n^i + J_b\,h\,c\,n^i - (1-\Lambda_f)\epsilon^\beta J_b N_b \mu\frac{u_b^i}{||\vec{q}_b||} + J_b s_f^i + J_b h g^i + \mathcal{O}(\epsilon^{1+\gamma})$$

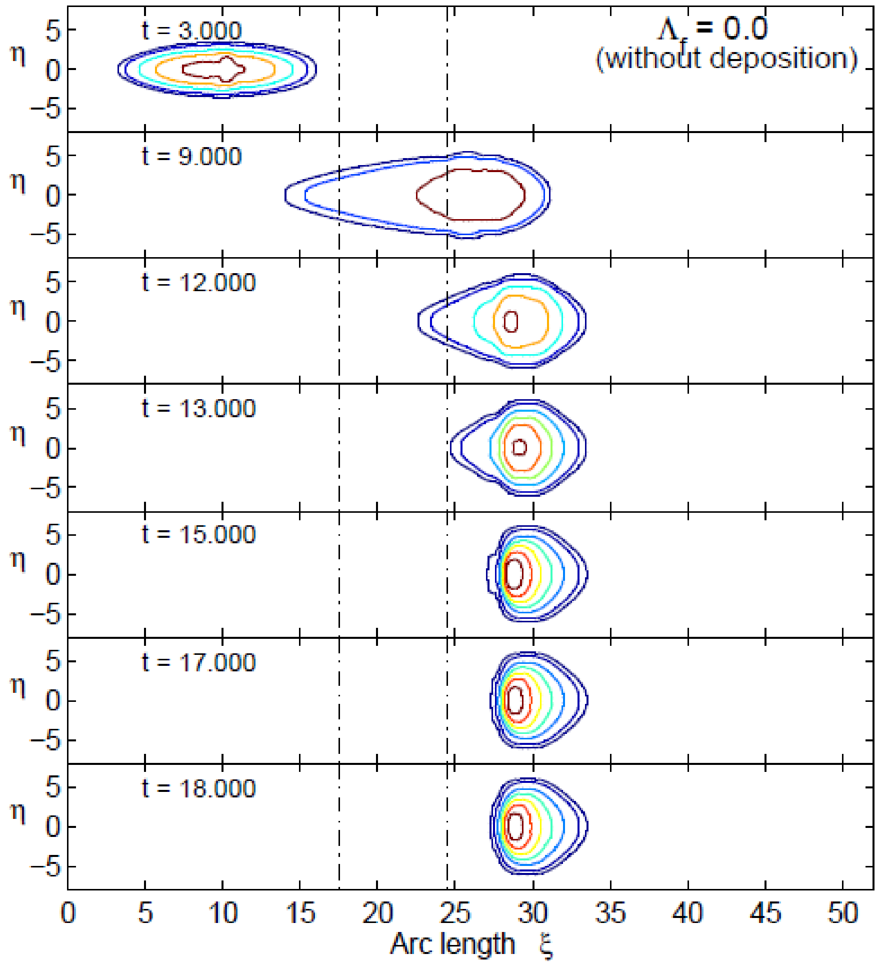
with

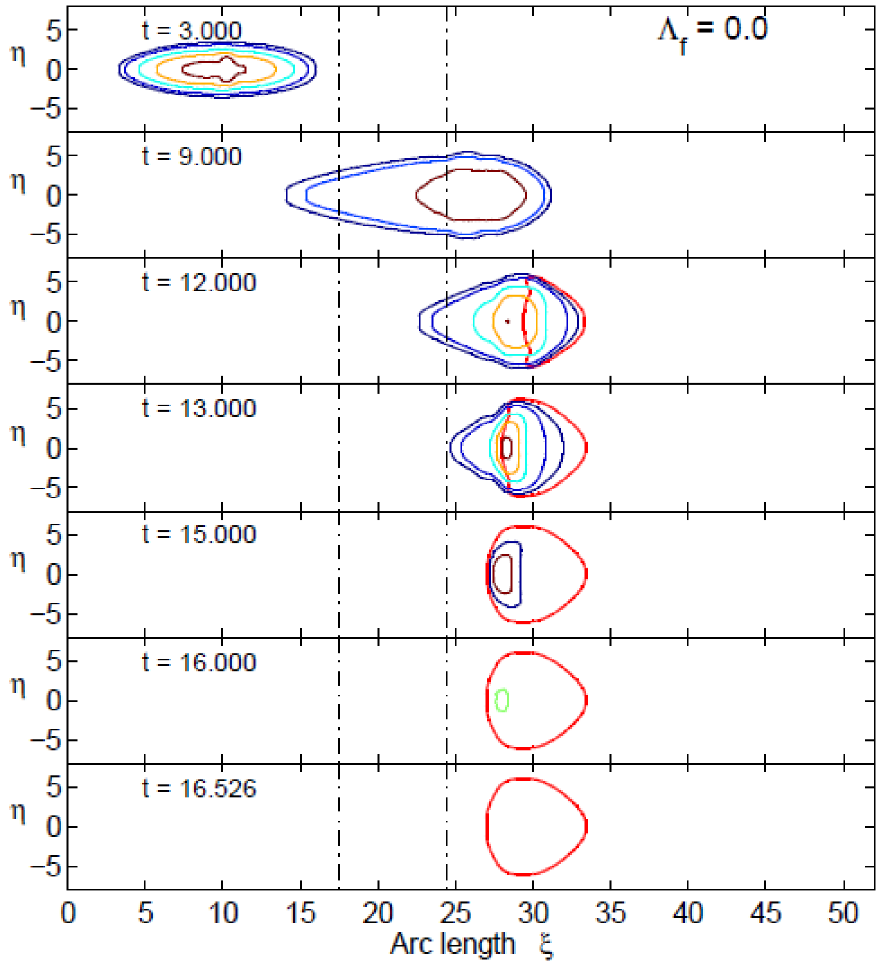
$$s_f^i = \tilde{\Omega}_m^i\left(-\epsilon h\frac{\partial(p_{bed})}{\partial m} + \epsilon\frac{\nu_f h}{N_R}\frac{\partial^2(q_0^m)}{\partial n^2} - \frac{\nu_f}{\epsilon}\frac{3}{N_R}\frac{q_0^m}{h}\right) \quad \text{and} \quad p_{bed} = \Lambda_f\,h\,c$$

$N_R = \rho H\sqrt{gL}/\mu$ is analogous to the Reynolds number for Newtonian fluid

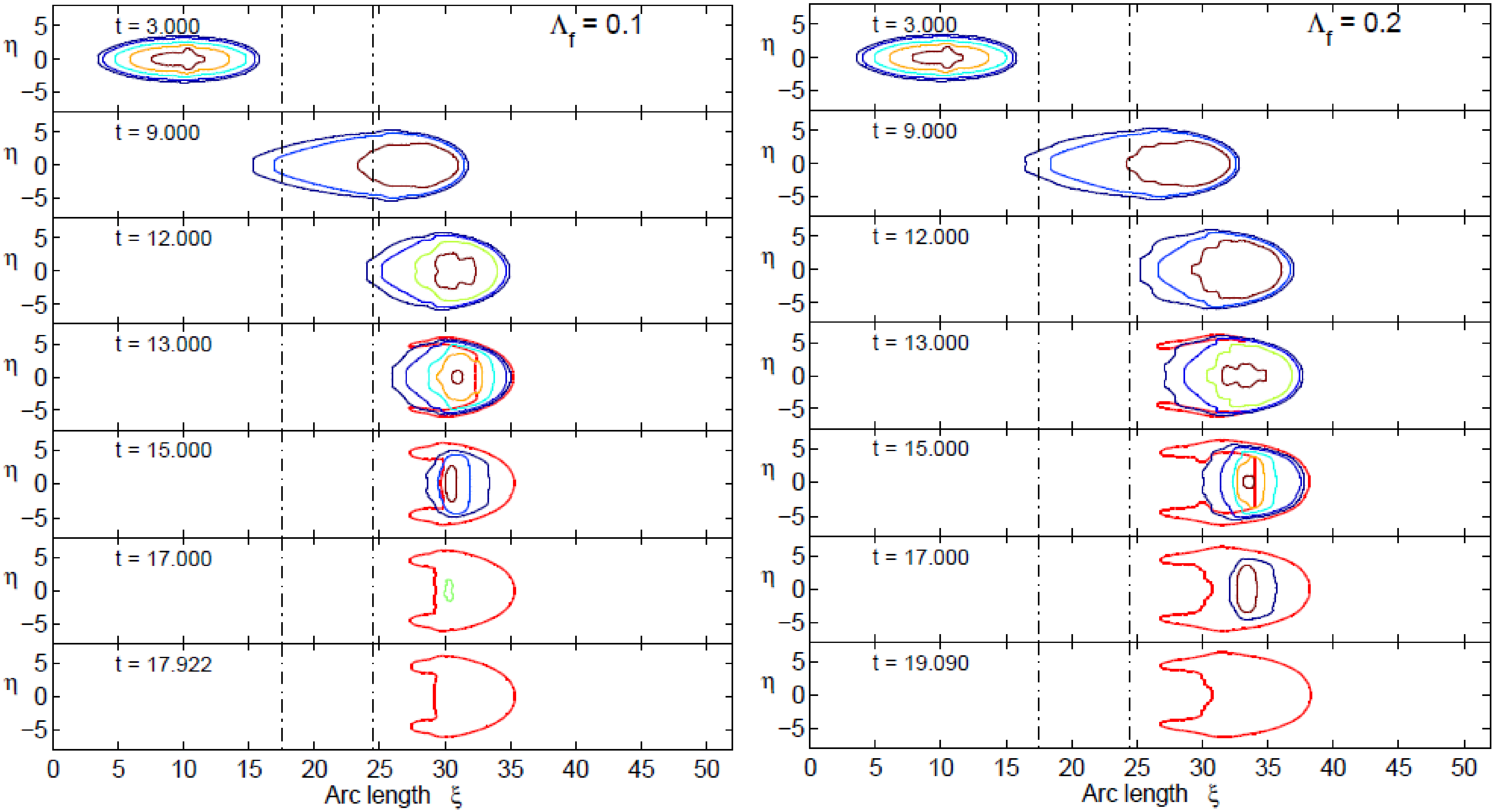
$$i \in \{x, y\}, \quad m \in \{\xi, \eta\}$$

