



UNIVERSITÀ DEGLI STUDI
DI CASSINO E DEL
LAZIO MERIDIONALE



INCONTRO ANNUALE DEI RICERCATORI DI GEOTECNICA
UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE
GAETA, 4-6 SETTEMBRE 2024



Scuola di Dottorato GNIG in Ingegneria Geotecnica 2024

Consolidamento dei terreni e delle rocce

2 - 4 settembre 2024

Il contributo della vegetazione nel rinforzo meccanico di coltri superficiali di versante

Manuela Cecconi

Dipartimento di Ingegneria, Università di Perugia

manuela.cecconi@unipg.it



A.D. 1308
unipg

DIPARTIMENTO
DI INGEGNERIA

DIPARTIMENTO DI ECCELLENZA
MUR 2023/2027

PARTE_1



Manuela Cecconi

IL CONTRIBUTO DELLA VEGETAZIONE NEL RINFORZO MECCANICO DI COLTRI SUPERFICIALI DI VERSANTE

SCUOLA DI DOTTORATO GNIG – Gaeta, 03/09/2024



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

Evidenza sperimentale

Interazione SVA

Condizioni sismiche: cenni



PROTEZIONE SUPERFICIALE DEI PENDII mediante TECNICHE DI INERBIMENTO

prevenzione dall'erosione

❖ stabilizzazione di coltri superficiali di versanti

Erosione

progressiva rimozione dalla superficie del suolo di strati di terreno, attraverso il distacco ed il trasporto di *singole particelle*, ad opera di vari agenti fisici (acqua, vento, ghiaccio, neve)

Frane

movimento verso valle di *porzioni di terreno* di varia forma e con diversi cinematismi

In entrambi i casi, nel nostro clima e sul nostro territorio: ruolo fondamentale dell'**acqua**.



Assorbimento di parte dell'energia cinetica dell'acqua battente e ruscellamento al di sopra della coltre vegetale



[da www.pratiarmati.it]

Orvieto (TR) – Versante «sigillato» dalla coltre vegetale



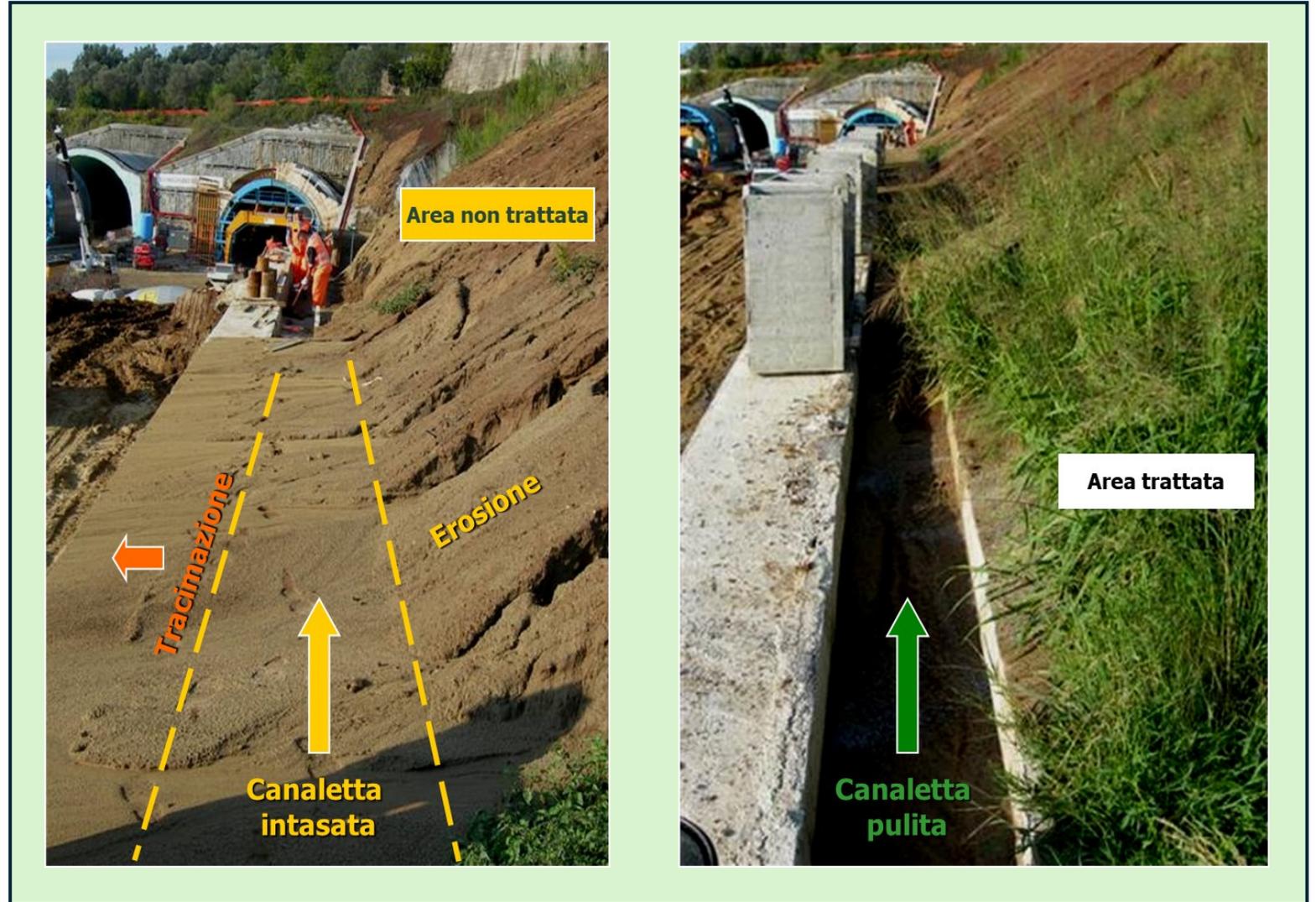
ORDINE degli INGEGNERI
PROGETTAZIONE E GESTIONE DELLA MANUTENZIONE
DELLE OPERE E DEL TERRITORIO
(Prevenire meglio che Curare)

Webinar 22 gennaio 2021

Protezione superficiale di versanti
mediante tecniche di inerbimento

Manuela Cecconi
Dipartimento di Ingegneria

UNIVERSITÀ DEGLI STUDI
DI PERUGIA



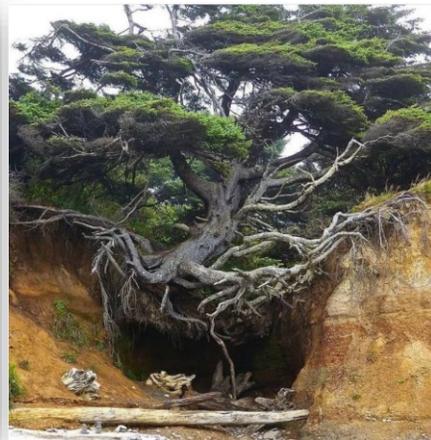
Manutenzione ↓ !!!



BOLDRIN, 2023



IL CONTRIBUTO DELLA VEGETAZIONE nel rinforzo meccanico di coltri superficiali di versante



Emilia Romagna, maggio 2023



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

Evidenza sperimentale

Interazione SVA

Condizioni sismiche: cenni



qualche definizione...

VEGETAZIONE:

assembly of plants (herbaceous or tree plants),
irrespective of their botanical species, incorporating both the above-ground portion and the embedded roots.

In questo contesto, trattiamo prevalentemente
“fibrous and small sized” roots with tension dominant mechanisms.

ROOTS TRAITS (FROM STOKES ET AL., 2009 – PLANT SOIL):

A trait is defined as a distinct, quantitative property of organisms, usually measured at the individual level and used comparatively across species.
A functional trait is one that strongly influences organismal performance (McGill et al. 2006).
Plant quantitative traits are extremely important for understanding the local ecology of any site.

NATURE BASED SOLUTIONS (NBS):

characterized by the use of natural materials, usually live material often combined with dead or inert material, and are based on design choices and technical solutions to preserve the territory, environment, and landscape.

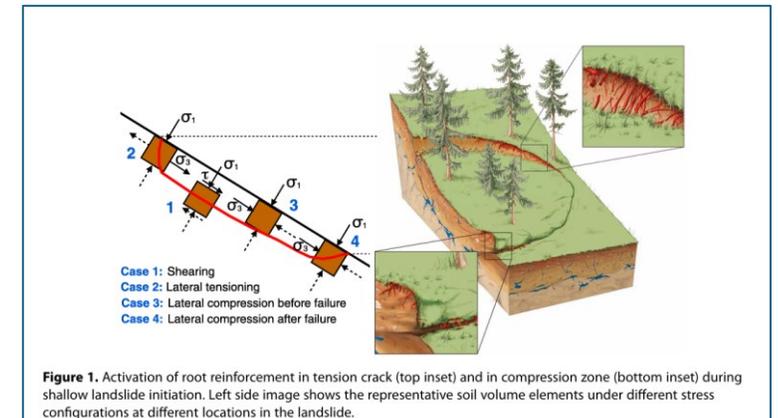
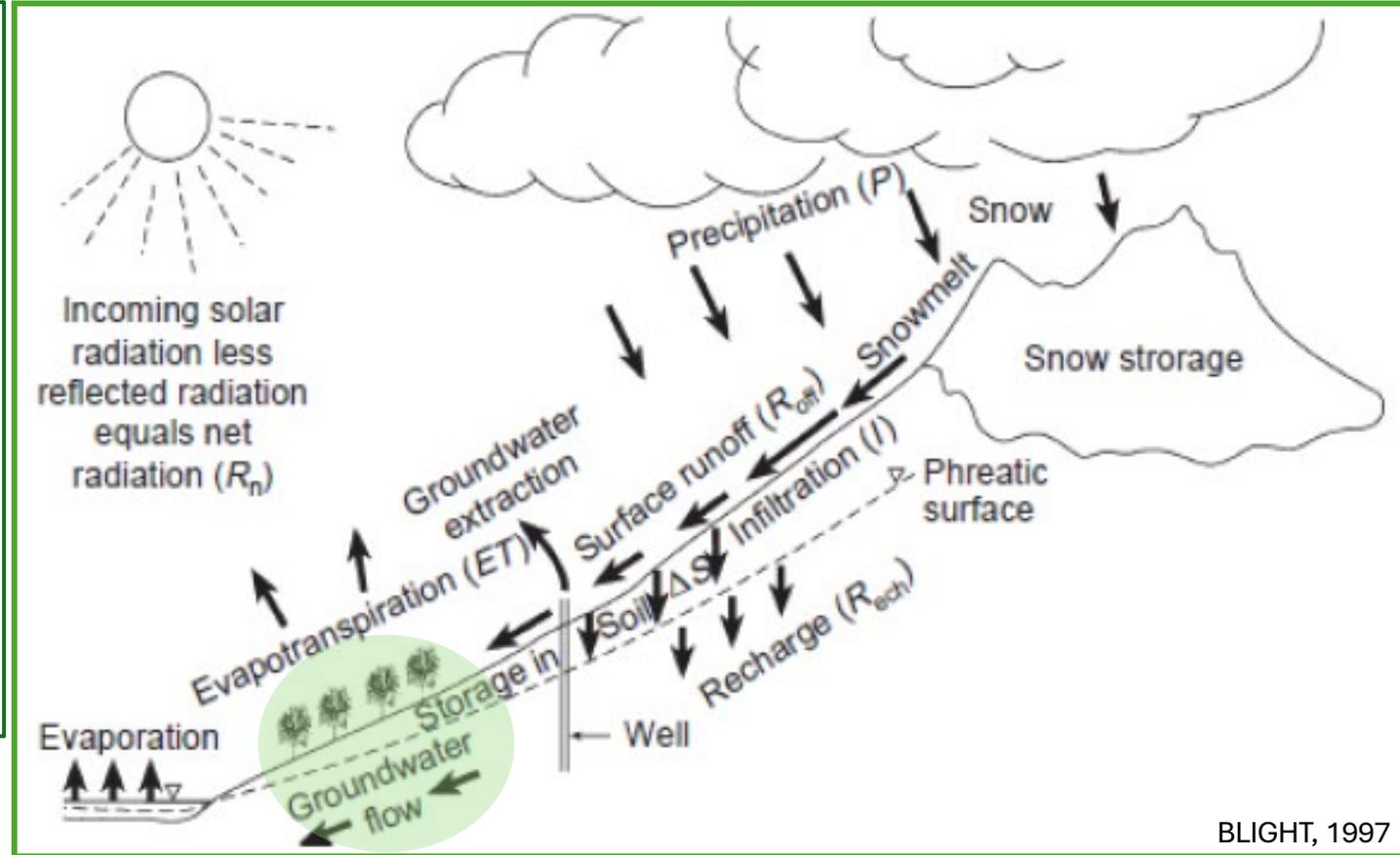
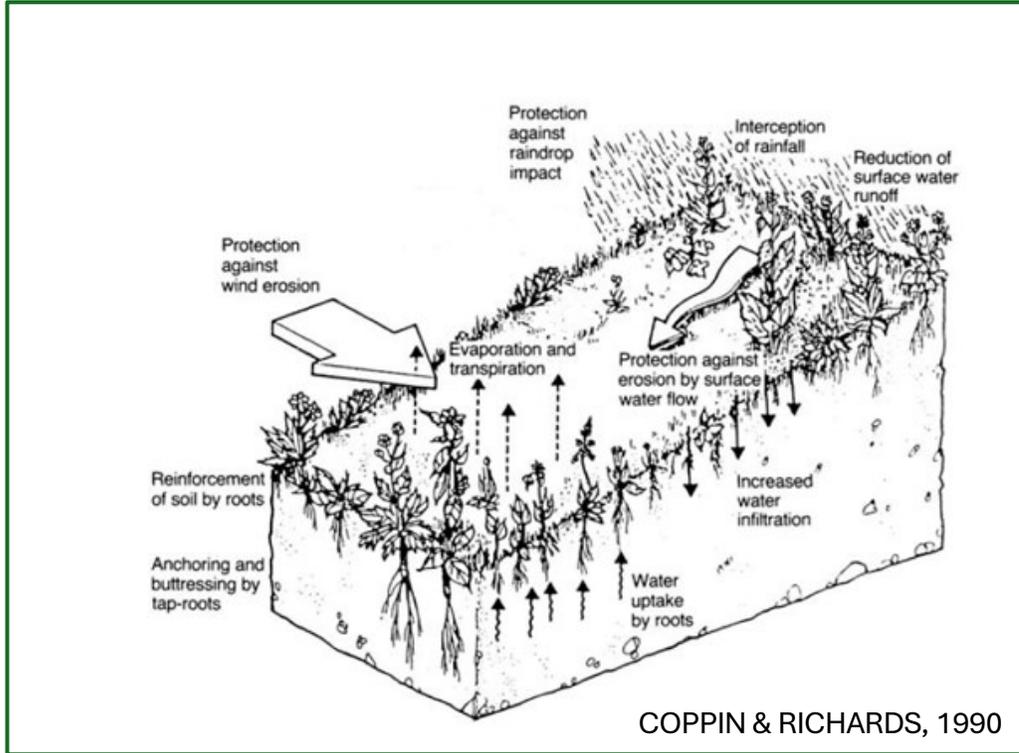


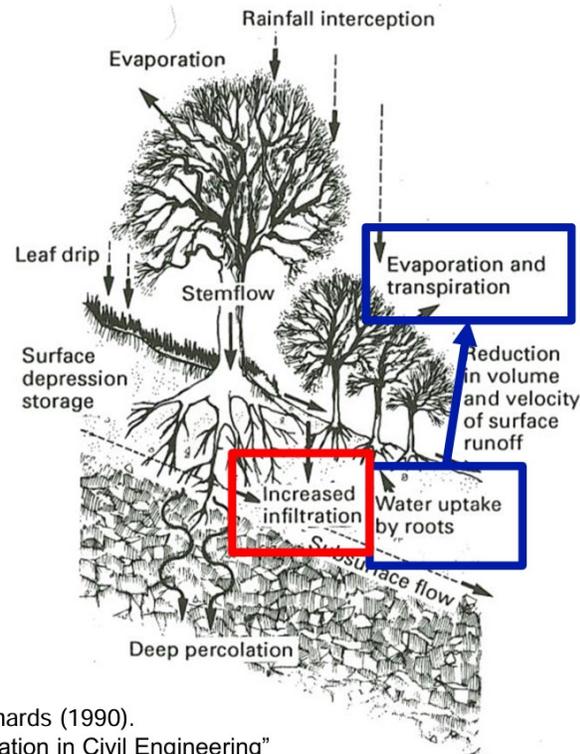
Figure 1. Activation of root reinforcement in tension crack (top inset) and in compression zone (bottom inset) during shallow landslide initiation. Left side image shows the representative soil volume elements under different stress configurations at different locations in the landslide.

SCHWARZ ET AL., 2013



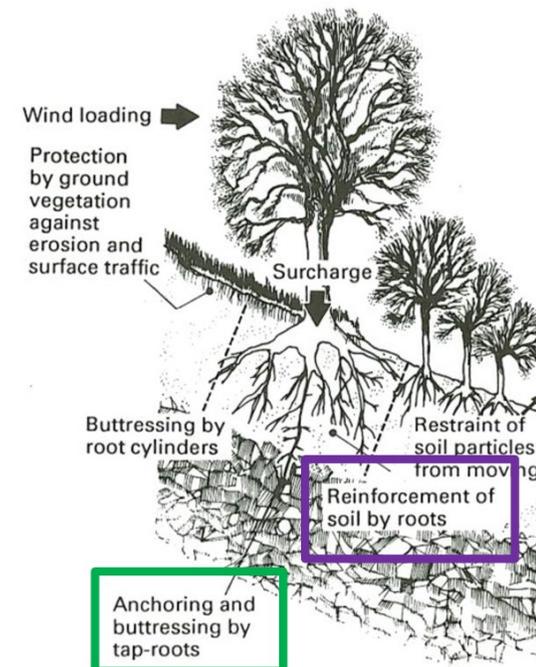


Hydrological effects



Coppin & Richards (1990).
"Use of Vegetation in Civil Engineering"

Mechanical effects



MEJIER, 2023

[COPPIN & RICHARDS (1990). "USE OF VEGETATION IN CIVIL ENGINEERING"]



SOIL (GROUND) MECHANICAL REINFORCEMENT

traditionally since the '70s

geotechnics on the soil reinforcement provided by roots...

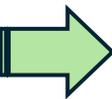
- Definition of the main factors which mutually affect soil properties and root growth and architecture, at different **scale of investigation**, through innovative exp. techniques and equipment
- How to properly measure soil reinforcement (proper evaluation, increased soil strength overestimated ?)
- How to predict soil reinforcement (different models/approaches)
- Find a compromise (?) between modelling of complex phenomena and current practice for risk reduction
- Seismic conditions: is it still possible and how to account for the mechanical effects of roots ?



