Hybrid Performance assessment of Sand Mitigation Measures

VKI Seminar

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March 16th, 2022

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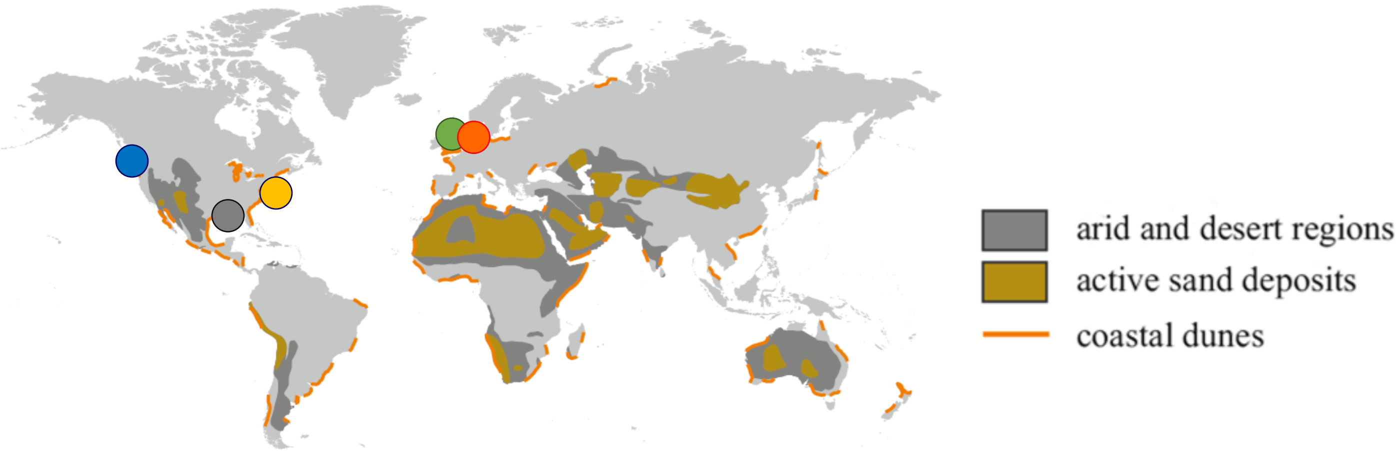
OPTIFLOW

Industrial Motivation: coastal zones

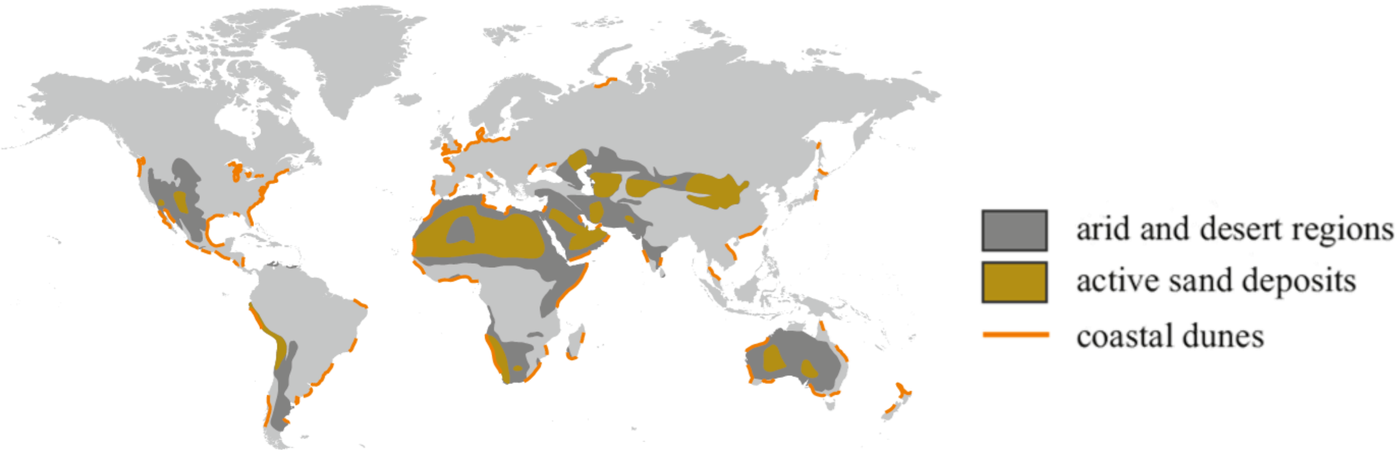


US

EU

Windstorm frequency	**+44%**
Windstorm intensity	**+96%**

Industrial Motivation: desert regions



Structure scale

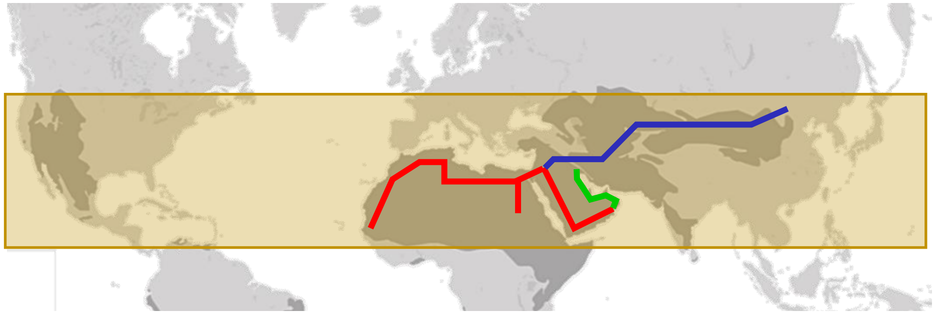
Urban scale

Infrastructure scale

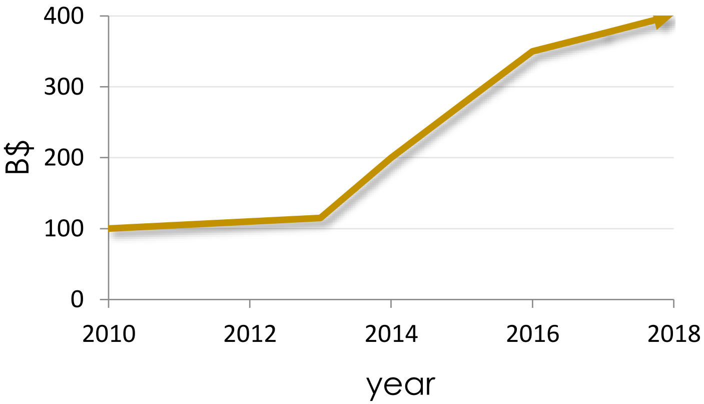
Industrial Motivation: railway megaprojects

Railway megaprojects

- Iron Silk Road
- Gulf Cooperation Council Network
- Arab League Network



- ▨ arid regions
- ▨ northern desert belt



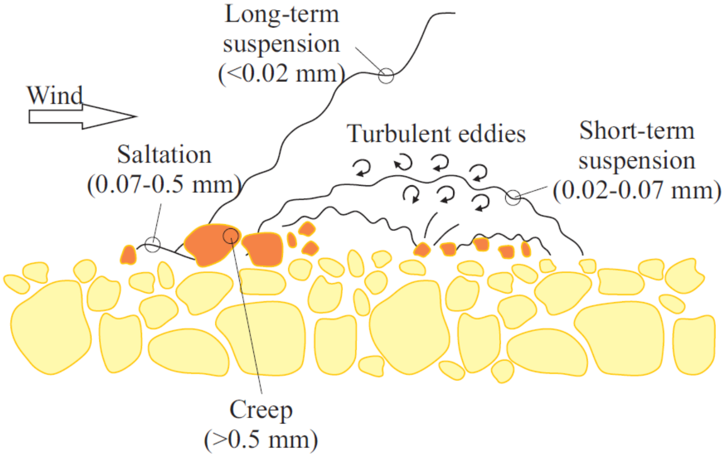
Market potential

- **000** B$

Railway length

- **00000** Km

Phenomenology

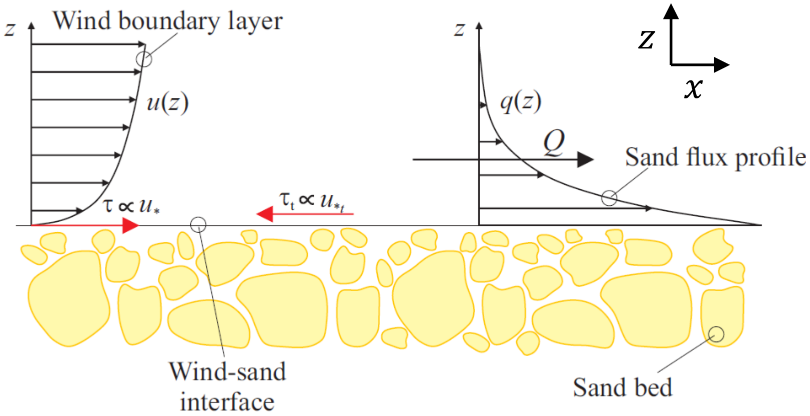


Dust $d < 0.063$ mm
- long-term suspension
- short-term suspension

Sand $d \in [0.063{,}2]$ mm
- creep
- saltation

Engineering interest

Saltation



$q(z) > 0 \Leftrightarrow \tau > \tau_t$

$u_* = \sqrt{\tau/\rho_a}$ $\quad u_* > \boxed{u_{*t}}$

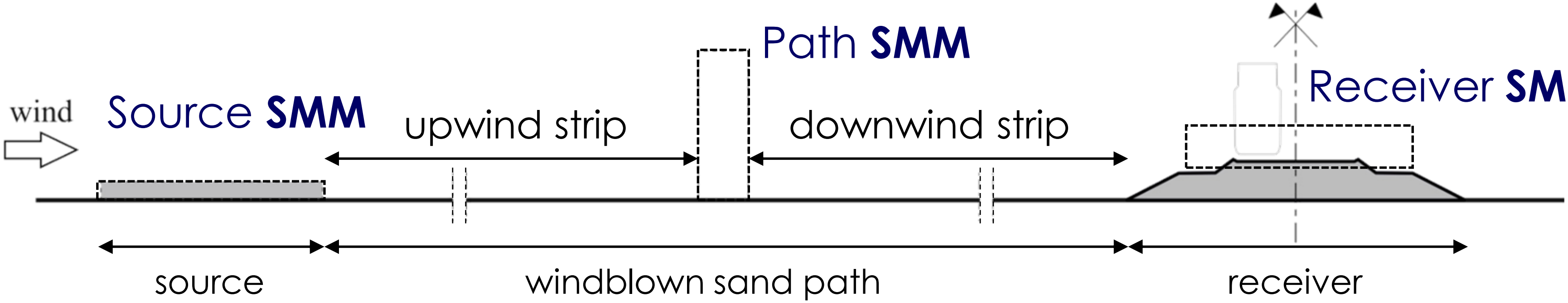
WbS saltation condition

Threshold shear velocity

Sand transport rate $[kg\,m^{-1}s^{-1}]$

$$Q = \int_0^{+\infty} q(z)\,dz$$

Sand Mitigation Measures: Source



from L. Bruno, M. Horvat, L. Raffaele (2018)

- Layer system

asphalt-latex mixture

natural crusting

$$Q \propto u_{*,eff} \propto \boxed{u_*^n} - \boxed{u_{*t}^n}$$

Hedge system

Layer system

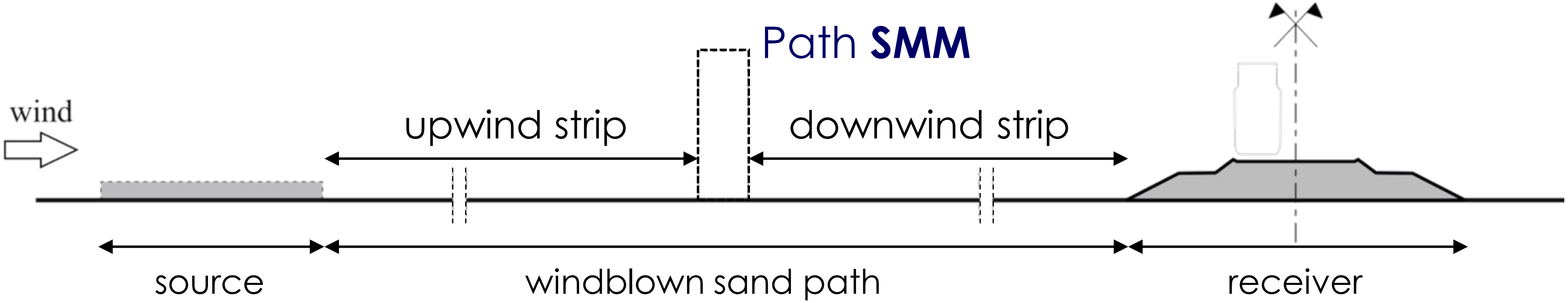
- Hedge system

straw checkerboard

array line-like obstacles

gravel surface

Sand Mitigation Measures: Path



Path **SMM**

wind

upwind strip

downwind strip

source

windblown sand path

receiver

from L. Bruno, M. Horvat, L. Raffaele (2018)

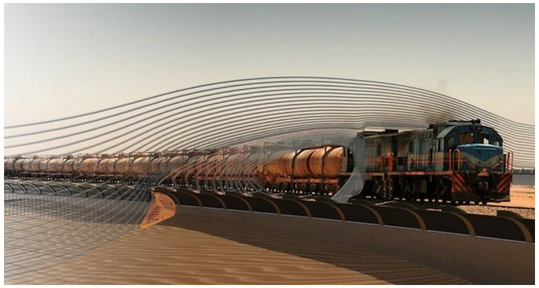
- Surface-like

porous

solid

porous fence

Straight Vertical Wall (SVW)



Shield for Sand (S4S)

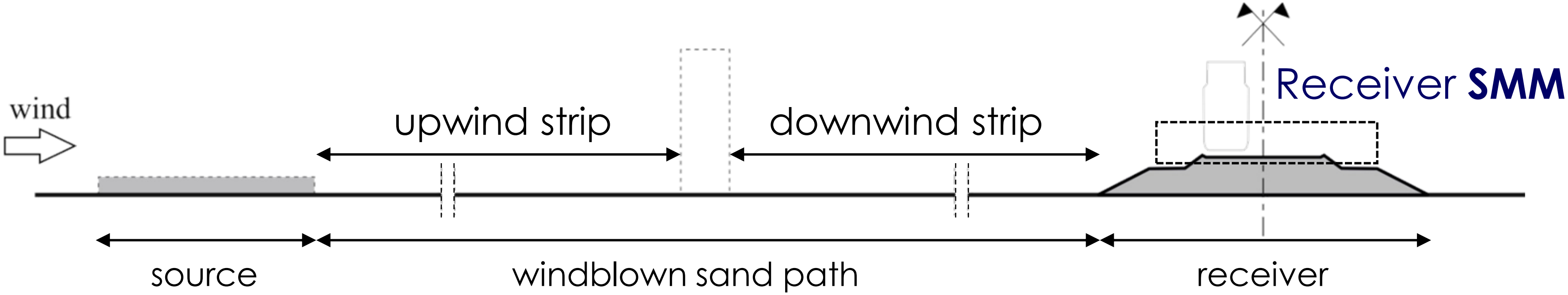
WO 2016/181417 A1

- Volume-like

berm

ditch

Sand Mitigation Measures: Receiver

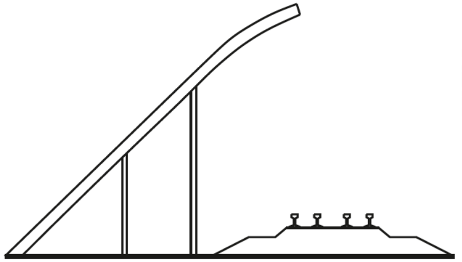


from L. Bruno, M. Horvat, L. Raffaele (2018)

- Aerodynamic based

Jet roofs

Venturi effect-based



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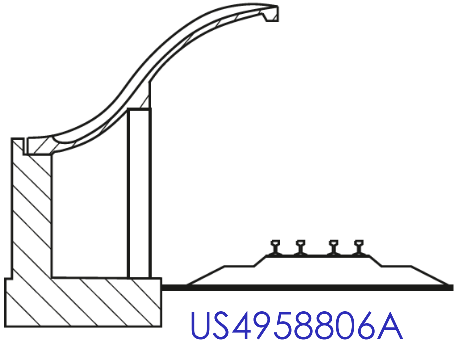

US4958806A

Humped sleepers

- Sand-resistant

T-Track system

Continuous slab

Lubricant free turnout

HyPer SMM

Hybrid **Per**formance assessment of
Sand **M**itigation **M**easures

EU Horizon 2020 Marie Curie Individual Fellowship

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OPTIFLOW

WSMM

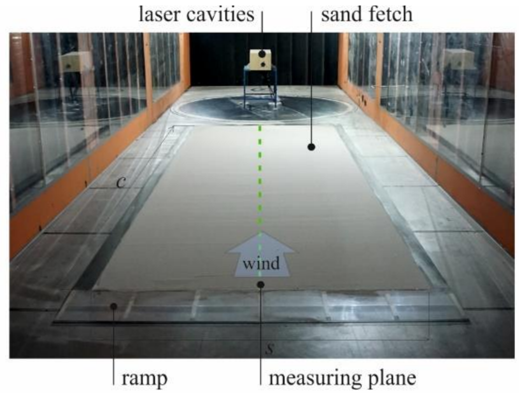
HyPer SMM received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 885985