Comparison without/with deposition procedure

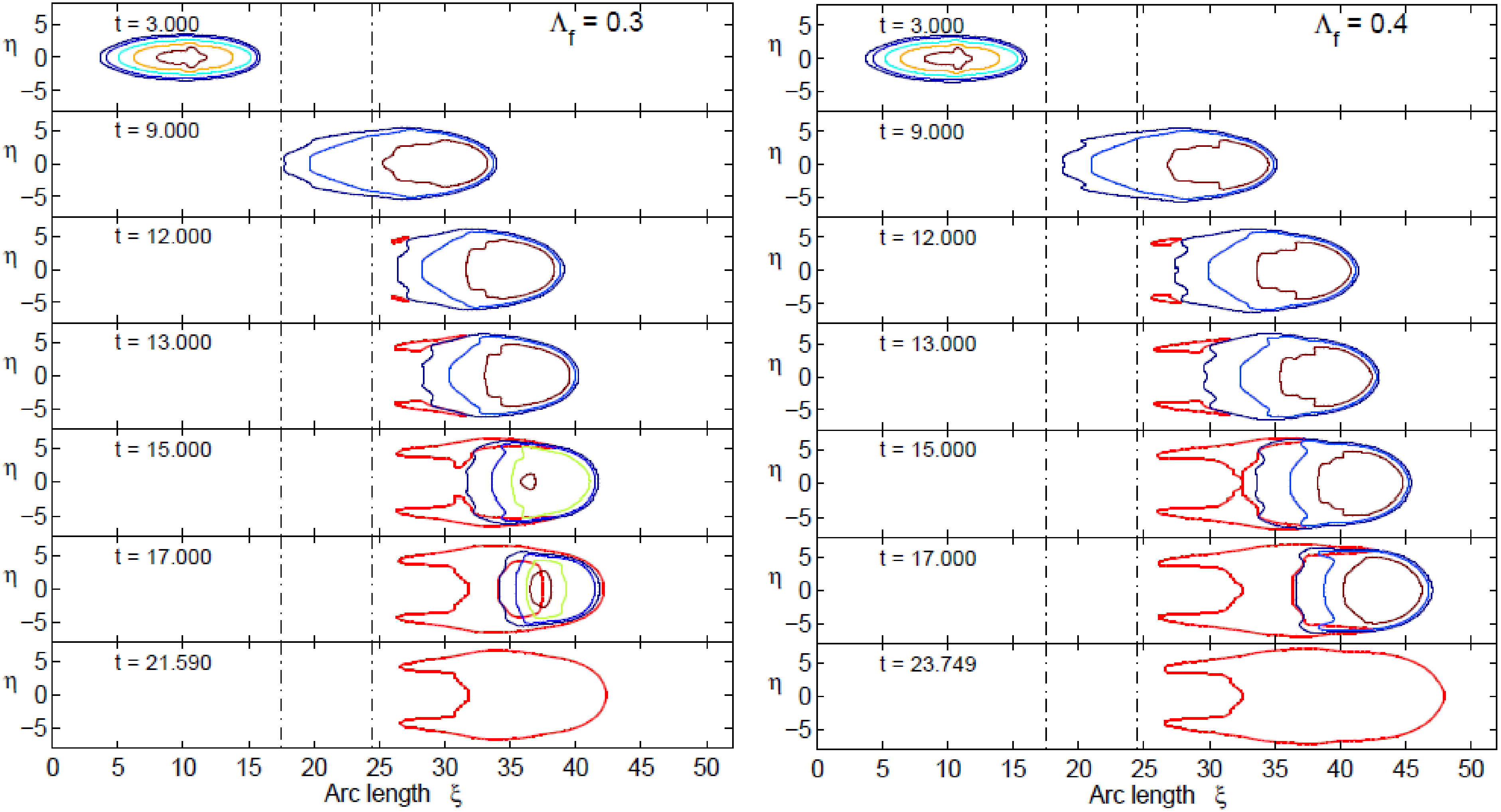




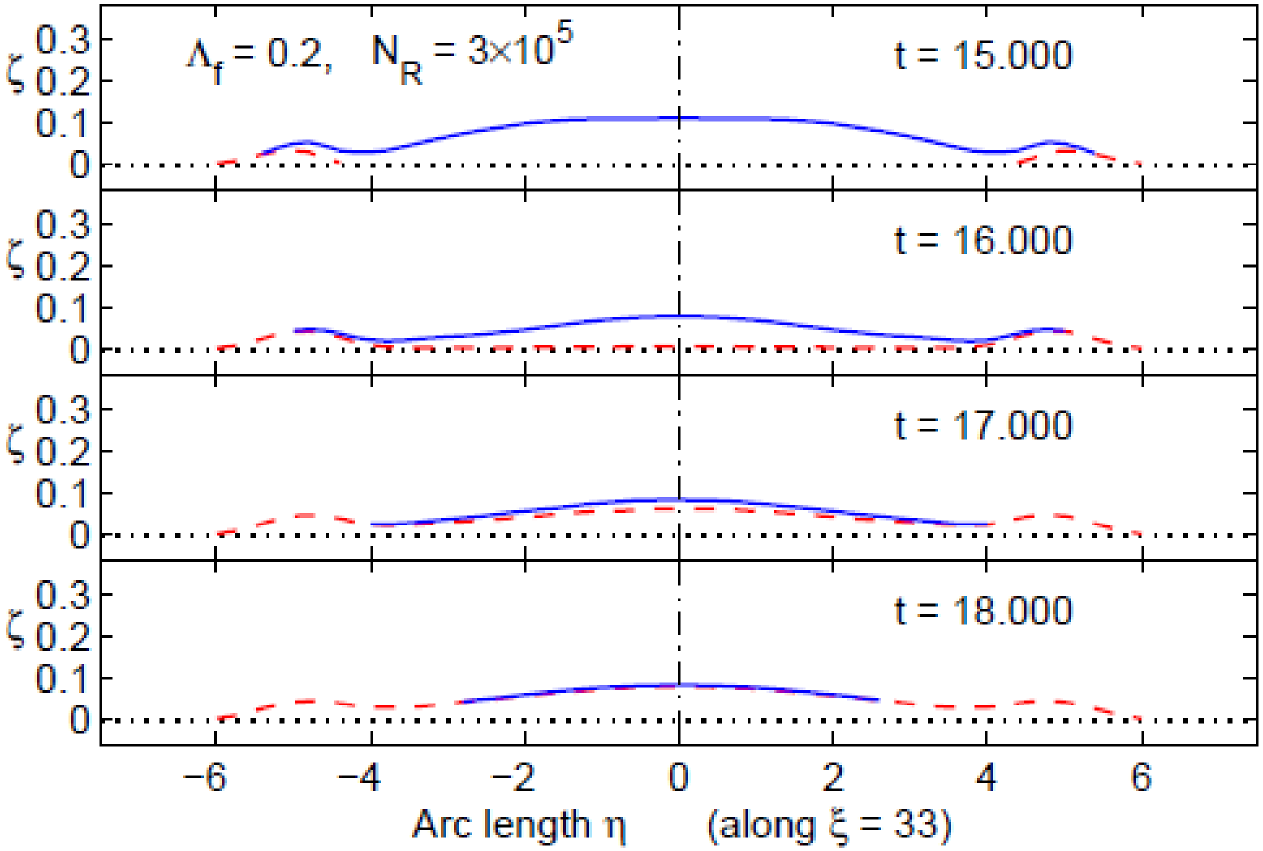
Levee formation

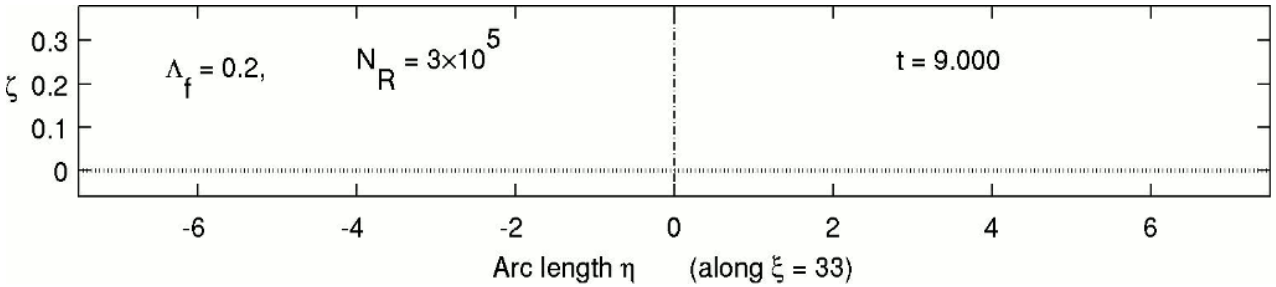


Levee formation



Levee formation (*cross section view*)





