Sediment Experiment Report

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CE5308QB: Sediment transport and coastal protection

5 April, 2024

Contents

1. Introduction

The shields parameter is a key criterion applied in incipient motion and sediment transport. Buffington appreciated that "the doctoral work of Albert Frank Shields (1936) has become legendary"[1], where Shields proposed that the incipient motion of sediment is defined as the condition at which a sediment particle is entrained. The hydrodynamic condition for determining the movement of sediments is generally defined in terms of critical shear stress.[2]

Nowadays, the modified shields diagram and the Shields regime diagram (SRD) are widely used, and the curve represents the critical condition between transport and no transport.

The physical models are often used to investigate design and operational issues pertaining to complex hydraulic phenomena.[3]

In this study, we use two experiments about the shields diagram to check the accuracy and summary of prediction in term of sediment transport, and the brief of experiments is in Table 1.

Table 1. Experiments and objectives

No. of Experiment	Concepts	Objectives
1. Incipient sediment motion	Flow velocity with which sediment particles of a certain size and specific mass start to move is referred to as incipient motion velocity.	1) Measure the critical Shields parameter of the particles at their incipient motion. 2) Predict and Plot vertical velocity profile
2. Sand ripples and Shields diagram	Apply the effective shields parameter *θ'* and the particle Reynolds number *Rp* in the SRD	Find the Shields number at the sand ripple regime

2. Methods and Materials

2.1. Velocity approach

Theoretical consideration of incipient motion of sediment in the flow is hydrodynamic forces equilibrium which are exerted on sediment particles at the bottom of the channel. At incipient motion, these are driving forces and stabilizing forces in equilibrium:

$$\frac{1}{2}\rho c_D \frac{\pi}{4} d^2 (\alpha U_{fc})^2 = \rho g(s-1)\frac{\pi}{6} d^3 \mu_s$$

The above balance between forces acting on sediment particles is utilized for the determination of the incipient motion velocity. Thus, the critical Shields parameter can be expressed as:

$$\theta_c = \frac{U_{fc}^2}{(s-1)gd} = \frac{\mu_s}{c_D}\frac{4}{3\alpha^2}$$

where *Ufc* is the critical friction velocity.

The shear velocity *Uf* is calculated in the vertical velocity profile:

$$\frac{u}{U_f} = \frac{1}{\kappa}\ln\left(\frac{30z}{k_N}\right)$$

where u is the streamwise flow local velocity at a specific depth z in the water depth, $\kappa=0.4$ is the von Karman constant, $k_N=2.5d$ is Nikuradse's equivalent sand roughness, d is the median grain diameter.

While we define the incipient motion criteria, the flow velocity we test can correspond to the critical shear velocity for the specific particles and flow conditions.

Another method for the critical flow condition for sediment motion depends on grain size and the flow depth to grain diameter ratio (also called relative submergence or relative flow depth), [4] and the suggested equation is written as follows:

$$\frac{V_c}{\sqrt{[g(s-1)d]}} = a\left(\frac{Y}{d}\right)^m$$

where Vc is incipient motion flow velocity, d is sediment particle size, Y is the flow depth, and a and m are coefficient which are calculated using experimental data under free flow condition. In this case, we don't consider this method.

2.2. Modified Shields diagram and Shields regime diagram

Sui et al. (2021) arranged the datasets about the live-bed and clear-water regime in the Fig 1, and provided an explicit formulation of the critical Shields curve in terms of the grain Reynolds number [5]:

$$\theta_c = 0.165\left(Re+0.6\right)^{-0.8} + 0.045\exp\left(-40Re^{-1.3}\right), \qquad Re \geq 1$$

After modification, the semi-theoretical rational formulation unifies the propagation velocity in both clear-water and live-bed regimes in Fig 1. [1]

