Windblown Sand Modelling and Mitigation

MAFD - TCS

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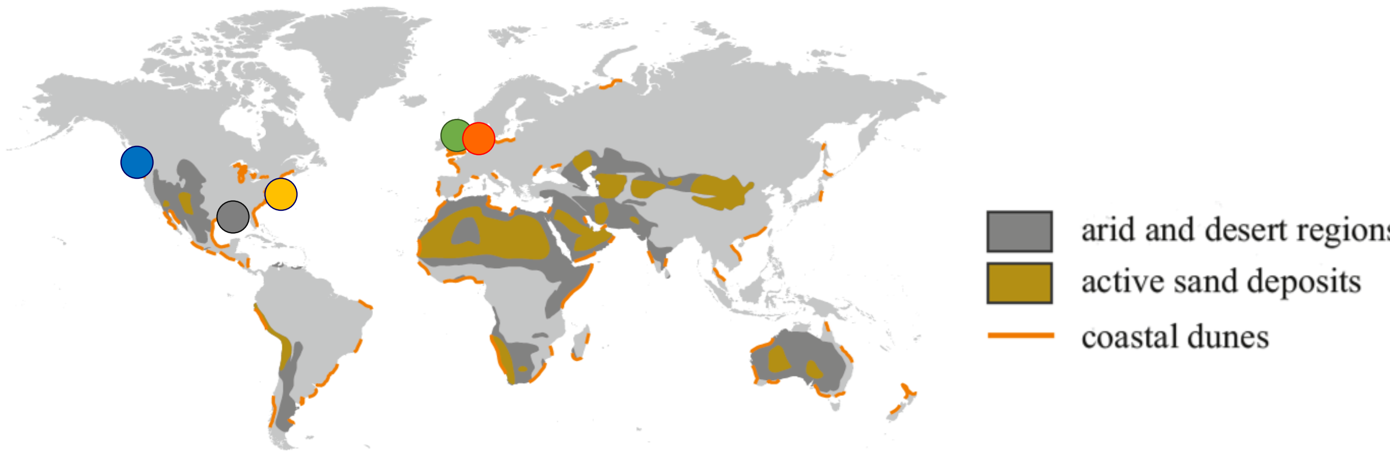
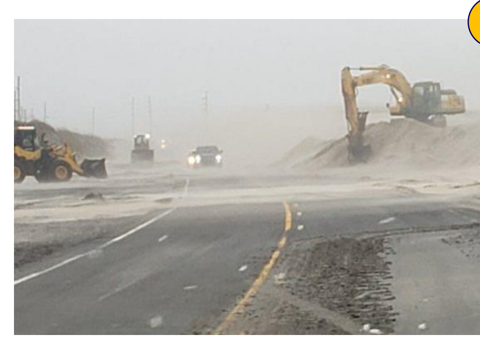
Industrial Motivation: coastal zones



US

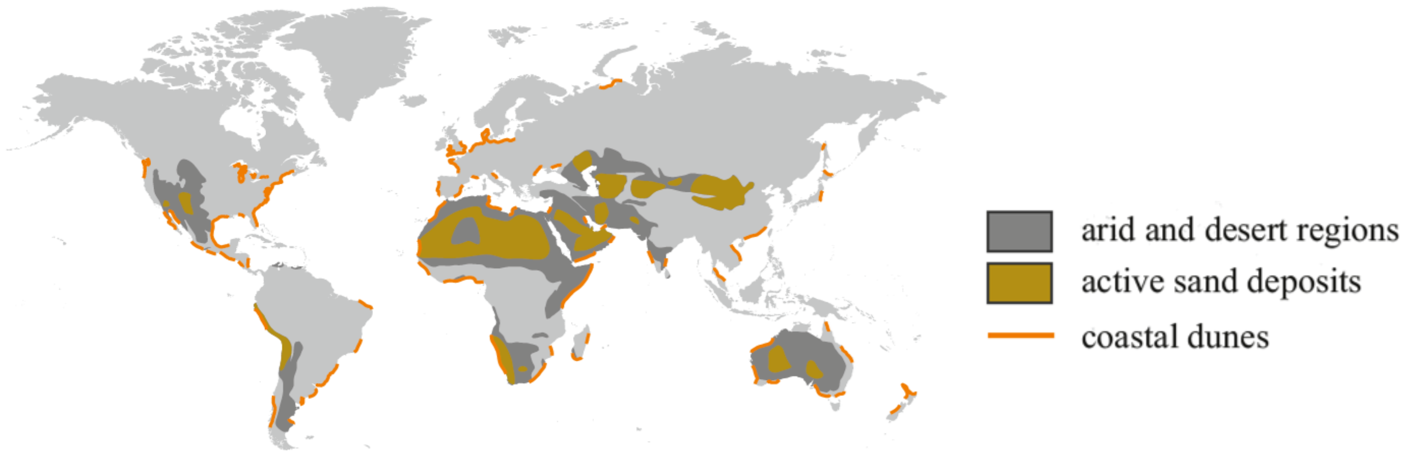


EU

Windstorm frequency **+44%**

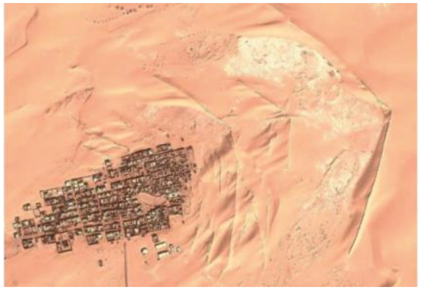
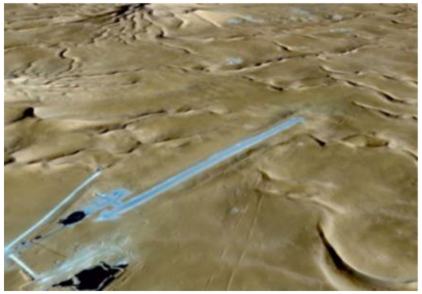
Windstorm intensity **+96%**

Industrial Motivation: desert regions







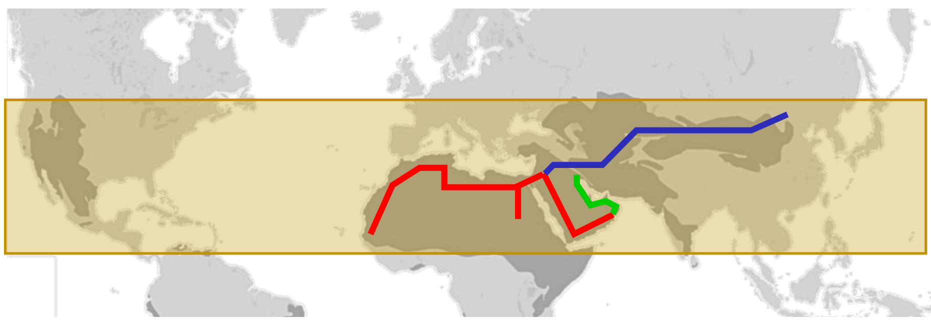





Structure scale | Urban scale | Infrastructure scale

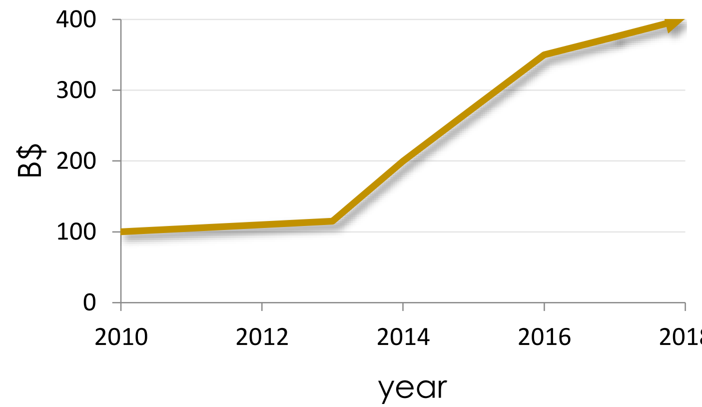
Industrial Motivation: railway megaprojects

Railway megaprojects

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



- arid regions
- northern desert belt



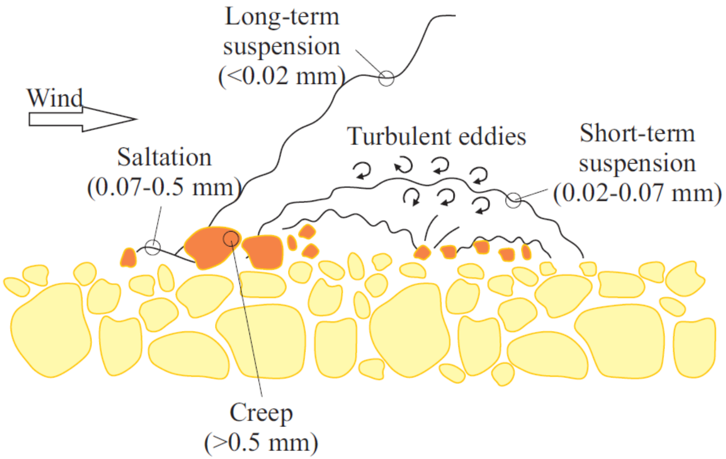
Market potential

- **000** B$

Railway length

- **00000** Km

Phenomenology

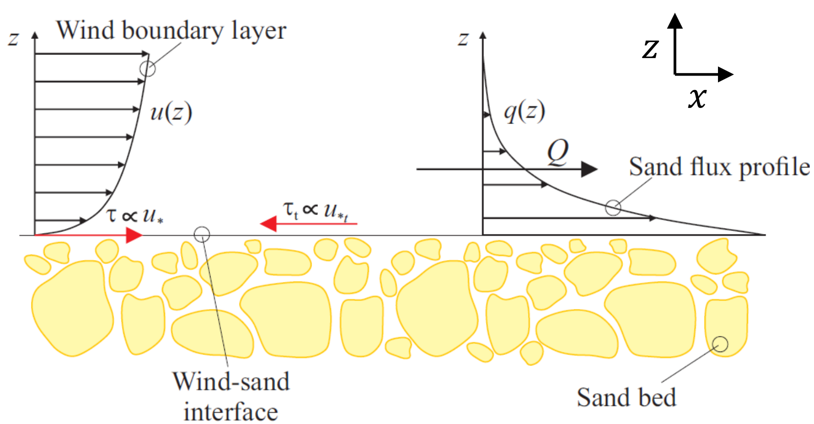


Dust $d < 0.063$ mm
- long-term suspension
- short-term suspension

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

Engineering interest

Saltation



$q(z) > 0$ ⟺ $\tau > \tau_t$ WbS saltation condition

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

Threshold shear velocity

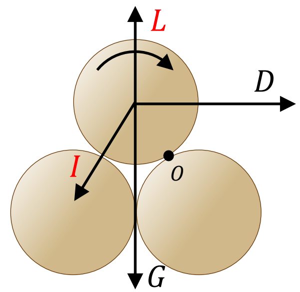
Sand transport rate $[kg\, m^{-1} s^{-1}]$ $Q = \int_0^{+\infty} q(z)\, dz$

Modelling: u_{*t}

Deterministic models

Microscopic models

- Equilibrium of the moments
  Entraining aerodynamic forces VS
  Stabilizing forces

