Waseda University

浮遊砂としての土砂移動の取り扱いの現状と課題

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浮遊砂理論の抱える課題

- 浮遊砂としての土砂輸送を移流拡散と捉えたとき，濃度拡散係数は力学的にどのように定めればよいのか？

→ 平均的には乱流拡散係数に等しい、あるいは比例するとされるが，掃流力が大きい条件下でこの近似は成り立たなくなる.

→ 土砂濃度が高くなると，粒子間接触の影響や粒子の存在が乱流場に与える影響が無視できない (乱流場の変質) .

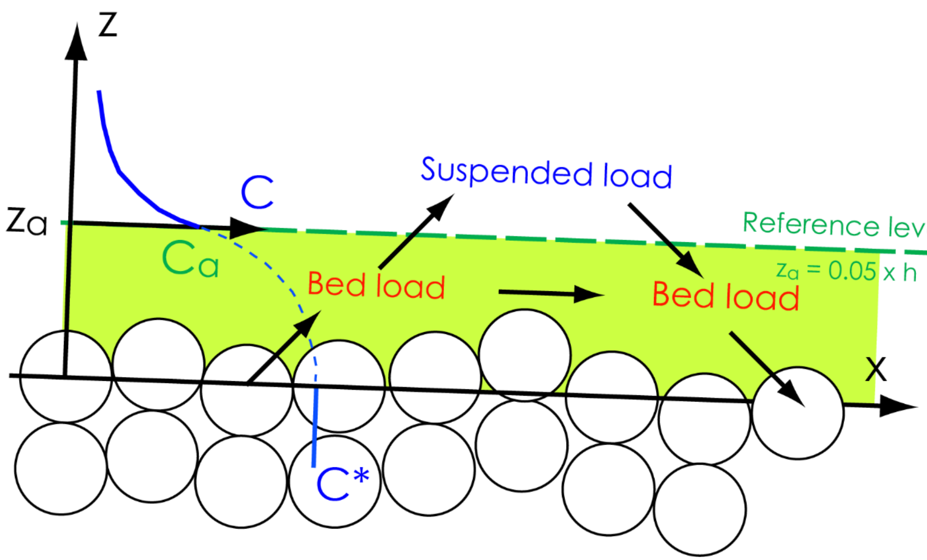
→ 浮遊砂の輸送には間欠的に発生する組織渦 (coherent structure of turbulence)が顕著な影響を及ぼす.

浮遊砂理論の抱える課題

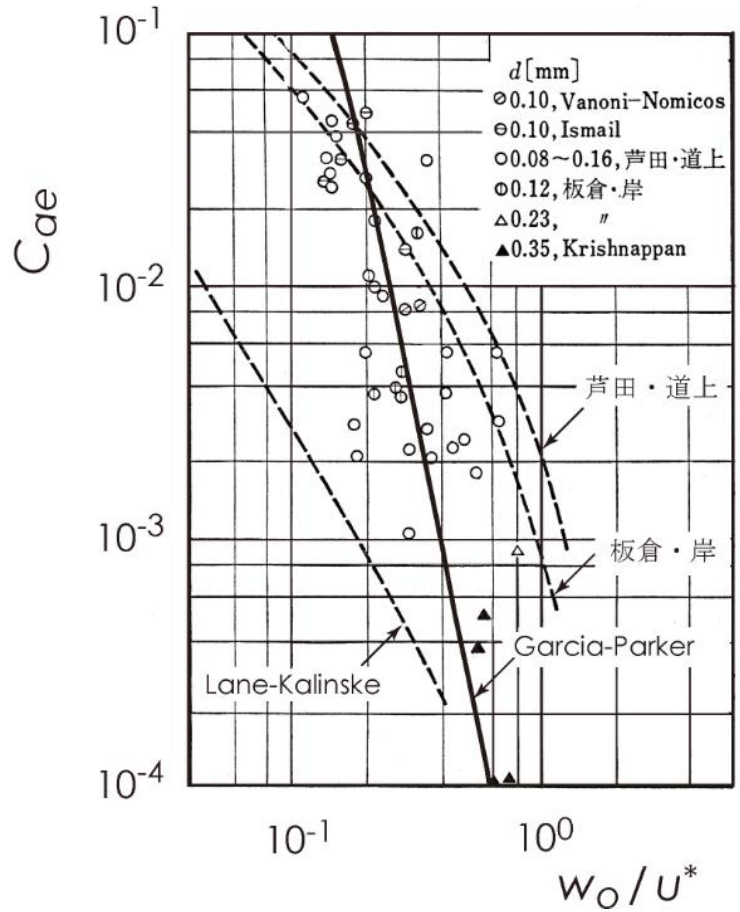
- 河床変動計算を行う際に，平衡状態で計測された基準面濃度 C_a と u^*/w_o の関係を，非平衡状態での巻き上げ速度 E_s と u^*/w_o の関係として用いられている．この考え方はどこまで正しいのか？

浮遊砂の基準面の高さ・基準面濃度

従来，濃度の鉛直方向勾配が相対的に大きい「水深の5%」の位置を基準面としてきた．この高さで計測された土砂濃度のデータには大きな誤差が含まれており，現在の体系ではこの点を克服しない限り大きな精度向上は期待できない．



浮遊砂の基準面濃度の実測値と評価式



浮遊砂運動の分散係数

- LES (Large-Eddy Simulation)モデルにより再現されたせん断乱流場における土砂粒子群の沈降運動の数値実験によって，土砂の分散プロセスを検討した.
- 水流に生じている乱流場は，統計的に見て均質なものではなく，「Bursting現象」として知られる乱れの組織的な構造 (Coherent structure) が存在する．この浮遊砂の運動にはこの影響が無視できない.

粒子の質点系の運動方程式

$$\rho\,\sigma_s\,V\,\frac{\partial \vec{u}_p}{\partial t} = \rho\,(\sigma_s - 1)\,V\,\vec{g} + \rho\,V\,\frac{\partial \vec{u}_f}{\partial t} + \frac{1}{2}\,\rho\,C_D\,A\,\mid \vec{u}_r \mid \vec{u}_r + \rho\,V\,C_M\,\frac{\partial \vec{u}_r}{\partial t} + \frac{1}{2}\,\rho\,C_L\,A\left[\left(u_r^2\right)_T - \left(u_r^2\right)_B\right]\vec{e}$$

重力項　抗力項　圧力項　揚力項

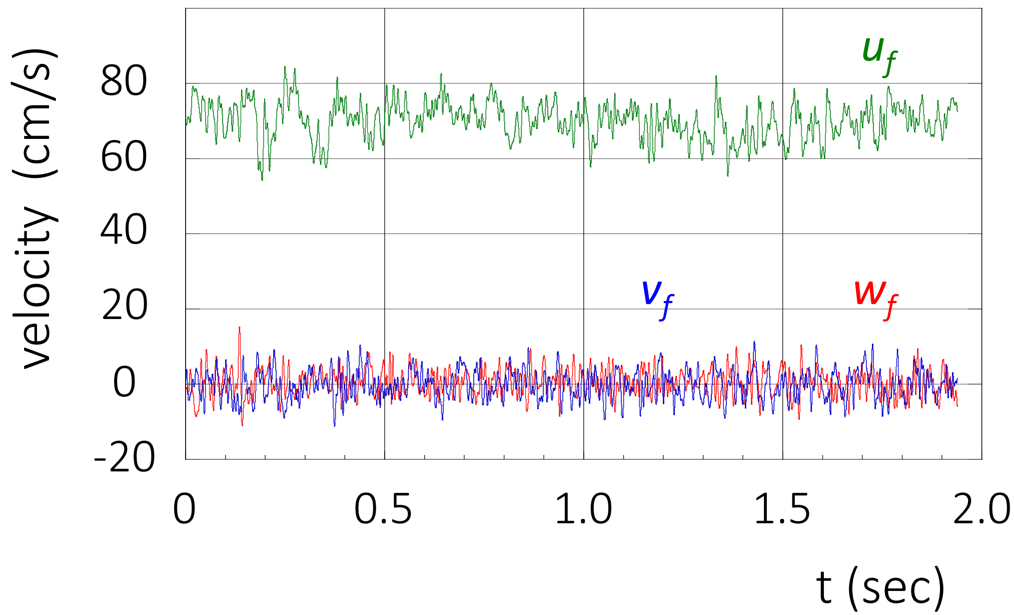
Subscriptの p，fと r：粒子速度，流速ならびに両者の間の相対速度を表す物理量.

C_D：抗力係数(= $24/R_e + 3/R_e^{0.5} + 0.34$)；$R_e \equiv |\vec{u_r}|\,D/\nu$

C_L：揚力係数（ = 0.2)

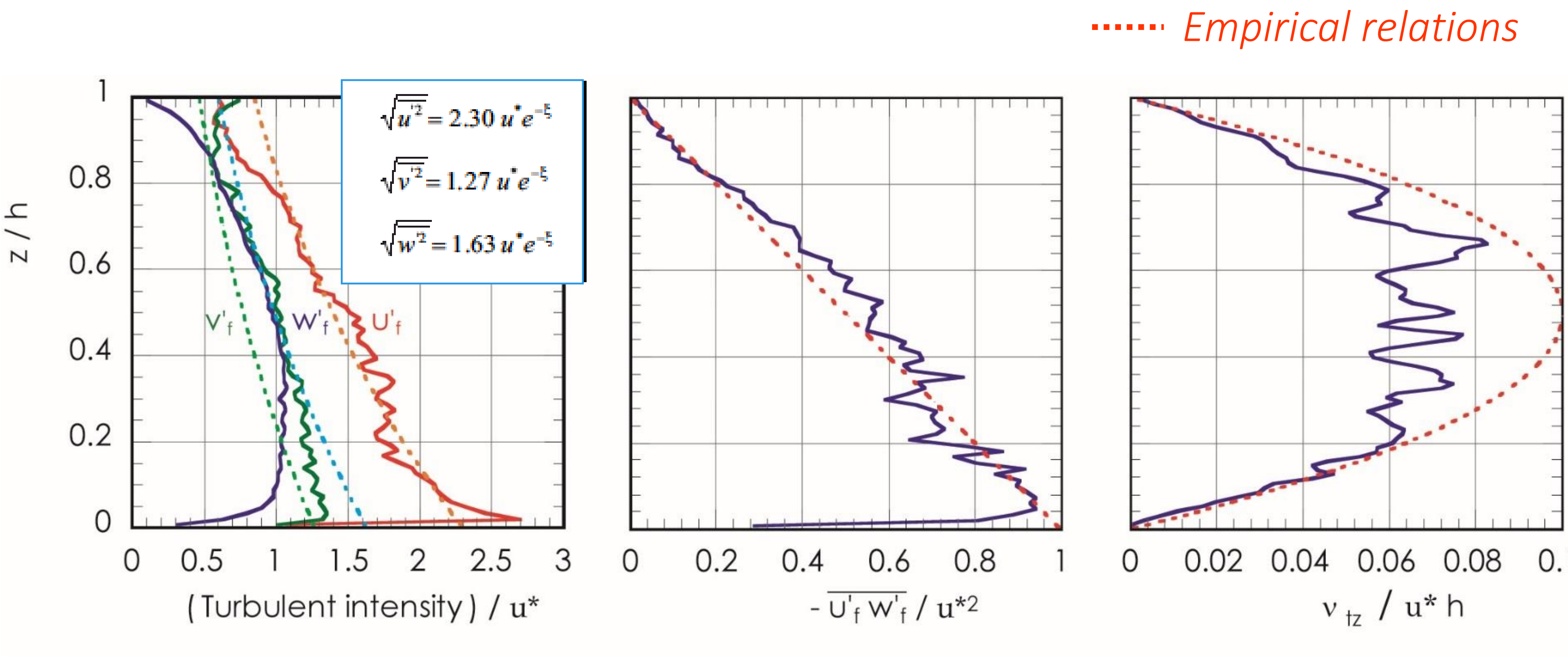
C_M: 付加質量係数 (= 0.5；球の場合)