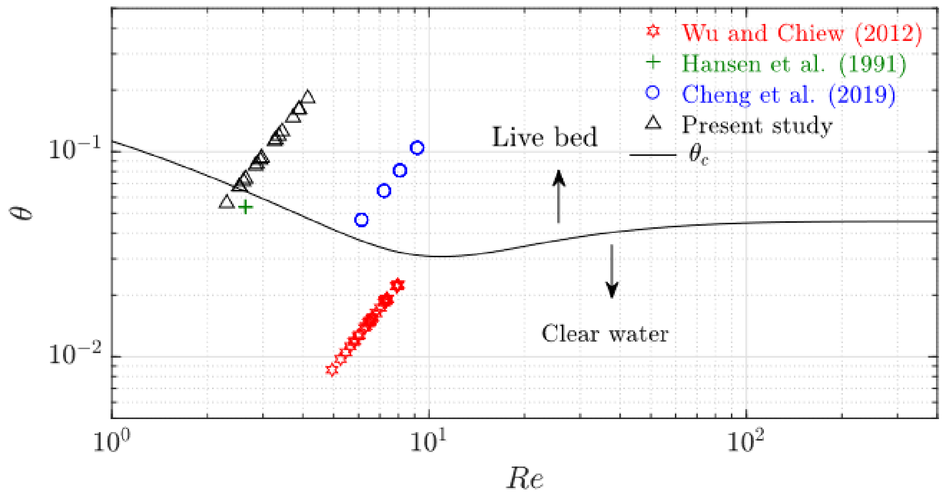

Fig 1. Placement of various bed regime conditions to a classical Shields diagram

Additionally, Garcia (2000) presents the Shields regime diagram (SRD) seen in Fig 1~Fig 2, that can be used to differentiate between alluvial and gravel bed rivers.[6] In the SRD, the criterion requires two equations to describe sediment similitude. The particle Reynolds number (Rp) and dimensionless shear stress (τ*) can be calculated from the hydraulic and sediment characteristics of the given flow. As the bed particles are generally moved by the actual shear stress and are essentially unaffected by the normal stress, [7] the dimensionless shear stress (τ*) is defined by the skin friction (effective shear stress). In this study, we use the generic symbol:

$$\theta' = \tau * = \frac{\tau'}{\rho g(s-1)d}$$

where the problem of estimating the effective shear stress τ' has not yet been solved in a completely explicit way.

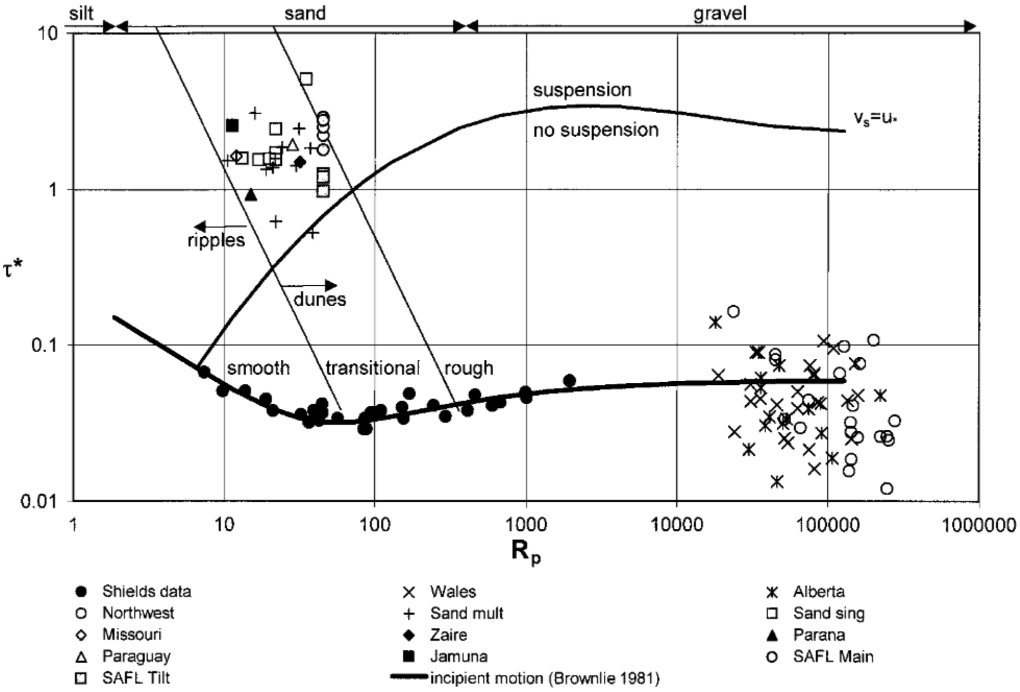

Fig 2. Shields regime diagram and critical Shields' data by Brownlie

And Garcia refers to the curve where *Uf=ws* for sand spheres as the transition between suspension and no-suspension of sediment particles on the SRD. [3]

2.3. Sand ripples and effective Shields parameter

For nature fine particles sediment, we determine a critical parameter in the SRD, the particle Reynolds number *Rp*, explicitly using the following formula [3]:

$$R_p = \frac{\mathrm{Re}}{\sqrt{\theta}} = \frac{\sqrt{(s-1)gd}d}{\nu}$$

where *Rp* depends (among other things) on the sediment size *d*, but not other hydro-dynamic factors.