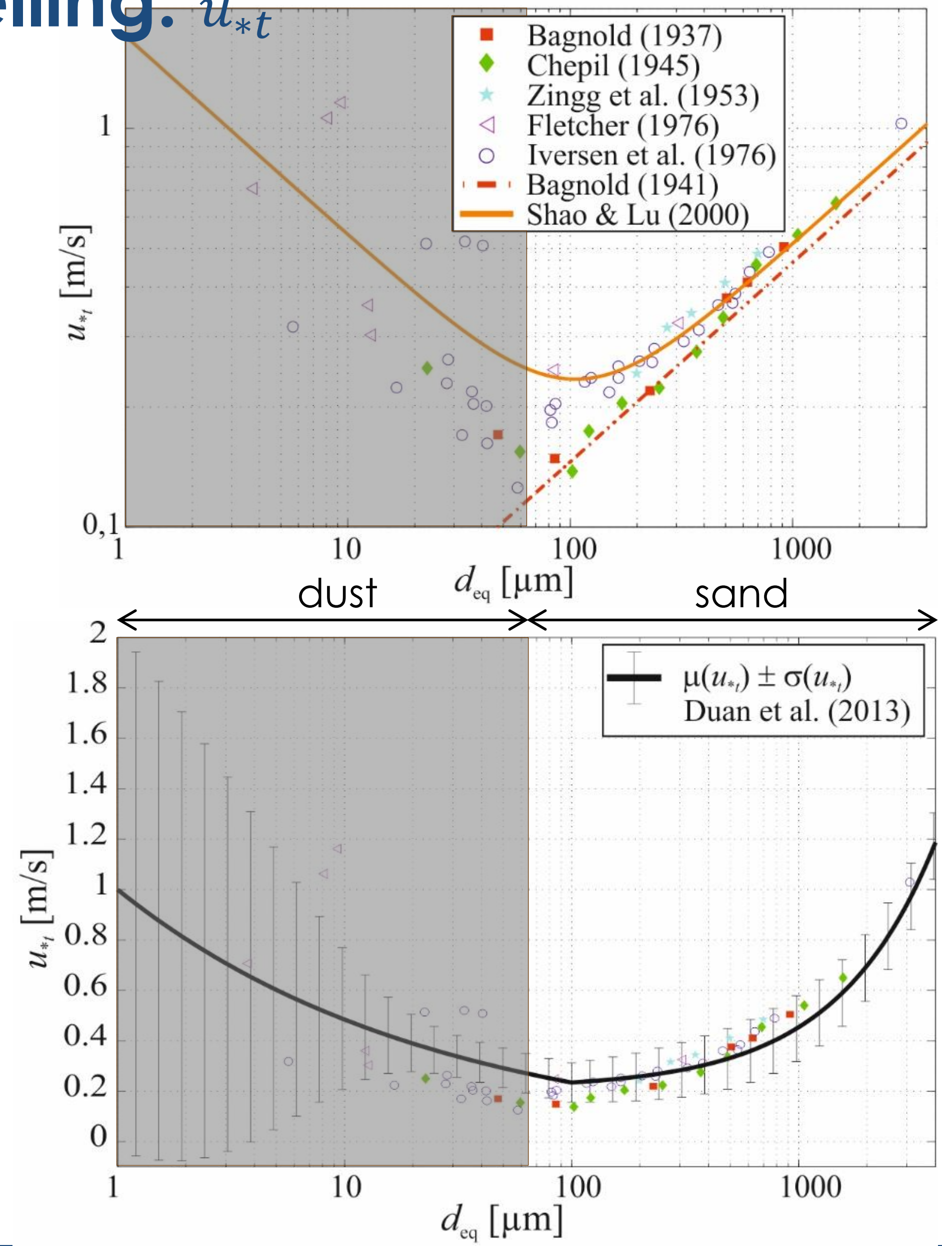


Macroscopic models

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

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

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: Q

Semi-empirical models

Bagnold type

$Q \sim u_*^3$

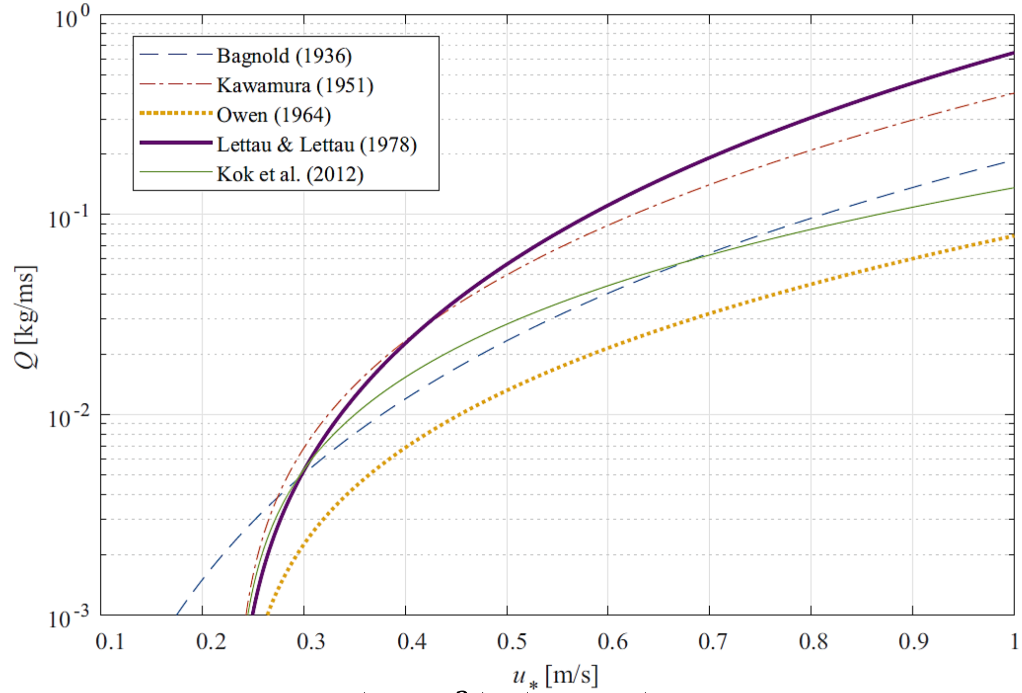
Modified Bagnold type

$Q \sim u_{*,eff}^3(u_*, u_{*t})$

O' Brien-Rindlaub type

$Q \sim u$ Dong et al. (2003)

Complex



$$Q = 2.78\frac{\rho_a}{g}u_*^3\left(1-\frac{u_{*t}^2}{u_*^2}\right)\left(1+\frac{u_{*t}}{u_*}\right)$$ Kawamura (1951)

$$Q = \left(0.25+\frac{\omega_s}{3u_*}\right)\frac{\rho_a}{g}u_*^3\left(1-\frac{u_{*t}^2}{u_*^2}\right)$$ Owen (1964)

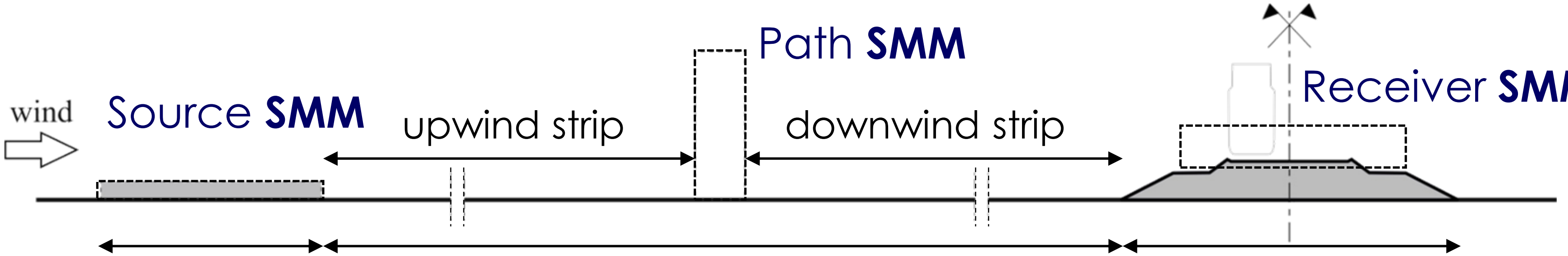
$$Q = 6.7\sqrt{\frac{d}{d_r}}\frac{\rho_a}{g}u_*^3\left(1-\frac{u_{*t}}{u_*}\right)$$ Lettau & Lettau (1951)

$$Q = 5\frac{\rho_a}{g}u_{*t}u_*^2\left(1-\frac{u_{*t}^2}{u_*^2}\right)$$ Kok et al. (2012)

Large discrepancies due to:

- large randomness of physical phenomenon
- debated scaling

Sand Mitigation Measures: Source



- Layer system

asphalt-latex mixture

natural crusting

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

Hedge system (u_*^n) — Layer system (u_{*t}^n)

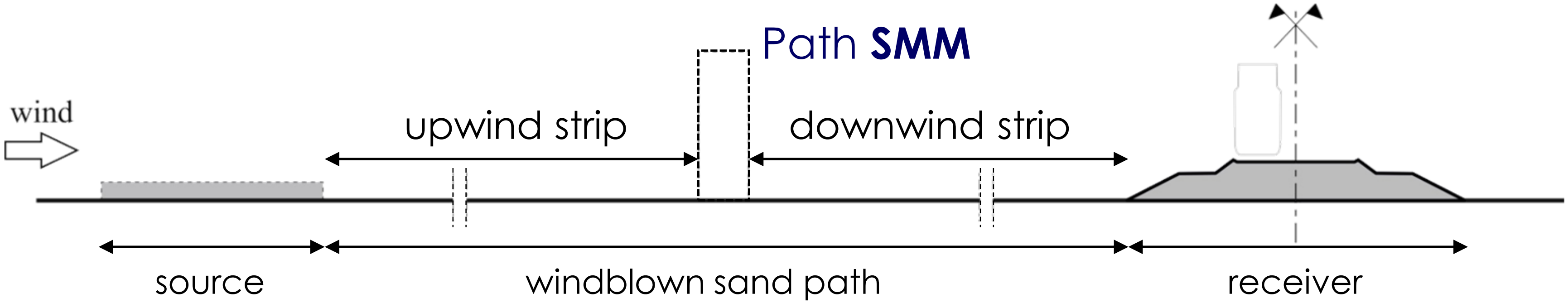
- Hedge system

straw checkerboard

array line-like obstacles

gravel surface

Sand Mitigation Measures: Path



- Surface-like

porous | solid


porous fence


Straight Vertical Wall (SVW)

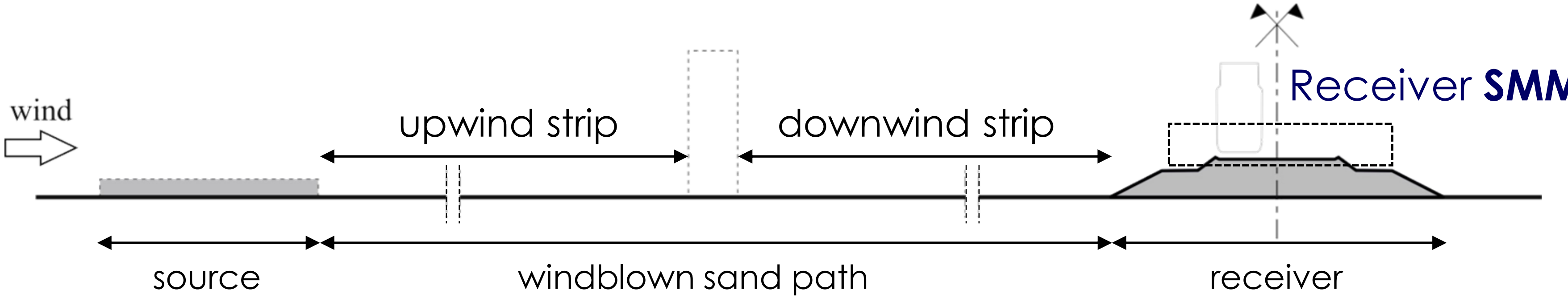

Shield for Sand (S4S)
WO 2016/181417 A1

- Volume-like


dyke

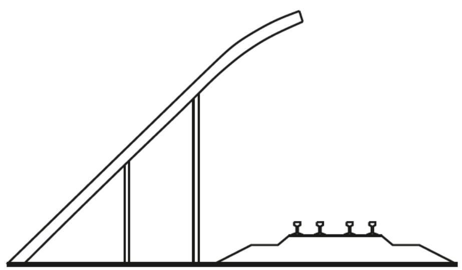

ditch

Sand Mitigation Measures: Receiver



- Aerodynamic based

Jet roofs



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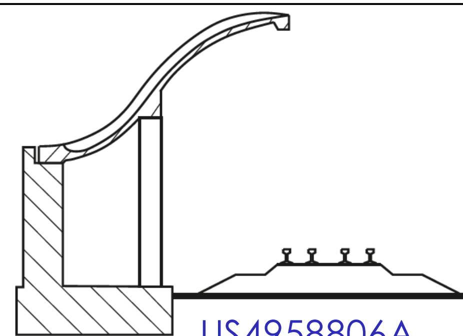


US4958806A

Venturi effect-based

Humped sleepers

- Sand-resistant

T-Track system

Continuous slab

Lubricant free turnout

an uncharted territory for modern engineering…

Windblown Sand Action: categorization

Environmental

- site-dependent
- inborn randomness

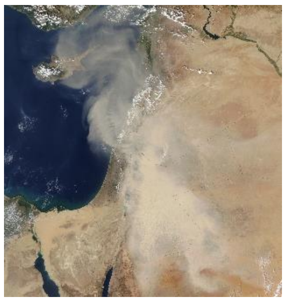
Free

- wind-dependent accumulation

Variable

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

Windblown Sand



2 months later…

analogous to

$\sim$ wind

$\sim$ windblown snow

$\sim$ snow

$\sim / \neq$ snow

modelling fallout

probabilistic modelling

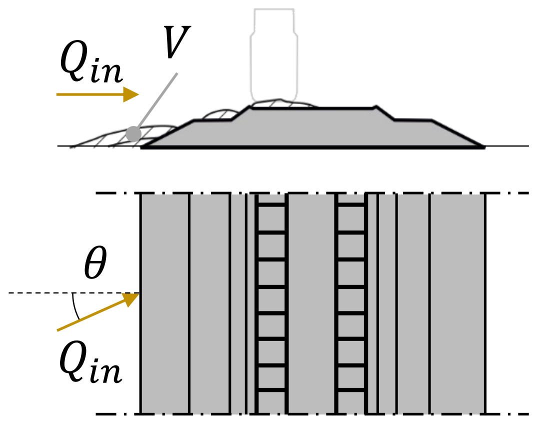
Wind and sand modelling

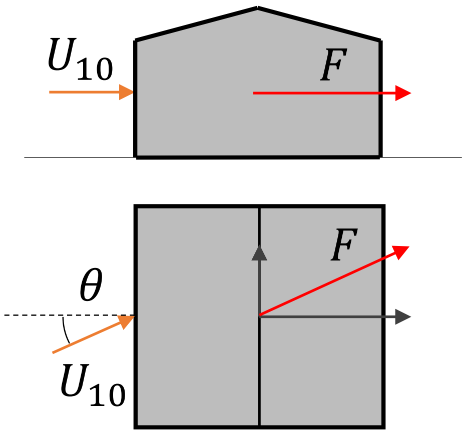
Time-variant reliability analysis

Evaluation of sand removal period

Windblown Sand Action: modelling chain

Windblown sand action VS **Wind action**





Site analysis

Windblown sand action		Wind action	
1 Incoming Windblown Sand	• $Q_{in}(U_{10}, d)$	Incoming Wind	• U_{10}

Assessment

Windblown sand action		Wind action	
2 Aerodynamics / Morphodynamics	• $C_s(\theta, \Gamma_0, V)$ — θ, Γ_0: aerodyn.; V: morphodyn.	Aerodynamics	• $C_f(\theta, \Gamma_0)$
3 Windblown sand action	• V ⇨ F ⇨ ...	Wind action	• F

Incoming Windblown Sand

$Q_{in}(\underline{u_{*t}}, \omega_s, u_*)$

Uncertainty

"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.

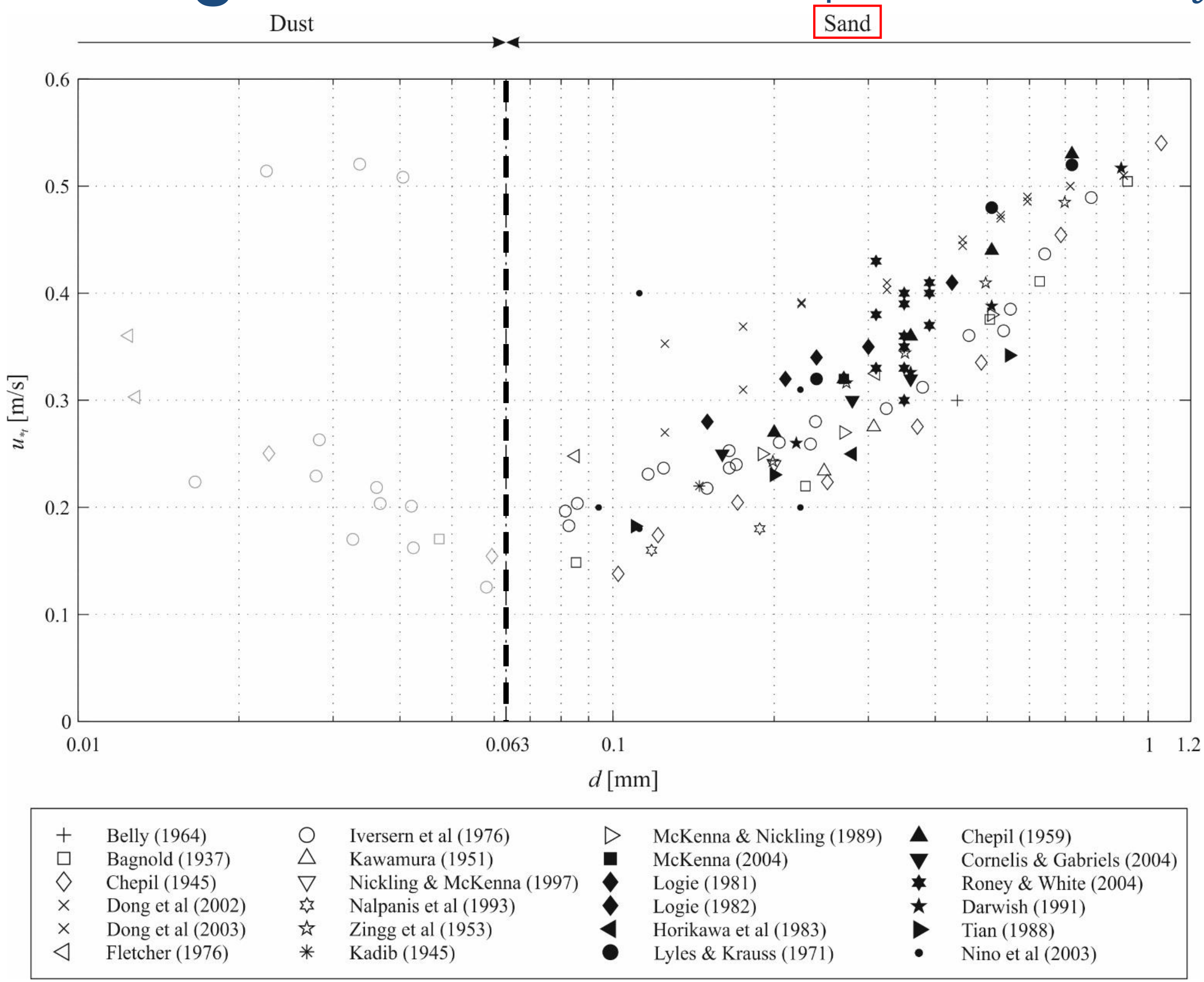
Epistemic

- 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.

