25th ALERT Workshop
Session II: Railway Geomechanics
Aussois – September 30th 2014

A simplified procedure for settlement analysis of ballasted tracks

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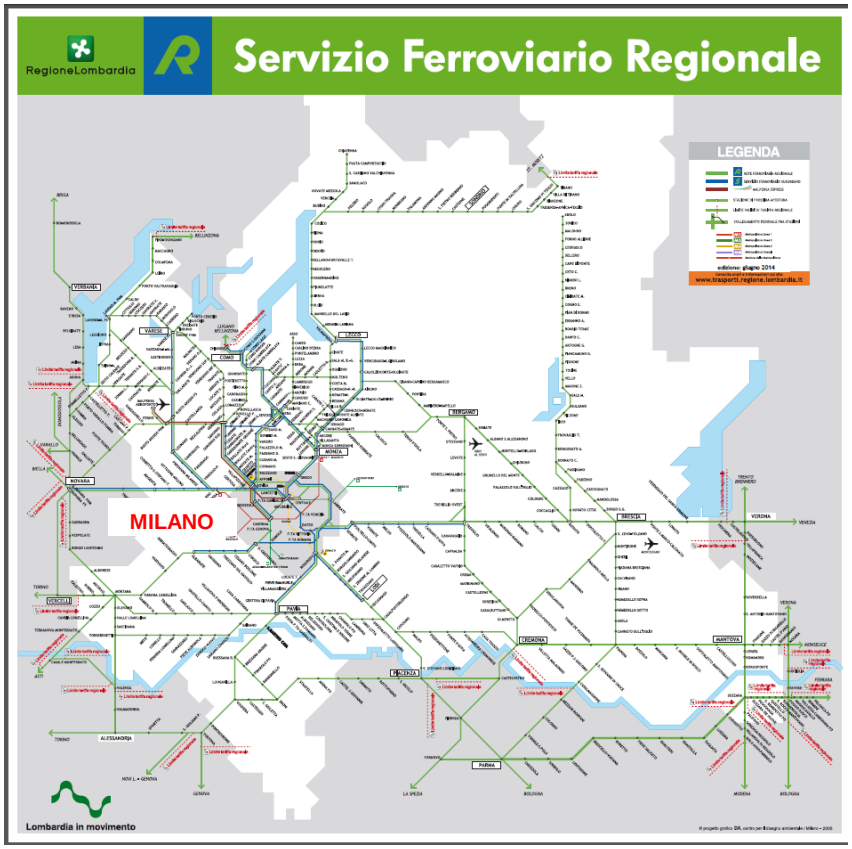
in collaboration with

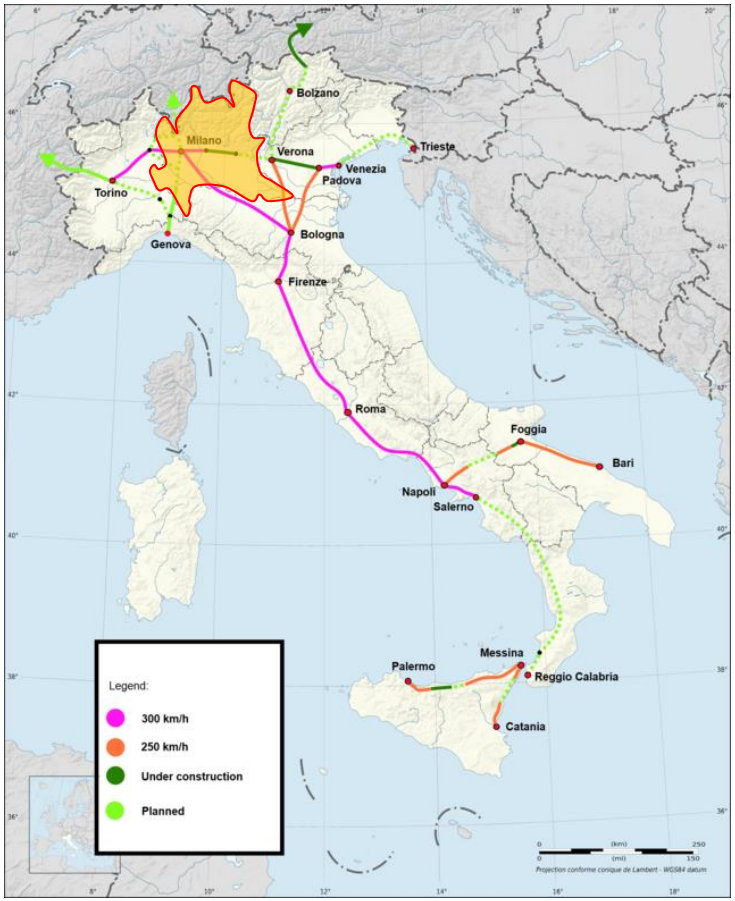
NORD_ING

Some introductory remarks

20255 km of railway lines in Italy

Strategic lifeline both at national ad regional level

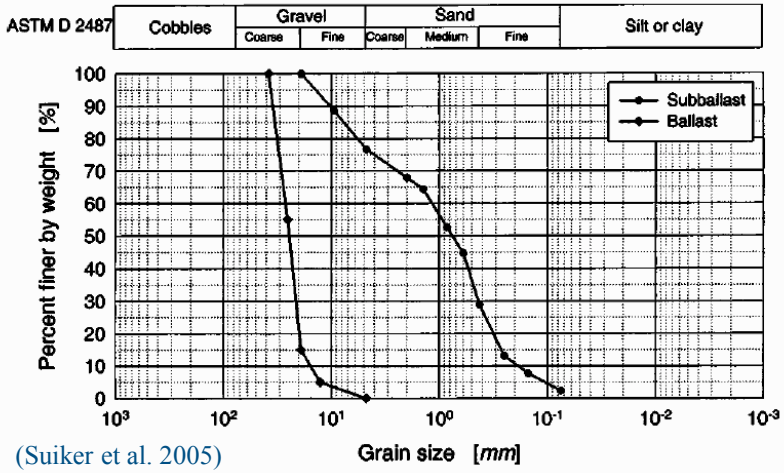




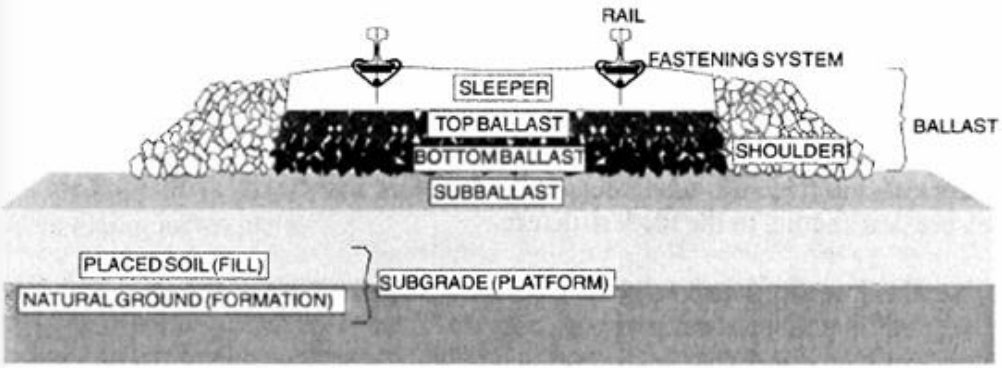
Some introductory remarks

- High technical/commercial **competition** with airlines, highways, and among railways operators
- Increasing **speed and weight** of trains
- Need for **cheaper** and more efficient railway tracks
- Need for **simpler** desing approaches
- **Maintainance** costs are often the most important part of railways management

Section of a railway track



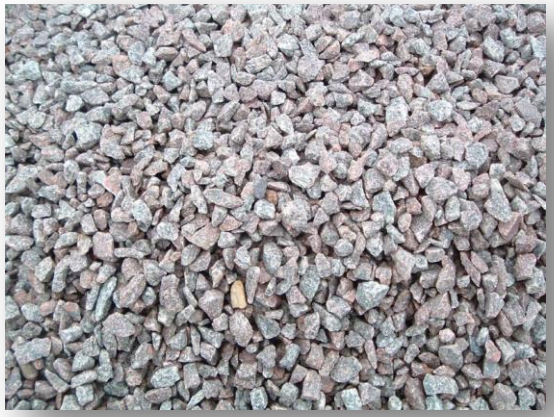
(Suiker et al. 2005)