Then, after calculating the mean flow velocity and corresponding to *Uf'* by the similar method in 2.1 Velocity approach, the effective Shields parameter can be obtained:

$$\theta = \frac{Uf^2}{(s-1)gd}$$

For the effective Shields parameter θ', the implicit solution and statement is required: Therefore, we can predict bedform type in the Shields regime diagram in terms of the particle Reynolds number in the Fig 2.

2.4. Flume Set-Up

These 2 experiments were conducted in a water-recirculating flume with glass walls (Fig 3). An ADV (Acoustic Doppler velocimetry) is installed to measure the horizontal flow velocity u at a location y from the bed, while u and y will be recorded during the experiments. The time interval for recording data by the ADV is 0.04 seconds.

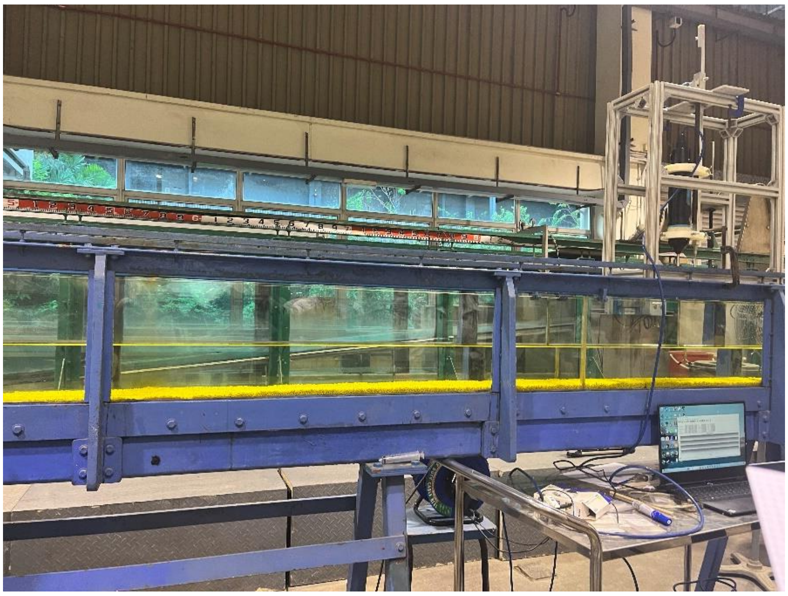

Fig 3. Experimental flume in No.1

The set-ups and experimental set-ups are recorded in Table 2.

Table 2. Physical properties and Set-ups in 2 experiments

Parameters	No.1	No.2
Grain Diameter d (mm)	3	0.5
Relative sediment density s (-)	1.1	2.65
Gravitational acceleration g (m/s2)	9.81	9.81
Kinematic viscosity ν (m2/s)	1.00E-06	1.00E-06
Measure Distance to the bed y (m)	0.011	0.001
Water depth in flume D (m)	0.1	0.1

3. Experimental Procedures

3.1. Incipient sediment motion

A visually-based 10 cm distance of continuous movement of a certain number of particles (i.e., more than five) over a surface area has been considered as the incipient motion criteria for sediment in the experiment 1. [4]

While the incipient motion of sediment starts, the data is recorded for 171 seconds as a time series.

3.2. Sand ripples

Record the velocity at one point by ADV over a 173-second time series.

4. Measurements and Results

4.1. ADV post-processed data

Before calculation, ADV data should be filtered from spikes and poor-quality data.

Besides, as the time series order in the data property is not significant in this analysis, we do not need to replace filtered out values by other data to ensure a complete time-series. [8]

The criteria used for filtering the available data are following:

1) The correlation is more than 40%;
2) The value of ux should be positive;
3) As recommended by manufacturer, SNR is greater than 20 dB (not apply here).