流速の時系列データの一例



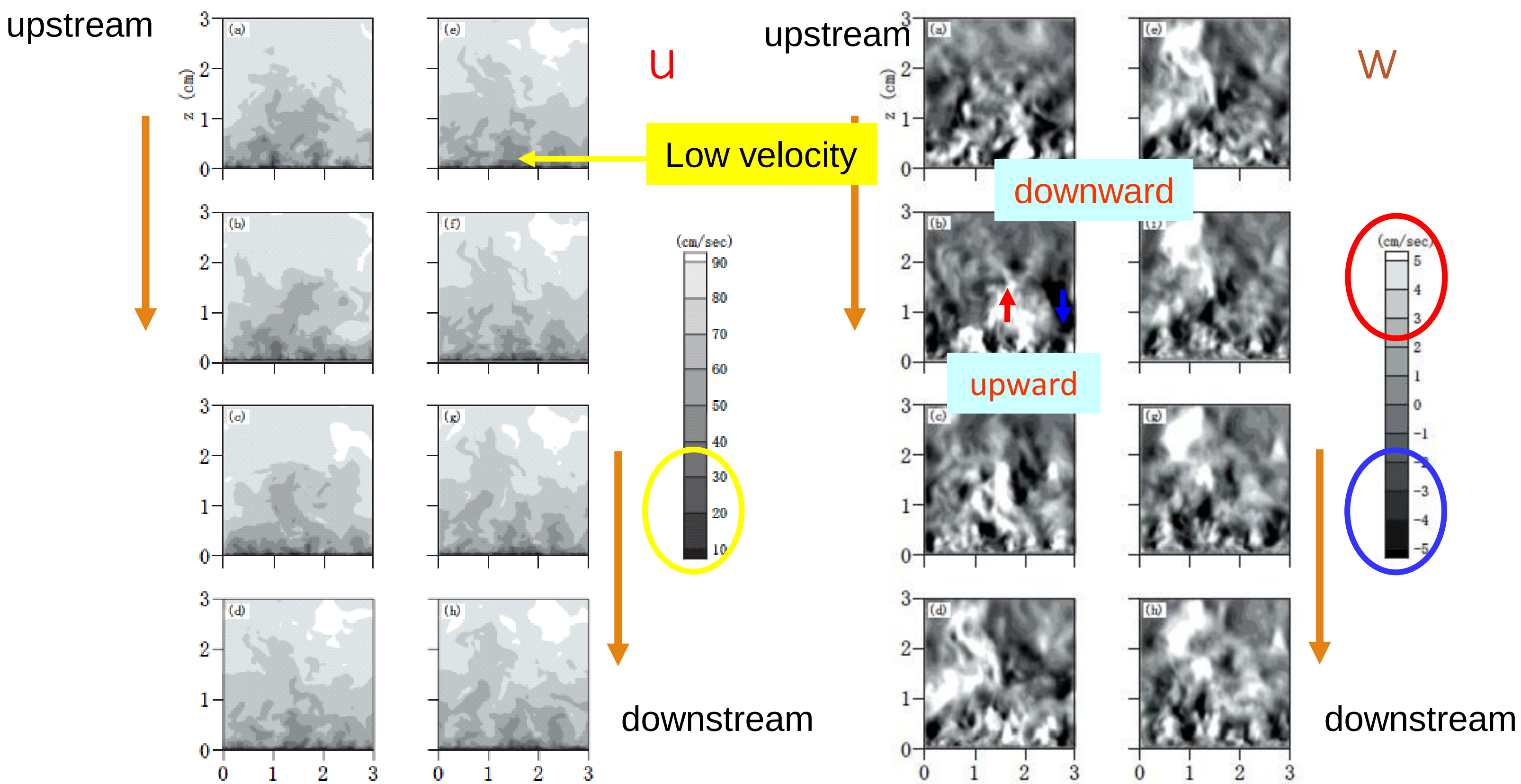
sampled at (x, y, z) = (6.0, 1.5, 1.0) (cm)

乱流特性量と乱流拡散係数の鉛直分布



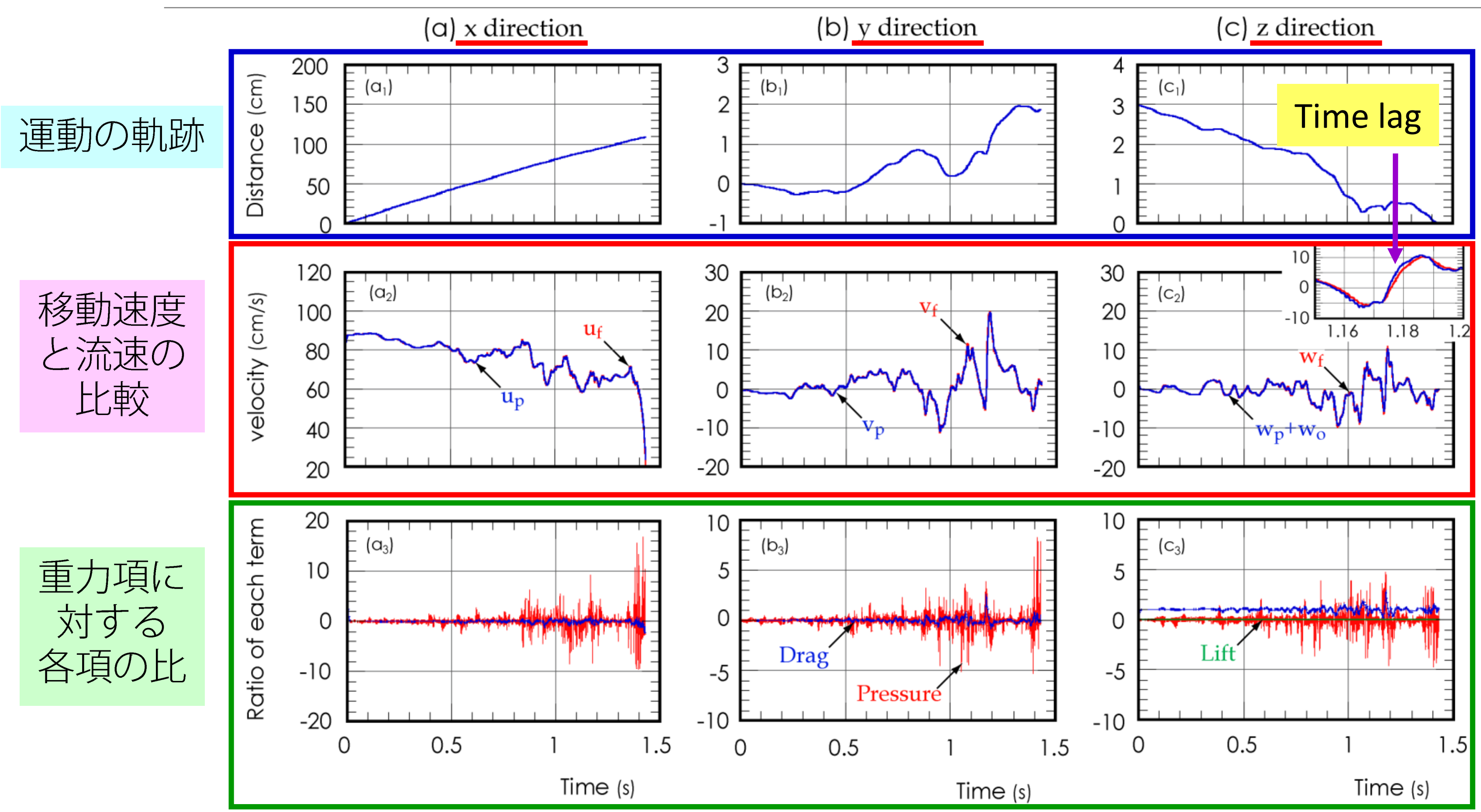
乱流強度　Reynolds応力　乱流拡散係数

乱流のCoherent structure (u－v のコンター図)

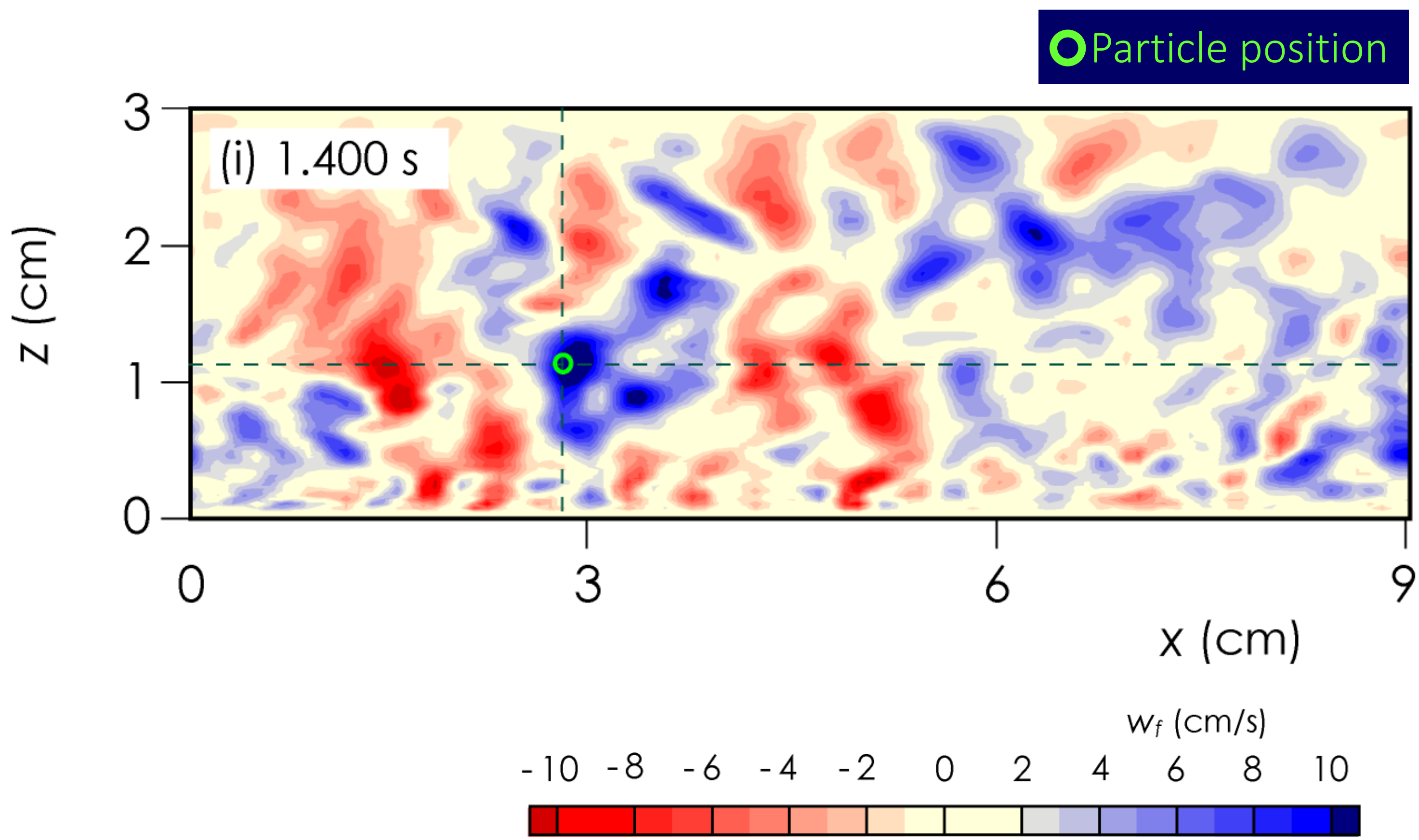


Bursting period T_B: $T_B U_{max} / h$ = 3 – 4: obtained by this simulation
= 2 – 5: obtained empirically by Nezu & Nakagawa