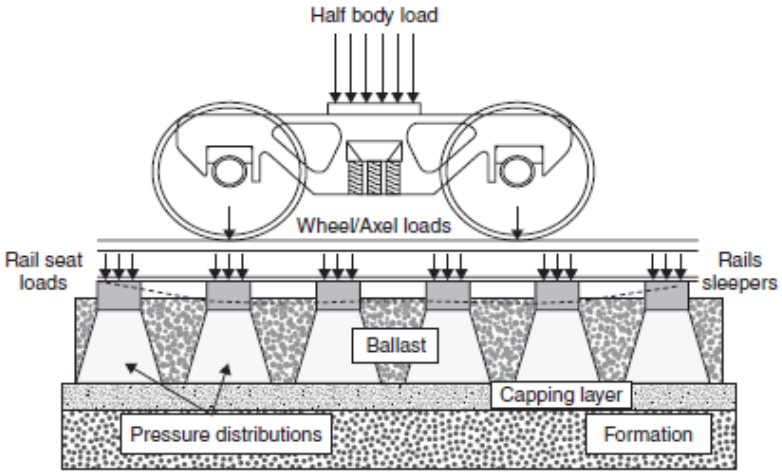
(Selig & Waters, 2004)

Layered strip foundation, subject to complex dynamic loads.

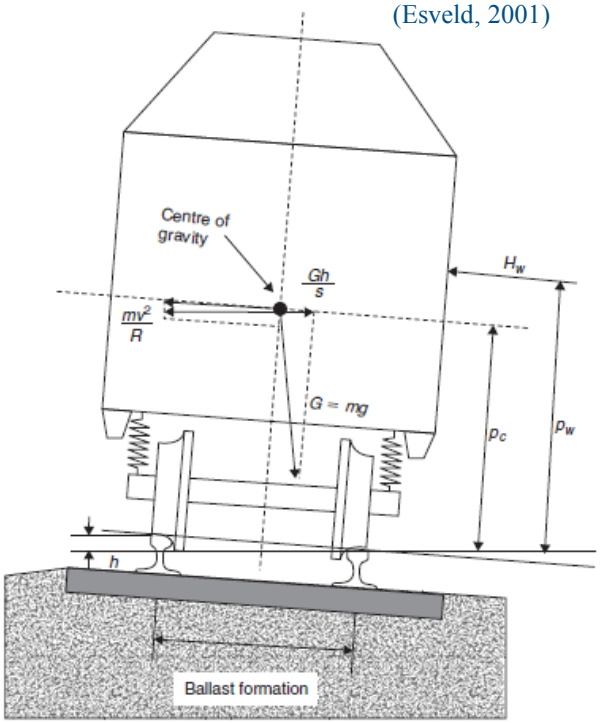
Cyclic settlement accumulation, due to permanent sliding between grains, ratcheting phenomena and grain breakage



Section of a railway track

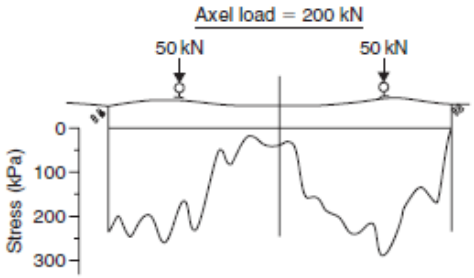


(Esveld, 2001)



Layered strip foundation, subject to complex dynamic loads.

Cyclic settlement accumulation, due to permanent sliding between grains, ratcheting phenomena and grain breakage



Limit states

Differential settlement

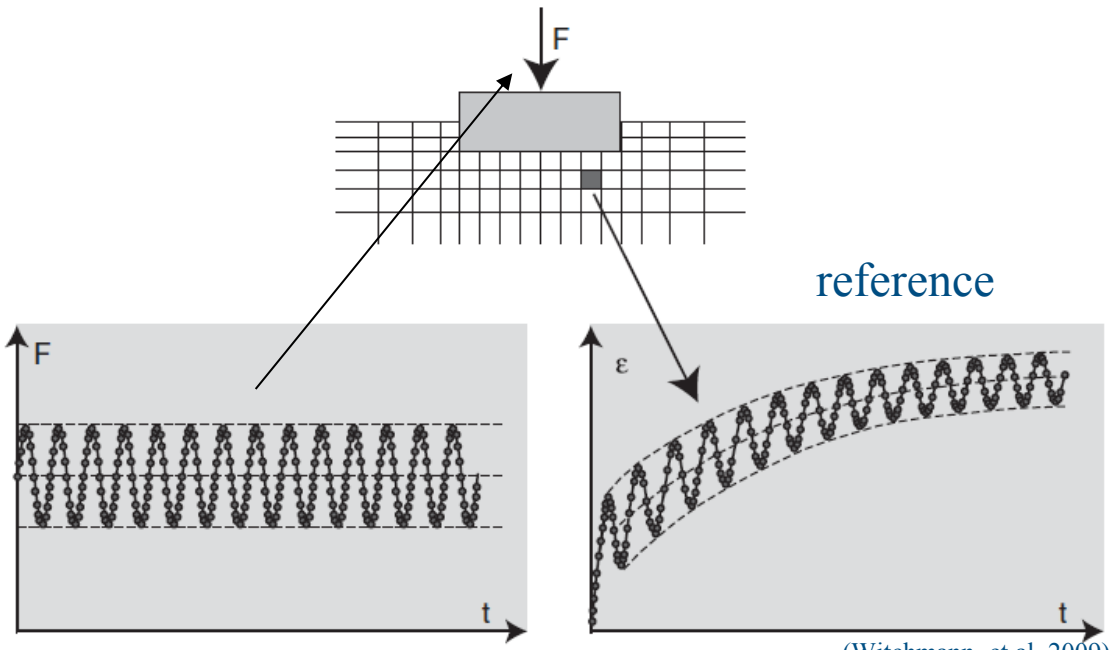
(Sucker, 2002)

Local “buckling” of the track

Insuffcent drainage, pumping of fines

(Indraratna et al., 2011)

Settlement computation: rigorous approach

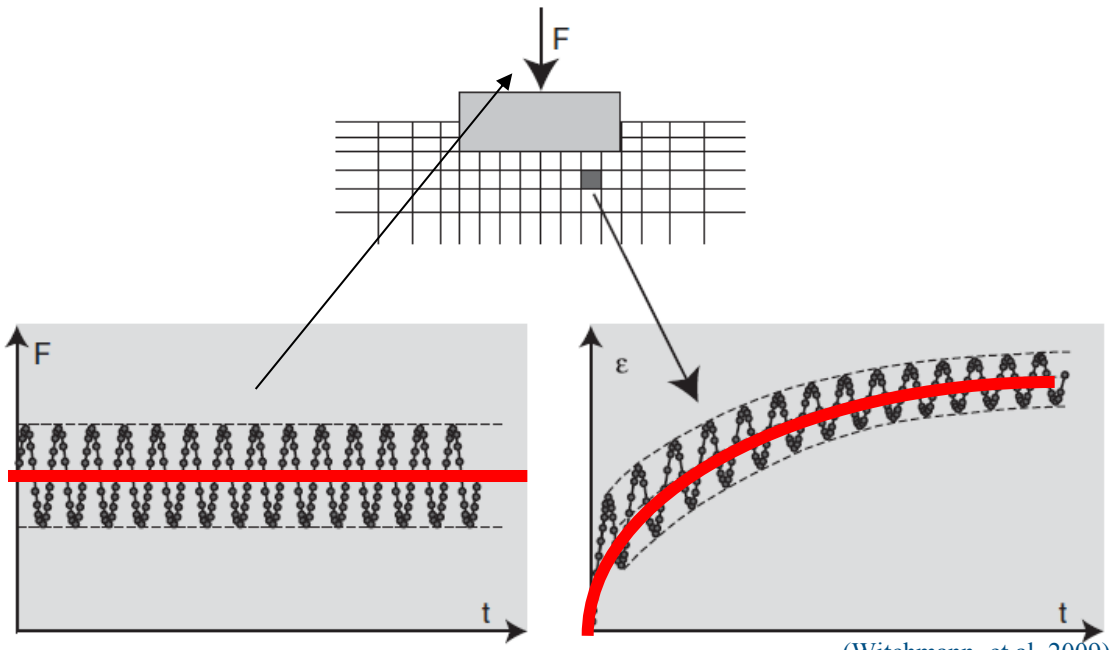


(Witchmann et al. 2009)