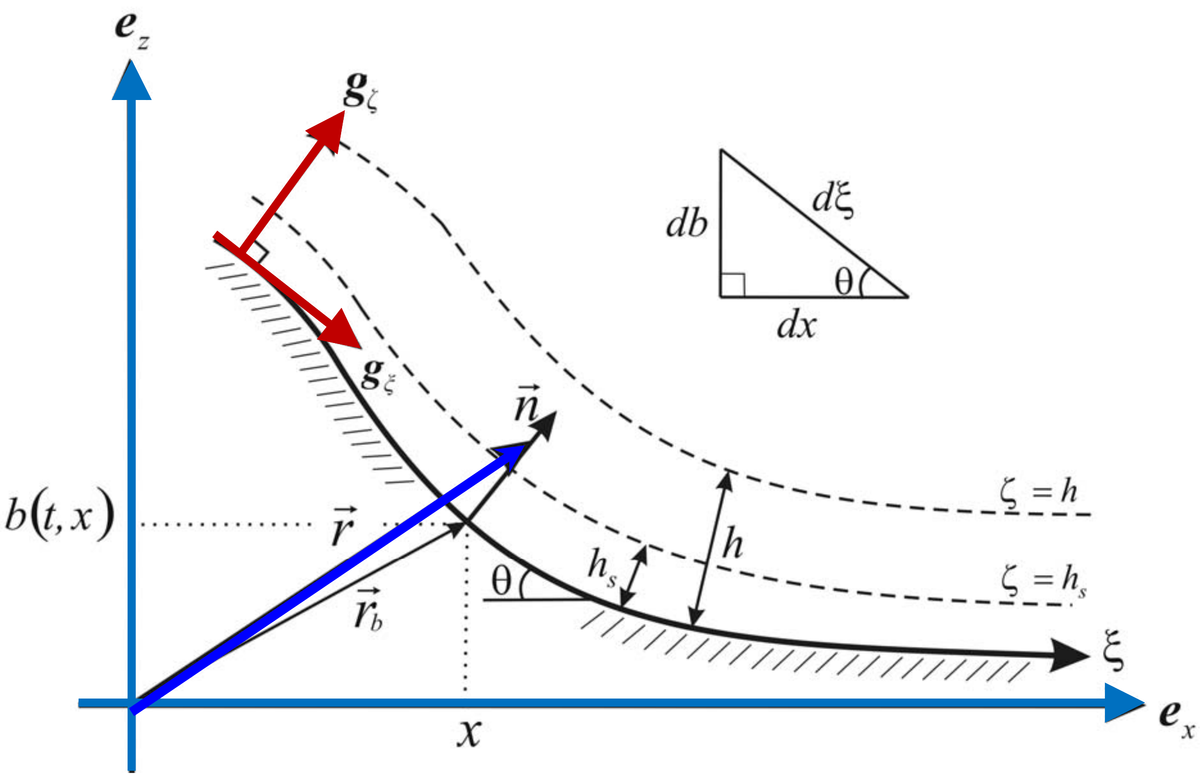
Further applications

- **Erosional Dam-Break Shear Flows**

by

Y. T. Huang and Y. C. Tai

Coordinate system for general topography



$$z - b(x,t) = 0$$

$$\vec{n} = -s_x\, \mathbf{e}_x + c\, \mathbf{e}_z$$

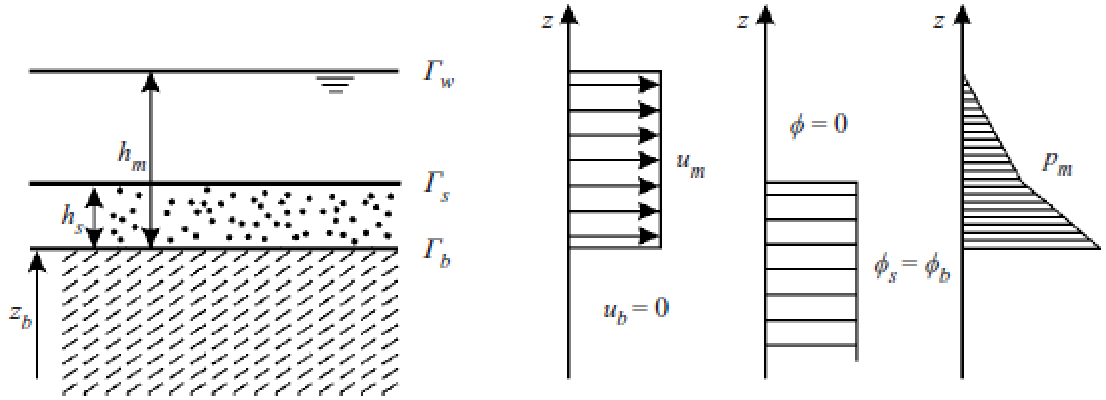
$$s_x = c\, \partial_x b$$

$$c = 1 \Big/ \sqrt{1 + (\partial_x b)^2}$$

$$\vec{r} \equiv r_x\, \mathbf{e}_x + r_z\, \mathbf{e}_z = \vec{r}_b + \zeta\, \vec{n}$$
$$= x\,\mathbf{e}_x + b\,\mathbf{e}_z + \zeta\,\vec{n}$$
$$= (x - \zeta\, s_x)\,\mathbf{e}_x + (b + \zeta\, c)\,\mathbf{e}_z$$

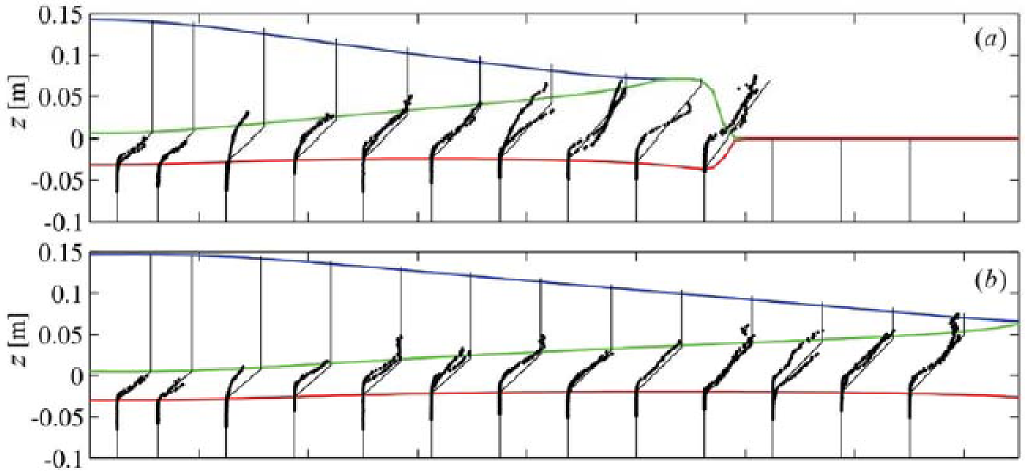
Flow structure postulation

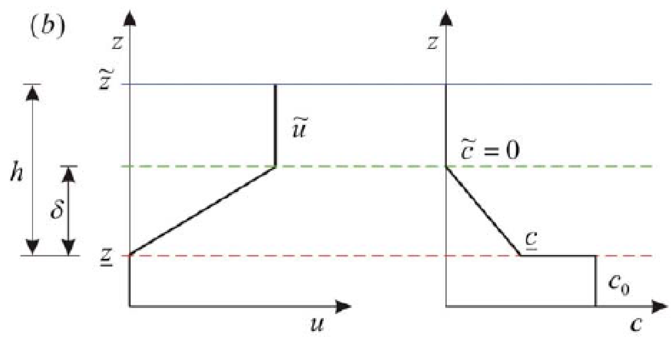
- ***Previous postulated flow structure*** *(Fraccarollo and Capart, 2002, JFM)*



  - *thin layers*
  - *almost uniform velocity profile*
  - *constant sediment concentration (mixture layer and bed)*
  - *hydrostatic pressure*