Post-processed ADV data are included into the dataset as Matlab data file (.mat), that are seen as a good (valid) dataset. Post-processed velocities are provided so that u is positive along the flume x-axis.

4.2. Incipient motion

After the incipient sediment transport starts, in the flume, we can see the dunes form and move.

Fig 4. Dunes - initial shape

Fig 5. Dunes - after 3 seconds

We can find the changes of boundary and shape in a dune comparing the Fig 4 and Fig 5, and the comparison in Fig 6 shows the height of dune grows (compared to the initial red area), and it moves along the flow (from right into left).

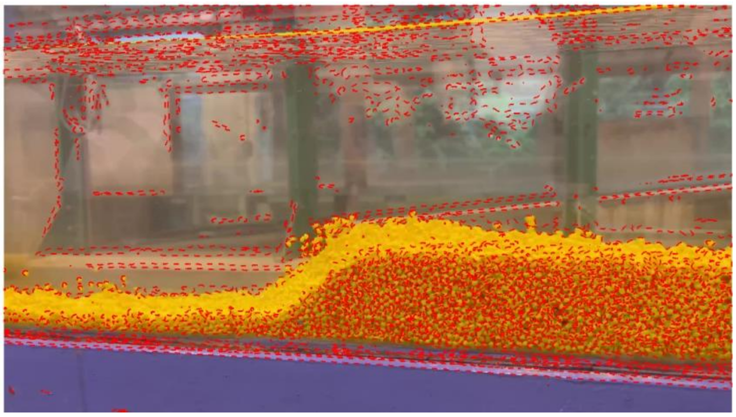

Fig 6. Comparison of dune's shape

We extract the first 10-, 20-, 60-, 120- second, and the whole 171s (after post-processed), and arrange several datasets by time series (TS) order. Then, calculate the mean value of ux, Uf, Re and θc in different datasets in Table 3, where the friction velocity Uf corresponds to the incipient motion.

And plot results in the modified Shields curve in the Fig 7.

Table 3. Different datasets and results

No.	TS	Number of data	ux (m/s)	Uf (m/s)	Re	θc
1	177	3700	0.1312	0.0139	41.6095	0.0654
2	10	212	0.1396	0.0148	44.2684	0.074
3	20	651	0.1349	0.0143	42.7729	0.0691
4	60	1301	0.135	0.0143	42.8131	0.0692
5	120	2590	0.133	0.0141	42.1759	0.0672

Note: No.1 results are the mean value of the post-process data set.

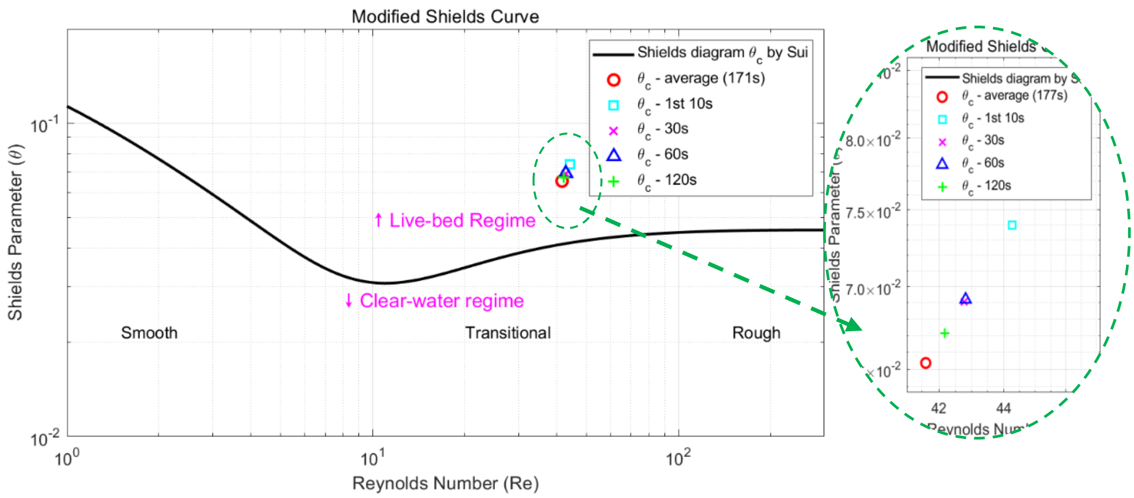

Fig 7. Dot related to incipient motion in Critical Shields Curve

With the longer observation time, the dot tends to close to the critical Shields curve. Besides, we can plot the vertical velocity profile by interpolating water depth, and the logarithmic profile is in Fig 8, where the relative velocity is also shown.