PHENOMENA AND COUPLED PROCESSES UNDERLYING SVA INTERACTION advanced, late '90s, birth of work of geotechnics on SVA interaction... in the last 20-25 years

- plant transpiration and soil water uptake – vegetation cycles
- soil water retention properties - drying/wetting cycles
- soil hydraulic conductivity and volume change upon shearing (unsaturated rooted soils)

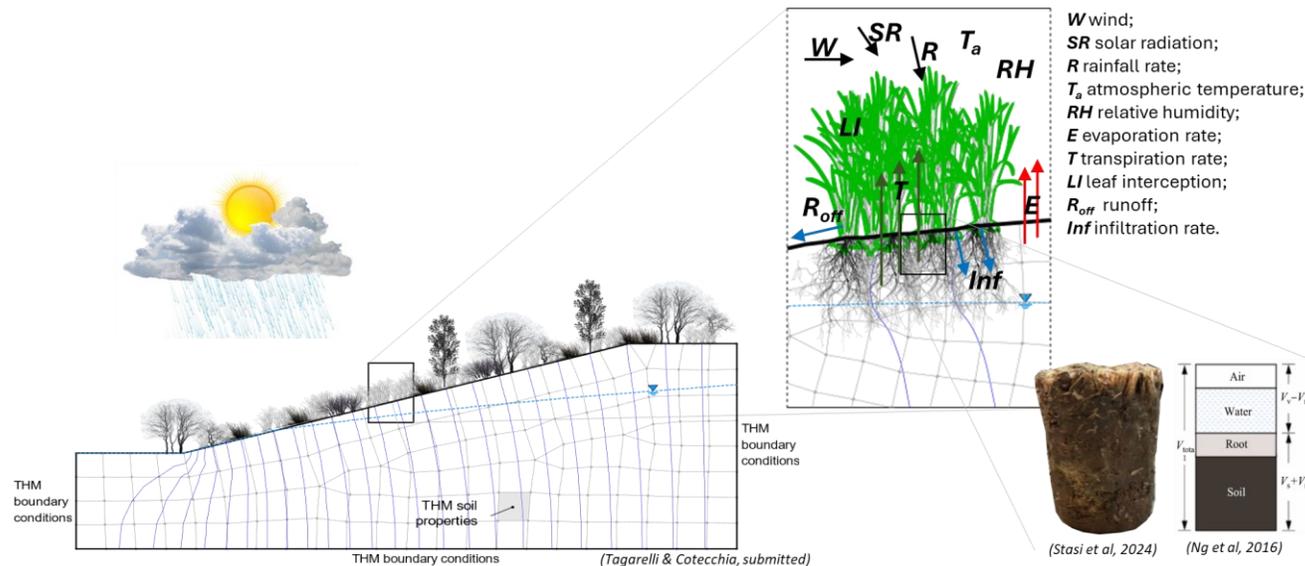
- local geomorphological factors and initial hydraulic conditions
- climate change impact
- predisposing factors and effects of phenomena and processes on slope stability assessment (primarily)





SHORT TERM GOAL: **Assessment** of SVA INTERACTION

- Proper understanding of mechanisms/processes involving all the “environmental compartments” and their mutual interaction,
- Investigation of SVA interaction through experimental, analytical and numerical studies.





LONG TERM GOAL: **Design of NBS - Support to the planning of earth use**

Key activities for disaster risk reduction:

- structural + non-structural measures into natural resources management approaches (**NBS**), **through** strategies for the reduction of disaster risk and adaptation to climate change (e.g.: UNISDR, 2015)

(geotechnical) systems' resilience  *for natural hazard risk reduction* 

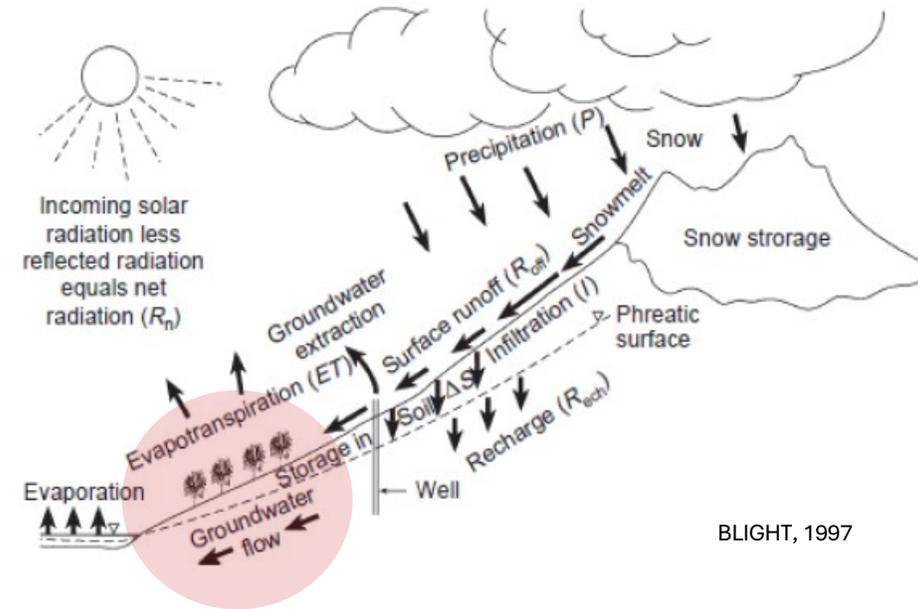
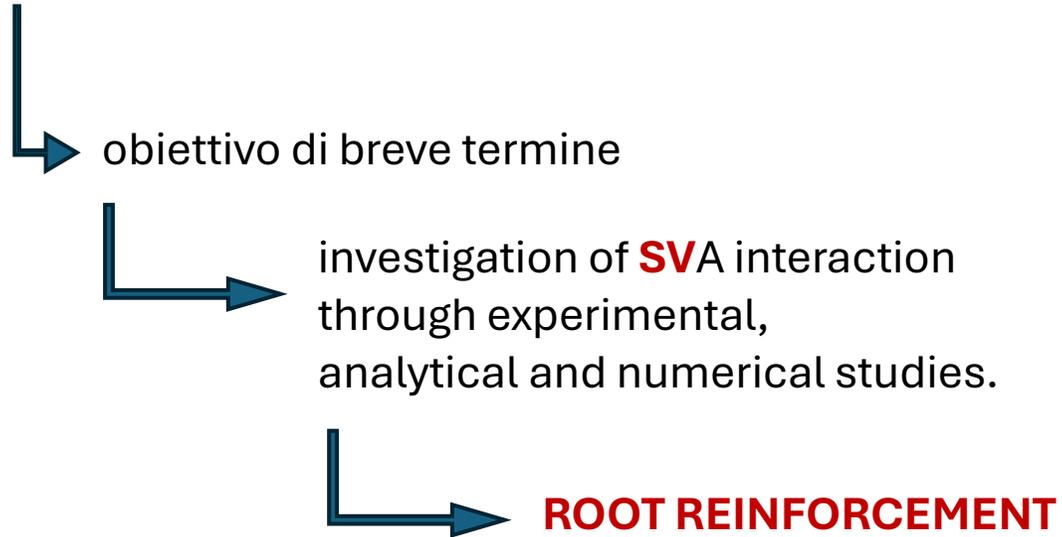


United Nations

- Support to the planning of land use.
Reducing deforestation and soil consumption represent critical issues to meet the 2030 global goals.



Il contributo della vegetazione nel rinforzo meccanico di coltri superficiali di versante



BLIGHT, 1997

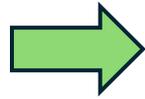


Scaletta

Introduzione

Posizione del problema

Un po' di storia...



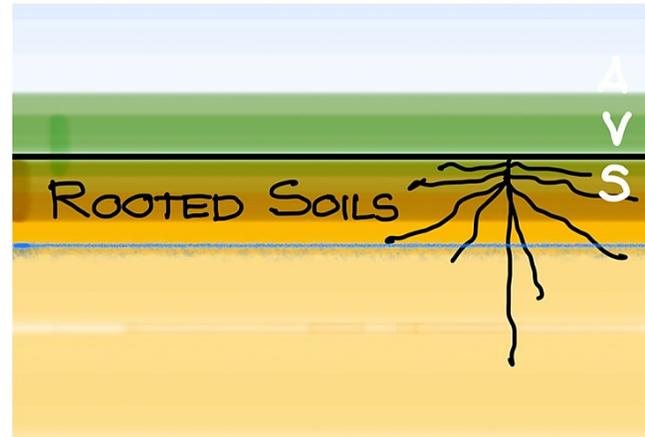
Modelli - RR

Esempi di calcolo: coltri superi

Evidenza sperimentale

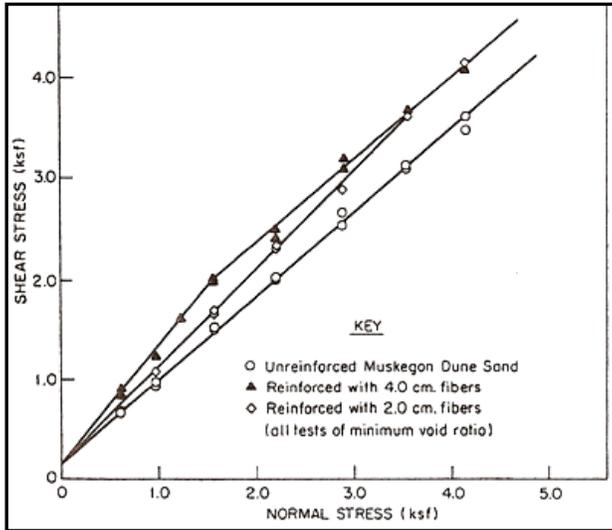
Interazione SVA

Condizioni sismiche: cenni

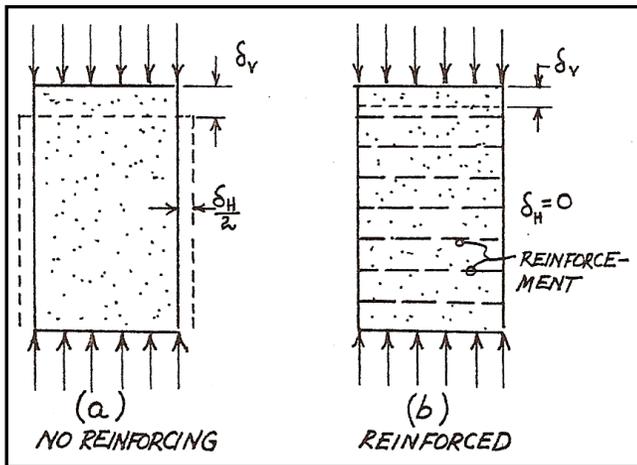




Prime evidenze sperimentali



← Risultati sperimentali di prove di taglio diretto
provini di sabbia asciutta costipata coltivati con radici di palma

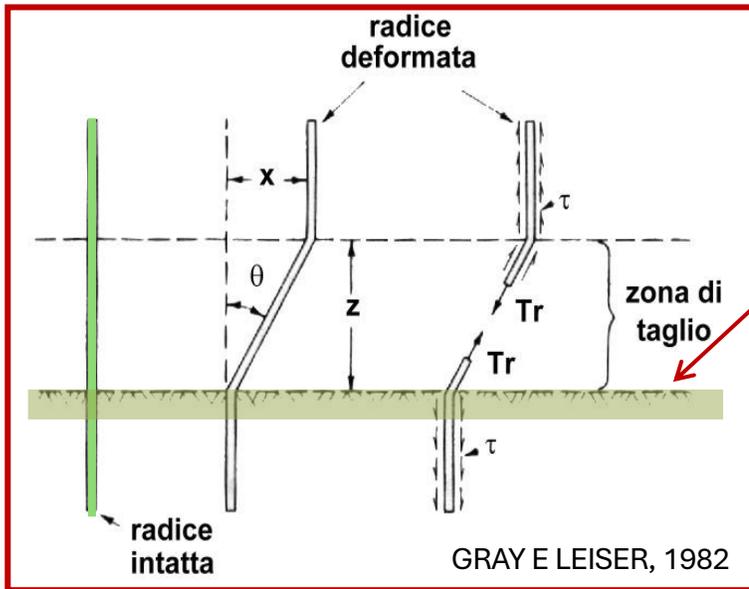


*Effetto:
limitare la deformazione nella
direzione del rinforzo*

GRAY E LEISER, 1982



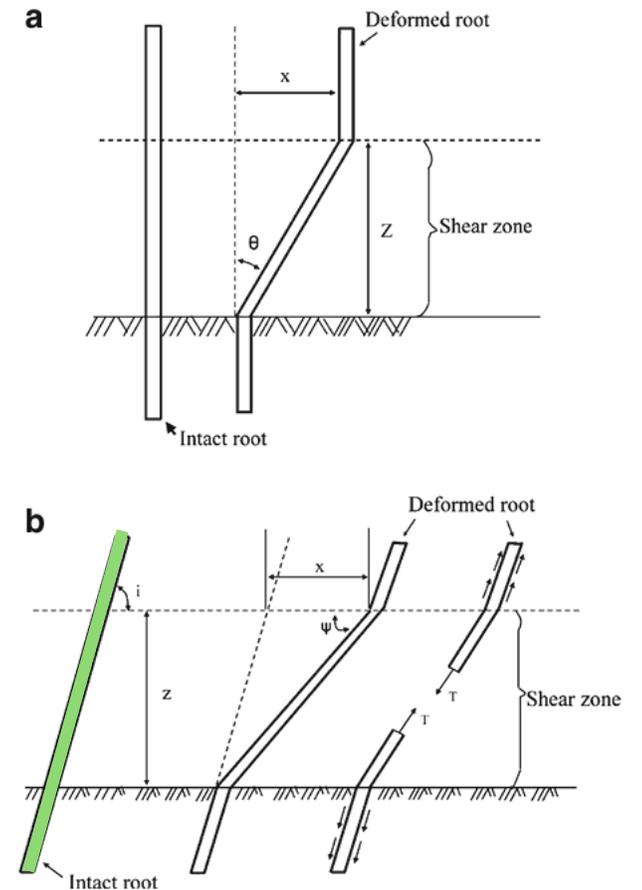
interazione terreno/radice: **radice singola**



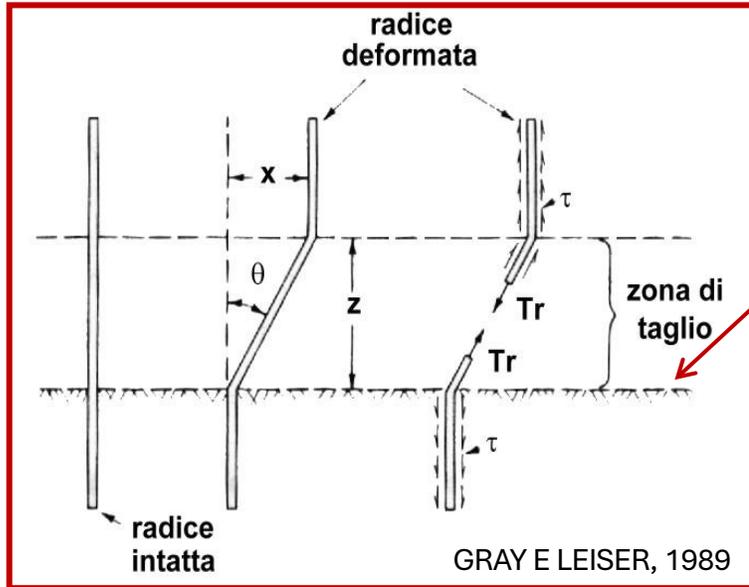
incremento di resistenza al taglio:

$$\Delta\tau_r = t_r (\cos\theta \cdot \tan\varphi + \sin\theta)$$

t_r : resistenza a trazione radice [kPa]



FAN and SU, 2009



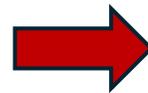
incremento di resistenza al taglio:

$$\Delta\tau_r = t_r (\cos\theta \cdot \tan\phi + \sin\theta)$$

t_r : resistenza a trazione radice [kPa]

...dalla radice singola all'apparato radicale:

In generale, incremento di resistenza al taglio (**RR**):

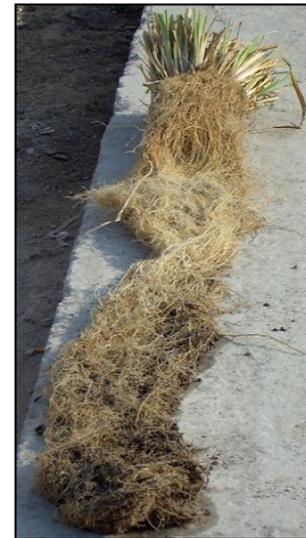
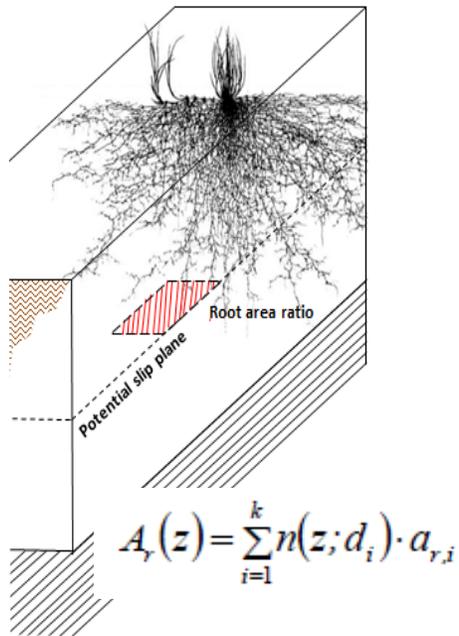


$$\Delta\tau_r(z) = k \cdot t_{rm} \cdot \frac{A_r(z)}{A_{rs}} = k \cdot t_{rm} \cdot \text{RAR}(z)$$

- k : fattore empirico (= 1.0 ÷ 1.2)
- $\text{RAR} = A_r(z)/A_{rs}$: rapporto di area radicata ()
- t_{rm} : sforzo di trazione (medio) mobilitato nella radice ($t_{rm} \leq t_r$)



Il profilo RAR tipicamente diminuisce con la profondità (z)

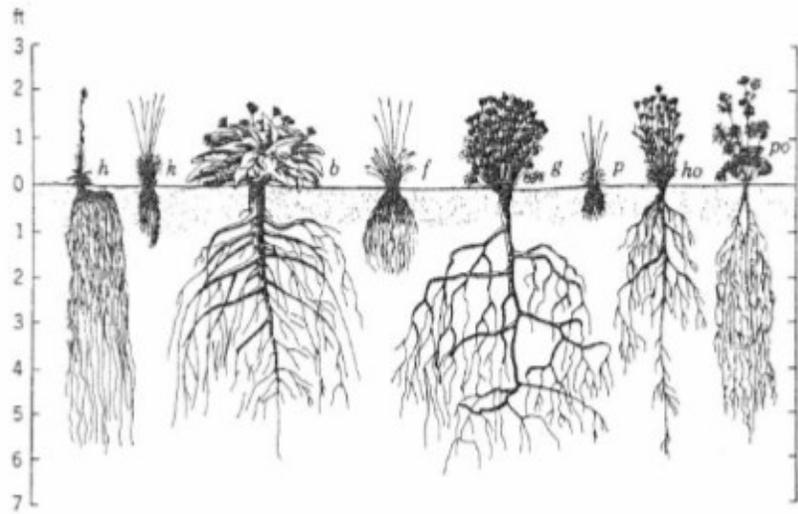


impianti radicali
profondi

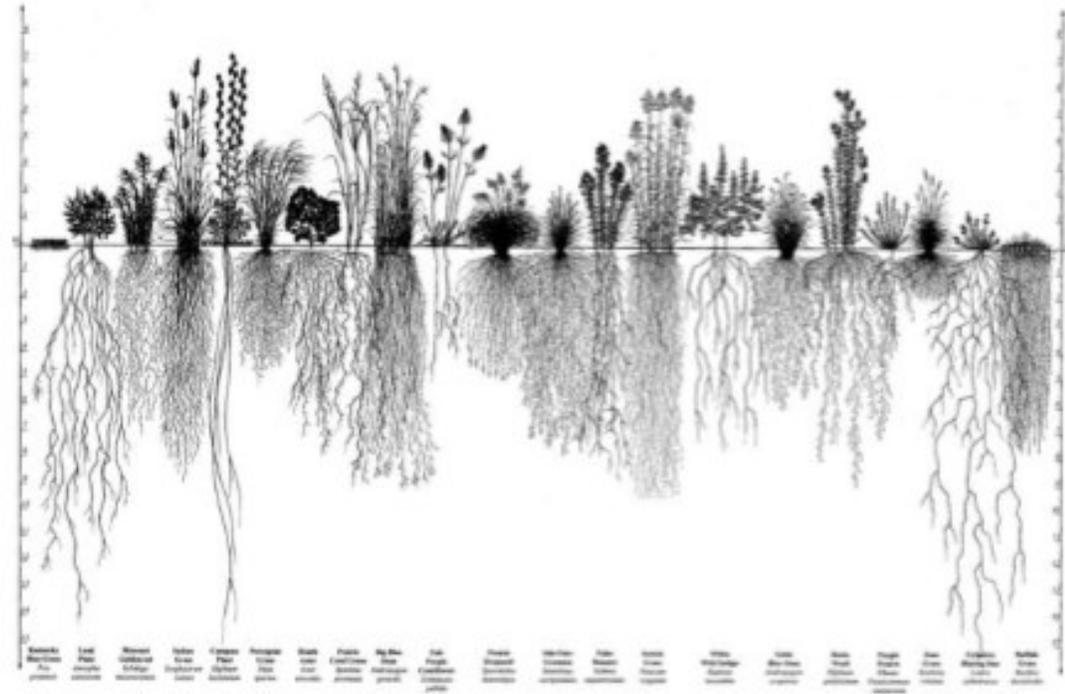


REFS. (solo alcuni):