FE analyses by employing advanced constitutive models specifically conceived for cyclic loads

High computational effort; difficult parameter calibration

Settlement computation: simplified approach



(Witchmann et al. 2009)

Simplified constitutive models, describing the accumulation of plastic strain

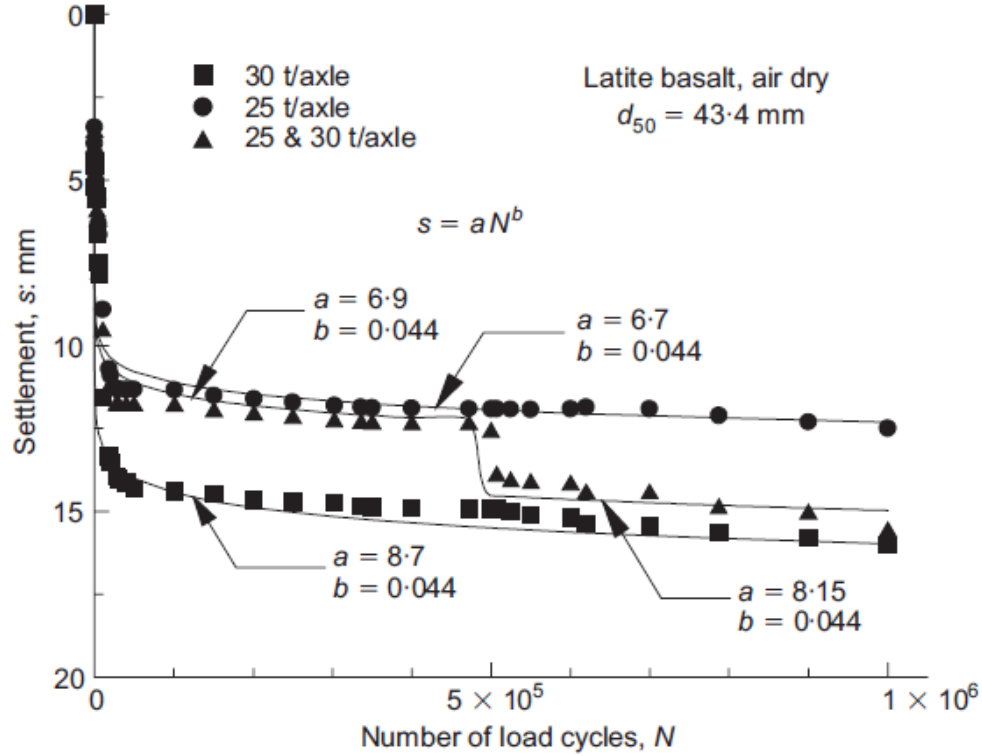
→ Viscous equivalent approach

Settlement computation: simplified approach – global vs local

GLOBAL (Indraratna et al. 2000; Indraratna et al 2003): direct evaluation of the settlement as a function of number of cycles N

$$s_N = a \cdot (1 + k \cdot \log N)$$

$$s_N = a \cdot N^b$$

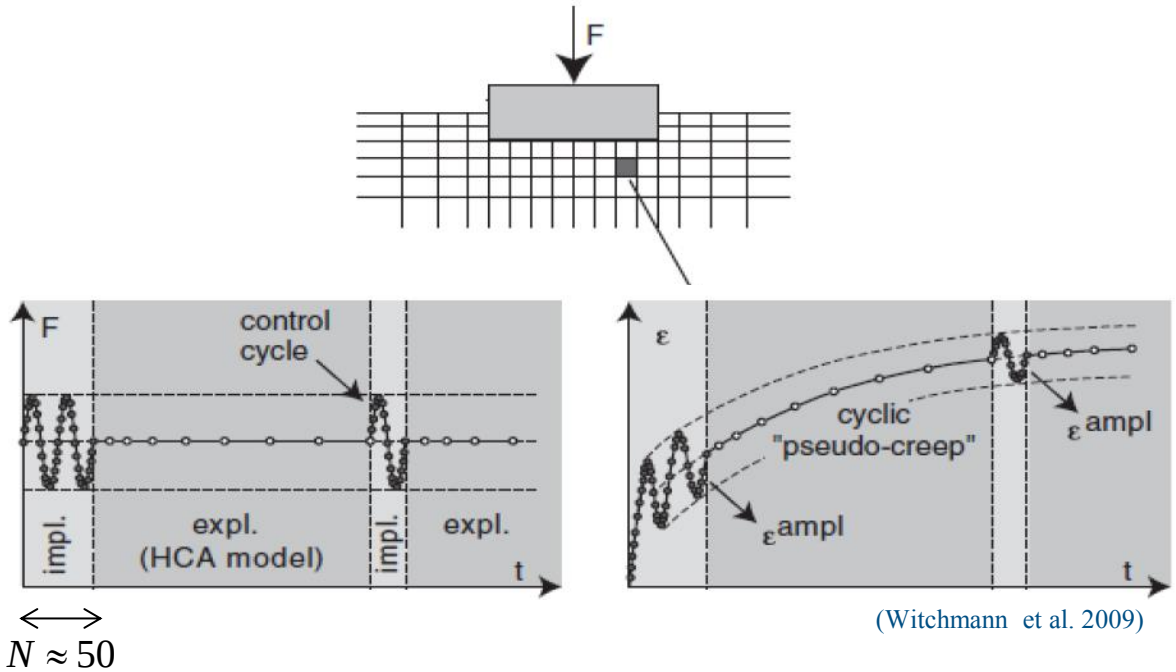


parameters do not have actually any physical meaning and depend both on structural mechanical properties and geometry and on the applied load

Settlement computation: simplified approach – global vs local

LOCAL

- FEM analyses on BVP
- Local constitutive relationship between strain and cycle number
- High number of parameters, sophisticated models
- Combination of "implicit" and "explicit" methods



(Witchmann et al. 2009)

Settlement computation: simplified approach – global vs local

LOCAL

HCA - "High Cyclic Accumulation Model" (Niemunis e Triantafyllidis, 2005)

$$\dot{\varepsilon}_{acc} = f_{ampl} \cdot \dot{f}_N \cdot f_e \cdot f_p \cdot f_Y \cdot f_\pi$$

effect of cycle amplitude $f_{ampl} = \min\left\{\left(\frac{\varepsilon^{ampl}}{\varepsilon^{ampl}_{ref}}\right)^2 ; 100\right\}$

effect of confining pressure $f_p = e^{\left[-C_p\left(\frac{p}{pref}-1\right)\right]}$

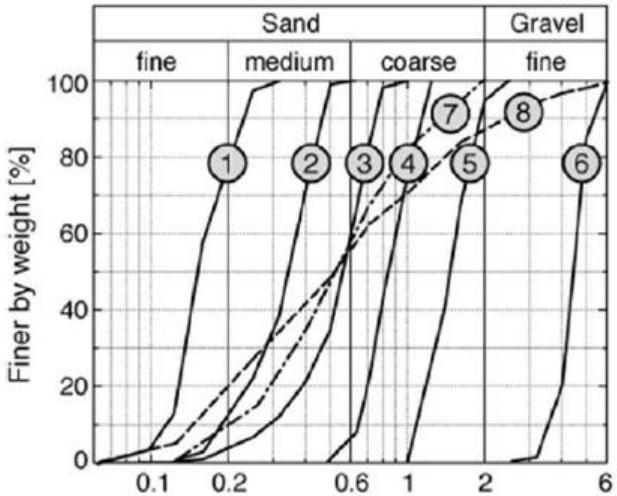
effect of cycle number $\dot{f}_N = \frac{C_{N1}C_{N2}}{1+C_{N2}N} + C_{N1}C_{N3}$

effect of void index $f_e = \frac{(C_e-e)^2}{1+e}\frac{1+e_{ref}}{(C_e-e_{ref})^2}$