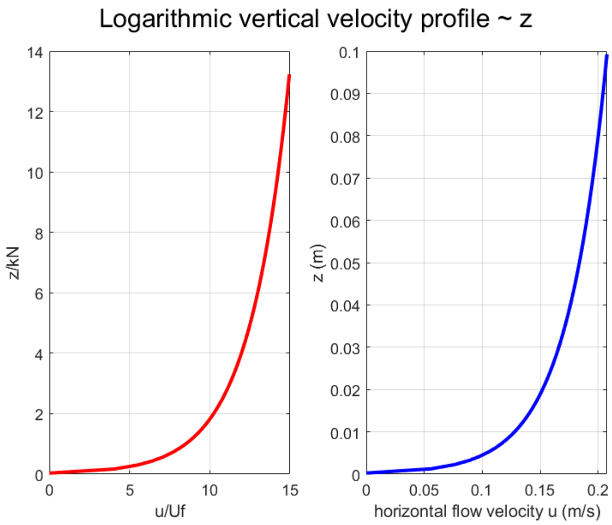

Fig 8. Logarithmic vertical velocity profile

4.3. Sand motion

In the flume, we can see the significant sand ripples formed in Fig 9.

Fig 9. Sand ripples in the experiment 2

The results show the sand particle within the flow condition is located in the lower regime, as *θ'= 0.0623 (Rp=44.98)*. And its shear velocity *Uf =0.0178* m/s.
Then, we plot the dot into the SRD in Fig 10, located to be in motion and slightly exceeding to the critical curve, with no suspension.

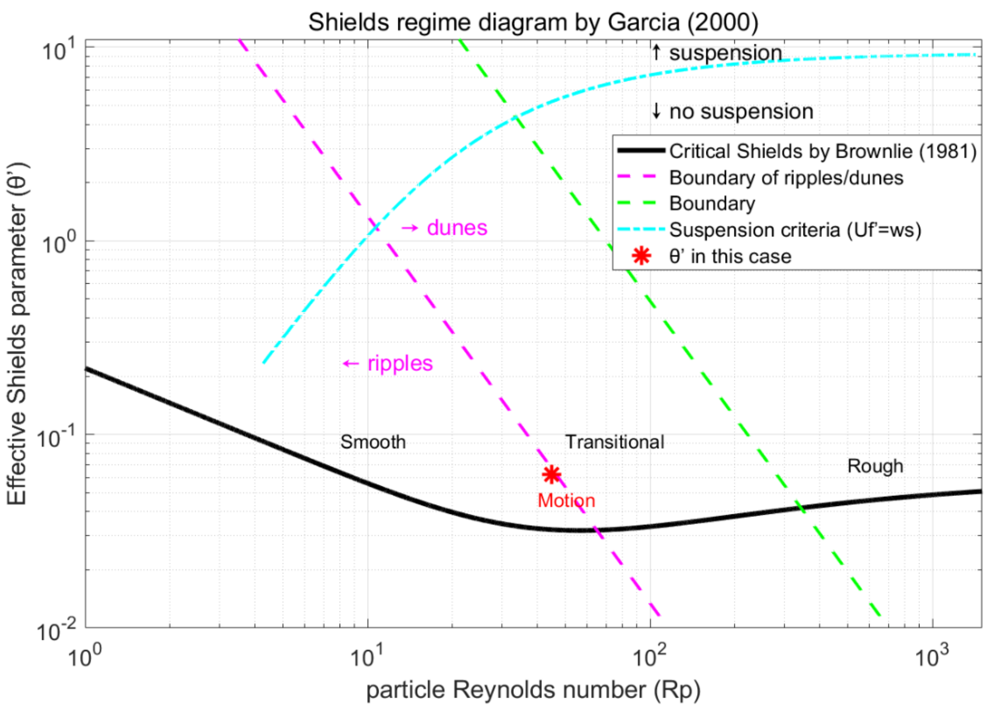

Fig 10. Dot of effective Shields parameter in the SRD

5. Analysis

5.1. Incipient motion

It is hard to capture the instant moment of the incipient motion.