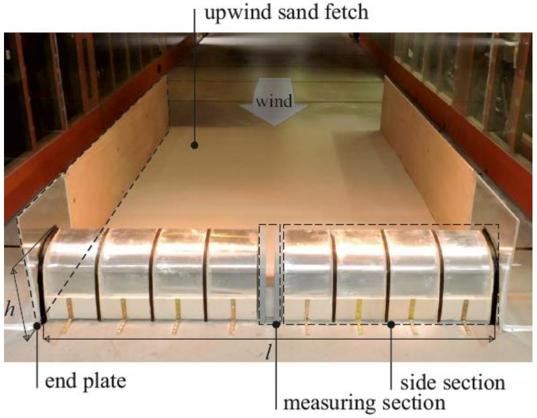
HyPer SMM

- Aim

Develop an innovative **hybrid approach** by combining **Wind-Sand tunnel tests** and **Wind-Sand CFD** simulations as a brand-new design-and-assessment methodology in the field

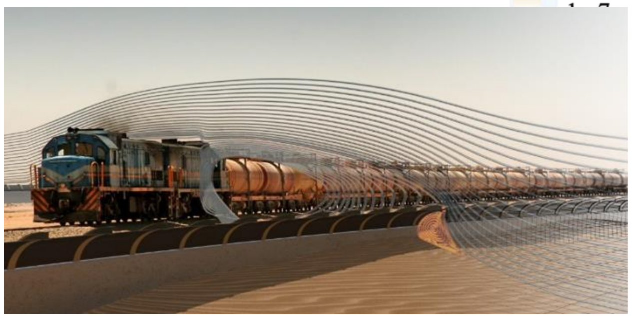
- Main Tasks





1. Development of highly reliable **Wind-Sand Tunnel Tests** to assess SMM performance (flat plane conditions + SMM obstacle)

2. Tuning and validation **Wind-Sand Eulerian multiphase CFD** model



3. Extrapolation of WSTT-based **performance from scale to full-scale** through Wind-Sand CFD simulations

Windblown Sand Action: categorization

Environmental

- site-dependent
- inborn randomness

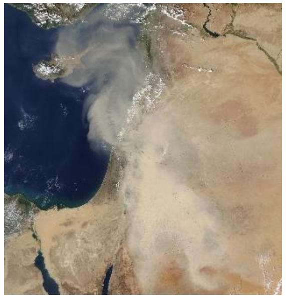
Free

- wind-dependent accumulation

Variable

- long-term varying accumulation process
- non monotonic (periodic sand removal)

Windblown Sand



2 months later…

analogous to

~ wind

~ windblown snow

~ snow

~/≠ snow

modelling fallout

probabilistic modelling

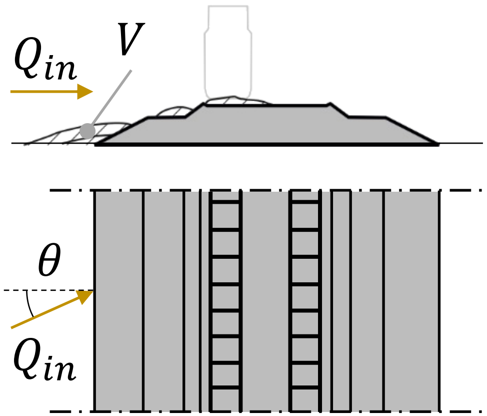
Wind and sand modelling

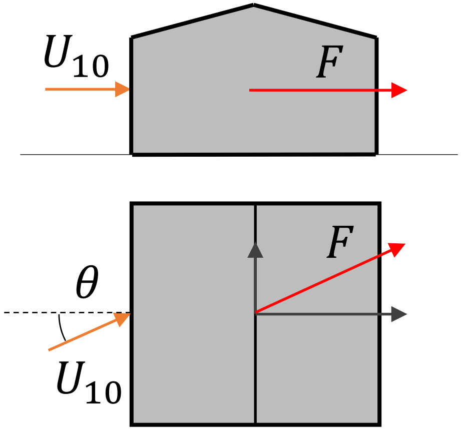
Time-variant reliability analysis

Evaluation of sand removal period

Windblown Sand Action: modelling chain

Windblown sand action VS **Wind action**





Site analysis

1 Incoming Windblown Sand

- $Q_{in}(U_{10}, d)$

Incoming Wind

- U_{10}

Assessment

2 Aerodynamics / Morphodynamics

- $C_s(\underbrace{\theta, \Gamma_0}_{\text{aerodyn.}}, \underbrace{V}_{\text{morphodyn.}})$

Aerodynamics

- $C_f(\theta, \Gamma_0)$

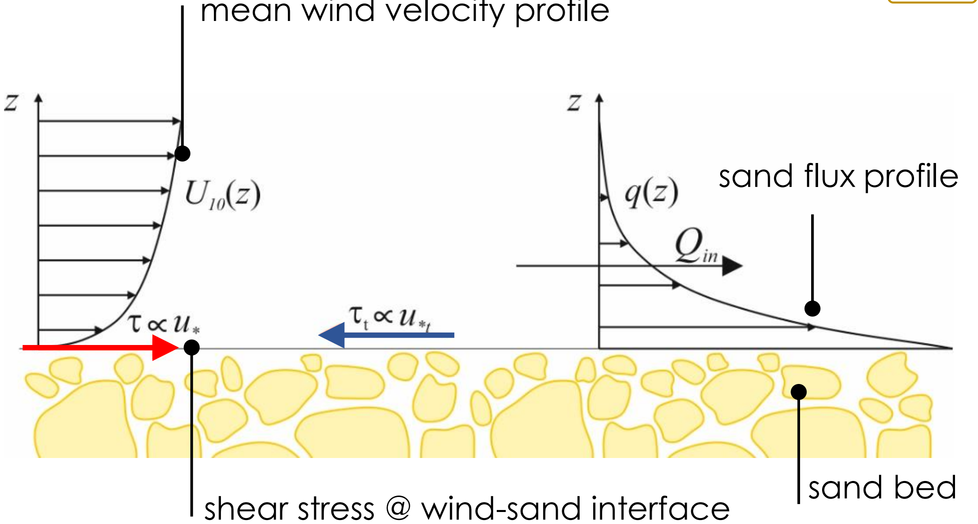
3 Windblown sand action

- V ⇨ F ⇨ …

Wind action

- F

Incoming Windblown Sand



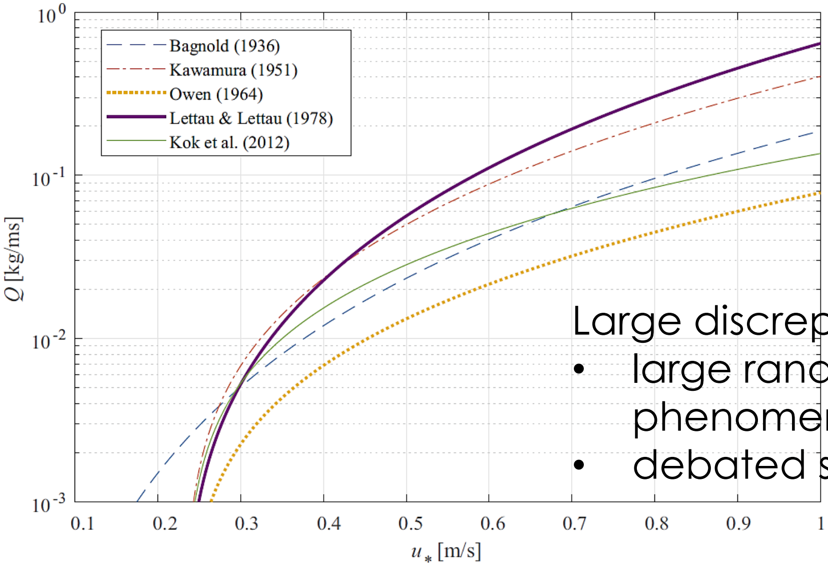
Semi-empirical models

- Bagnold type

  $Q \sim u_*^3$
- Modified Bagnold type

  $Q \sim u_{*,eff}^3(u_*, u_{*t}), \omega_s$
- O' Brien-Rindlaub type

  $Q \sim u$
- Complex



Large discrepancies due to:

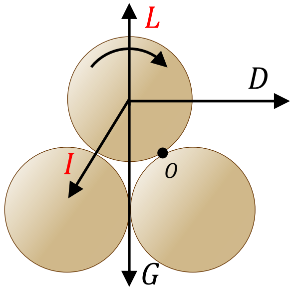
- large randomness of physical phenomenon
- debated scaling

Modelling: u_{*t}

Deterministic models

Microscopic models

- Equilibrium of the moments
  Entraining aerodynamic forces VS
  Stabilizing forces



Macroscopic models

- Semi-empirical (free parameters)
- Trend VS d

$$u_{*t} = A\sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd}$$

Bagnold (1941)

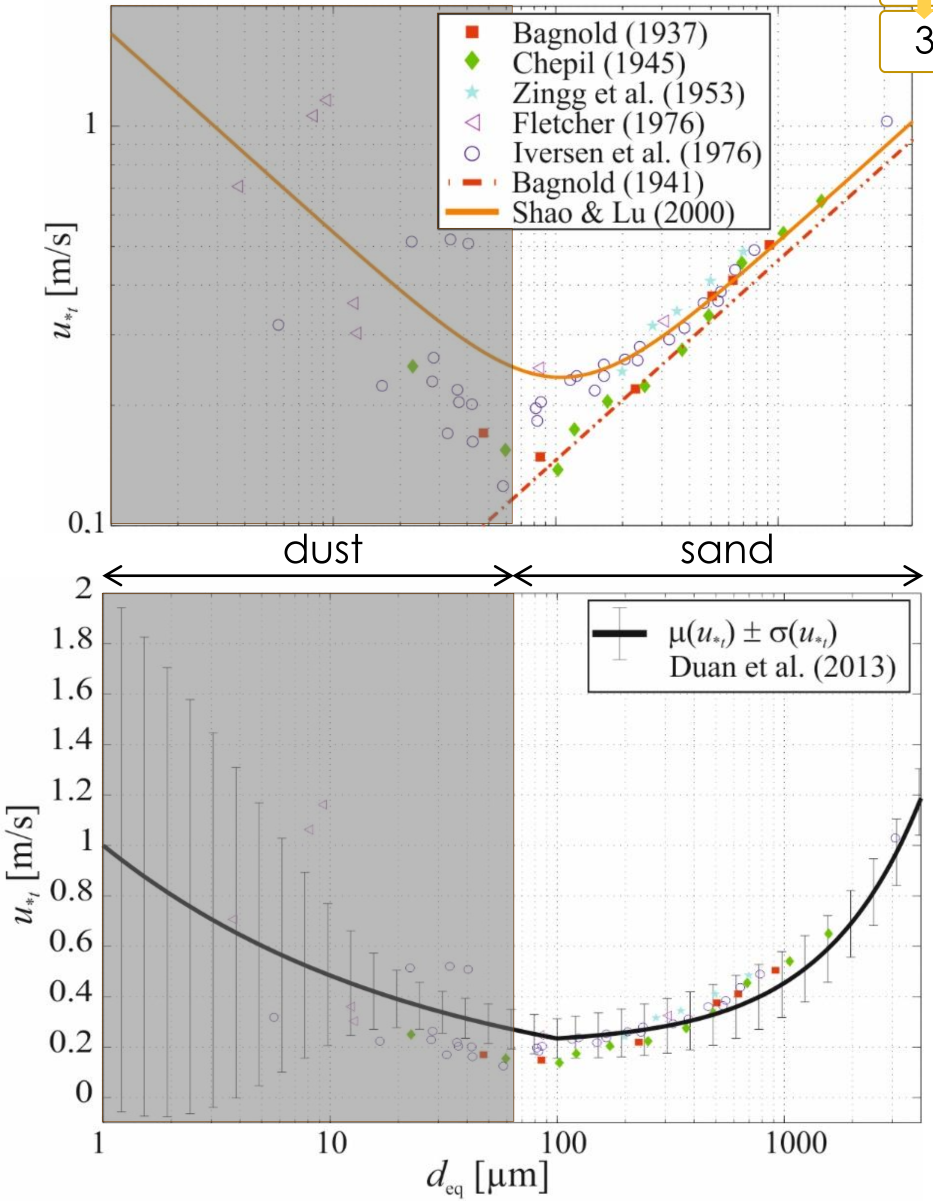
Probabilistic models

- Scatter of experimental data
- Random turbulent wind flow, bed grain geometry, interparticle forces Zimon (1982)

Duan et al. (2013)

4 microscopic r.v.s

Modelling and *technical* difficulties



Modelling: u_{*t}

Statistical approach

"Lack of exact knowledge, regardless of what is the cause of this deficiency" Refsgaard et al. (2007)

Aleatory

- Sand uncertainties: grain size, shape, relative position, surface cleanliness, grain size distribution.
- Wind uncertainties: turbulent flow inborn variability, uncontrolled environmental conditions, e.g. temperature, humidity.

Epistemic

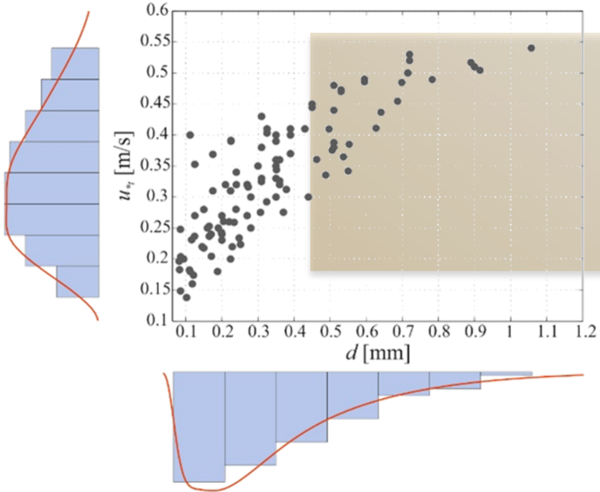
- Model uncertainty: simplified representation of the real physical behaviour, identification of relevant variables, hypothesis, interactions left out. Lack of a shared definition of u_{*t} Shao (2008)
- Measurement uncertainty: errors and/or different procedures.
- Parameter uncertainty: values of model parameters.