$C_{N1} = 0{,}0002 \exp(-0{,}65\, d_{50}) \exp(0{,}91\, U_c)$;
$C_{N2} = 0{,}95 \exp(0{,}33\, d_{50}) \exp(-0{,}90\, U_c)$;
$C_{N3} = 0{,}00003 \exp(-0{,}69\, d_{50}) \exp(0{,}26\, U_c)$;

effect of stress level $f_Y = e^{(C_Y Y^{av})}$

$C_Y = 2{,}6$;
$Y_{av} = \frac{Y-9}{Y_c-9}$;
$Y_c = \frac{9-\sin^2\varphi_c}{1-\sin^2\varphi_c}$;
$Y = \frac{27\,(3+\eta)}{(3+2\eta)(3-\eta)}$;



(Triantafyllidis et al. 2009)

Settlement computation: simplified approach – global vs local

LOCAL

Tseng and Lytton (1989)

$$\varepsilon_p(N) = \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_v$$

$$log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) = -1{,}69867 + 0{,}09121 w_c - 0{,}11921 \sigma_d + 0{,}91219 \log(E_{SG});$$

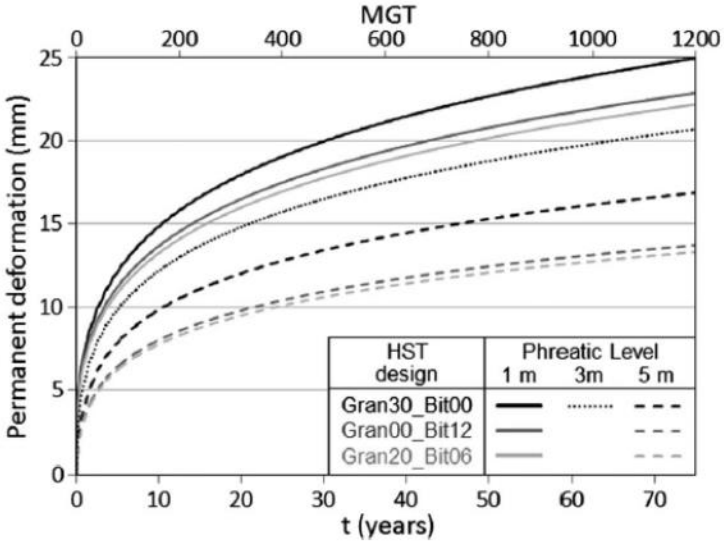
$$log(\beta) = -0{,}9730 - 0{,}0000278\, w_c^2\, \sigma_d + 0{,}017165\, \sigma_d - 0{,}00000338\, w_c^2 \sigma_\theta;$$

$$log(\rho) = 11{,}009 + 0{,}0000681\, w_c^2 \sigma_d - 0{,}40260\, \sigma_d + 0{,}00000545\, w_c^2 \sigma_\theta;$$

σ_d = deviatoric stress

σ_θ = isotropic pressure

w_c = water content



(Tseng and Lytton, 1989)

Settlement computation: simplified approach – global vs local

LOCAL

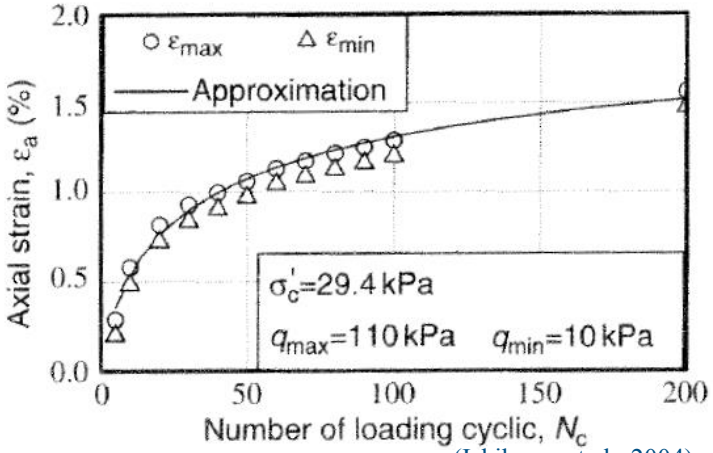
Cumulative Damage Model (Ishikawa et al., 2004)

$$(\varepsilon_a)_{max} = \left(\frac{SR_d}{a1\cdot(1-a2\cdot SR_s^{a3})\cdot N_c^{a4}}\right)^{a5\cdot N_c^{a6}}$$

σ_d = deviatoric stress at the Ncth cycle
σ_s = initial deviatoric stress
σ_m = mean principal stress
a_1.. a_6 = model parameters

$$SR_s = \frac{\sigma_s}{(2\sigma_m)}$$

$$SR_d = \frac{\sigma_d}{(2\sigma_m)}$$



(Ishikawa et al., 2004)

Liu and Carter (2004)

$$\varepsilon_p = a\left(\frac{\Delta q}{q_f - \Delta q}\right)(lnN)^b$$

"distance" from failure

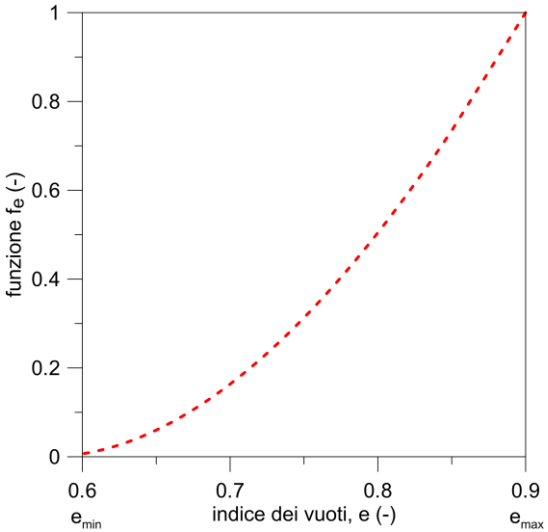
Settlement computation: New simplified local model

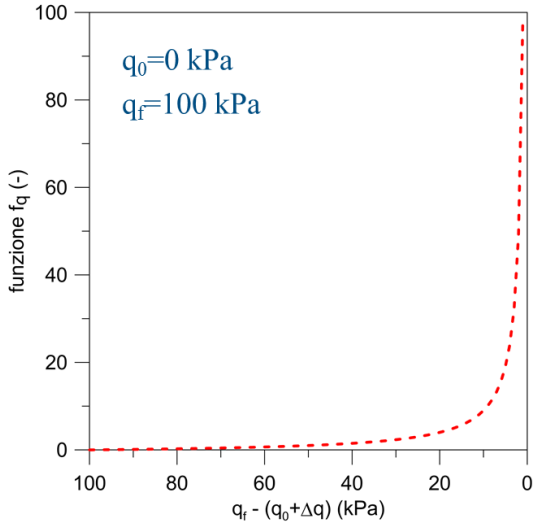
$$\dot{\varepsilon}_{acc} = a \cdot f_e \cdot f_q \cdot f_N$$

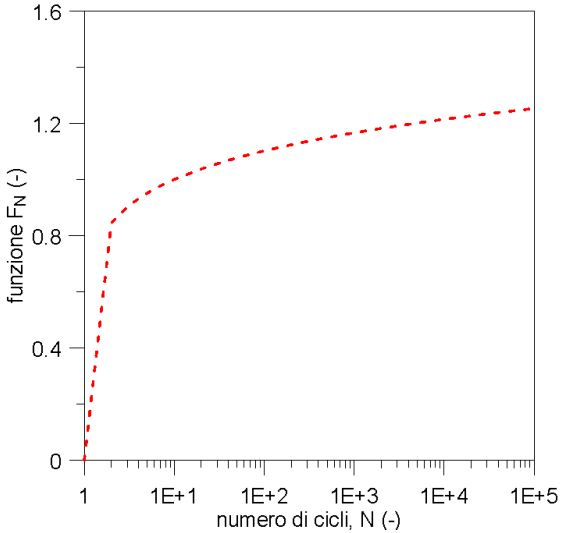
$$f_e = \left(\frac{(C_e - e)^2}{1+e} \frac{1+e_{ref}}{(C_e - e_{ref})^2} \right)$$

$$f_q = \left(\frac{q_0 + \Delta q}{q_f - (q_0 + \Delta q)} \right)^c$$

$$f_N = \frac{b(\log(N+1))^{b-1}}{1+N}$$







a, b, c = model parameters to be calibrated

$$F_N = \int f_N \mathrm{d}N = (\log(N+1))^b$$

Settlement computation: New simplified local model

$$f_e = \left(\frac{(C_e - e)^2}{1+e} \frac{1+e_{ref}}{(C_e - e_{ref})^2} \right)$$

