

利用現地試驗來驗證 震波式推移質跳躍模型(2)

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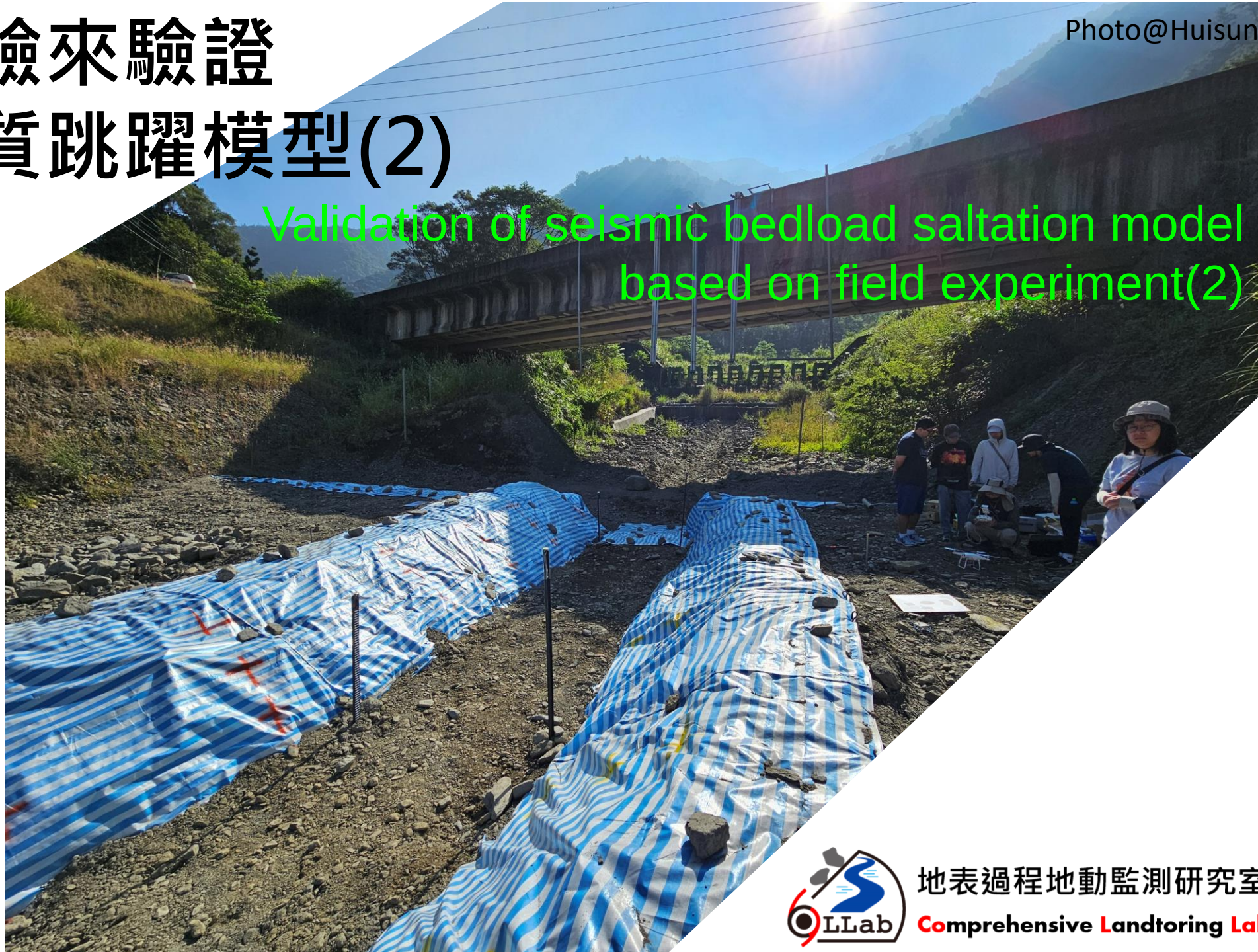
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3 國立成功大學防災研究中心

Validation of seismic bedload saltation model
based on field experiment(2)



國立中興大學
NATIONAL CHUNG HSING UNIVERSITY



國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY



地表過程地動監測研究室
Comprehensive Landtoring Lab

SEISMIC OBSERVATIONS

Photo@Buluowan



Riverine
Seismometer

Signal duration (T)

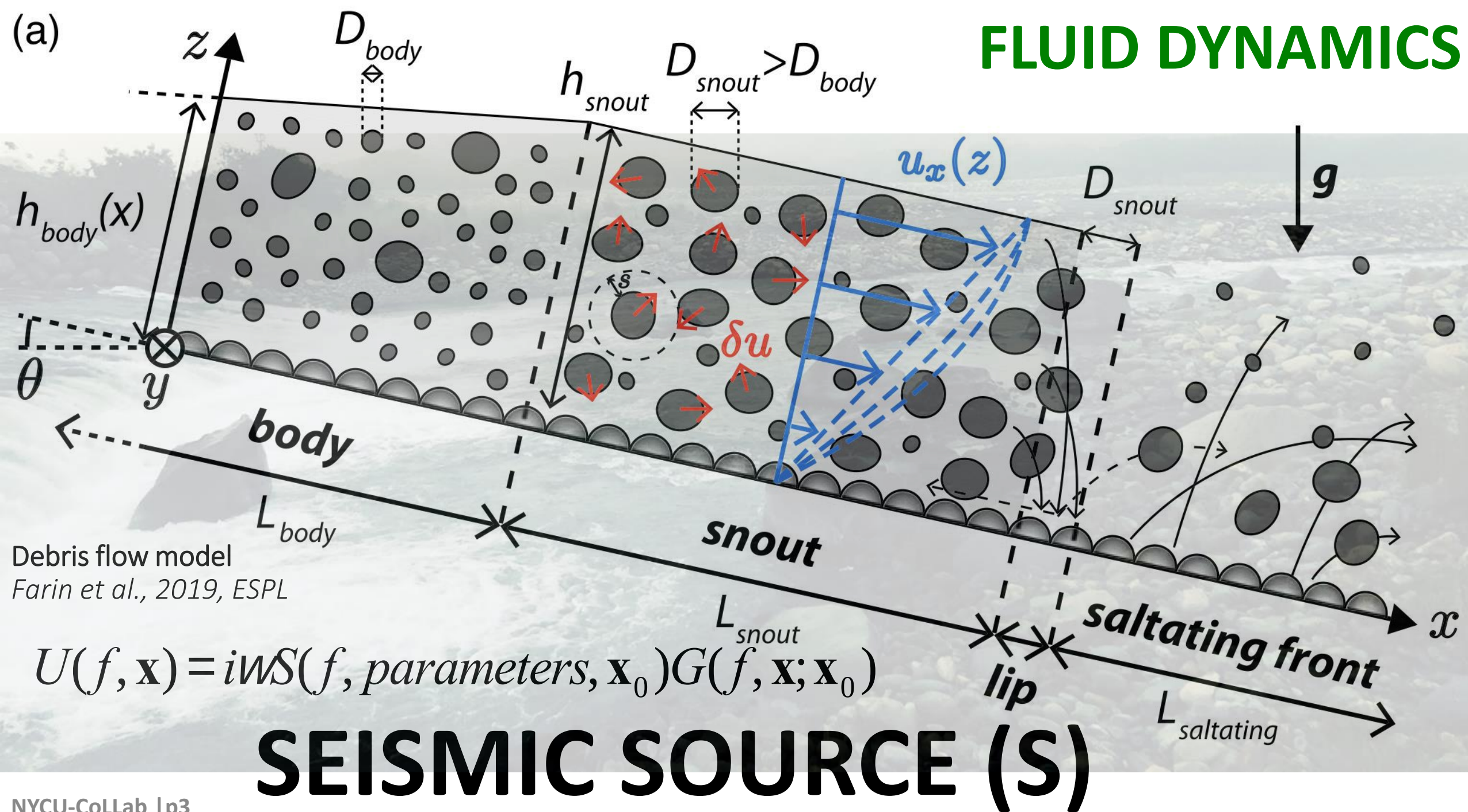
Power spectral density of ground velocity at location $\mathbf{x}$

$$P(f, \mathbf{x}) = \frac{U(f, \mathbf{x})^2}{T}$$

$$U(f, \mathbf{x}) = S(f, \text{parameters}, \mathbf{x}_0)G(f, \mathbf{x}; \mathbf{x}_0)$$

Ground velocity to be observed data

$$U(f, \mathbf{x}) = \mathcal{F} \left[\int_0^T U(t, \mathbf{x}) e^{-2\pi i f t} dt \right]$$



- Grains impact the river bed vertically
- Impacts occur randomly in time, they are uncorrelated with each other
- Constant values for hop time and impact velocity
- Impact contact time (tc) ~1 ms, resulting $f_{\max} \sim 1000$ Hz
- Impact is perfectly elastic (reflection = incident)

$U(f, \mathbf{x}) = i\omega S(f, parameters, \mathbf{x}_0)G(f, \mathbf{x}; \mathbf{x}_0)$

GREEN's Function (G)

Vertical-to-vertical G for *Rayleigh* wave in vertically heterogeneous medium :

$$G^R(\omega) = \frac{e^{i(k_R r + \frac{\pi}{4})}}{8c_R U_R I_1^R} \sqrt{\frac{2}{\pi k_R r}} \begin{bmatrix} r_1(z)r_1(h) \cos^2 \phi & r_1(z)r_1(h) \sin \phi \cos \phi & -ir_1(z)r_2(h) \cos \phi \\ r_1(z)r_1(h) \sin \phi \cos \phi & r_1(z)r_1(h) \sin^2 \phi & -ir_1(z)r_2(h) \sin \phi \\ ir_2(z)r_1(h) \cos \phi & ir_2(z)r_1(h) \sin \phi & \boxed{r_2(z)r_2(h)} \end{bmatrix}$$

Tsai and Atiganyanun (2014), BSSA

$$U(f, \mathbf{x}) = iWS(f, parameters, \mathbf{x}_0)G(f, \mathbf{x}; \mathbf{x}_0)$$

Power Spectral Density (P) caused by sediment saltation

Signal Window (T)

Average hop time between impacts of grains of diameter D (t_{hop})

The number of moving grains per unit grain size and per unit river length (n_D)

$$P(f, x, D; x_0) = \frac{|U(f, x, D; x_0)|^2}{T}$$

$$= \frac{n_D(D)}{t_{hop}(D)} F^2(f, D, x_0) G^2(f, x; x_0)$$

BED SHEAR VELOCITY: u^* (assuming steady and uniform flow)

$$u^* = \sqrt{gH \sin \theta}$$

TERMINAL SETTLING VELOCITY: W_{st}

$$W_{st} = \sqrt{4RgD / 3C_d}$$

SHIELDS STRESS: τ^*

$$\tau^* = (u^*)^2 / (RgD)$$

CRITICAL VALUE OF SHIELDS STRESS: τ_c^*

$$\tau_c^* = \tau_{cD50}^* (D / D_{50})^{-0.9}$$

FLAT IMPACT AMPLITUDE SPECTRUM:

$$F(f, D, x_0) = m \int_0^{t_c} \ddot{a}(t) dt = m(W_{inc} + W_{ref}) = (1 + C_1)mW_{inc}$$

Total vertical impact at location x_0 :

$$F(f, x_0) = \int_D \frac{n_D(D)}{t_{hop}} F(f, D, x_0) dD$$

Saltation model

Tsai et al., 2012, GRL

Gimbert et al., 2019, ESPL

Water Depth (H)

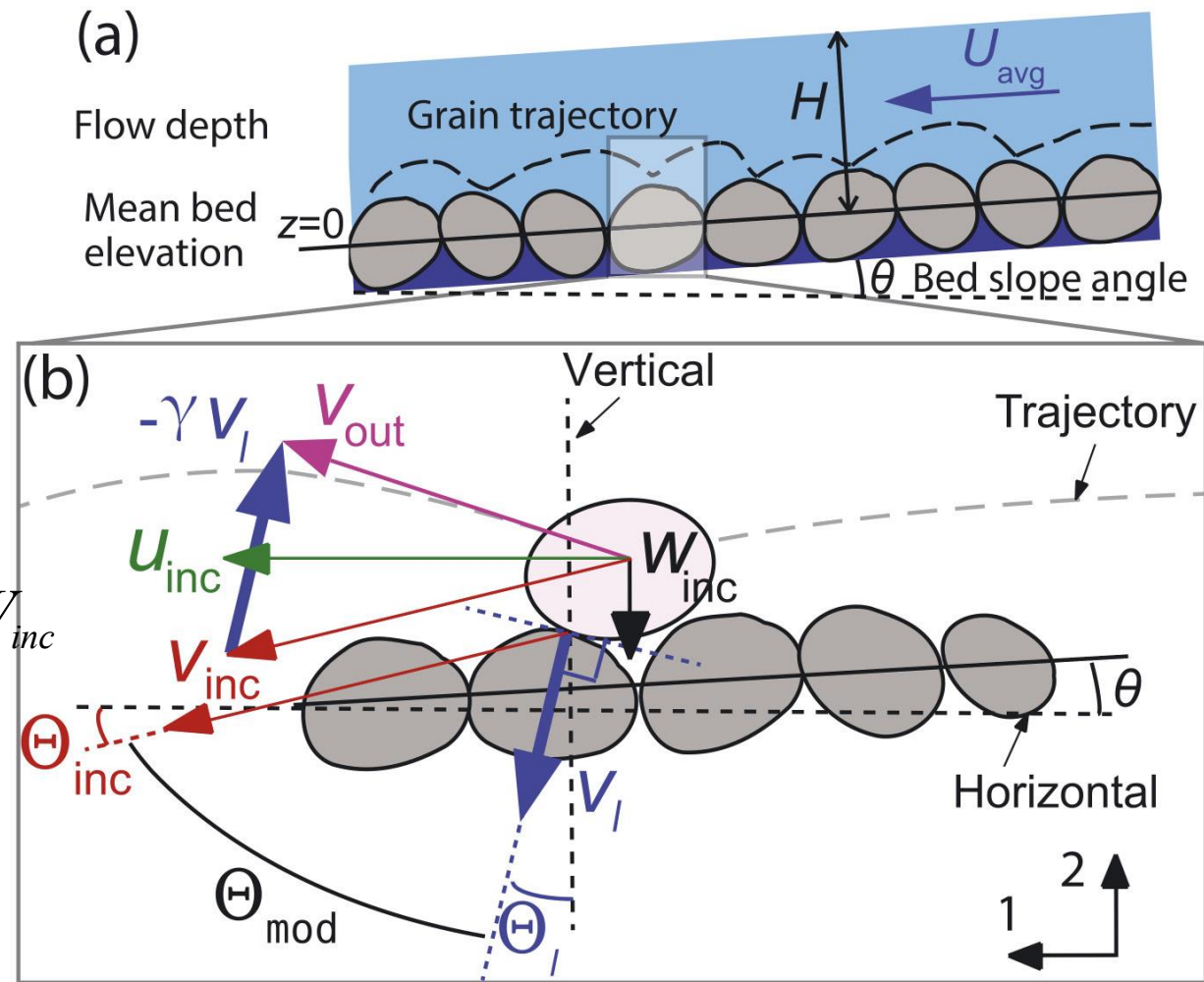
Gravity (g)

Slope Angle of riverbed (θ)

Relative Density Ratio (R)

Grain Diameter (D)

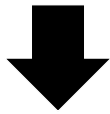
Drag Coefficient (C_d)



Parker (1990); Dietrich (1982); Sklar and Dietrich (2004); Lamb et al., (2008)

$$F(f, x_0) = \int_D \frac{n_D(D)}{t_{hop}} F(f, D, x_0) dD$$

Average hop time between impacts of grains of diameter D (t_{hop})
 The number of moving grains per unit grain size and per unit river length (n_D)
 The average stream-wise bedload velocity (u_s)



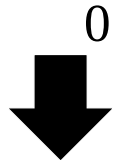
$$I_r = \frac{n_D(D)}{t_{hop}} = \frac{q_{bD} W}{V} \frac{2}{3} \frac{\bar{w}_s}{u_s H_b}$$

Bedload layer height (H_b)
 Vertical incident Impact Velocity (W_{inc})
 Water Depth (H)
 Particle mass (m)
 Grain volume (V)

Bedload flux per unit grain size per unit length (q_{bD})
 Total bedload flux (q_b)

$$F(f, D, x_0) = m \int_0^{tc} a(t) dt = m(W_{inc} + W_{ref}) = (1 + C_1) m W_{inc}$$

Slope Angle of riverbed (θ)
 Drag Coefficient (C_d)



$$W_{inc} = \sqrt{\frac{4RgD}{3C_d}} \cos q \left[1 - \exp \left(- \frac{3C_d r_f 1.44 D \frac{gH \sin q}{RgDt_c^*(D)} \frac{u_s^{0.5}}{2 r_s D \cos q} \right) \right]$$

Saltation model
 Tsai et al., 2012, GRL

Integrated P along entire river length R for a specific diameter D :

$$P(f, x, D; x_0) = \frac{|U(f, x, D; x_0)|^2}{T} = \frac{n_D(D)}{t_{hop}(D)} F^2(f, D, x_0) G^2(f, x; x_0)$$

$$P(f, x, D) = \int_R P(f, x, D; x_0) dx_0$$

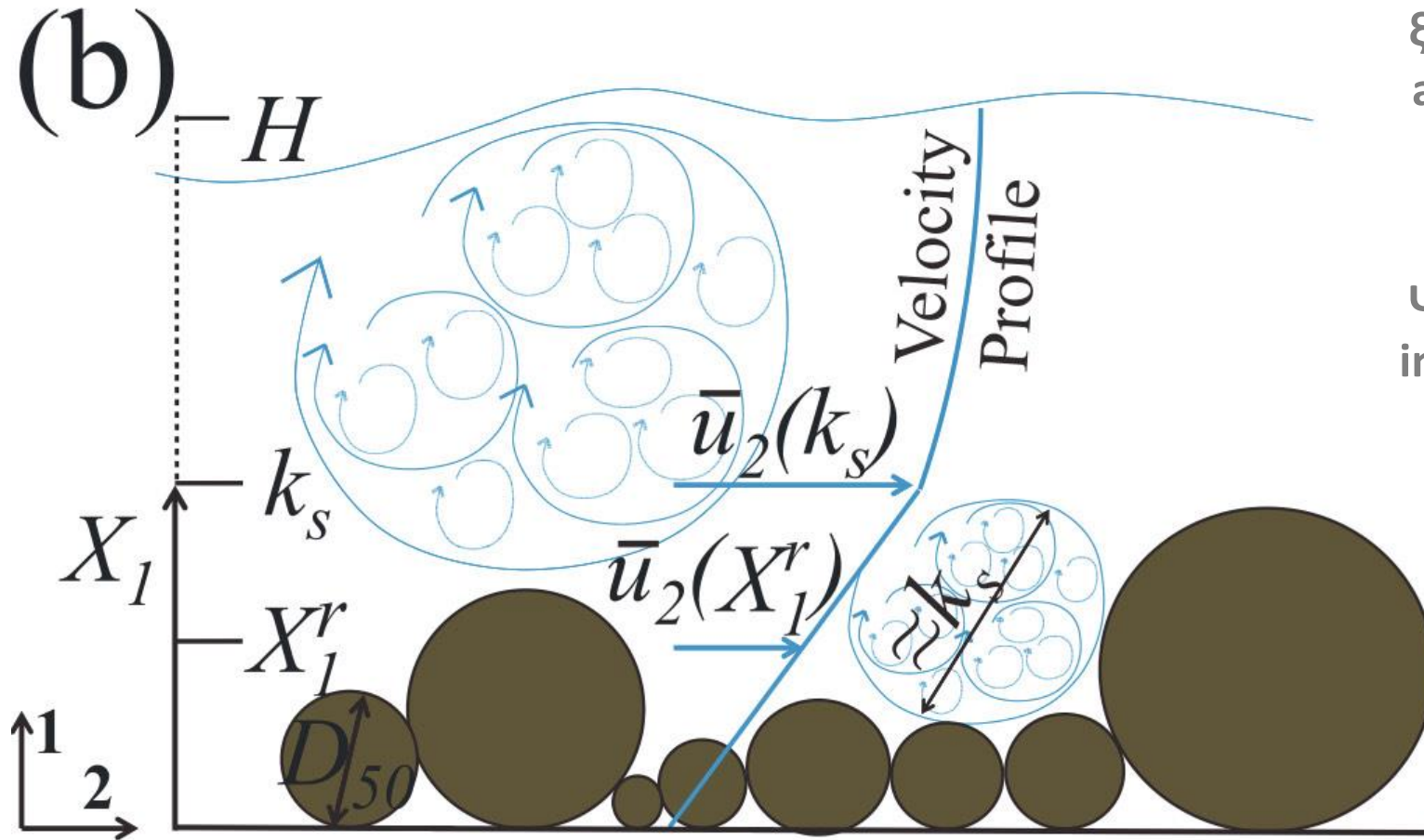
$$= \frac{n_D(D)}{t_{hop}(D)} \int_R F^2(f, D, x_0) G^2(f, x; x_0) dx_0$$

assumption : $R \gg r_0$

$$P(f, D, r_0) @ \frac{n_D(D)}{t_{hop}(D)} \frac{\rho^2 f^3 m^2 W_{inc}^2}{r_s^2 v_c^3 v_u^2} c(b) (1 + C_1)^2 C_2^2(f)$$

Seismic Turbulent Flow Model

FLUID DYNAMICS



$\xi (H/k_s)$ account for the effect of variations in average velocity and turbulent intensity with apparent roughness into variations in the amplitude of flow force spectrum

$\Psi_\beta(f)$ accounts for geometrical spreading and inelastic attenuation of seismic waves as they propagate into the ground

$\phi_D(f)$ accounts for the modulation of ground motion power by grain size (m^2)

Kolmogorov constant ($K=0.5$)

Gimbert et al. (2014)
Turbulent flow model

$$P(f) \approx \frac{KW}{3k_s^{\frac{2}{3}}} \left(\frac{\rho_w}{\rho_s(0)} \right)^2 \frac{(1 + \xi)^2}{f_0^{5\xi} v_{c0}^5} \cdot \xi \left(\frac{H}{k_s} \right) \cdot \psi_\beta(f) \cdot \phi_D(f) \cdot f^{\frac{4}{3} + 5\xi} \cdot g^{\frac{7}{3}} \sin(\theta)^{7/3} \cdot C^2 H^{7/3}$$

WRA PROJECT

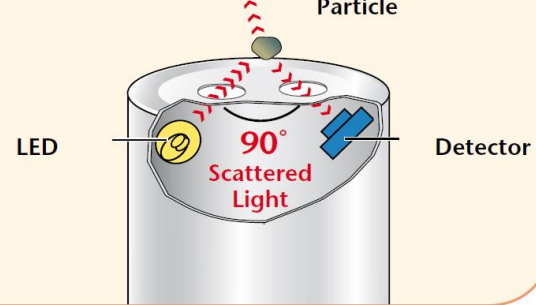
水利署計畫|中央管河川自動化土砂量測技術之發展應用

RiverSurveyor M9



Turbidity Sensor VisoTurb® 700 IQ

Optic Turbidity



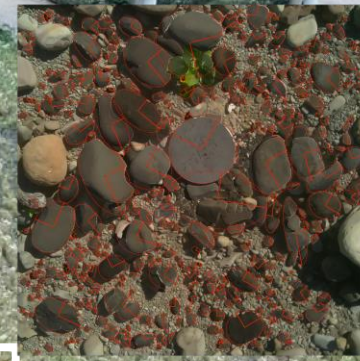
CHANGYUNG BRIDGE

Channel Width ~ 500 m

Flow path (3)