From the Fig 7, we can see that the dot about the shields parameter of experiment 1 is located in the live-bed regime, corresponding to the experimental phenomenon, the dunes move along the flow direction (Fig 6).
With the longer observation time, the dot tends to close to the critical Shields curve.
And most correlations of ux are more than 40% and the mean correlation is more than 92%, showing a higher quality dataset.

5.2. Sand ripples

According to the results and dot in the SRD in the sand bed, it predicts that the sand particles develop ripples with no suspension and being in motion, that mostly corresponds to the experimental observations, showing that the sand ripple shape is long in the clear water. And the dot is in the sand bed, that matches the experimental set-ups.
Considering the measure is close to the ripple surface, the prediction in diagram shows a motion statement but we cannot see obviously the significant movement of particles.
Also, the another reason leading to the slight derivation of dot is about the data quality, showing the mean correlation of ux is only equal to 38%.

6. Conclusion

From these two experiments, we verify the usage and accurate prediction of different Shields diagrams. Compared to the modified Shields diagram, the SRD (Fig 2) is an excellent summary of differences between sand-bed and gravel-bed with regard to transport thresholds, style of sediment transport (bed-load versus suspended), and channel morphology. [6]
In the SRD, the dimensionless effective shear stress $\tau*$ (θ') is calculated from boundary stresses corrected for bed-form drag (ripples or dunes), rather than calculated from the total boundary shear stress.
Long live the legend of Shields! :)

7. References

[1] Buffington, J.M. 1999 The legend of A. F. Shields. J. Hydraul. Eng.-ASCE 125, 276—387.

[2] Shields, A. (1936c). ‘‘Application of similarity principles and turbulence research to bed-load movement.’’ Hydrodynamics Laboratory Publ. No. 167, W. P. Ott, and J. C. van Uchelen, trans., U.S. Dept. of Agr., Soil Conservation Service Cooperative Laboratory, California Institute of Technology, Pasadena, Calif

[3] R. A. Gaines and R. H. Smith, “Micro-Scale Loose-Bed Physical Models,” in *Hydraulic Measurements and Experimental Methods 2002*, Estes Park, Colorado, United States: American Society of Civil Engineers, Oct. 2002, pp. 1–12. doi: 10.1061/40655(2002)78.

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[5] T. Sui, L. H. Staunstrup, S. Carstensen, and D. R. Fuhrman, “Span shoulder migration in three-dimensional current-induced scour beneath submerged pipelines,” *Coast. Eng.*, vol. 164, p. 103776, Mar. 2021, doi: 10.1016/j.coastaleng.2020.103776.

[6] M. H. García, E. M. Laursen, C. Michel, and J. M. Buffington, “The Legend of A. F. Shields,” *J. Hydraul. Eng. N. Y. N*, vol. 126, no. 9, pp. 718–723, 2000, doi: 10.1061/(ASCE)0733-9429(2000)126:9(718).

[7] J. Freds?e and R. Deigaard, *Mechanics of Coastal Sediment Transport*, vol. Volume 3. in Advanced Series on Ocean Engineering, no. Volume 3, vol. Volume 3. WORLD SCIENTIFIC, 1992. doi: 10.1142/1546.

[8] G. Caroppi, K. Västilä, P. Gualtieri, J. Järvelä, M. Giugni, and P. M. Rowiński, “Acoustic Doppler velocimetry (ADV) data on flow-vegetation interaction with natural-like and rigid model plants in hydraulic flumes,” *Data Brief*, vol. 32, p. 106080, Oct. 2020, doi: 10.1016/j.dib.2020.106080.