$$\begin{cases} \dot{\varepsilon}_v = \dot{\varepsilon}_1 + 2\,\dot{\varepsilon}_3 \\ \dot{\varepsilon}_d = \frac{2}{3}(\dot{\varepsilon}_1 - \dot{\varepsilon}_3) \end{cases}$$

update of void index $\varepsilon_v = -\dfrac{\Delta e}{1+e_0}$

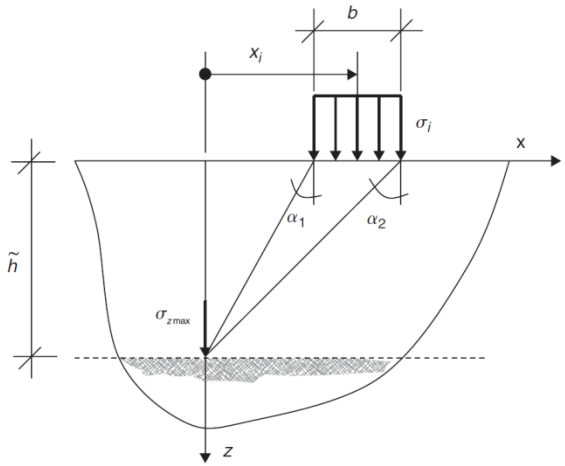
$$\dot{\varepsilon}_1 = \dot{\varepsilon}_{acc}$$

MMC flow rule $\dfrac{\dot{\varepsilon}_v^{acc}}{\dot{\varepsilon}_d^{acc}} = \dfrac{M_C^2 - \eta^2}{2\eta} = d$

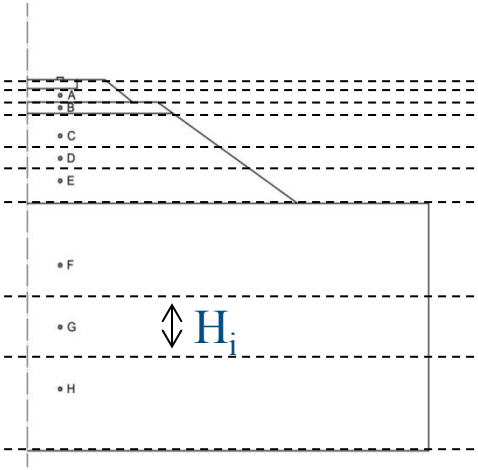
$$\dot{\varepsilon}_3 = -\sqrt{\frac{\dot{\varepsilon}_{acc}{}^2}{2 + \left(\frac{(2 + \frac{2}{3}d)}{(1 - \frac{2}{3}d)}\right)^2}}$$

Computational approach: a depth-integrated stress path method

Elastic analysis of the geostatic state of stress and of the stress increment due to trains



Evaluation of the cyclic strain increment in a given set of points along depth



$$\varepsilon_{acc,i}(N+\Delta N) = \varepsilon_{acc,i}(N) + \dot{\varepsilon}_{acc,i}(N)\cdot\Delta N$$

?

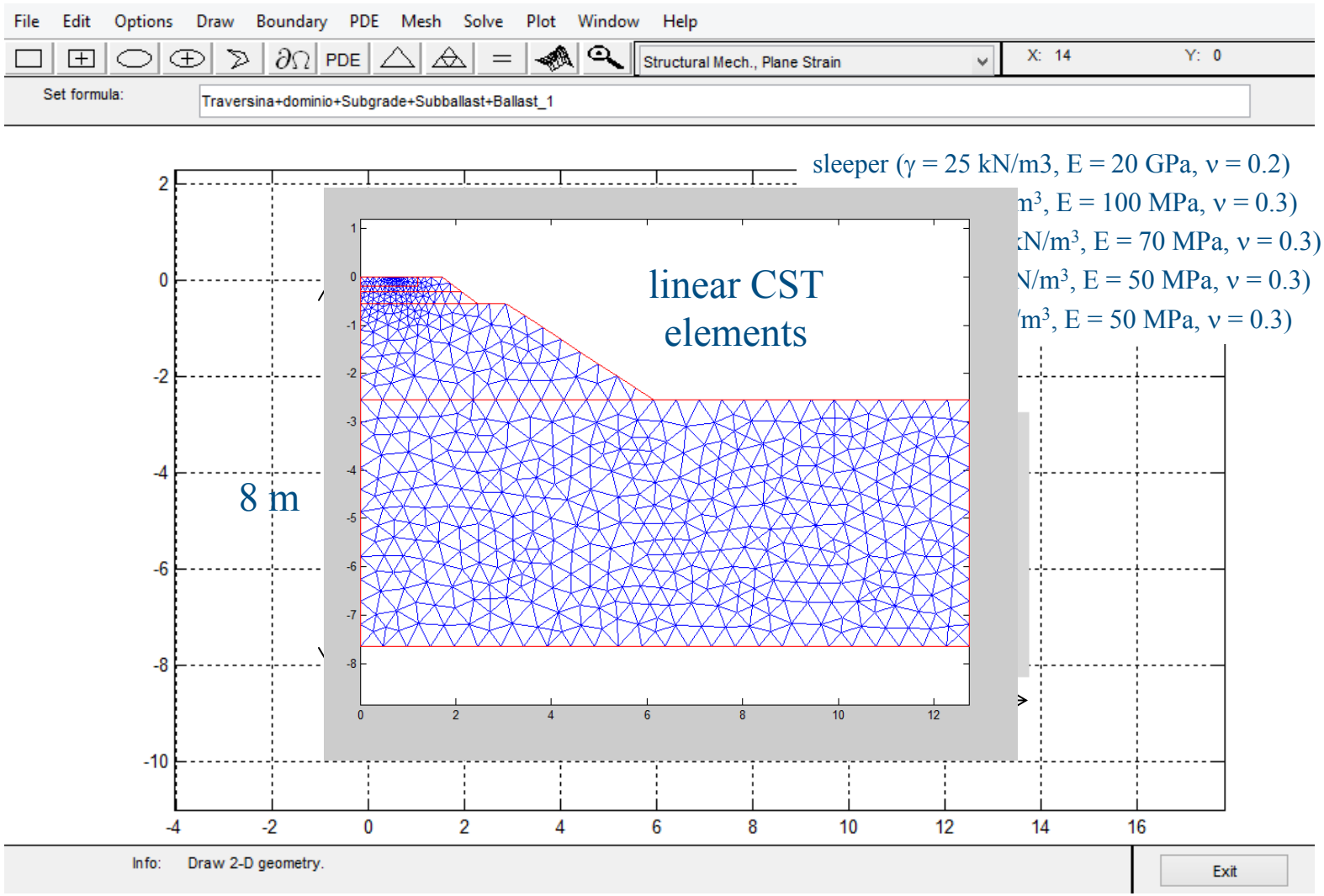
Integration of strain along depth

$$s_i(N) = \varepsilon_{acc,i}(N) \quad H_i$$

$$s(N) = \sum_{i=1}^{m} s_i(N)$$

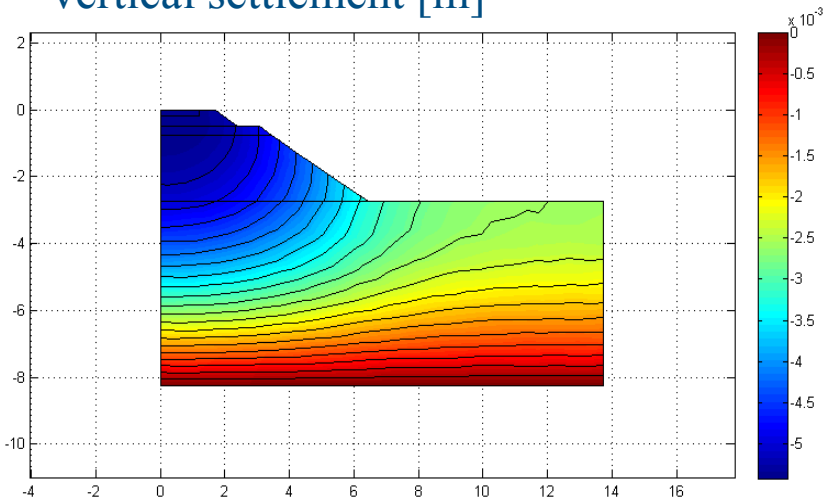
Example of application

Elastic solution by Matlab PDE tool (plane strain analysis, linear elasticity, static loads)