ABE & ZIEMER, 1991;
FEDDES ET AL., 2001;
OSMAN & BARAKBAH, 2006;
ZUO ET AL., 2004]



sviluppi radicali di diverse specie vegetali

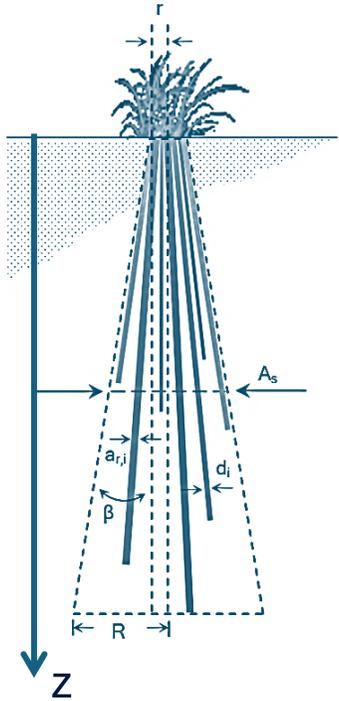


WEAVER, 1919

specie erbacee



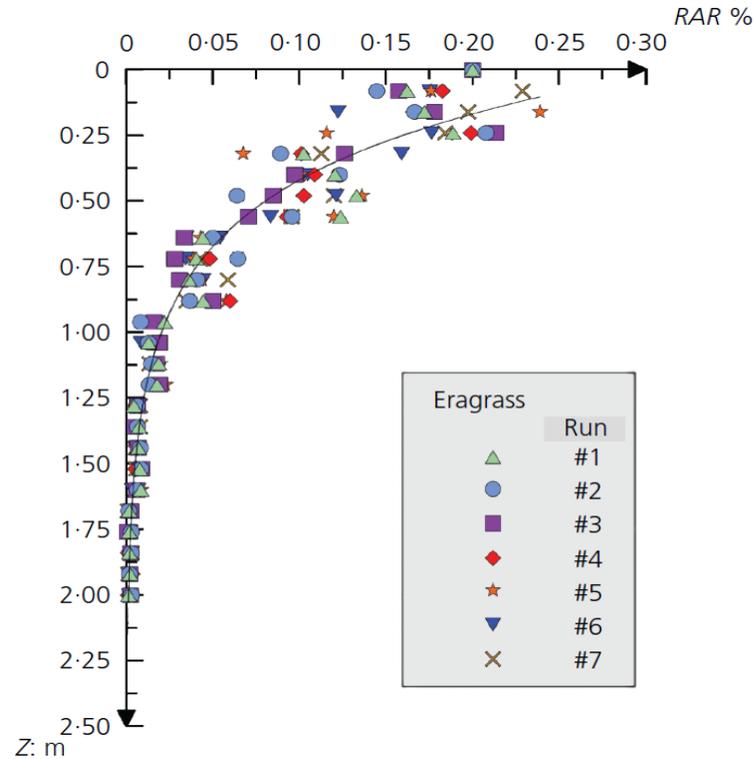
modello geometrico: sistema radicale “fascicolato”



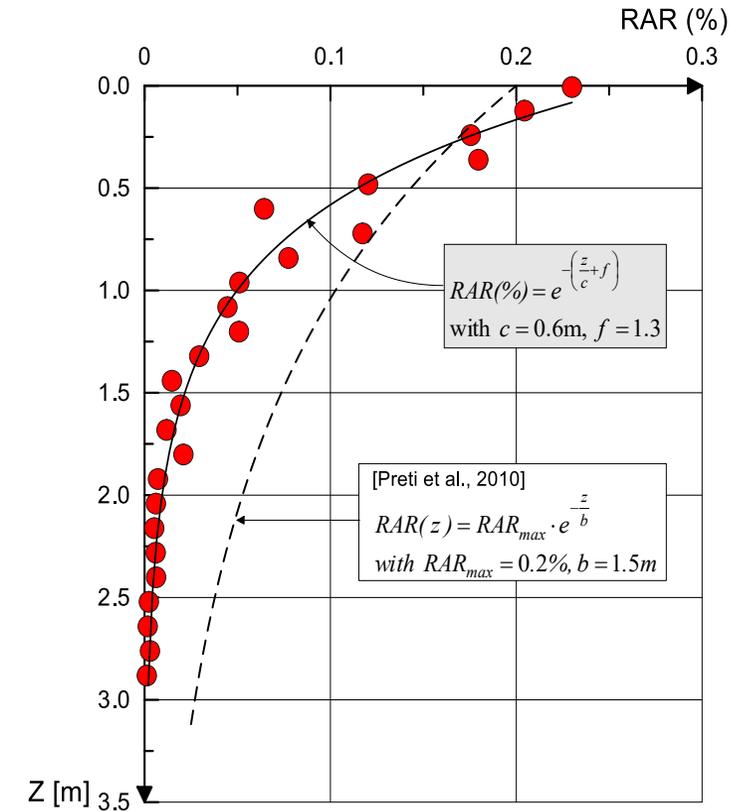
il numero di radici $n(z,d)$ varia con z e con il diametro della radice

$$A_s(z) = \pi \cdot (z \tan \beta + r)^2$$

$$A_r(z) = \sum_{i=1}^m n(z, d_i) \cdot a_{r,i}$$



“funzione random” genera il numero di radici $n(z, d_i)$ per ogni strato e diametro della radice
 m classi di diametro, n variabile con z ($n = 10 - 40$)



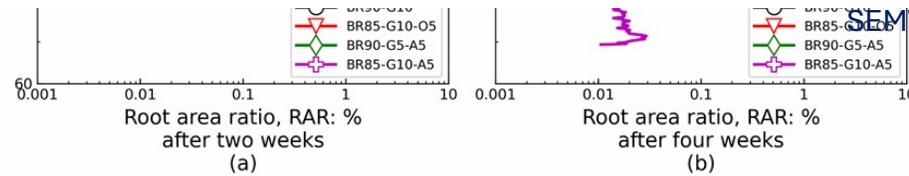
CECCONI ET AL., 2013, 2015



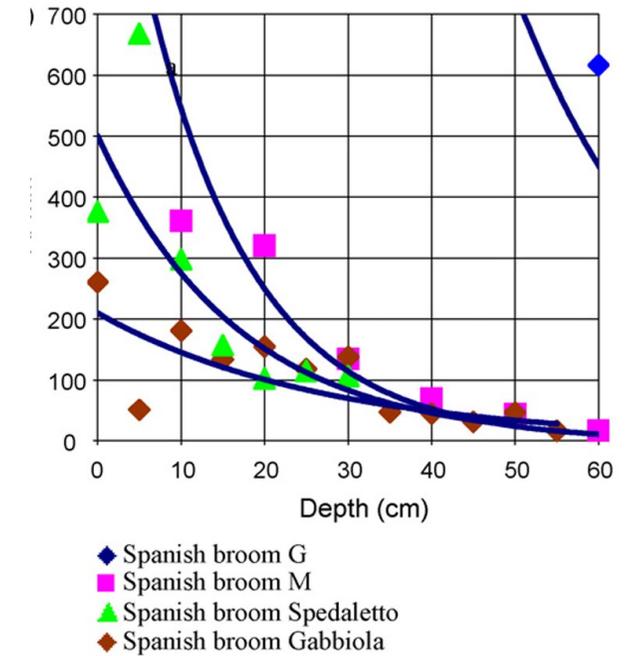
osservazioni in sito NECESSARIE !!!



S. no.	Species	RAR profile	Root type	Root property	Potential application
1	<i>L. leucocephala</i> , <i>P. cerasoides</i>		VH type	More root concentration at the top and decreases gradually along the depth	Reinforcement and erosion reduction potential
2	<i>B. variegata</i> , <i>P. granatum</i> , <i>S. mukorossi</i>		V type	Root concentration uniform along the depth, indicating seldom branching	Reinforcement for a mass movement

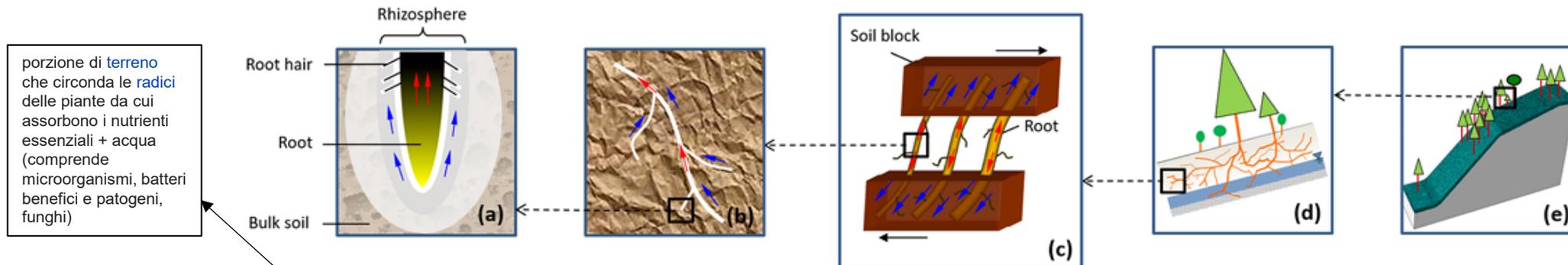


from CAPOBIANCO, 2023





ROOT REINFORCEMENT (RR) : scala di osservazione e comprensione dei meccanismi



porzione di terreno che circonda le radici delle piante da cui assorbono i nutrienti essenziali + acqua (comprende microorganismi, batteri benefici e patogeni, funghi)

Scale: Rhizosphere Individual root Root bundle Individual plant, population or community Slope

Unit for size: μm to mm mm to cm cm cm to m m to km

SCALA !!!

Root feature related to root reinforcement in question:

- | | | | | |
|---|--|--|---|---|
| <ul style="list-style-type: none"> • Shear resistance along the root–soil interface • Effect of root hairs • Effect of mycorrhizal fungi • Effect of root exudation | <ul style="list-style-type: none"> • Root morphology (diameter, length, tortuosity etc.) • Root mechanical traits • Root failure mode • Root–soil friction | <ul style="list-style-type: none"> • Root reinforcement value • Root diameter spectrum • Root orientation • Root spacing • Root failure order • Load sharing among roots • Root system architecture | <ul style="list-style-type: none"> • Root system architecture • Root demography • Spatiotemporal pattern of root reinforcement | <ul style="list-style-type: none"> • Spatiotemporal pattern of root reinforcement • Slope stability and roots’ contribution |
|---|--|--|---|---|



Overview of roots' features for geotechnical purposes (terminology)

Roots features commonly evaluated in geotechnical studies	Acronyms	Description
BRANCHING POINT DISTANCE	BPD	average distance between two branches on a root
LEAF AREA INDEX	LAI	sum of the upper-side leaves' areas per unit soil surface
ROOT AREA/VOLUME RATIO/ROOT VOLUME DENSITY	RVR - RVD	sum of root's section areas/volumes per unit soil section/bulk volume
ROOT ORIENTATION	RO	root inclination angle
ROOT LENGTH DENSITY	RLD	sum of root lengths per unit soil bulk volume
ROOT DECAY RATIO	RDR	volumetric percentage of root decayed, with respect to the whole root architecture's volume
ROOT/SHOOT BIOMASS	RB	dry/wet root or shoot (above-ground plant) mass. sometimes normalised per unit bulk volume of soil
BASAL DIAMETER	BD	tree diameter at 1.3 m above the ground surface
PLANT SPACING	PS	distance between plant individuals
SEEDING DENSITY	SD	seed mass per unit soil surface

STOKES ET AL. (2009)



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

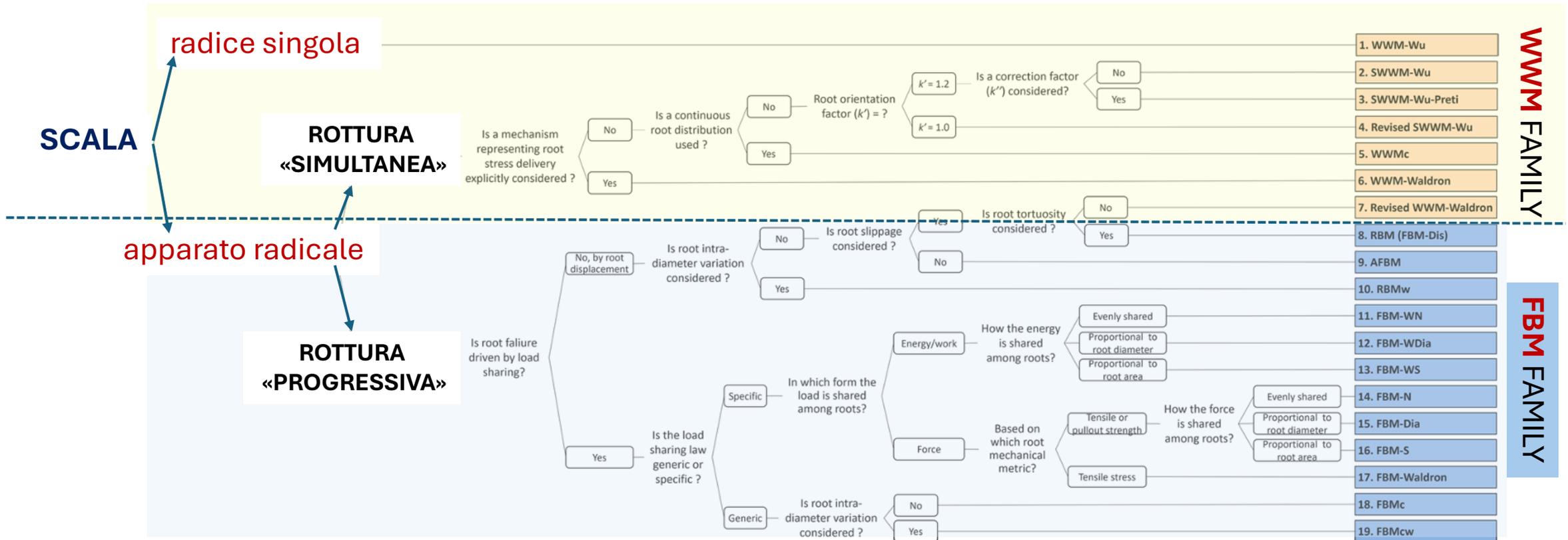
Modelli - RR

Esempi di calcolo: coltri superficiali

Evidenza sperimentale

Interazione SVA

Condizioni sismiche: cenni



(adattato da MAO, 2022.

Nota: refs. indicati per i diversi models)



RR: ROOT REINFORCEMENT models

(MAO, 2022)

↳ Modelli - **WWM** FAMILY

Scala:

↳ Singola radice

↳ Apparato radicale

Nel secondo caso, rottura «**simultanea**» delle radici

In tutti i casi, **RR** è rappresentato dall'incremento di resistenza a taglio $\Delta\tau$
(se MC failure criterion → incremento di **coesione**)

REFS. (solo alcuni...)

WU, 1976;

WALDRON, 1977;

WU ET AL., 1979

GRAY & LEISER, 1989;

GRAY & SOTIR, 1996;

WANG & LEE, 1998;

POLLEN ET AL., 2004

POLLEN & SIMON, 2005

QI & HU, 2006;

SCHWARTZ ET AL., 2010, 2013;

WU, 2013;

CAZZUFFI, CARDILE, GIOFFRÈ, 2014;

CECCONI ET AL., 2014

DIAS, PIRONE, URCIUOLI, 2017

JI ET AL., 2020

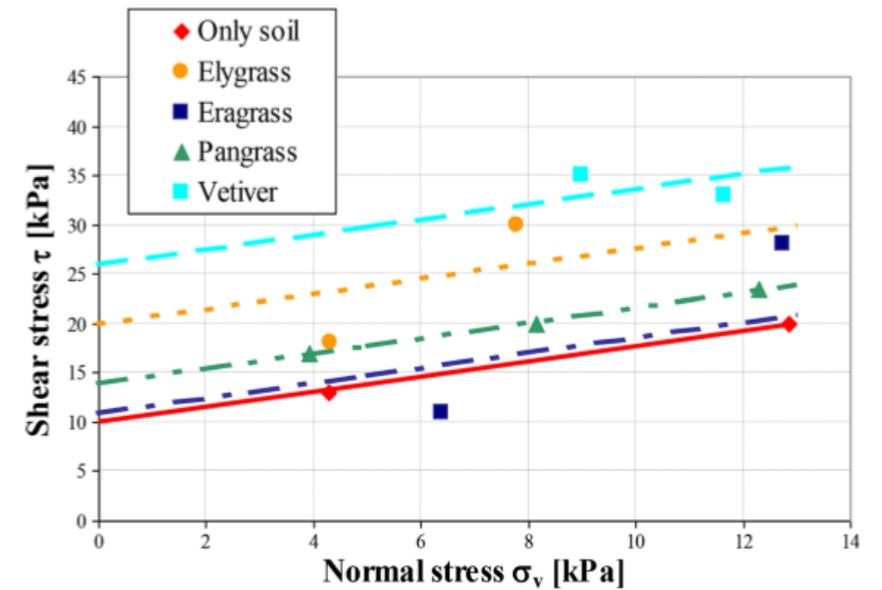
MEIJER, 2021



Risultati di prove di taglio diretto su provini cilindrici (diam: 200mm)



CAZZUFFI and CRIPPA, 2005



CAZZUFFI ET AL., 2014



RR: ROOT REINFORCEMENT models

(MAO, 2022)

↳ Modelli **FBM – Fiber Bundle Models** FAMILY

Scala:

↳ Apparato radicale

Algoritmi FBM

RR è ancora rappresentato da incremento di **coesione**

REFS. (solo alcuni)

WU, 1976;

WALDRON, 1977;

WU ET AL., 1979

GRAY & LEISER, 1989;

GRAY & SOTIR, 1996;

WANG & LEE, 1998;

POLLEN ET AL., 2004

POLLEN & SIMON, 2005

QI & HU, 2006;

SCHWARTZ ET AL., 2010, 2013;

WU, 2013;

CAZZUFFI, CARDILE, GIOFFRÈ, 2014;

CECCONI ET AL., 2014

DIAS, PIRONE, URCIUOLI, 2017

JI ET AL., 2020

MEIJER, 2021



Basic principle of a standard FBM:

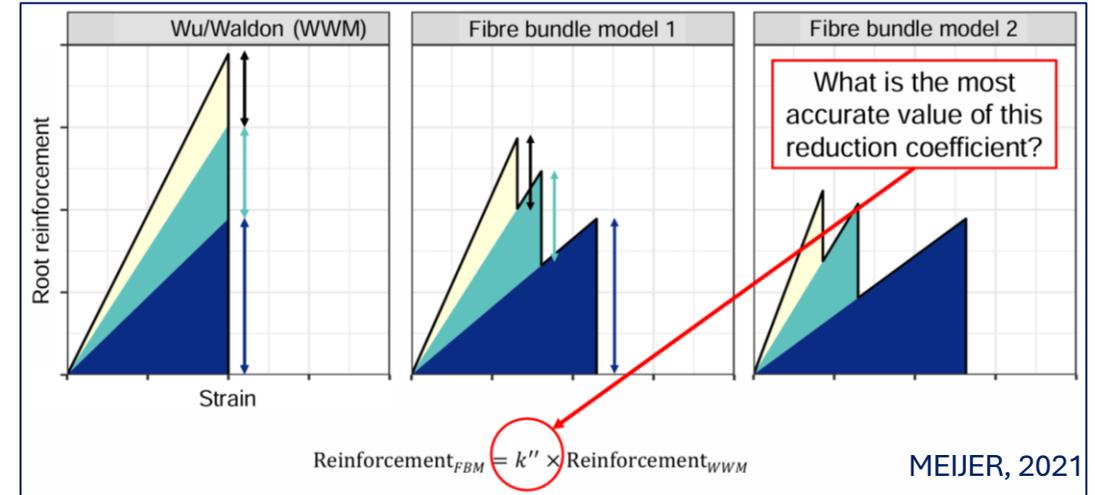
The maximum load withstood by the bundle of fibers is **lower** than the sum of each of their individual strengths (**rottura non simultanea**)

Simple rules:

- an initial load is added to the bundle, containing a number, n , of parallel fibers.
- Although at first the load is distributed equally between the n fibers, once the load is increased sufficiently for a fiber to break, the load that was carried by the fiber is redistributed to the remaining intact roots, each of which then bears a larger amount of the load than before.
- If this redistribution of load causes any further roots to break, further redistribution of load occurs and so on until no more breakages occur.
- Another increment of load is then added to the system, and the process is repeated until either all of the fibers have been broken

The simplest of FBM models assume that the load from the broken fibers is distributed evenly between the remaining intact fibers, **according to their diameters**.