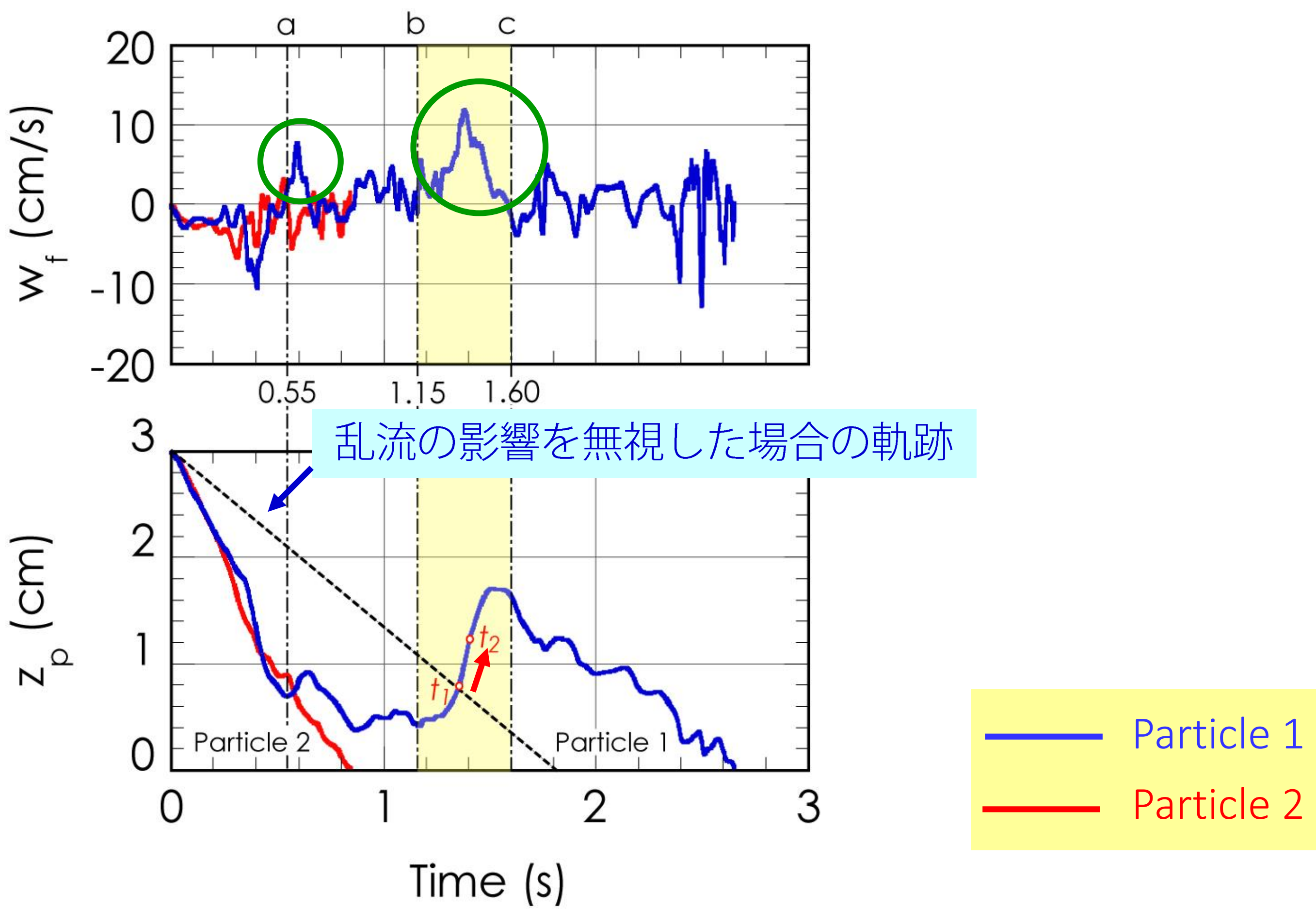
粒子軌跡と移動中に作用する諸量



流速の鉛直方向成分のコンター図と粒子位置



典型的な粒子軌跡と作用流速との関係



粒子の分散係数の試算 (G.I. Taylorの拡散理論)

座標　　　　移動速度

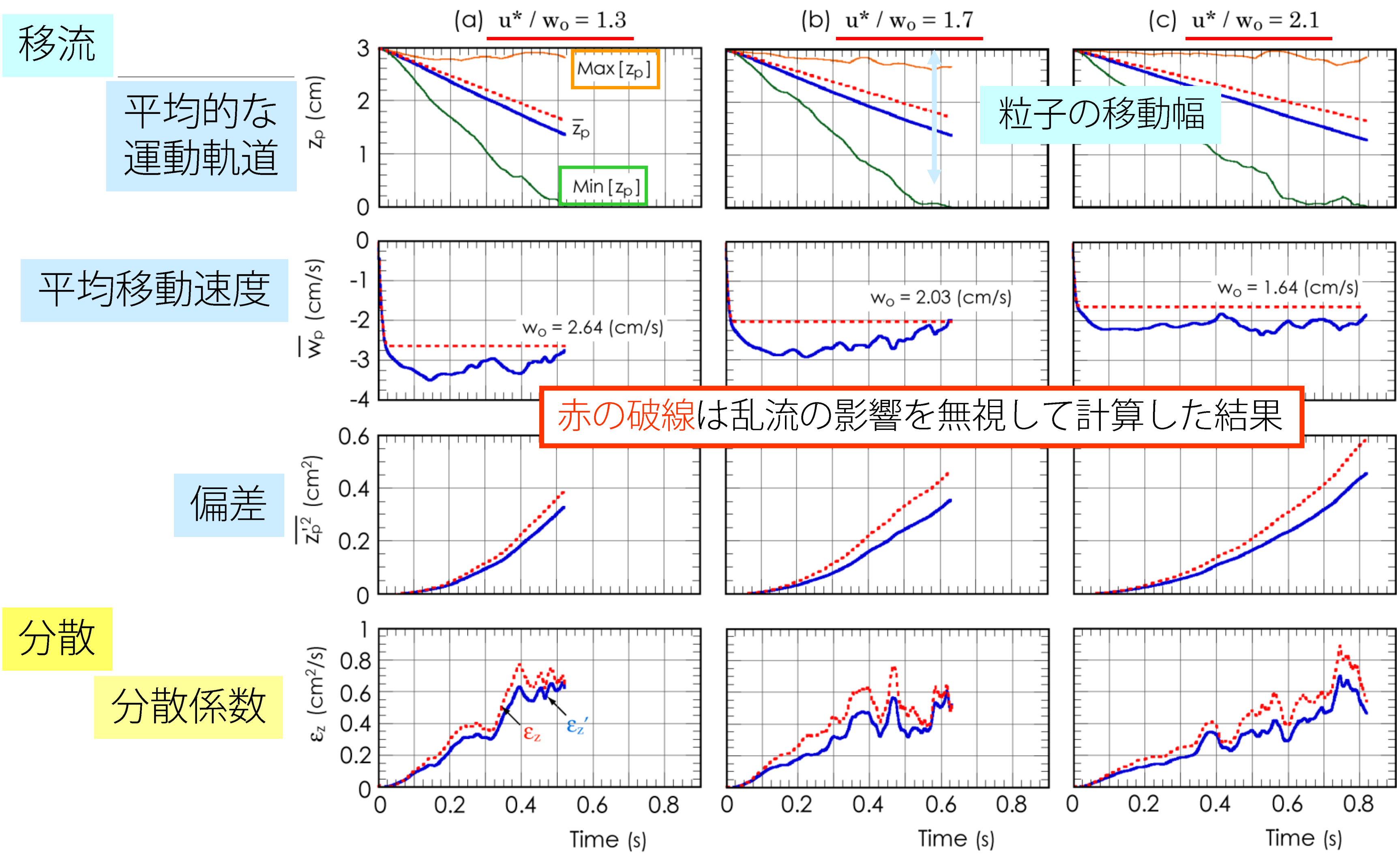
$$X_p' = X_p - \bar{X}_p, \quad V_p' = V_p - \bar{V}_p$$

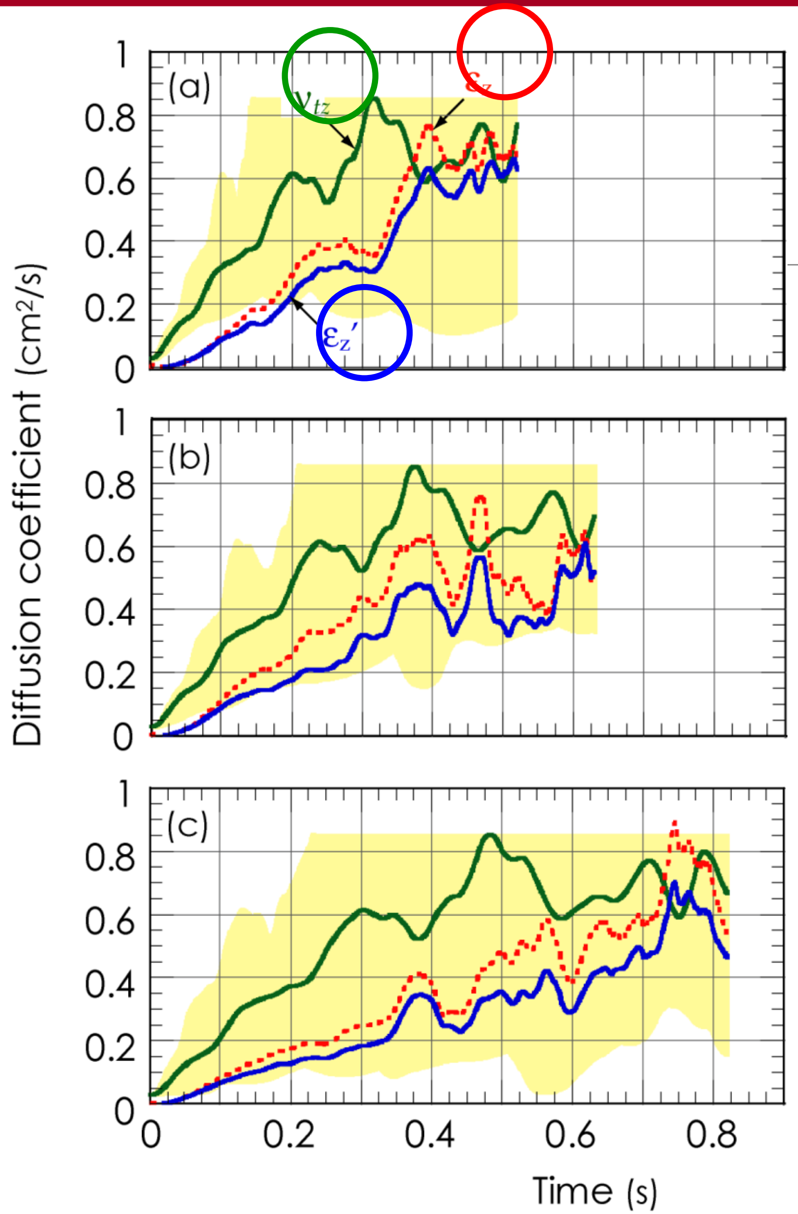
分散係数 ε

$$\epsilon = \frac{1}{2}\frac{d\,\overline{X_p'^2}}{dt} = \overline{V_p'^2} \times T_L$$

$$T_L = \int_0^\infty R(\tau)\,d\tau = \int_0^\infty \frac{\overline{V_p(t)\,V_p(t+\tau)}}{\overline{V_p'^2}}\,d\tau$$