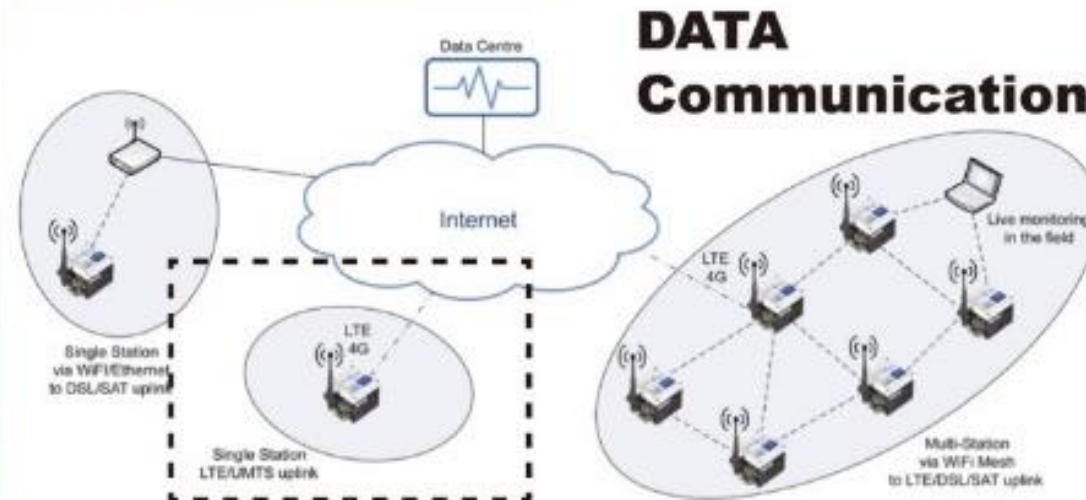
Flow path (2)

Flow path (1)



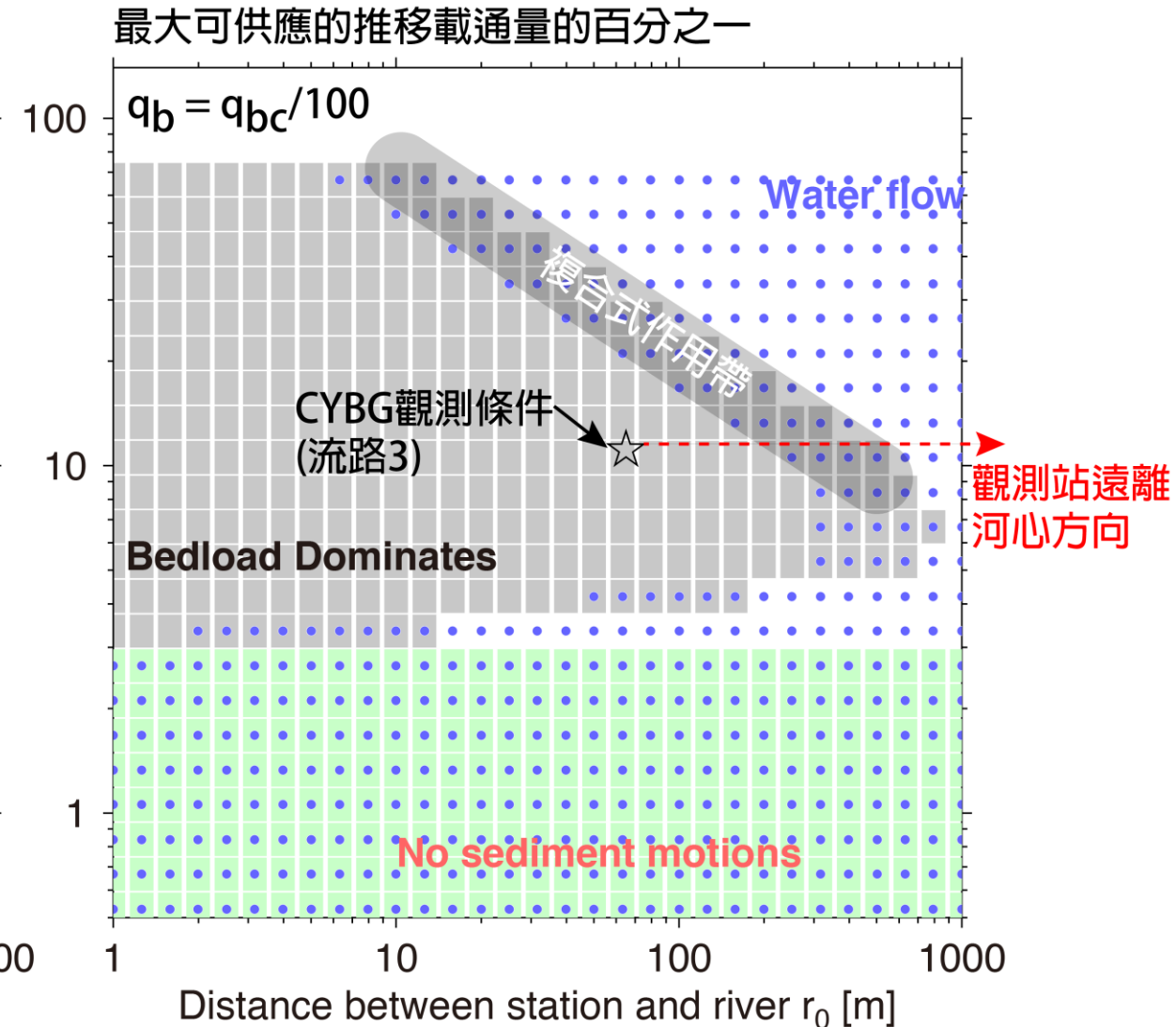
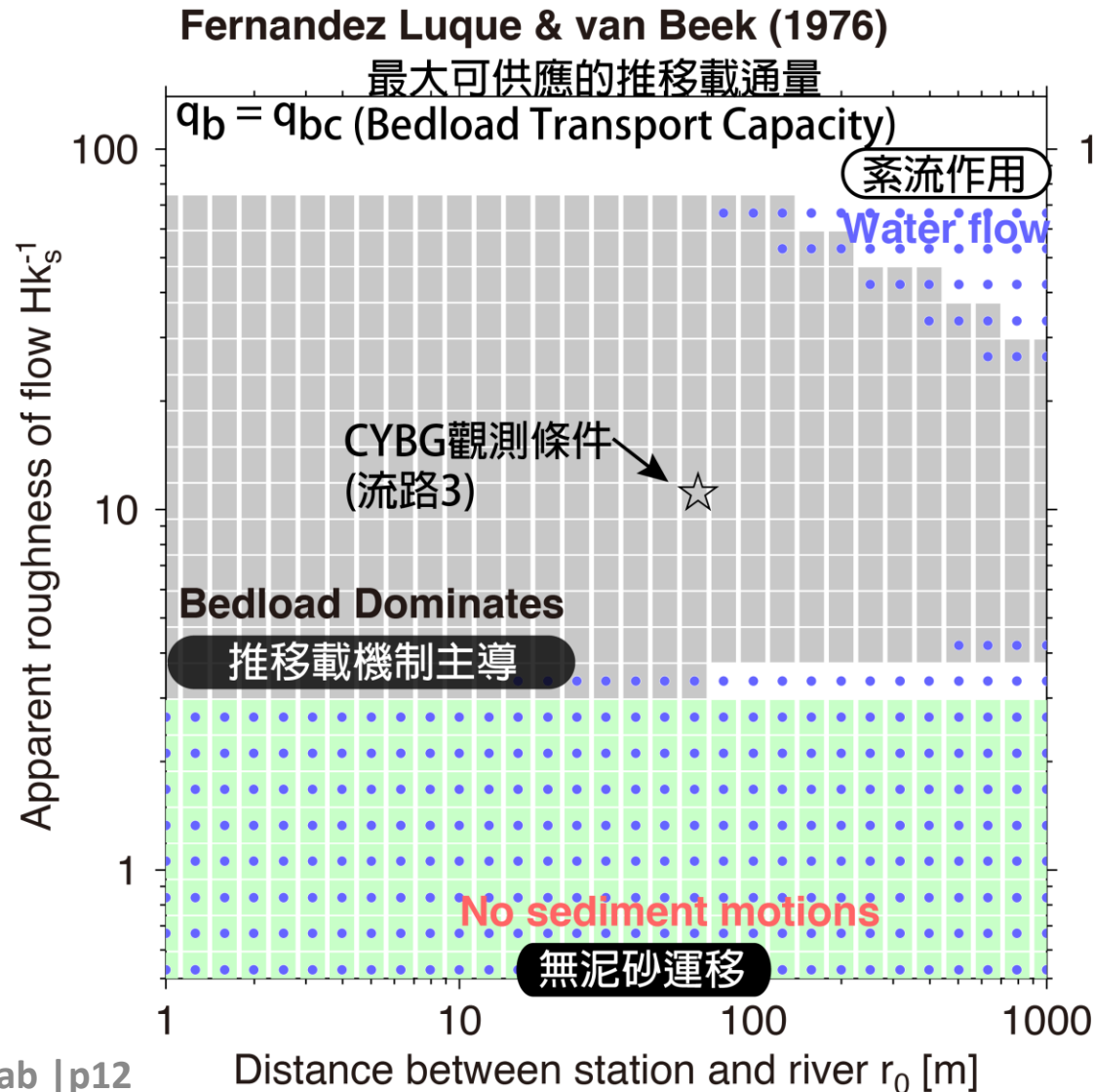
Photo@ChoShuiRiver

Seismic station installation



Phase diagrams showing the primary mechanism

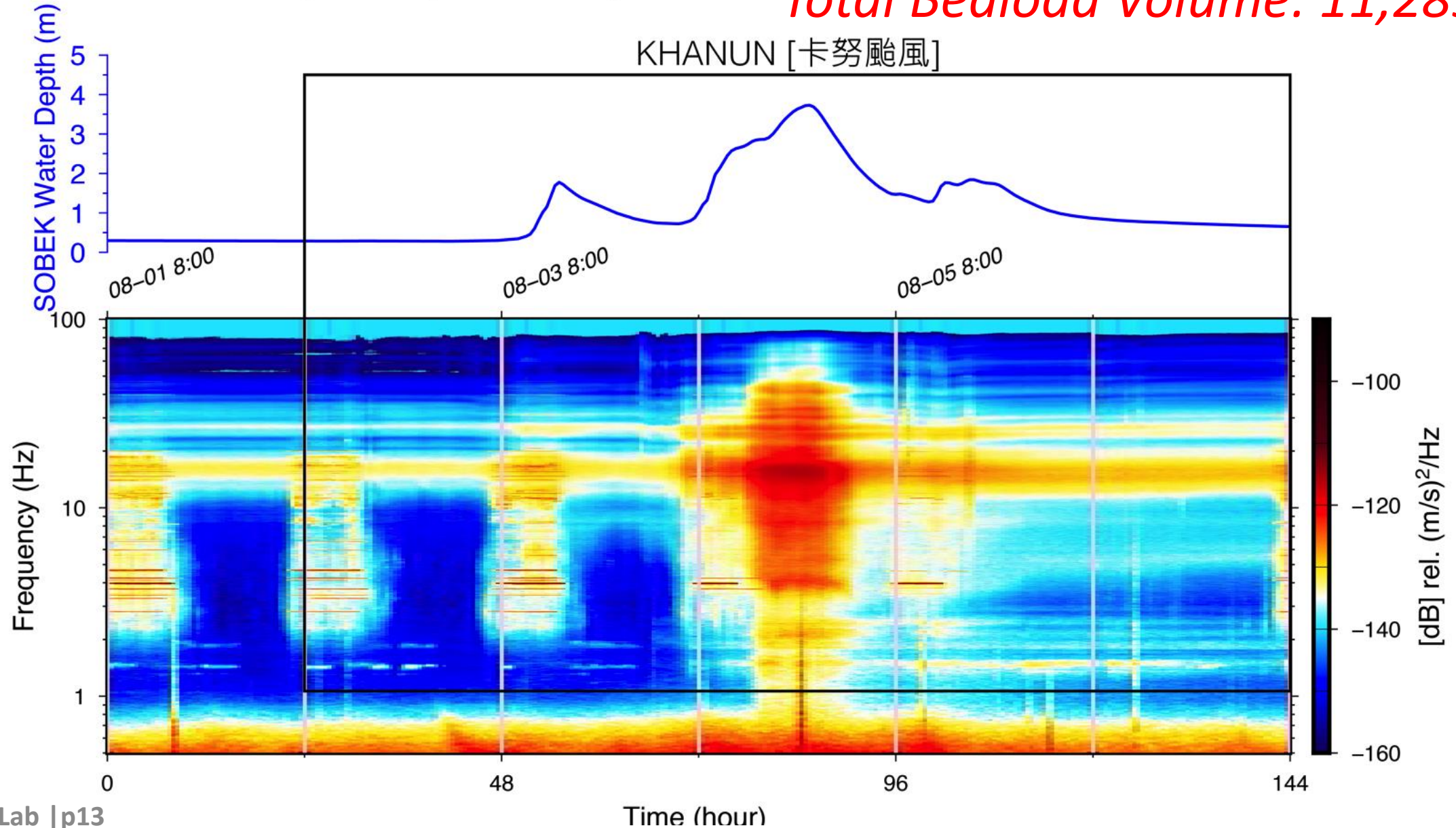
Water flow(dot), bedload(gray square)



Typhoon Khanun

Total Bedload Volume: 11,289.7m³

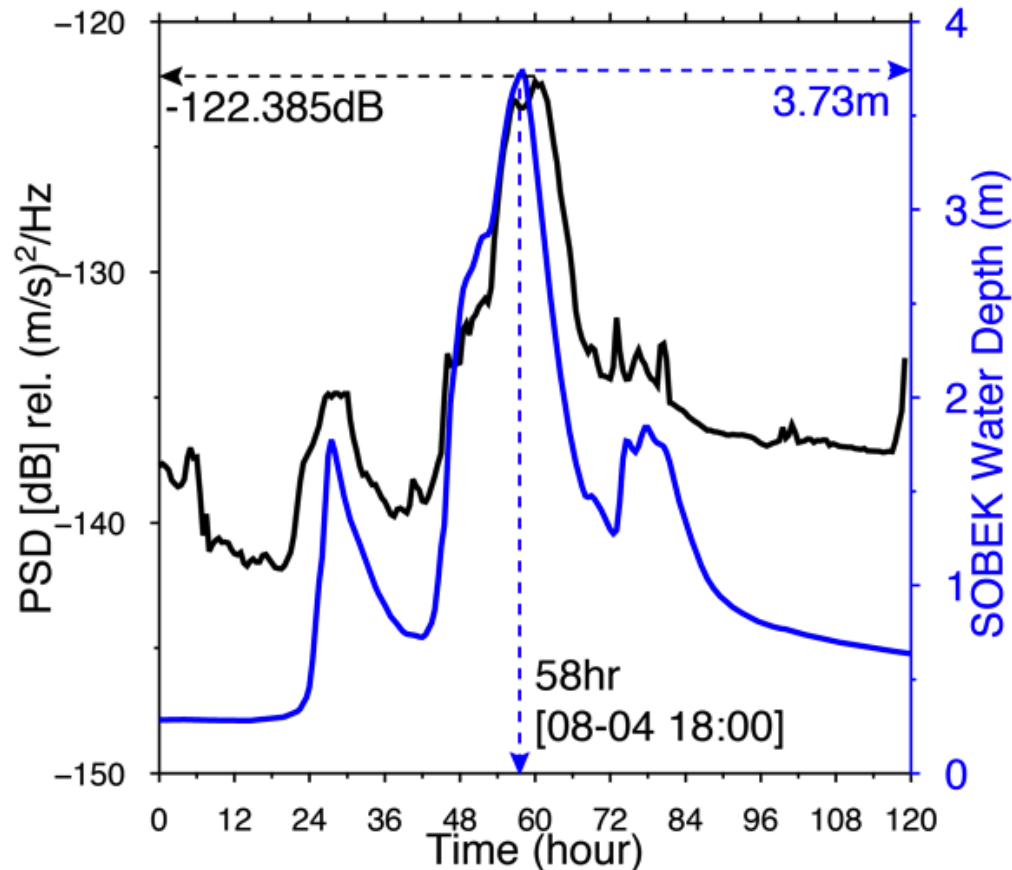
A. 2023-08-01 8:00 [local time] CLBB Z-component



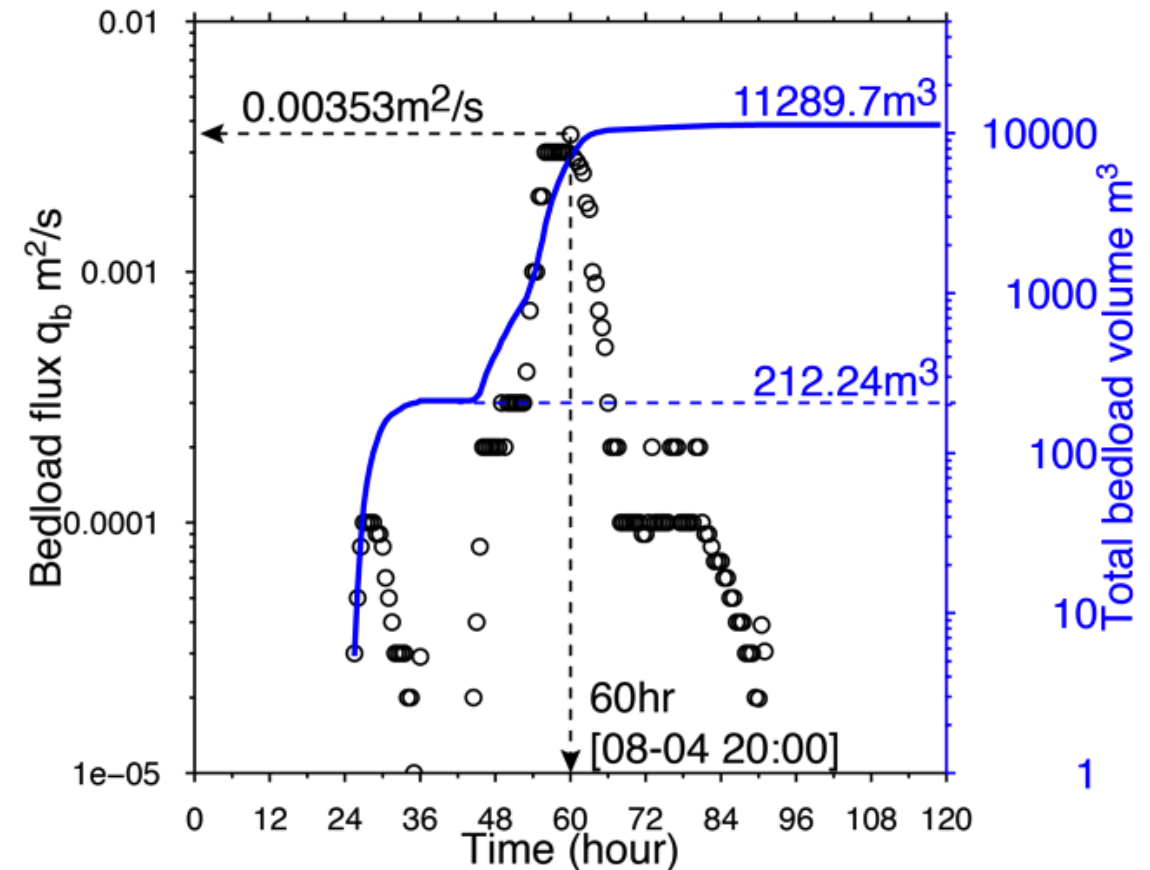
Typhoon Khanun

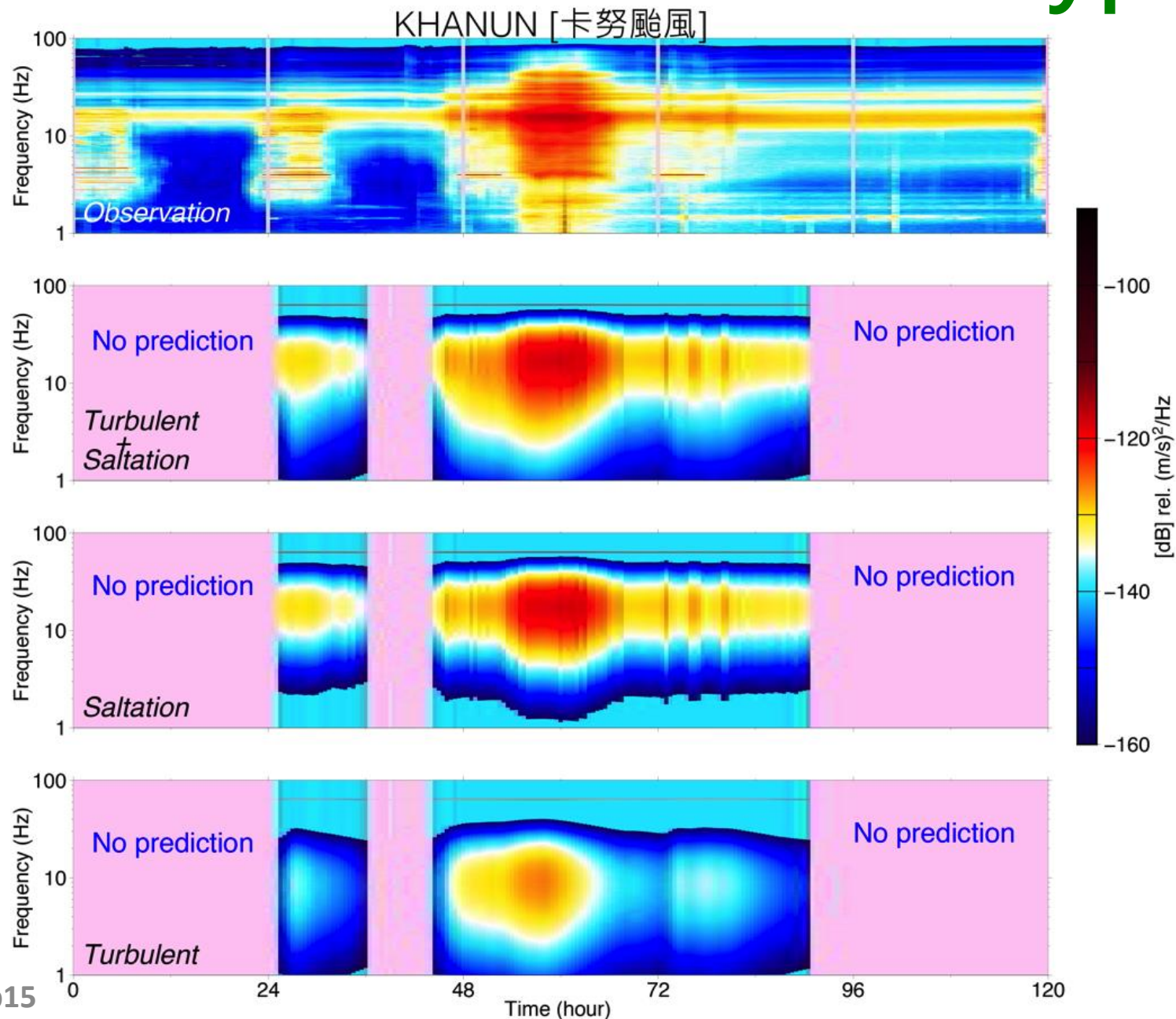
Total Bedload Volume: 11,289.7m³

B. 2023-08-02 08:00 [local time] 5-40 Hz



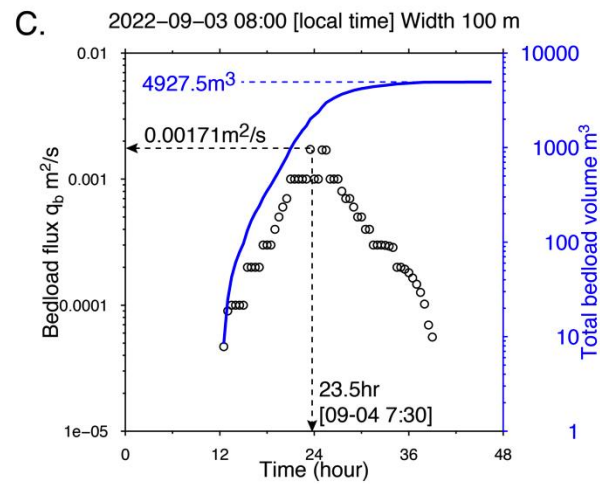
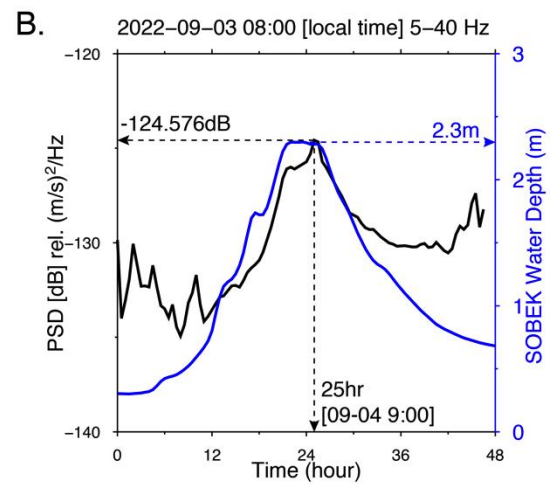
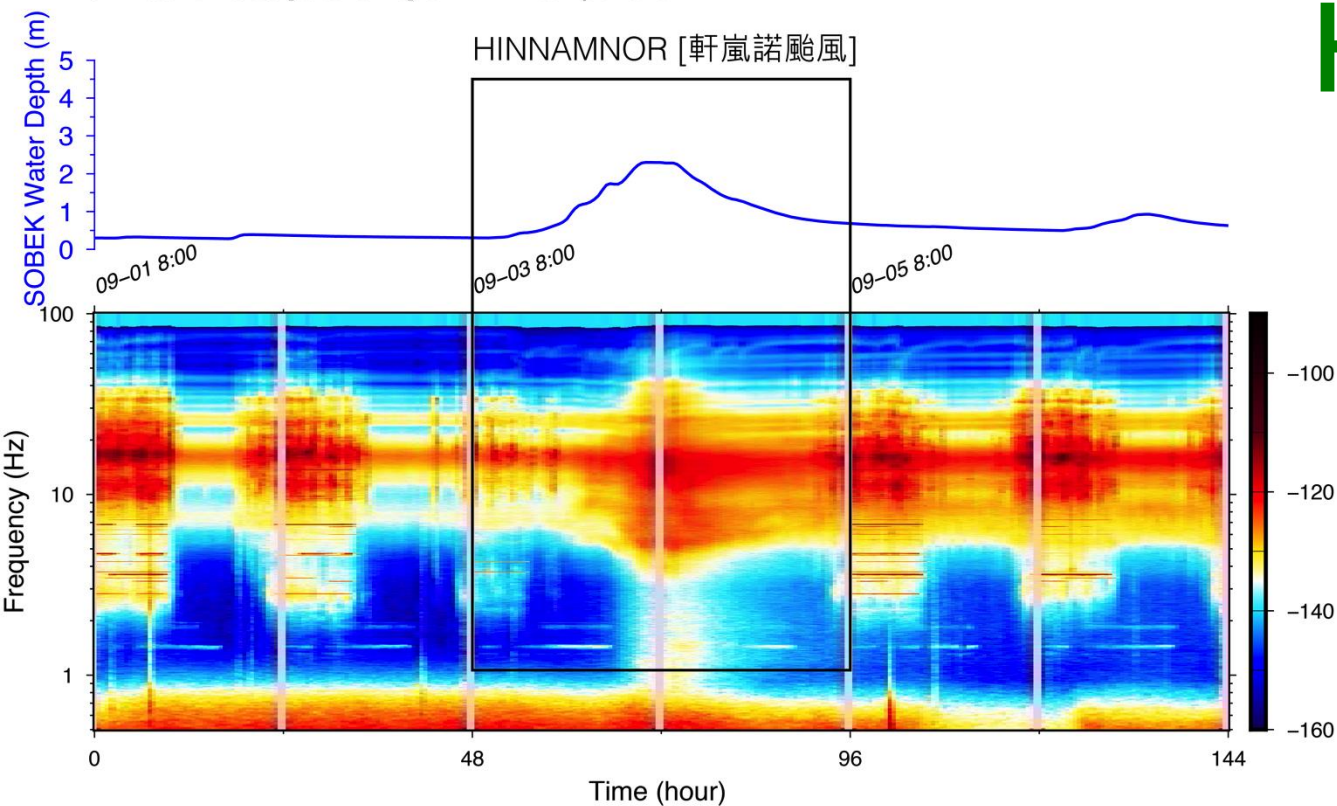
C. 2023-08-02 08:00 [local time] Width 100 m