POLLEN AND SIMON, 2021



Nota:

ipotesi: relazioni empiriche tra

tensile strength
elasticity modulus

power law function



root diameter

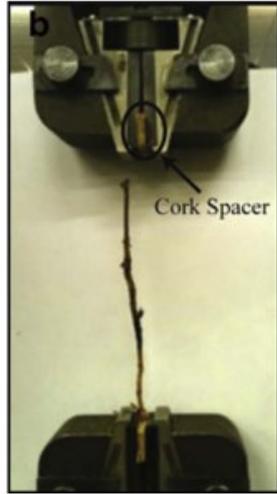


Risultati sperimentali di prove a trazione su specie erbacee

[CAZZUFFI E TIRONI, 2003; CAZZUFFI E CRIPPA, 2005; BONFANTI E BISCHETTI, 2009; BISCHETTI ET AL, 2003; BISCHETTI, 2003]

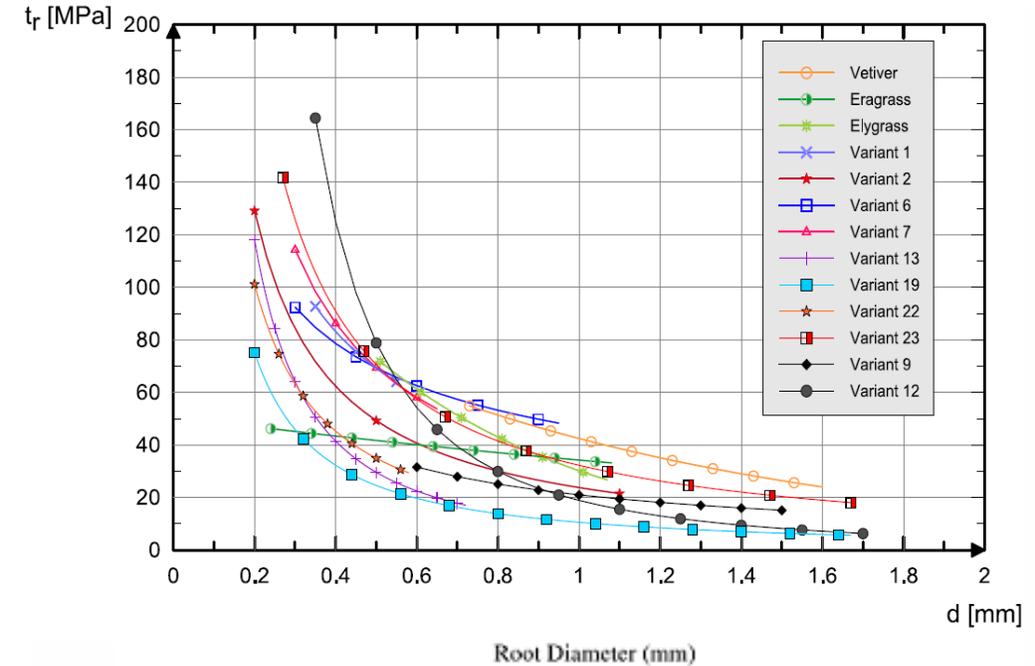


GIADROSSICH ET AL., 2017



BOLDRIN, 2023
(after SIMON, COLLISON 2002)

tensile strength vs. root diameter



$$t_r = f(\text{diametro}) = a \cdot d^{-b} \quad [MPa]$$

coefficienti a, b funzione della specie



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

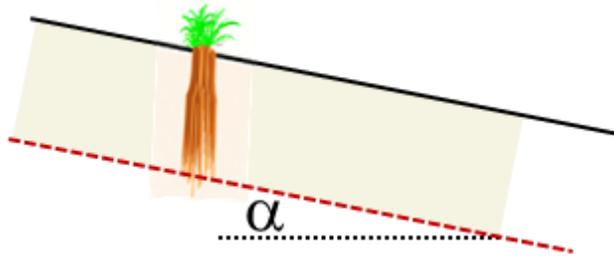
Evidenza sperimentale

Interazione SVA

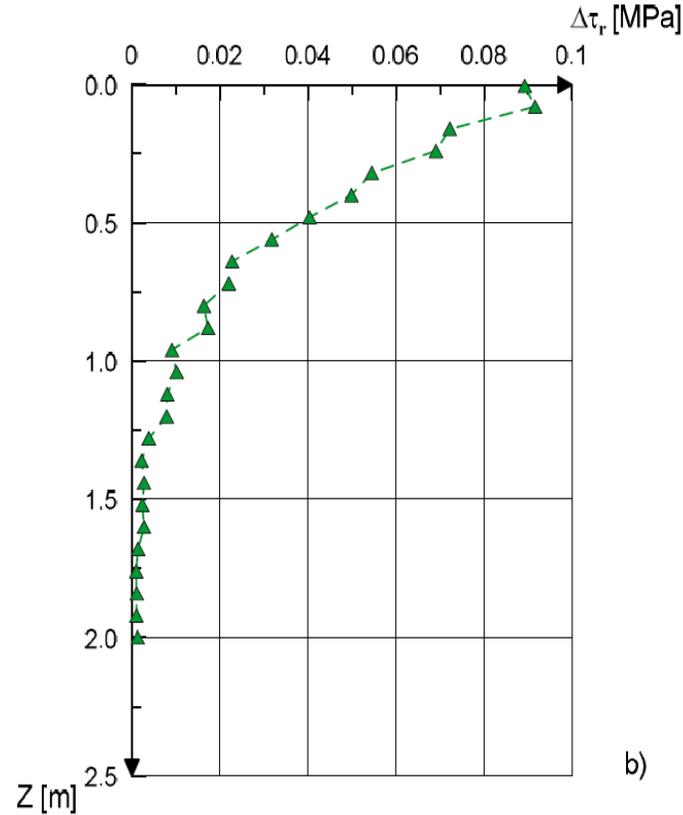
Condizioni sismiche: cenni



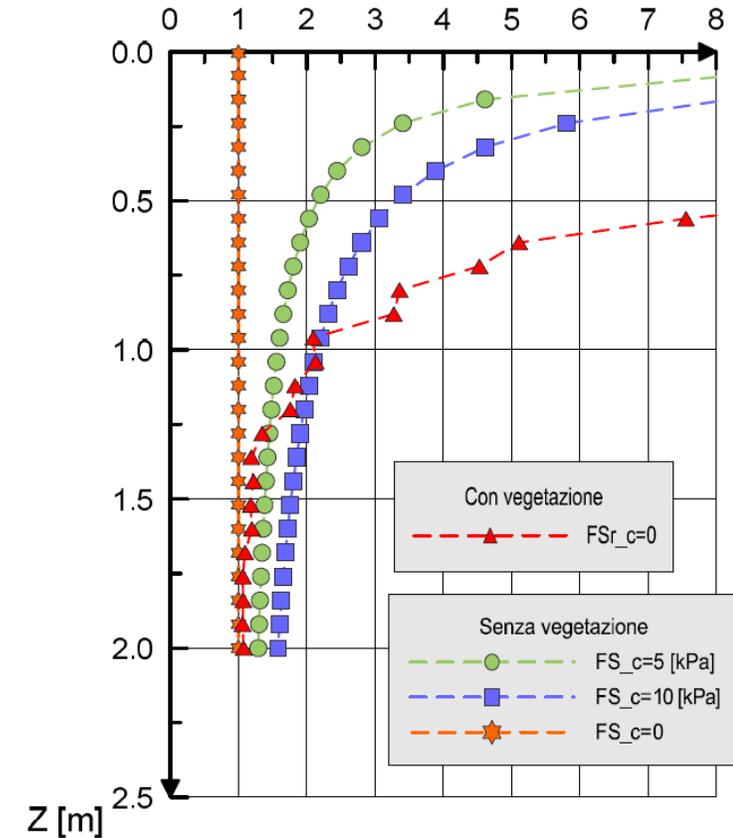
schema molto semplice di **pendio indefinito**



$$SF(z) = \frac{\tan \phi'}{\tan \alpha} + \frac{c' + \Delta\tau_r(z)}{\gamma z \cdot \cos \alpha \cdot \sin \alpha}$$

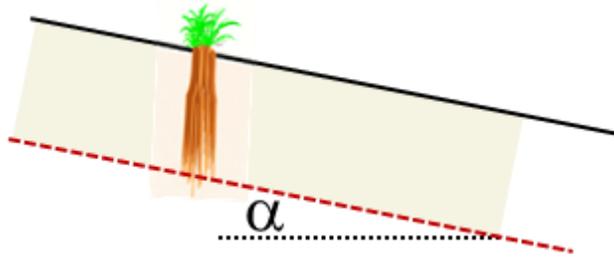


SF (z) , per $\alpha = 30^\circ$, $\phi = 30^\circ$

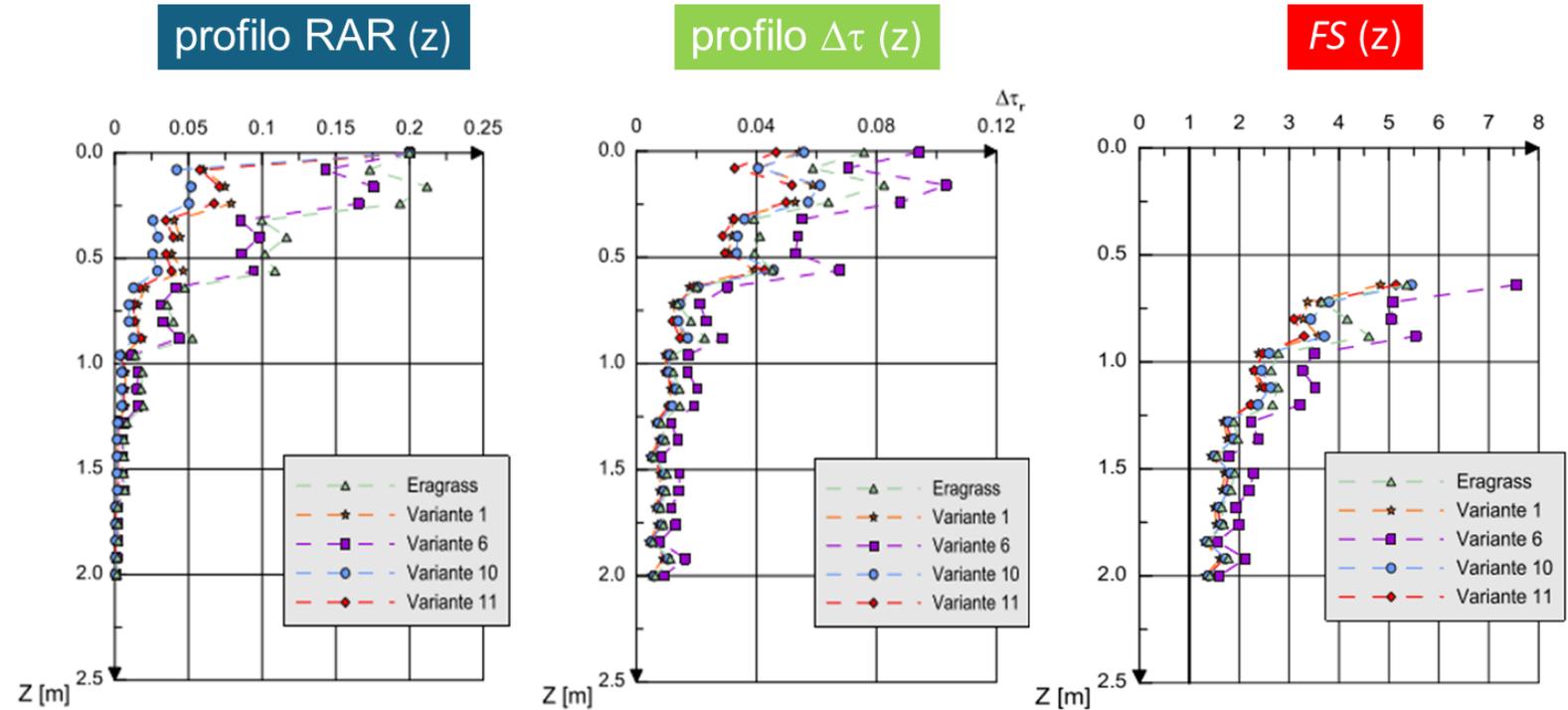




Schema (molto semplice) di **pendio indefinito**: effetto specie veg.

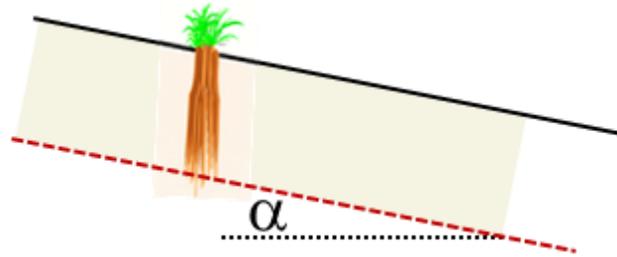


$$SF(z) = \frac{\tan \phi'}{\tan \alpha} + \frac{c' + \Delta\tau_r(z)}{\gamma z \cdot \cos \alpha \cdot \sin \alpha}$$

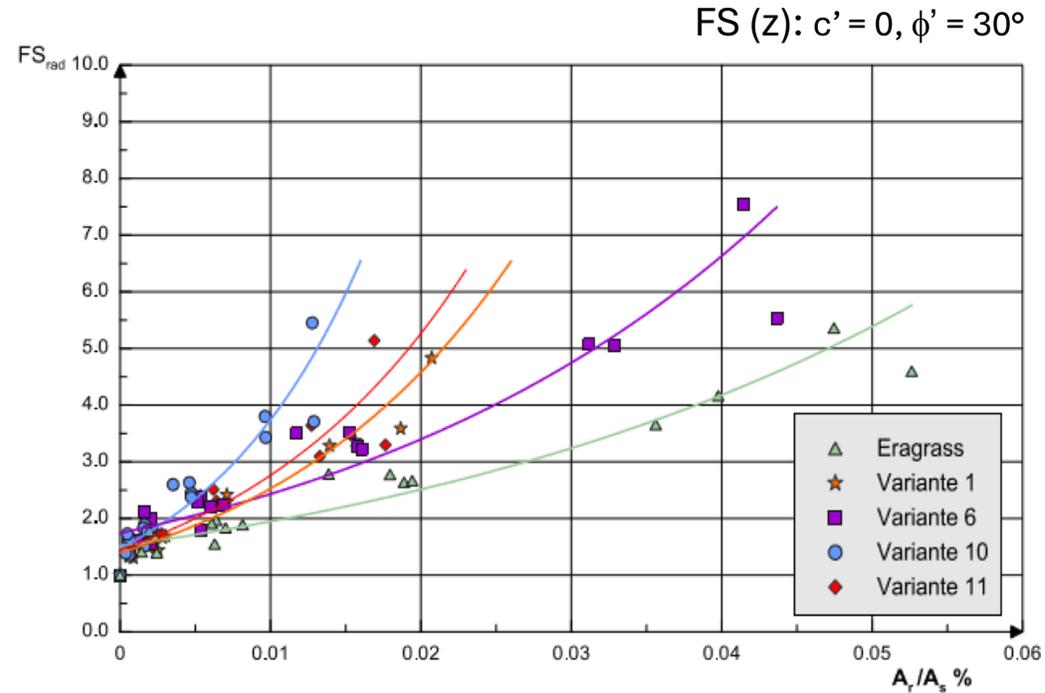




pendio indefinito: effetto specie veg.