鉛直方向への運動の解析結果





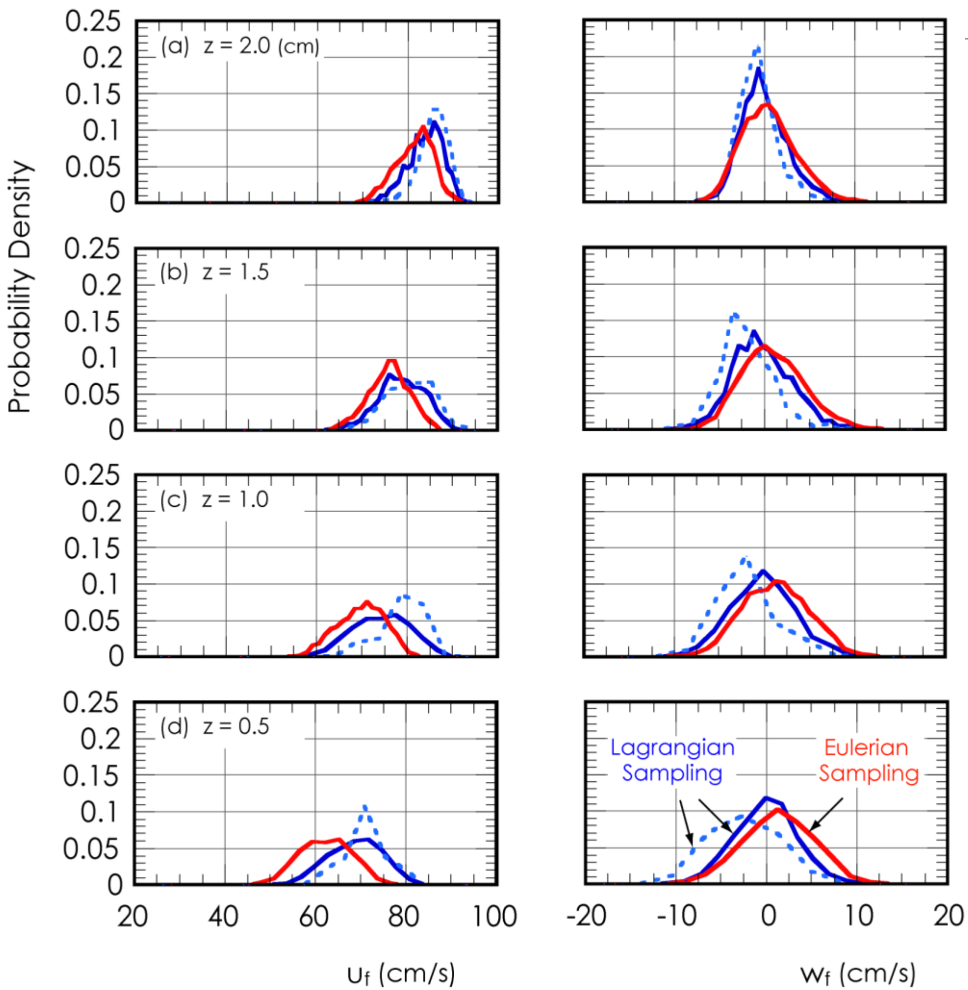
青色の実線と赤色の破線：
平均移動経路に沿う粒子の分散係数

緑色の実線：
平均移動経路の局時局所の乱流拡散係数 ν_{tz}

黄色のゾーン：
移動経路の範囲内の地点において取り得る乱流拡散係数の範囲

統計的に見れば，粒子の分散係数と乱流拡散係数は同オーダーの値となる．

粒子に作用した流速成分の確率密度分布

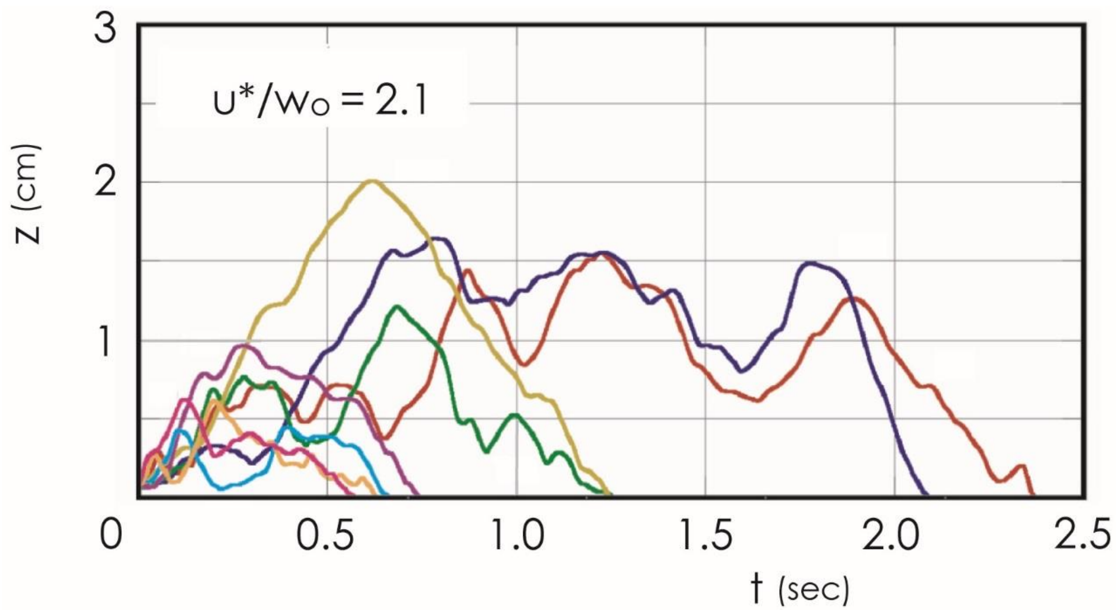


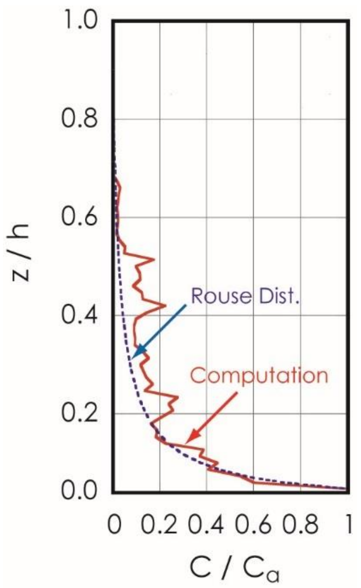
青線：*Lagrangian sampling*
粒子の移動中に作用した
流速の確率密度分布

平均的には水流の “Sweep motion” の効果が支配的である！

赤色：*Eulerian sampling*
同一高さでサンプリング
された流速値の確率密度
分布

浮遊砂として移動する粒子の相対濃度分布





相対速度分布

河床面より粒径分だけ上方から初速度ゼロで移動を開始した土砂粒子群の軌跡と相対濃度分布

今後に向けて

- 粒度幅の広い材料からなる河床上で生じる流砂現象
- 河床材料に粘土が含有される場合の流砂現象
- あ

粒度幅の広い材料からなる河床上で生じる流砂現象

- Model riverbed in experimental flume is composed of three groups of sediment grain sizes.
- Each group is represented by a sediment particle of one size. This means that the bed is composed of three kinds of sediment.
- It should be noted that each size differs from its nearest alternative size(s) by one order of magnitude, and that following relation is satisfied; $D_L \gg D_M \gg D_S$.
- Experiments were conducted several times under the same condition in order to verify the accuracy of data measured.

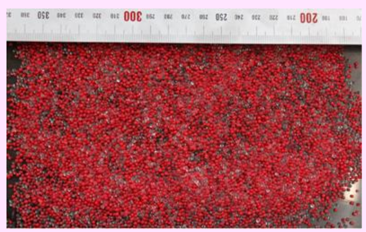
模擬河床材料

- Cobble (or Boulder) is the Largest size of sediment which cannot move at all even during flood. It is called L-particles.
- Gravel, sand (or silt) is filled in the void space of L-particles
  - Gravel is the Intermediate size of sediment, and it moves as bedload. It is called M-particles.
  - Sand (or Silt) is the smallest size of sediment, and it moves as suspended load. It is called S-particles.

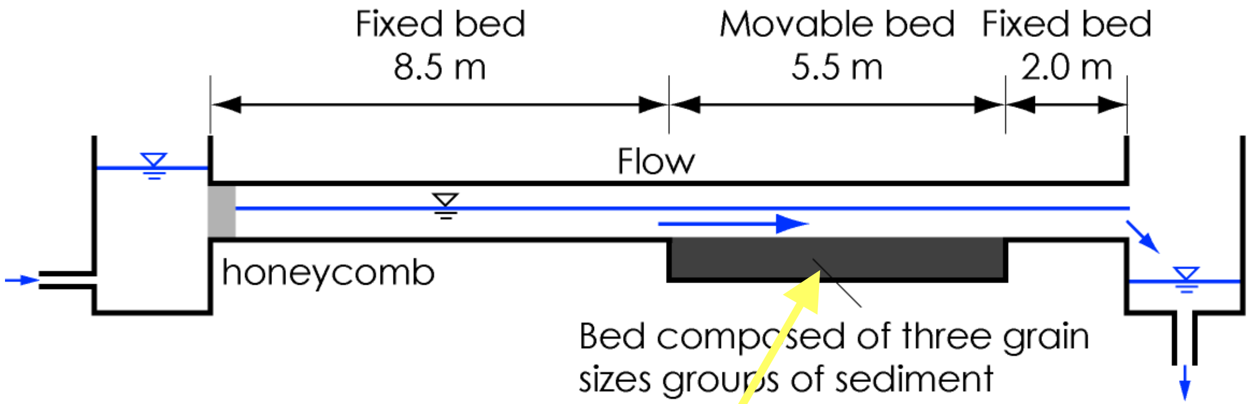
In such a bed, the hiding effect or the sheltering effect of L-particle on the movement of M- and S- particle is important!