8. Appendix: Script in MATLAB

8.1. Process data in the experiment 1 - dunes

```
incipient_motion = readtable('incipient motion.csv');
%%% extract
ts_series = incipient_motion{:,2};
ux = incipient_motion{:,5};
cor_x =incipient_motion{:,17};

%%% Parameter:
y_bed = 0.011; %Distance to the bed:    0.011 m
s = 1.1;       %Relative density:        1.1
d = 3e-3;      %Sediment diameter:       3e-3 m
D = 0.1;       %Water depth in flume:    0.10 m
g = 9.81;
%%% calculated parameters
kN= 2.5*d;
z_BL = kN /30;
```

```
kappa = 0.4;
vi = 1e-6; % Kinematic viscosity

%% check if in rough tubulence flow
%criteria_70 = kN*Uf/vi;

%% 1) horizontal: x
x_dim_all = [ts_series, cor_x, ux];  % ~3mins ~180s
% ADV post-processed data, based on the criteria
x_dim_eff = x_dim_all(cor_x > 40 & ux > 0, :);
ux_valid = x_dim_eff(:, 3);
% mean horizontal flow velocity; streamwise flow velocity
ux_mean = mean(ux_valid);
% critical friction velocity
Uf = ux_mean / (1/kappa) / log(30*y_bed/kN);

%% 2) method: focus on the first 1min - 10s
x_dim_eff_1 = x_dim_all(ts_series < 10 & cor_x > 40 & ux > 0, :);
ux_10s = x_dim_eff_1(:, 3);
ux_1st_ave = mean(ux_10s);
% critical friction velocity
Uf_1st = ux_1st_ave / (1/kappa) / log(30*y_bed/kN);
…

%% 1: plot the logarithmic velocity profile
% u=0 -> z starts from z=kN/30
z_0 = kN/30;
interval = 0.001;
z_range = z_0 : interval : D;
% y-axis: z_var = z/kN
z_var = z_range/kN;
% x-axis: x = u/Uf
u_instant_x = Uf * (1/kappa) * log(30*z_var);
x = u_instant_x/Uf;

% plot
figure(1)
subplot(1,2,1)
set(gca, 'FontSize', 14);
plot(x, z_var,'r', 'LineWidth', 2);
grid on;
ylabel('z/kN');
xlabel('u/Uf');
hold on;
```

```
subplot(1,2,2) % single axis variable
plot(u_instant_x, z_range, 'b-', 'LineWidth', 2);
ylabel('z (m)');
xlabel('horizontal flow velocity u (m/s)');
grid on;
sgtitle('Logarithmic vertical velocity profile ~ z');

%% 2: critical Shields parameter
Re_spe_all = Uf*d/vi;
theta_cri_spe_all = Uf^2/(s-1)/g/d;
Re_spe_1st = Uf_1st*d/vi;
theta_cri_spe_1st = Uf_1st^2/(s-1)/g/d;

% base plot: Sui et al. (2021) provide an explicit formulation of the
critical Shields curve
% in terms of the grain Reynolds number
N = 1000;
Re_upper = 300;
% Logarithmically spaced horizontal coordinates Re; if normal axis: Re =
linspace(1, Re_upper, N);
Re_xlog = logspace(log10(1),log10(Re_upper),N);
% Logarithmically spaced vertical coordinates - Shield_critical
theta_cri = 0.165.*(Re_xlog+0.6).^(-0.8) + 0.045*exp(-40.*Re_xlog.^-1.3); %
Sui - Explicit formulation

% loglog() : https://www.mathworks.com/help/matlab/ref/loglog.html
% plot the critical Shields parameter on the Shields diagram of Sui et al.
figure(2)
loglog(Re_xlog, theta_cri, 'black', 'LineWidth', 2);
hold on;
plot(Re_spe_all, theta_cri_spe_all, 'ro', 'MarkerSize', 8, 'LineWidth',
2); % case point
plot(Re_spe_1st, theta_cri_spe_1st, 'cs', 'MarkerSize', 8, 'LineWidth',
1.5); % case point
%yticks([1e-2 1e-1]);
ytickformat('%.1e');
ylim([1e-2, 2e-1]);
xlim([1, 3e2]);
ylabel('Shields Parameter (\theta)');
xlabel('Reynolds Number (Re)');
grid on;
title('Modified Shields Curve');
```