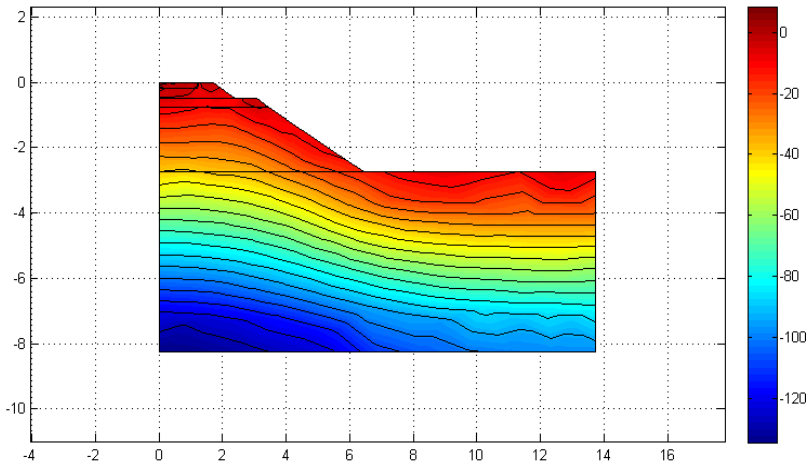


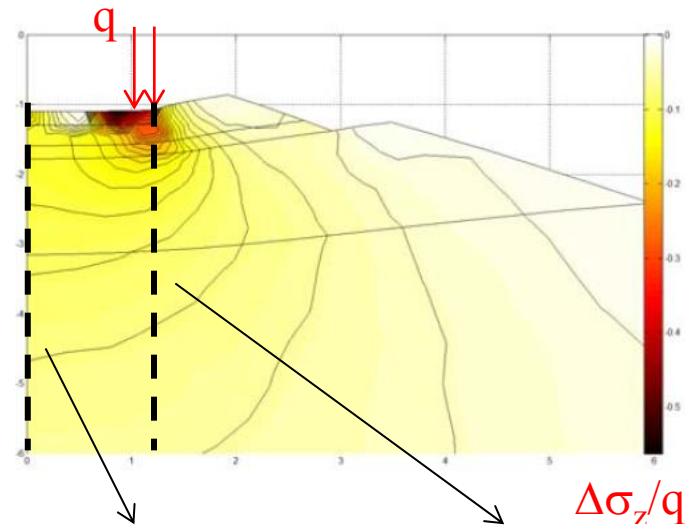
Example of application

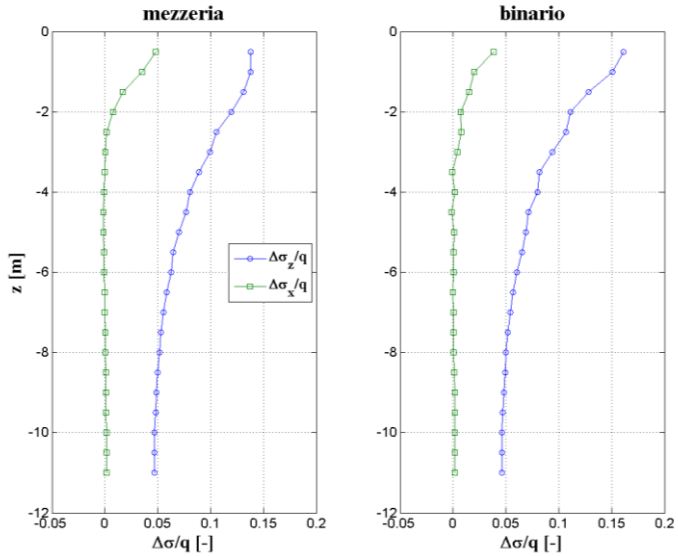
vertical settlement [m]



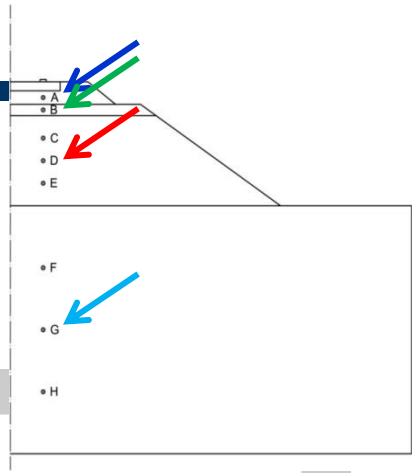
vertical stress [m]