模擬河床材料

$D_L \gg D_M \gg D_S$

Boulder or Cobble	*L-particle*		Alumina ball	D_L = 50.0 (mm)
Gravel	*M-particle*		Glass bead or Silica sand (control experiment)	specific weight : 2.5 grain size : 2.0 mm D_M = 2.0 (mm) grain size : 3.5 mm
Sand or Silt	S-particle		Silica sand	D_S = 0.2 (mm)

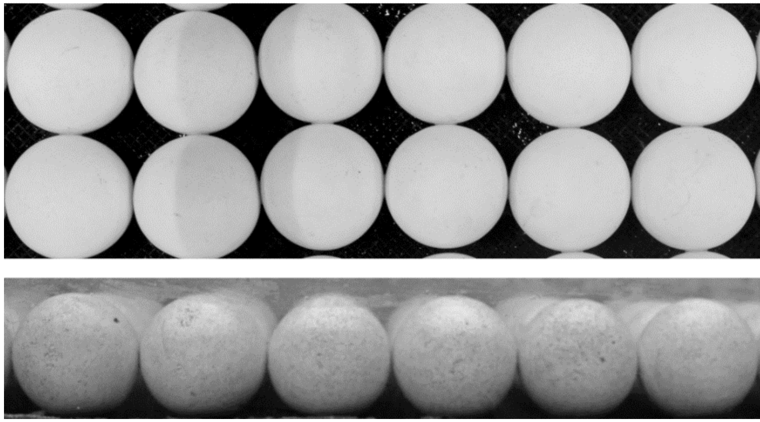
実験装置の概要



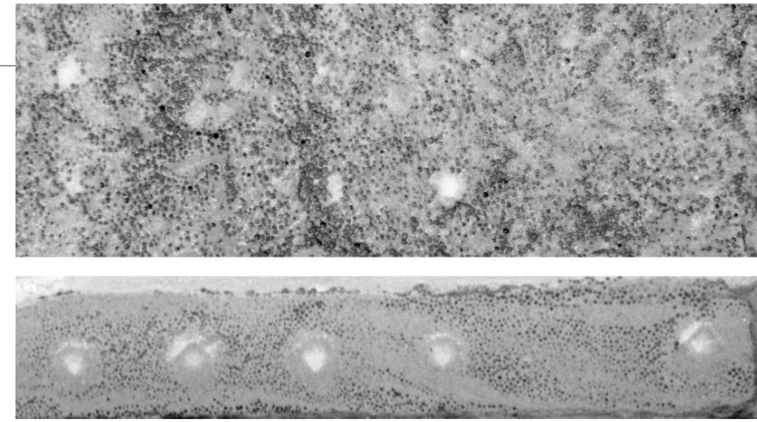
- Open channel (length 16 m, width 0.2 m, gradient 1/250)
- Movable bed is located between 8.5 and 14 m from the upstream end of the channel.
- The channel bottom of this location is 0.05 m lower than that of the upstream and downstream. The erodible-bed reach was filled with sediment up to this elevation difference.

初期河床

Elevation of top of L-particles is equivalent to that of M-S particles.

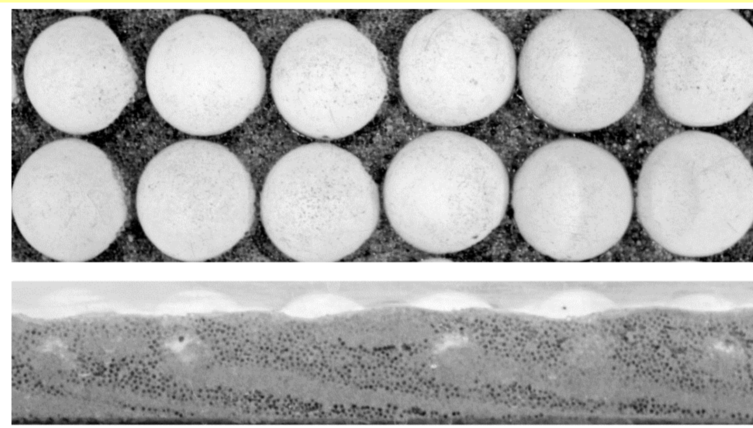


Arrangement of L-particles



water flow only

Initial bed for main experiment = Static equilibrium state



The purpose was to answer the question:

water flow and sediment supply

How is the state of dynamic equilibrium bed?

Main exp.

実験概要

Case	Q_w (m^3/s)	$\bar{u}^*$ (m/s)	Q_M $\times 10^6$(m^3/s)	Q_S $\times 10^6$(m^3/s)
1A-0	0.0052	0.047	0.0	0.0
1A-1	0.0052	0.042	1.2	0.0
1A-2	0.0052	0.043		0.4
1A-3	0.0051	0.040		1.4
1A-4	0.0052	0.041		2.8
1A-5	0.0053	0.042		3.1
1B-0	0.0052	0.047	0.0	0.0
1B-1	0.0051	0.046	0.4	0.0
1B-2	0.0051	0.046		0.2
1B-3	0.0053	0.047		0.4
1B-4	0.0052	0.045		2.5
1B-5	0.0049	0.039		3.8
1B-6	0.0050	0.038		4.5
1C-0	0.0092	0.053	0.0	0.0
1C-1	0.0090	0.051	0.4	0.0
1C-2	0.0093	0.052		0.4
1C-3	0.0090	0.052		1.4
1C-4	0.0091	0.052		2.5
1C-5	0.0091	0.052		3.4
1C-6	0.0091	0.052		4.5
1C-7	0.0088	0.048		5.0
1C-8	0.0091	0.051		5.7

In Case 1A-0, 1B-0 and 1C-0, bed finally attains the static equilibrium state as time passes.

Q_w : water discharge.

Q_M : sediment supply rate of M-particles.

Q_S : sediment supply rate of S-particles.

Q_{Be} : the equilibrium bedload transport rate evaluated by formula of Meyer-Peter & Muller.

EXPERIMENTAL CONDITION with sediment supply

Case	Q_w (m^3/s)	$\bar{u}*$ (m/s)	Q_M $\times 10^6 (m^3/s)$	Q_S $\times 10^6 (m^3/s)$
1A-0	0.0052	0.047	0.0	0.0
1A-1	0.0052	0.042	1.2	0.0
1A-2	0.0052	0.043		0.4
1A-3	0.0051	0.040		1.4
1A-4	0.0052	0.041		2.8
1A-5	0.0053	0.042		3.1
1B-0	0.0052	0.047	0.0	0.0
1B-1	0.0051	0.046	0.4	0.0
1B-2	0.0051	0.046		0.2
1B-3	0.0053	0.047		0.4
1B-4	0.0052	0.045		2.5
1B-5	0.0049	0.039		3.8
1B-6	0.0050	0.038		4.5
1C-0	0.0092	0.053	0.0	0.0
1C-1	0.0090	0.051	0.4	0.0
1C-2	0.0093	0.052		0.4
1C-3	0.0090	0.052		1.4
1C-4	0.0091	0.052		2.5
1C-5	0.0091	0.052		3.4
1C-6	0.0091	0.052		4.5
1C-7	0.0088	0.048		5.0
1C-8	0.0091	0.051		5.7

In Cases 1A, Q_M was set equal to the equilibrium bed load transport rate Q_{Be} under each flow condition.

Q_w : water discharge.

Q_M : sediment supply rate of M-particles.

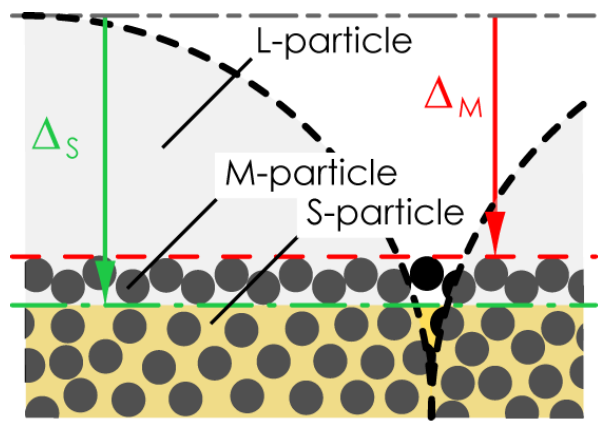
Q_S : sediment supply rate of S-particles.

Q_{Be} : the equilibrium bedload transport rate evaluated by formula of Meyer-Peter & Muller.

EXPERIMENTAL CONDITION with sediment supply

Case	Q_w (m^3/s)	$\bar{u}*$ (m/s)	Q_M $\times 10^6 (m^3/s)$	Q_S $\times 10^6 (m^3/s)$
1A-0	0.0052	0.047	0.0	0.0
1A-1	0.0052	0.042	1.2	0.0
1A-2	0.0052	0.043		0.4
1A-3	0.0051	0.040		1.4
1A-4	0.0052	0.041		2.8
1A-5	0.0053	0.042		3.1
1B-0	0.0052	0.047	0.0	0.0
1B-1	0.0051	0.046	0.4	0.0
1B-2	0.0051	0.046		0.2
1B-3	0.0053	0.047		0.4
1B-4	0.0052	0.045		2.5
1B-5	0.0049	0.039		3.8
1B-6	0.0050	0.038		4.5
1C-0	0.0092	0.053	0.0	0.0
1C-1	0.0090	0.051	0.4	0.0
1C-2	0.0093	0.052		0.4
1C-3	0.0090	0.052		1.4
1C-4	0.0091	0.052		2.5
1C-5	0.0091	0.052		3.4
1C-6	0.0091	0.052		4.5
1C-7	0.0088	0.048		5.0
1C-8	0.0091	0.051		5.7

- In Cases 1B and 1C, Q_M is much less than Q_{Be}.
- In the dynamic equilibrium state, the top of L-particles would be exposed to some extent on the bed surface in the range of Q_S here.



大粒径の石礫による遮蔽効果

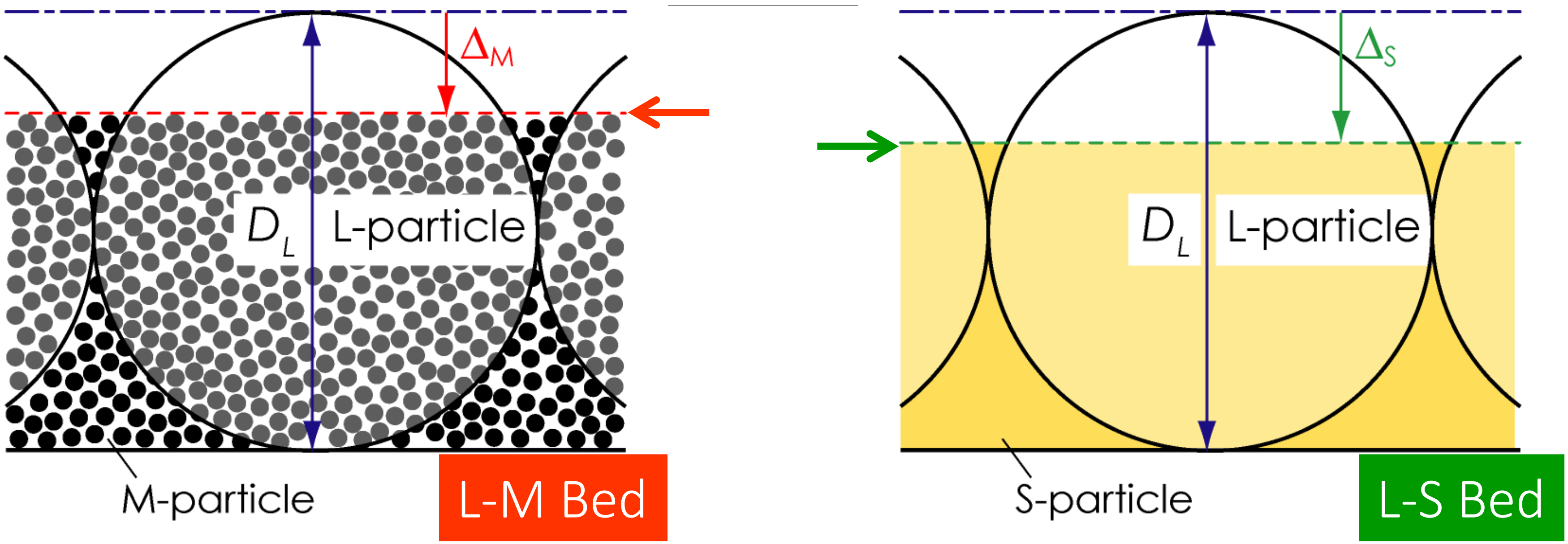
- In order to clarify this hiding effect, the special experiments were conducted under the condition that the bed was composed of two grain size sediment only.

  L-M Bed : bed is composed of L- and M-particles.

  L- S Bed : bed is composed of L- and S- particles.

- No sediment was supplied in this case. This means that the bed would not attain the dynamic equilibrium state but a static equilibrium state.