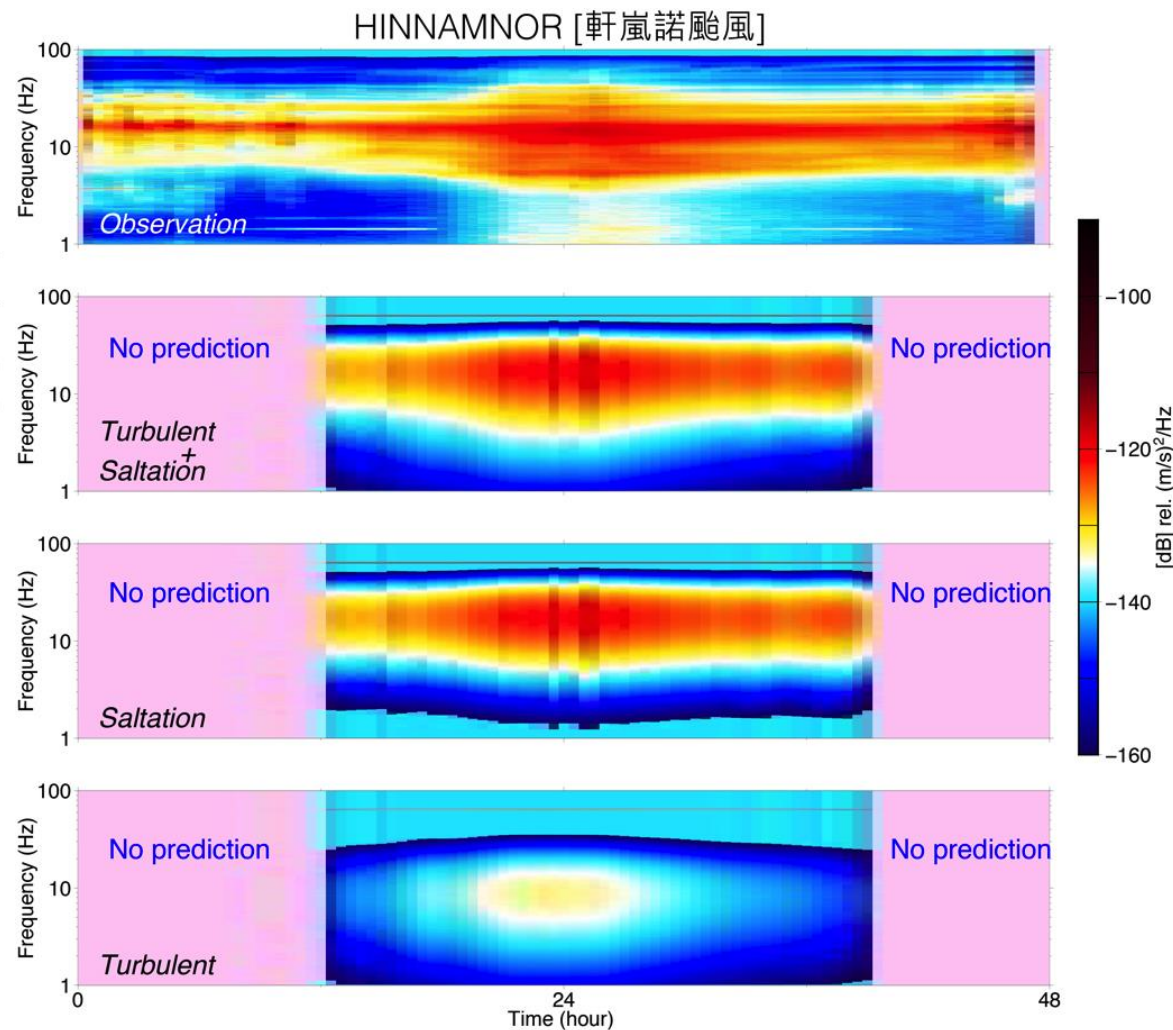
Not bad!
But
Not
Perfect?

A. 2022-09-01 8:00 [local time] CLBB Z-component



Hinnamnor軒嵐諾颱風

Total Bedload Volume: 4,927.5m³



CHALLENGE Impact Particle Kinematics?

$$\frac{n_D}{t_{hop}}, W_{inc}, C_1$$

$$F(f, x_0) = \int_D \frac{n_D(D)}{t_{hop}} F(f, D, x_0) dD$$

$$L_s(D) = 2.3Dt_{stage}^{0.8}$$

Auel et al., 2017

$$n_D(D) = \frac{p_D N}{L_s}$$

$$n_D(D) = \frac{q_{bD} W}{Vu_s}$$

$$\frac{n_D(D)}{t_l(D)} = \frac{q_{bD} W}{Vu_s t_l(D)} = \frac{q_{bD} W}{VL_s}$$

Lajeunesse et al., 2010

$$L_s(D) = 1.19\sqrt{RgDt}^{0.3}_{stage} \times 0.14t^{0.28}_{stage}$$

$$R = \frac{r_s - r_f}{r_f}$$

Gimbert et al., 2019

$$W_{inc} = 0.84\sqrt{RgDt}^{0.18}_{stage}$$

$$W_{inc} = 0.51\sqrt{RgDt}^{0.25}_{stage}$$

CHALLENGE seismic wave propagation?

Seismic Parameters: $c(b), v_c, v_u, C_3, C_4, C_5$

$$P(f, D, r_0) @ \frac{n_D(D)}{t_{hop}(D)} \frac{p^2 f^3 m^2 W_{inc}^2}{r_s^2 v_c^3 v_u^2} c(b)(1+C_1)^2 C_2^2(f)$$

$$c(b) @ 2 \ln \left(1 + \frac{1}{b} \right) e^{-2b} + \left(1 - e^{-b} \right) e^{-b} \sqrt{\frac{2p}{b}}$$

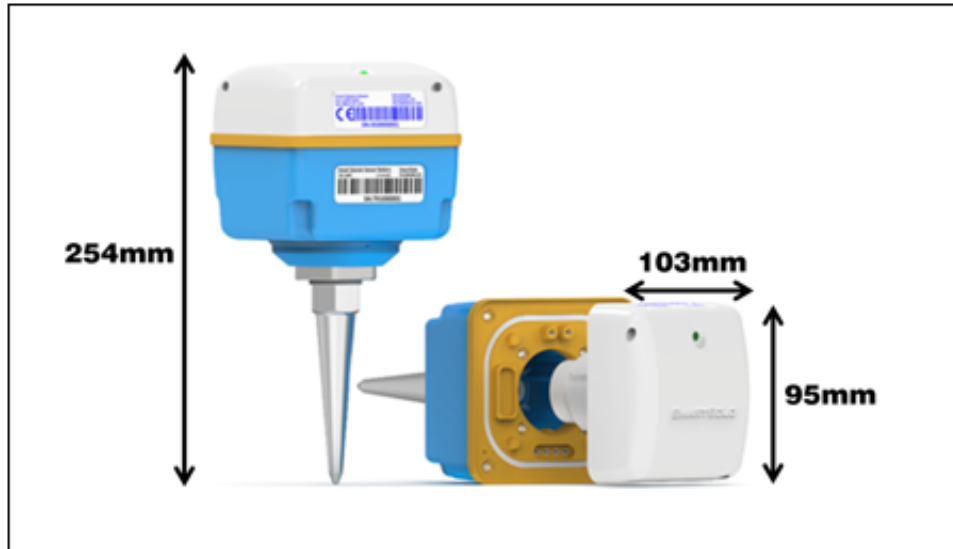
$$b = 2pr_0 (1 + C_4) f^{1+C_4-C_5} / (v_{c0} C_3 f_0^{C_4-C_5})$$

CHALLENGE

Seismic Parameters: $c(b)$, v_c , v_u , C_3 , C_4 , C_5

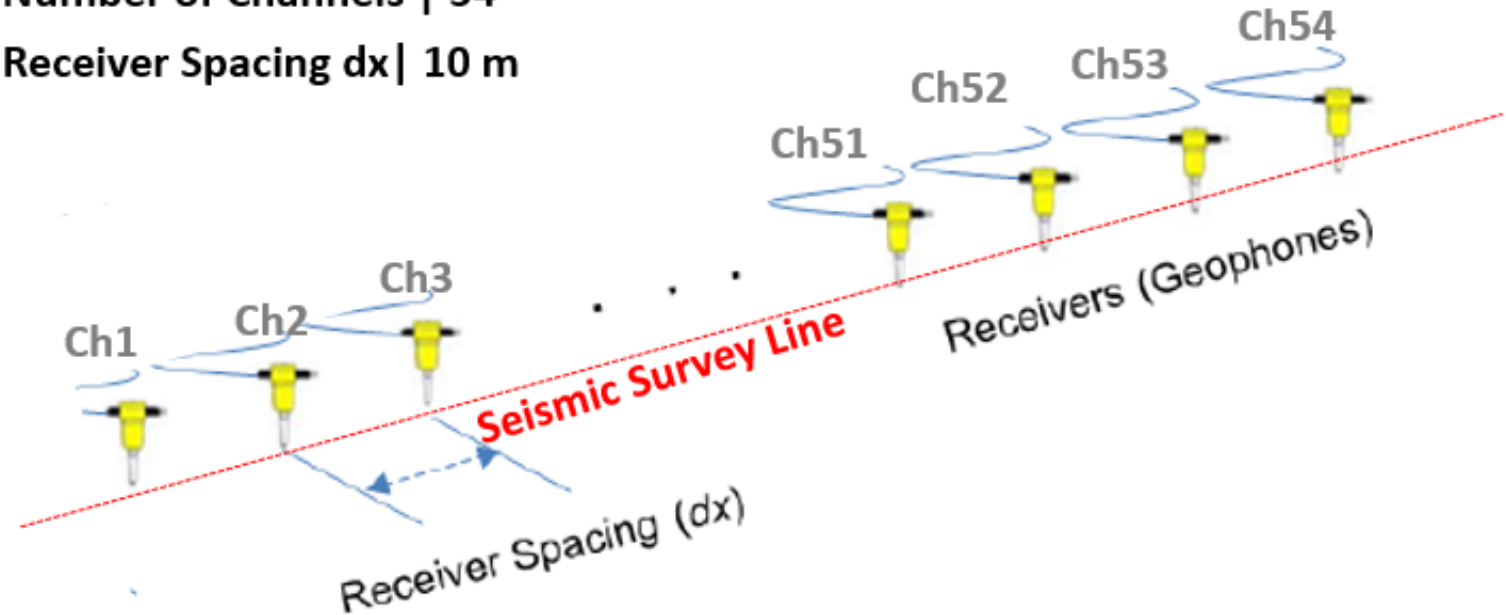
*Large uncertainties in estimation of bedload flux caused by indirect measurements of water depth, grain size distribution, suspended load and **seismic velocity model**.*

Receiver: SmartSolo Geophone



Number of Channels | 54

Receiver Spacing dx | 10 m



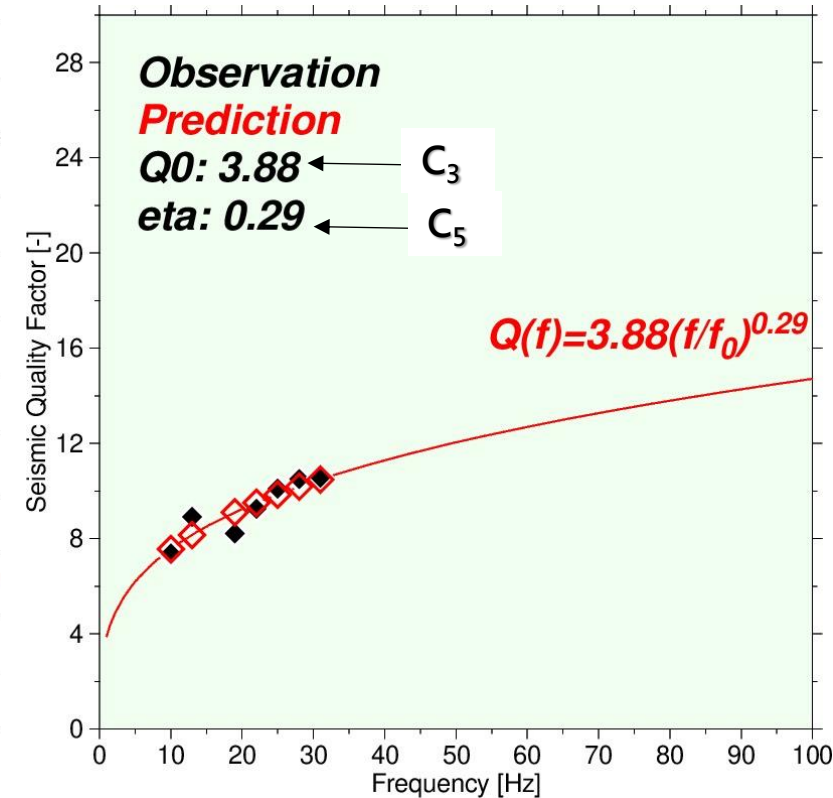
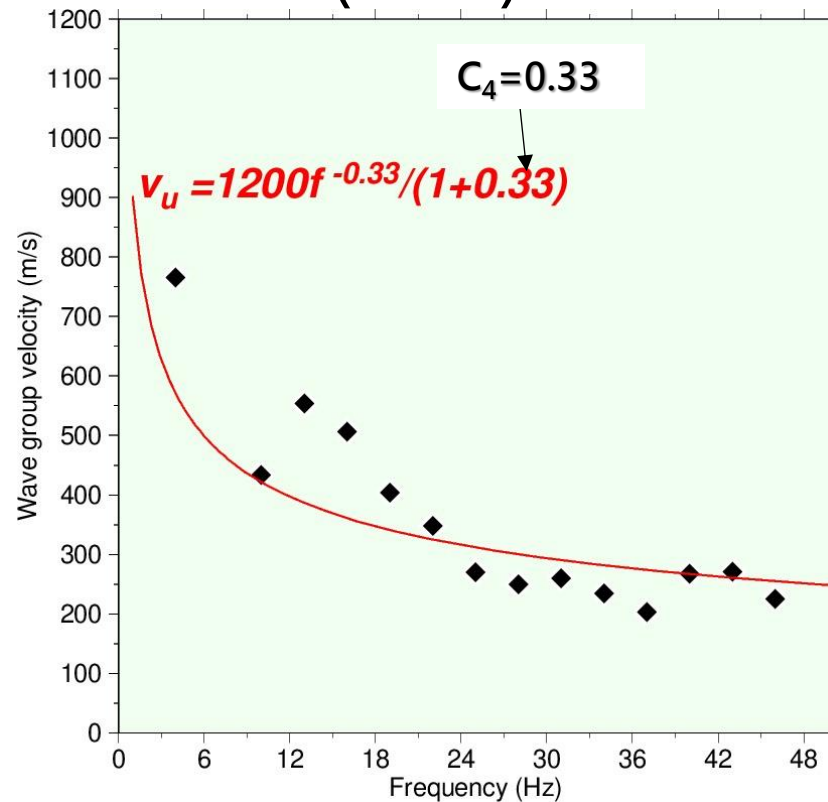
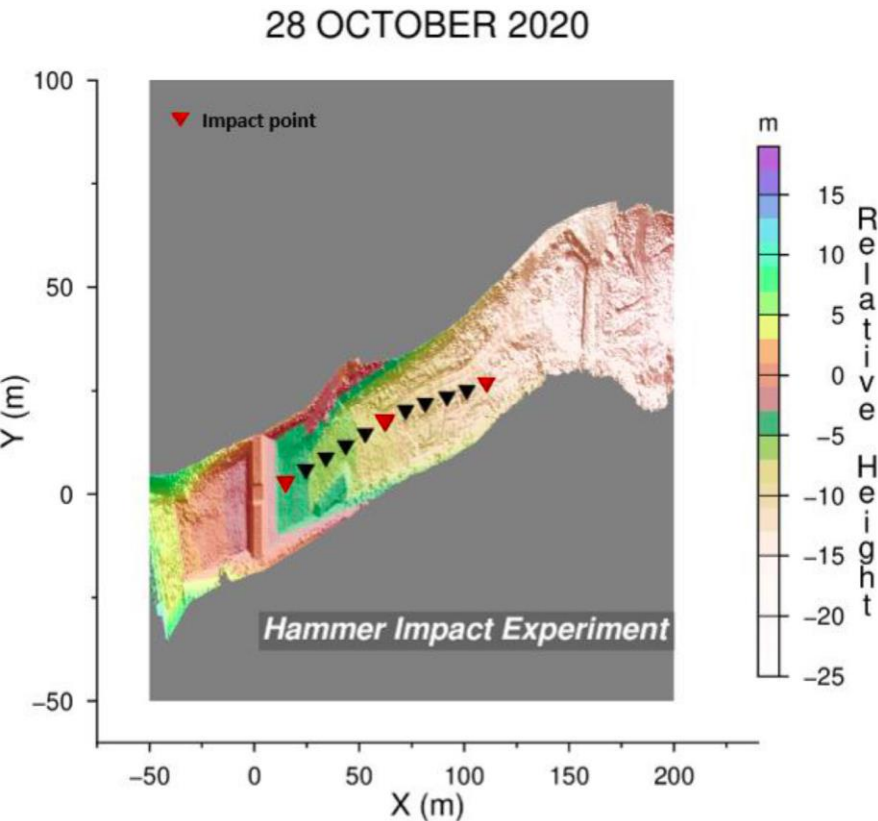
CHALLENGE

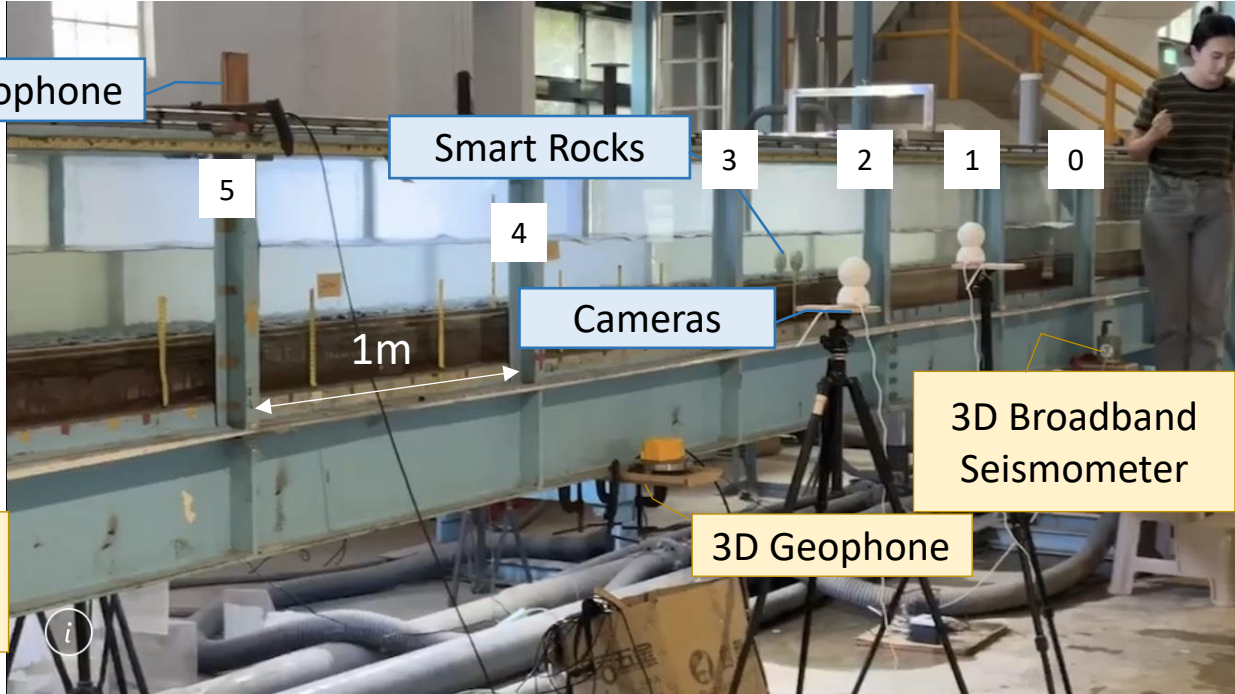
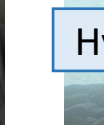
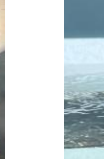
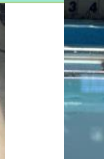
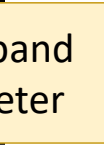
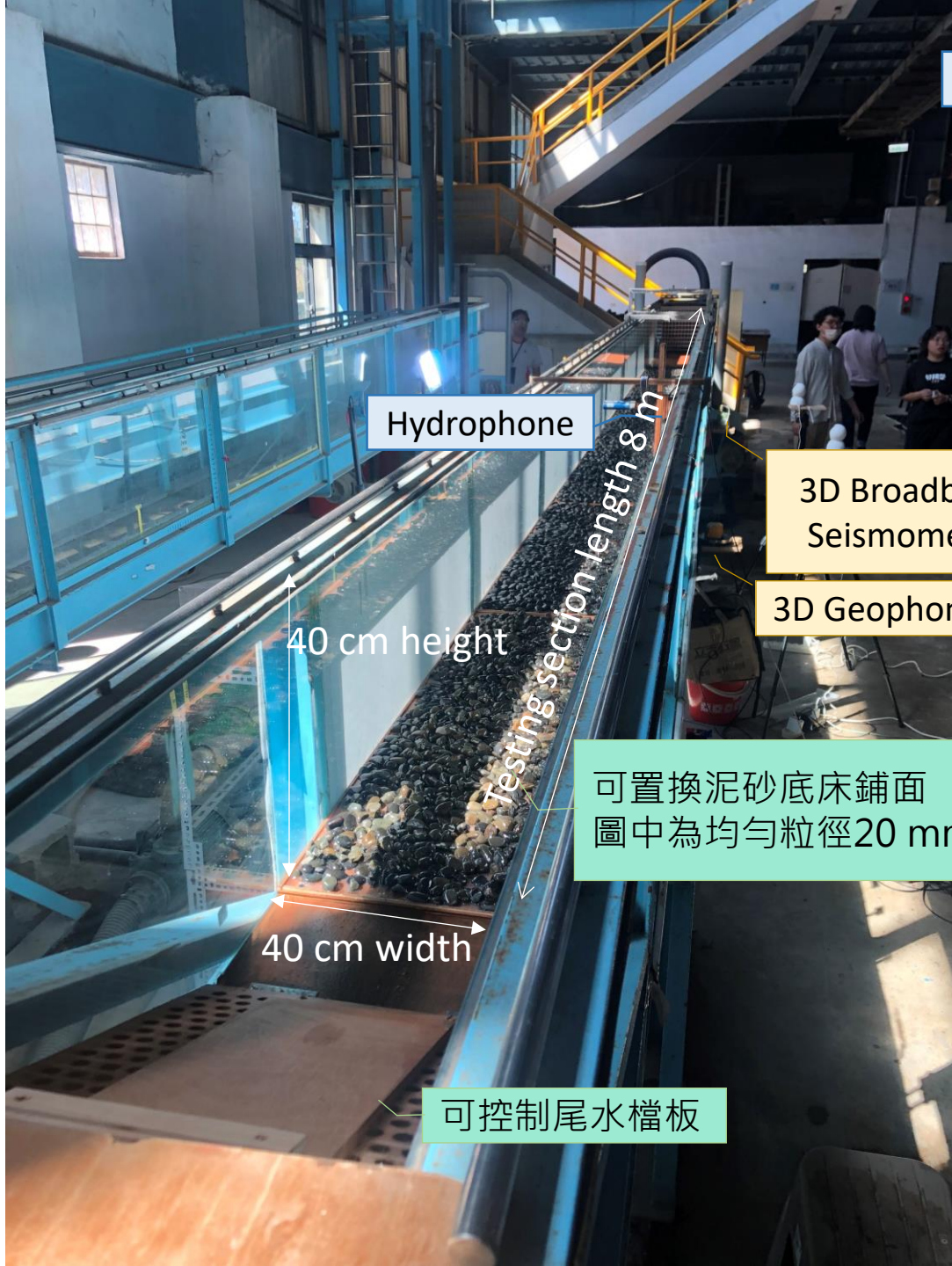
Seismic Parameters: $c(b)$, v_c , v_u , C_3 , C_4 , C_5