Statistical approach

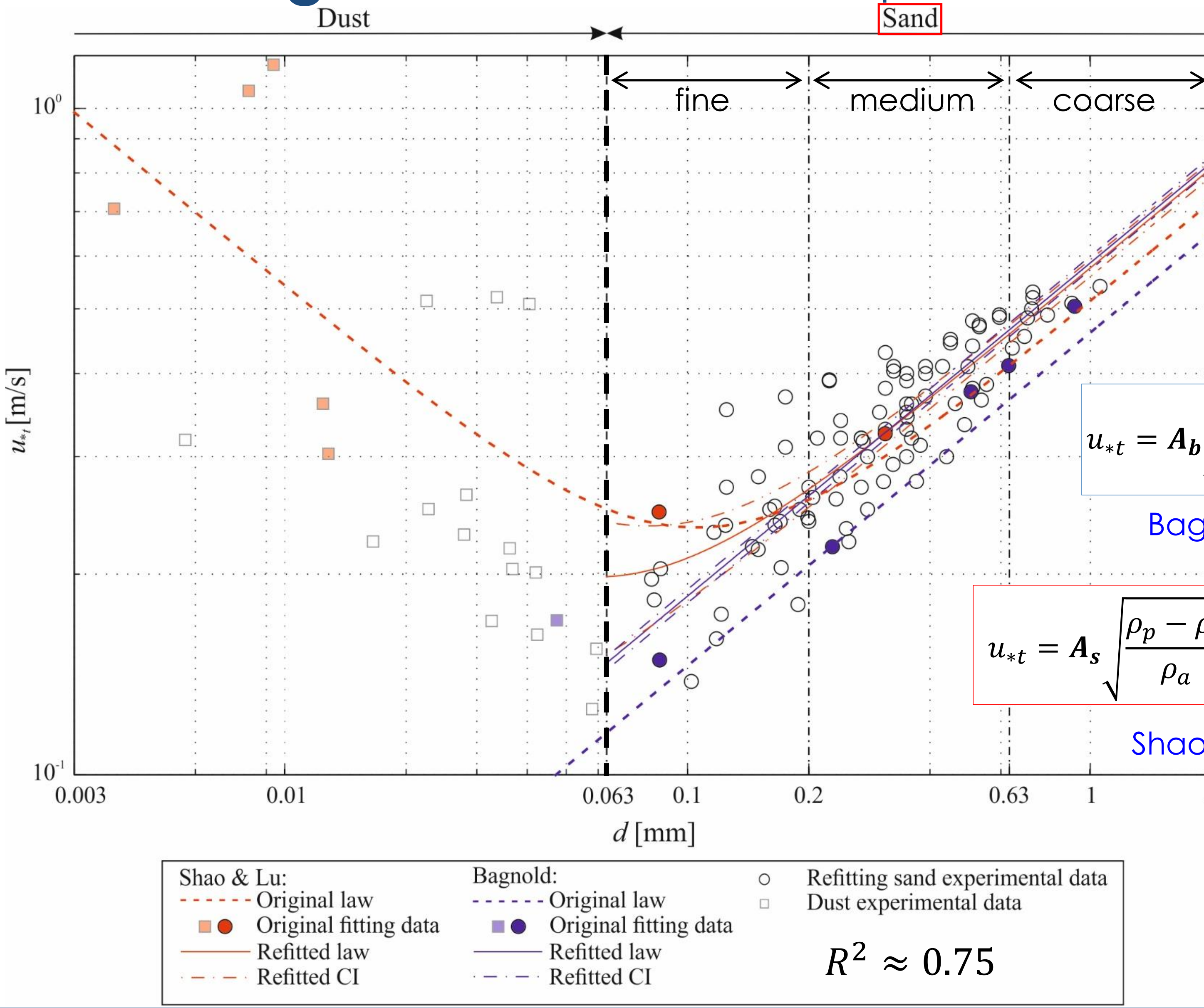
- Nonlinear regression
- Copula-based regression

Incoming Windblown Sand: probabilistic u_{*t}



- Collected studies range from 1937 to 2004.
- #=133 → #=109 from in L. Raffaele, L. Bruno, F. Pellerey, L. Preziosi (2016), Aeolian Res.

Incoming Windblown Sand: probabilistic u_{*t}



$$u_{*t} = \boldsymbol{A_b}\sqrt{\frac{\rho_p - \rho_a}{\rho_a} g d}$$

Bagnold (1941)

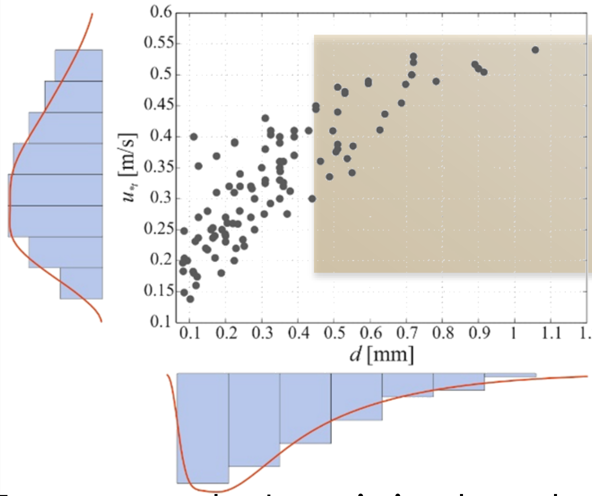
$$u_{*t} = \boldsymbol{A_s}\sqrt{\frac{\rho_p - \rho_a}{\rho_a} g d + \frac{\boldsymbol{\gamma}}{\rho_a d}}$$

Shao & Lu (2000)

Incoming Windblown Sand: probabilistic u_{*t}

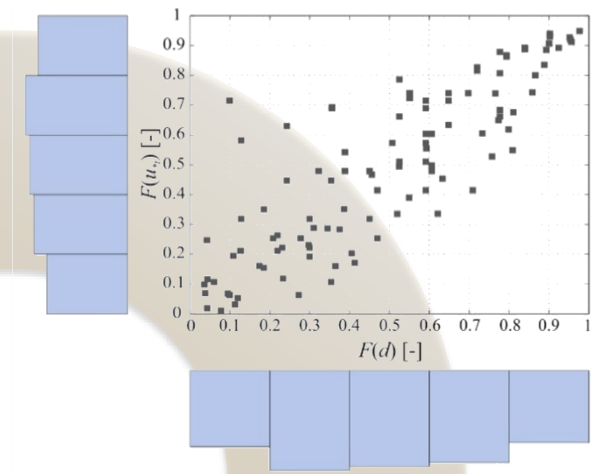
1 Fitting of marginal distributions

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



2 From original to copula scale

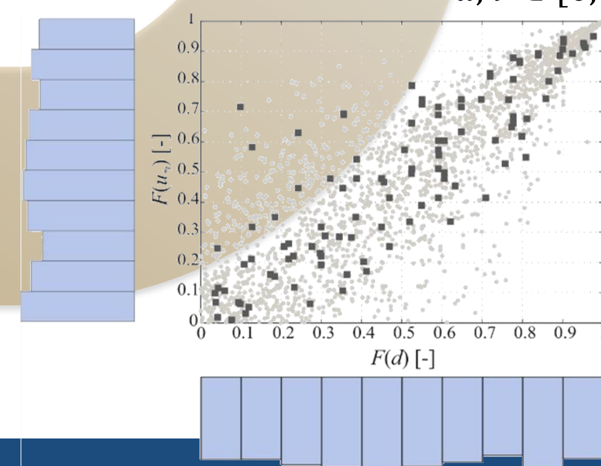
$F(d, u_{*t}) = C\{F(d), F(u_{*t})\} \quad C: [0,1]^2 \rightarrow [0,1]$



3 Fitting of Inverted Clayton Copula

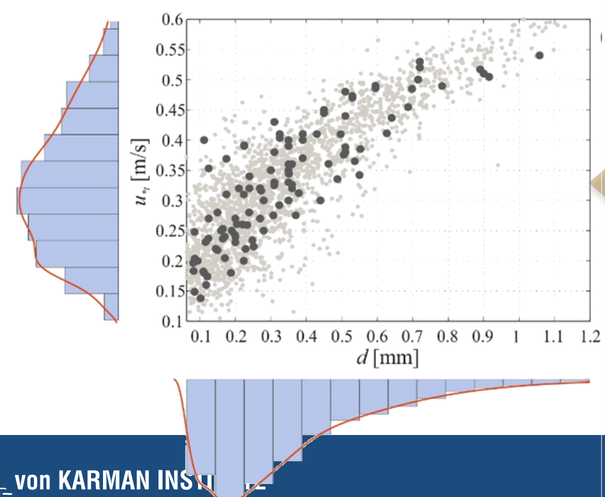
$$C(u,v) = u + v - 1 + \left[(1-u)^{-1/\alpha} + (1-v)^{-1/\alpha} - 1\right]^{-\alpha}$$