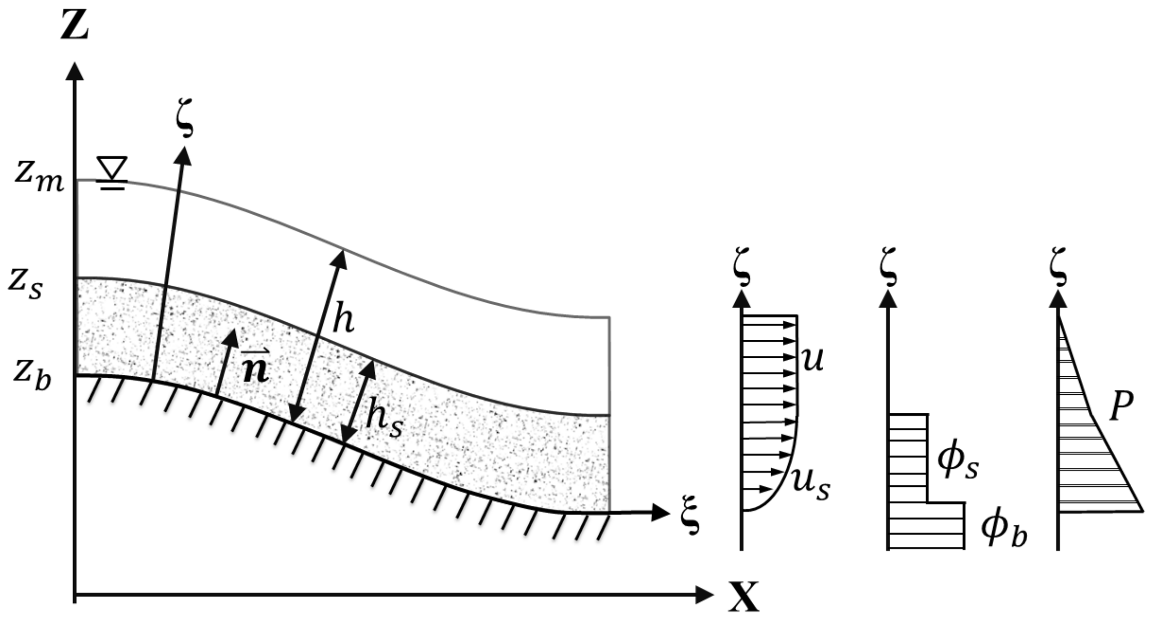
- ***Measurement of a sudden dam break*** *(Spinewine and Capart, 2013, JFM)*





Flow structure postulation

- ***Current postulated flow structure over the terrain-fitted coordinate system***



- *thin layers*
- *almost uniform velocity profile for water layer and linear velocity profile for mixture layer*
- *constant sediment concentration for mixture layer and bed but of different values*
- *hydrostatic distribution for the pressure*

Depth-integrated equations

- ***Equations of mass balance***

$$\partial_t\left(J_b h\right)+\partial_\xi\left(J_b u^\xi\left(h-\tfrac{1}{2}h_s\right)\right)=-J_b\mathsf{E}$$

$$\partial_t\left(J_b h_s\right)+\partial_\xi\left(\tfrac{1}{2}J_b h_s u^\xi\right)=-J_b\alpha_C^{-1}\mathsf{E}$$

$$\alpha_C=\phi_s/\phi_b,\quad r=\left(\rho_s/\rho_w-1\right)\phi_s$$

$$\Sigma^{x\xi}=\Omega_m^x t^{m\xi},\quad \Sigma^{x\zeta}=\Omega_m^x t_b^{m\zeta}$$

$$J_b=\det\tilde{\boldsymbol{\Omega}}_b$$

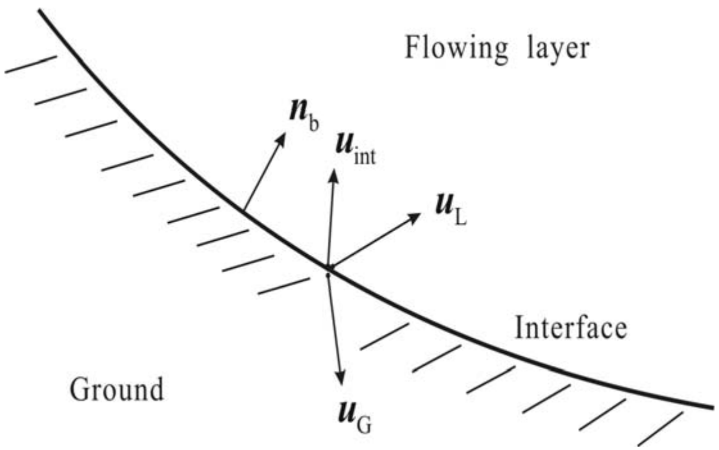
- ***Equations of momentum balance***

$$\partial_t\left(J_b\left(h+\tfrac{r-1}{2}h_s\right)u^x\right)+\partial_\xi\left(J_b\left[\left(h+\tfrac{r-2}{3}h_s\right)u^x u^\xi+\Sigma^{x\xi}\right]\right)$$
$$=-J_b\mathsf{E}\left(h+r\,h_s\right)u_b^x-J_b s_x\,c\left(h+r\,h_s\right)g-J_b\Sigma_b^{x\zeta}$$

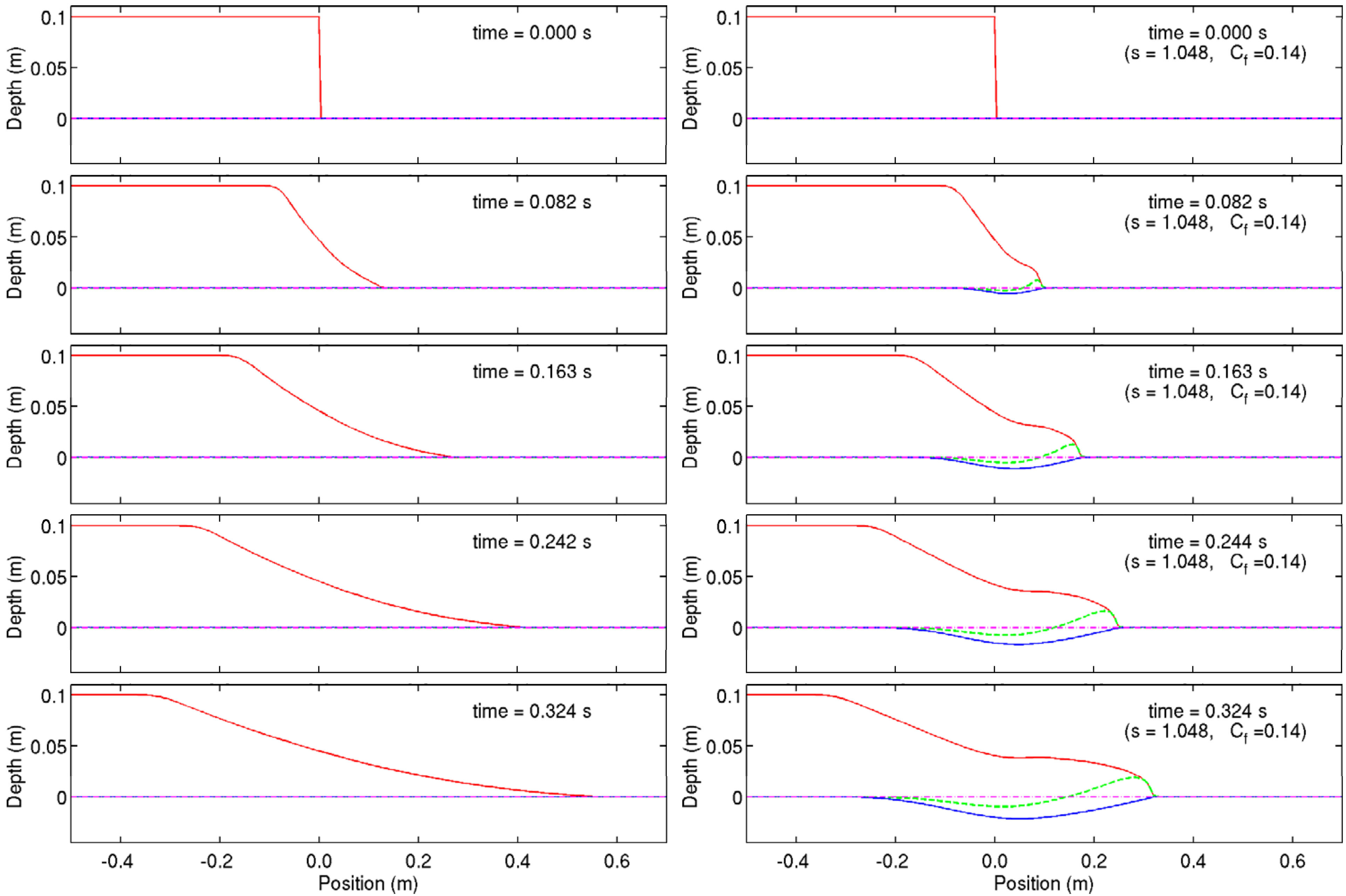
where jump conditions at bed

$$M_{\text{basal}}=\rho_{\text{G}}\left(\boldsymbol{u}_{\text{int}}-\boldsymbol{u}_{\text{G}}\right)\cdot\boldsymbol{n}_{\text{b}}=\rho_{\text{L}}\left(\boldsymbol{u}_{\text{int}}-\boldsymbol{u}_{\text{L}}\right)\cdot\boldsymbol{n}_{\text{b}}$$