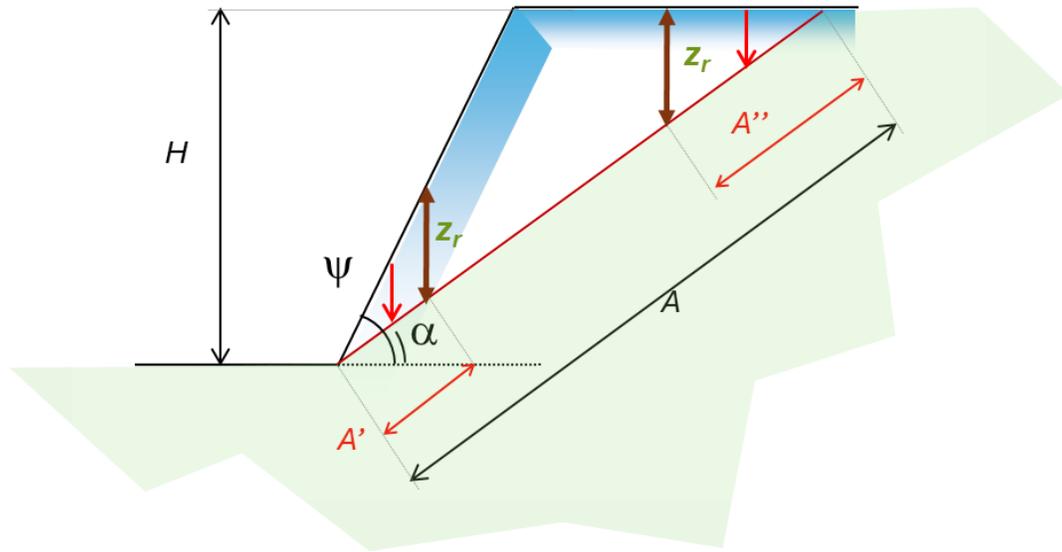
$$SF(z) = \frac{\tan \phi'}{\tan \alpha} + \frac{c' + \Delta\tau_r(z)}{\gamma z \cdot \cos \alpha \cdot \sin \alpha}$$



FS vs. RAR per diverse specie erbacee ($z > 0.5m$)



Schema di cuneo piano_contributo apparato radicale



$$A' = z_r \frac{\cos \psi}{\sin(\psi - \alpha)} \quad A'' = \frac{z_r}{\sin \alpha}$$

$$A' + A'' = z_r \frac{\sin \psi \cos \alpha}{\sin(\psi - \alpha) \sin \alpha}$$

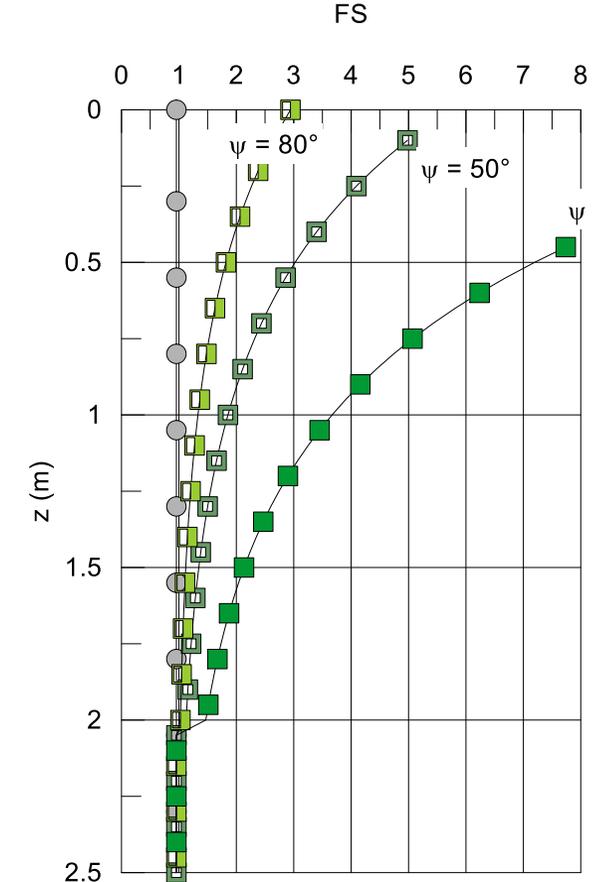
$$\Delta \tau_r(z) = 1.2 \cdot t_r \cdot RAR(z)$$

$$FS = \frac{\tan \phi}{\tan \alpha} + \frac{cA + \Delta \tau_r(A' + A'')}{W \sin \alpha}$$

scivolamento piano:

$H = 10 \text{ m}$,
 $\gamma = 20 \text{ kN/m}^3$
 $\phi = 25^\circ, \alpha = 26^\circ$

$t_{r,m} = 1 \text{ MPa}$



BIONDI and CECCONI (2024, in preparation)



UNIVERSITÀ DEGLI STUDI
DI CASSINO E DEL
LAZIO MERIDIONALE



INCONTRO ANNUALE DEI RICERCATORI DI GEOTECNICA
UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE
GAETA, 4-6 SETTEMBRE 2024



Scuola di Dottorato GNIG in Ingegneria Geotecnica 2024

Consolidamento dei terreni e delle rocce

2 - 4 settembre 2024

Il contributo della vegetazione nel rinforzo meccanico di coltri superficiali di versante

Manuela Cecconi

Dipartimento di Ingegneria, Università di Perugia

manuela.cecconi@unipg.it



A.D. 1308

unipg

DIPARTIMENTO
DI INGEGNERIA

DIPARTIMENTO DI ECCELLENZA
MUR 2023/2027

PARTE_2



Manuela Cecconi

IL CONTRIBUTO DELLA VEGETAZIONE NEL RINFORZO MECCANICO DI COLTRI SUPERFICIALI DI VERSANTE

SCUOLA DI DOTTORATO GNIG – Gaeta, 03/09/2024



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

Evidenza sperimentale

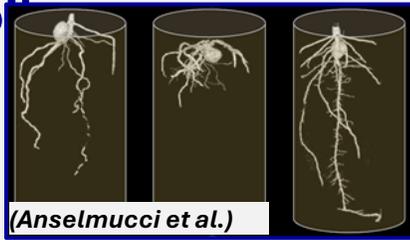
Interazione SVA

Condizioni sismiche: cenni

LAB. TESTING: roots/rooted soil



(Mao et al.)



(Anselmucci et al.)



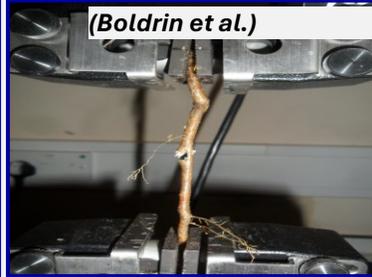
(Stasi et al.)



(Stasi et al.)



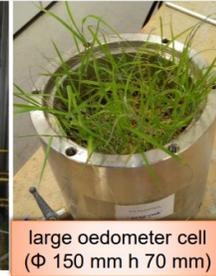
(Yildiz et al.)



(Boldrin et al.)



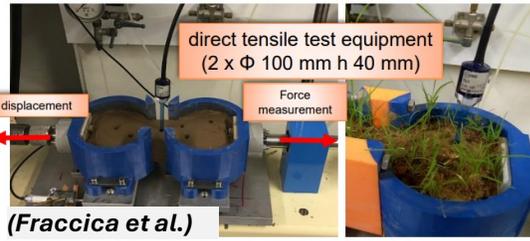
large triaxial equipment
(Φ 200 mm h 400 mm)



large oedometer cell
(Φ 150 mm h 70 mm)

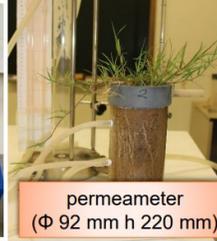


large direct shear equipment
(300x300x180 mm³)

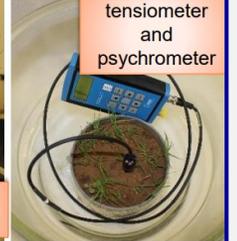


direct tensile test equipment
(2 x Φ 100 mm h 40 mm)

(Fraccica et al.)



permeameter
(Φ 92 mm h 220 mm)



tensiometer
and
psychrometer

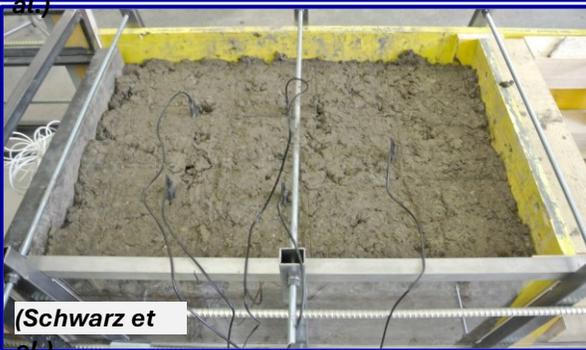
PHYSICAL MODELLING



(Bertolini et al.)



(Pagano et al.)



(Schwarz et al.)



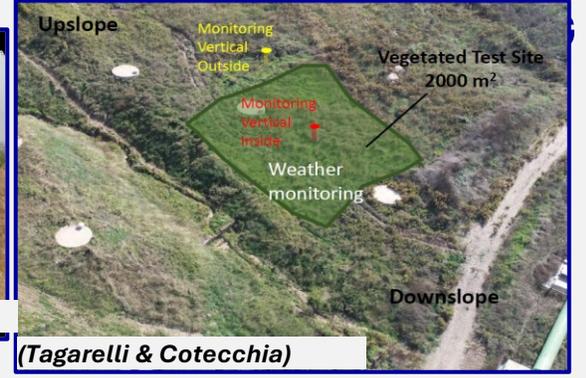
IN-SITU TESTING and



(Schwarz et al.)



(Boldrin et al.)



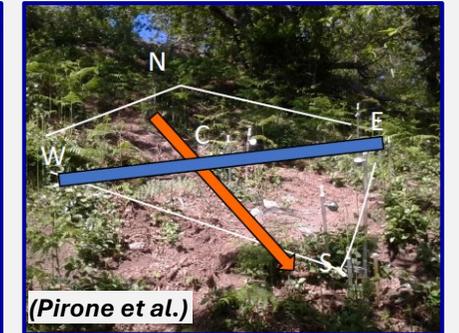
(Tagarelli & Cotecchia)



(Cuomo & Moscarriello)



(Meijer et al.)

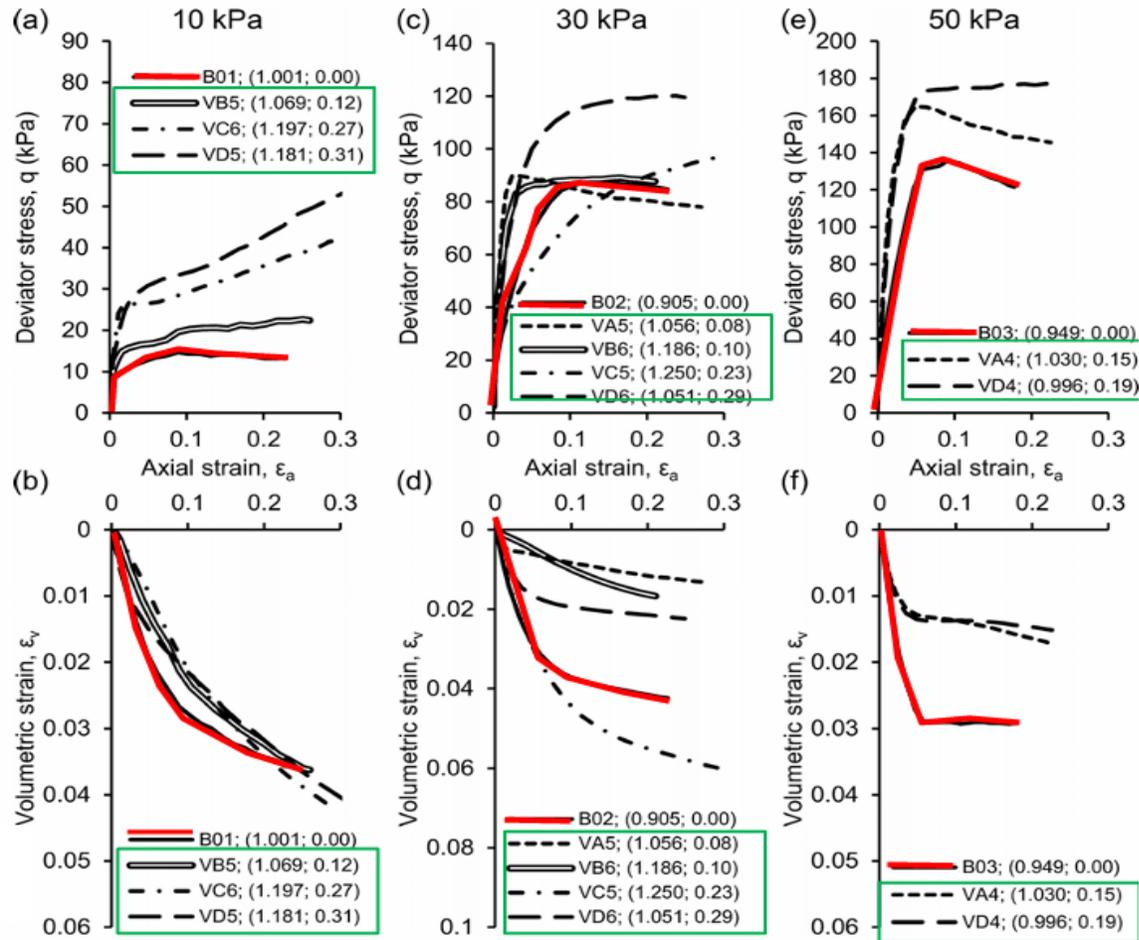


(Pirone et al.)



Prove TX CD

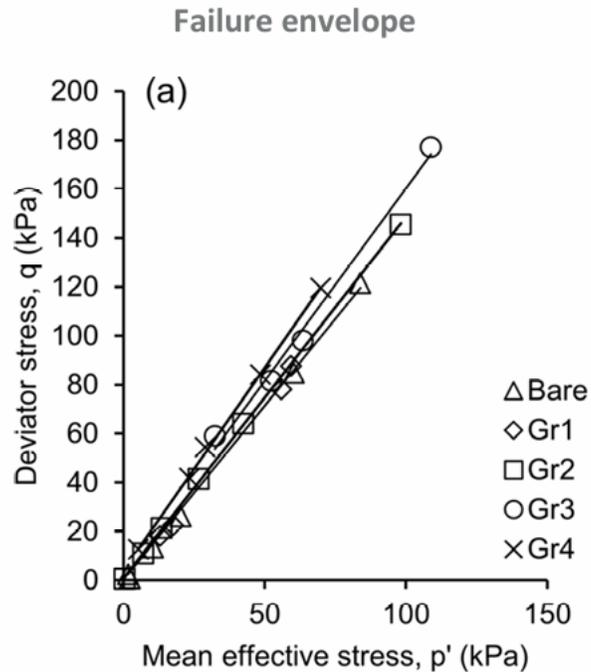
FORESTA ET AL., 2020



Hardening behaviour
incremento della resistenza a taglio
incremento della rigidità



Prove TX CD



FORESTA ET AL., 2020

Increment in mechanical parameters

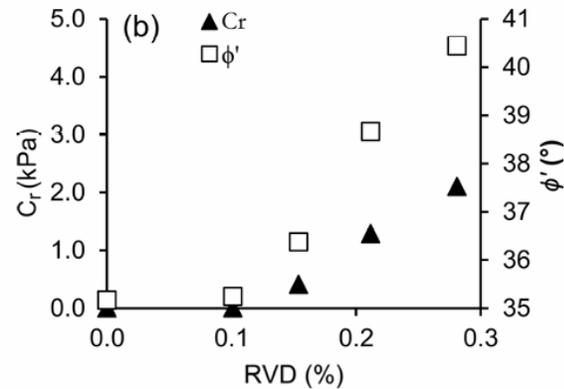
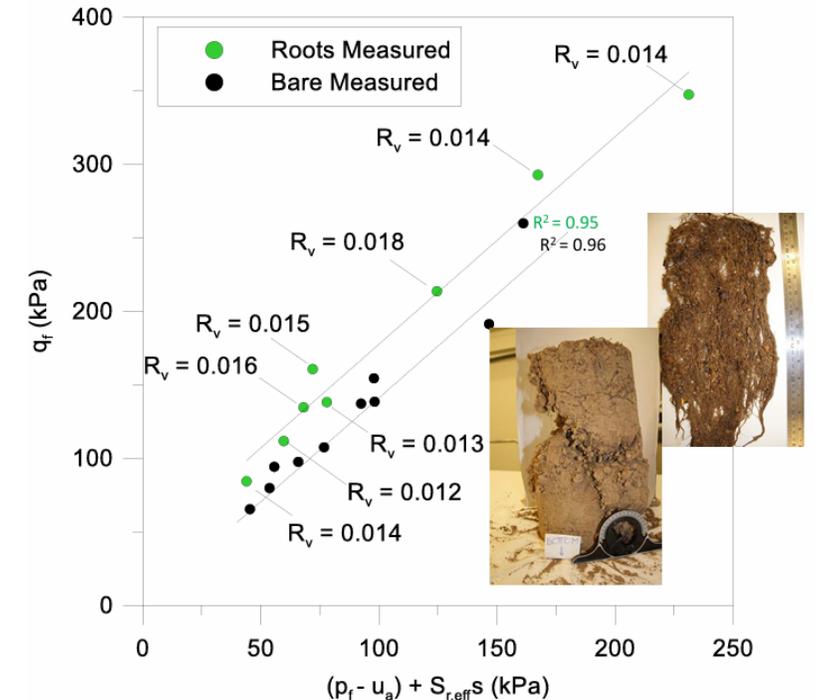


Table 3. Details of parameters at failure stage for vegetated soils grouped in RVD classes and bare specimens.

Group	a (kPa)	M	C_r (kPa)	ϕ' ($^\circ$)	RVD (%)	
					Average	SD
Bare	0.0	1.4	0.0	35.2	0	0
Gr1	0.0	1.4	0.0	35.2	0.10	0.02
Gr2	0.8	1.5	0.4	36.4	0.15	0.02
Gr3	2.5	1.6	1.3	38.7	0.21	0.02
Gr4	4.1	1.7	2.1	40.4	0.28	0.02

Note: a , intercept of failure envelope in q - p' plane; M , slope of failure envelope in q - p' plane; C_r , root cohesion; ϕ' , integrated friction angle.