- Nonlinear regression
- Copula-based regression

Modelling: u_{*t}

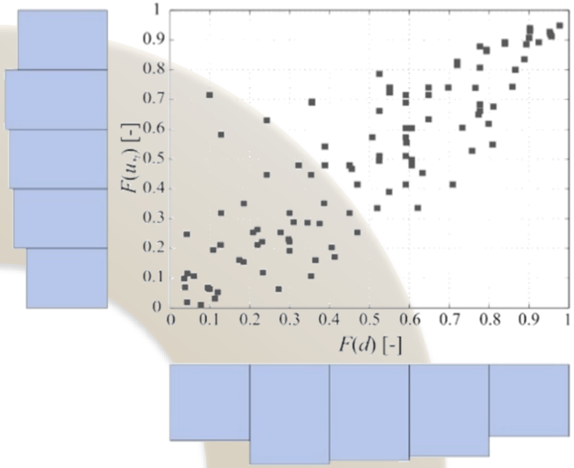
1 Fitting of marginal distributions

$$F(d), F(u_{*t})\,,\quad d, u_{*t} \in \mathbb{R}$$



2 From original to copula scale

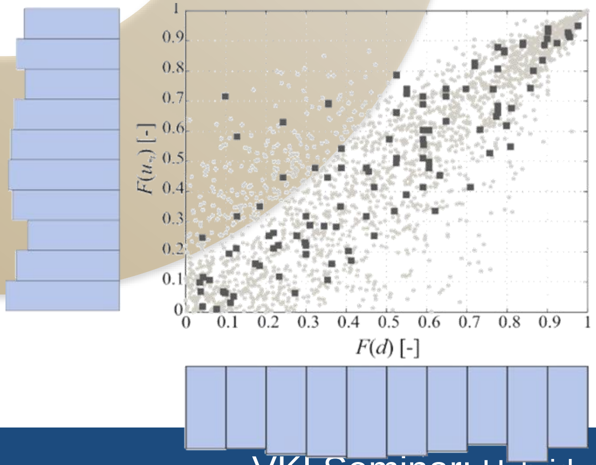
$$F(d, u_{*t}) = C\{F(d), F(u_{*t})\}\quad C: [0,1]^2 \to [0,1]$$



3 Fitting of Inverted Clayton Copula

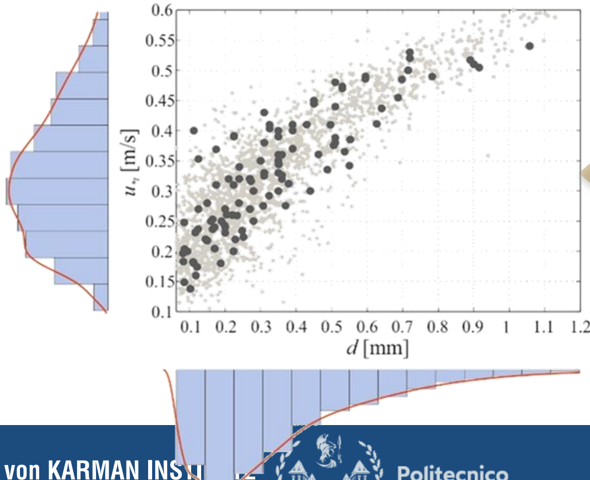
$$C(u,v) = u + v - 1 + \left[(1-u)^{-1/\alpha} + (1-v)^{-1/\alpha} - 1\right]^{-\alpha}$$

$$u, v \in [0,1], \alpha > 0$$

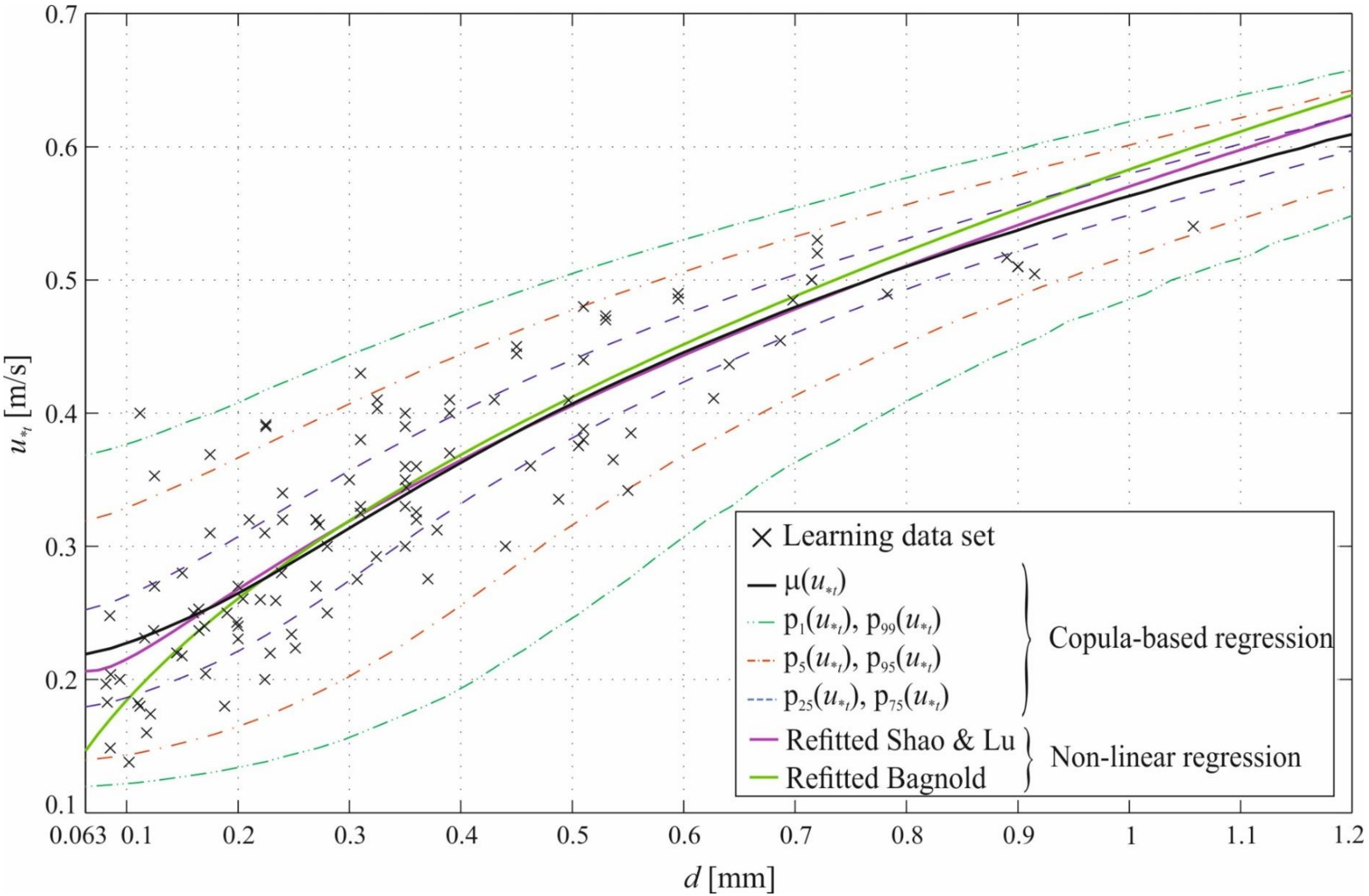


4 From copula to original scale

$$(d, u_{*t}) = \left(F^{-1}(u), F^{-1}(v)\right)$$



Modelling: u_{*t}

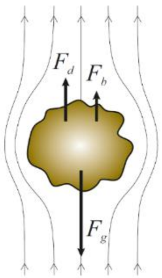


from L. Raffaele, L. Bruno, F. Pellerey, L. Preziosi (2016)

Modelling: ω_s

Statistical approach

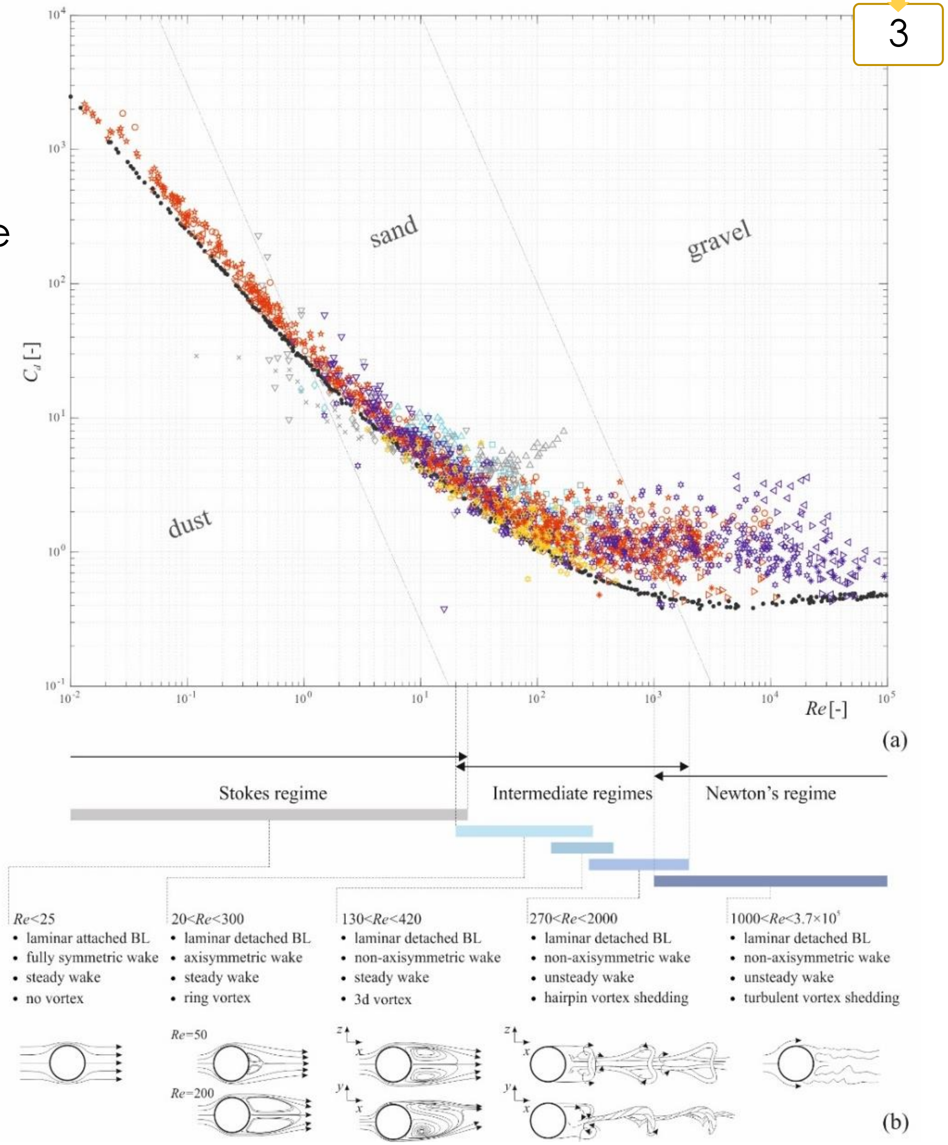
- Sedimentation velocity affects the mode of transport, distribution of particles above the ground, and transport rate
- Discrepancy among semi-empirical laws
- Sedimentation velocity bound to drag coefficient

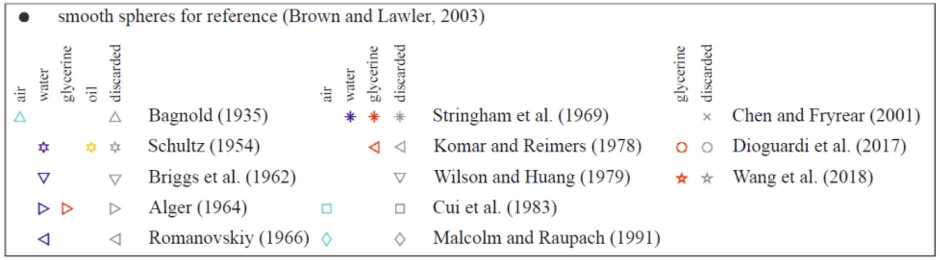


$$F_d = \frac{1}{2}\rho_f \omega_s^2 C_d \frac{\pi d^2}{4}$$

$$F_g = \rho_p g \frac{\pi d^3}{6}$$

$$F_b = \rho_f g \frac{\pi d^3}{6}$$

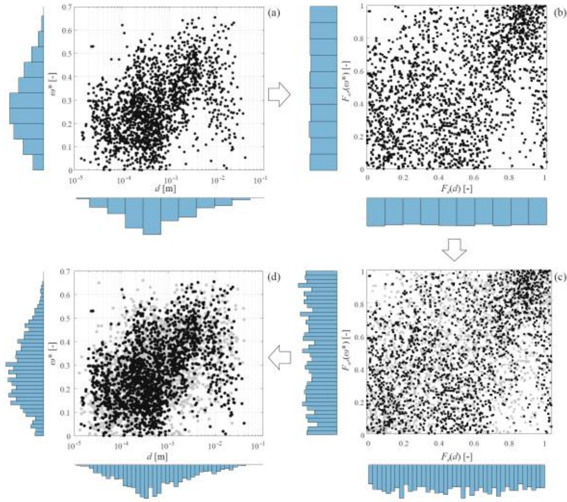


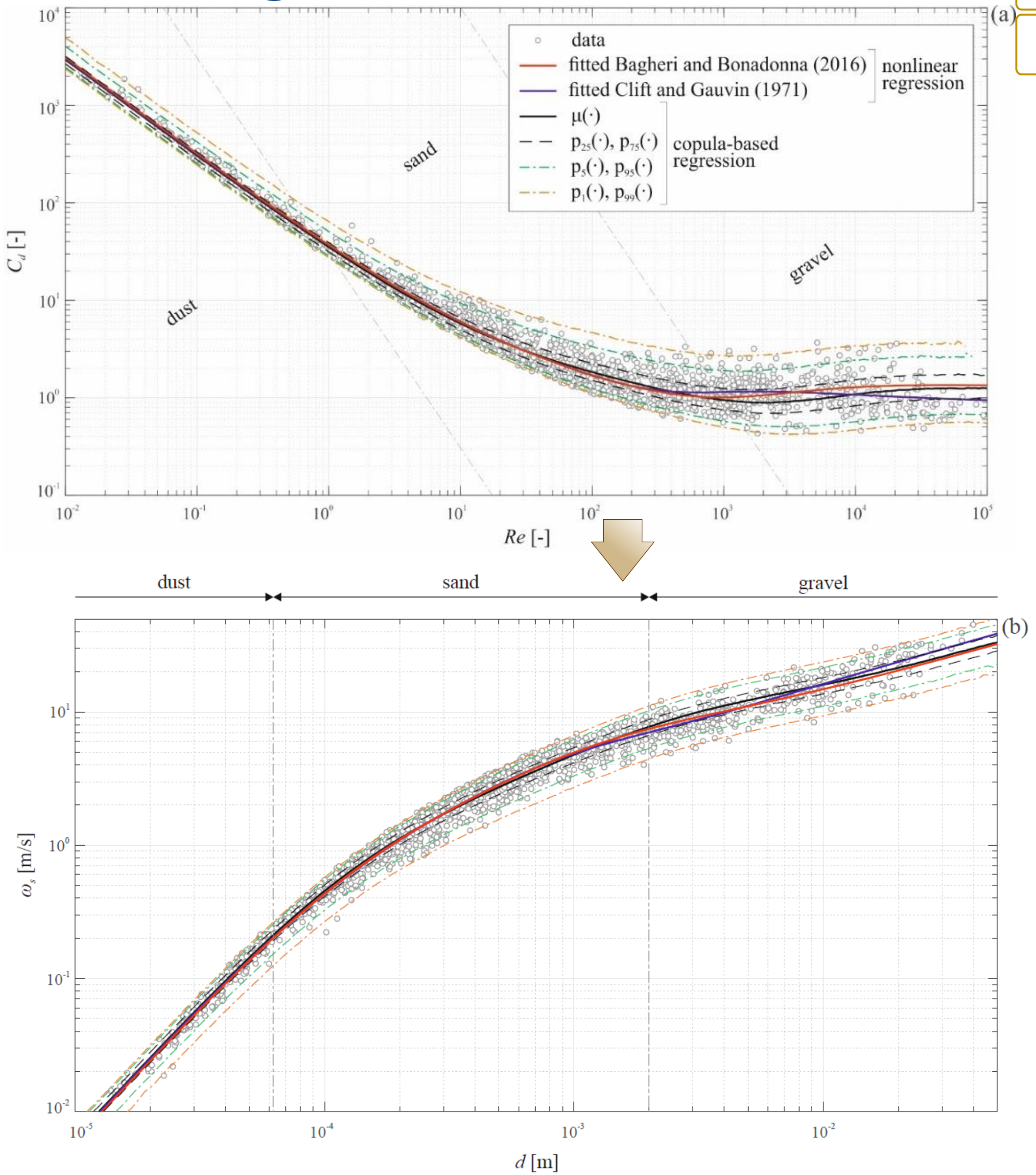


from L. Raffaele, L. Bruno, D. Sherman (2020)

Modelling: ω_s

copula-based regression

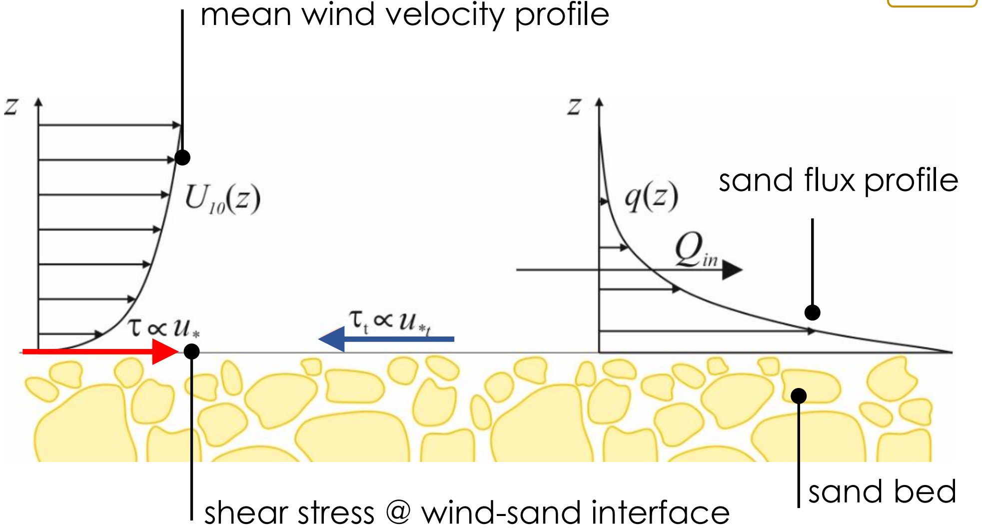




$$
\begin{cases}
Re = \dfrac{\omega_s d}{\nu_f} \\
C_d = \dfrac{4}{3}\dfrac{\rho_f(\rho_p - \rho_f)}{Re^2 \mu_f^2} g d^3
\end{cases}
$$

$$
\begin{cases}
d = \left[\dfrac{3}{4}\dfrac{C_d Re^2 \mu_f^2}{\rho_f(\rho_p - \rho_f) g}\right]^{1/3} \\
\omega_s = \dfrac{Re\, \nu_f}{d}
\end{cases}
$$