*Large uncertainties in estimation of bedload flux caused by indirect measurements of water depth, grain size distribution, suspended load and **seismic velocity model**.*

$$v_c = v_{c0} f^{-C_4}$$
$$v_u = v_c / (1 + C_4)$$

$$Q = Q_0 f^{C_5}$$



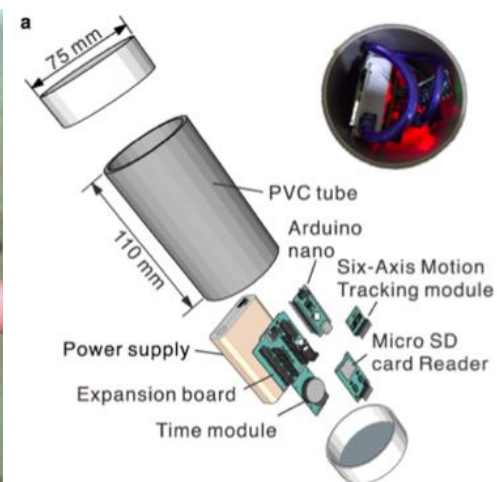
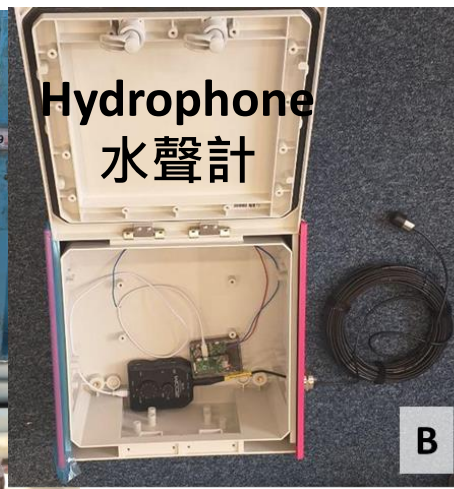
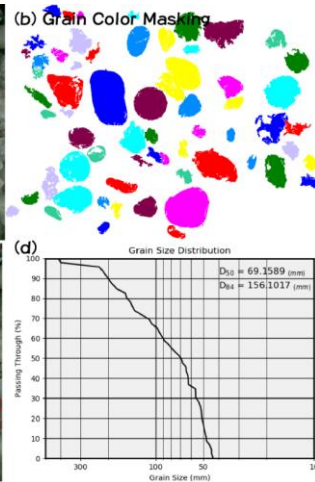
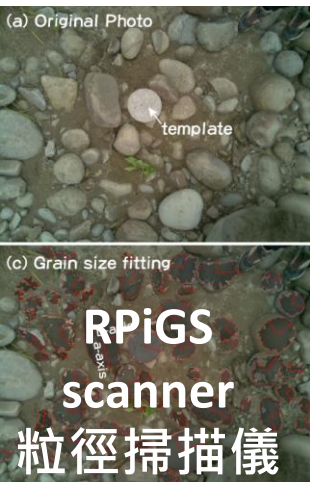


Flume experiment

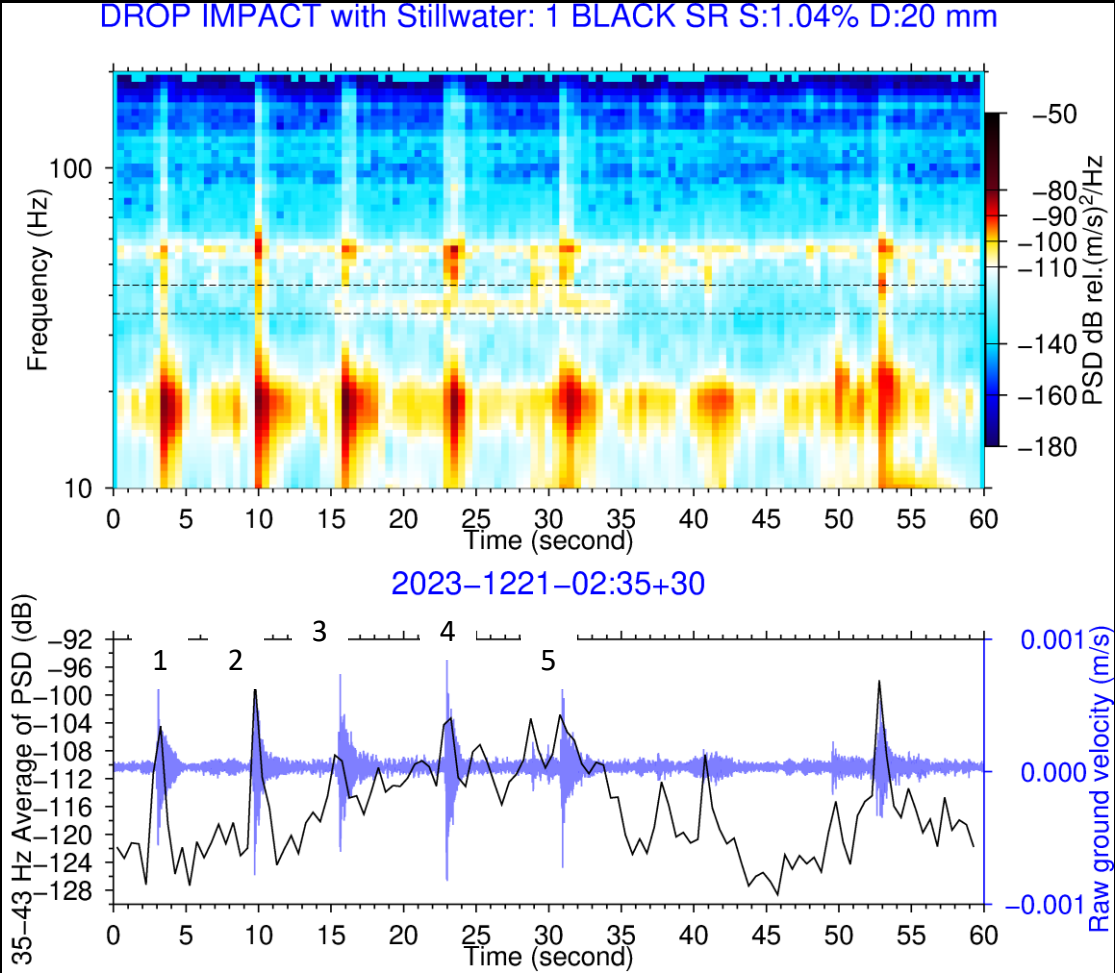
$$P(f, x, D; x_0) = \frac{|U(f, x, D; x_0)|^2}{T} = \frac{n_D(D)}{t_{hop}(D)} F^2(f, D, x_0) G^2(f, x; x_0)$$

Particle Kinematics: $\frac{n_D}{t_{hop}}, W_{inc}, C_1$

Seismic Parameters: $c(b), v_c, v_u, C_3, C_4, C_5$



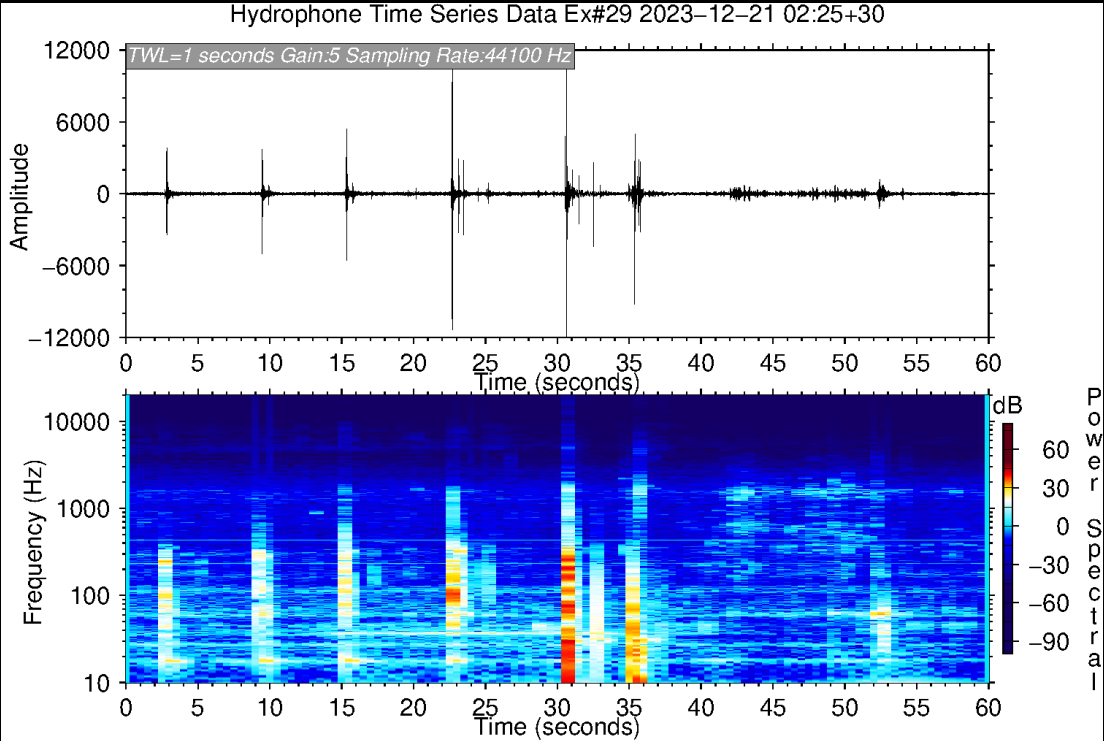
Smart Rock Drop Experiment



$$g = 1 + C_1 = 1 + \frac{W_{ref}^{drop}}{W_{inc}^{drop}}$$

Flume Green' s function, G_F

$$G_{Flume}(f) = \sqrt{TP(f) / F_{l,vertical}(f)^2}$$
$$F_{l,vertical} = gmW_{inc}^{drop}$$
$$W_{inc}^{drop} = \sqrt{2gz^{drop}}$$
$$z^{drop} = 40cm$$

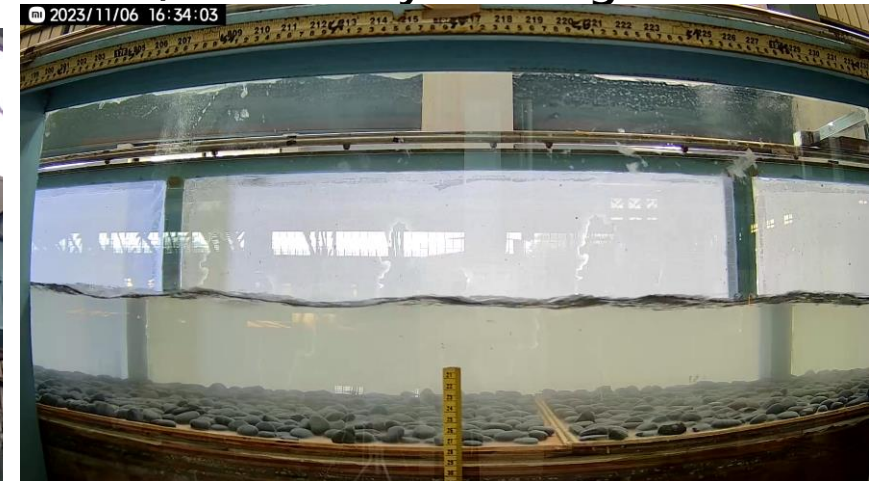


Flume experiment

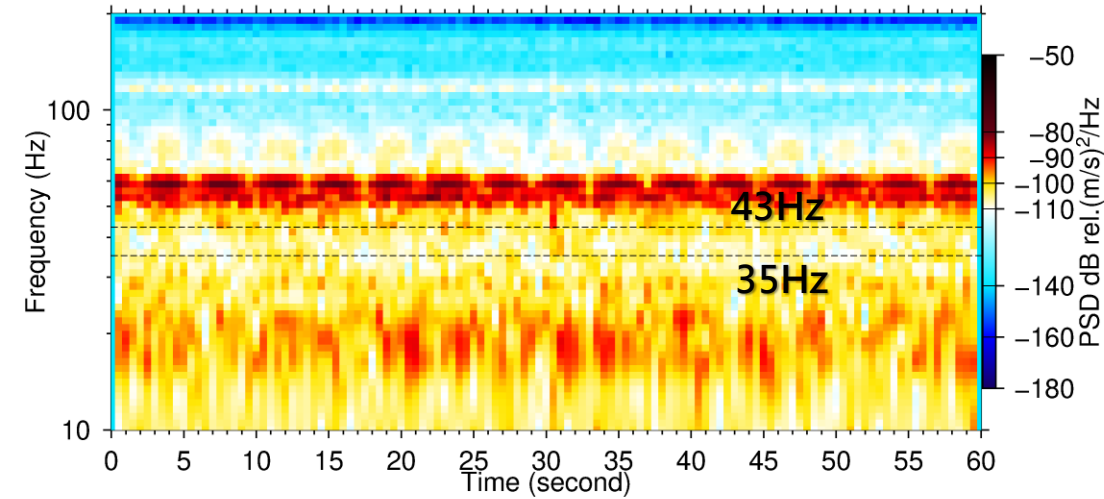
Particle Kinematics: $\frac{n_D}{t_{hop}}, W_{inc}, C_1$

The average downstream velocities of transported sediments, u_s

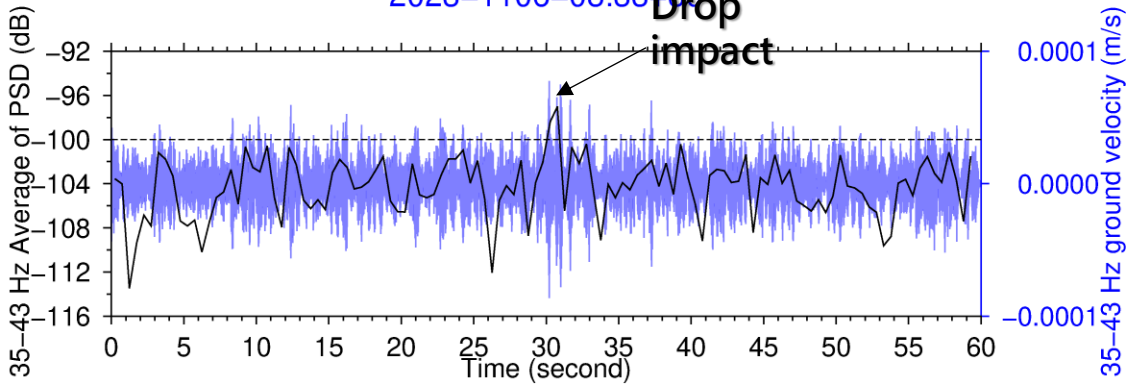
S: 1.16% (u, H) at x=1m : (0.69 m/s, 11cm), u at x=3m: 0.42 m/s, one black SR, SR density: 1.113 g/cm³



Base Station: DEMO 1 White SR S:1.04% D:20 mm

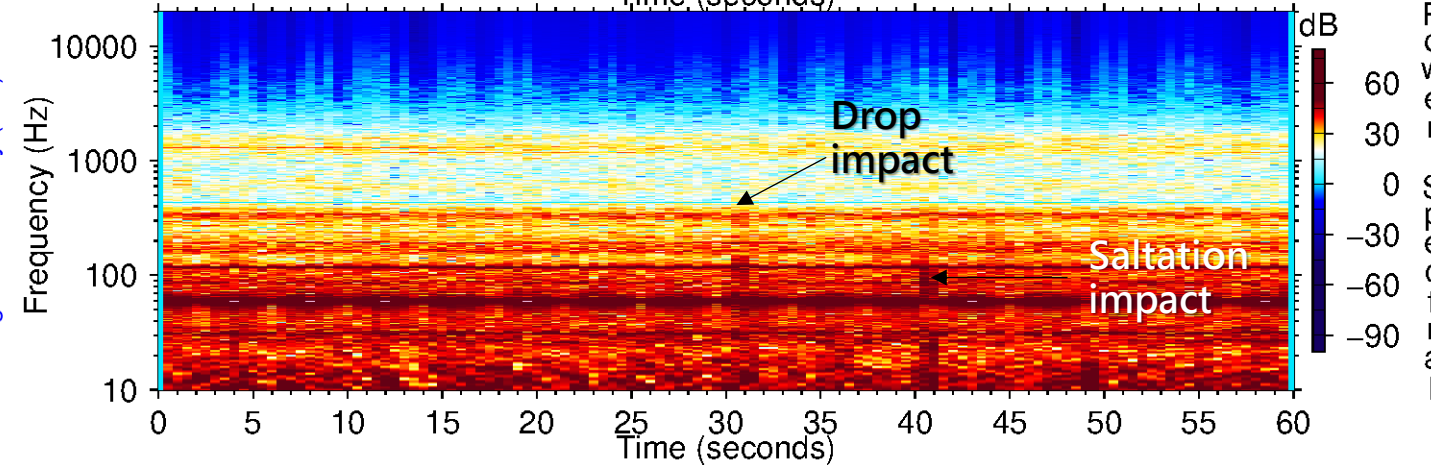
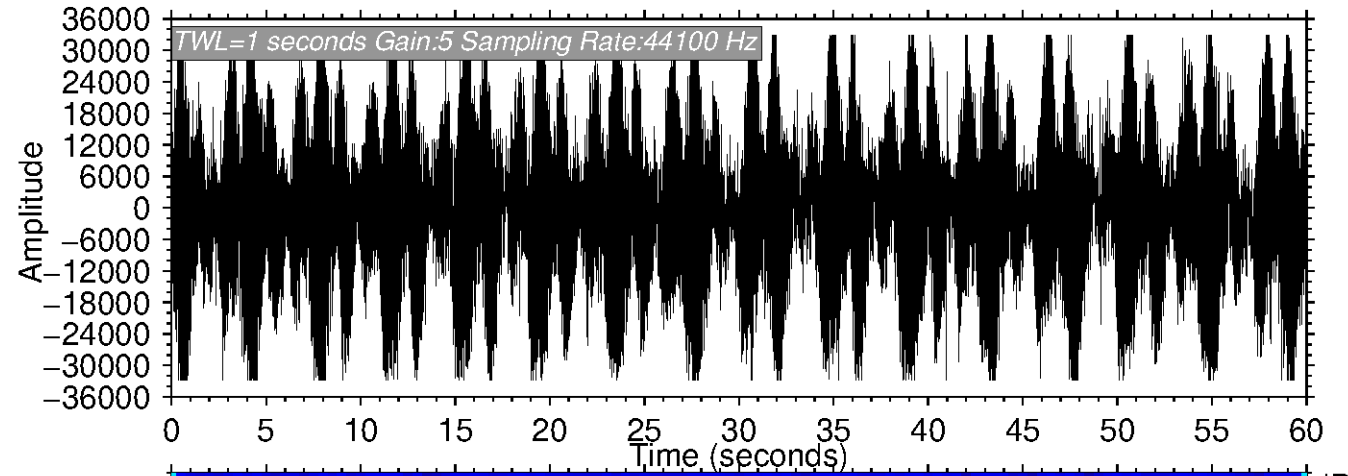


2023-11-06-08:33-30



Geophone

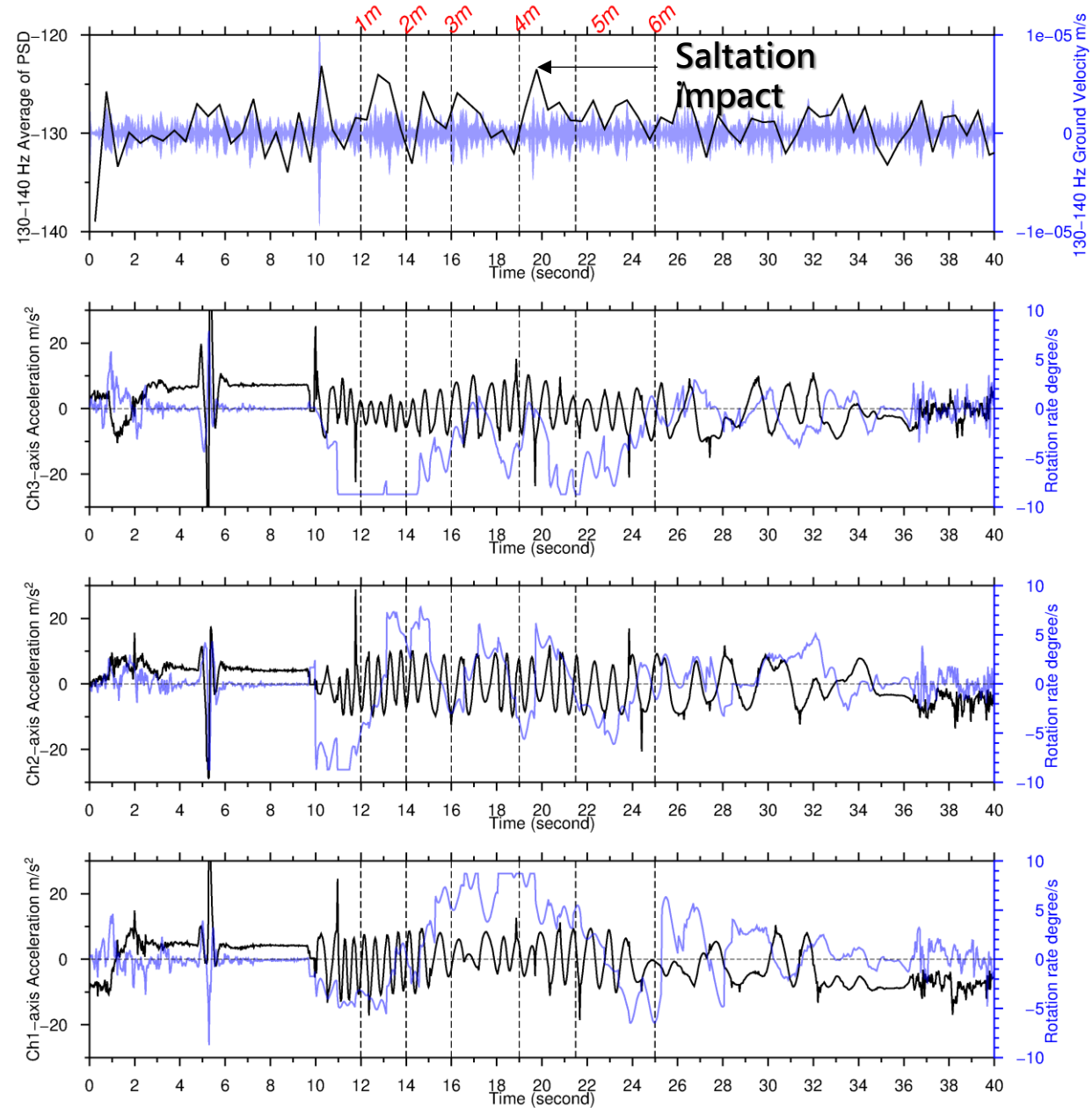
Hydrophone Time Series Data Ex#6 2023-11-06 08:33+30