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

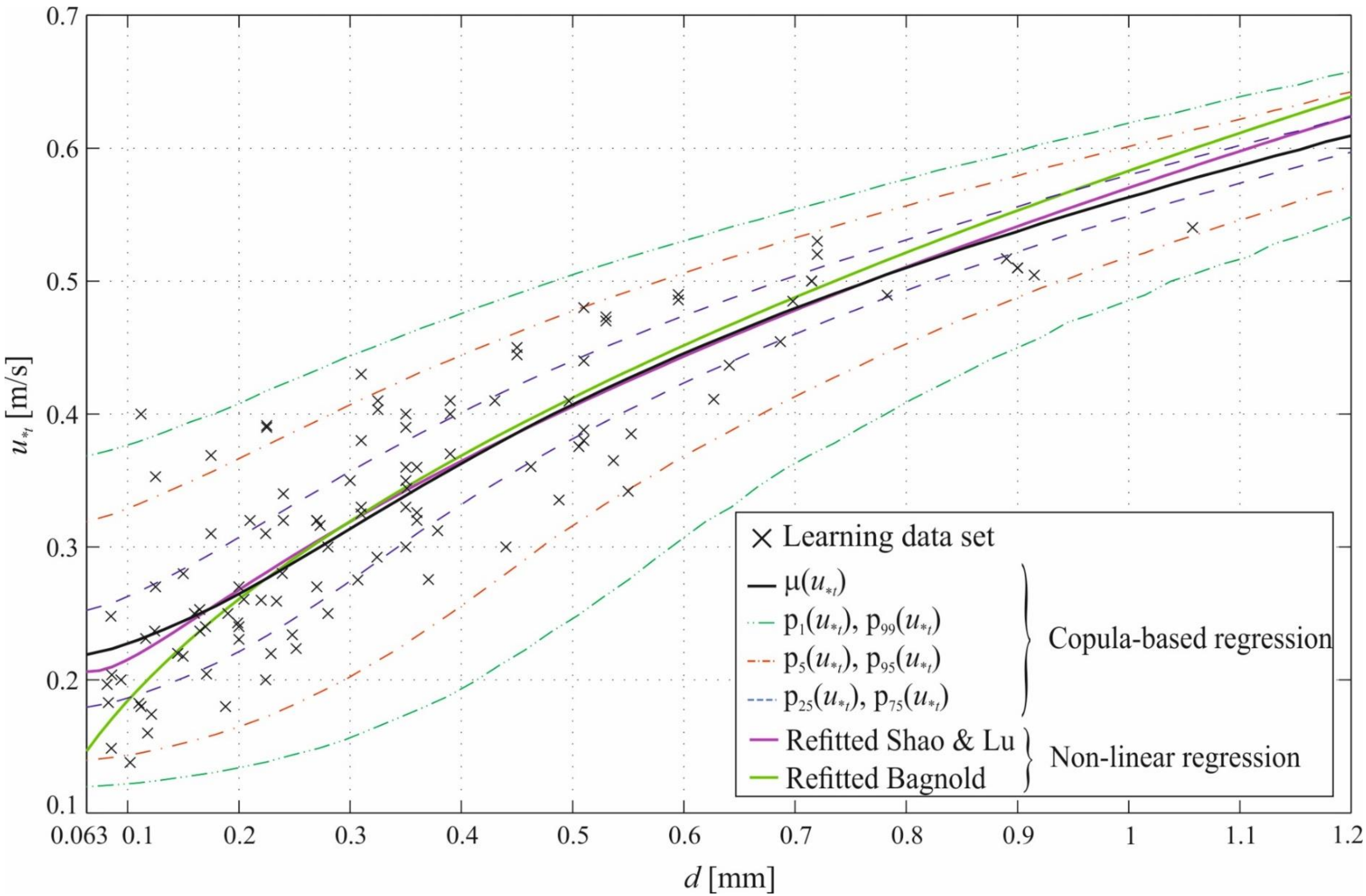


4 From copula to original scale

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



Incoming Windblown Sand: probabilistic u_{*t}

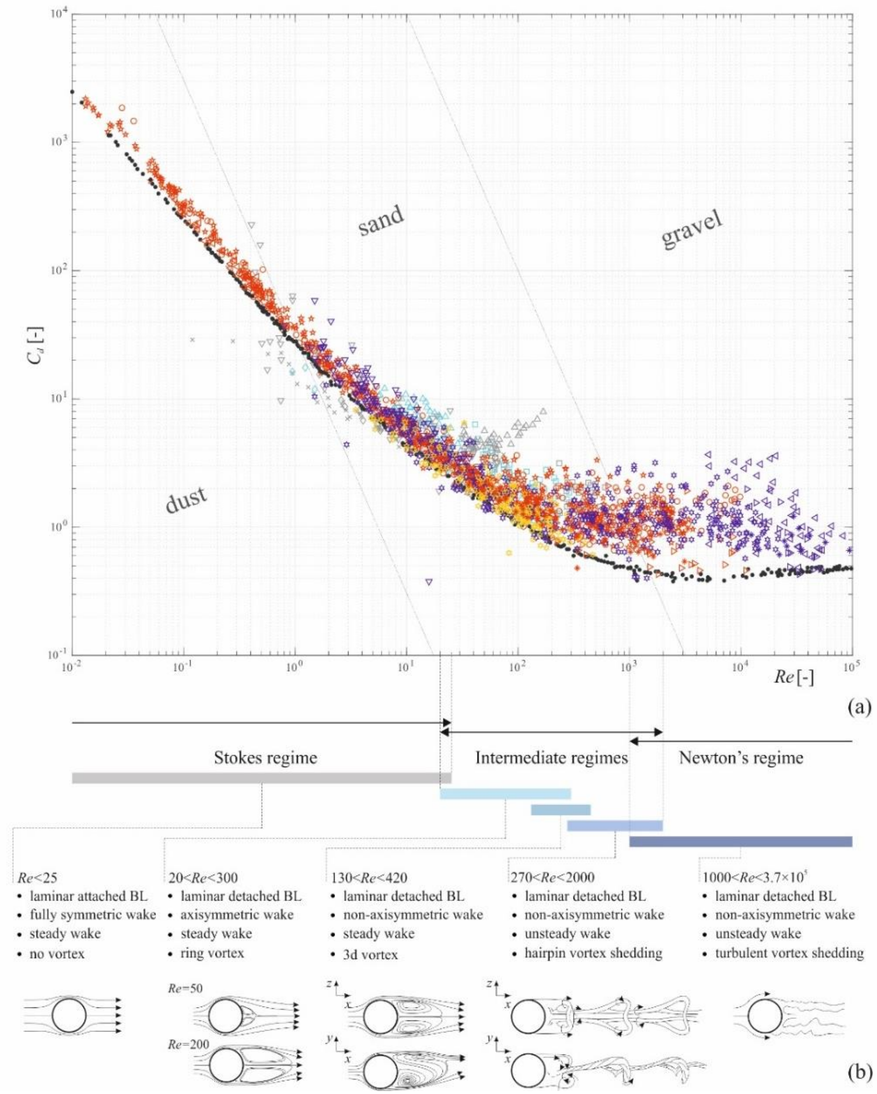


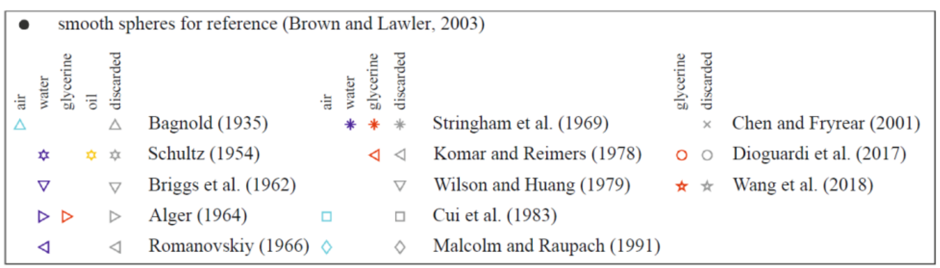
from in L. Raffaele, L. Bruno, F. Pellerey, L. Preziosi (2016), Aeolian Res.

Incoming Windblown Sand: probabilistic ω_s

$Q_{in}(u_{*t}, \underline{\omega_s}, u_*)$

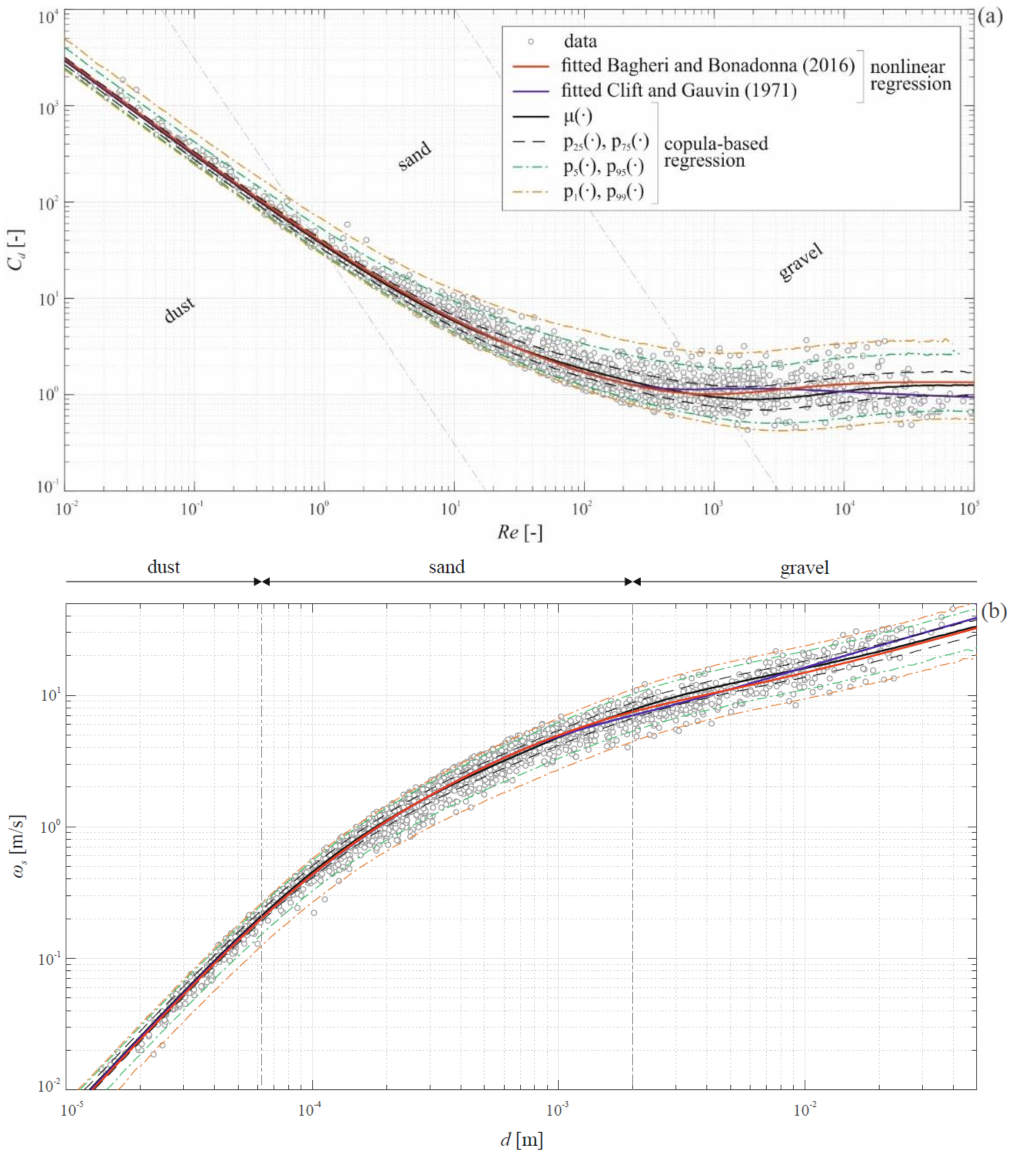
- Sedimentation velocity affects the mode of transport, distribution of particles above the ground, and transport rate
- Discrepancy among semi-empirical laws
- Sedimentation velocity bound to drag coefficient



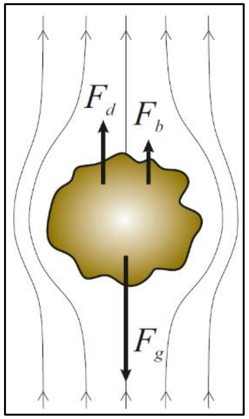


from L. Raffaele, L. Bruno, D. Sherman (2020), Aeolian Research

Incoming Windblown Sand: probabilistic ω_s



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



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

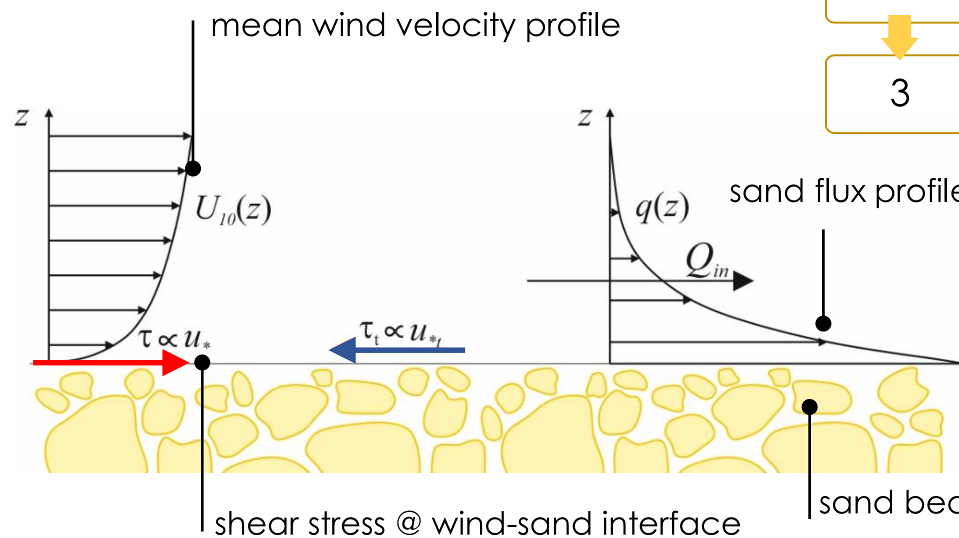
$$F_g = \rho_p g \frac{\pi d^3}{6}$$

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

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

Incoming Windblown Sand

1 → 2 → 3



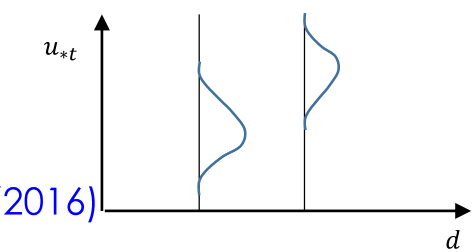
<u>Wind shear velocity</u>

$$u_* = u_*(U_{10}, z_0) \qquad f(u_*) = \frac{k f(U_{10,ref})}{\ln z_{ref}/z_0}$$

<u>Threshold shear velocity</u>

$$u_{*t} \approx u_{*t}(d)$$

$f(u_{*t}|d)$ from Raffaele et al (2016)



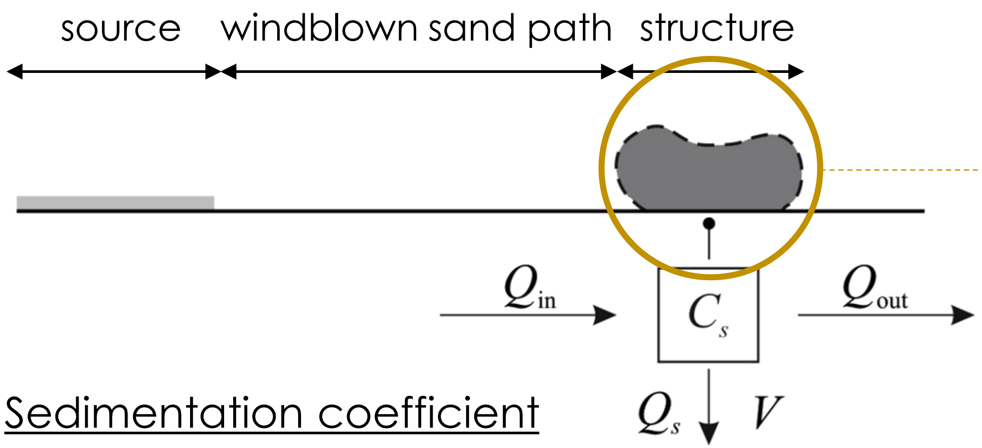
<u>Incoming</u>
<u>sand transport rate</u>

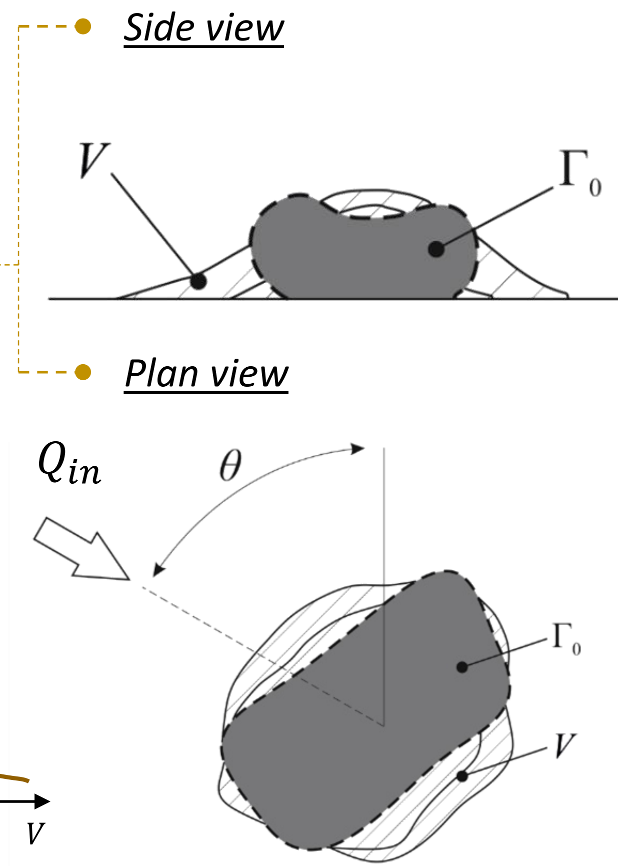
$$Q_{in} = \int_0^{+\infty} q(z)\, dz \approx Q_{in}(u_*, u_{*t})$$

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

from Raffaele et al (2017a)