FORESTA ET AL., 2020



	Bare soil	Vegetated soil
M_c (-)	1.42	1.45
c' (kPa)	0	10.3
ϕ' ($^\circ$)	35.1	35.8

FRACCICA ET AL., 2023



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

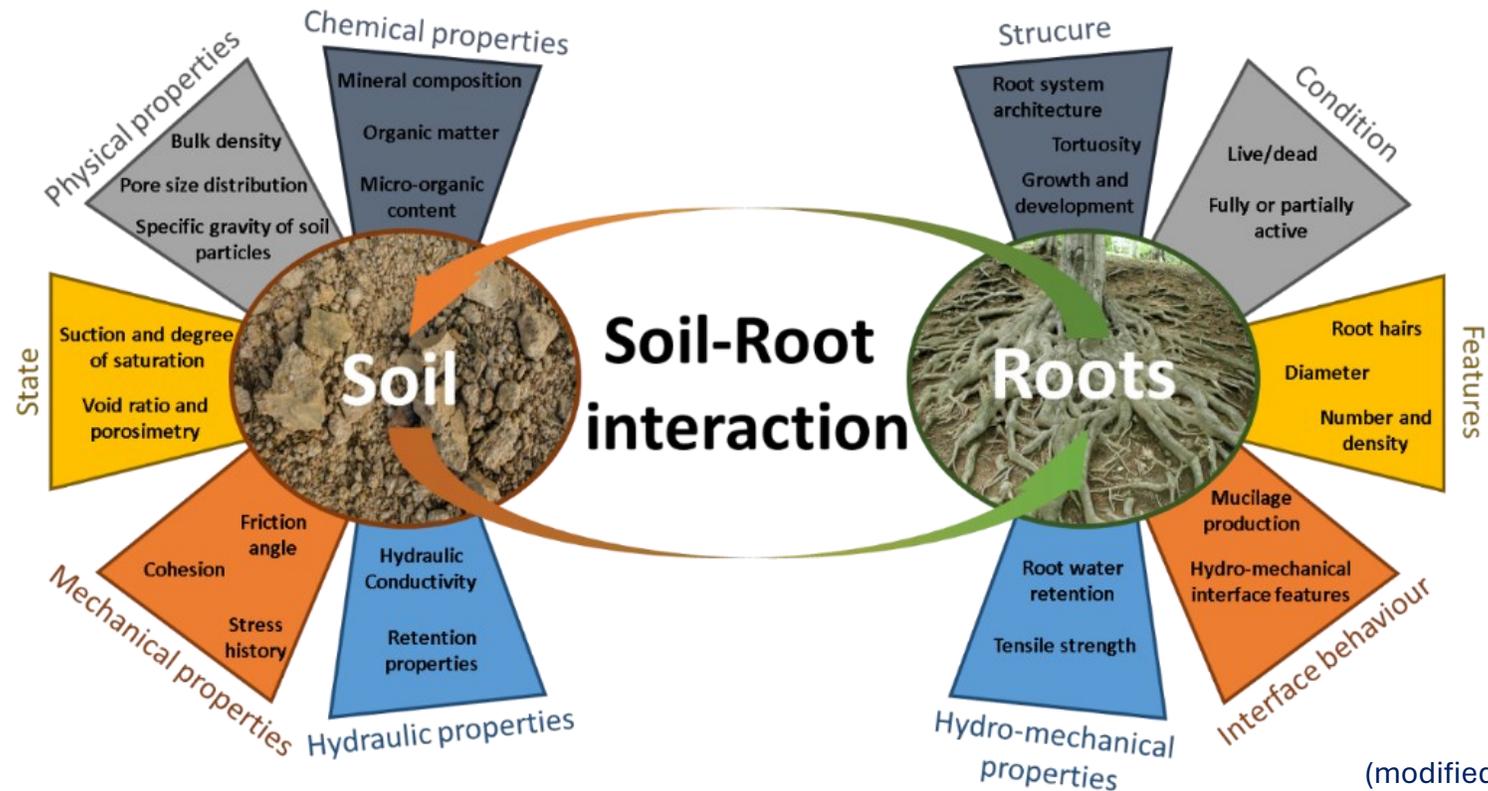
Evidenza sperimentale

Interazione SVA

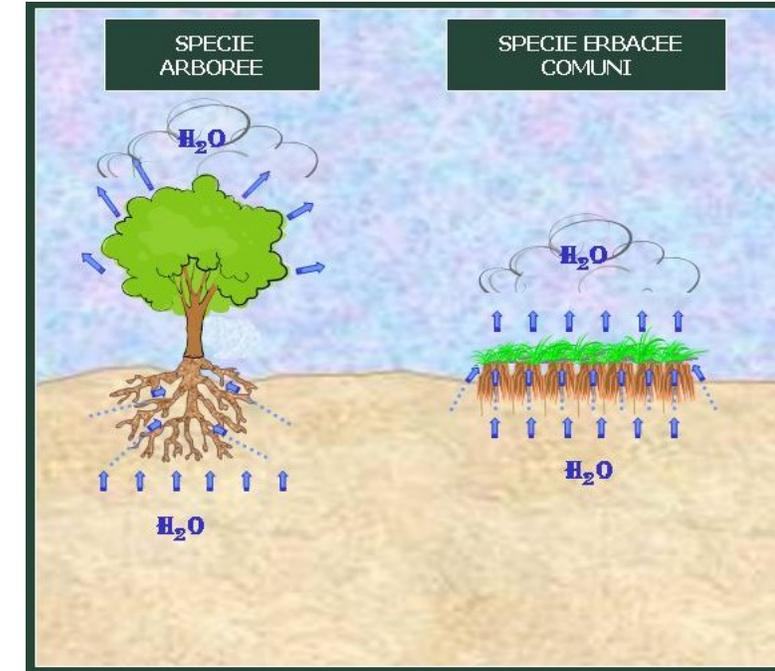
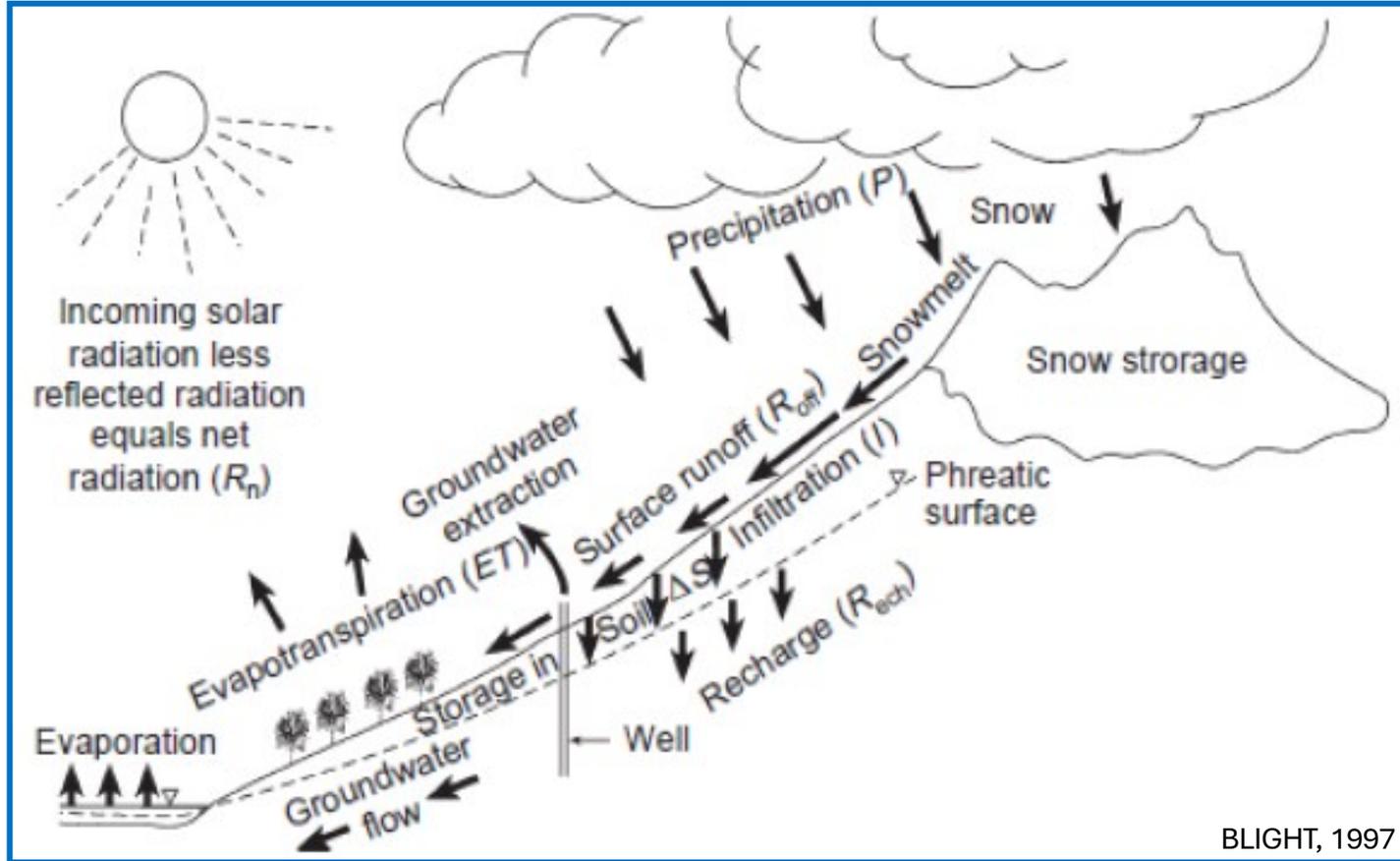
Condizioni sismiche: cenni



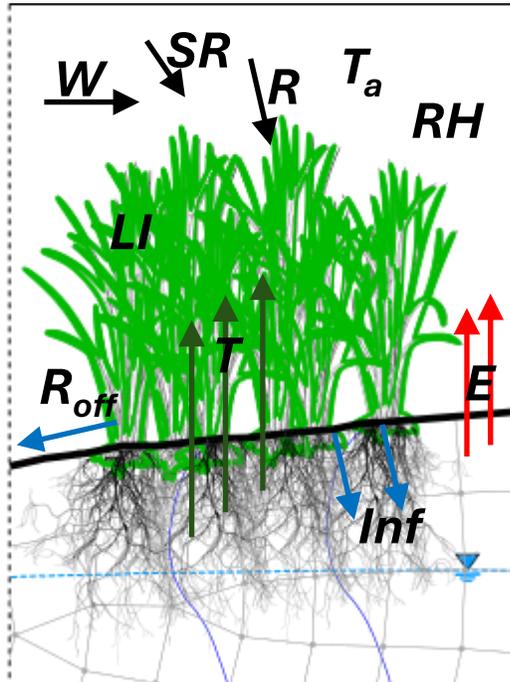
Multiple interactions between roots and hosting soil



(modified from LOADES ET AL., 2010).



(adattata from TAGARELLI, 2022)



W wind;
SR solar radiation;
R rainfall rate;
T_a atmospheric temperature;
RH relative humidity;
E evaporation rate;
T transpiration rate;
LI leaf interception;
R_{off} runoff;
Inf infiltration rate.

(adattata from COTECCHIA ET AL., 2024)

Water balance

$$Inf = R - (R_{off} + ET + LI)$$

Interazione terreno (non saturo)/radice:

Water uptake

Modifiche suzione e conducibilità idraulica

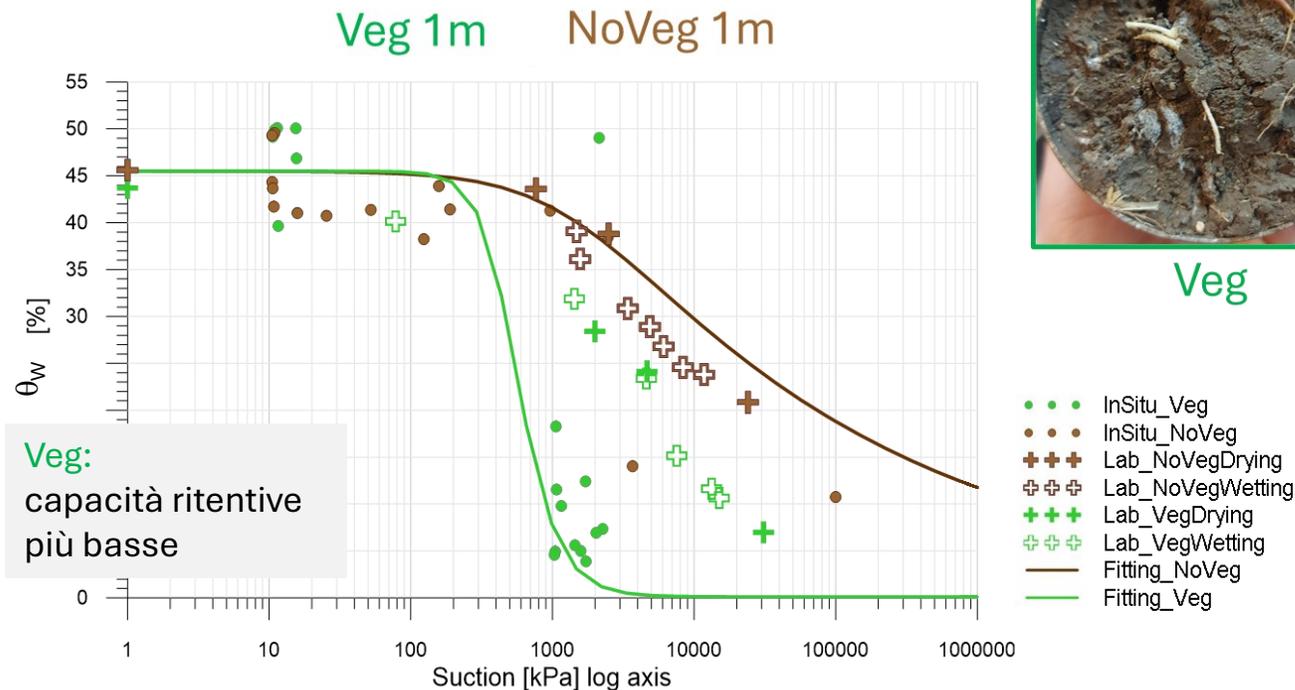


Variazione **resistenza a taglio terreno radicato**



Soil retention properties

misure indipendenti di w , s



Veg



NoVeg

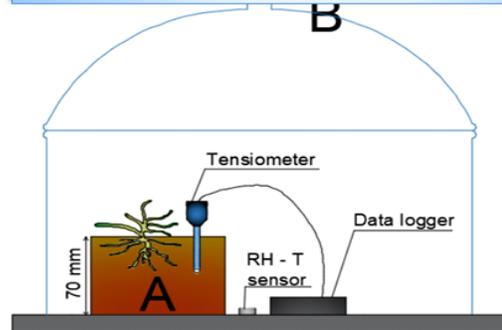
Le radici modificano
le proprietà ritentive
del terreno

TAGARELLI ET AL., 2023

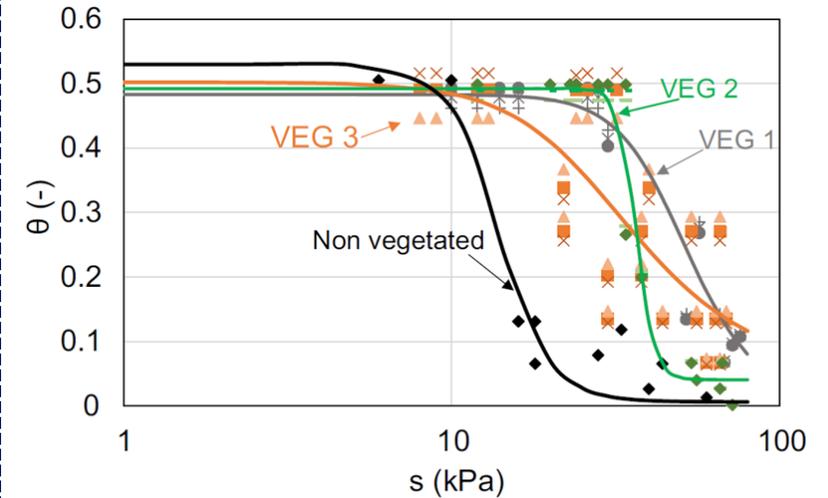
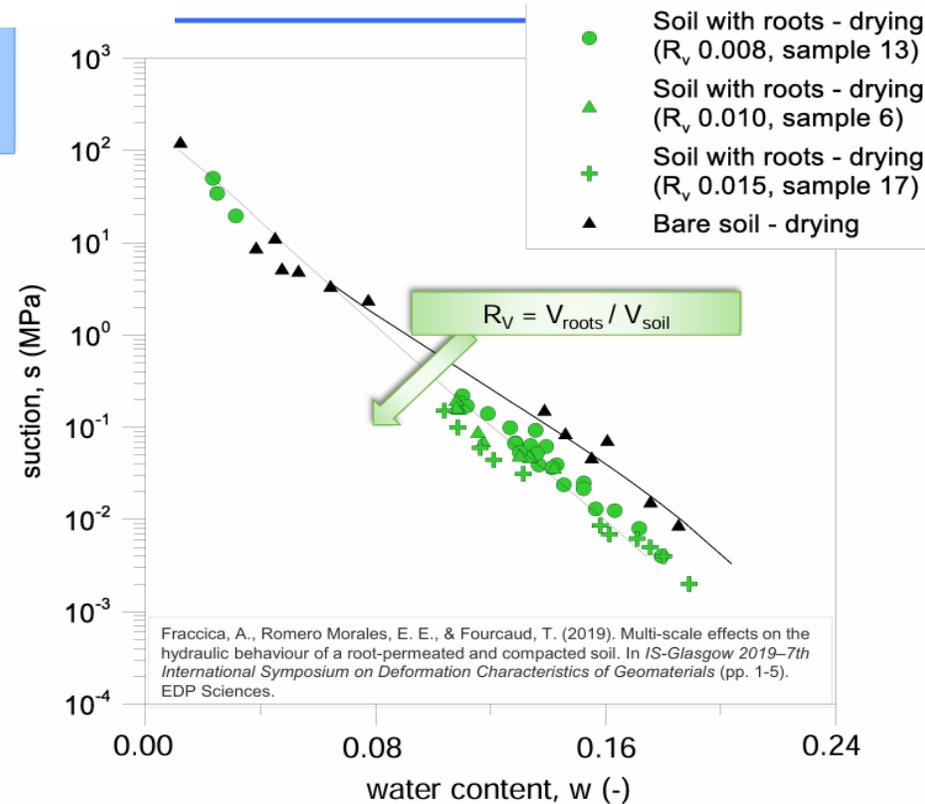


Soil retention properties

measurements done after 24 hours of **suction equilibration** and 2 hours in **darkness** (to avoid contribution of evapotranspiration) in sealed glass container



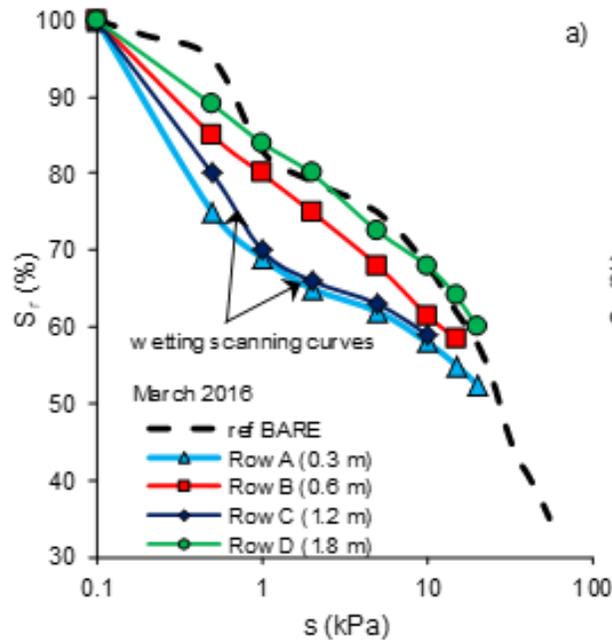
FRACCICA ET AL., 2019



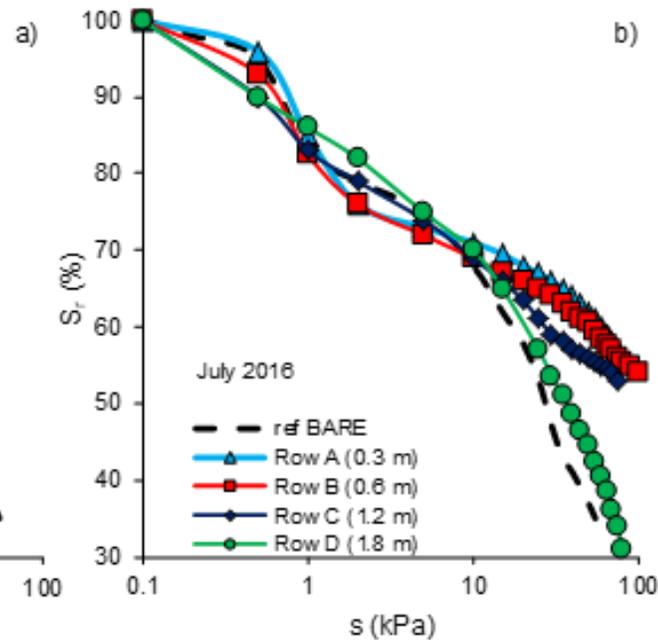
CECCONI ET AL., 2024 (submitted)
(after CUOMO ET AL., 2023)



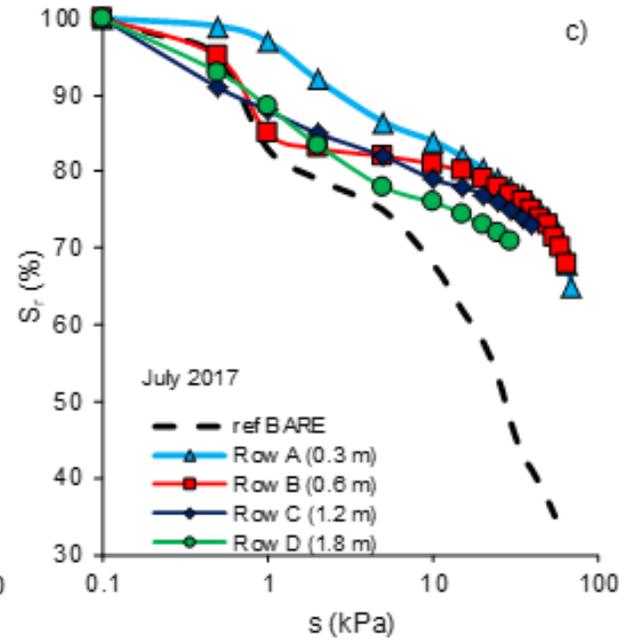
Soil retention properties



3 stages: (a) beginning;



(b) middle vegetation growth



(c) end of the monitoring period

CAPOBIANCO ET AL., 2020



apero una parentesi: (.....)