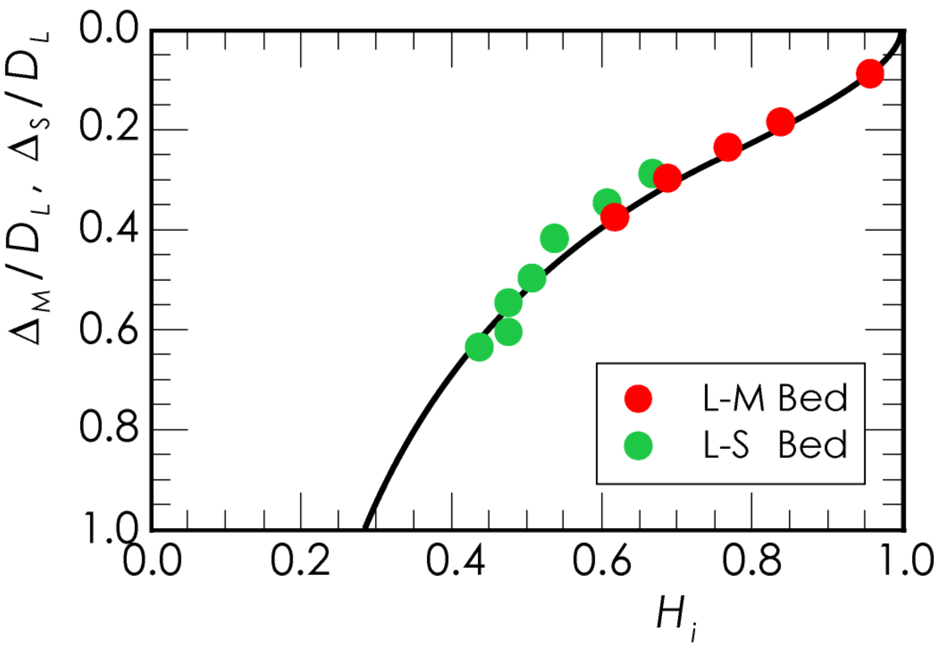
大粒径の石礫による遮蔽効果

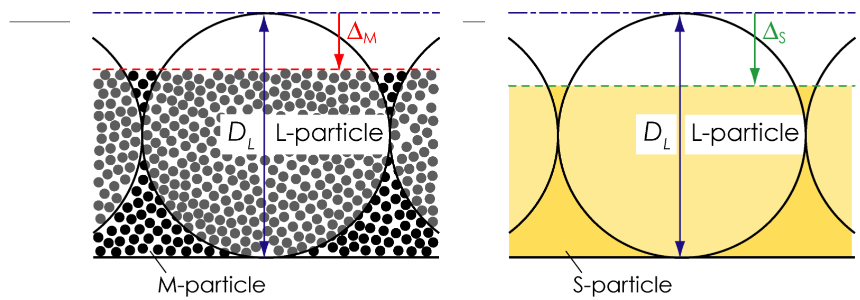


Hiding function H_i (= $u_i^* / \overline{u^*}$): the ratio of the friction velocity u_i^* which is actually exerted on the upper surface of an M- or S-particle exposed on the bed surface to the average value $\overline{u^*}$ acting on the entire bed surface.

Actual shear stress exerted on the upper surface of M-particles or S-particles becomes equaled to the critical tractive force at this static equilibrium state.

大粒径の石礫による遮蔽関数



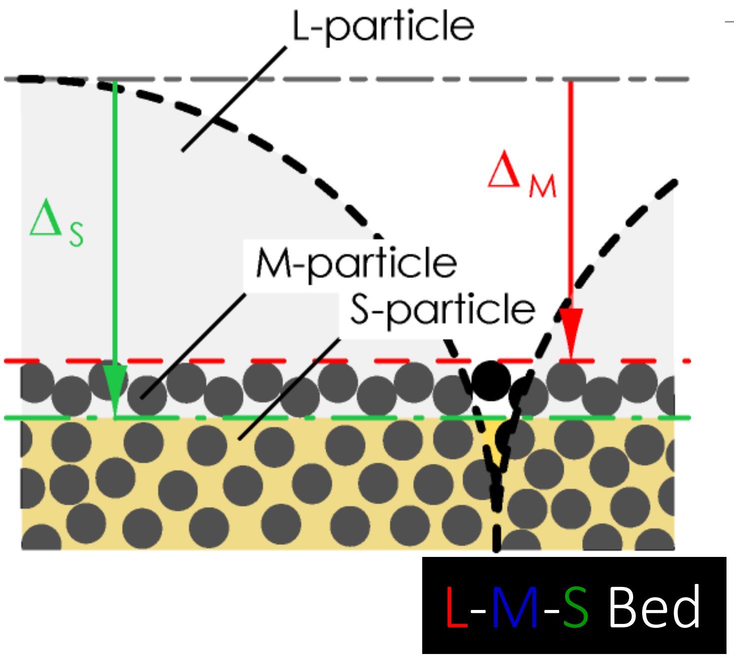


$$H_i \equiv u_e^* \,/\, \bar{u}^* = \left[1 + \frac{1}{{k_e}^2}\left(\frac{\Delta}{D_L}\right)^2\right]^{-1/2}$$

The above circles of L-M Bed or L-S Bed denotes the experimental results when the bed is composed only of L- and M-particles, or L- and S-particles, respectively.

- k_e is constant (= 0.3).
- The distance Δ corresponds to Δ_M in case of L-M Bed, and Δ_S in case of L-S Bed.

静的平衡状態における河床の鉛直構造



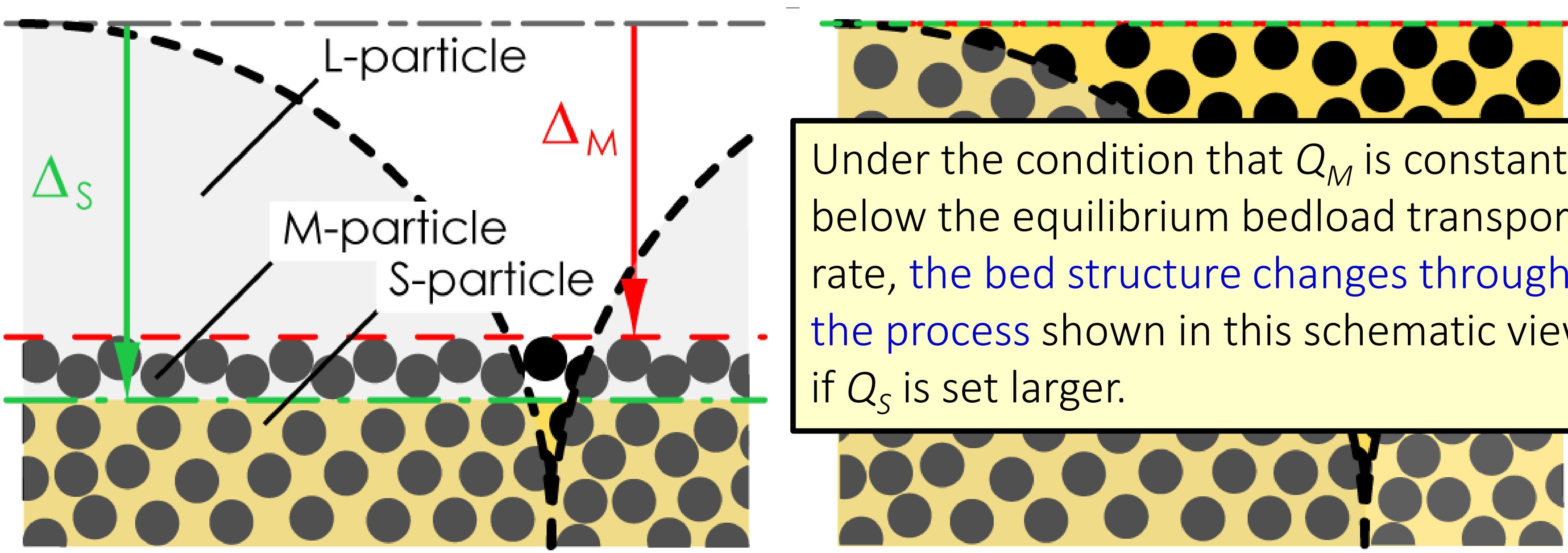
- Layer of M-particles only was formed at the exposed bed surface between L-particles.
- According to our experimental results (Sekine, Hiramatsu and Kadoi, 2013), the thickness of this layer takes almost constant value about 1 ~ 2 times the diameter D_M of an M-particle.

動的平衡状態における河床の鉛直構造

Q_S = 3.8 (cm³/s)

Stage 4

$\Delta_M = \Delta_S = 0$



Under the condition that Q_M is constant below the equilibrium bedload transport rate, the bed structure changes through the process shown in this schematic view if Q_S is set larger.

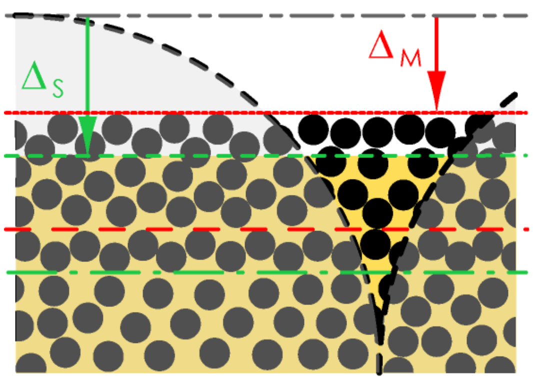
STATIC EQUILIBRIUM STATE → DYNAMIC EQUILIBRIUM STATE

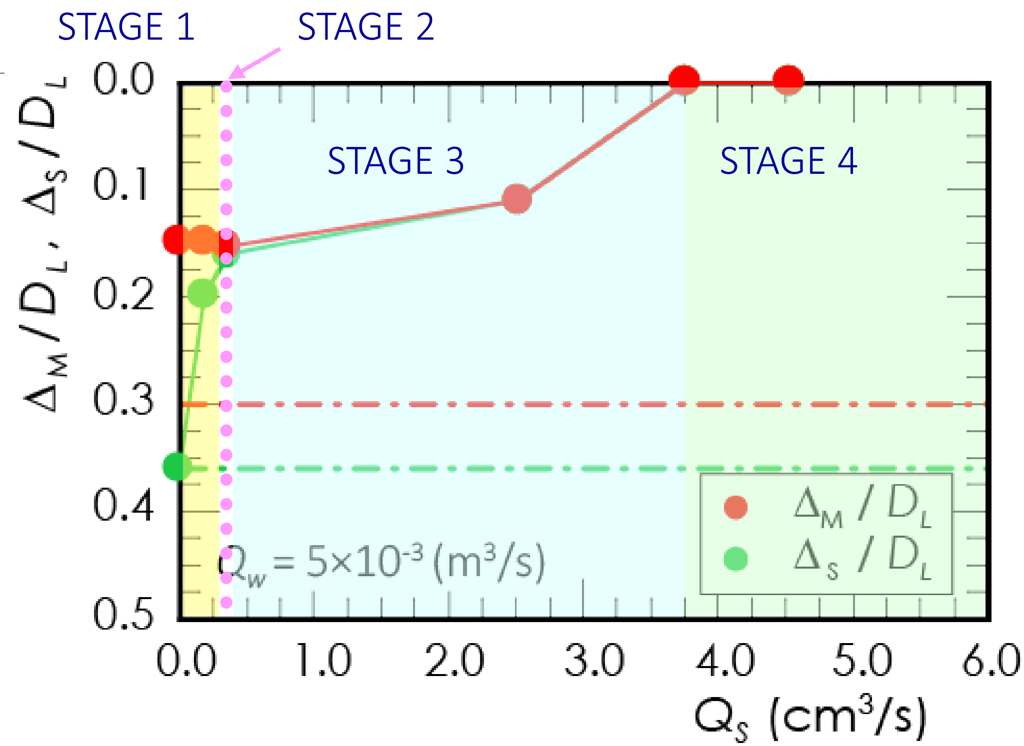
INITIAL BED CONDITION

According to the experiments, it was found that the bed structure can be classified into four stages in this process.