Incoming Windblown Sand



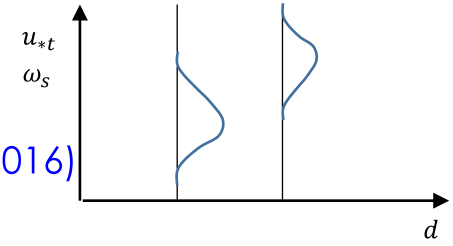
mean wind velocity profile

sand flux profile

sand bed

shear stress @ wind-sand interface

Wind shear velocity $u_* = u_*(U_{10}, z_0)$ $f(u_*) = \dfrac{k f(U_{10,ref})}{\ln z_{ref}/z_0}$



Threshold shear velocity $u_{*t} \approx u_{*t}(d)$ $f(u_{*t}|d)$ from Raffaele et al (2016)

Sedimentation velocity $\omega_s \approx \omega_s(d)$ $f(\omega_s|d)$ from Raffaele et al (2020)

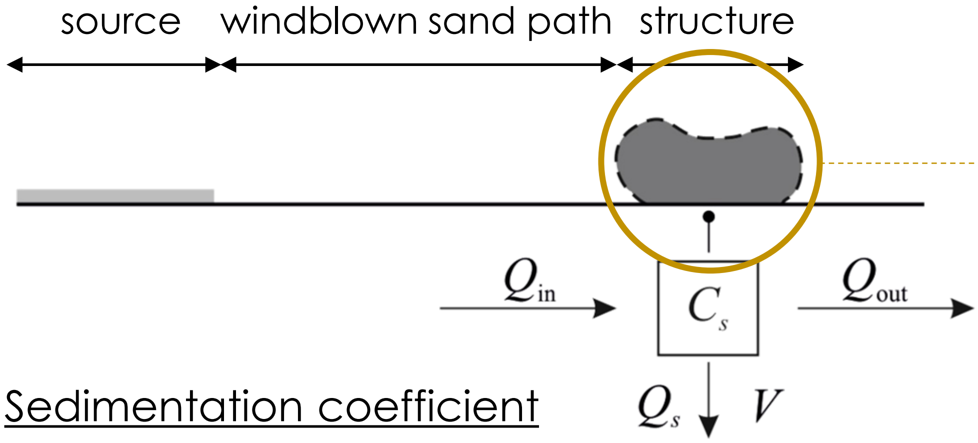
Incoming
sand transport rate

$$Q_{in} = \int_0^{+\infty} q(z)\, dz \approx Q_{in}(u_*, u_{*t}, \omega_s)$$

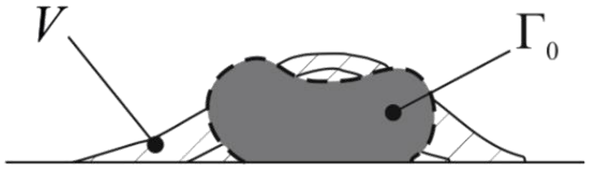
$$f(Q_{in}) = \begin{cases} A\sqrt{\dfrac{d}{d_r}}\dfrac{\rho_a}{g} f(u_*)^3 \left[1 - \dfrac{f(u_{*t}|d)}{f(u_*)}\right] & \text{if } u_* > u_{*t} \\ 0 & \text{if } u_* \leq u_{*t} \end{cases}$$

from Raffaele et al (2017a)

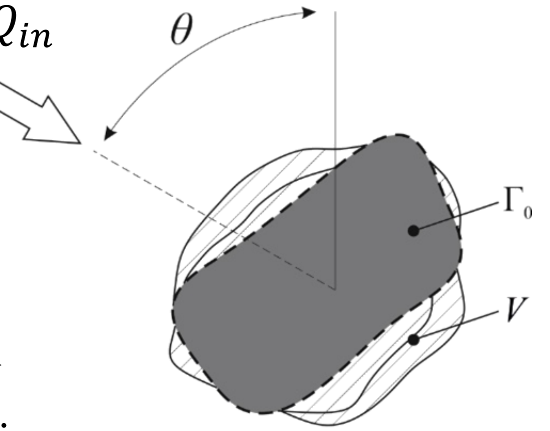
Aerodynamics/Morphodynamics



- *Side view*

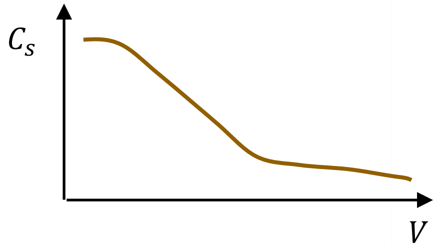


- *Plan view*



Sedimentation coefficient

- $C_s = Q_s/Q_{in} \in [0,1]$
- $C_s(\theta, \Gamma_0, V)$
- monotonic decreasing vs V

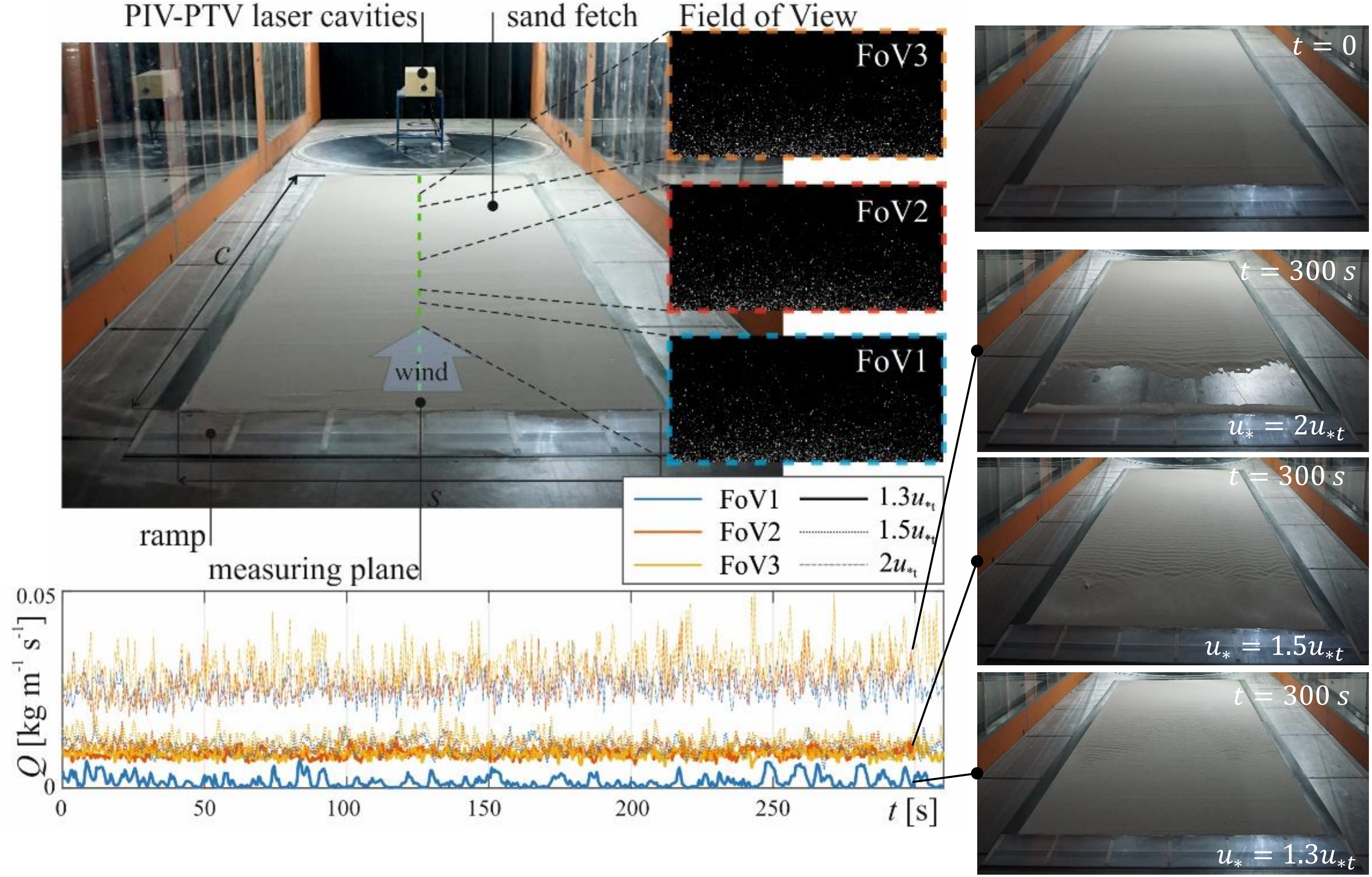


- No closed forms ➡ WT or multiphase CFD testing

Sedimentation rate $f(Q_s) = C_s f(Q_{in})$

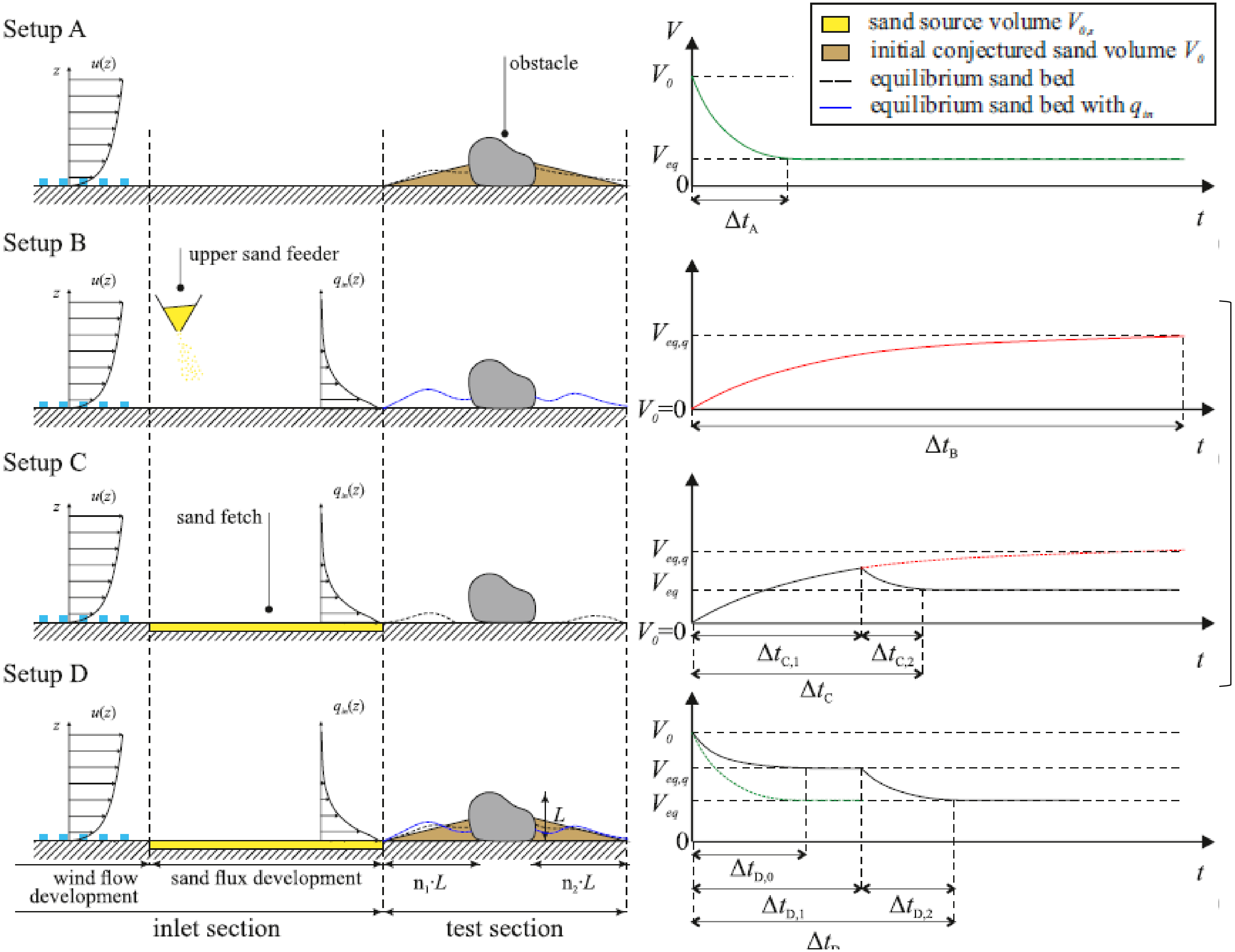
Outgoing transport rate $f(Q_{out}) = [1 - C_s]\, f(Q_{in})$

Wind-Sand Tunnel Testing: flat sand bed



Wind-Sand Tunnel Testing: obstacle

- State-of-the-art



Identification erosion/
sedimentation zones

Sand transport and
sedimentation regions
around clean obstacle

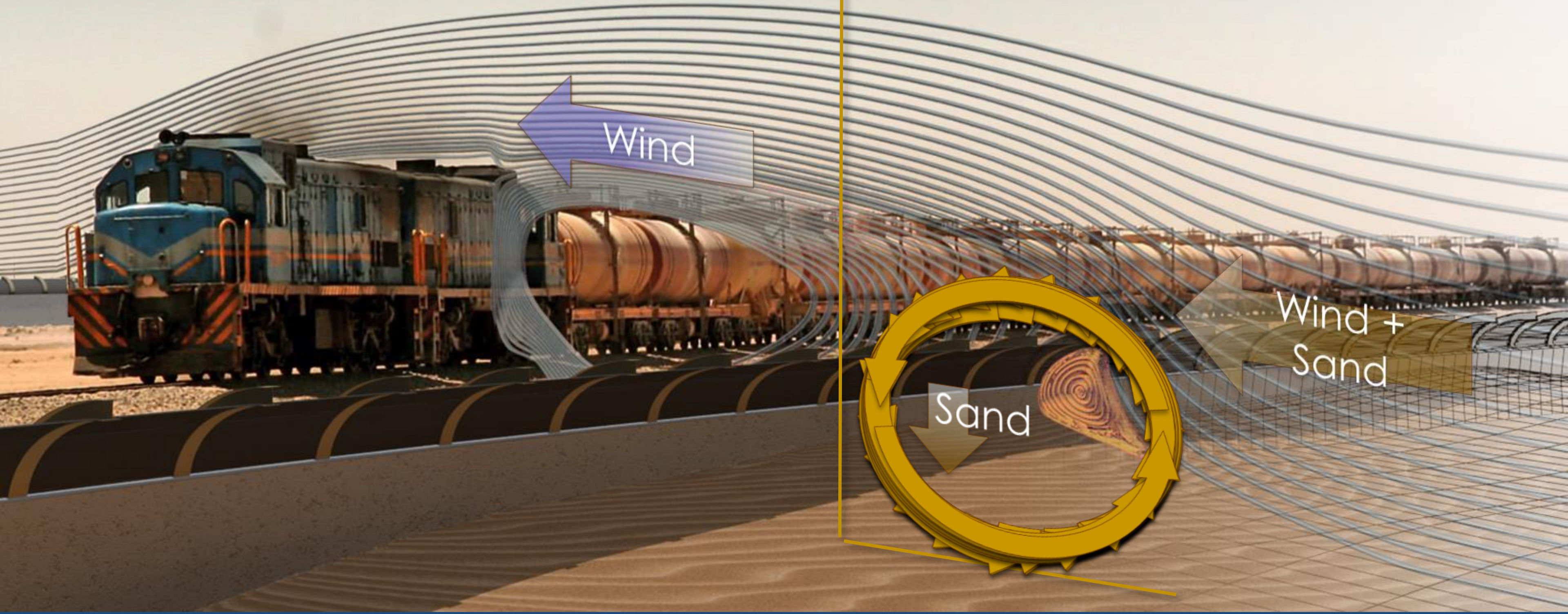
SMM performance
assessment

Wind-Sand Tunnel Testing: S4S

S4S Shield for Sand

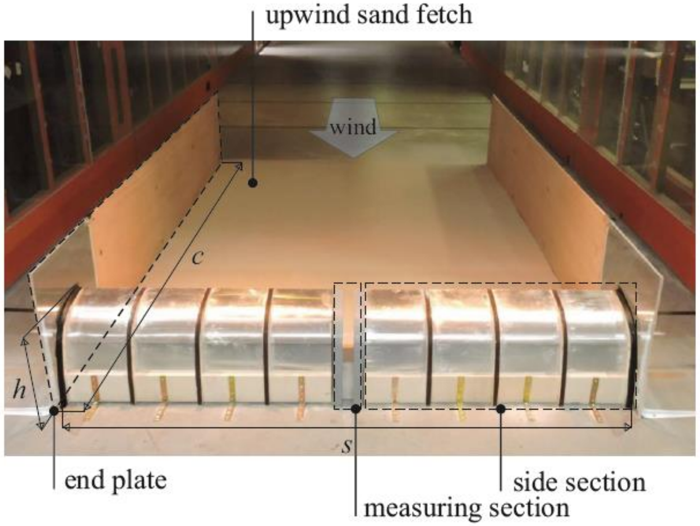
1
2
3

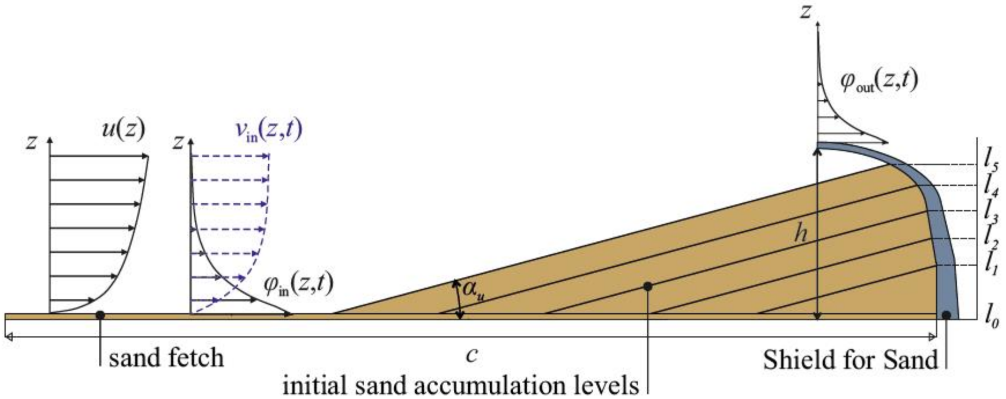
1. Trapping vortex
2. Reversed flow close to the ground
3. Sand subtraction from the incoming flux