COLLINA SPERIMENTALE @UNITUS

PROGETTO GEST RIVER (UNIPG – CIRIAF + UNITUS + UNISTRA)

«Metodologie integrate per le attività di manutenzione e gestione delle opere di difesa del territorio», finanziato dal Ministero dell'Ambiente e della Tutela del Territorio e del Mare (2018-2021)



COLLINA SPERIMENTALE STRUMENTATA,
Azienda Agraria Università della Tuscia, UniTUS - Viterbo
Vol. terreno: 7 x 7 m², pendenza 17%, altezza max 1.2 m.
Terreno: sabbie argillose con limo
Canalette di raccolta alla base

Simulatori di pioggia (40 – 140 mm/h)
Misure di contenuto d'acqua

[Grimaldi et al, 2018; Petroselli A et al., 2019.
Apollonio et al., 2021]

Attività svolte

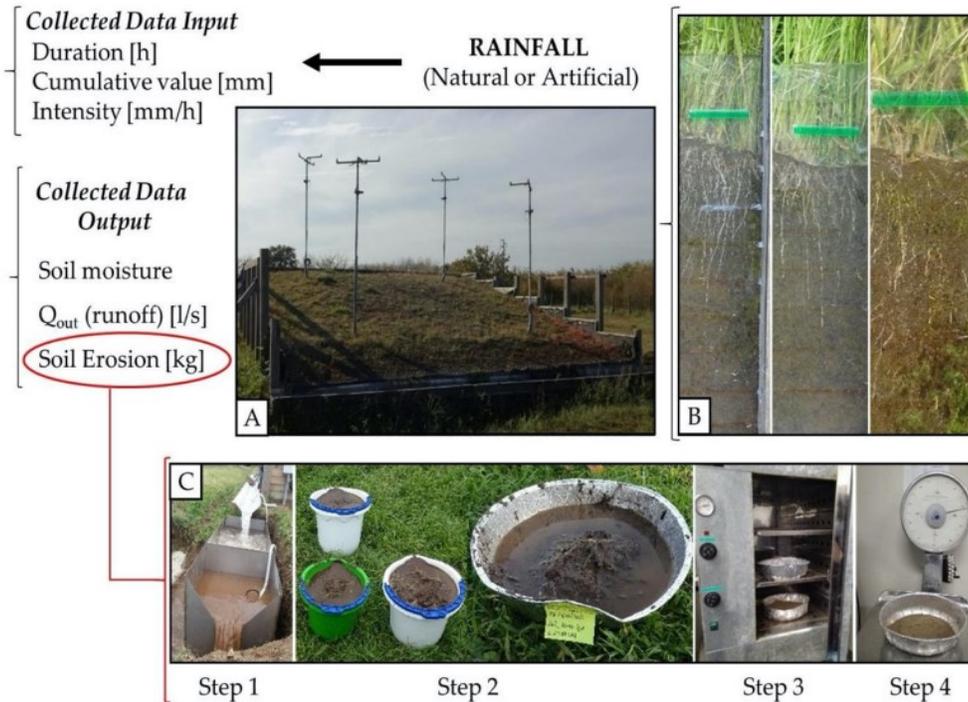
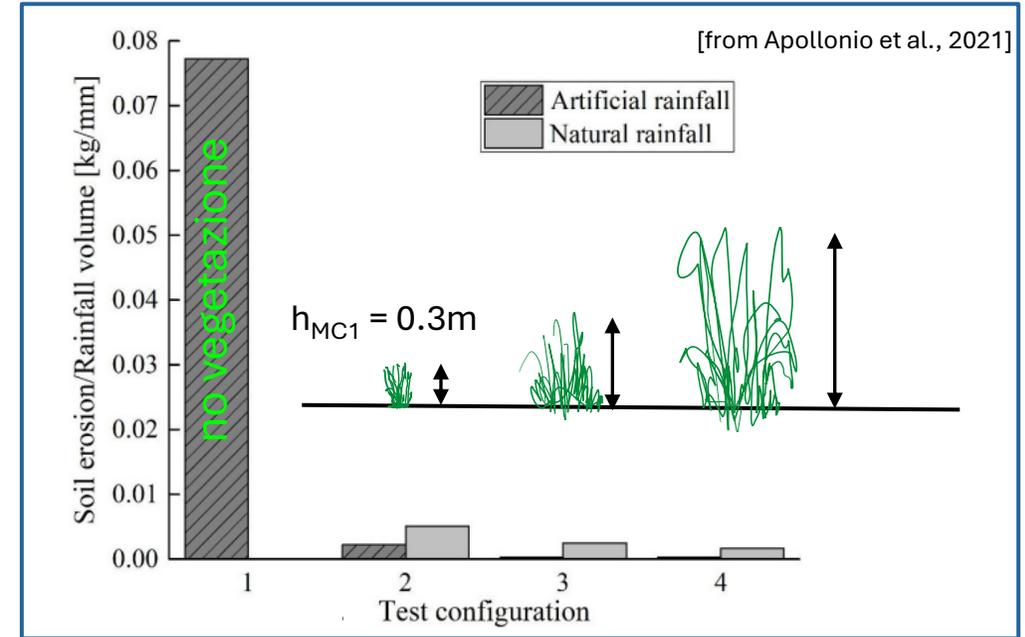
- semina di sementi di una miscela di specie erbacee (MC1)
- simulazioni di pioggia (24 h) per diverse configurazioni di «spessore inerbito»
- misure di portata
- sviluppo dell'apparato radicale e osservazioni in sito

Specie erbacee MC1

Table 1. Rainfall characteristics during the four tests.

Test	h_{MC1} (cm)	Rainfall Type	Cumulative Rainfall Value (mm)	Max Rainfall Intensity (mm/h)	Rainfall Duration (Wet Period) (h)
No. 1	0	- Artificial	- 680	- 170	- 4
No. 2	30	Natural Artificial	121 3360	42.6 140	42.1 24
No. 3	70	Natural Artificial	70 4080	92.2 170	12.9 24
No. 4	140	Natural Artificial	110 3840	141.8 160	17.5 24

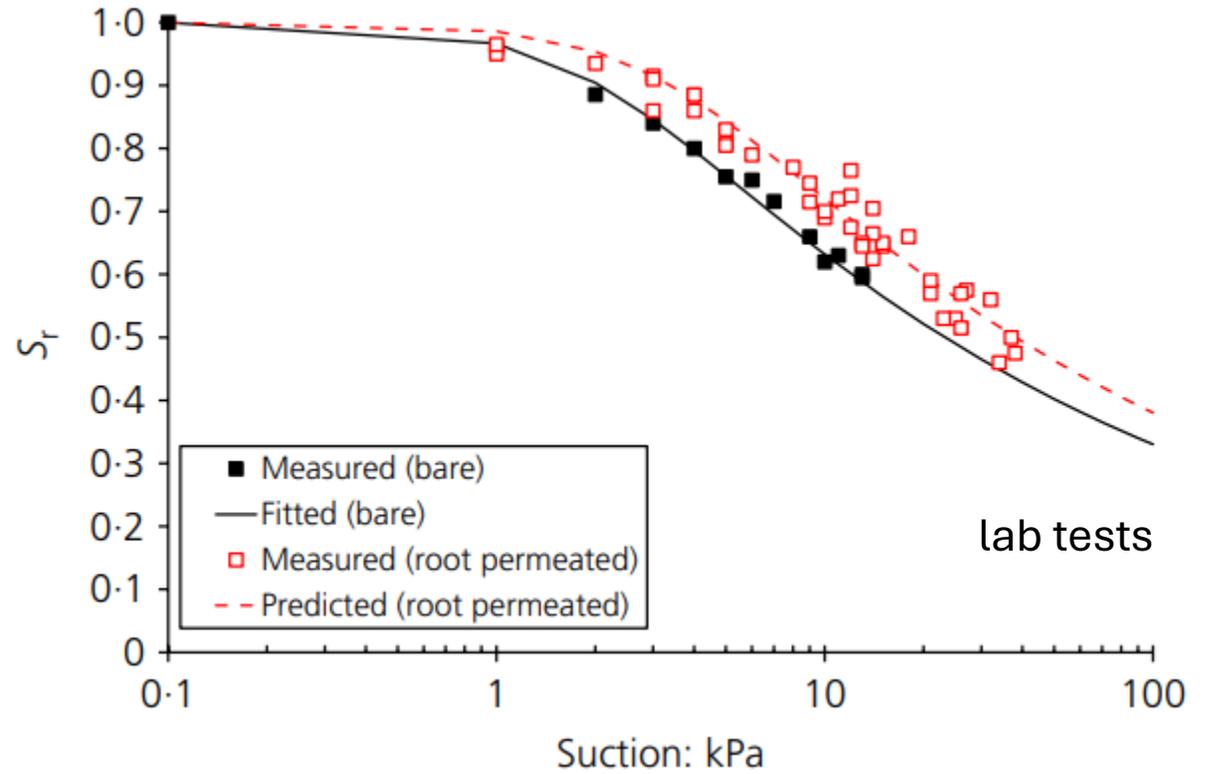
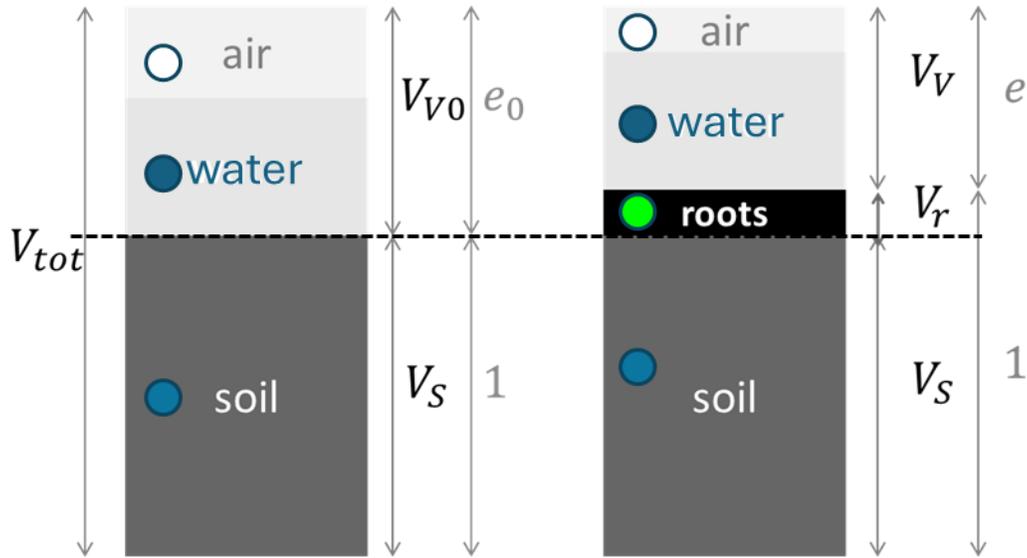
rapporto materiale eroso [kg]/
pioggia cumulata [mm]



RAR, porosità



proprietà di ritenzione



(1)
$$e = \frac{e_0 - R_v (1 + e_0)}{R_v \cdot (1 + e_0) + 1}$$
 [da Ng et al, 2016]

con

e_0 : indice dei vuoti del terreno in assenza di radici

$R_v = V_r / V_{tot} = \text{RAR}$

(2)
$$S_r = \left[1 + \left(\frac{se^{m_4}}{m_3} \right)^{m_2} \right]^{-m_1} \quad (a)$$
 $m_{\#}$ model parameters [Gallipoli, 2003; 2012]

Tabella 1 – Caratteristiche fisiche dei terreni in esame

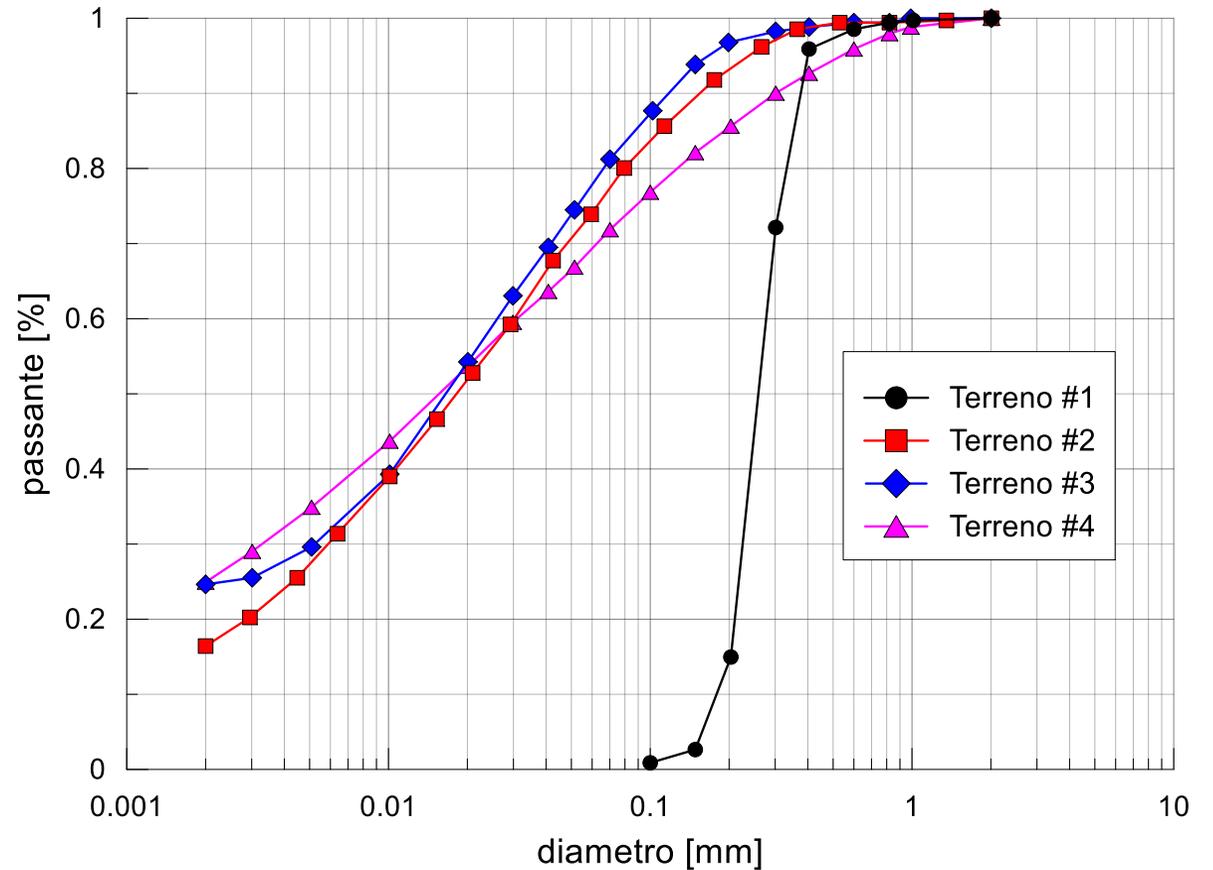
	γ_d (kN/m ³)	G_s	e_0
Terreno #1: sabbia*	16.5	2.67	0.618
Terreno #2: limo sabbioso†	18.7	2.764	0.838
Terreno #3: limo*	16.58	2.72	0.640
Terreno #4: limo argilloso /sabbioso*	16.96	2.72	0.603