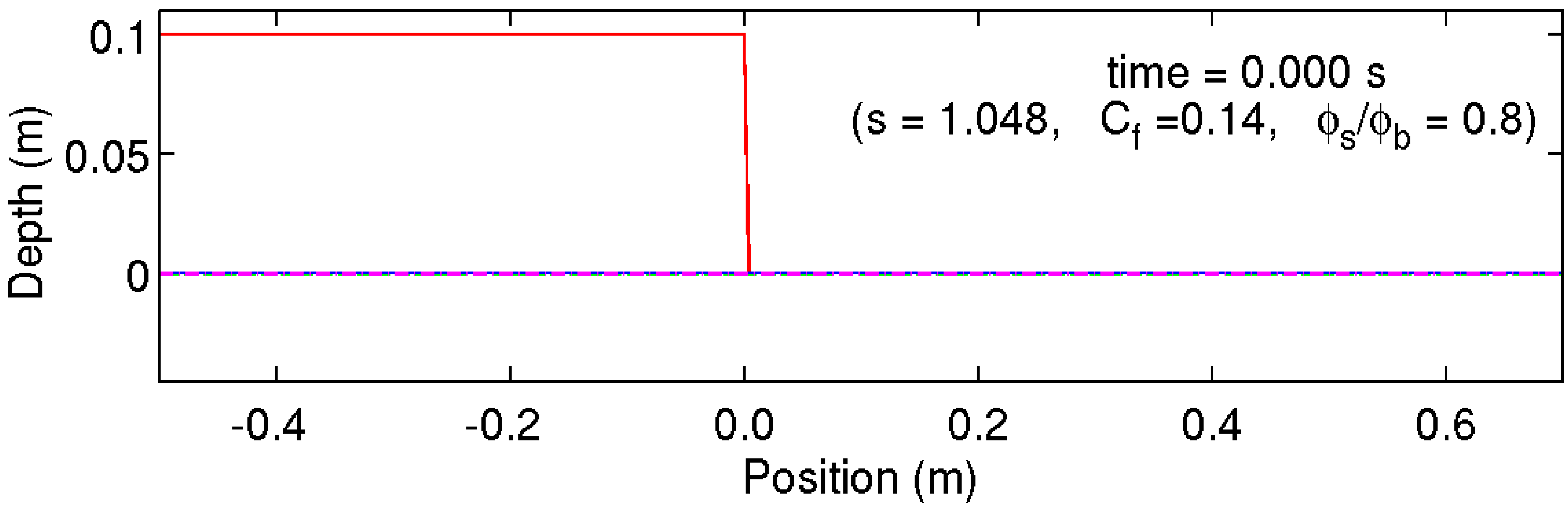
$$M_{\text{basal}}\left(\boldsymbol{u}_{\text{G}}-\boldsymbol{u}_{\text{L}}\right)=\boldsymbol{t}_{\text{G}}\,\boldsymbol{n}_{\text{b}}-\boldsymbol{t}_{\text{L}}\,\boldsymbol{n}_{\text{b}}$$