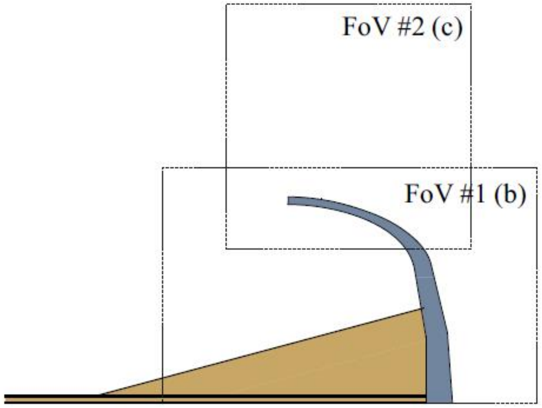
Wind-Sand Tunnel Testing: S4S

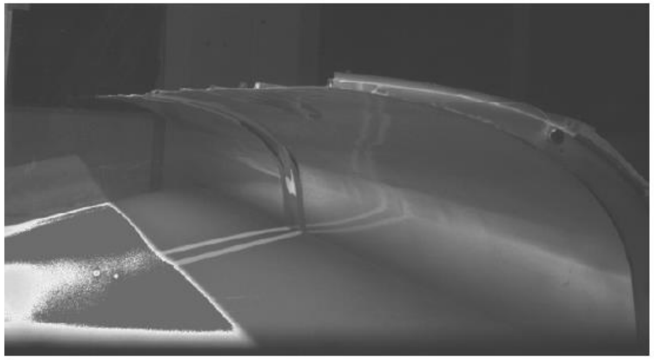
- Wind tunnel setup in L-1B

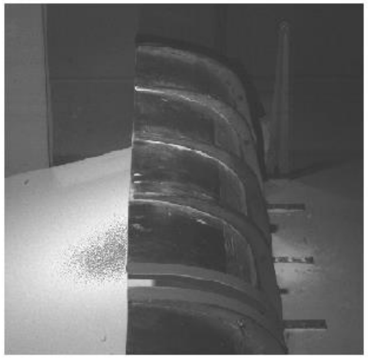




- PIV-PTV measurement setup

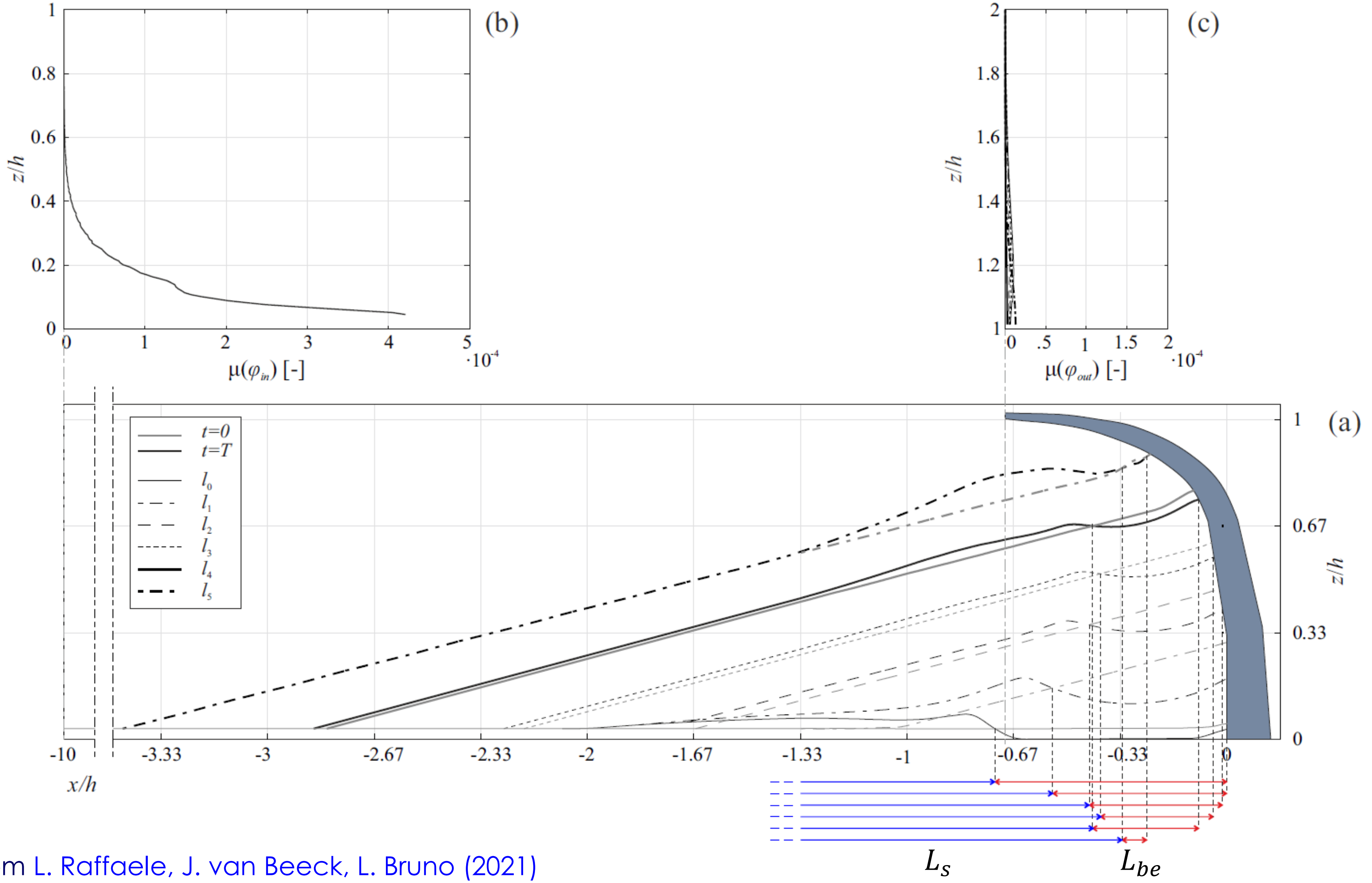






Wind-Sand Tunnel Testing: S4S

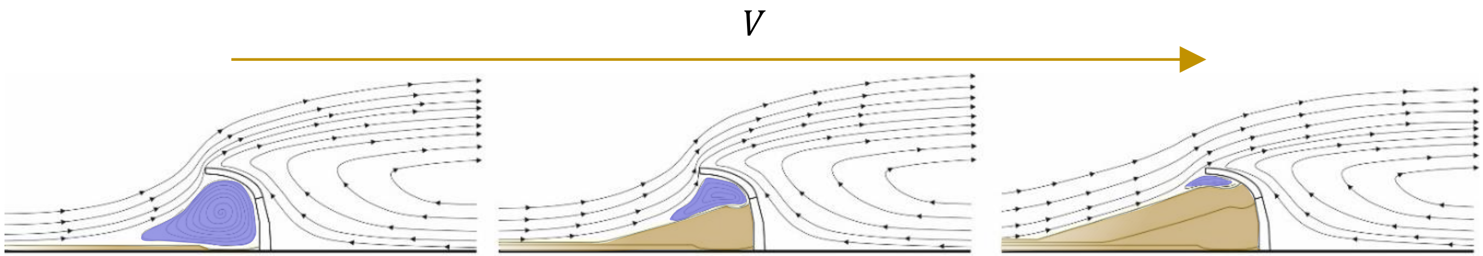
- Sand concentration and morphodynamics



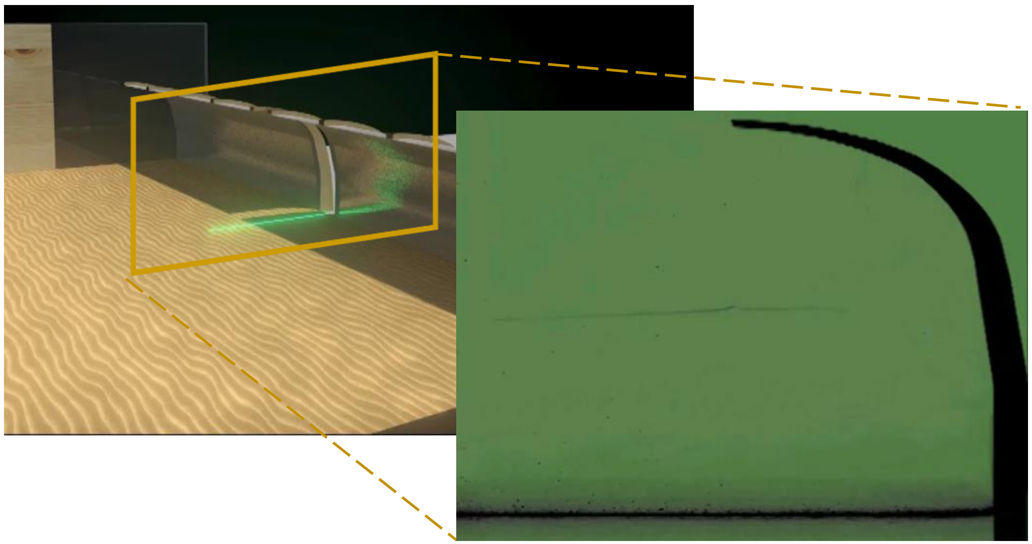
from L. Raffaele, J. van Beeck, L. Bruno (2021)

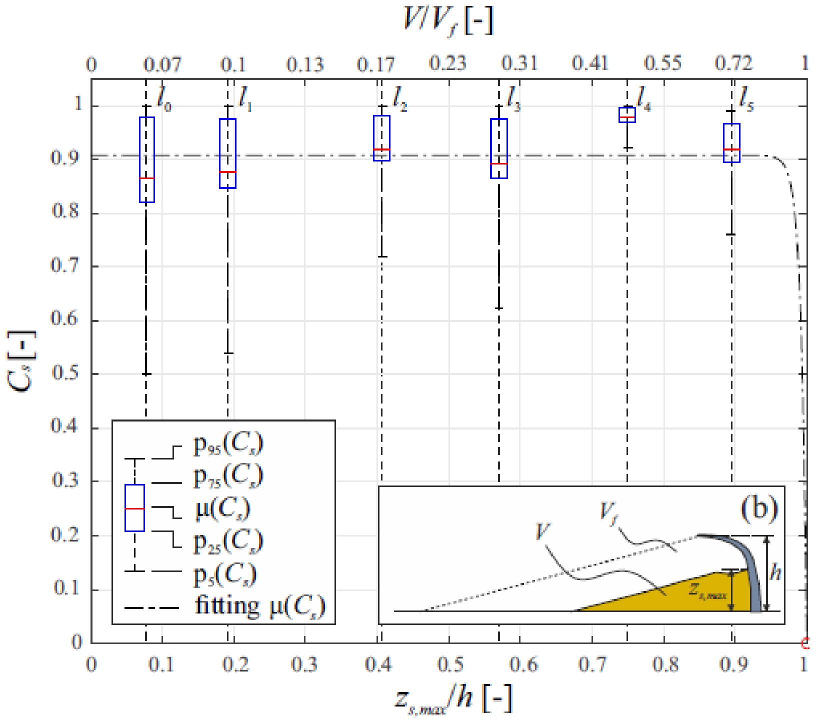
Wind-Sand Tunnel Testing: S4S

- Wind flow & morphodynamics pattern



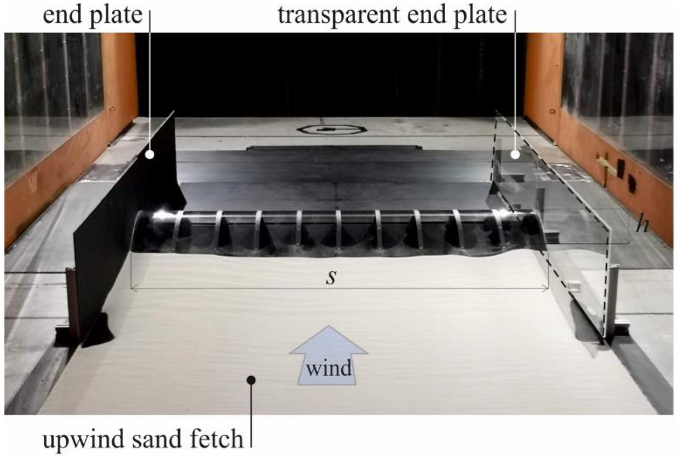
- Sedimentation Coefficient





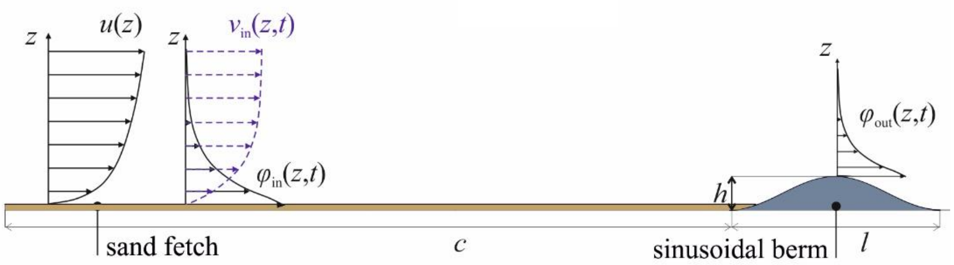
Wind-Sand Tunnel Testing: sinusoidal berm