Hydrophone

Impact velocity normal to bed roughness, v_l

2023-11-06-16-33-50 Experiment#6 1 Black SR



Particle Kinematics:

$$\frac{n_D}{t_{hop}}, W_{inc}, C_1$$

Acceleration of smart rock (SR)

$$a(t) = \sqrt{\sum_{j=1}^3 \dot{a}_j(t)^2}$$

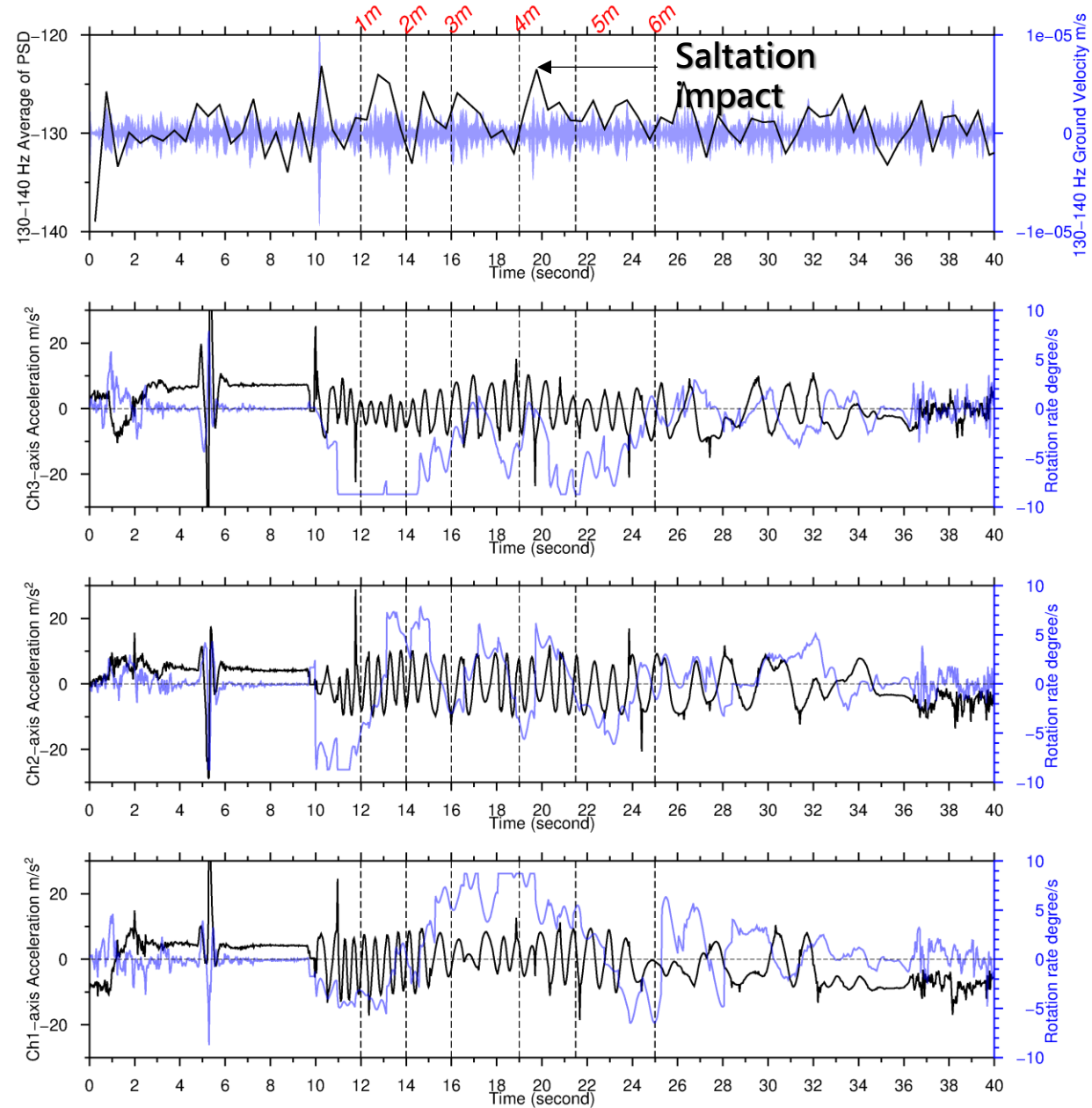
Pick up the impact-induced spike, and then do integration

$$g = 1 + C_1 = 1 + \frac{v_r}{v_l}$$
$$\triangleright g v_l = v_l + v_r = dv$$
$$\triangleright v_l = dv / g$$

$$dv = \int_{t_1}^{t_2} a(t) dt$$

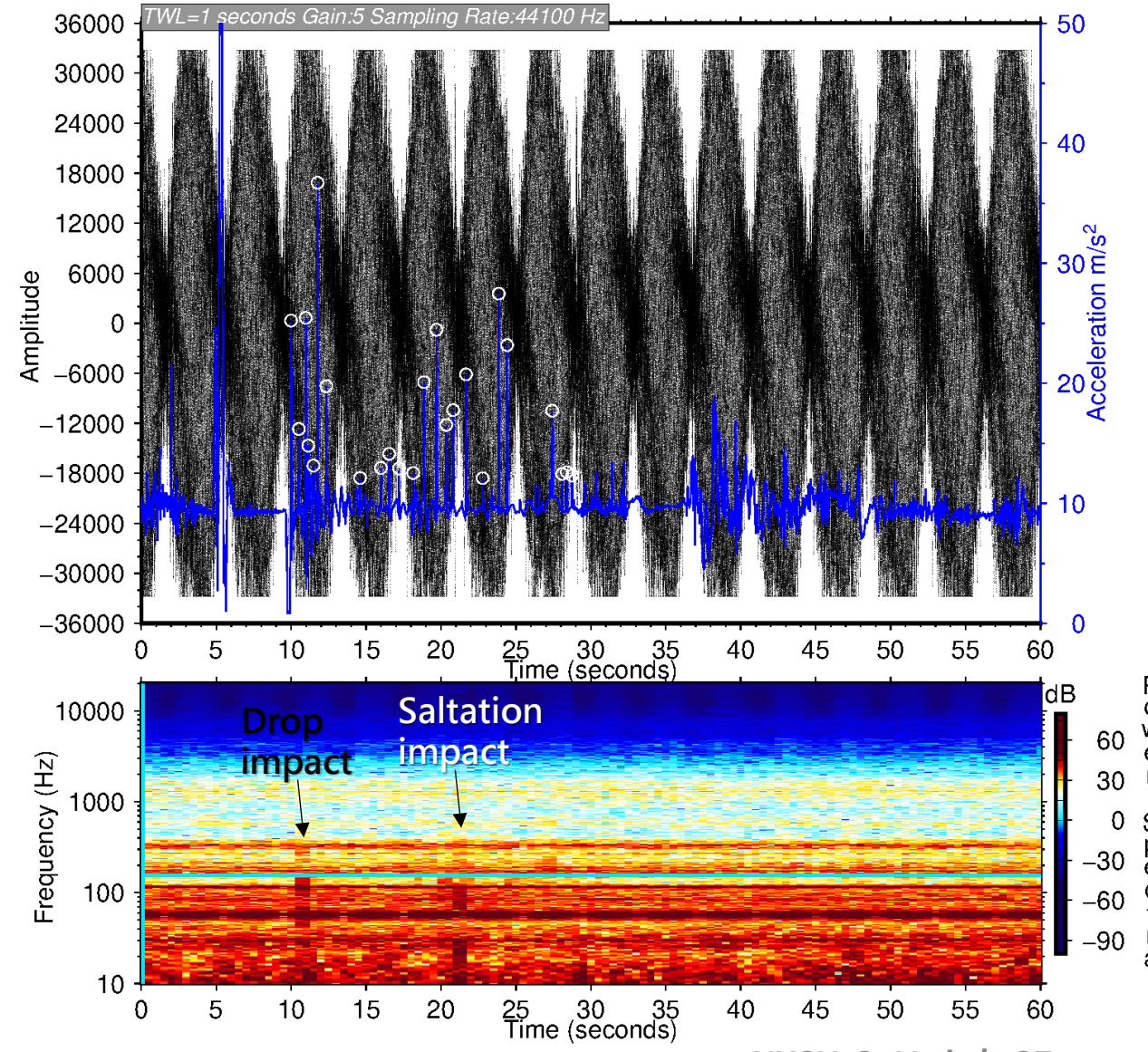
Hydrophone audio and spectrogram (black SR)

2023-11-06-16-33-50 Experiment#6 1 Black SR



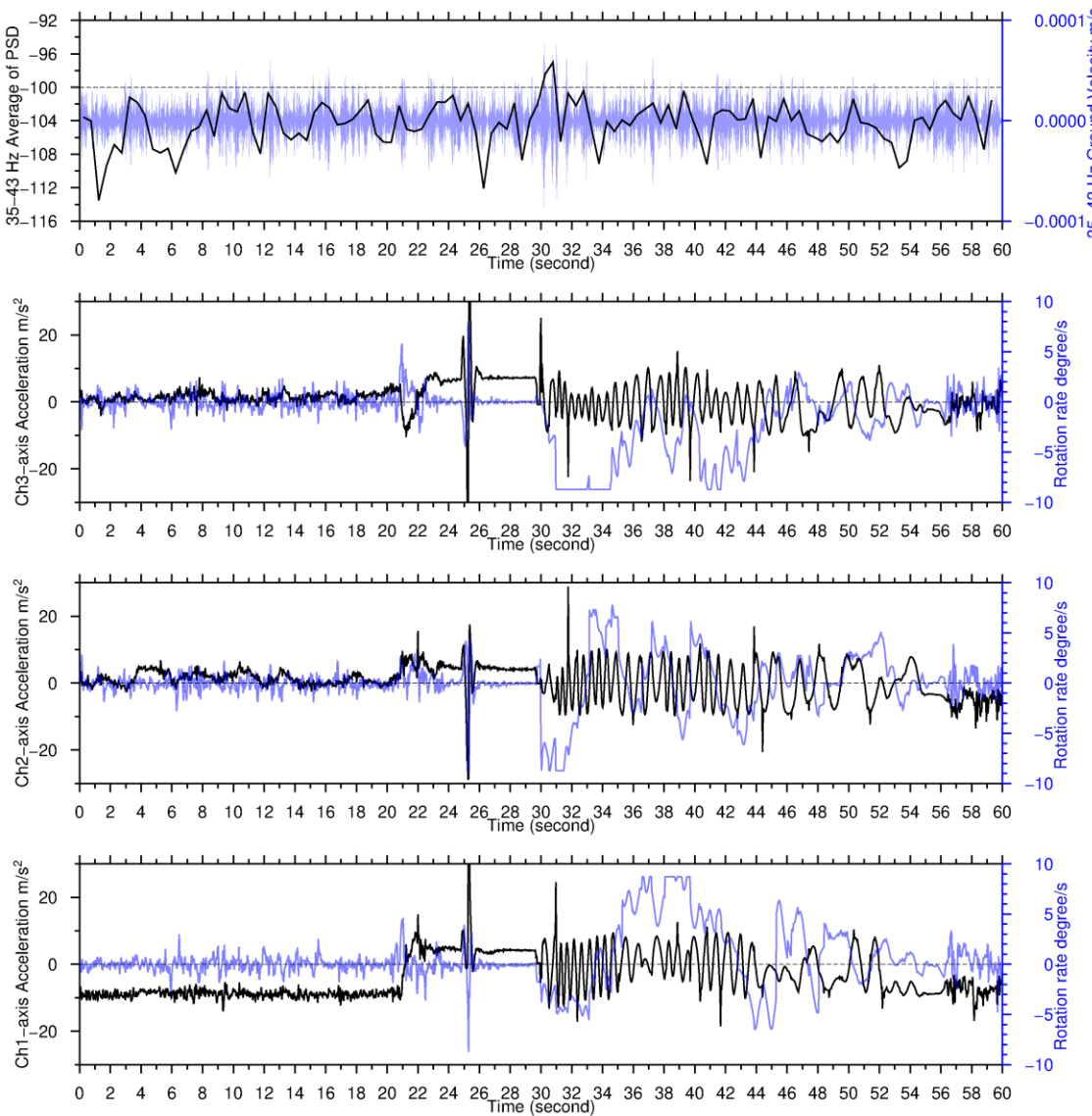
Impact number=24 (assumption $a > 12 \text{ m/s}^2$)

Hydrophone amplitude time series Experiment#6 2023-11-06 16:34

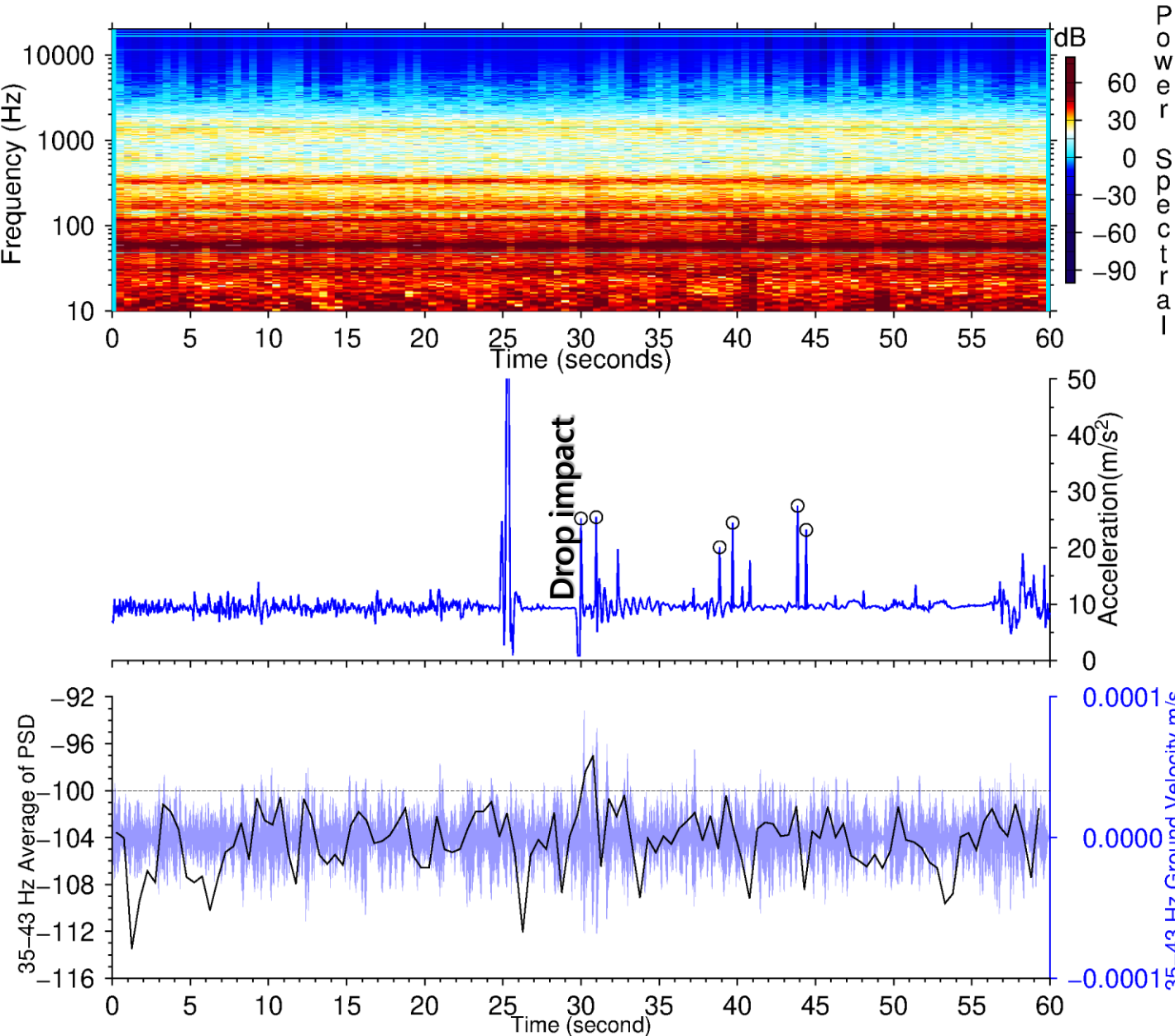


(white SR)

2023-12-20-05-28-30 Experiment#23 1 White SR



Hydrophone spectrogram Experiment#6 2023-11-06 08:33+30



Based on the observation PSD, the respective numbers of transported grains can be inverted as

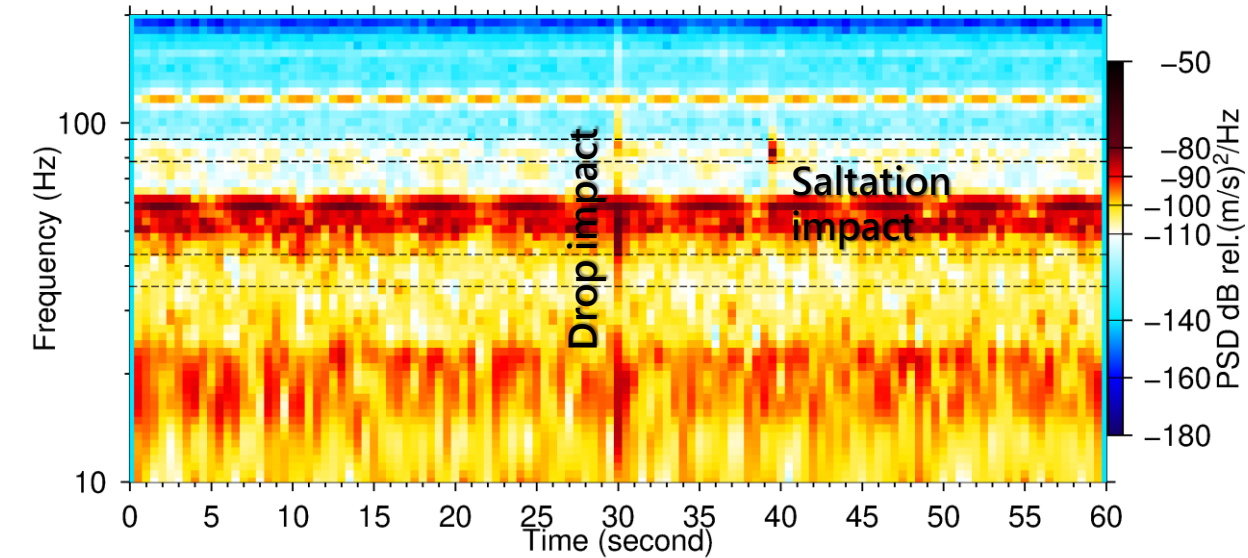
$$N_{SR}^{inv} = \frac{P^{obs}(f) \bar{t}_l}{[g_s V_{SR} \bar{v}_l]^2 \bar{G}_{Flume, vertical}^2}$$

Inverted grains numbers can finally be converted into an inverted **sediment flux**:

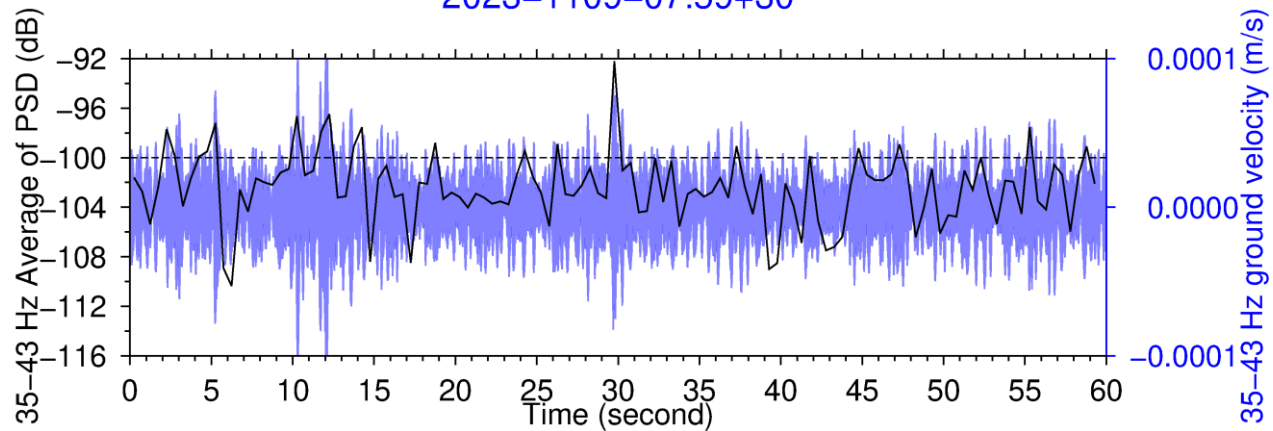
$$q_{b,SR}^{inv} = N_{SR}^{inv} \frac{u_s V_{SR}}{WL}$$

Flume experiment (Saltation, six SR)

Base Station: DEMO 6 BLACK SR S:1.04% D:20 mm

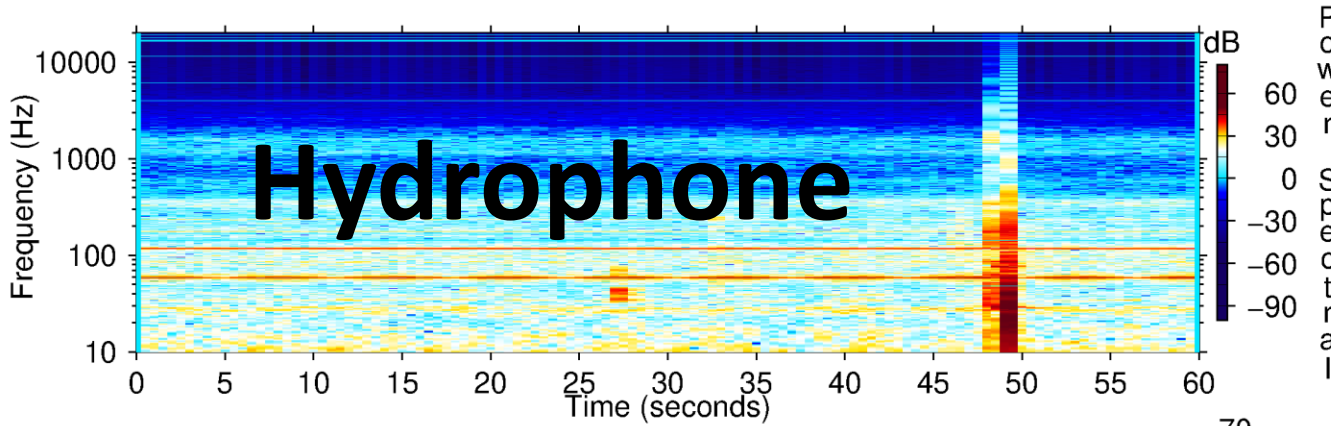


2023-1109-07:59+30

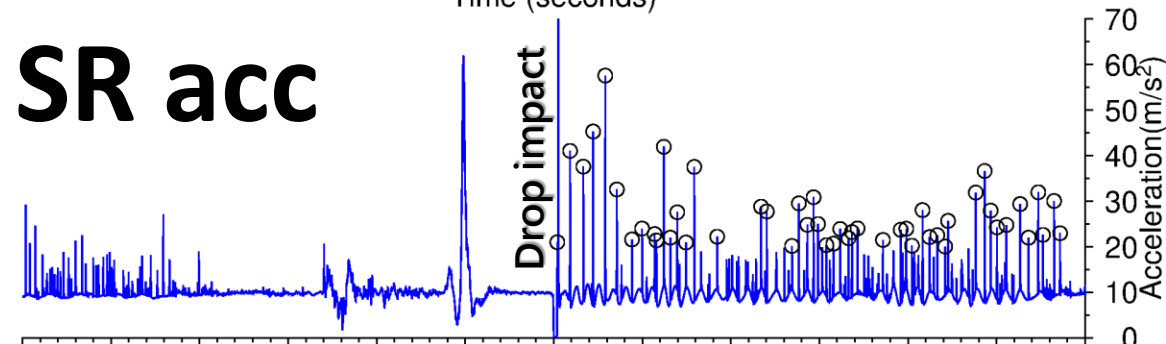


Flume experiment (Rolling)