UPPER SURFACE ELEVATION OF M- & S-PARTICLES

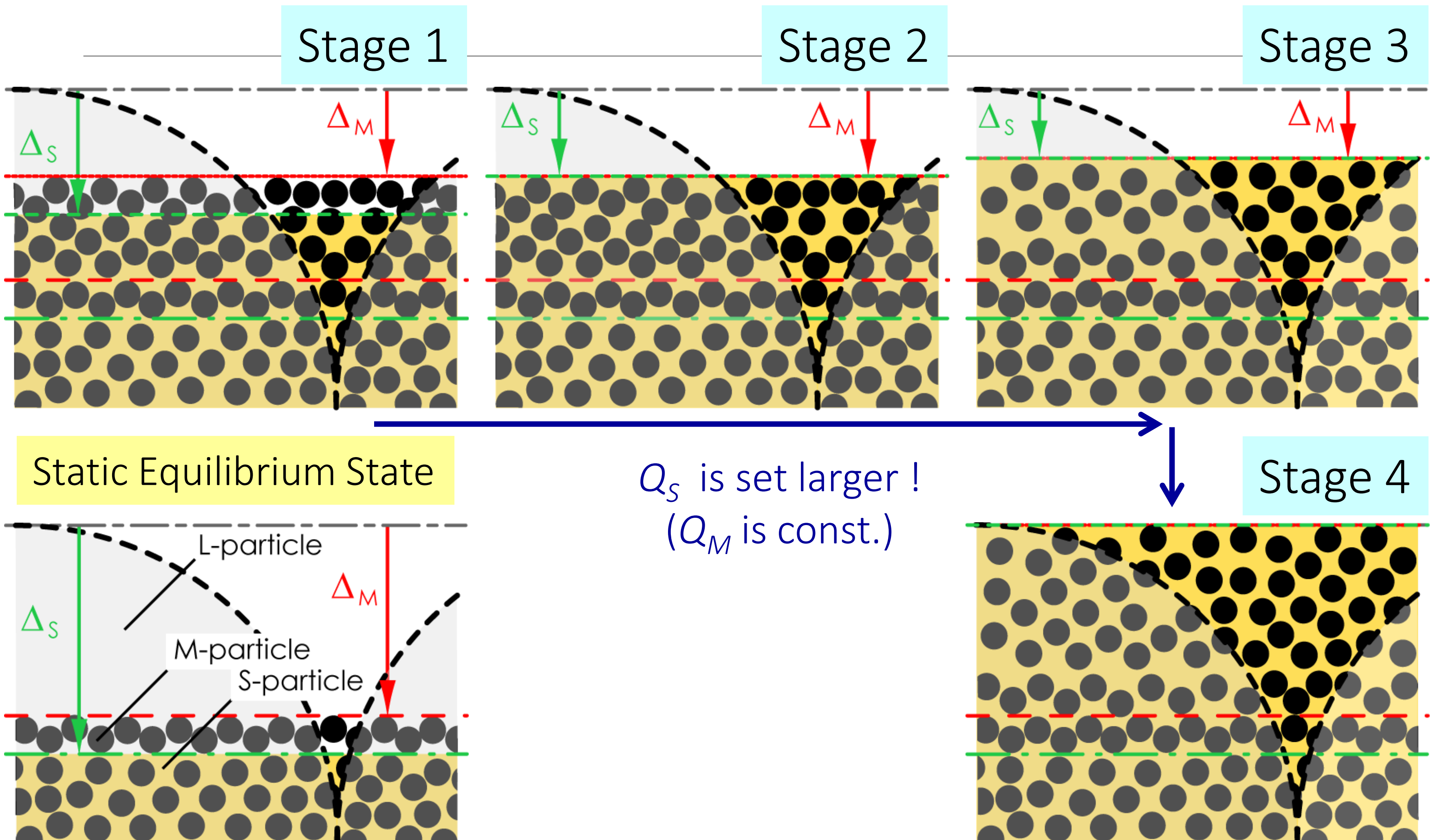
[Example] STAGE 1



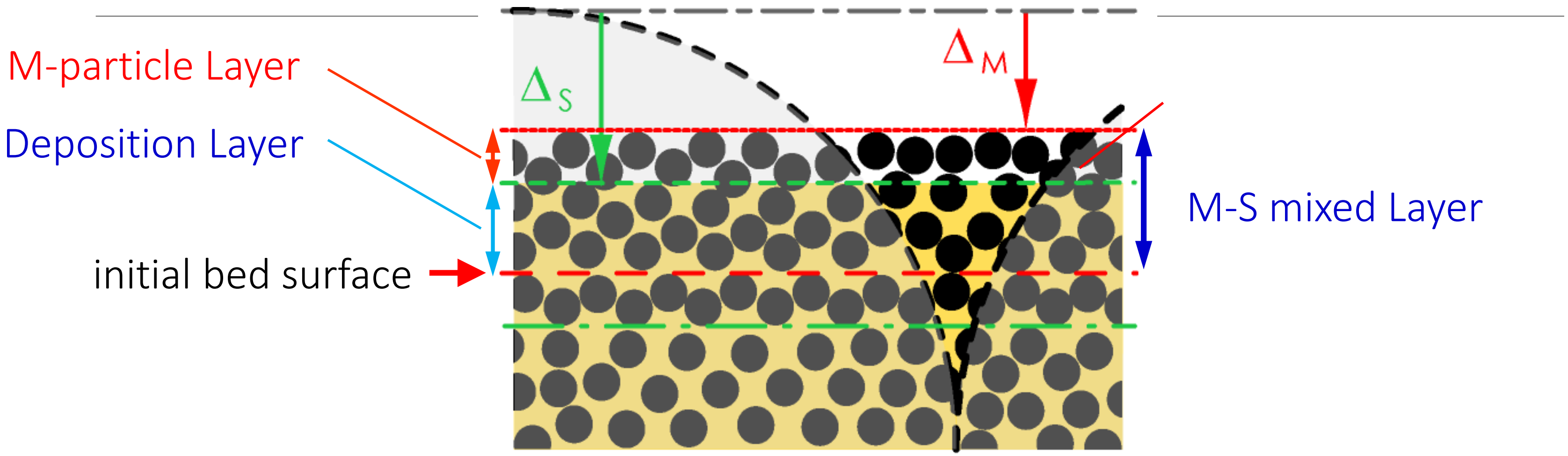


- This figure shows the relationship between the supply rate Q_S of S-particle and the vertical distance Δ_M (or Δ_S). / Experimental results to quantify the supplemented behavior based on actual measured data.

DYNAMIC EQUILIBRUM STATE OF BED

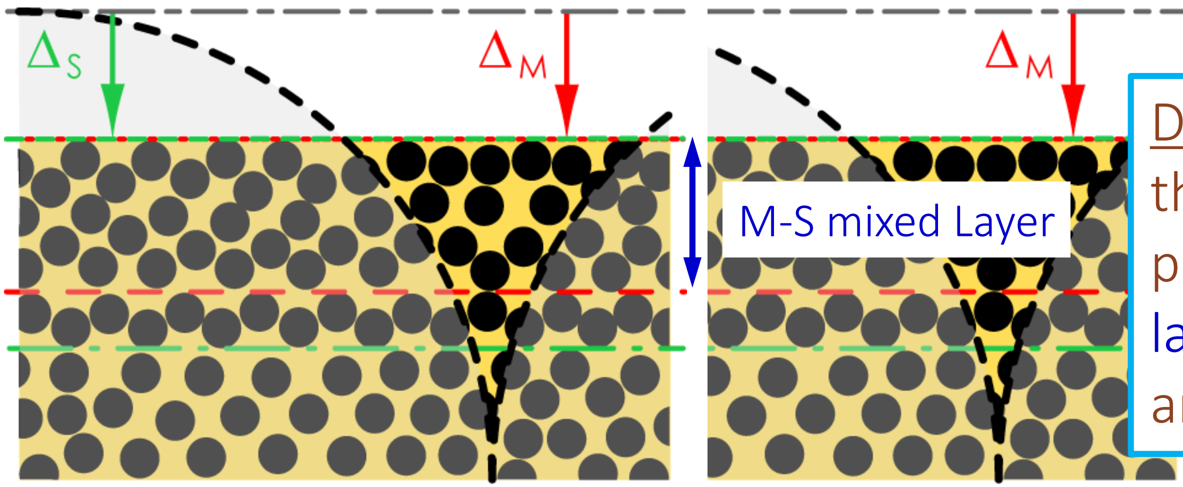


STAGE 1



- M-particle layer still forms in the upper part of the bed surrounded by L-particles.
- Distance between each individual M-particle is not different from the one in the static equilibrium state.

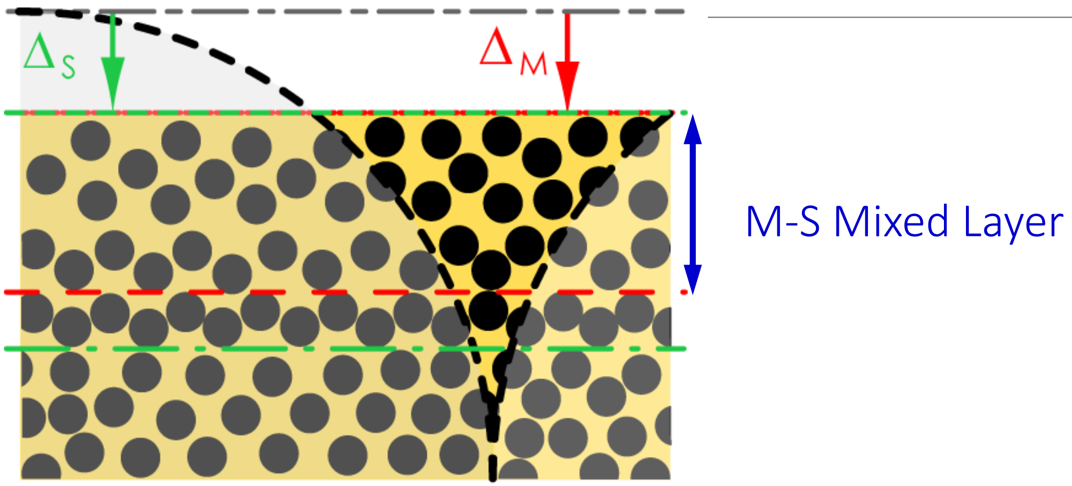
STAGE 2



Definition of R_M :
the volume ratio of M-particles in M-S mixed layer to the sum of M- and S-particles.

- The volume ratio R_M in this layer is almost same as the value of the layer at Stage 1. It is almost between 0.7 and 0.8.
- The porosity λ, which is defined as the ratio of water volume in this layer to the total volume except L-particles, was about 0.4.