- Wind tunnel setup in L-1B

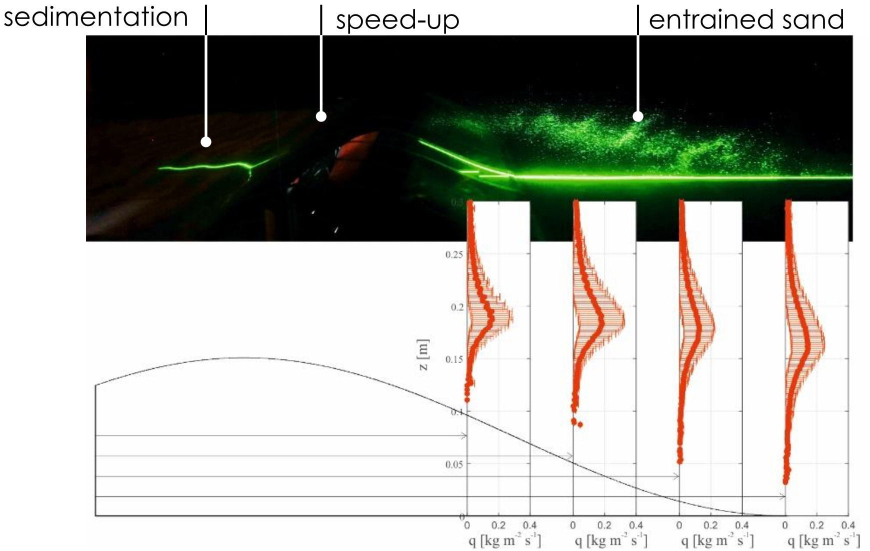


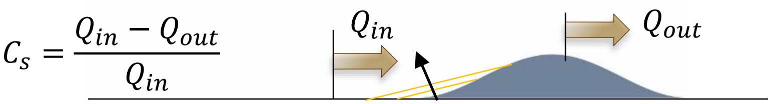
coast in Belgium

Mecca-Medina line

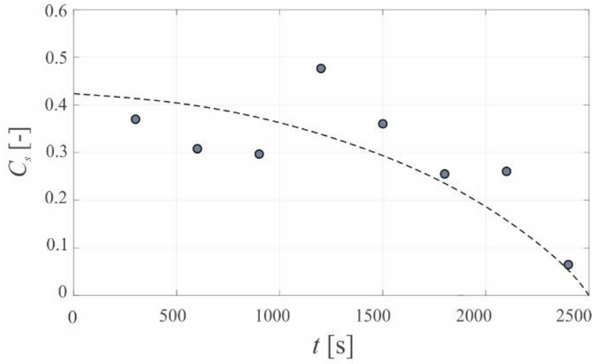


- Some results



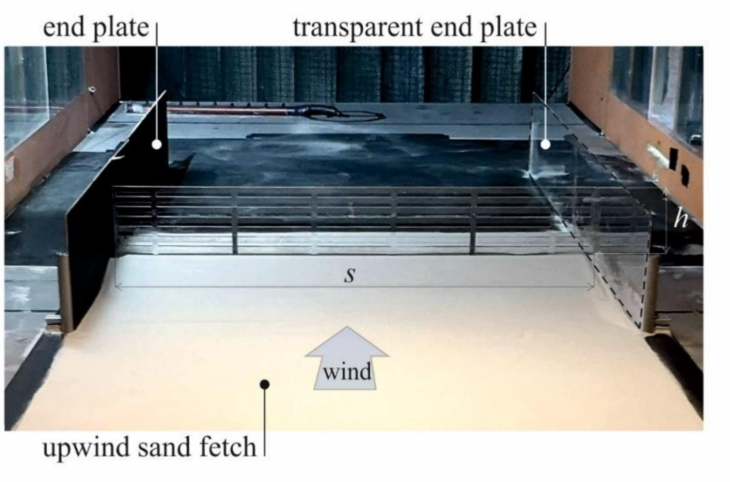


$$C_s = \frac{Q_{in} - Q_{out}}{Q_{in}}$$



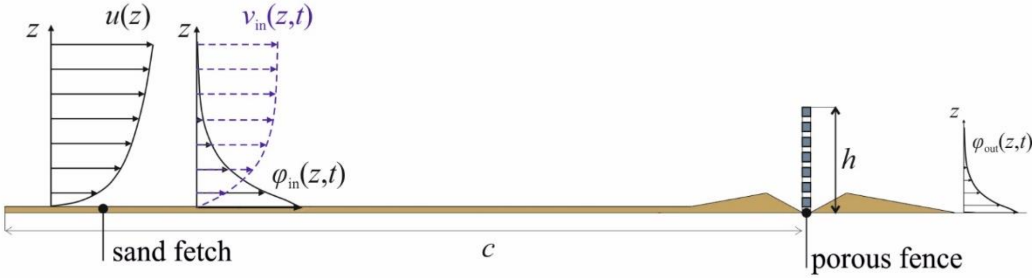
Wind-Sand Tunnel Testing: porous fence

- Wind tunnel setup in L-1B

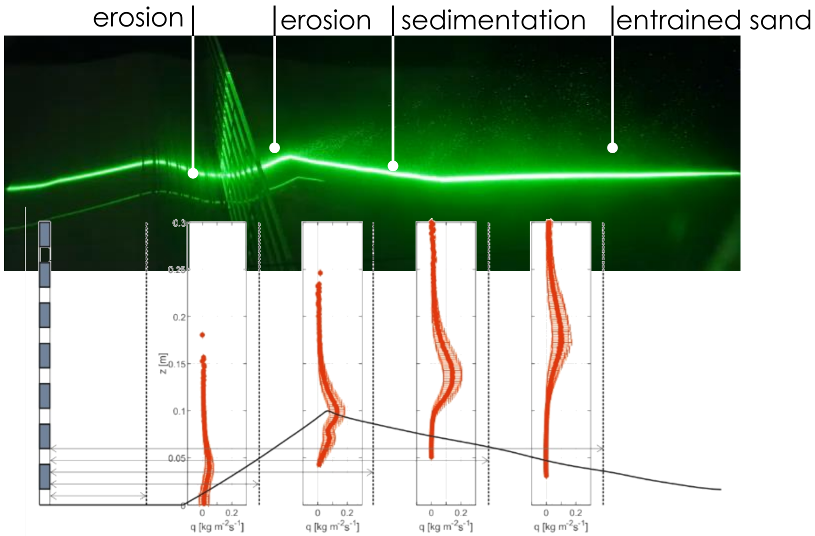


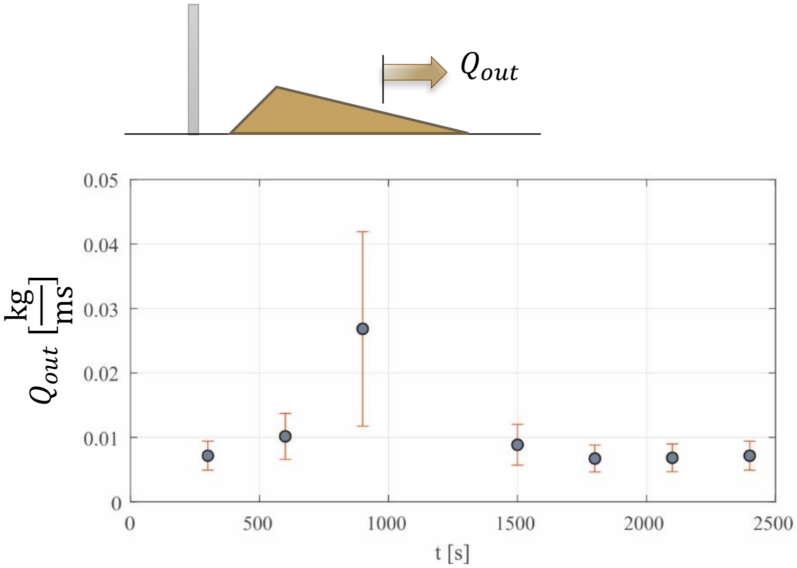
coast in Germany

railway in China



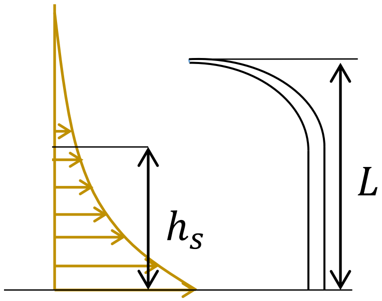
- Some results





Similarity mismatching

- Similarity requirements VS past studies

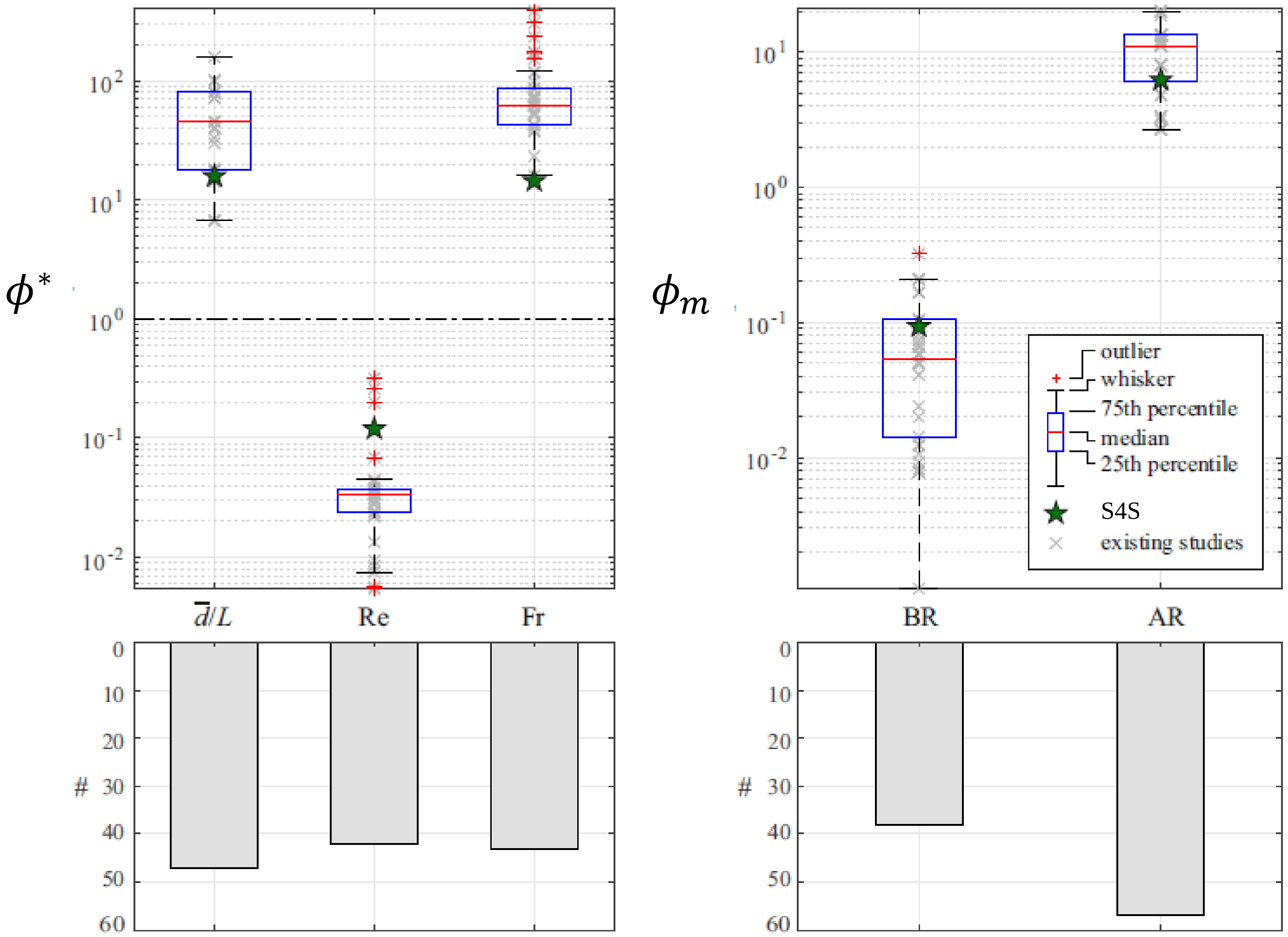


$$\left(\frac{L}{h_s}\right)_m \gg 1$$

$$\left(\frac{u_*}{u_{*t}}\right)_m = \left(\frac{u_*}{u_{*t}}\right)_p$$

$$\phi^* = \frac{\phi_m}{\phi_p}$$

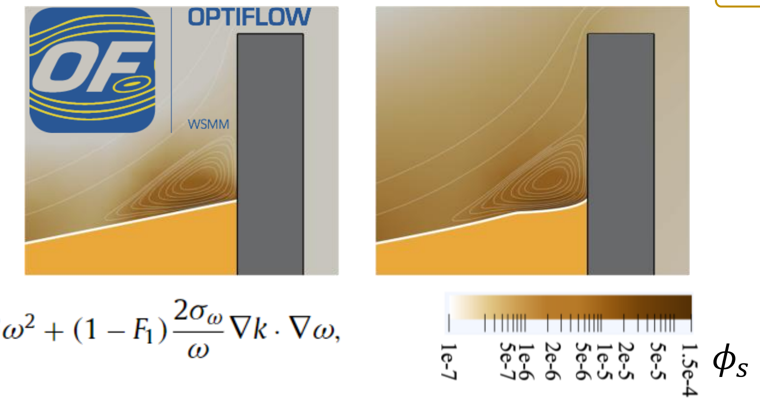
$$\phi = \left\{\frac{\bar{d}}{L}, Re, Fr\right\}$$



from L. Raffaele, J. van Beeck, L. Bruno (2021)

Wind-Sand CFD model

- Eulerian 1st order multiphase model



Wind flow:

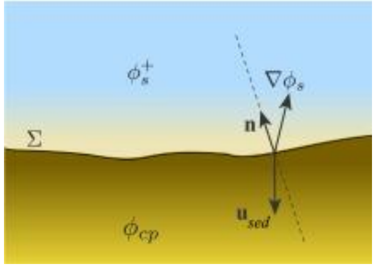
RANS k-ω SST

$$\begin{cases} \nabla\cdot\overline{\mathbf{u}}_f = 0, \\ \dfrac{\partial\overline{\mathbf{u}}_f}{\partial t} + \overline{\mathbf{u}}_f\cdot\nabla\overline{\mathbf{u}}_f = -\dfrac{1}{\hat{\rho}_f}\nabla\overline{p} + \nabla\cdot\left[(\nu_f+\nu_t)\nabla\overline{\mathbf{u}}_f\right], \\ \dfrac{\partial k}{\partial t} + \nabla\cdot(k\overline{\mathbf{u}}_f) = \nabla\cdot[(\sigma_k\nu_f+\nu)\nabla k] + \tilde{P}_k - \beta^* k\omega, \\ \dfrac{\partial\omega}{\partial t} + \nabla\cdot(\omega\overline{\mathbf{u}}_f) = \nabla\cdot[(\sigma_\omega\nu_f+\nu)\nabla\omega] + \alpha\dfrac{\omega}{k}P_k - \beta\omega^2 + (1-F_1)\dfrac{2\sigma_\omega}{\omega}\nabla k\cdot\nabla\omega, \end{cases}$$

Sand phase:

Sand mass conservation equation

$$\begin{cases} \dfrac{\partial\phi_s}{\partial t} + \nabla\cdot\boldsymbol{q} = 0 \\ \boldsymbol{q} = \boldsymbol{u}_{tr}\phi_s + \boldsymbol{u}_{sed}\phi_s - \nu_{eff}\phi_s^{k-1}\nabla\phi_s \end{cases}$$



Sand erosion B.C.

$$-\nu_{eff}\phi_s^{k-1}\nabla\phi_s\cdot n = A_H\hat{\rho}_f\sqrt{\frac{d}{g}}\left(u_*^2 - u_{*t}^2\right)_+$$

Ho et al. (2012)

Sand bed morphodynamic evolution

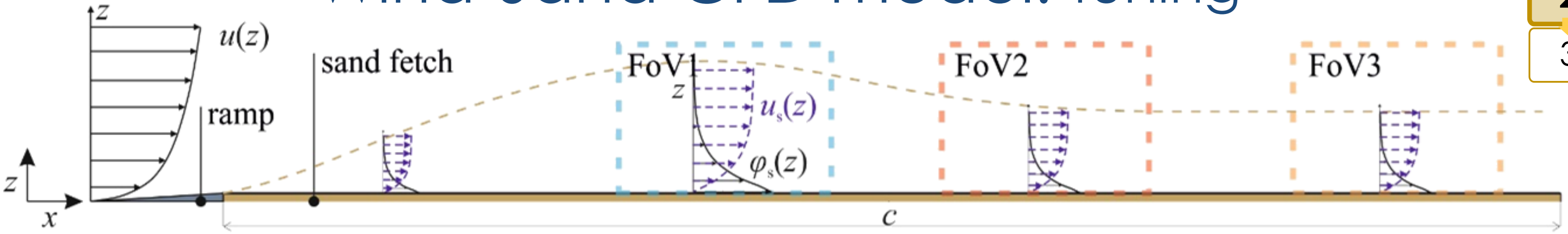
$$v_\Sigma^{ED}\cdot n = -\frac{1}{\phi_{cp}-\phi_s}\boldsymbol{q}\cdot\boldsymbol{n} = \underbrace{\frac{\phi_s(\boldsymbol{u}_{tr}+\boldsymbol{u}_{sed})\cdot n}{\phi_{cp}-\phi_s}}_{Deposition} + \underbrace{\frac{\nu_{eff}\phi_s^{k-1}\nabla\phi_s\cdot n}{\phi_{cp}-\phi_s}}_{Erosion}$$

Sand avalanching

$$\frac{\partial h}{\partial t} = \nu_{av}\nabla\cdot\left[\frac{(|\nabla h| - \tan\theta_{cr})_+}{\sqrt{1+|\nabla h|^2}}\frac{\nabla h}{|\nabla h|}\right] + Deposition + Erosion$$

Lo Giudice and Preziosi, Appl. Math. Model. (2020)