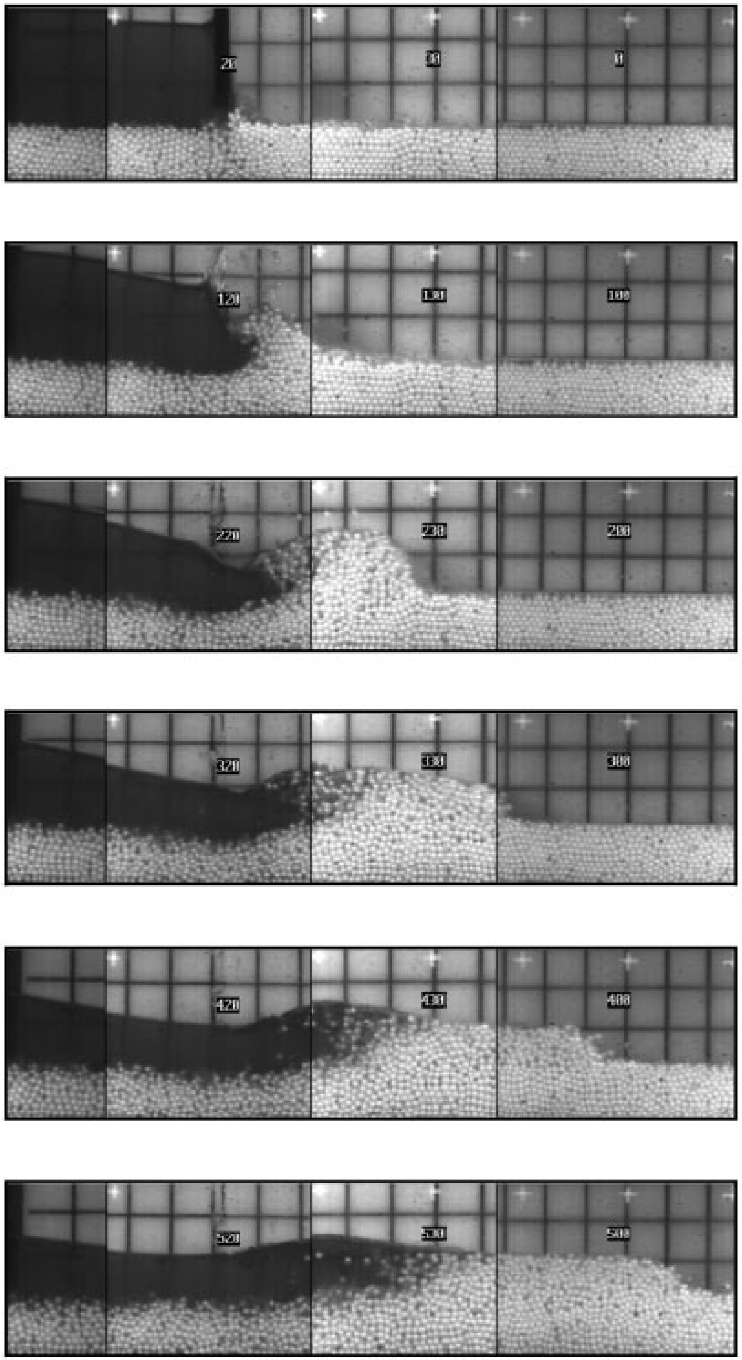
- ***Effect of erosion***

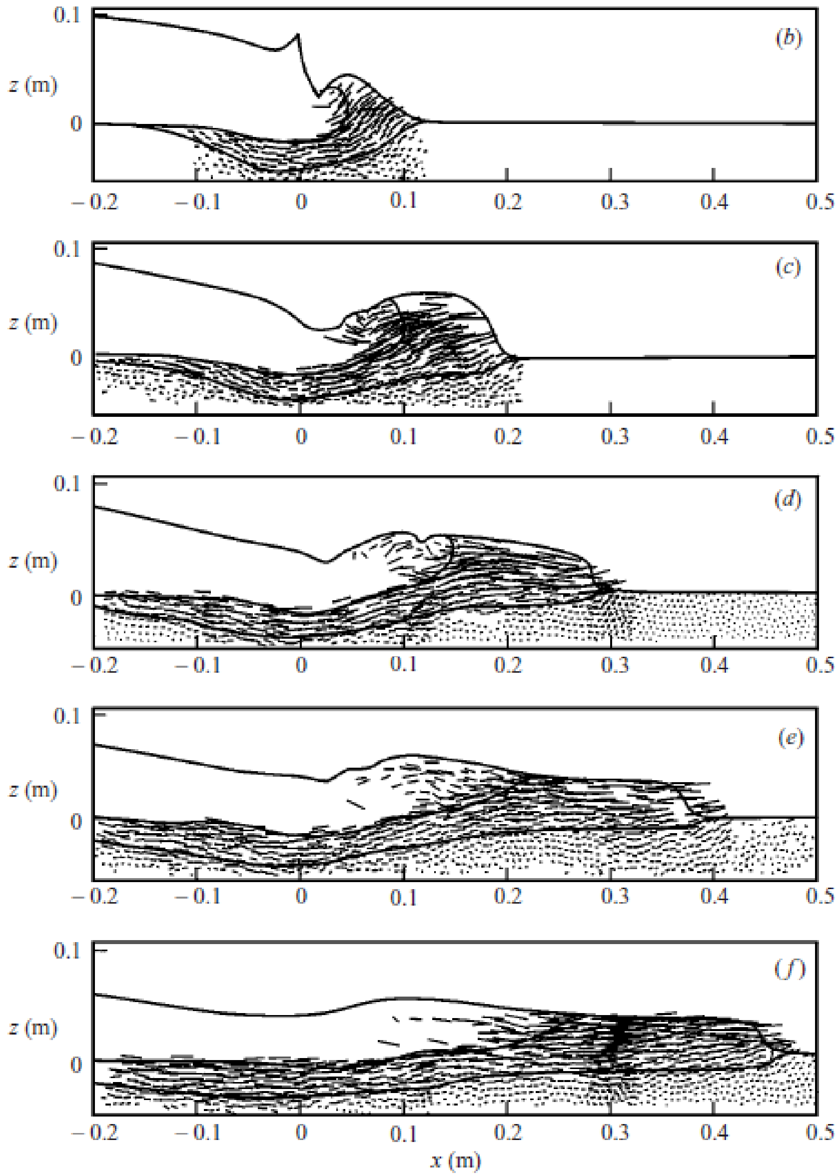


- ***Result of simulation***

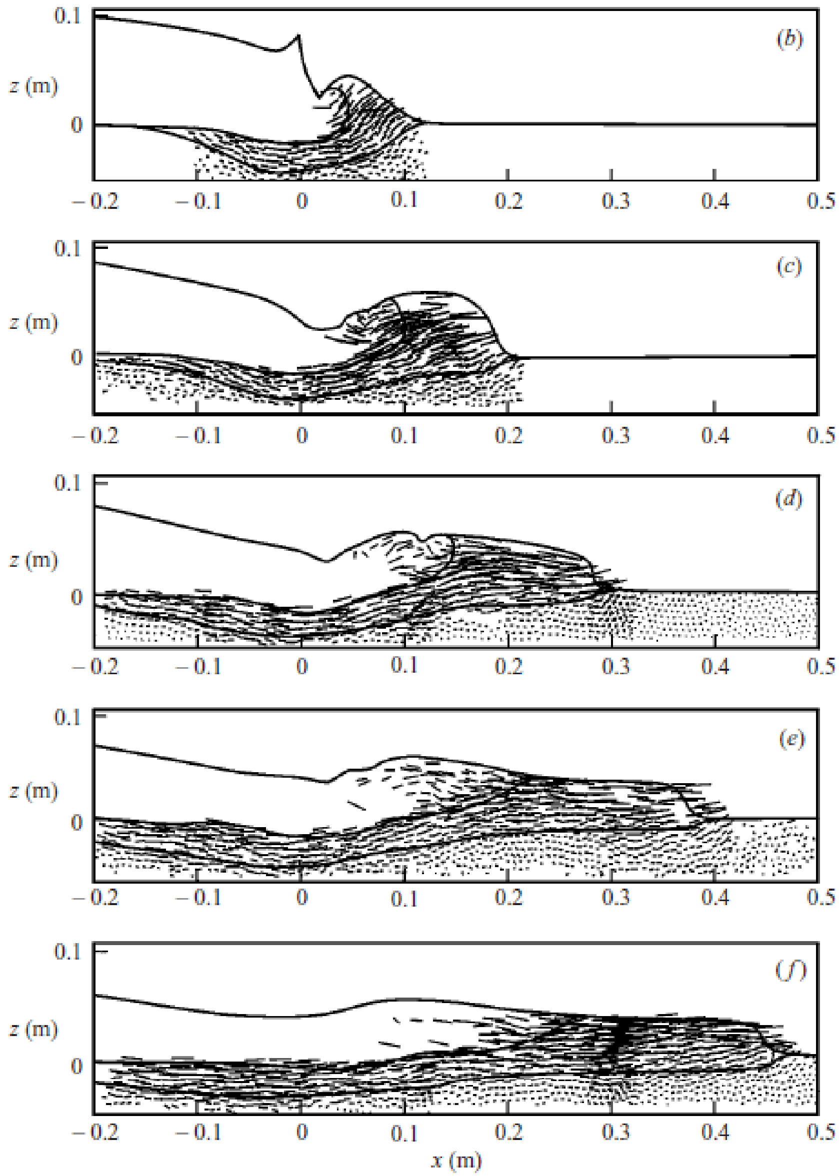


Experiment by Fraccarollo & Capart (2002)

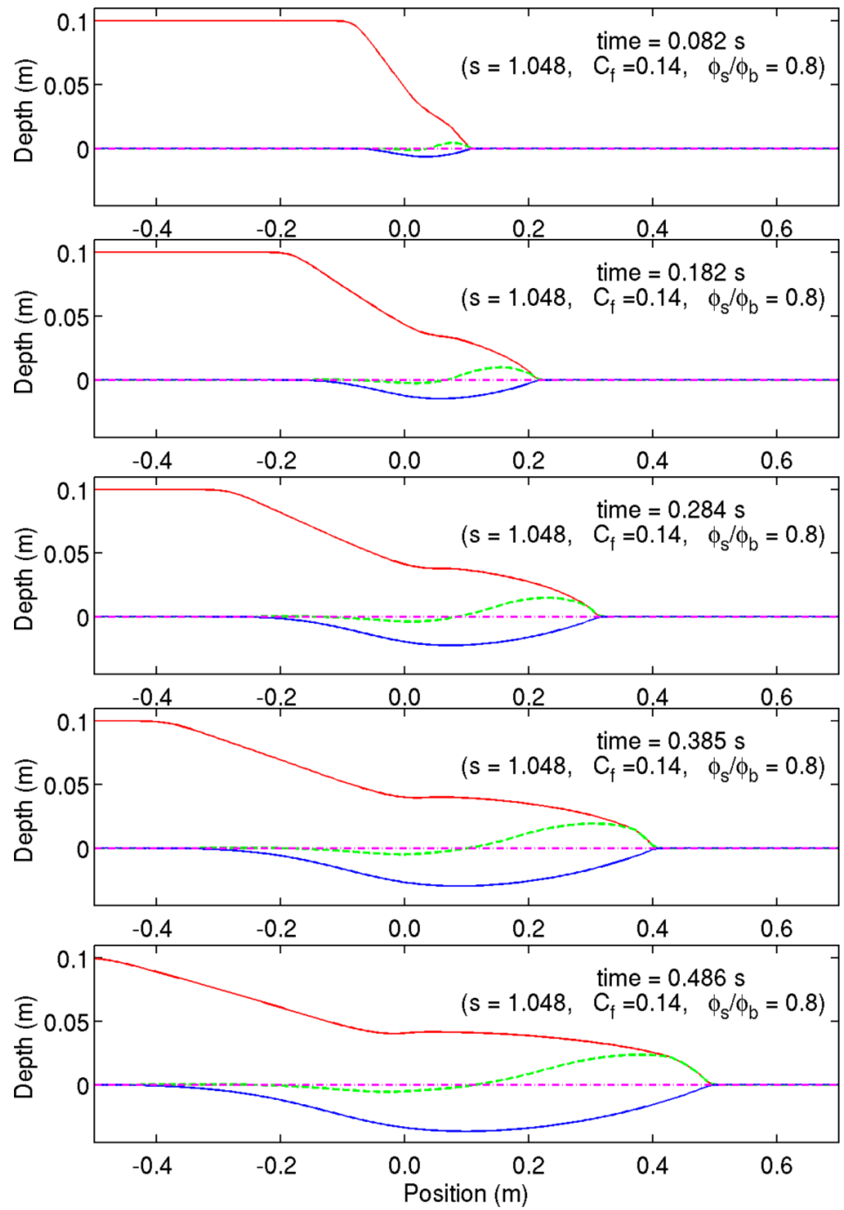




Experiment by Fraccarollo & Capart (2002)