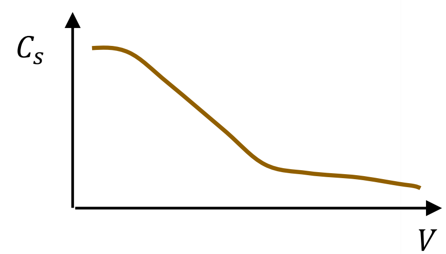
Aerodynamics/Morphodynamics





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 CFD testing



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

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

Windblown sand action

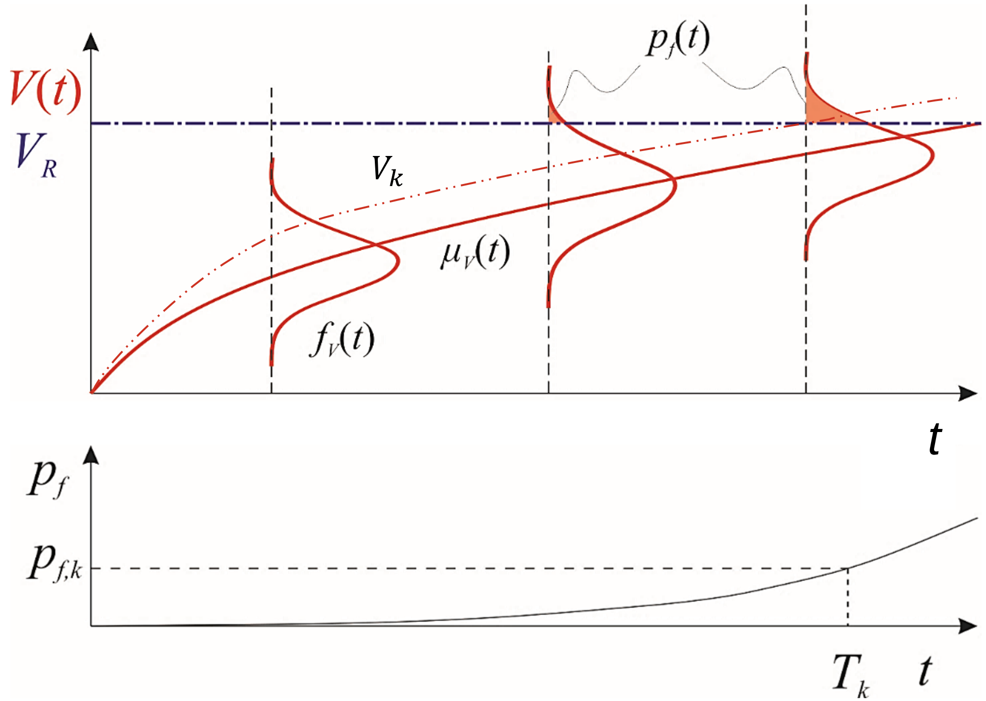
Time-variant WbS action $V(t)$

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

Resistant sand volume V_R

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

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



Probability of failure

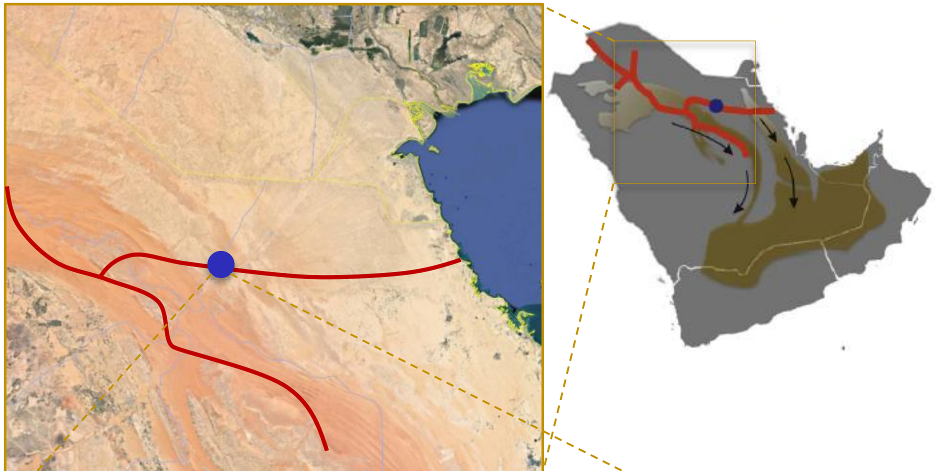
$$p_f(t) = P[V(t) \geq V_R]$$
$$= \int_0^{+\infty} F_{V_R}(x) f_V(x,t) dx = 1 - F_V(V_R, t)$$

Characteristic time of failure

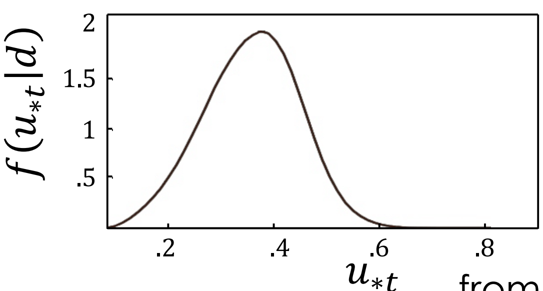
$$T_k = p_f^{-1}(p_{f,k}) \quad \text{e.g. } p_{f,k} = 5\%$$

sand removal period $\leq T_k$

Site characteristics



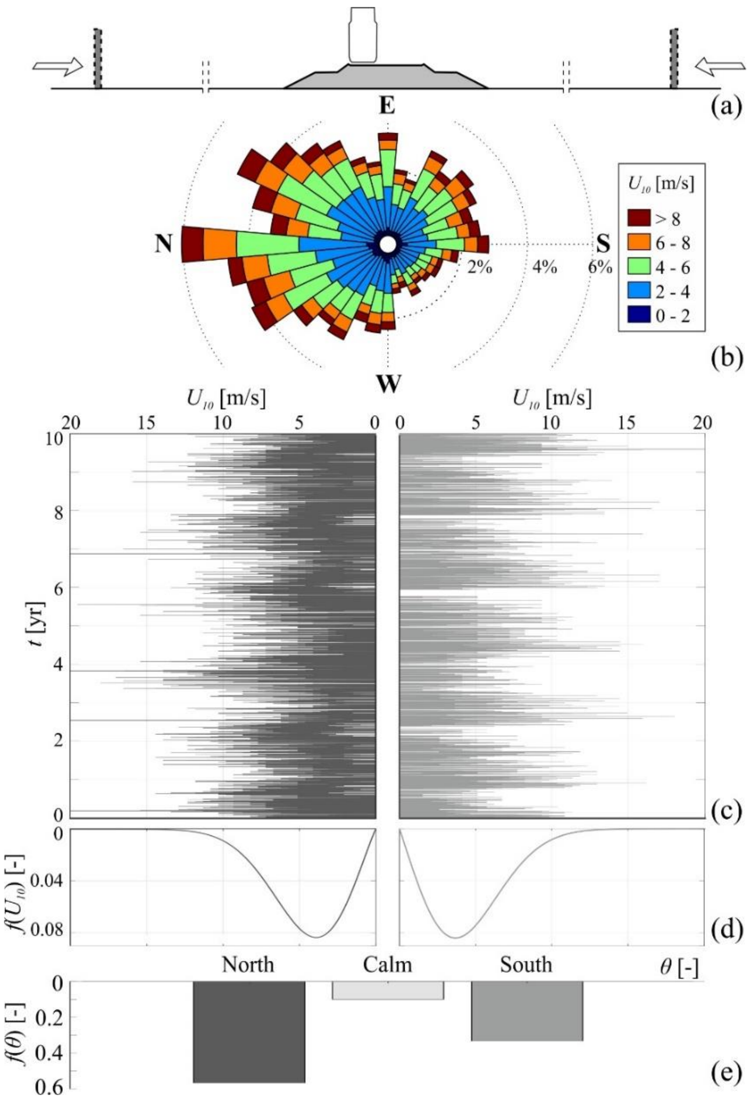
u_{*t} statistics $(d = 0.35$ mm$)$



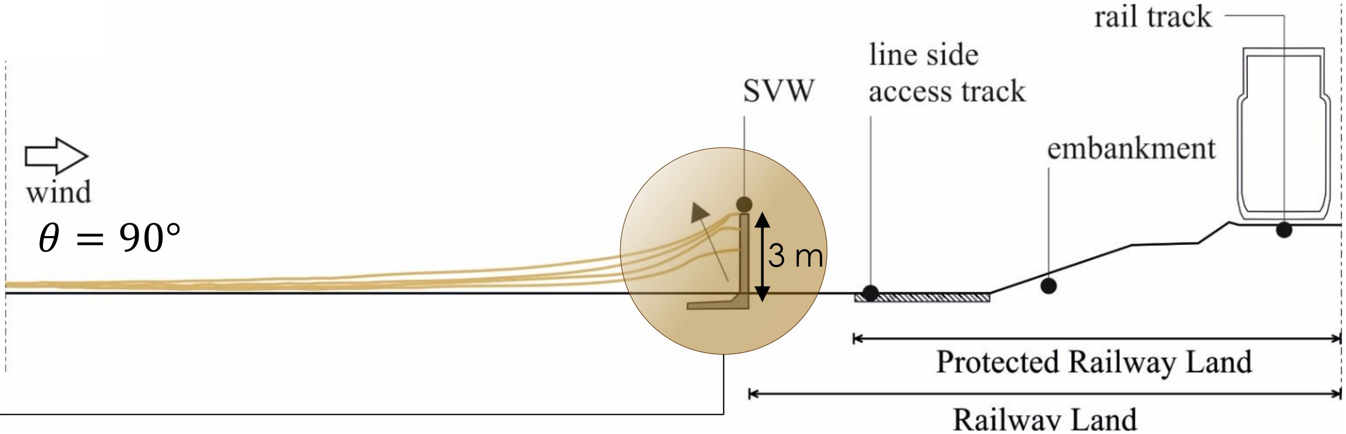
from Raffaele et al (2017b)

Wind statistics

$z_0 = 4e - 3$ m



Sedimentation coefficient: SVW



- Straight Vertical Wall (SVW) from multiphase CFD simulation

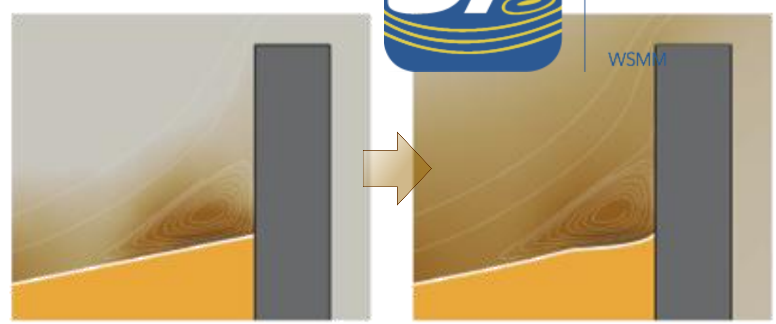
Eulerian 1st order multiphase model for windblown sand

Wind flow:
RANS k-ω

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

Sand phase:
sand mass
conservation equation

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

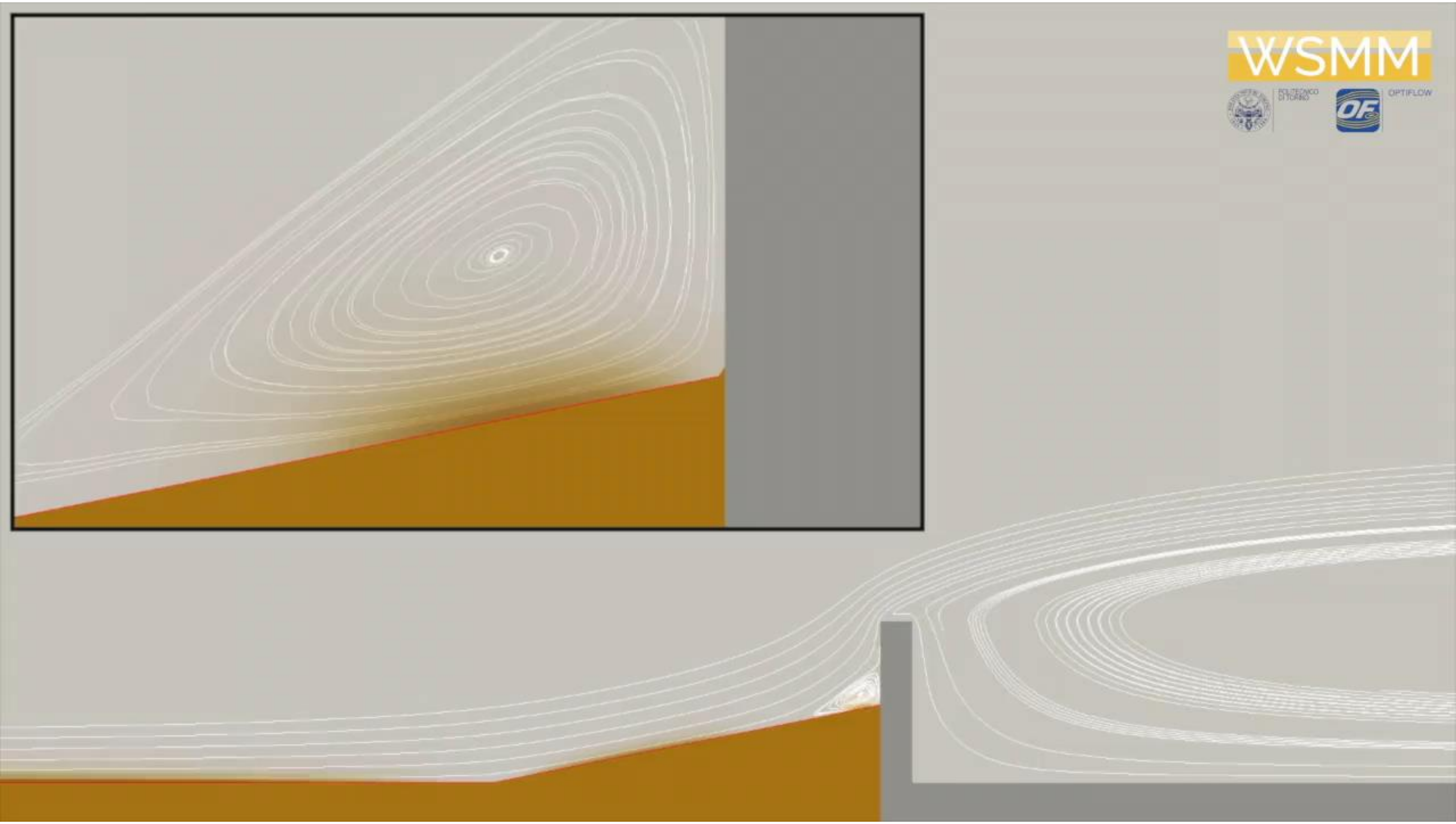


OPTIFLOW

WSMM

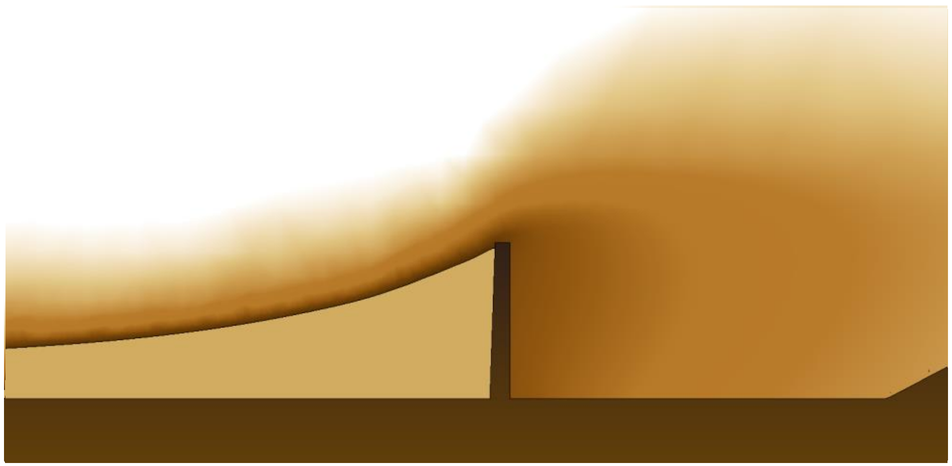
from A. Lo Giudice, L. Preziosi (2020), App. Math. Modelling