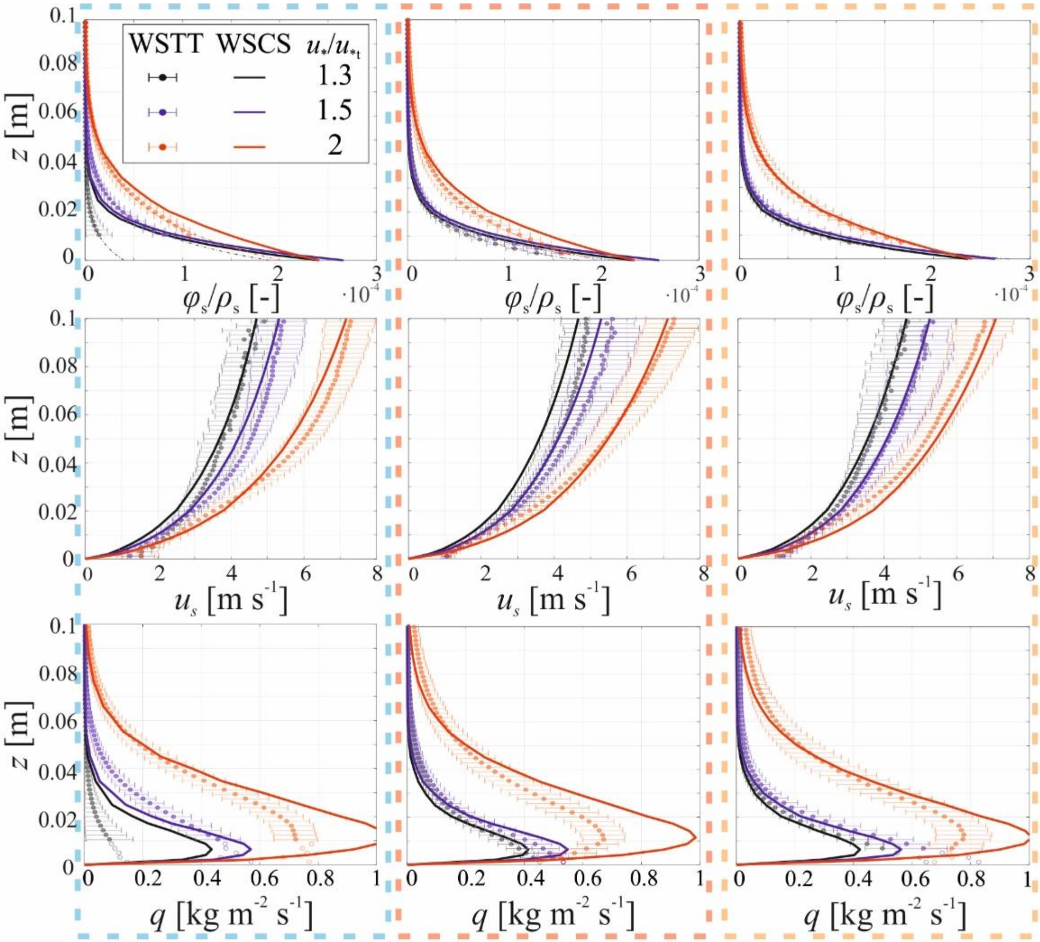
Wind-Sand CFD model: tuning



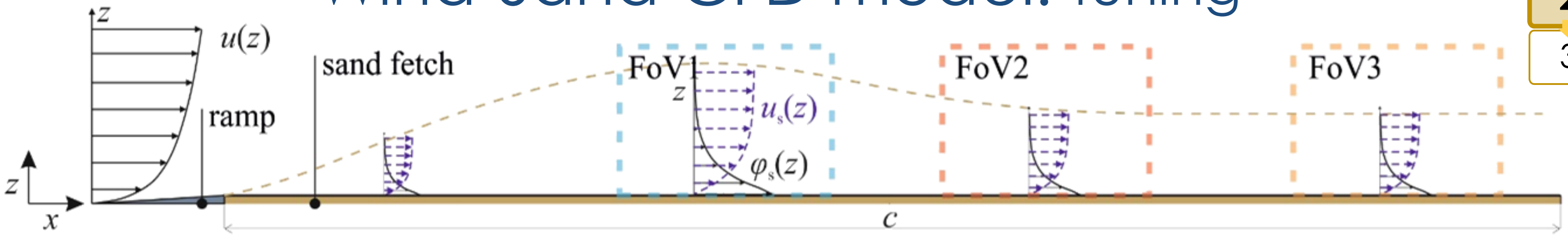
Mean sand concentration φ_s

Mean sand velocity u_s

Mean sand flux q

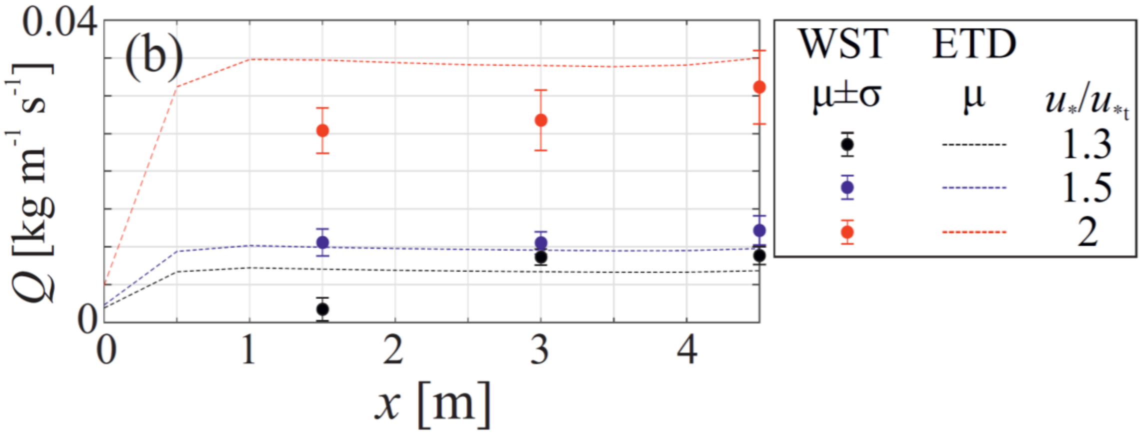


Wind-Sand CFD model: tuning



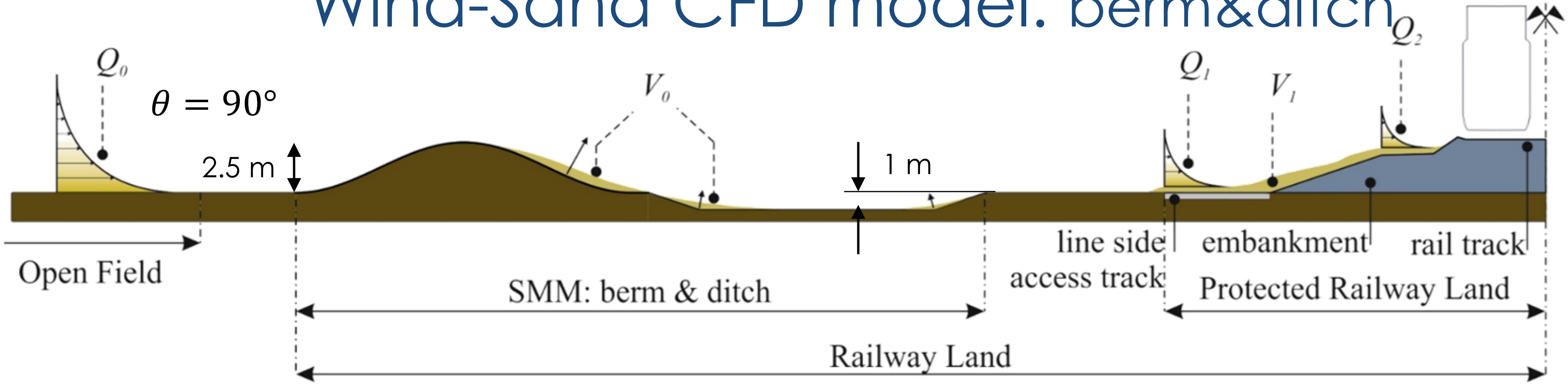
sand transport rate

$$Q = \int_0^{+\infty} q\,(z)\,dz$$

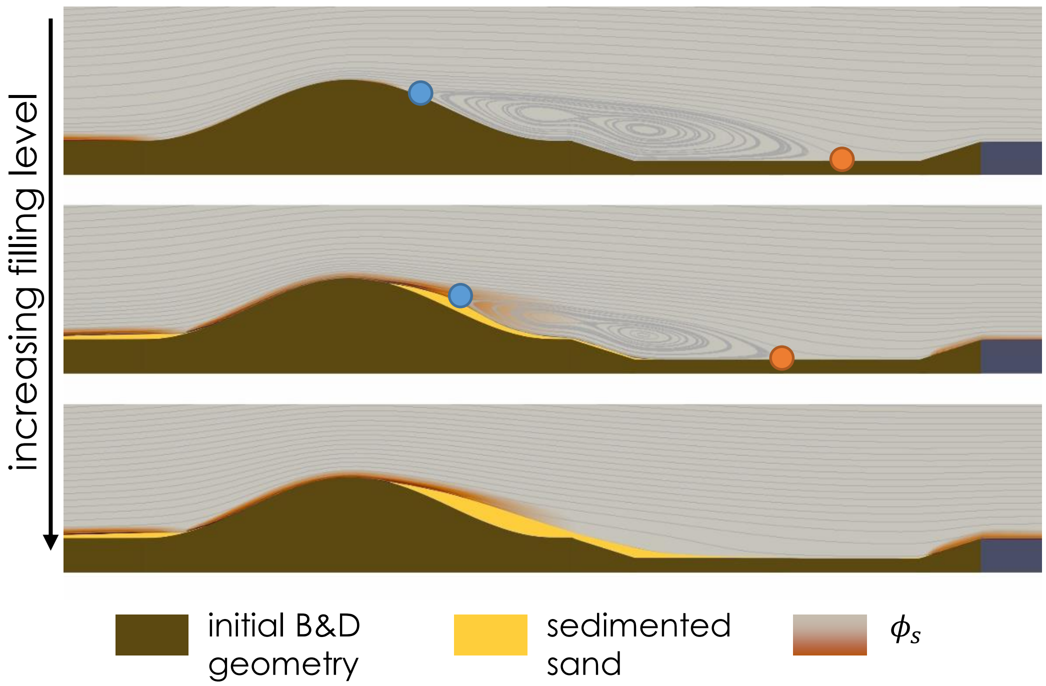


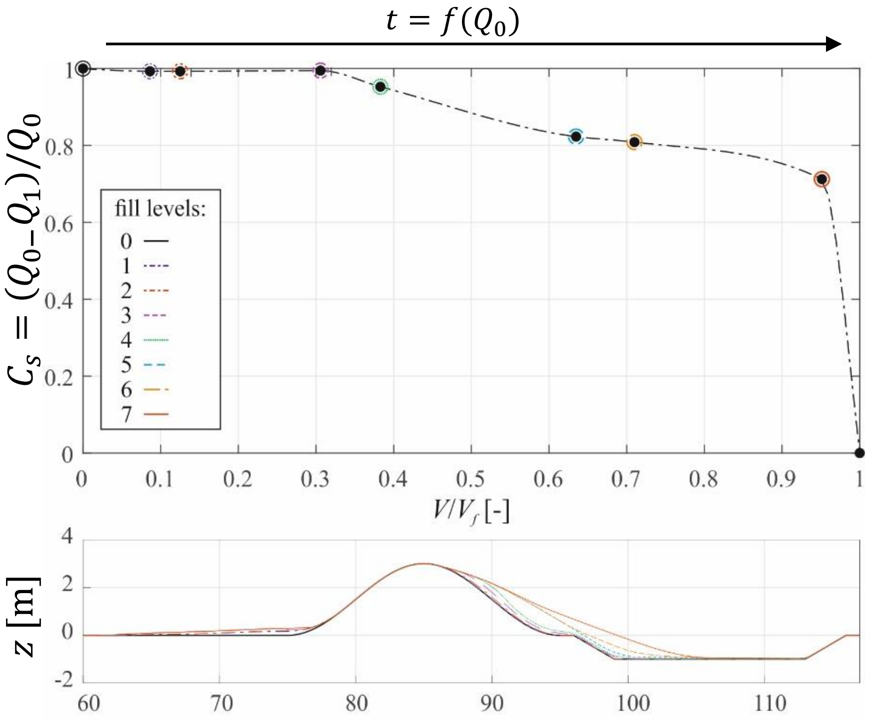
- WSTTs results are reproduced fairly good
- Mismatching of experimental results induced by:
  (i) high intermittency for $u_*/u_{*t} = 1.3$
  (ii) short fetch length
  (iii) 1st order nature of the model

Wind-Sand CFD model: berm&ditch



SMM aerodynamic working principle





from L. Raffaele, N. Coste, G. Glabeke (2022)

Windblown sand action

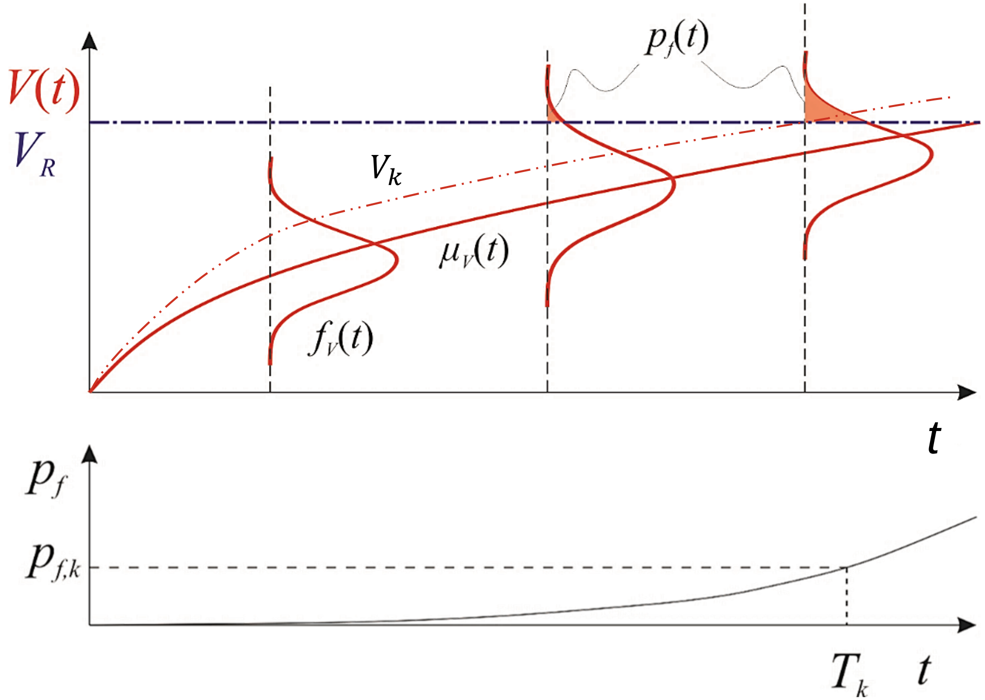
Time-variant WbS action $V(t)$

$$f_V(t) = \sum_{n=1}^{\infty} (g_1 * g_i * \cdots * g_n)\boldsymbol{C_s}\boldsymbol{Q_{in}}\mathrm{P}[N_\theta = n]$$

Resistant sand volume V_R

- Structure/Infrastructure ⇐ **SLS**
- SMM ⇐ efficiency ($\boldsymbol{C_s}$)

Time variant reliability analysis $V(t) < V_R$



Probability of failure

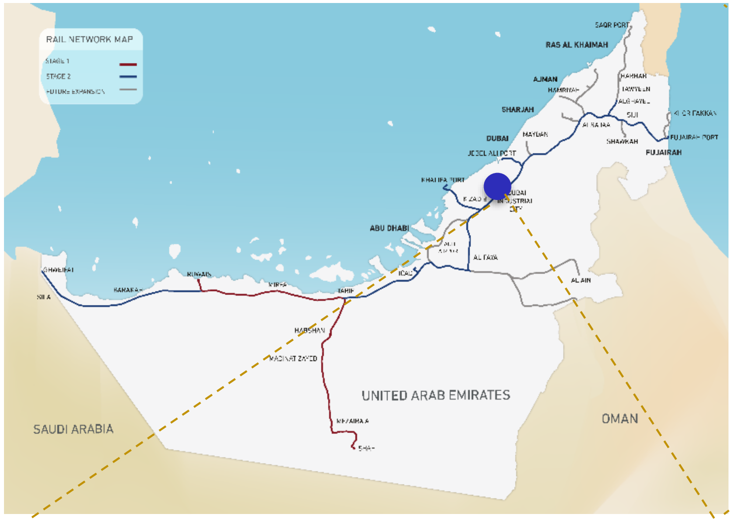
$$p_f(t) = P[V(t) \geq V_R]$$
$$= \int_0^{+\infty} F_{V_R}(x) f_V(x,t)dx = 1 - F_V(V_R, t)$$