STAGE 3



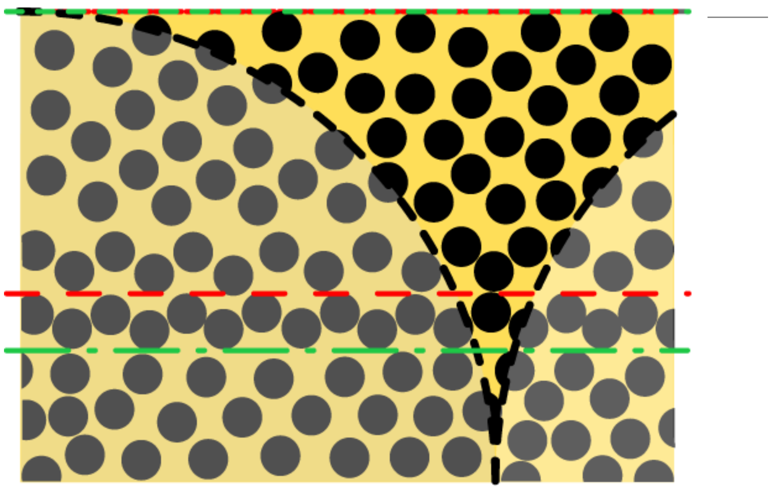
Definition of R_M :
the volume ratio of M-particles in M-S mixed layer to the sum of M- and S-particles.

- This means that the distance between individual M-particles in this layer becomes larger than that in Stage 1 and 2.
- The porosity λ hardly change from about 0.4.

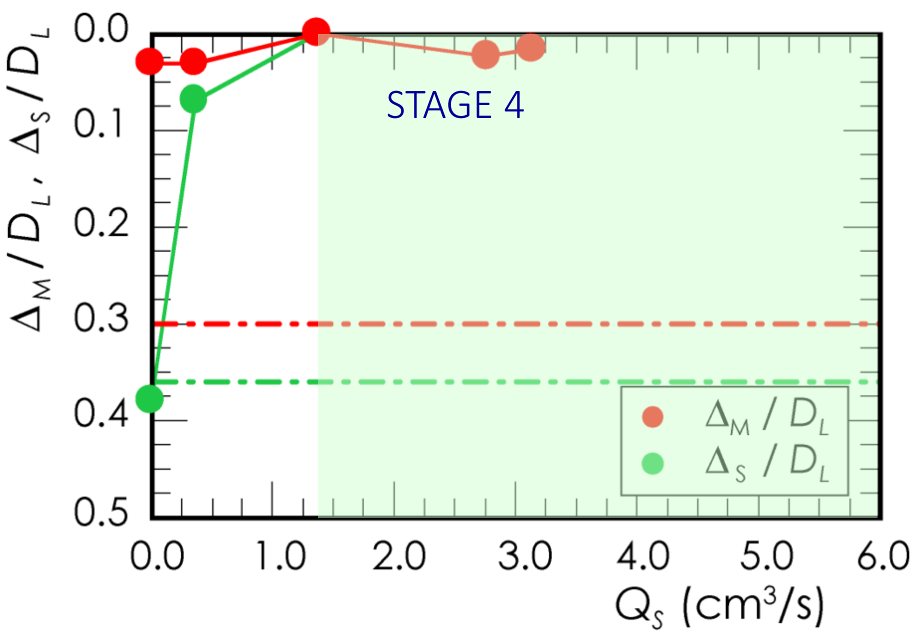
Q_S increases .

ANOTHER INVESTIGATION

- Q_M is set equal to Q_{BE} (equilibrium bedload transport rate) -

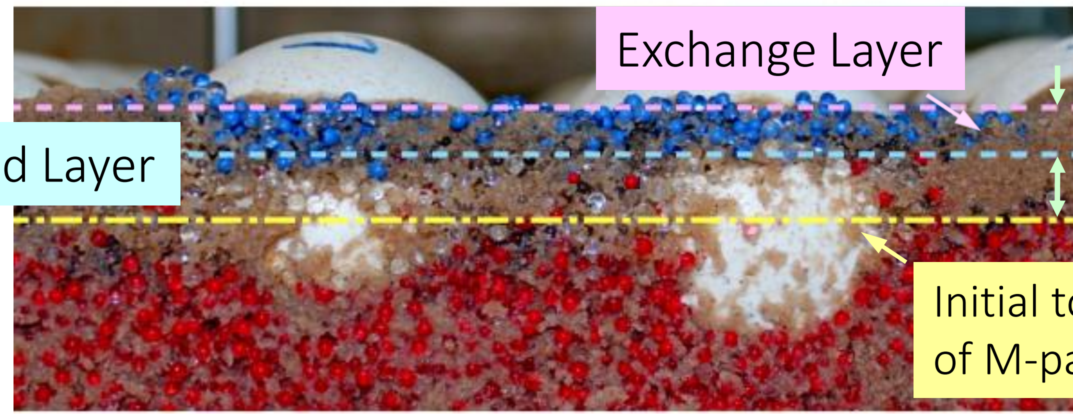


CASE 1A: Q_w = 5 x 10^{-3} (m^3/s)
Q_M = 1.2 (cm^3/s)



- In this case, the bed surface attains the dynamic equilibrium state of Stage 4 (i.e. Δ_M = 0) even if S-particle is supplied by some small amount.

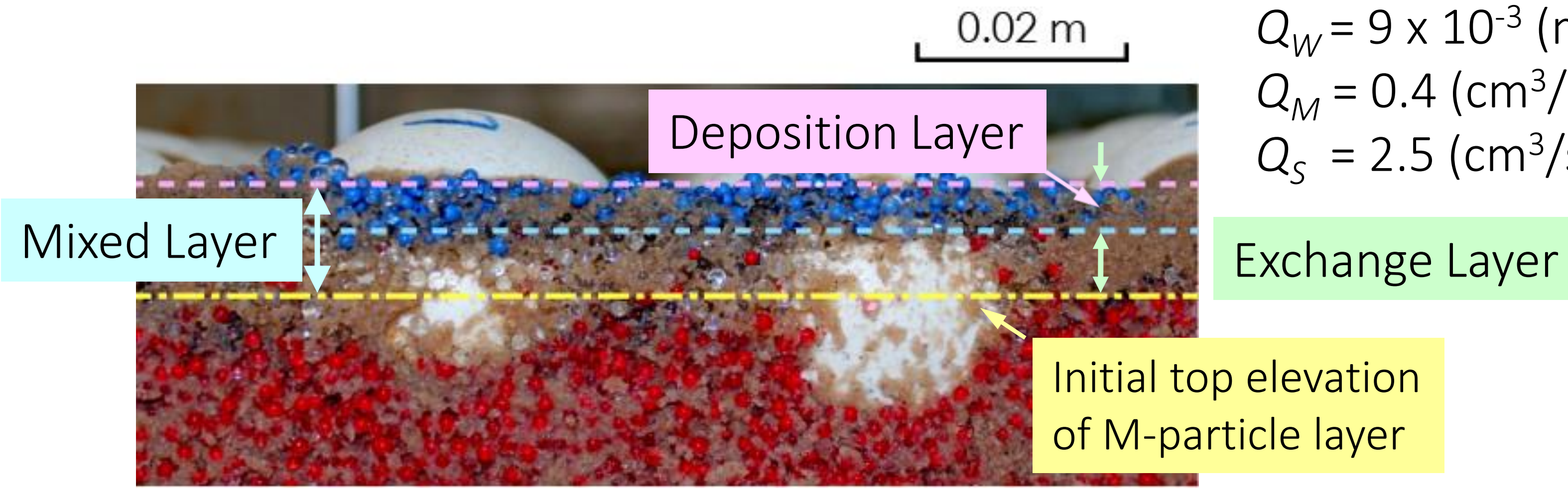
DEFINITION OF SOME LAYERS OF BED SURFACE



$Q_W = 9 \times 10^{-3}$ (m^3/s)
$Q_M = 0.4$ (cm^3/s)
$Q_S = 2.5$ (cm^3/s)

- M-S mixed layer can be divided into two layer. The upper layer is the exchange layer, and the lower one is the deposition layer.
- In this experiment, the color of M-particles supplied from upstream was changed from red to blue after the bed attains the dynamic equilibrium.

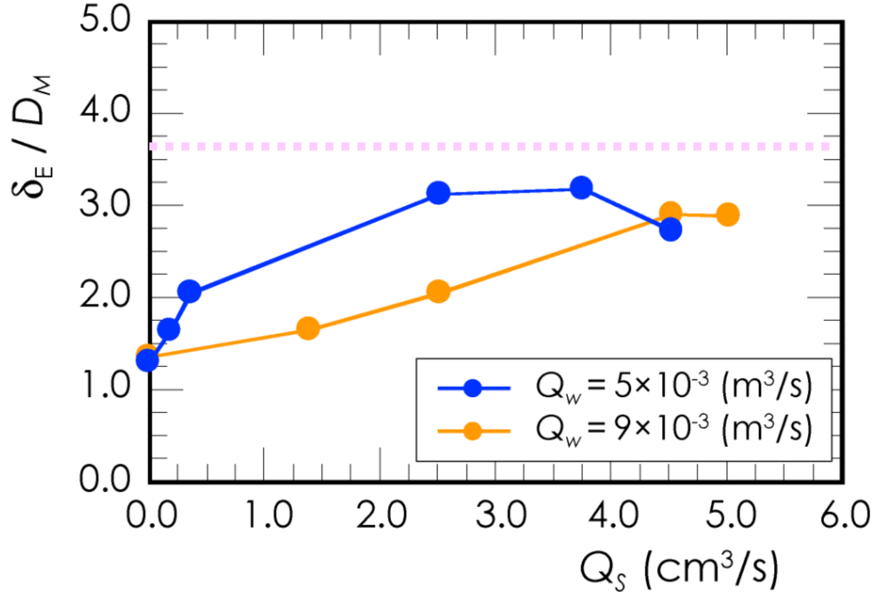
EXCHANGE LAYER AND DEPOSITION LAYER



$Q_W = 9 \times 10^{-3}$ (m^3/s)
$Q_M = 0.4$ (cm^3/s)
$Q_S = 2.5$ (cm^3/s)

- Eventually, the exchange layer became composed of S-particles and blue M-particles only.
- M-S particles in the exchange layer are continually and repeatedly exchanged with particles transported as bedload or suspended load.
- Any particles in the deposition layer are not replaced by transported particles.

THICKNESS OF EXCHANGE LAYER



- Thickness of exchange layer δ_E becomes larger if S-particle is supplied more.
- <u>This thickness δ_E approaches a constant value of about 3 times the diameter D_M</u> of M-particle.

VERTICAL STRUCTURE IN MIXED LAYER

- In the void space of L-particles, vertical structure of the bed can be characterized by its porosity λ and a volume containing ratio R_M of M-particle.
- Each value takes almost constant value in vertical direction, but the value slightly depends upon the combination of Q_M and Q_S.
- In case of constant Q_M, and if Q_S is set larger,
  - ✓ the distance between individual M-particles in this layer becomes larger.
  - ✓ R_M decreases to 0, and λ changes slightly from 0.6 to 0.4 approximately.

まとめ

- 浮遊砂としての土砂移動には，解決すべき課題が多く残されている．ひとつの近似として，その輸送を「乱流拡散現象」と捉えるとしても，基準面濃度と分散係数の合理的な評価法が見いだせない限り，今以上に精度のよい流路・河床変動計算は見込めない．本質的な検討を行うべきであろう．
- 最近では，何でも変動計算でもできるかのように勘違いしている人が少なくないようですが，実はまだまだ未解明の点が残っています．まずは適用限界を知る必要であります．若手研究者や学生は安易に計算に走るのではなく，現象の本質を見極めるような研究をして下さい．

まとめ

- 基礎的な実験は重要であり，その蓄積からいずれ本質的なことが見えてくる可能性があります．ただし，先が見えてくるまでに時間がかかるため忍耐力を要します．そこで，「この実験により何が見えてくるのか」ということを事前によく考えてから始めるのがよいと思います．
- 頑張って研究してみませんか？何かお役に立つことがあれば下記までご連絡下さい．

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The end !