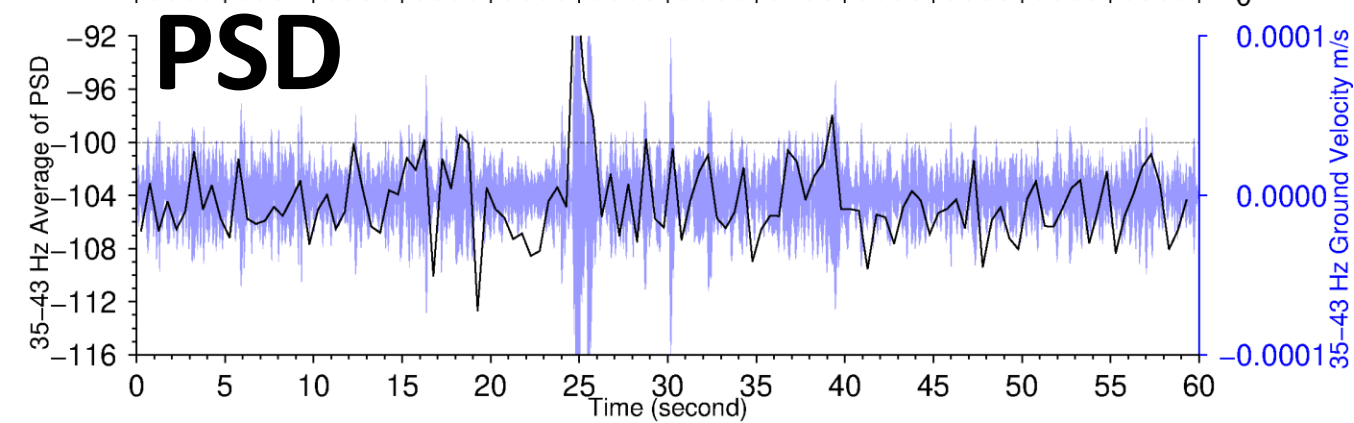
Hydrophone spectrogram Experiment#23 2023-12-20 05:31+30



SR acc



PSD



An aerial photograph showing a large-scale experimental setup in a field. A long, narrow, light blue channel, likely a flume, runs diagonally across the frame. The channel is bordered by dark, possibly black, material. The surrounding ground is a mix of brown soil and green grass. Several small white markers or flags are visible along the edges of the channel. In the bottom left corner, a few people are standing on a dirt path, providing a sense of scale to the large experiment.

Field-scale flume experiment

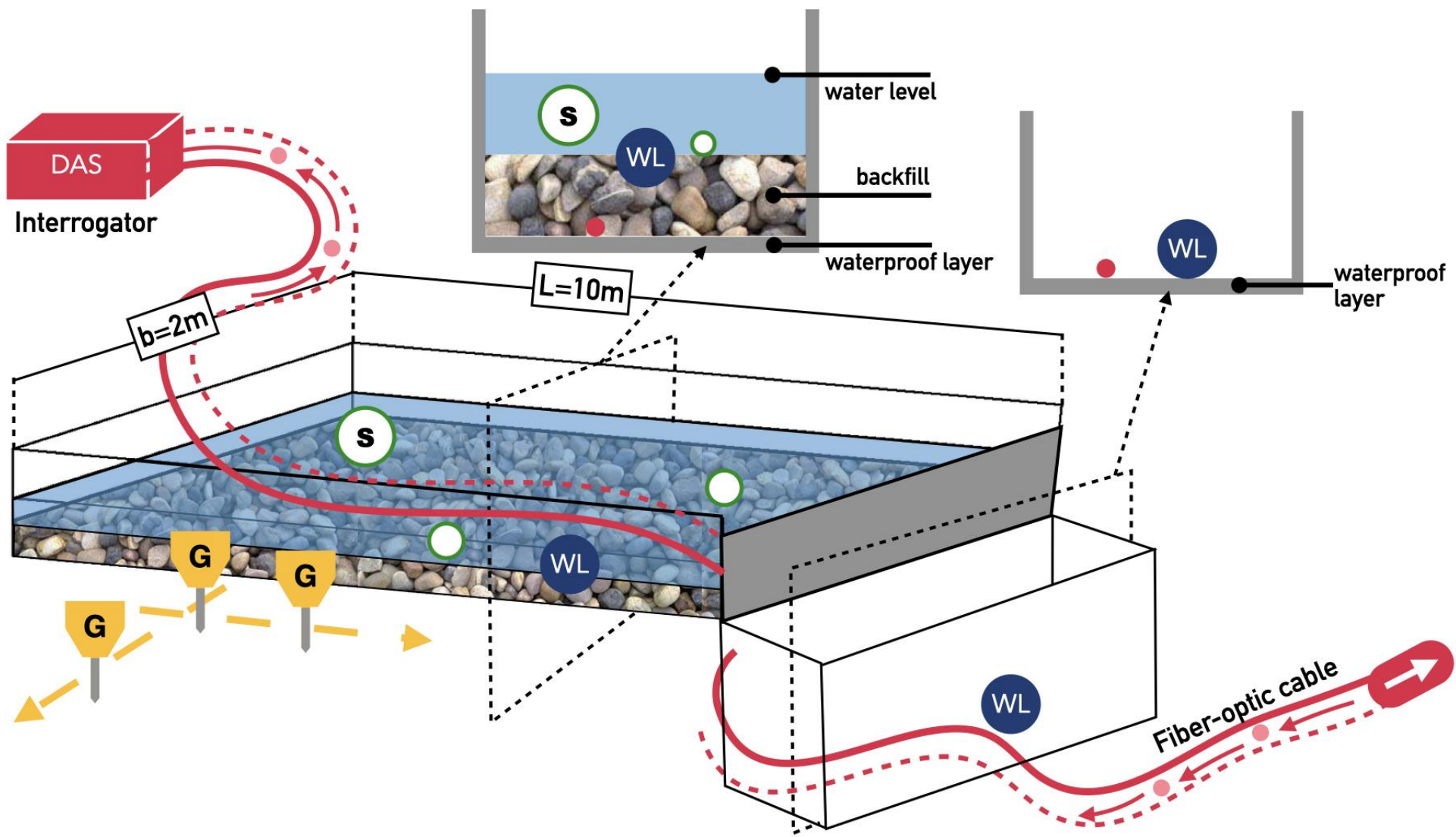
October 20, 2024

Nodal Seismic Array:
Geophone
(PE-6/B & SmartSolos)
Silixa iDASv2

Hydro-instrument
HOBO-Onset U20 Water
Gauge
Hydrophone H2a-XLR-
0+Zoom U22 amplifier

**Sediment
measurements/Investig-
ation:**
USFS Bedload Sampler
Particle tracer
Auto Sediment Supply
Grain-size distribution

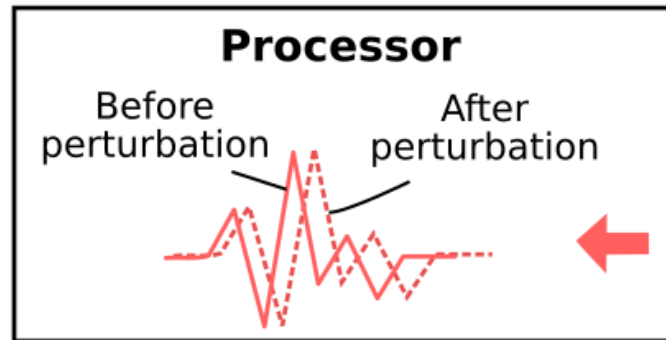
Image and Camera
UAV Survey
Digital Camera



FLUVIAL DAS

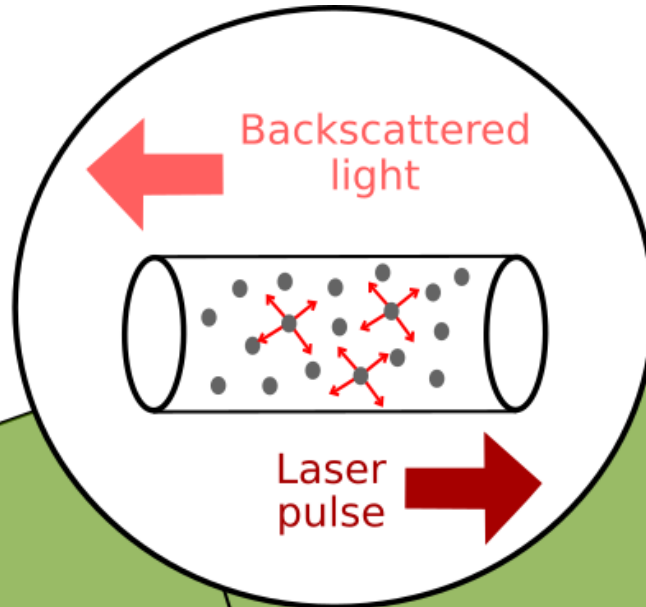
High temporal and spatial resolution in measuring strain rate in riverbed

Mass flow rate?
Flow dynamics?

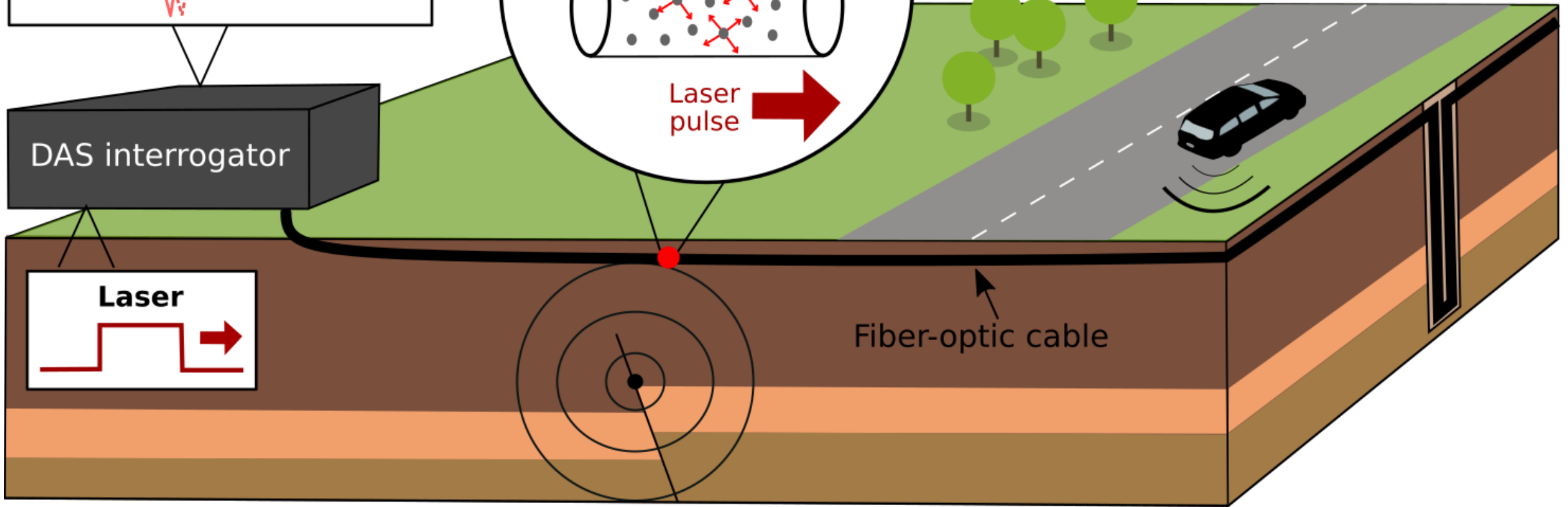


DAS interrogator

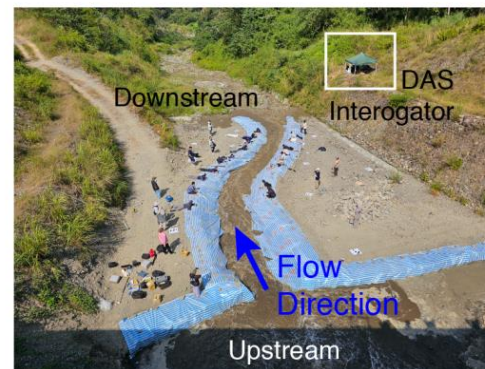
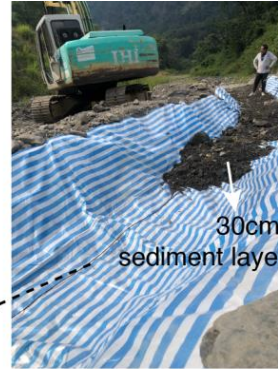
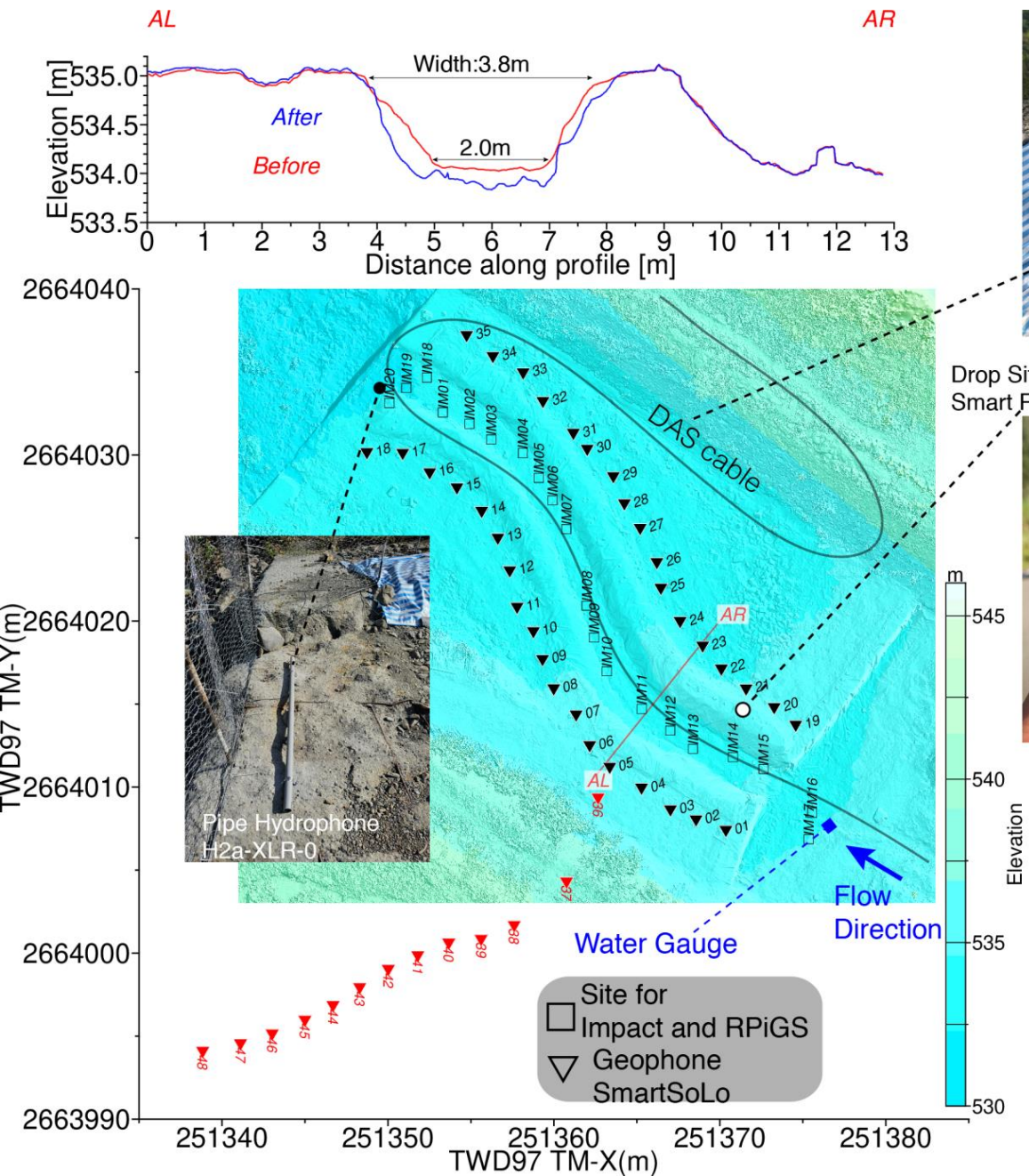
Laser



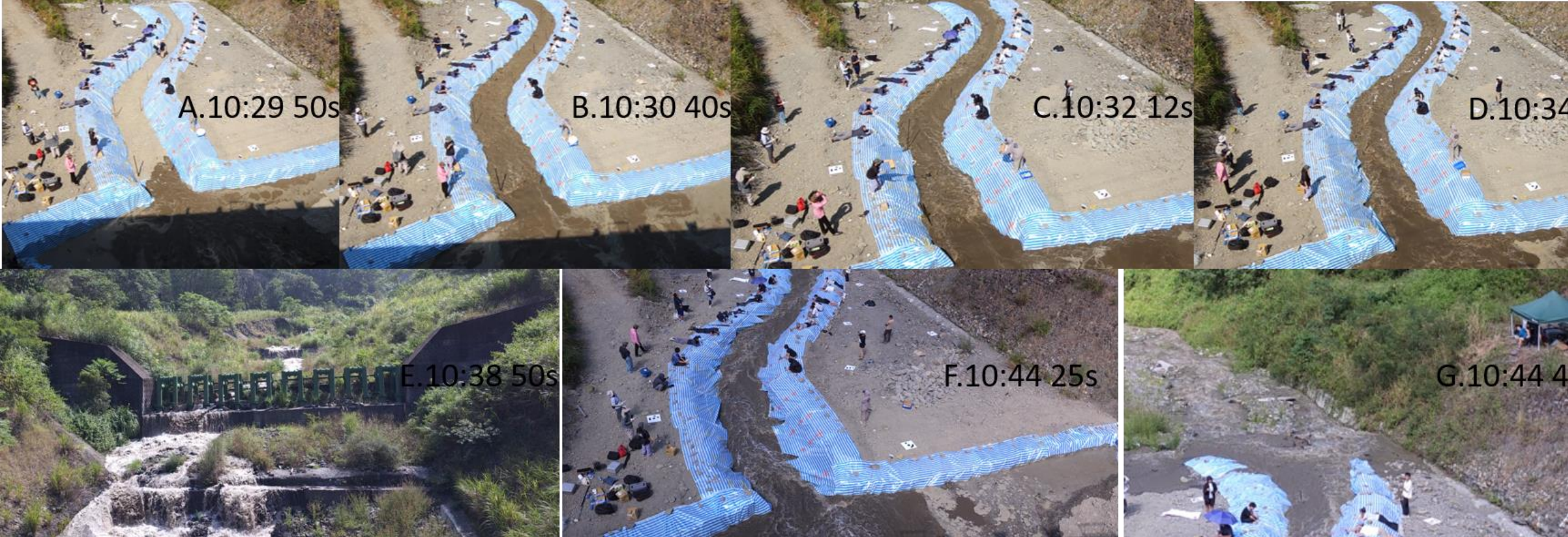
Fiber-optic cable



Field Experiment Setting

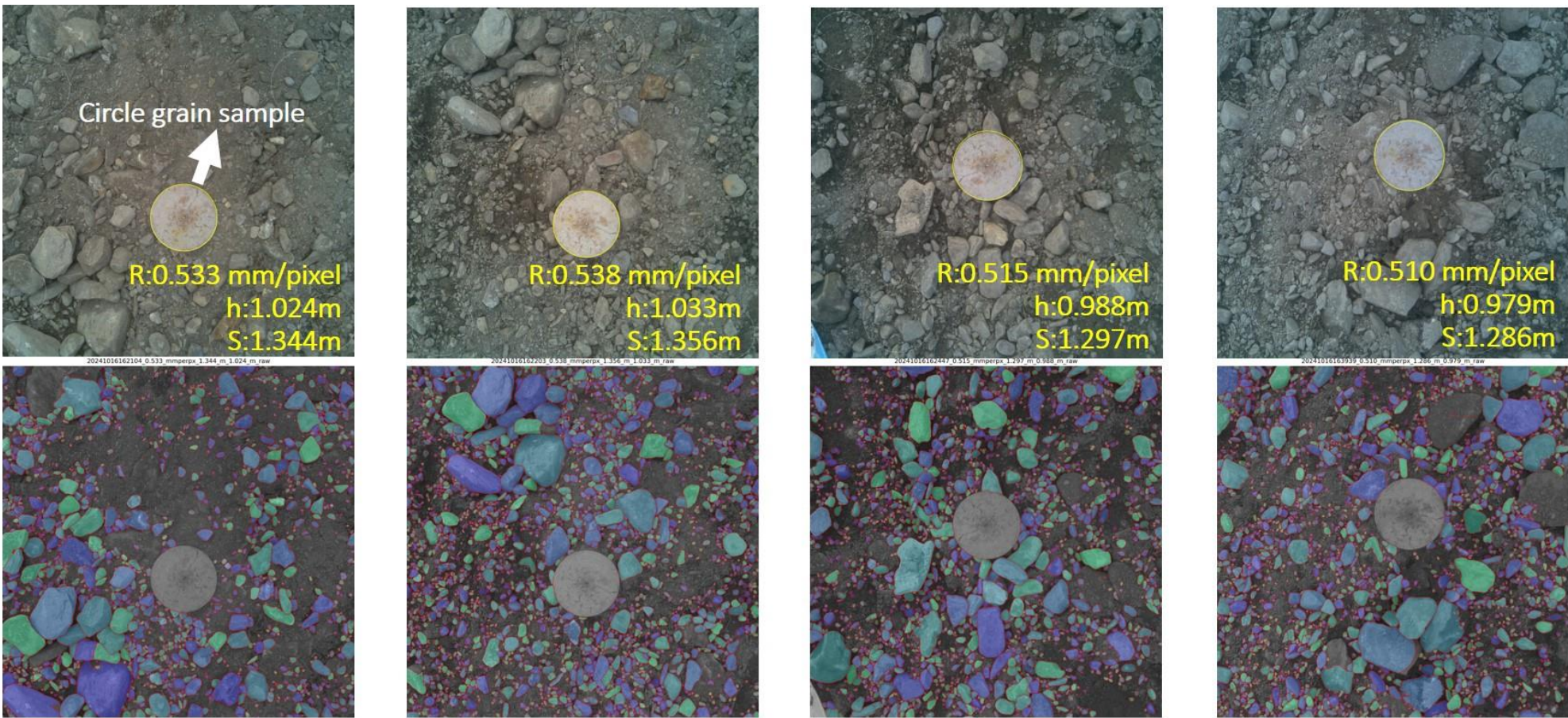


Channel Length **30 m**
 Channel slope **4°**
 Trapezoid shape cross-section:
2 m in bottom, **3.8 m** top width,
 depth **1 m**
 Flow cross-section area ~ **2.9 m²**