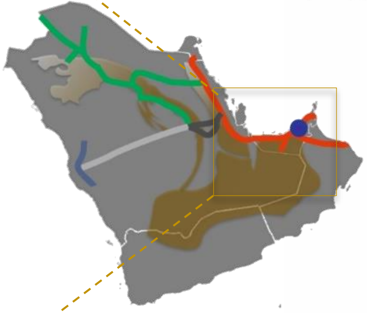
Characteristic time of failure

$$T_k = p_f^{-1}(p_{f,k}) \quad \text{e.g. } p_{f,k} = 5\%$$

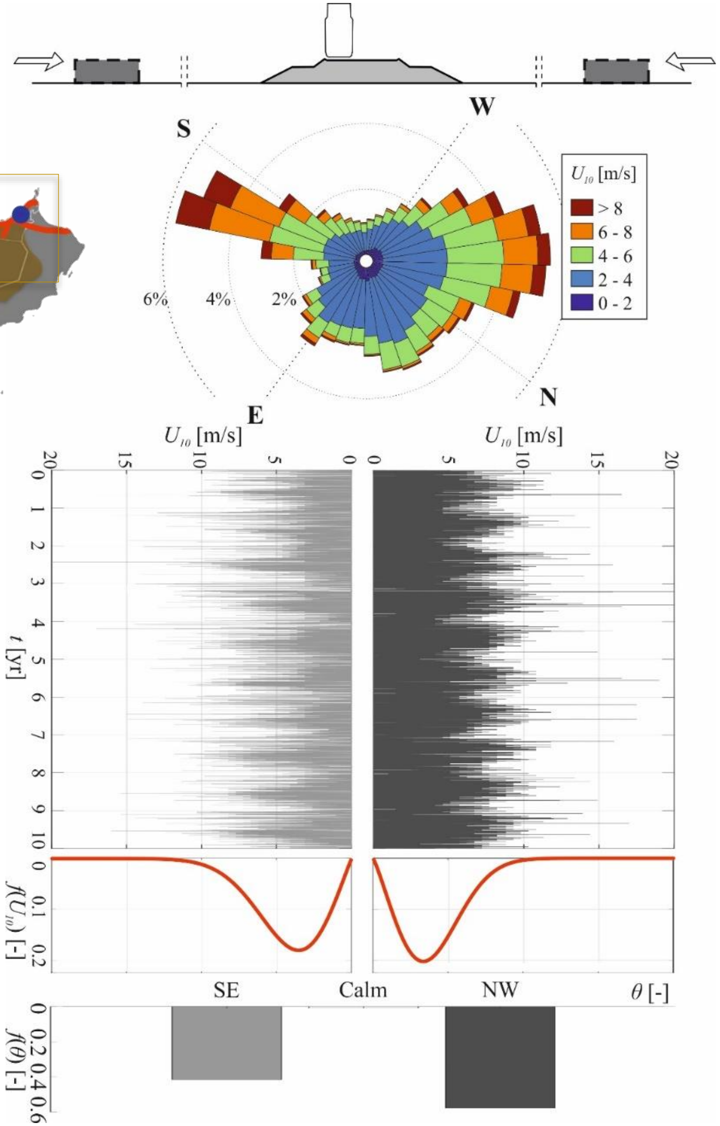
⇒ sand removal period $\leq T_k$

A case study: wind-sand site analysis

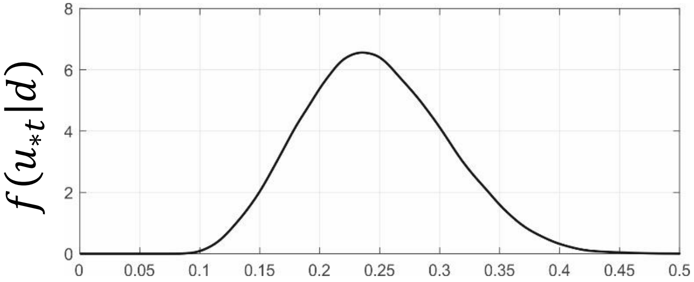




Wind statistics $z_0 = 4e - 3$ m

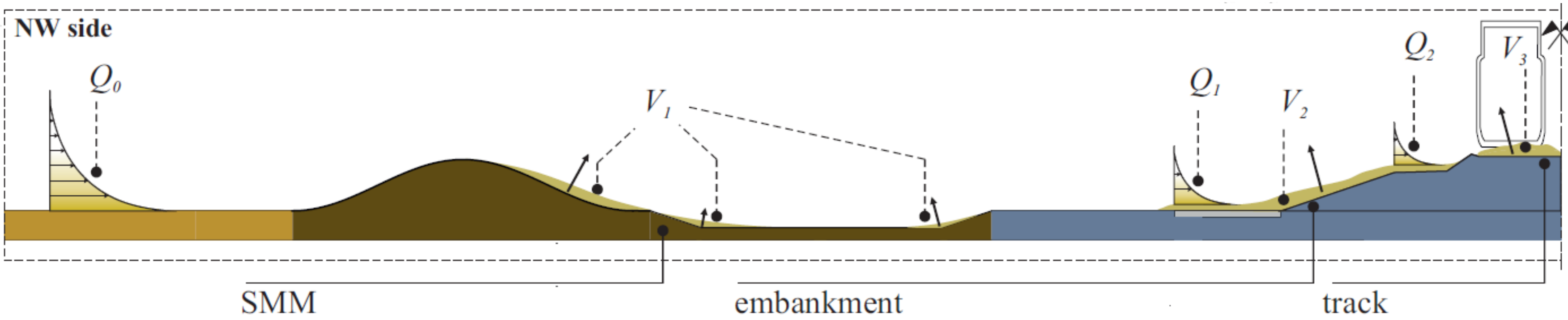


u_{*t} statistics $(d = 0.147$ mm)

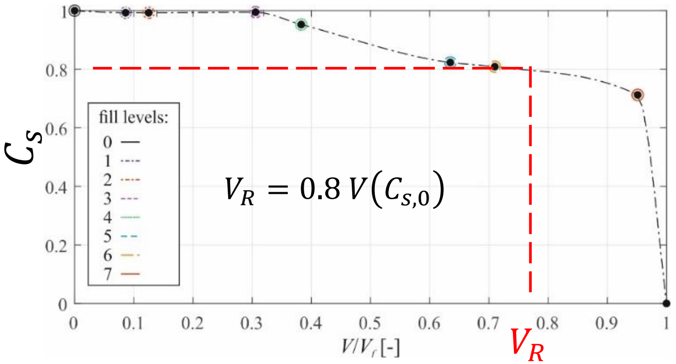


u_{*t} from Raffaele et al (2016)

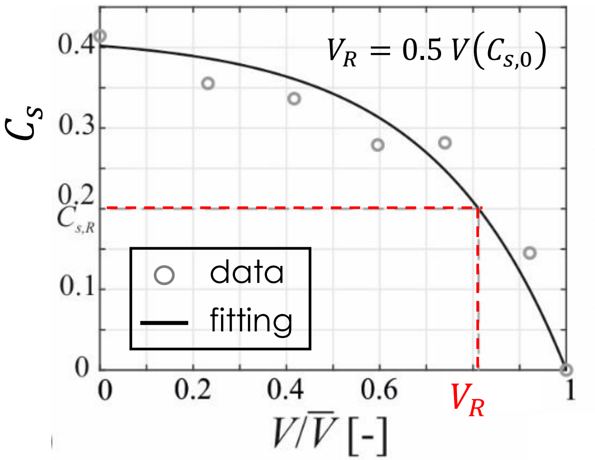
A case study: sedimentation coeffs



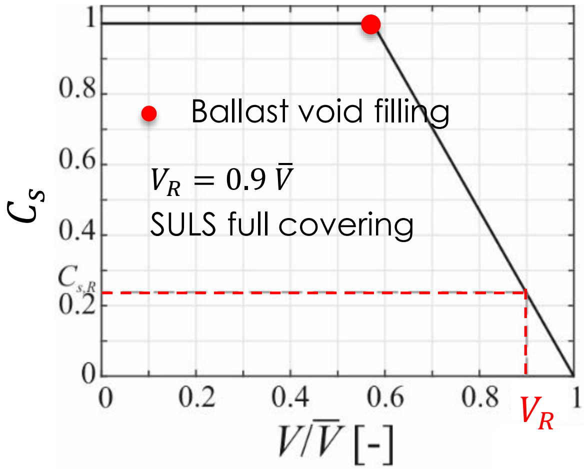
from WT+CFD Raffaele et al. (2022)

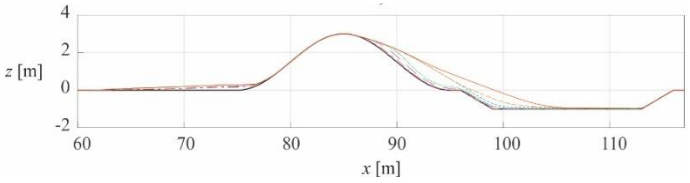


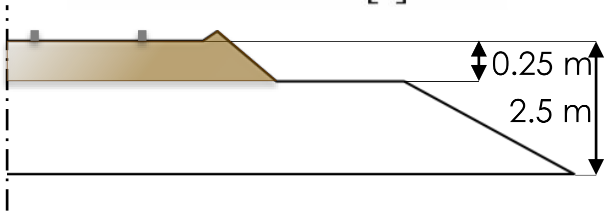
from WT tests Hotta & Horikawa (1990)



conjectured





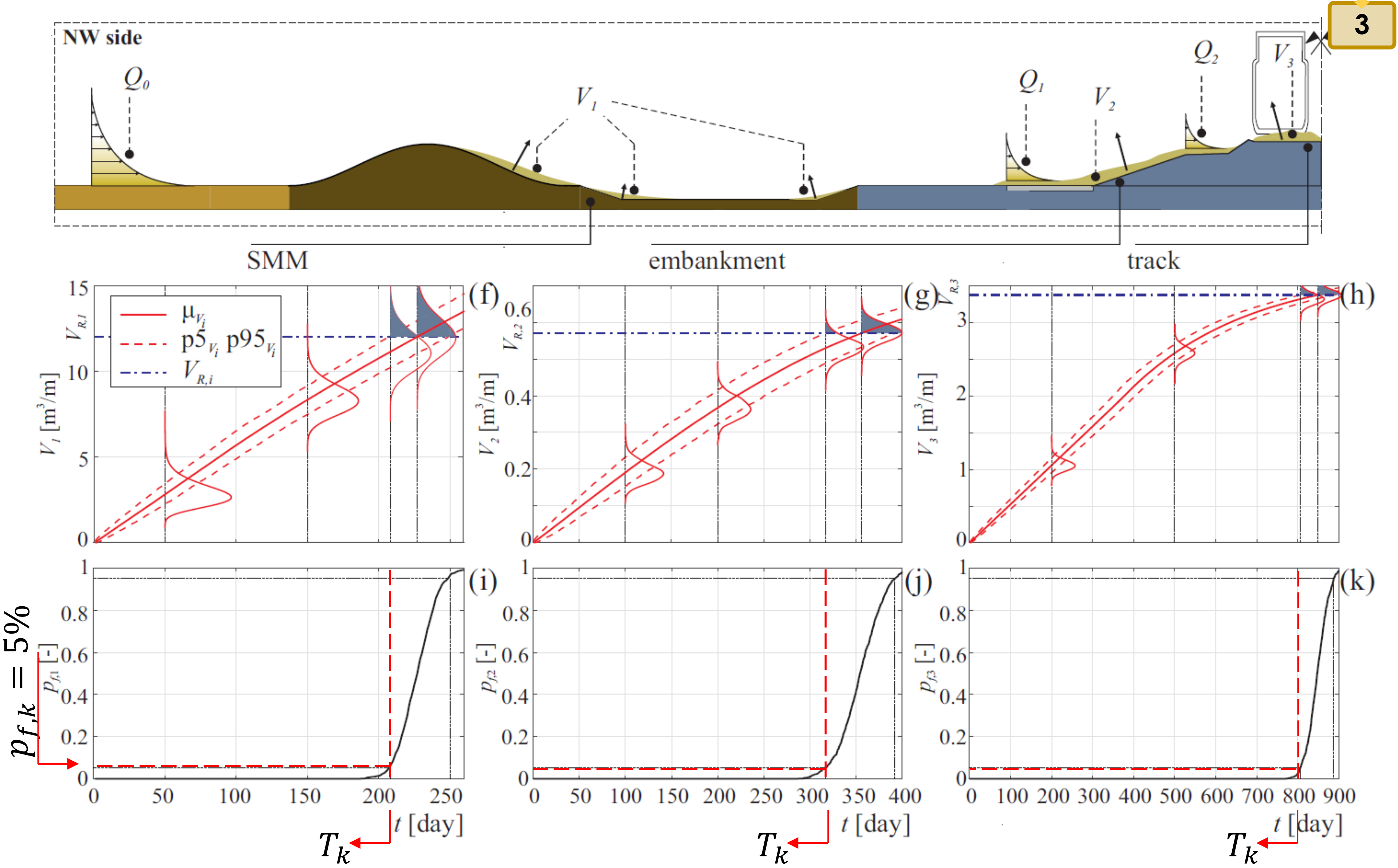


1

2

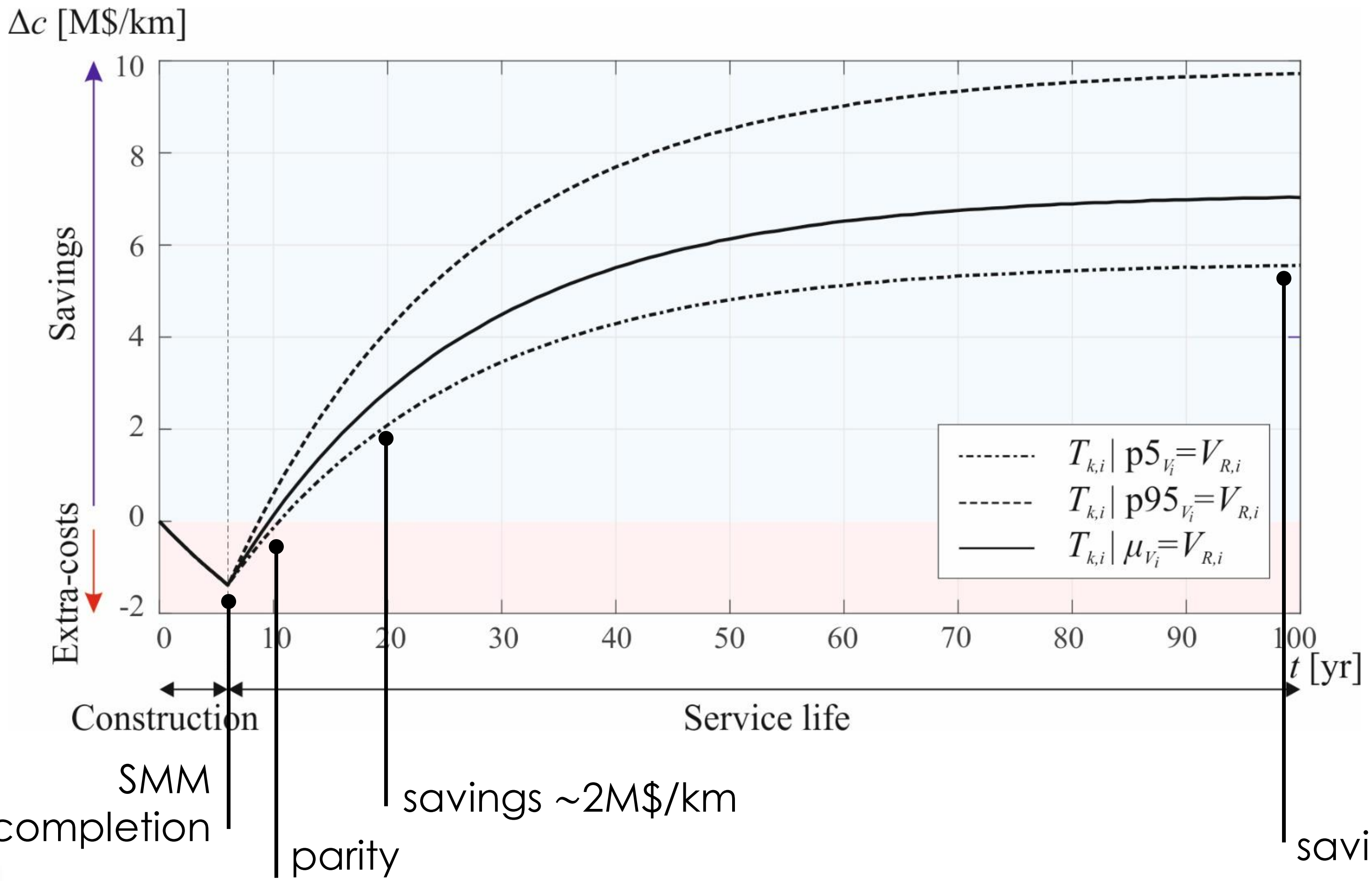
3

A case study: windblown sand action (NW)



A case study: LCCA

$$c(t_L) = \sum_{t=1}^{t_L} \left[\frac{c_d/T_d + \sum_{i=1}^{N} c_{s,i}/T_{k,i}}{(1+r)^t} \right] \Rightarrow \Delta c = c(t_L)_{SMM} - c(t_L)_0$$



SMM completion

parity

savings ~2M$/km

savings ~5M$/km

cumulated savings are impressive w.r.t. railway avg worth (in ME ~4M$/km)

To sum up

The proposed modelling framework allows to:

- Move from trial-and-error to rationale design
- Assess the performances of SMMs
- Plan sand removal maintenance operations
- Assess the economic impact of SMMs

Next steps…

- Validation of Wind-Sand CFD model thanks to wind tunnel testing
- Quantification of scale effect induced by wind tunnel scaling by means of Wind-Sand CFD simulations

HyPer SMM

Hybrid **Per**formance assessment of **S**and **M**itigation **M**easures

EU Horizon 2020 Marie Curie Individual Fellowship

von KARMAN INSTITUTE FOR FLUID DYNAMICS

OPTIFLOW

WSMM

HyPer SMM received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 885985