8.2. Process data in the experiment 2 - ripples

```
% read the lab data.csv
ripples = readtable('ripples.csv');
%%% extract
ts_series = ripples{:,2};
ux = ripples{:,5};
cor_x =ripples{:,17};

%%% Parameter:
y_bed = 0.001; %Distance to the bed:    0.001 m
s = 2.65;      %Relative density:        2.65
d = 5e-4;      %Sediment diameter:       5e-4 m
D = 0.1;       %Water depth in flume:    0.10 m
%%% calculated parameters
kN= 2.5*d;
z_BL = 0.4*D;
kappa = 0.4;
vi = 1e-6; % Kinematic viscosity
g = 9.81;

% check the BL
z_0 = kN/30;
if z_0 < y_bed
    disp('The measurement point is above the boundary layer');
end

% Uf -> shield parameter
% horizontal: x
x_dim_all = [ts_series, cor_x, ux];
% ADV post-processed data, based on the criteria
x_dim_eff = x_dim_all(cor_x > 40 & ux > 0, :);
ux_valid = x_dim_eff(:, 3);
% mean horizontal flow velocity; streamwise flow velocity
ux_mean = mean(ux_valid);

% friction velocity
Uf = ux_mean / (1/kappa) / log(30*y_bed/kN);
% shields parameter
theta_spe = Uf^2/(s-1)/g/d;
Re_spe = Uf*d/vi;
Rp_spe = Re_spe /sqrt(theta_spe);
% Rp_spe = sqrt((s-1)*g*d)*d/vi;

% if statement for the lower or upper regime
```

```
theta_prime_spe = 0.06 + 0.3*theta_spe^1.5; % for theta_prime <= 0.55,
lower regime
if theta_prime_spe > 0.55 % upper regime
    theta_prime_spe = (0.702*theta_spe^(-1.8)+0.298)^(-1/1.8); % for
theta_prime > 0.55, upper regime
end

%% base plot: the Shields regime diagram by Garcia (2000)
% in terms of the particle Reynolds number

N = 1e4;
Rp_upper = 1e5;
Rp = linspace(1, Rp_upper, N);

% Logarithmically spaced vertical coordinates - Shield_critical
% Brownlie (1981) gives the following fit of Shields' data
% the skin friction component of the Shields parameter θ'
theta_prime = 0.22.*Rp.^(-0.6) + 0.06*exp(-17.77.*Rp.^-0.6); % note: use
'Rp_xlog' in mulitpling cal
%log_theta_prime = logspace(log10(min(theta_prime)),
log10(max(theta_prime)), N);

theta_pri_ripple = (11.6 ./ Rp).^2;
%log_theta_pri_ripple = logspace(log10(min(theta_pri_ripple)),
log10(max(theta_pri_ripple)), N);

theta_pri_dune = (70 ./ Rp).^2;
%log_theta_pri_dune = logspace(log10(min(theta_pri_dune)),
log10(max(theta_pri_dune)), N);

% theta_pri_suspension: iterviation for ws and Rp
Rp_suspension = readtable('Rp_thetap_more1.csv');
% extract
Rp_susp = Rp_suspension{:,1};
theta_susp = Rp_suspension{:,2};


%% plot
figure(1)
loglog(Rp, theta_prime, 'black', 'LineWidth', 3);
hold on;
loglog(Rp, theta_pri_ripple , 'm--', 'LineWidth', 2);
loglog(Rp, theta_pri_dune, 'g--', 'LineWidth', 2);
loglog(Rp_susp, theta_susp, 'c-.', 'LineWidth', 2);
```

```
% case point
plot(Rp_spe, theta_prime_spe, 'r*', 'MarkerSize', 12, 'LineWidth', 2);
ytickformat('%.1e');
ylim([1e-2, 11]);
xlim([1, 1500]);
ylabel('Effective Shields parameter (θ’)');
xlabel('particle Reynolds number (Rp)');
grid on;
title('Shields regime diagram by Garcia (2000)');
set(gca, 'FontSize', 14);
legend('Critical Shields by Brownlie (1981)', 'Boundary of
ripples/dunes', ...
         'Boundary', 'Suspension criteria (Uf’=ws)', 'θ’ in this case',
'Location', 'best')
```

8.3. Script to match dune figures in the experiment 1

```
start = imread("dunes - frame at 0m1s.JPG");
endd = imread("dunes - frame at 0m3s.JPG");
% Calculate the absolute difference and convert it to a grayscale image
diff_image = rgb2gray(imabsdiff(start, endd));
% Manually choose a threshold and binarize the difference image
threshold = graythresh(diff_image);
binary_diff_image = imbinarize(diff_image, threshold);
% Find the boundaries of the binary difference image
boundaries = bwboundaries(binary_diff_image);
% show the comparison on the later figure  %% dunes move forwards
figure(3);
imshow(endd);
hold on;
for k = 1:length(boundaries)
    boundary = boundaries{k};
    plot(boundary(:,2), boundary(:,1), 'r--', 'LineWidth', 1);
end
hold off;
```