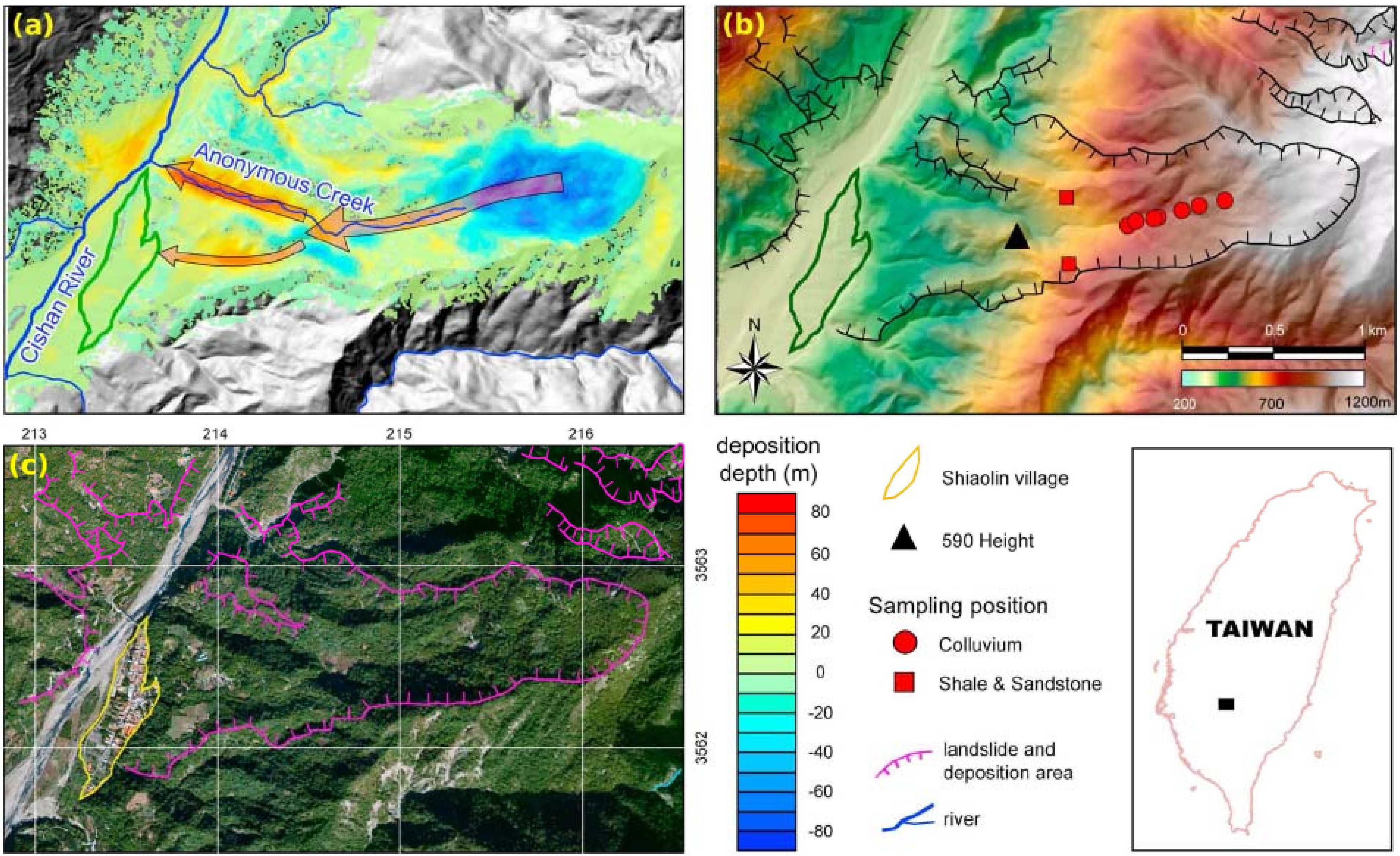


Numerical simulation by current method



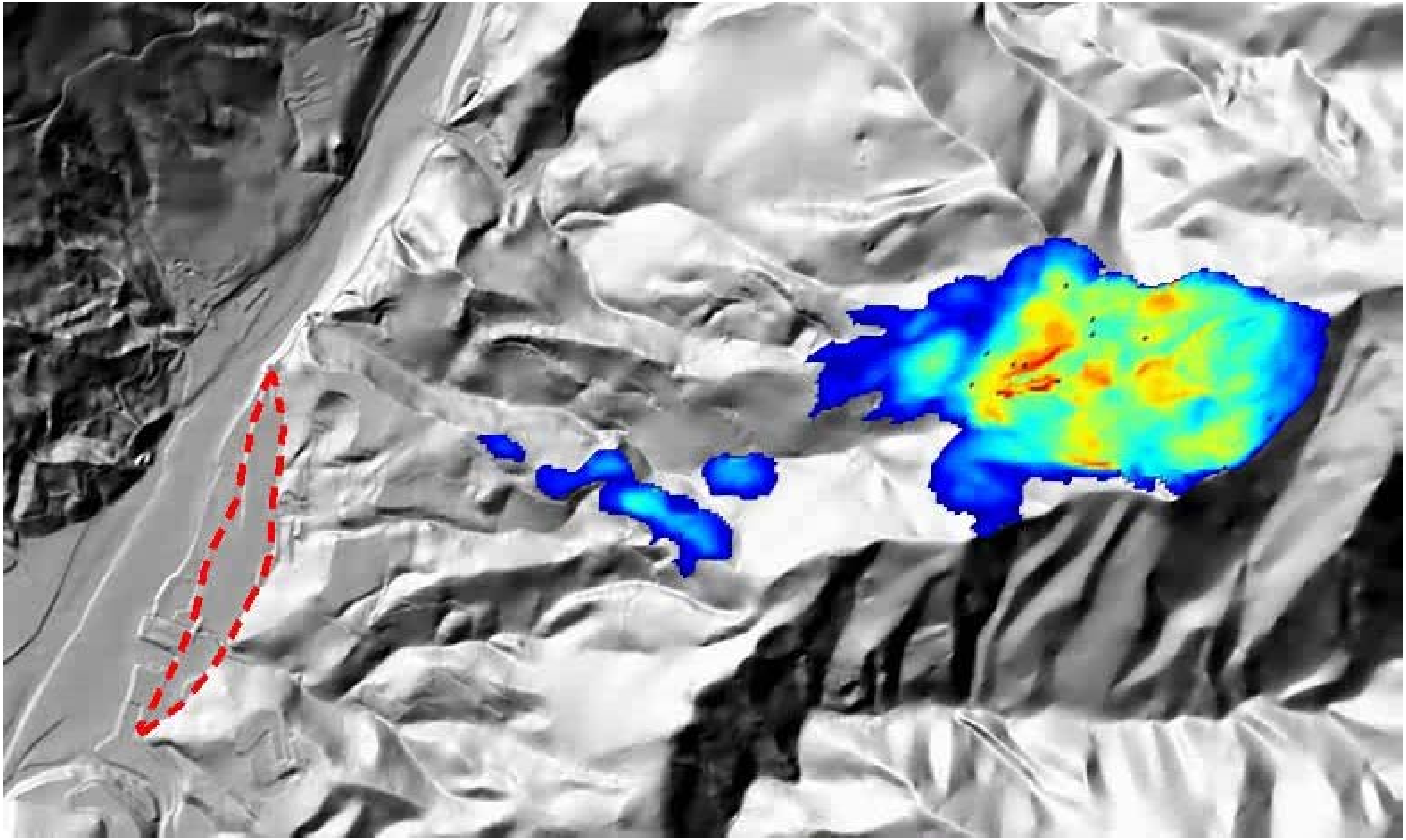
Reconstruction of the Hsiaolin Landslide Catastrophe, Taiwan 2009

by
C. Y. Kuo, Y. C. Tai, C. C. Chen, K. J. Chang, A. Y. Siau, J. J. Dong, R. H. Han, T. Shimamoto and C. T. Lee, JGR (2011)



(a)
Anonymous Creek
Cishan River
(b)
N
0
0.5
1 km
200
700
1200m
213
214
215
216
(c)
3563
3562
deposition depth (m)
80
60
40
20
0
-20
-40
-60
-80
Shiaolin village
590 Height
Sampling position
Colluvium
Shale & Sandstone
landslide and deposition area
river
TAIWAN