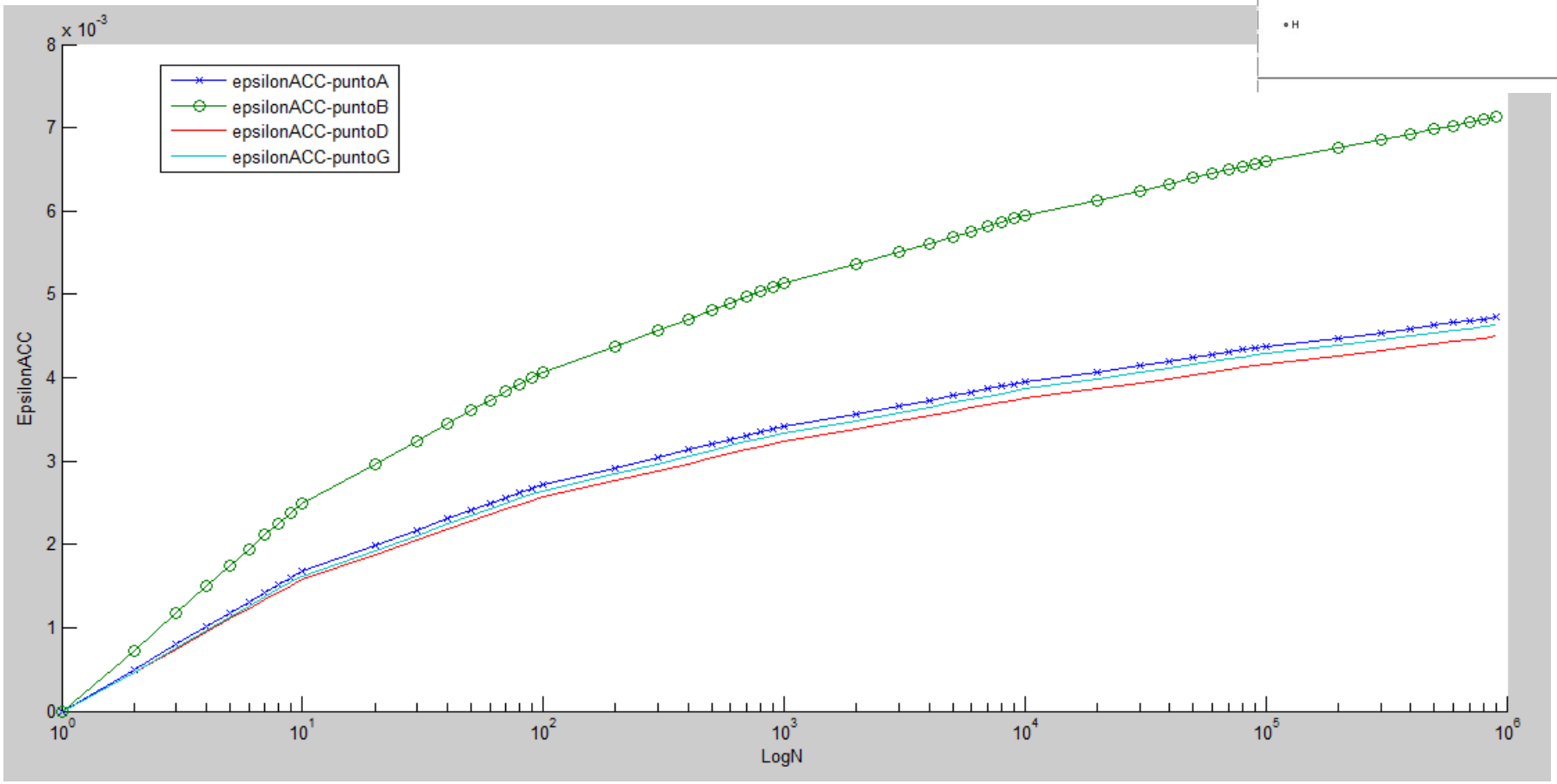




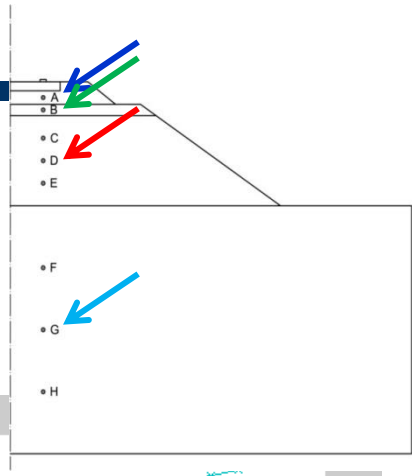
Example of application



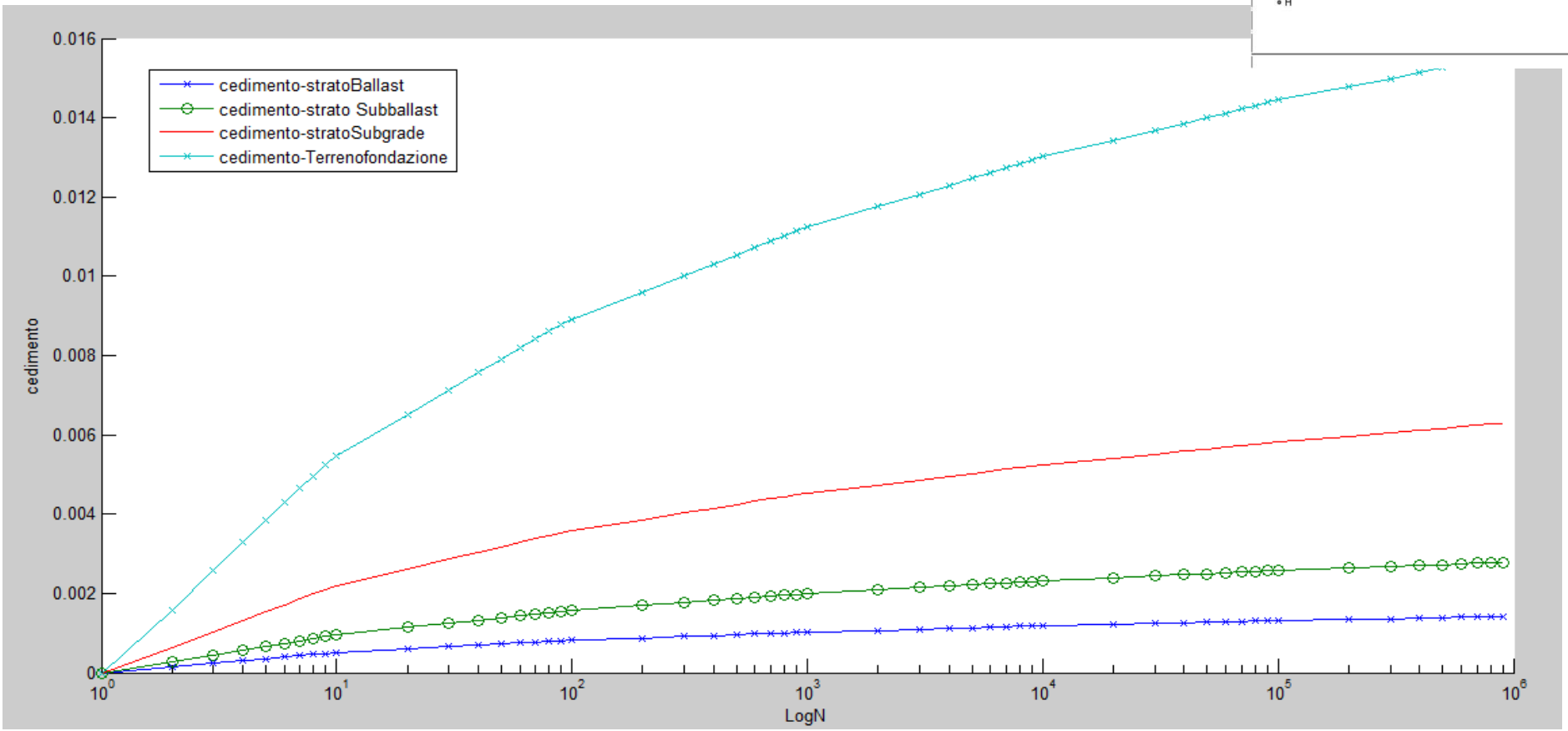
Cumulated vertical strain ε_{acc}



Example of application

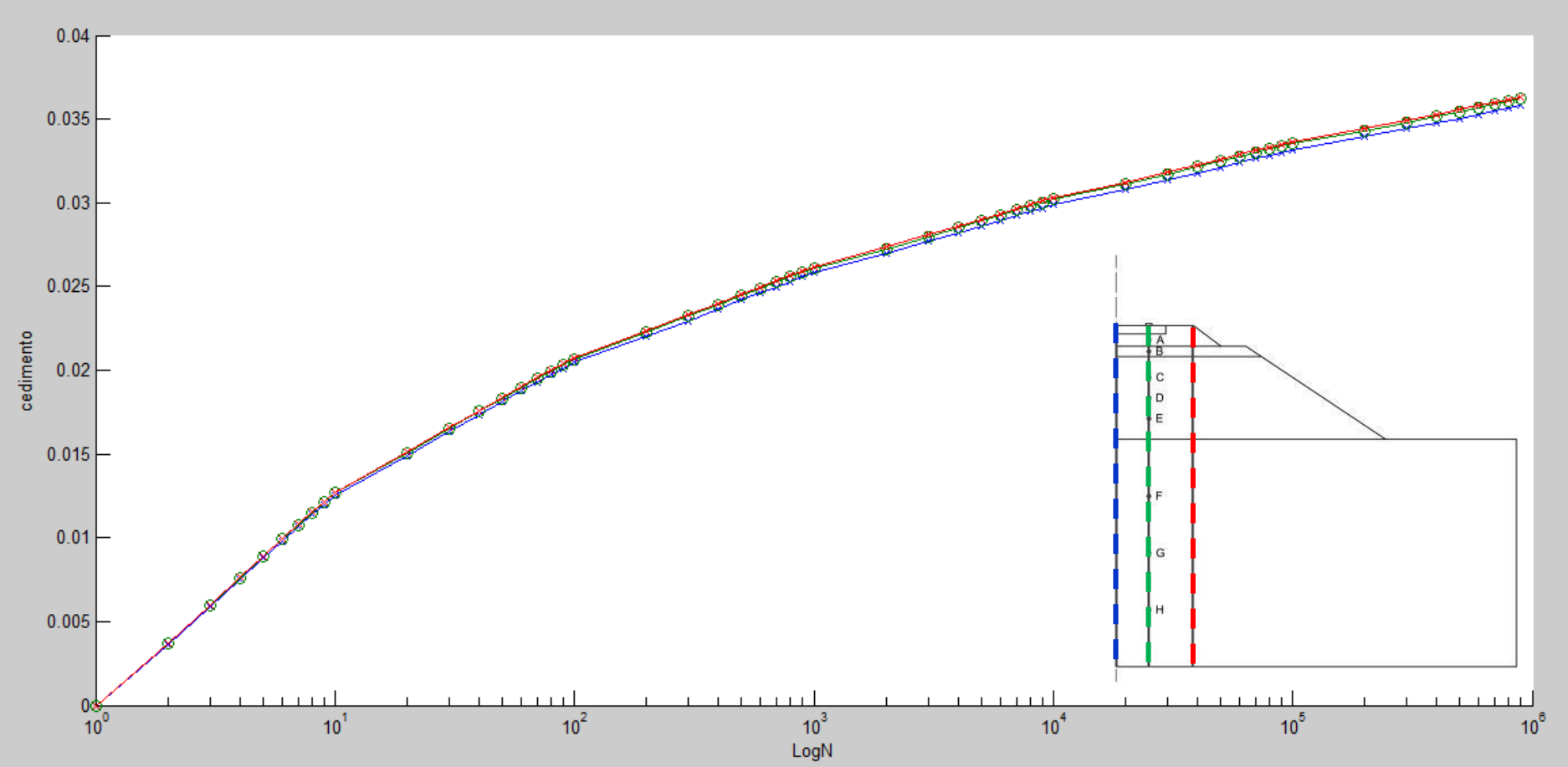


Cumulated vertical settlement of each layer



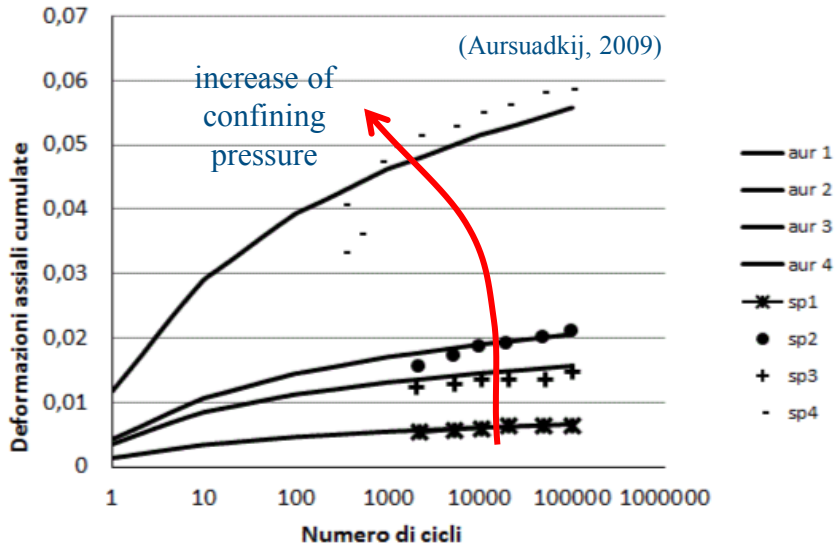
Example of application

Total cumulated vertical settlement
(and differential settlement along the sleeper)



Remarks and open issues…

Cyclic triaxial tests on ballast

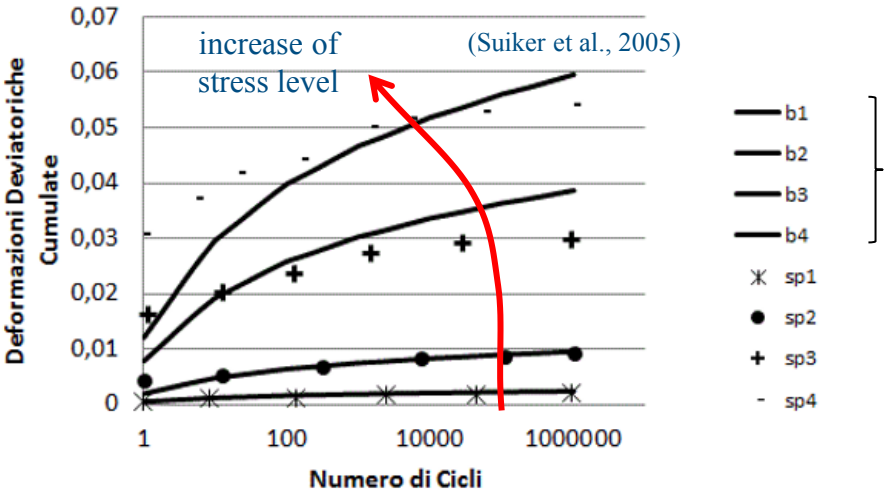


Calibration of constitutive parameters a, b, c

a=0,01	b=0,14	c=0,3	(p_c = 10 kPa)
a=0,035	b=0,14	c=0,3	(p_c = 30 kPa)
a=0,11	b=0,14	c=0,3	(p_c = 60 kPa)