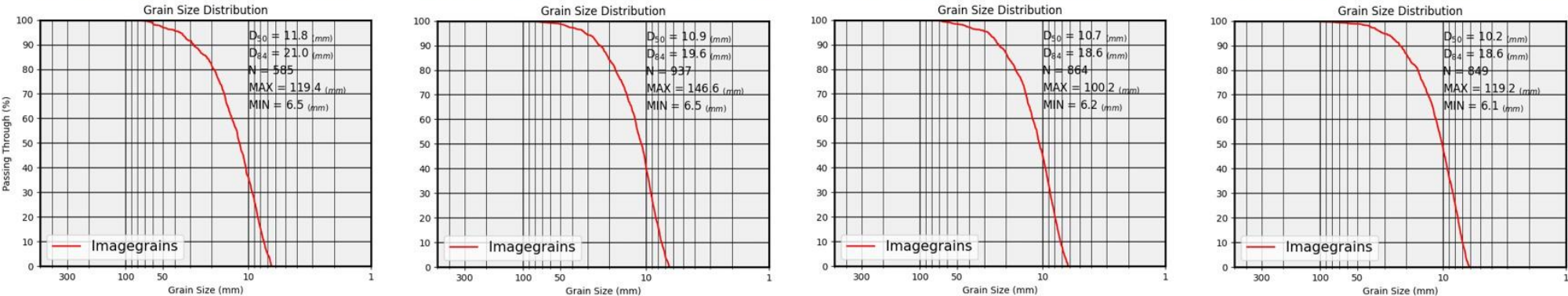


Time-lapse photos:

Grain size distribution before experiment



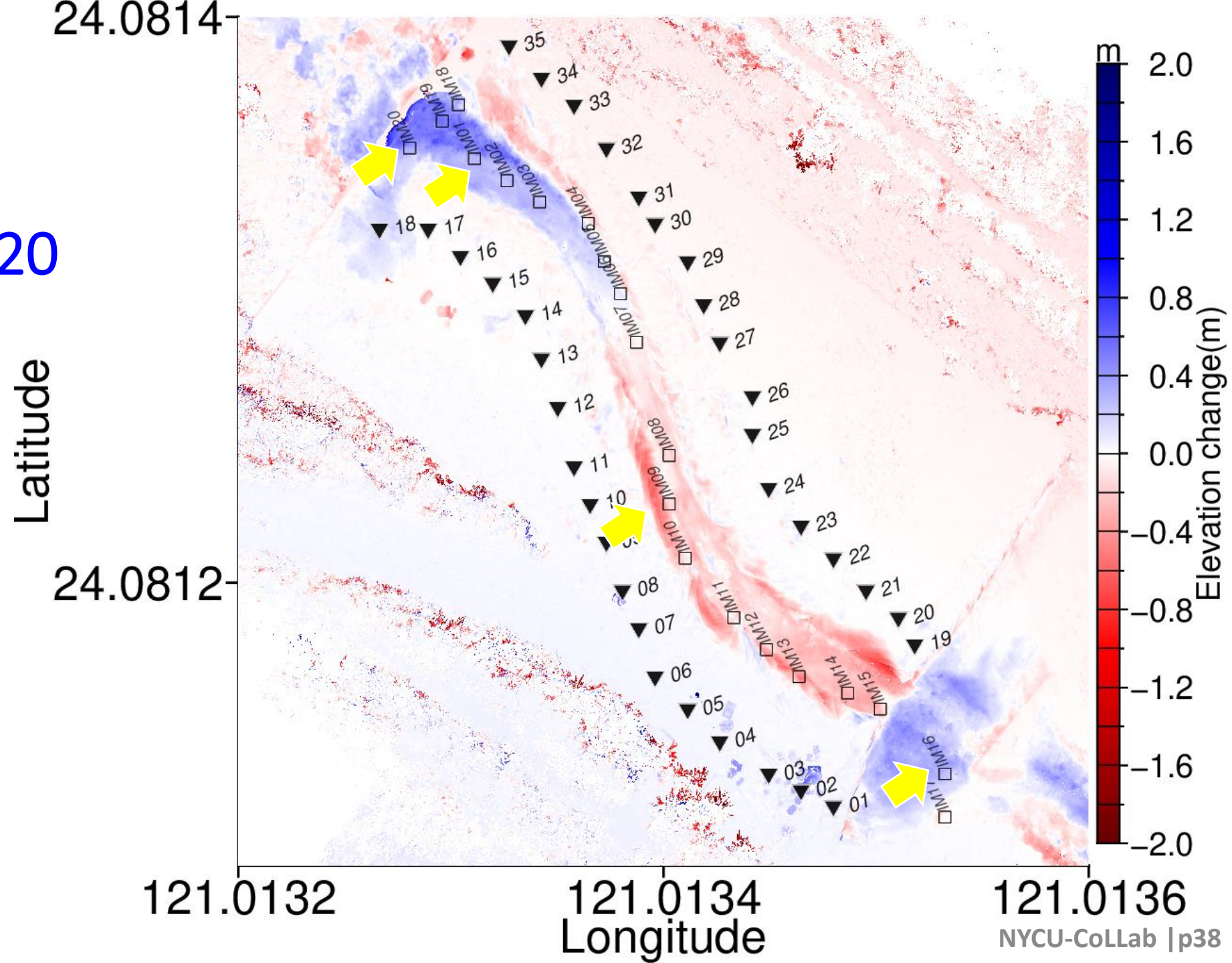
D50= 10mm~12mm



DOD analysis

Deposit sites:
IM01, IM16, IM20

Erosion site:
IM09



Grain size distribution after experiment

D50:

15.6mm(CI95%, [15. 16.4])

16.4mm([15.3 17.8])

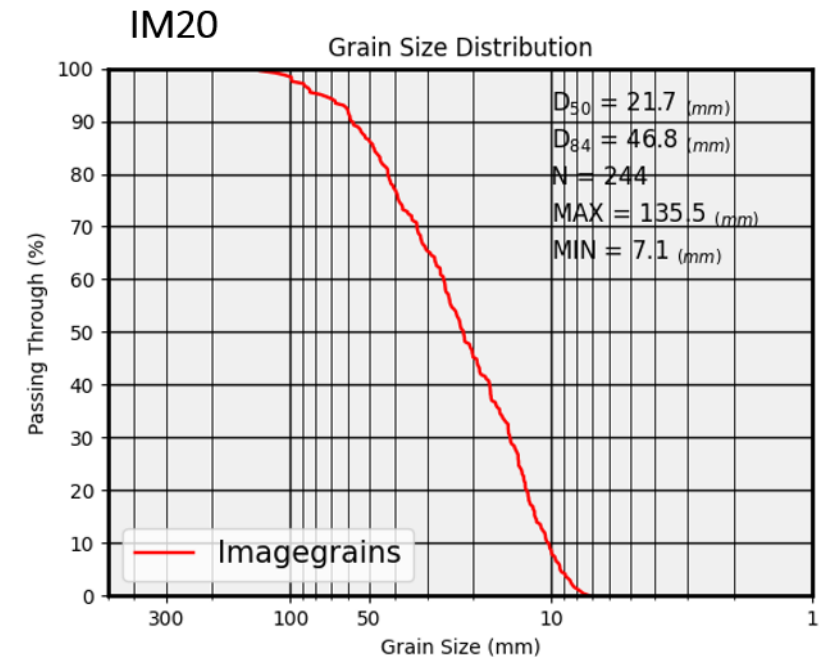
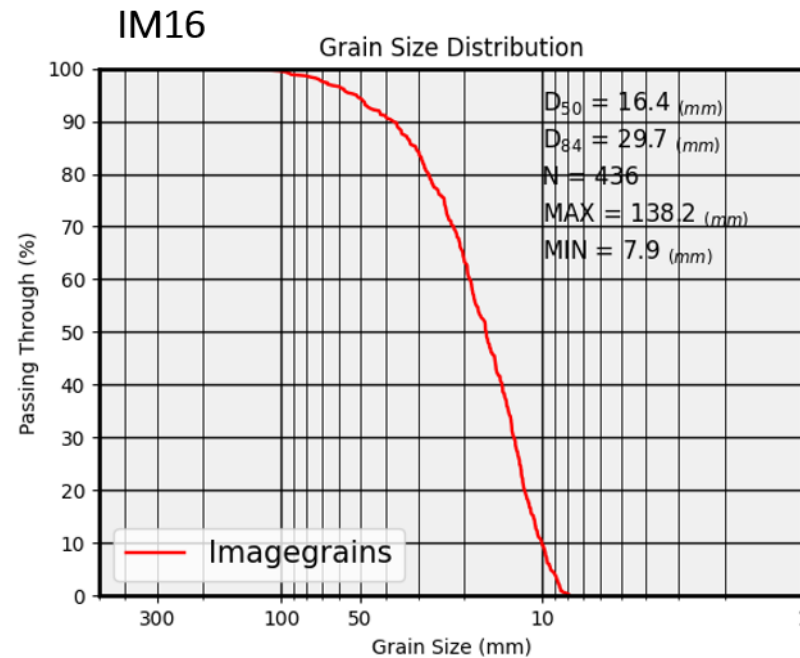
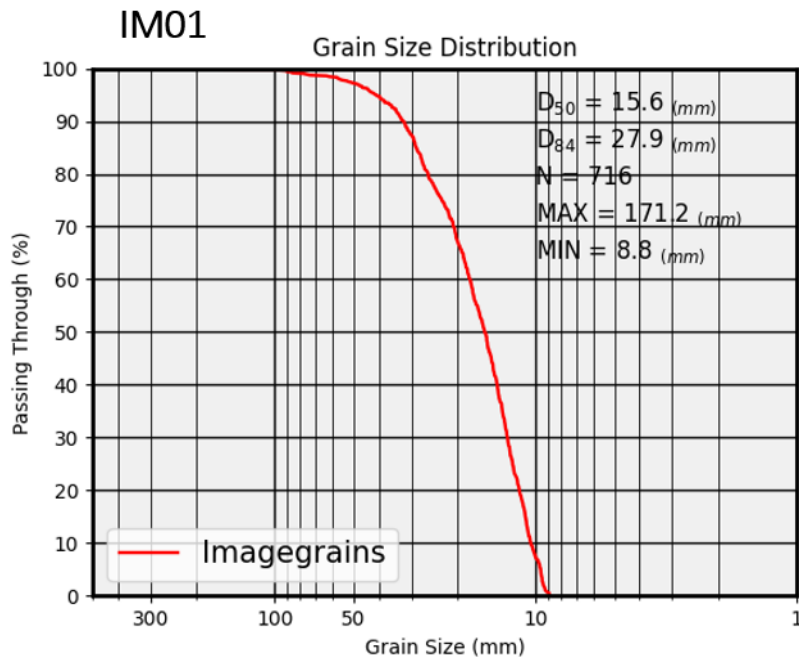
21.7mm([19.2 24.5])

D84:

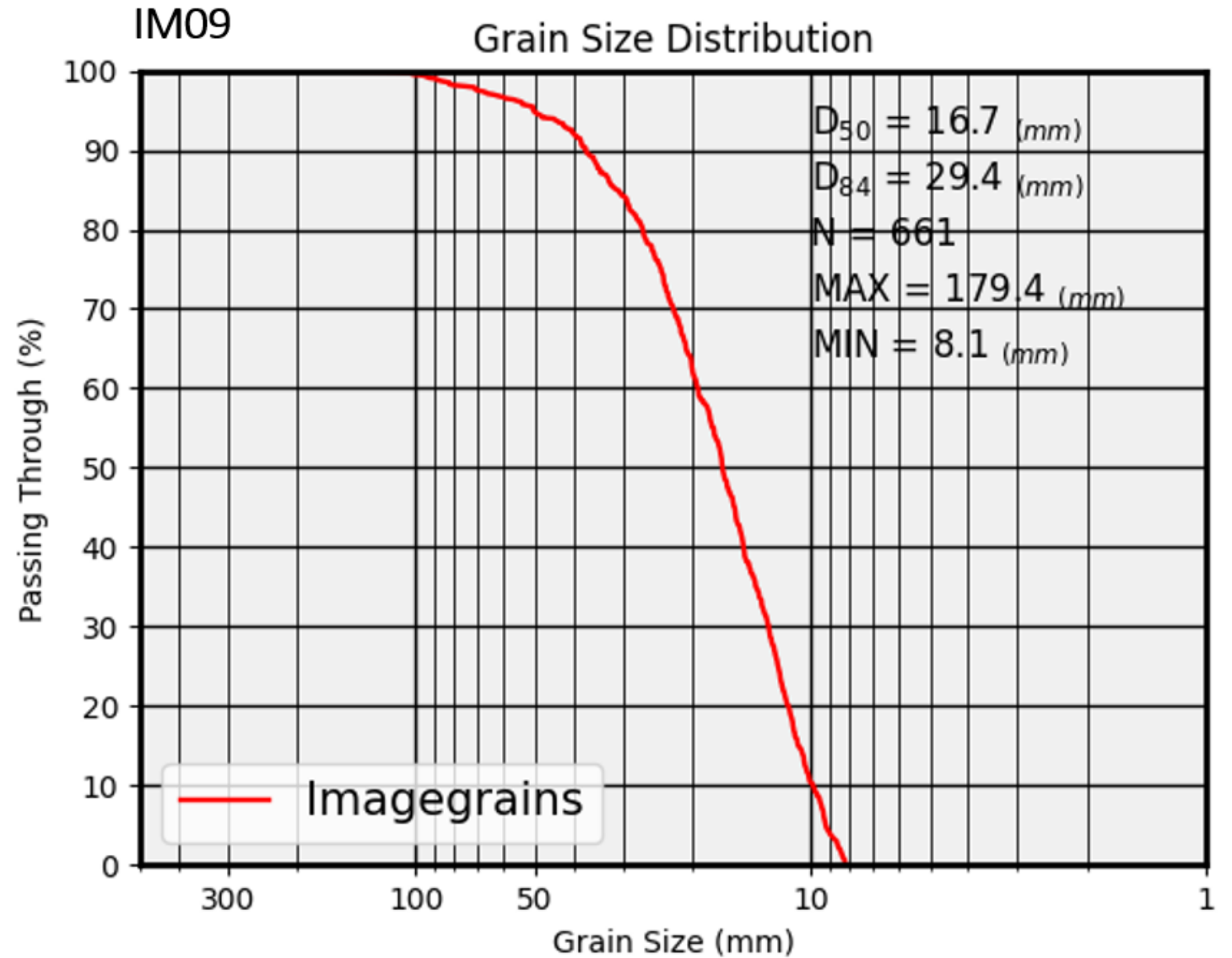
27.9mm(CI95%, [26.7 29.3])

29.7mm([28. 33.3])

46.8mm([41.8 53.7])



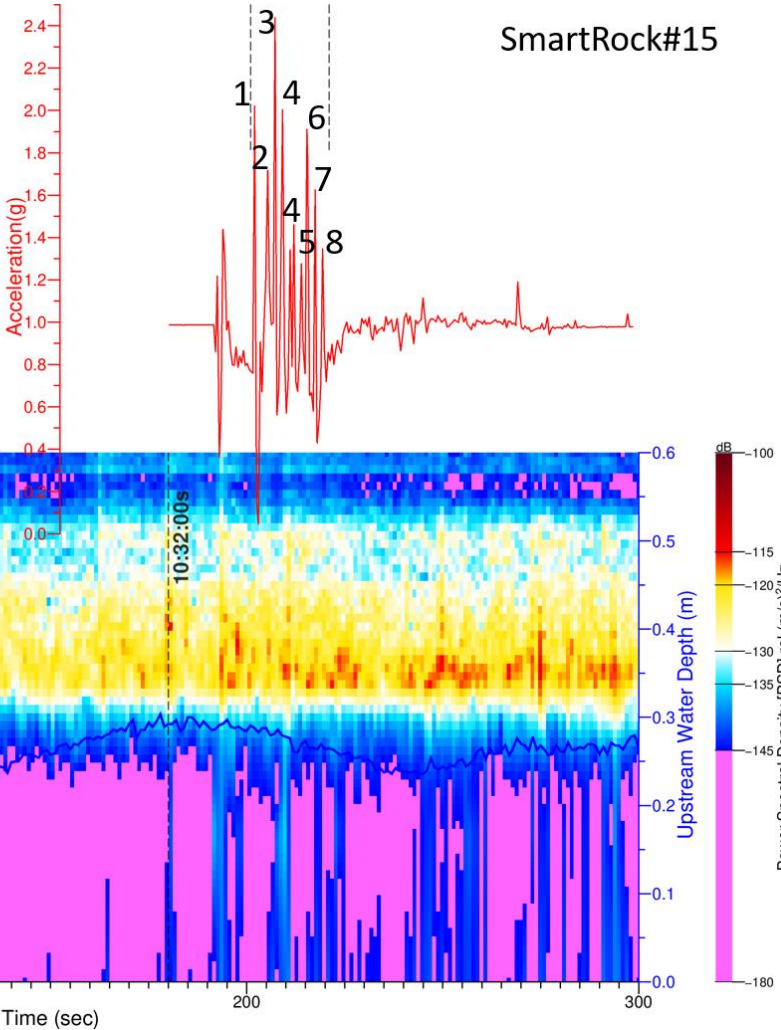
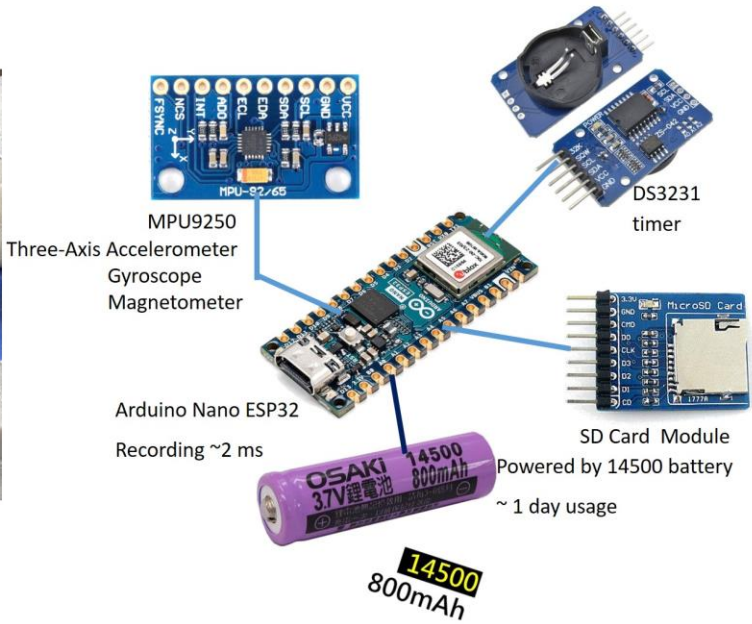
Grain size distribution after experiment



D50:16.7mm([15.8 17.3])

D84:29.4mm([27.5 32.7])

Smart Rock(智能球)

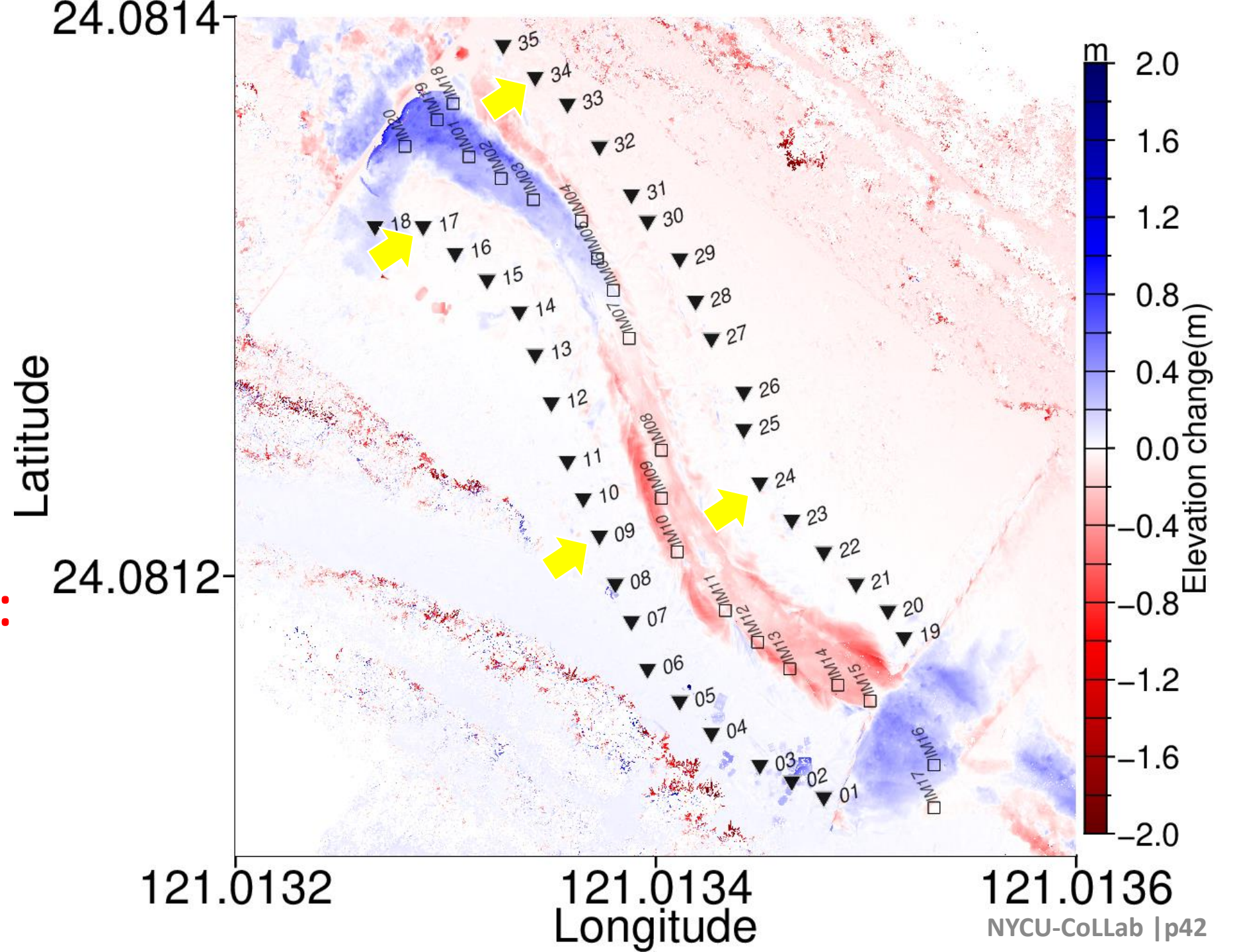


智能球編號15的加速度數據之三軸平方和開根號之加速度值如圖所示，最大加速度值為2.44g(1g=9.81m/s²)，顆粒總躍移時間約為20秒(如圖中之灰色垂直虛線區間)，該時間內發生撞擊次數為8次，顆粒主要運移的渠道長度約為30m，平均顆粒的躍移速度約為1.5m/s。