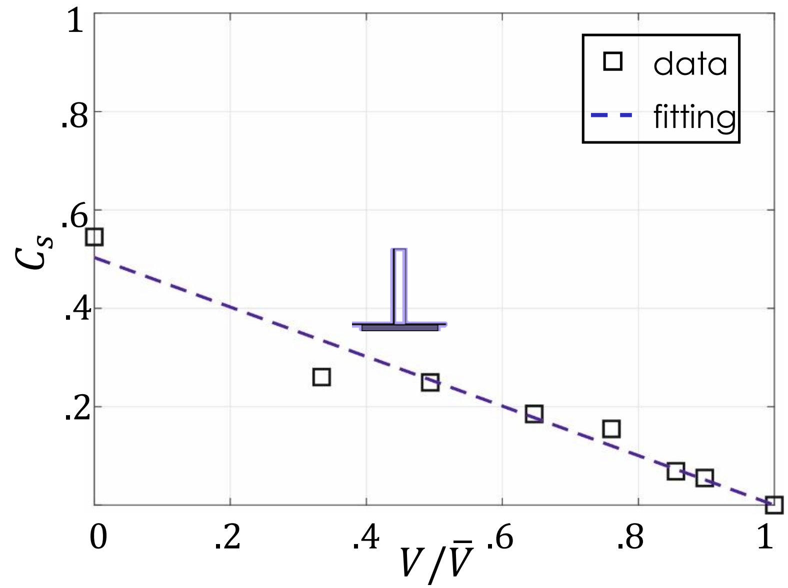
Sedimentation coefficient: SVW



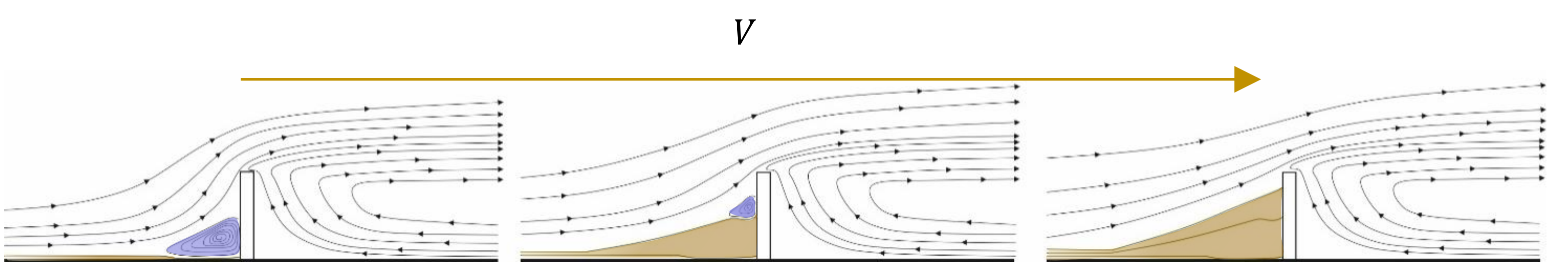
Sedimentation coefficient: SVW

- Multiphase simulation

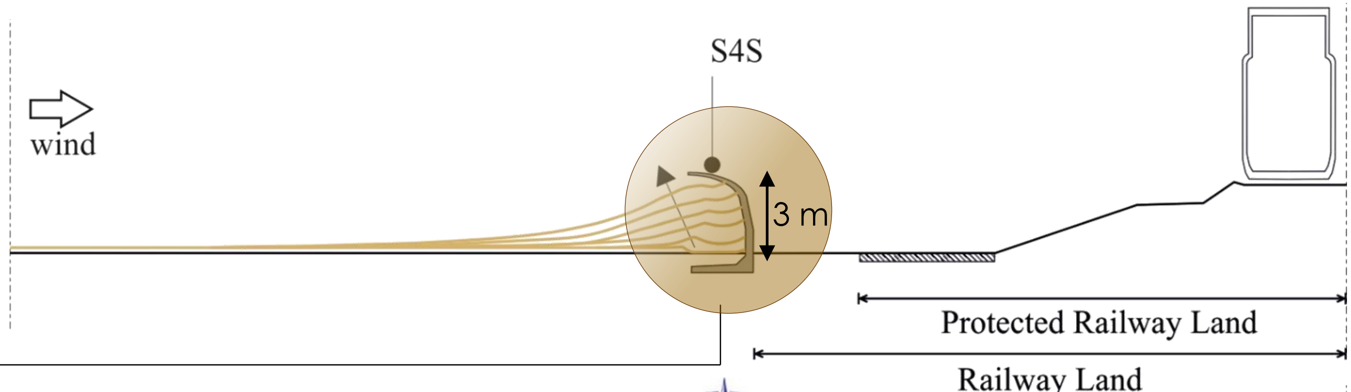




- Standard CFD simulation

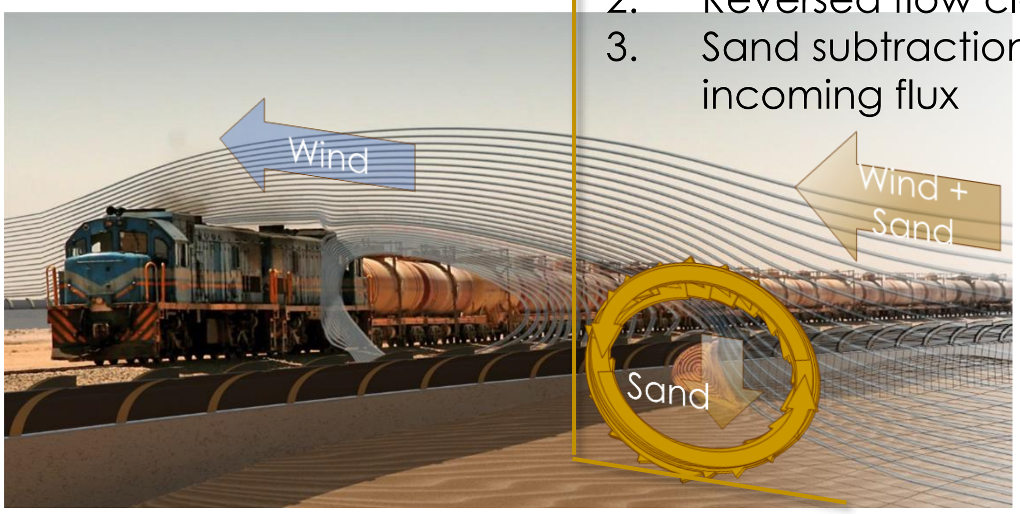


Sedimentation coefficient: S4S



- Shield for Sand (S4S) from WT tests @ von KARMAN INSTITUTE FOR FLUID DYNAMICS

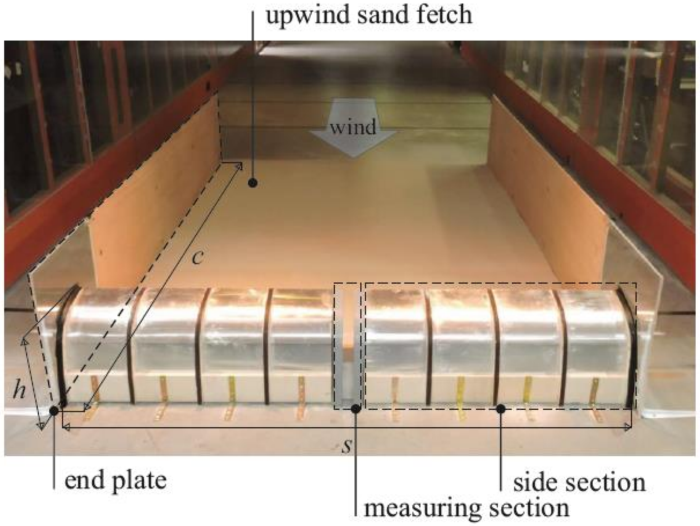
1. Trapping vortex
2. Reversed flow close to the ground
3. Sand subtraction from the incoming flux