a=0,1	b=0,14	c=0,3	(p_c = 60 kPa)

parameter "a" is mainly affected by the confining pressure

parameter "b" and "c" appear to be independent of the confining pressure



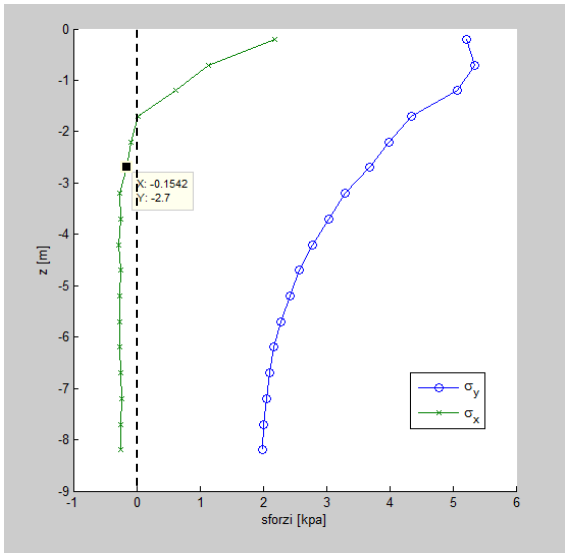
a=0,046	b=0,14	c=1	(p_c = 68,9 kPa)

Actually "a" and "c" seem to depend on a combination of confining pressure and cyclic stress level.

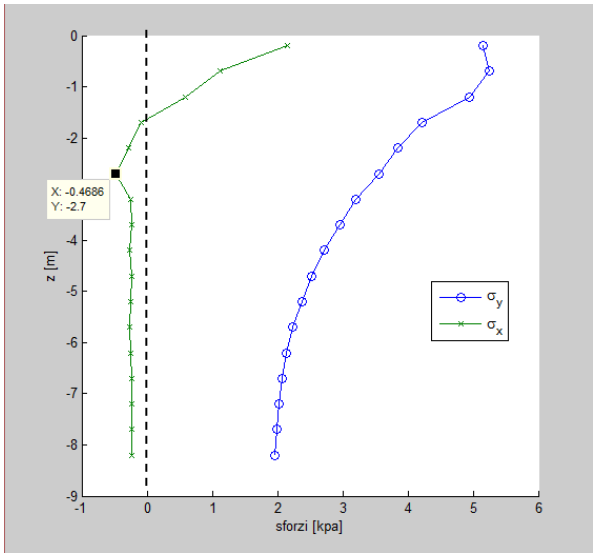
Parameter "b" is apparently uniquely dependent on the type of material

Remarks and open issues…

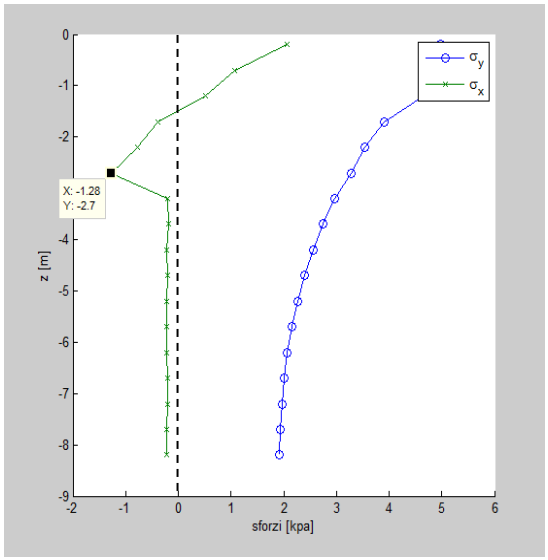
Vertical and horizontal stress increments



E_{sub}= 100 MPa

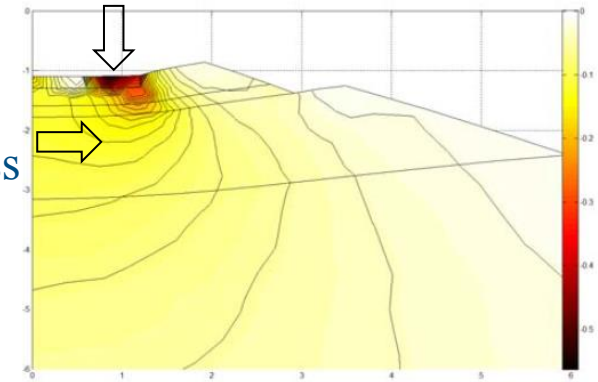


E_{sub}= 80 MPa



E_{sub}= 50 MPa

horizontal tensile stress



Conclusions

work in progress….