Animation



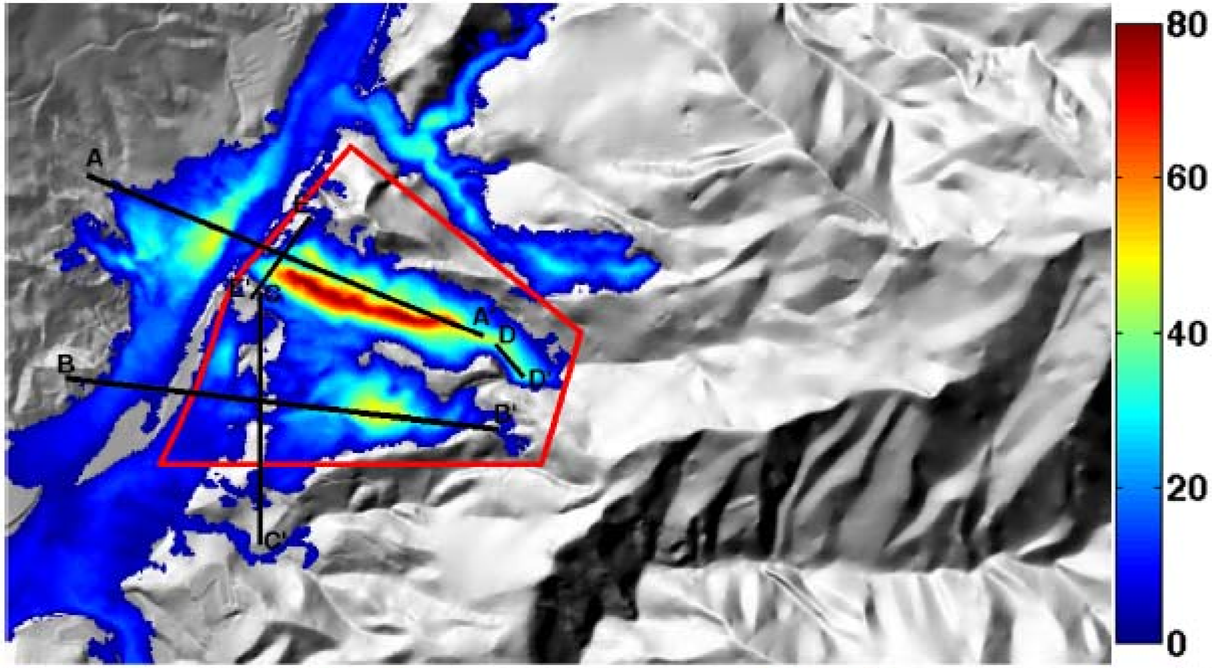
Optimal friction angle: 11.47°

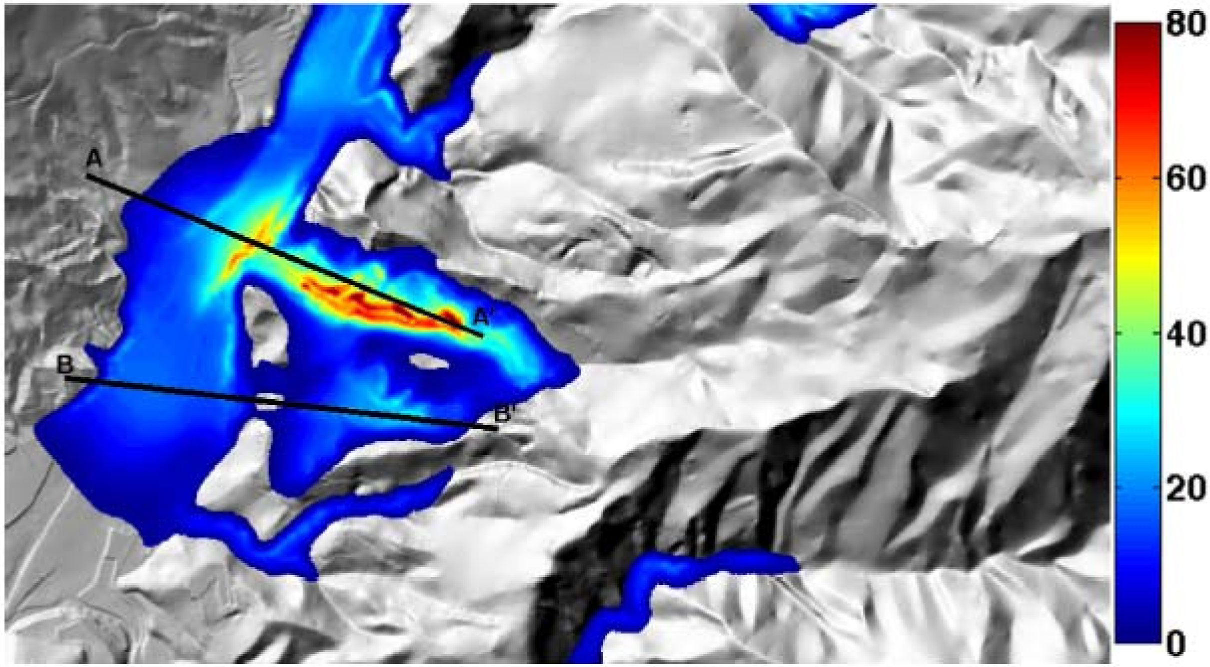
(agree with the friction coefficient projection relation on the geometric constraint, and Staron & Lajeunesse ,2009)

Duration: 110 s
Volume: 26.17 Mm^3
Comput. domain:
3,710 × 2,220 m^2
Mesh size: 10× 10 m^2

Optimization process:

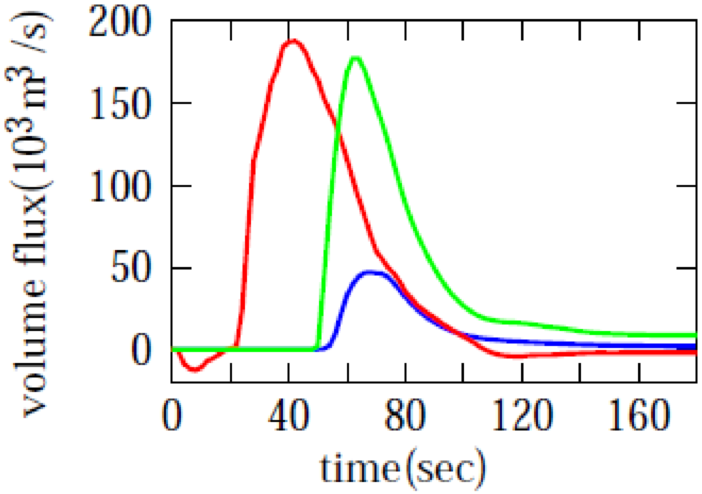
$$h^2_{std}(\mu) = \min_{\mu} \frac{1}{A} \int_A \left(h(\mathrm{x};\mu) - h_{meas}(\mathrm{x})\right)^2 dA$$

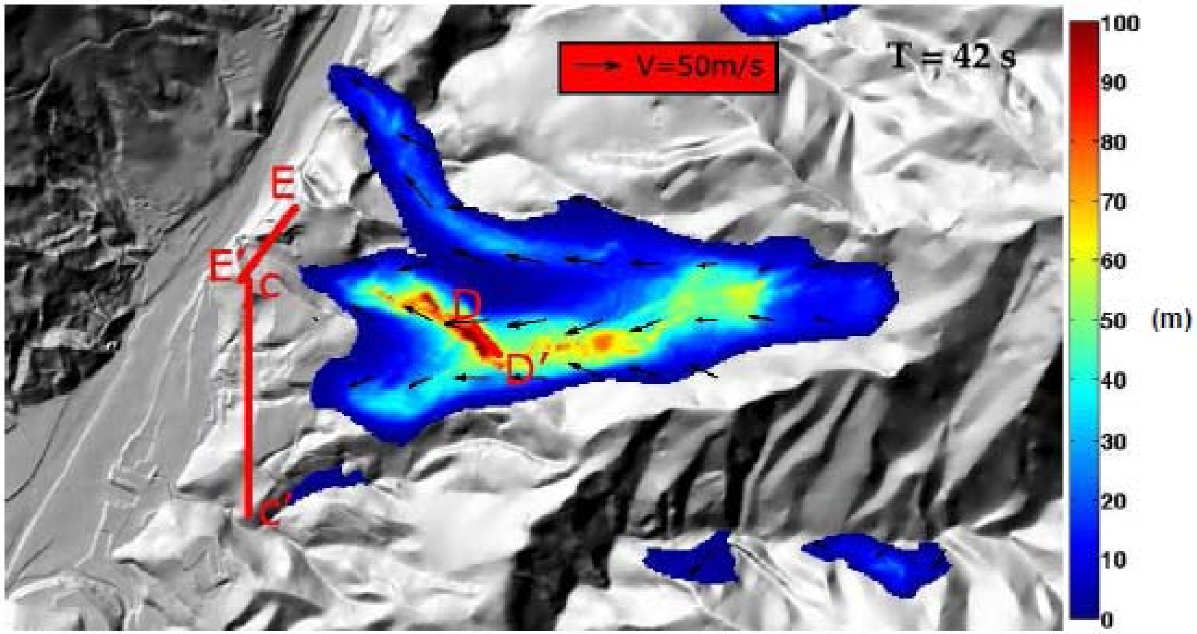




Transient volume fluxes

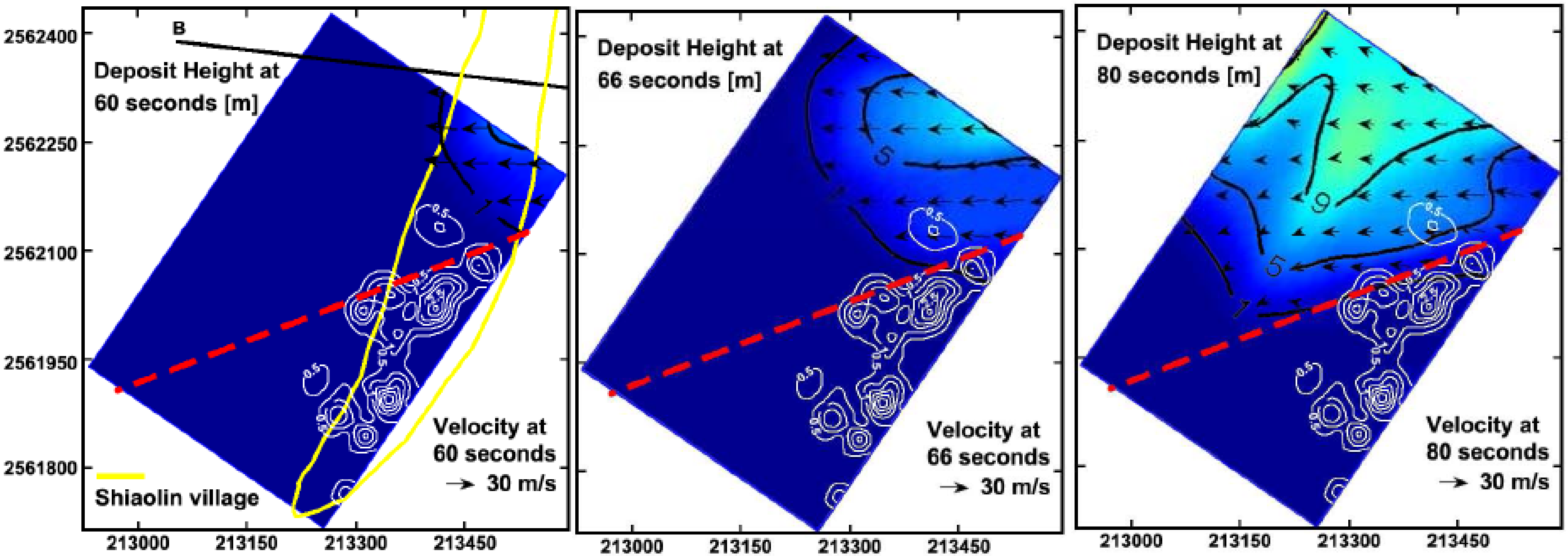
- *The max. speed reaches about 50 m/s in the anonymous creek valley.*
- *The flux across section DD' peaks at about 42 sec.*
- *The two streams reach their maxima at about 62 and 64 sec.*
- *About 7% of the slid volume flow through the village.*





Flow snapshots in comparison with the near-surface magnetic surveys

- *Yellow line indicates the village area*
- *Red dashed line indicates the boundary of the magnetic anomalies (destruction front)*
- *Coincidence with the flow boundary (1 m depth)*



Concluding remarks

Modeling part:

- *An alternative formulation for shallow hazardous flows over non-trivial and deforming topography is presented.*
- *The key features of this formulation are illustrated by the numerical examples.*

Application part:

- *Experimental validation: Upstream traveling wave; Chute experiment.*
- *Numerical example: Levee formation by Coulomb-mixture theory; Erosional dam-break shear flows.*
- *With the hydrodynamic model over general topography, the Hsiaolin landslide event can be favorably reconstructed.*

However, ……