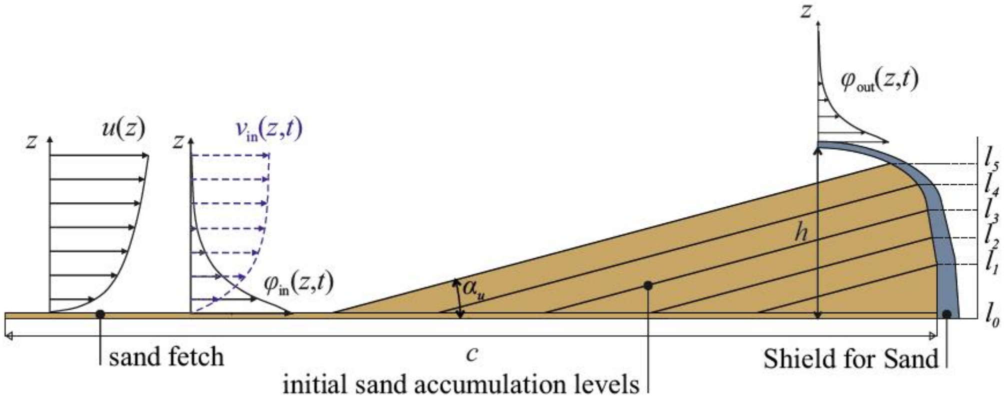


S4S Shield for Sand

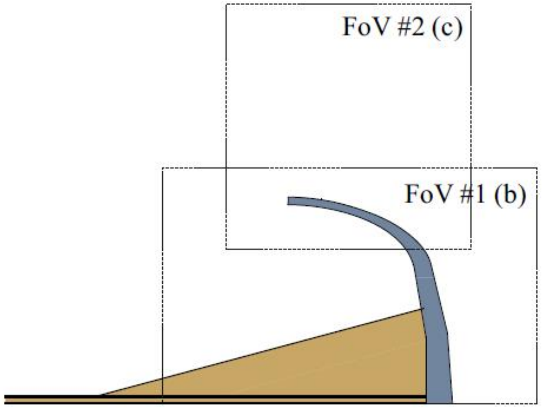
Sedimentation coefficient: S4S

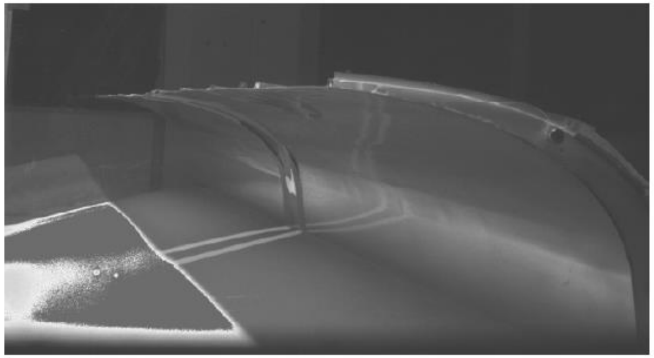
- Wind tunnel setup in L-1B

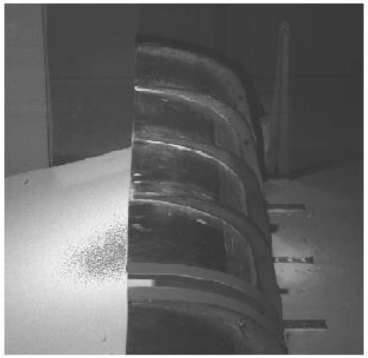




- PIV-PTV measurement setup

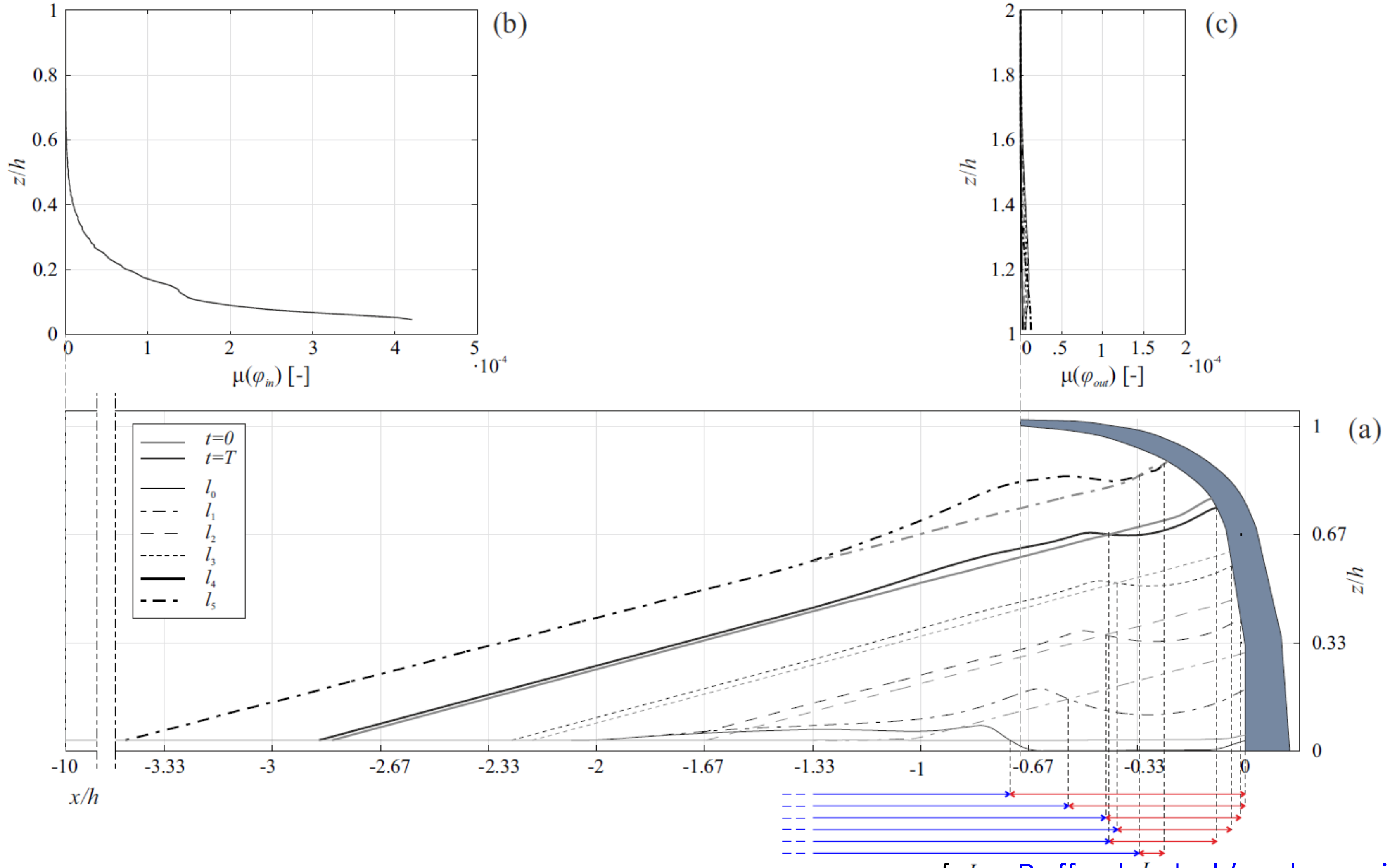






Sedimentation coefficient: S4S

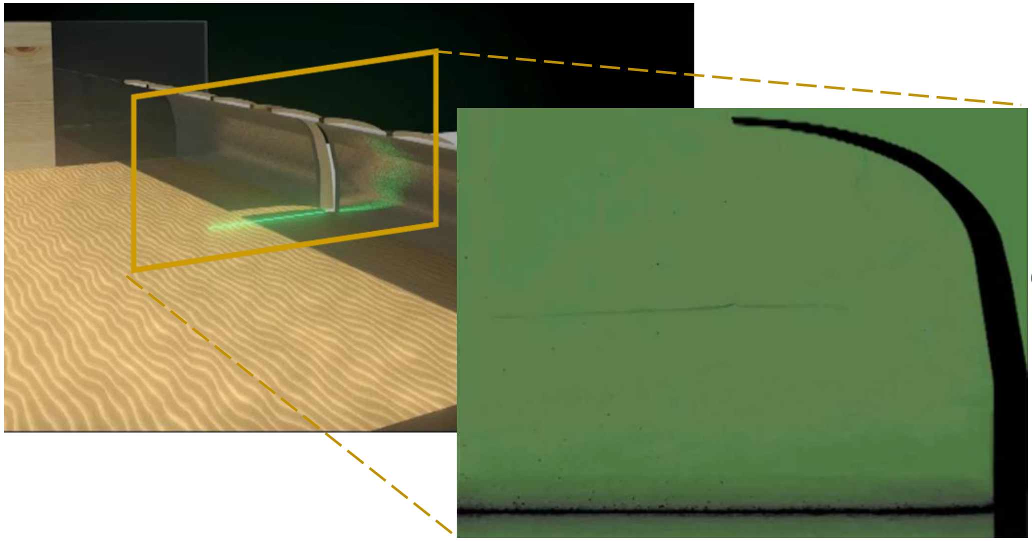
- Sand concentration and morphodynamics

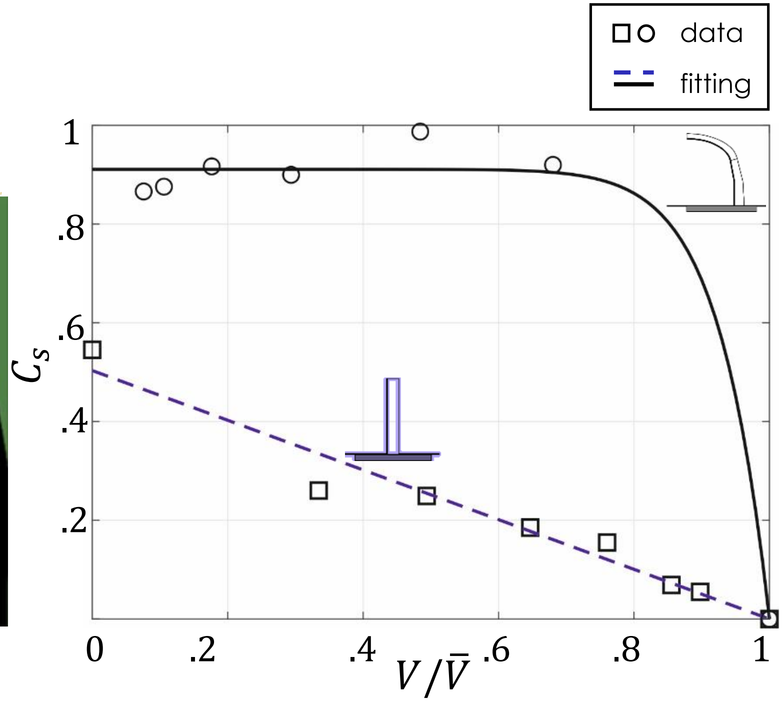


from Raffaele et al (under review)

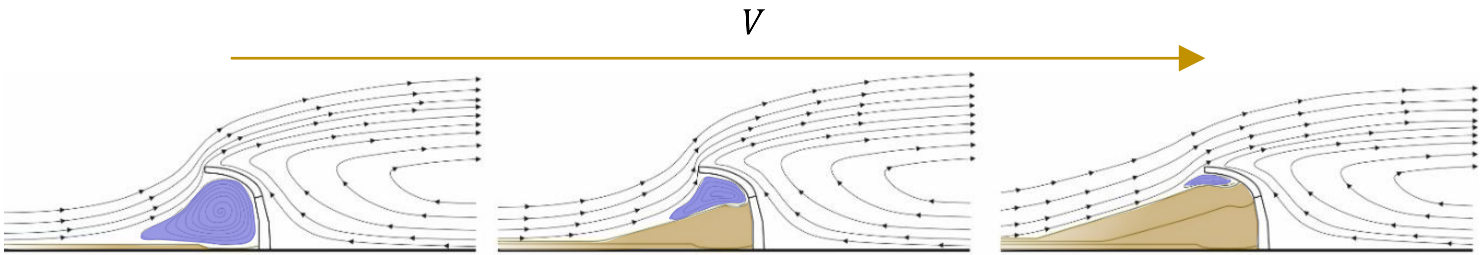
Sedimentation coefficient: S4S

- Wind Tunnel test

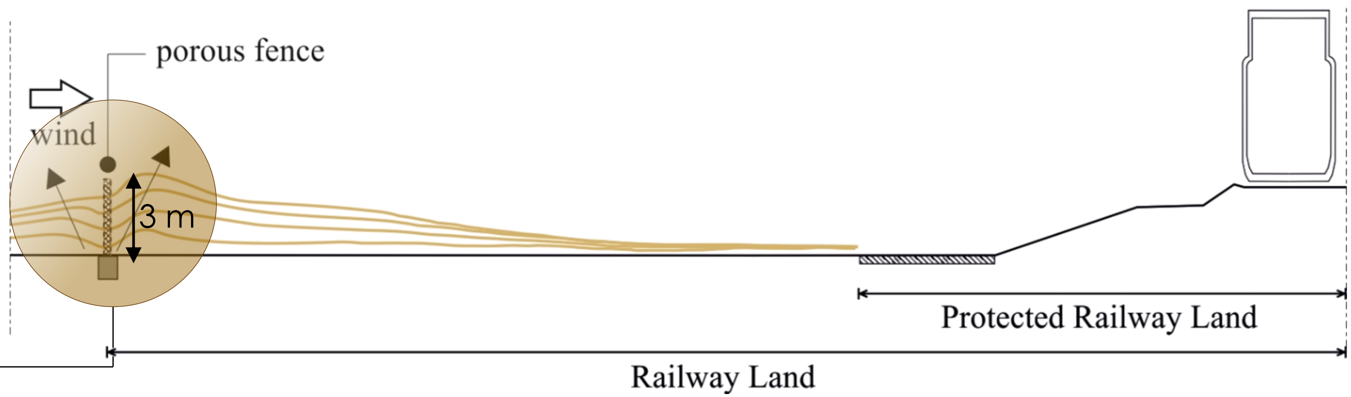




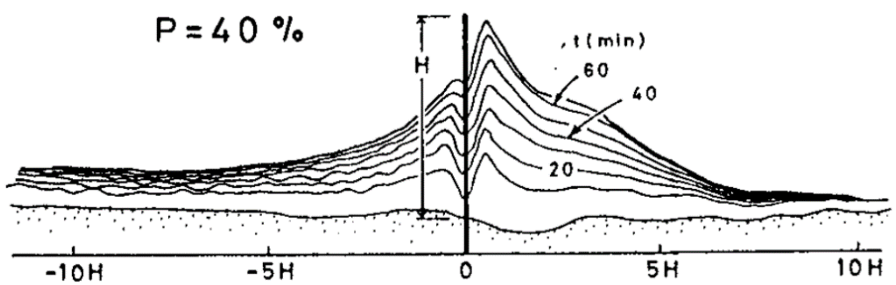
- Standard CFD simulation

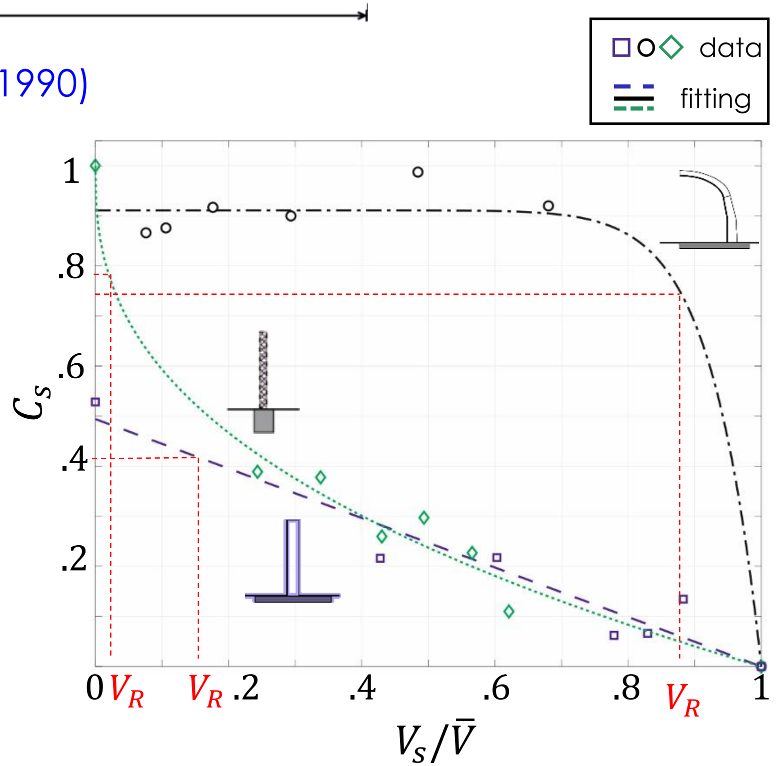


Sedimentation coefficient: porous fence

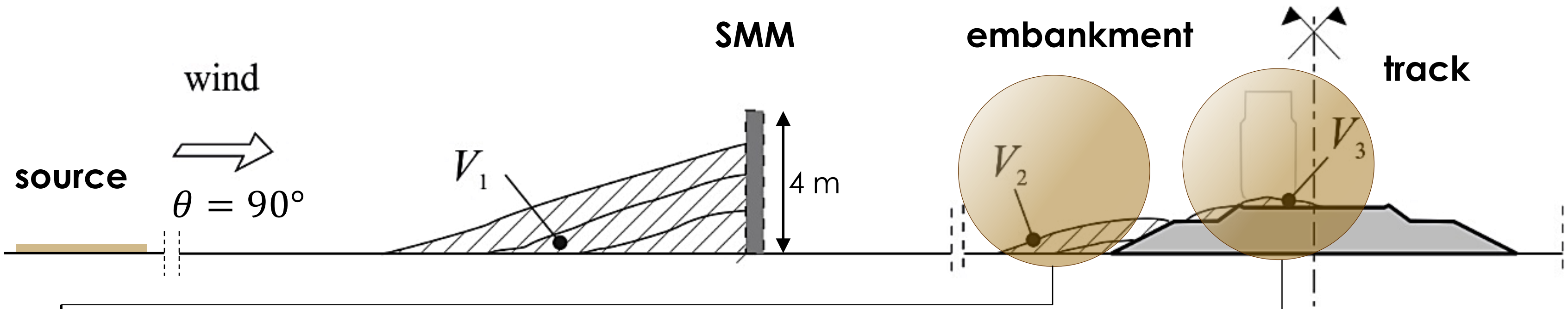


- <u>40% porosity fence</u> from WT tests Hotta and Horikawa (1990)

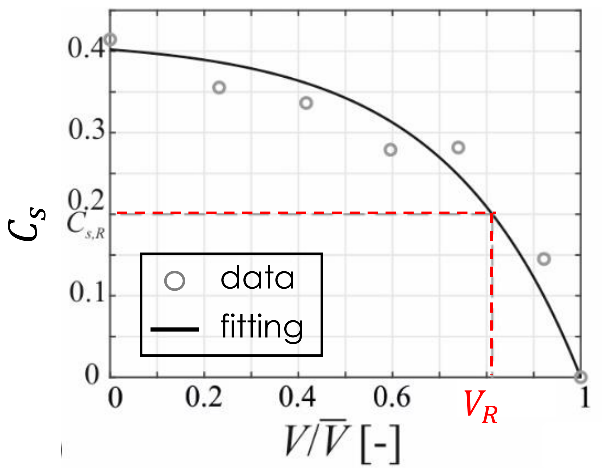


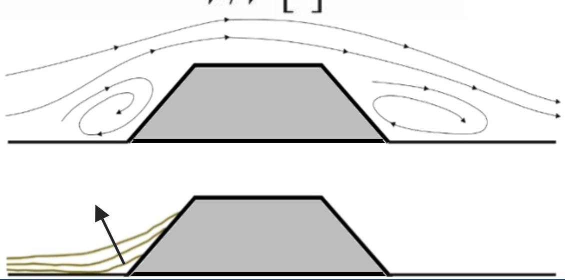


Sedimentation coefficient: embankment & track

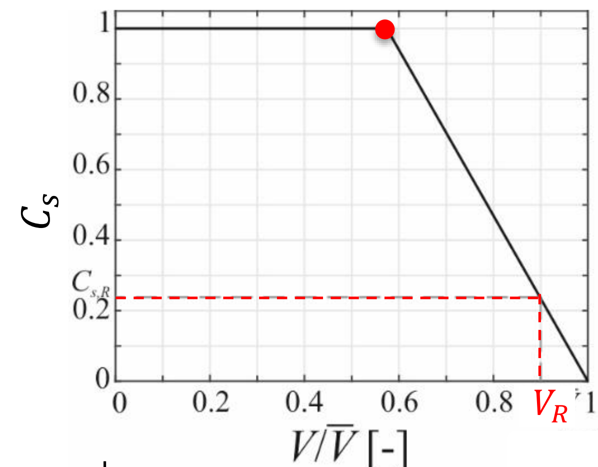


From WT tests Hotta & Horikawa (1990)