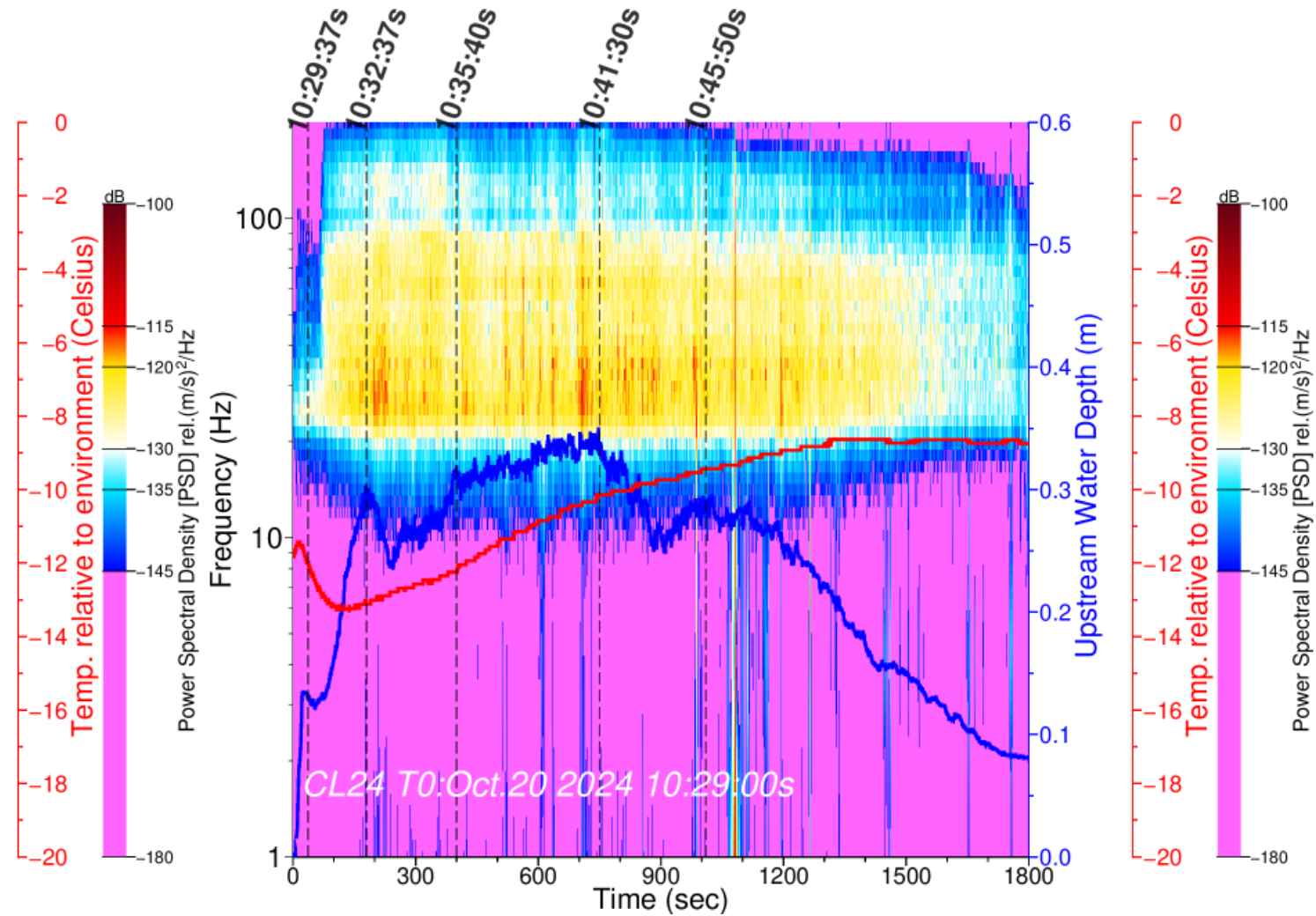
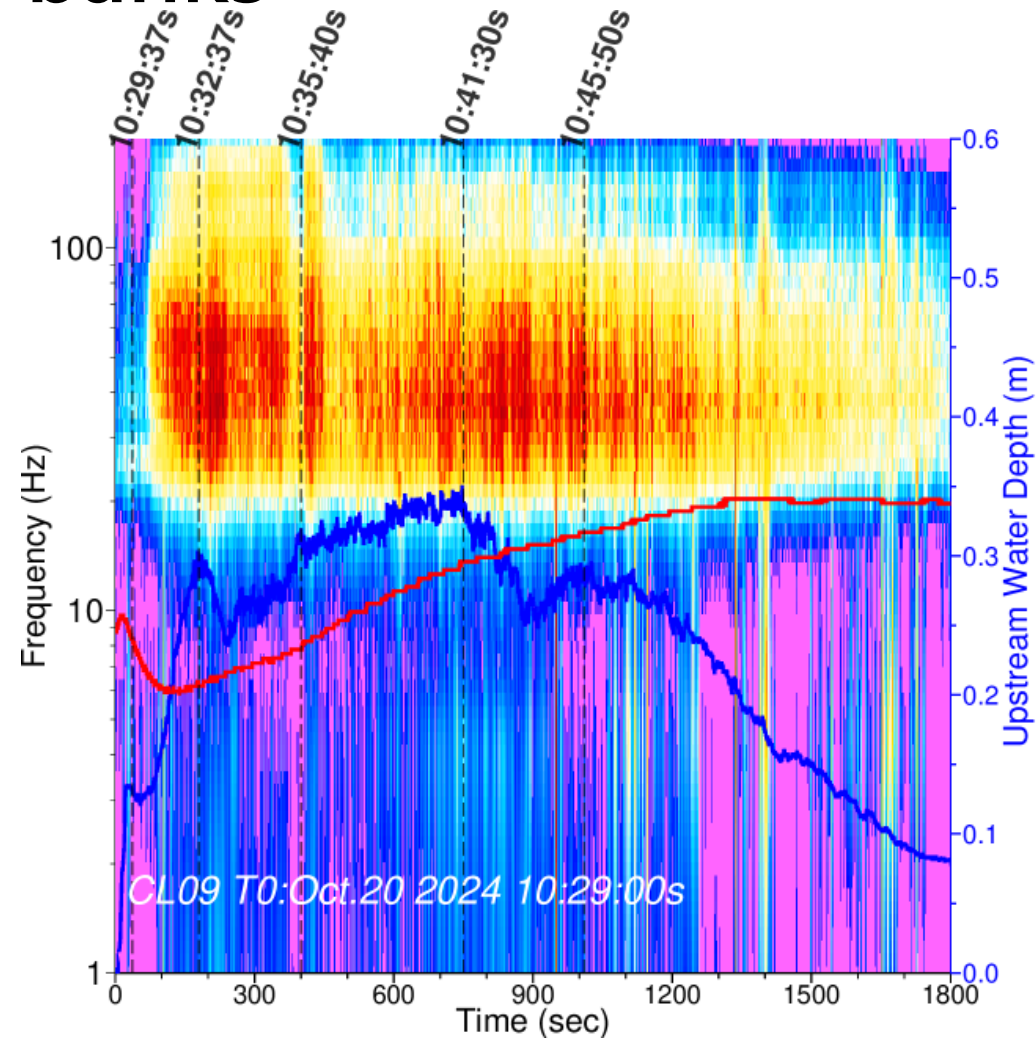
DOD analysis

Left bank sites:
IM09, IM17

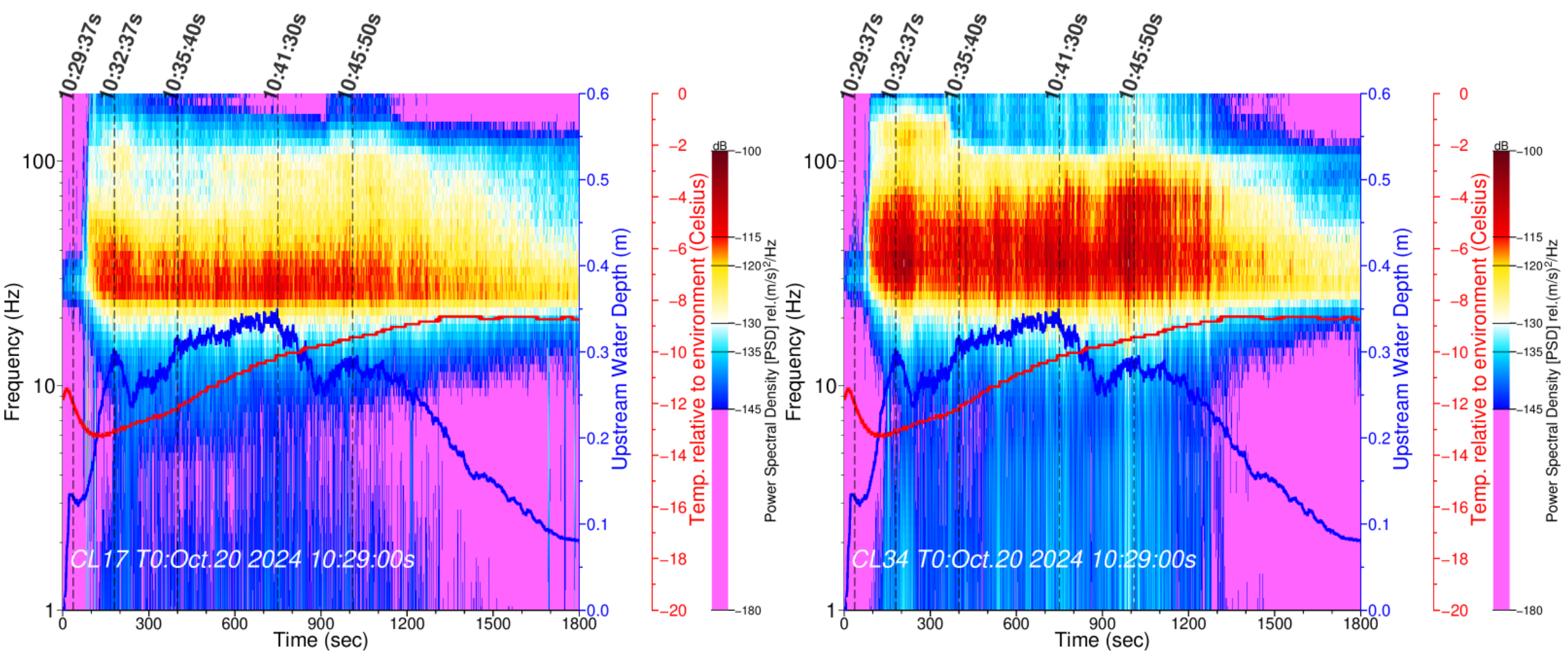
Right bank sites:
IM24, IM34



Spectrograms: left (**erosion, CL09**) and right (**deposit, CL24**) banks



Spectrograms: left (CL17) and right (CL34) banks



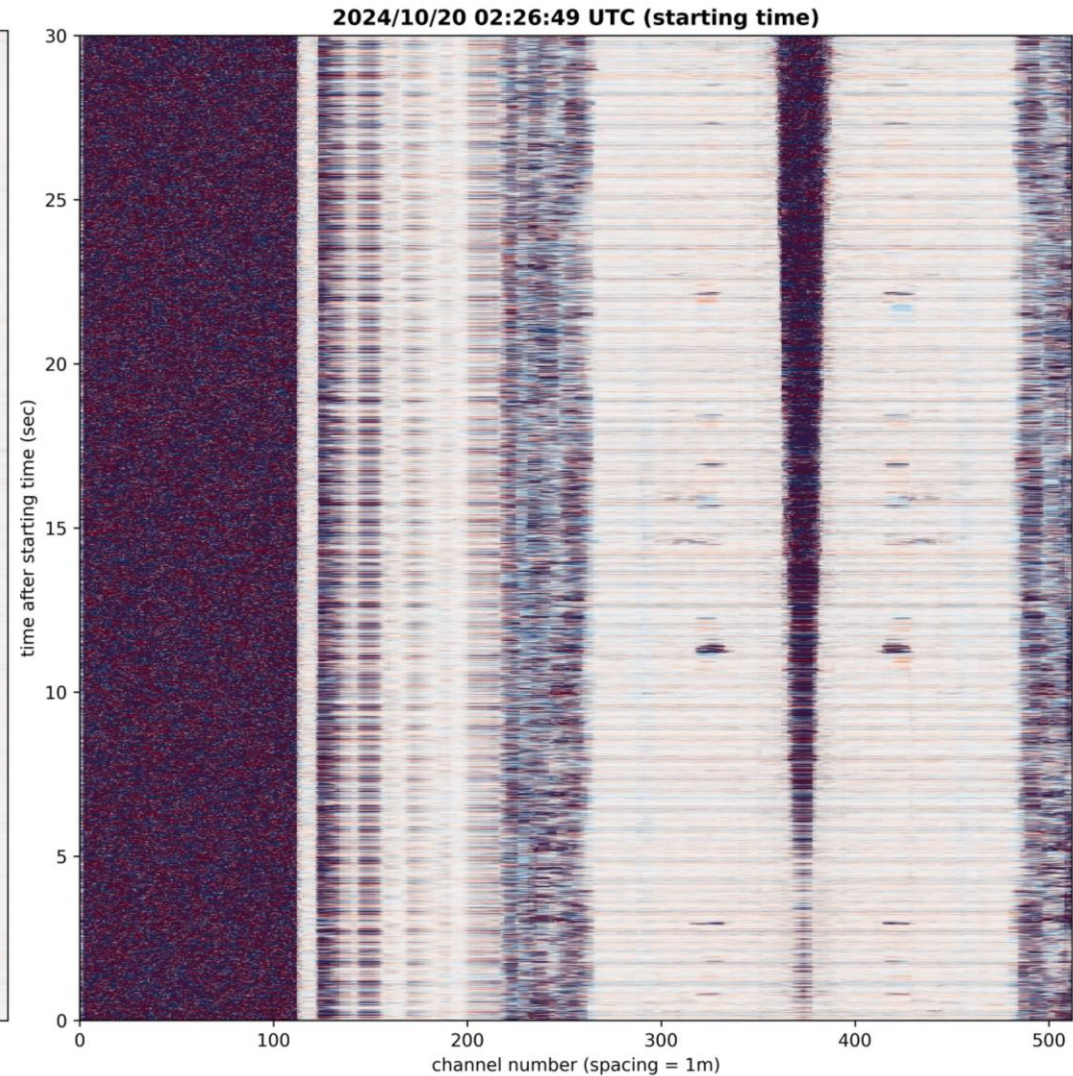
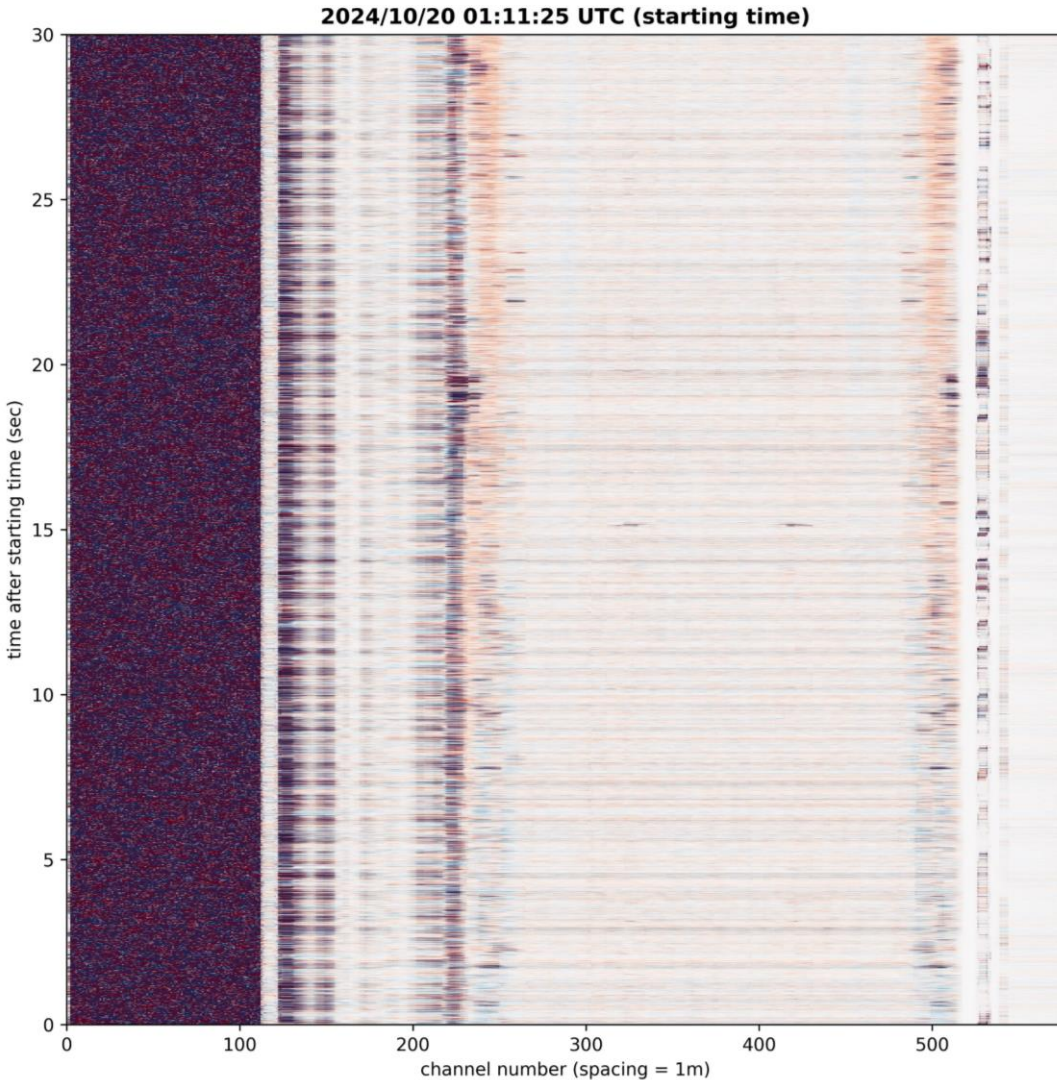
Fluvial DAS observations

Spacing interval: 1m

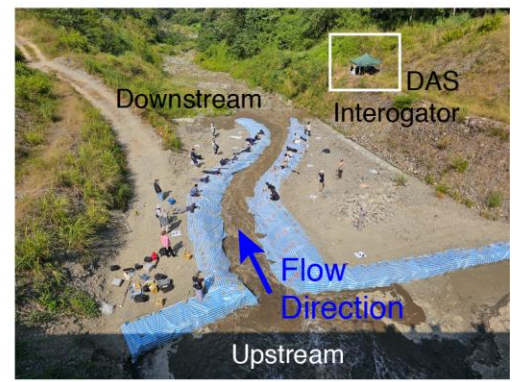
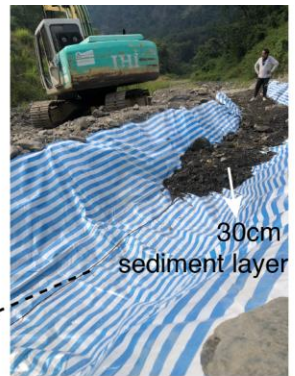
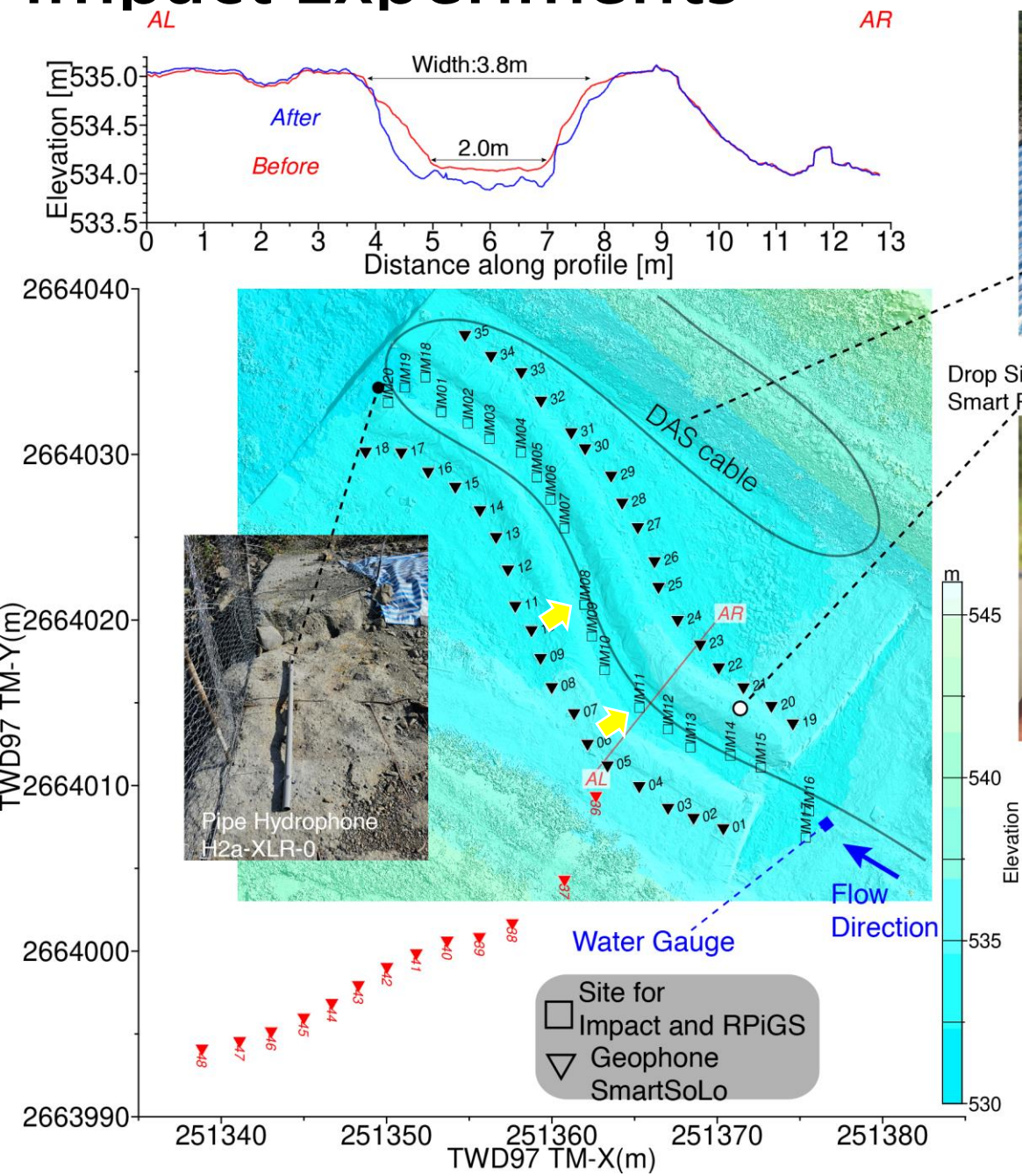
Cable length: 150 m

Sampling rate: 1,000 Hz

Flow induced Strain rate: $\pm 1.16 \times 10^{-5}$

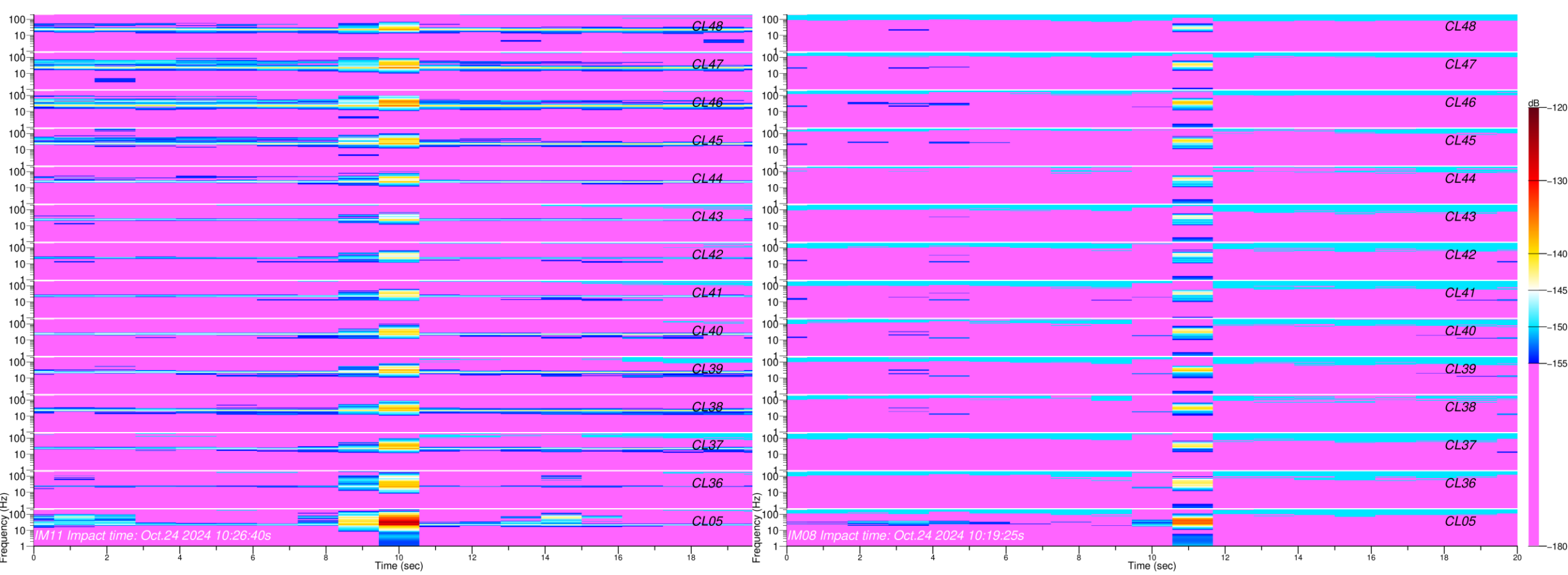


Impact Experiments



Impact location:
IM11
IM08

Impact Experiments



Take Home Message

- on-site, controlled experimental channel
- micro-seismic signals along river channels
- **SMART ROCK** six-axis sensors for gravel particle tracking
 - First fluvial DAS observations
 - AI-RPiGS-Scanner

NEXT: Validation of seismic bedload saltation model

The project aims to develop and improve the application evaluation procedure for the river seismic wave physical model, promoting its technical value for application in other rivers.

<https://sites.google.com/view/collabnycu/home>

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