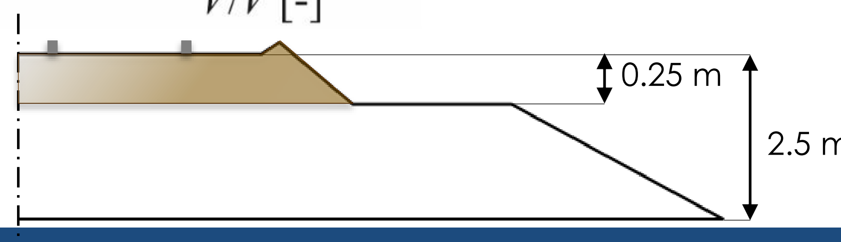
conjectured



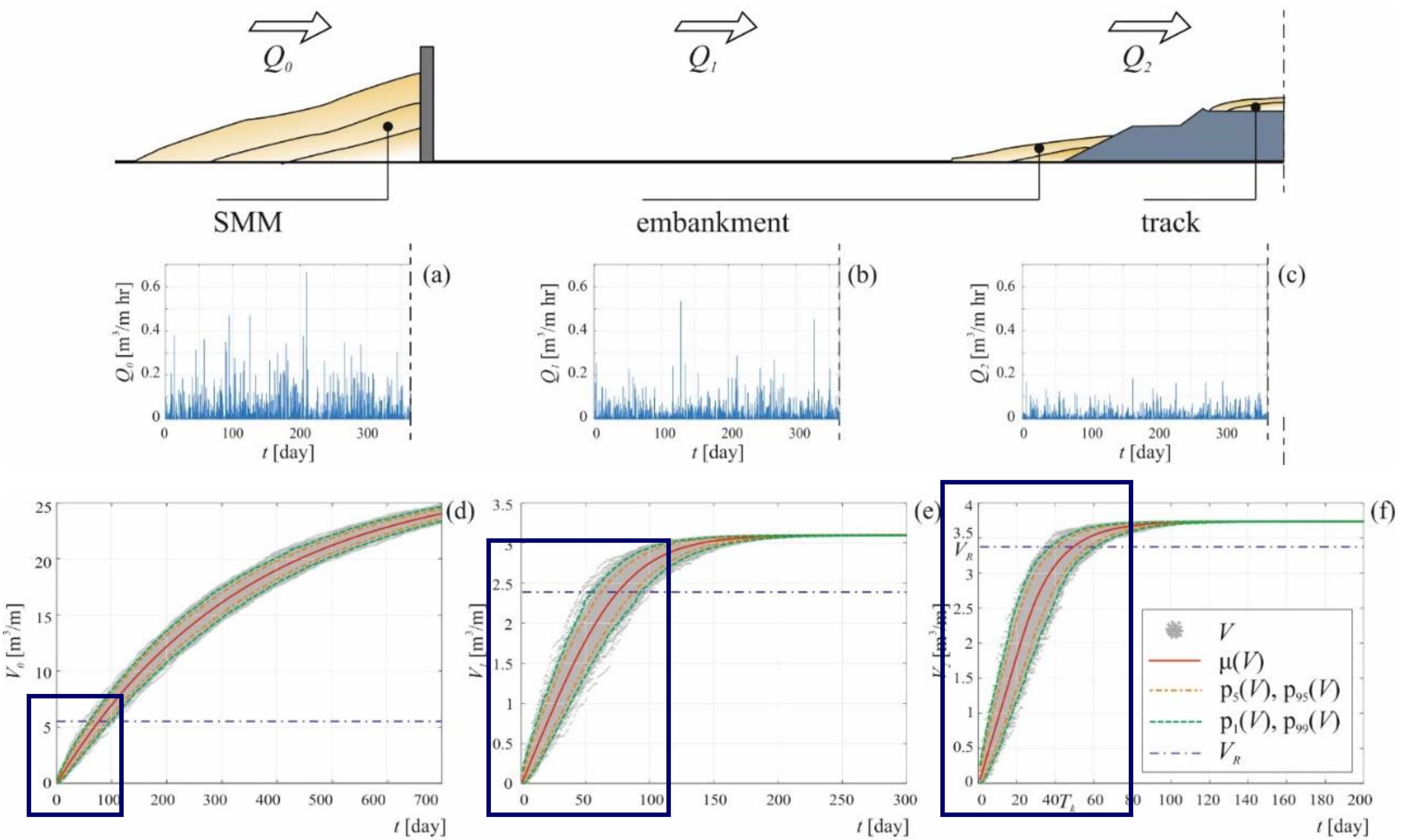
- Ballast void filling

$V_R = 0{,}9\ \overline{V}$

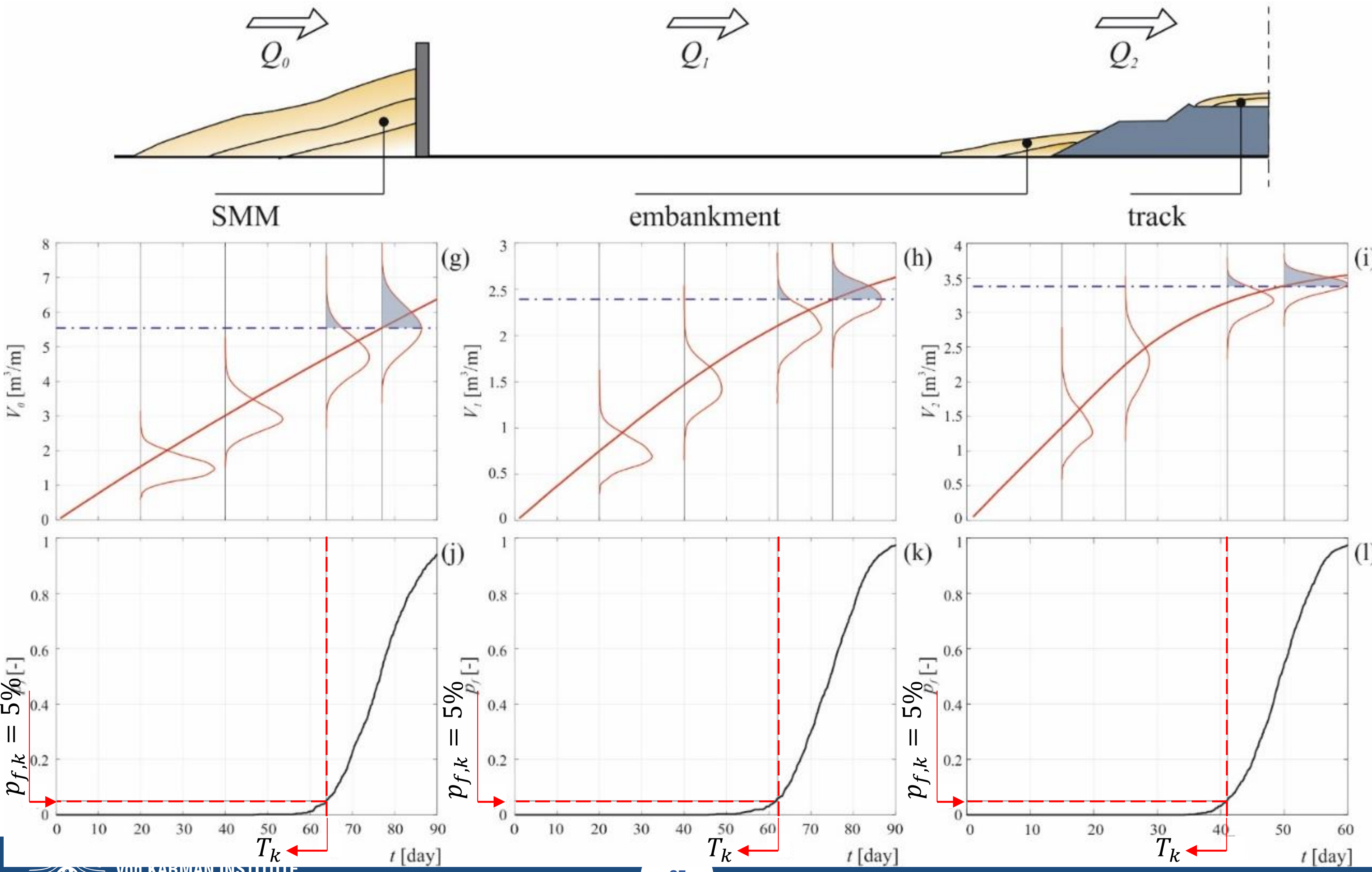
SULS full covering



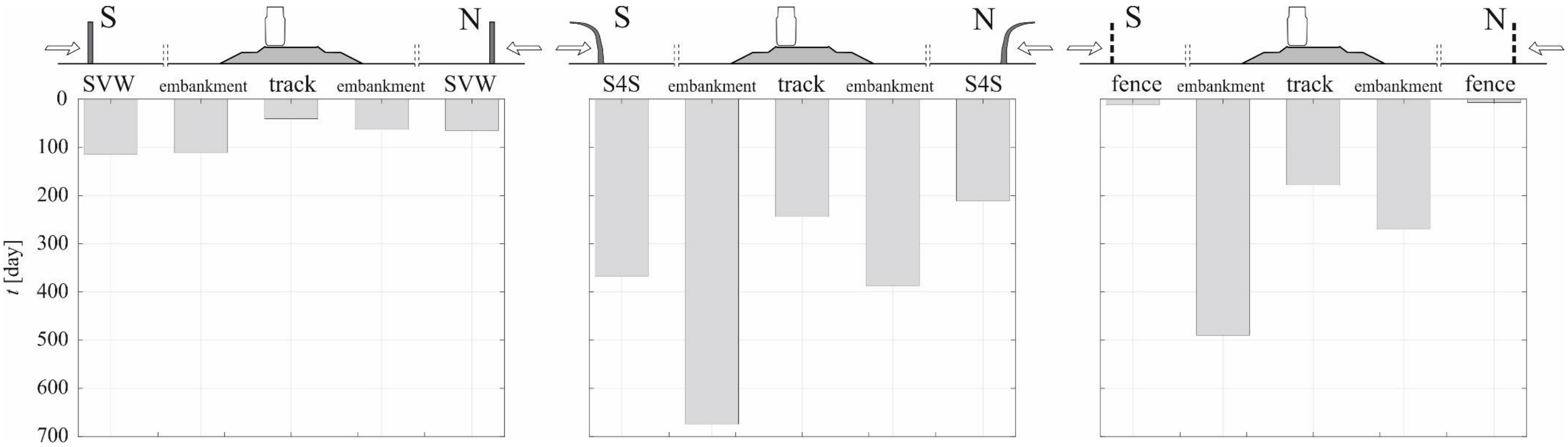
Results: SVW configuration, North side



Results: SVW configuration, North side



Lesson learnt: design perspective



- **S4S** scores overall good performance, while **SVW** shows the poorest performance.

$$\frac{T_{k,track}(\mathrm{S4S})}{T_{k,track}(\mathrm{SVW})} \sim 6 \qquad \frac{T_{k,emb}(\mathrm{S4S})}{T_{k,emb}(\mathrm{SVW})} \sim 6 \qquad \frac{T_{k,SMM}(\mathrm{S4S})}{T_{k,SMM}(\mathrm{SVW})} \sim 3$$

- The higher the wind occurrence (i.e. North side):
  - the lower T_k, for a given SMM capacity
  - the higher the required capacity, for a given T_k

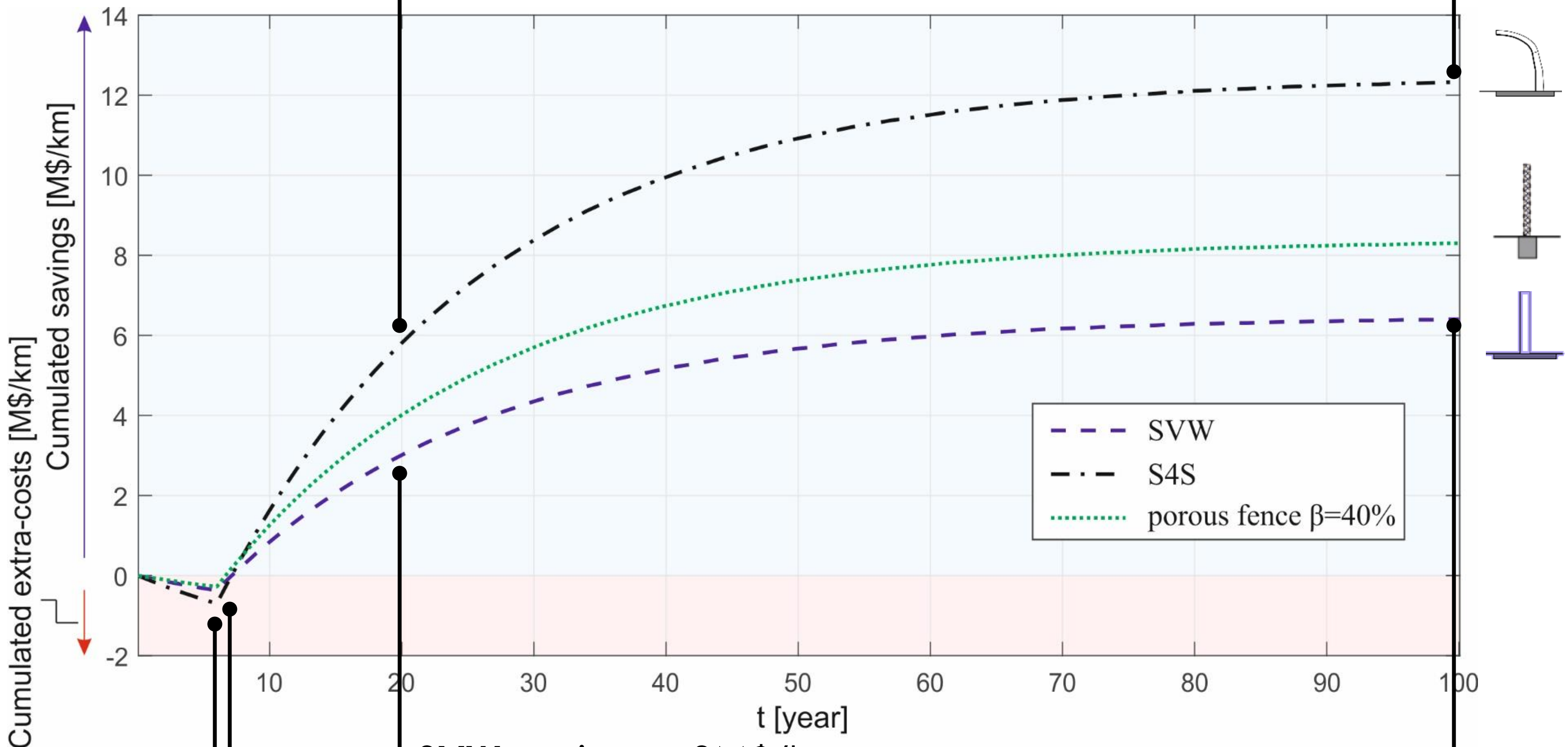
→ T_k as a design requirement for SMM

from Raffaele & Bruno (2020)

Life Cycle Cost Analysis

S4S savings ~6M$/km

S4S savings ~12M$/km



parity

SVW savings ~3M$/km

SVW savings ~6M$/km

SMM completion

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

from Raffaele & Bruno (2020)

Conclusion & Perspectives

To conclude..

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

Some perspectives…

- Development of innovative Wind-Sand tunnel tests to assess the sedimentation coefficient of different SMM
- Extrapolation from scale to full-scale conditions under different environmental setups

Conclusion & Perspectives

HyPer SMM

Hybrid Performance assessment of Sand Mitigation Measures

EU Horizon 2020 Marie Curie Individual Fellowship

von KARMAN INSTITUTE FOR FLUID DYNAMICS

OPTIFLOW

WSMM

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