Tabella 2 – Valori di e_0 , e per i terreni in esame

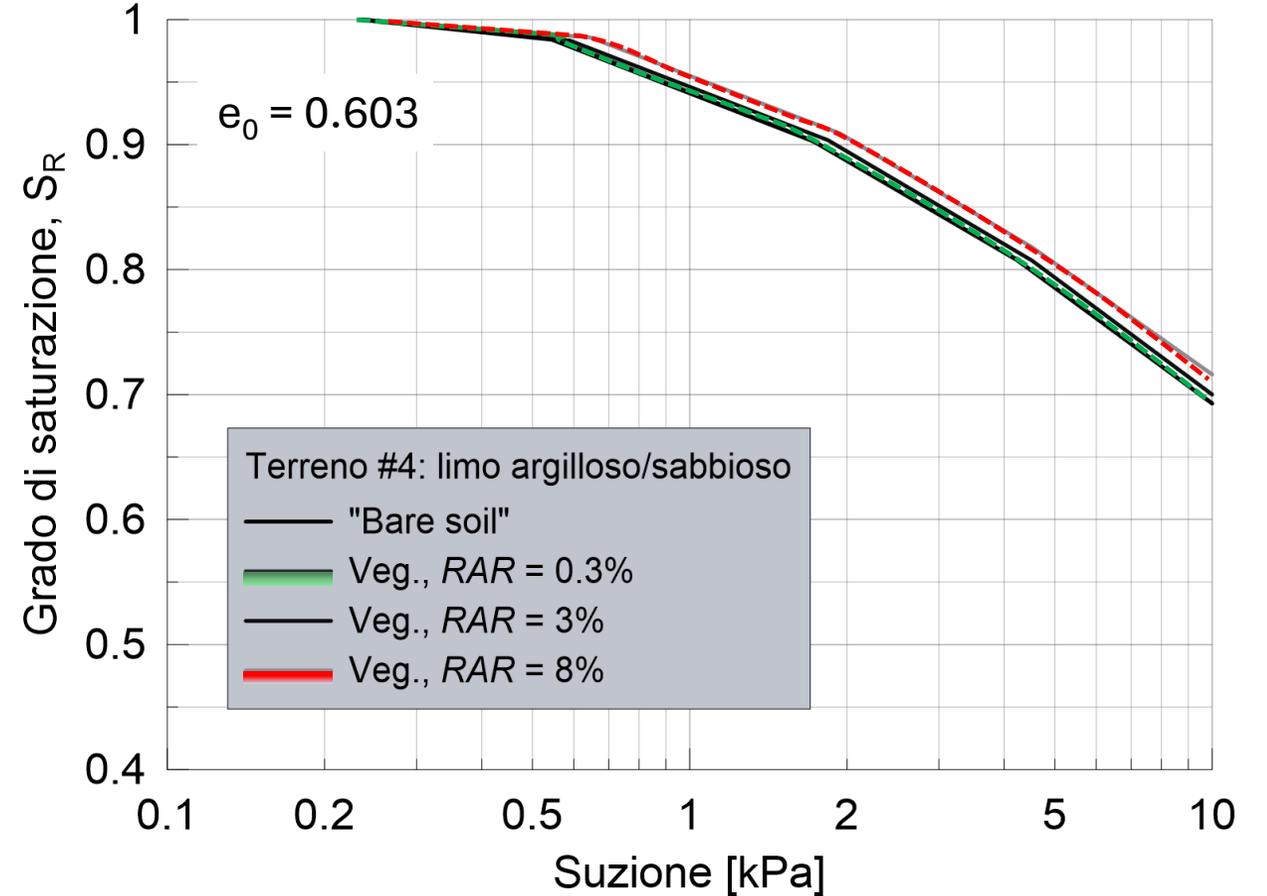
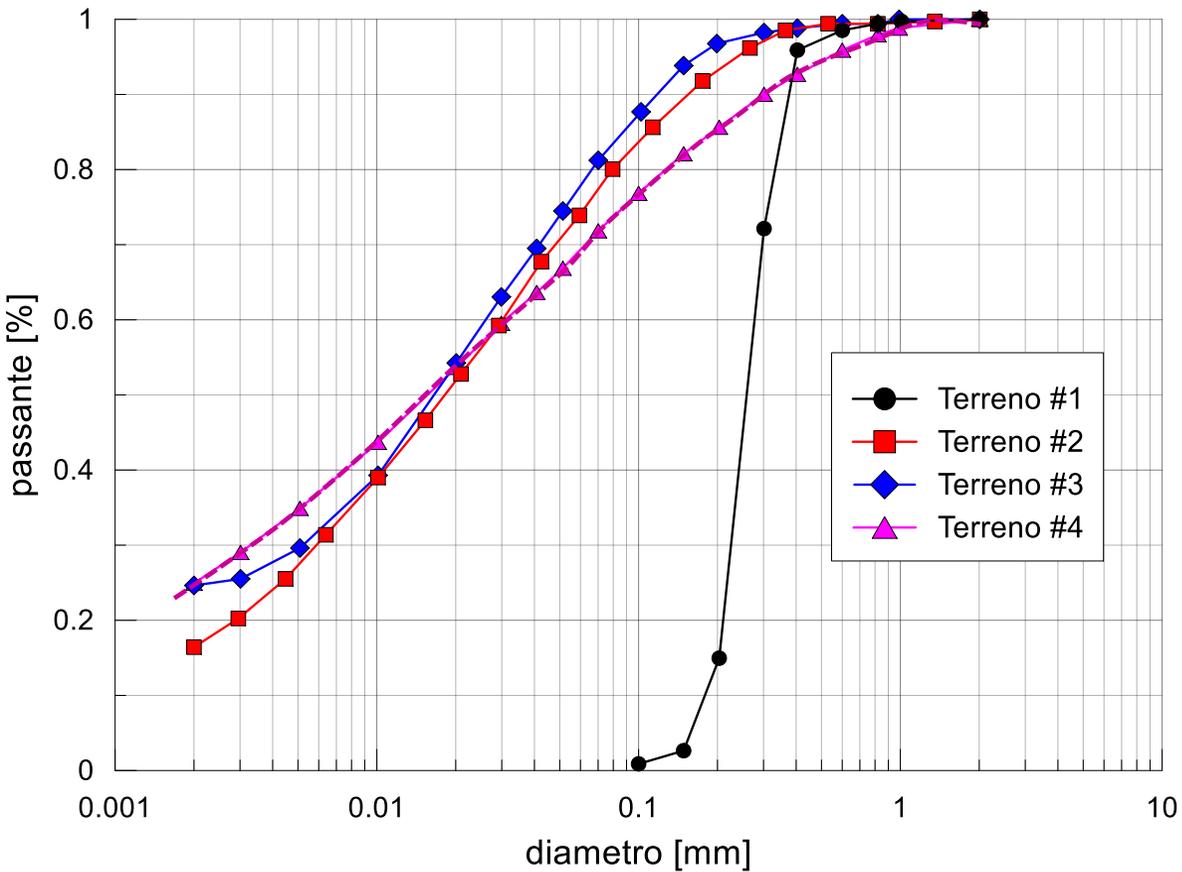
	e_0	e RAR 0.3%	e RAR 3%	e RAR 8%
Terreno #1	0.618	0.610	0.543	0.433
Terreno #2	0.838	0.828	0.742	0.602
Terreno #3	0.640	0.632	0.563	0.450
Terreno #4	0.603	0.595	0.529	0.421

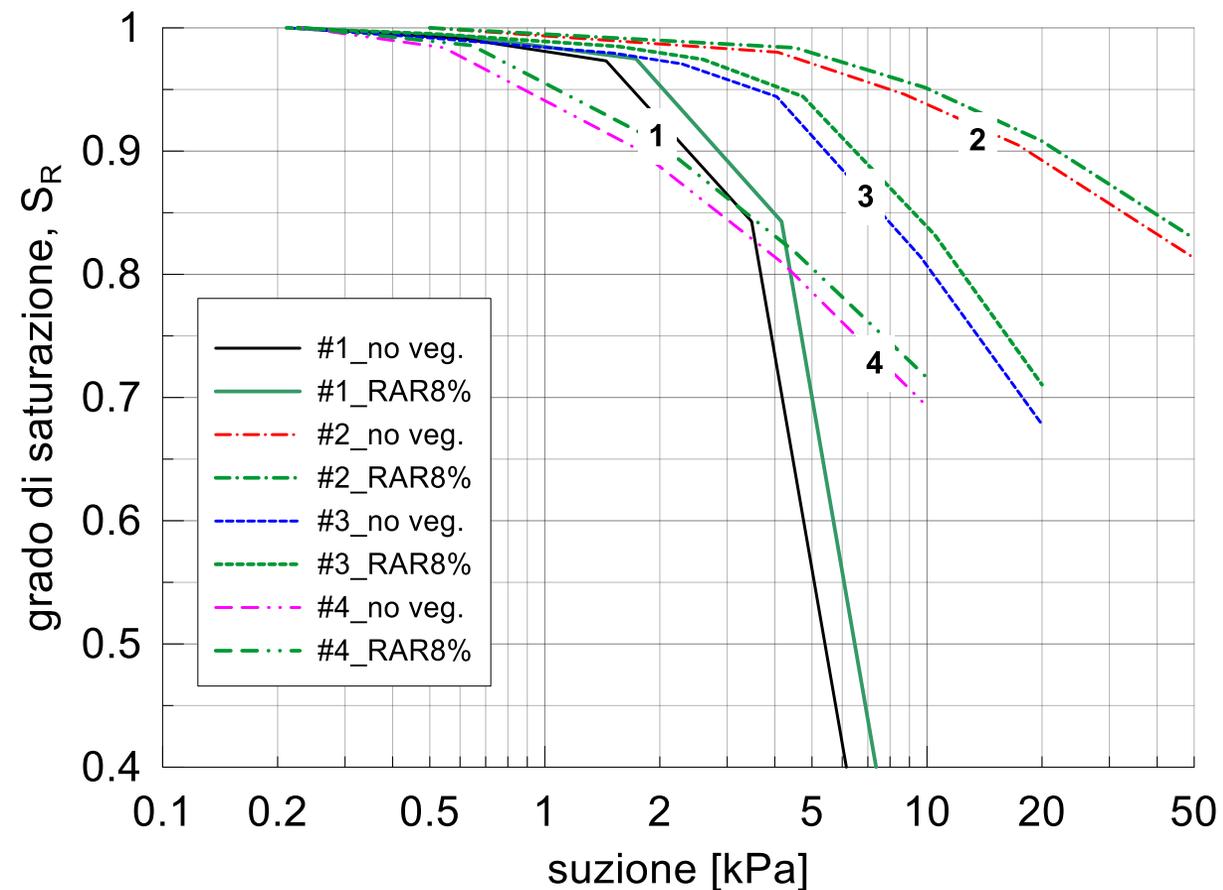
$$e = \frac{e_0 - R_V (1 + e_0)}{R_V \cdot (1 + e_0) + 1}$$

$$\Delta e = (e_0 - e_{\text{RAR8\%}}) = 28 \div 30 \%$$



Risultati





	AEV (kPa) "Bare soil"	AEV RAR 0.3%	AEV RAR 3%	AEV RAR 8%
Terreno #1	3.0	3.1	3.2	3.6
Terreno #2	13.5	13.5	14.3	15.9
Terreno #3	5.5	5.5	5.9	6.6
Terreno #4	1.6	1.6	1.7	1.9

incremento AEV:

= 6 - 7% se **RAR = 3%**

= 18 - 20 % se **RAR = 8%**

(incremento più significativo per terr. 1)

no effetto porosità iniziale

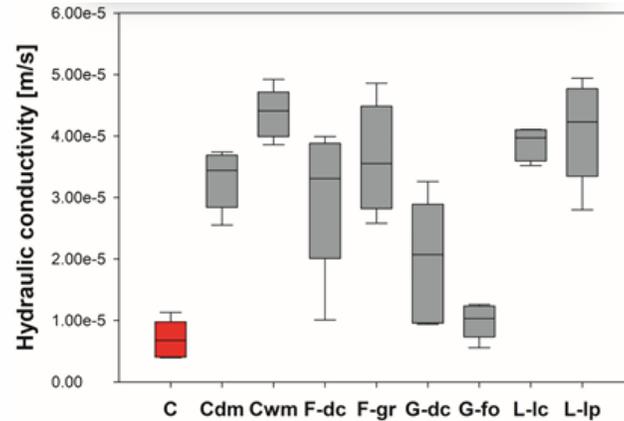
e chiudo la parentesi:)



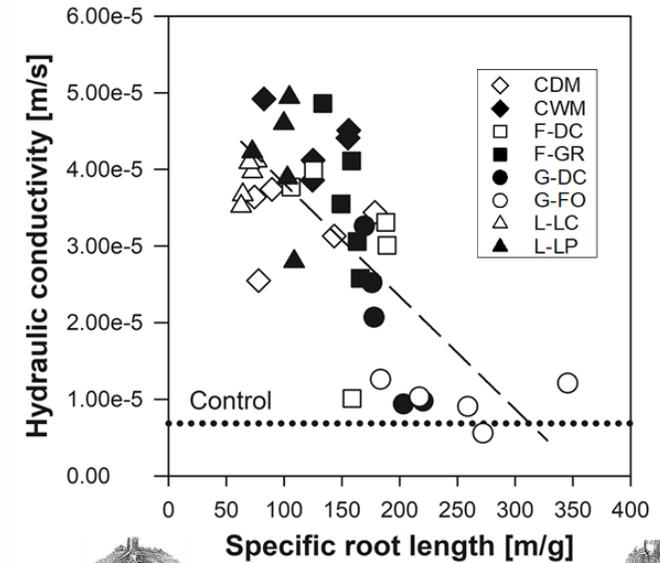
In presenza di roots/veg. anche la **conducibilità idraulica** (sat.) si modifica.
Effetto della crescita/sviluppo delle radici



BOLDRIN ET AL., 2022
LEUNG et al., 2022



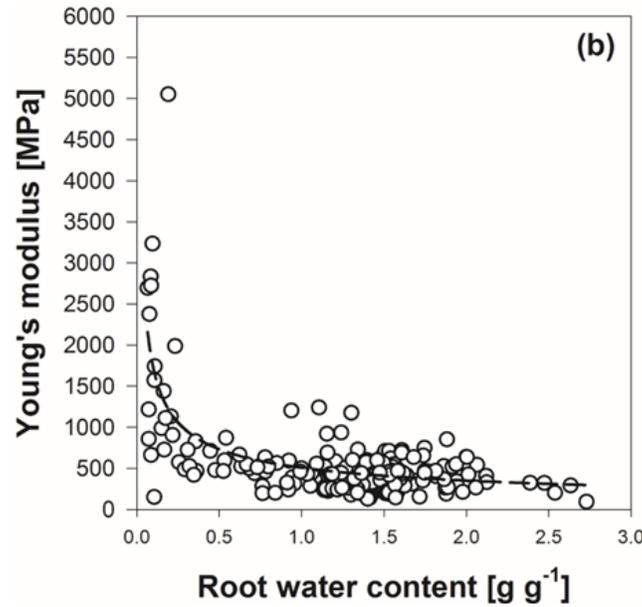
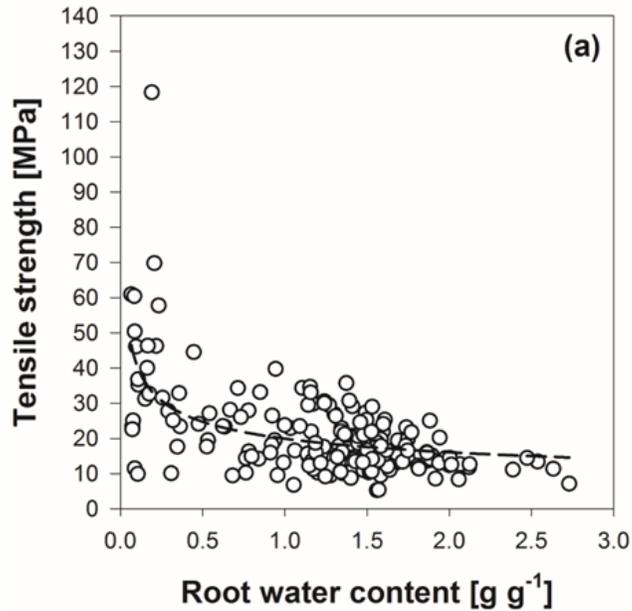
Acronyms: C (Fallow soil), Cdm (Dry meadow community), Cwm (Wet meadow community), F-dc (Forb - *Daucus carota*), F-gr (Forb - *Geum rivale*), G-dc (Grass - *Deschampsia cespitosa*), G-fo (Grass - *Festuca ovina*), L-lc (Legume - *Lotus corniculatus*), L-lp (Legume - *Lotus pedunculatus*)



$$\text{Specific root length} = \frac{\text{Root length}}{\text{Root mass}}$$



tensile strength and stiffness vs. root water content



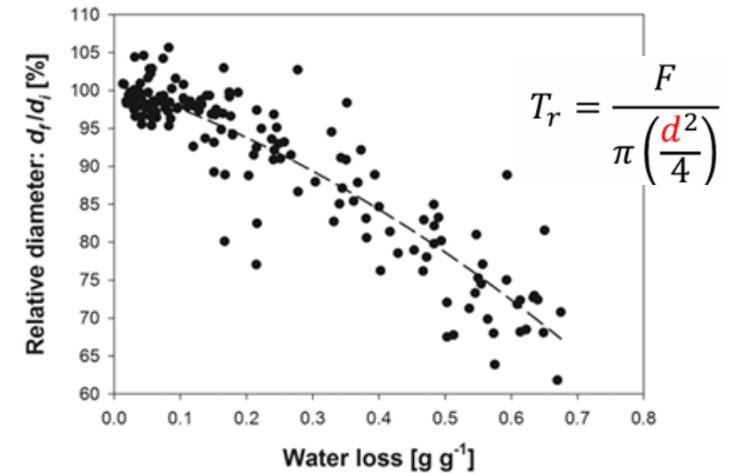
BOLDRIN ET AL., 2018

root drying → root strength increase

The drop of root water content (< 0.5 g/g) induce an abrupt increase of root strength and stiffness



The strength increase is the result of root shrinkage with drying

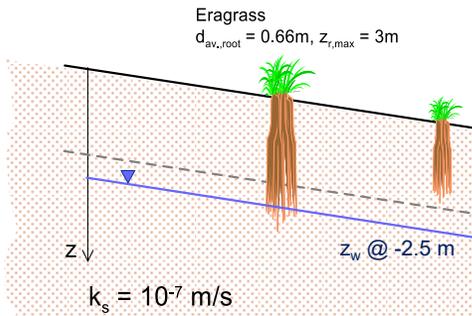




Analisi numeriche Vadose/W

Esempio di calcolo (ancora molto semplice!):

pendio : $\alpha = 30^\circ$
 sabbia fine : $\phi' = 30^\circ, c' = 0$
 specie erbacea: Eragrass



Analisi di stabilità

$$SF_r(z) = \frac{\tau_{r_unsat}(z) + \Delta\tau_r(z)}{\gamma z \cdot \cos \alpha \cdot \sin \alpha}$$

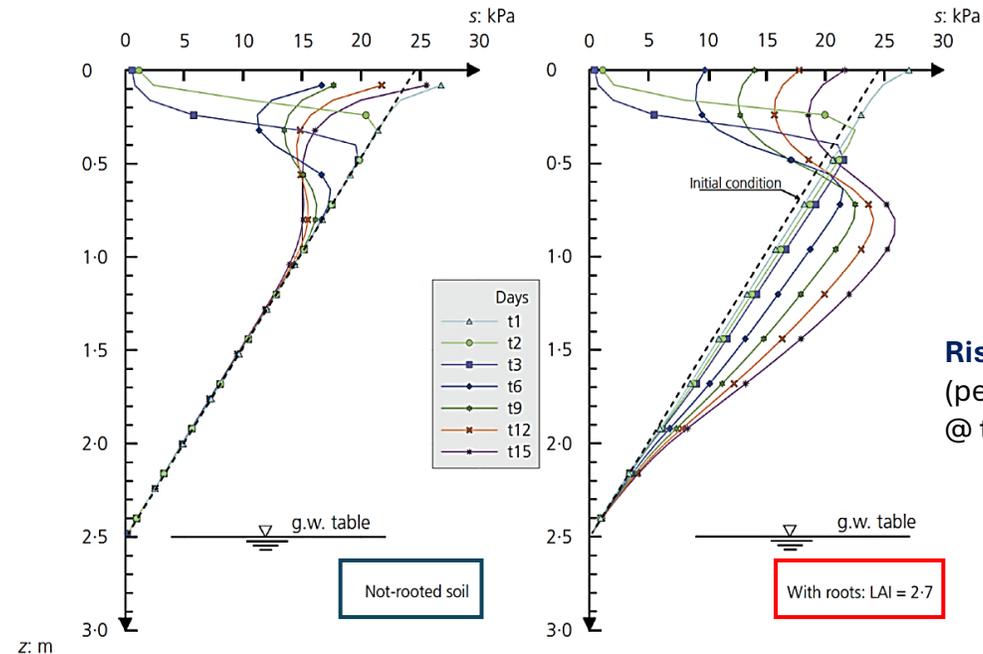
$$SF(z) = \left(1 + \frac{S_r(z)s(z)}{\gamma z \cos^2 \alpha} \right) \frac{\tan \phi'}{\tan \alpha} + \frac{c' + \Delta\tau_r(z)}{\gamma z \cos \alpha \sin \alpha}$$

VANAPALLI ET AL., 1996

RR

Soil – physical properties		Soil–water retention properties, (van Genuchten, 1980)	
Saturated volumetric water content θ_s (mm ³ /mm ³)	0.508	$n = 1.39$	$\alpha^{-1} = 12.2 \text{ kPa}$
Residual volumetric water content θ_r (mm ³ /mm ³)	0.120	Saturated hydraulic conductivity k_s (m/s)	1.1×10^{-7}
Vegetation boundary conditions		Wiltng point (kPa)	
Max. root depth $Z_{r,max}$ (m)	2 m	LAI	1500 kPa
Average root diameter (mm)	0.66 mm		2.7
Climate boundary conditions		Wind speed (m/s)	
T_{max} (°C)	26°C		3.6
T_{min} (°C)	18°C		

Table 1. Hydrological soil properties, climate and vegetation boundary conditions



Risultati:
 (per evento di pioggia
 @ t = 2 ÷ 4giorni)

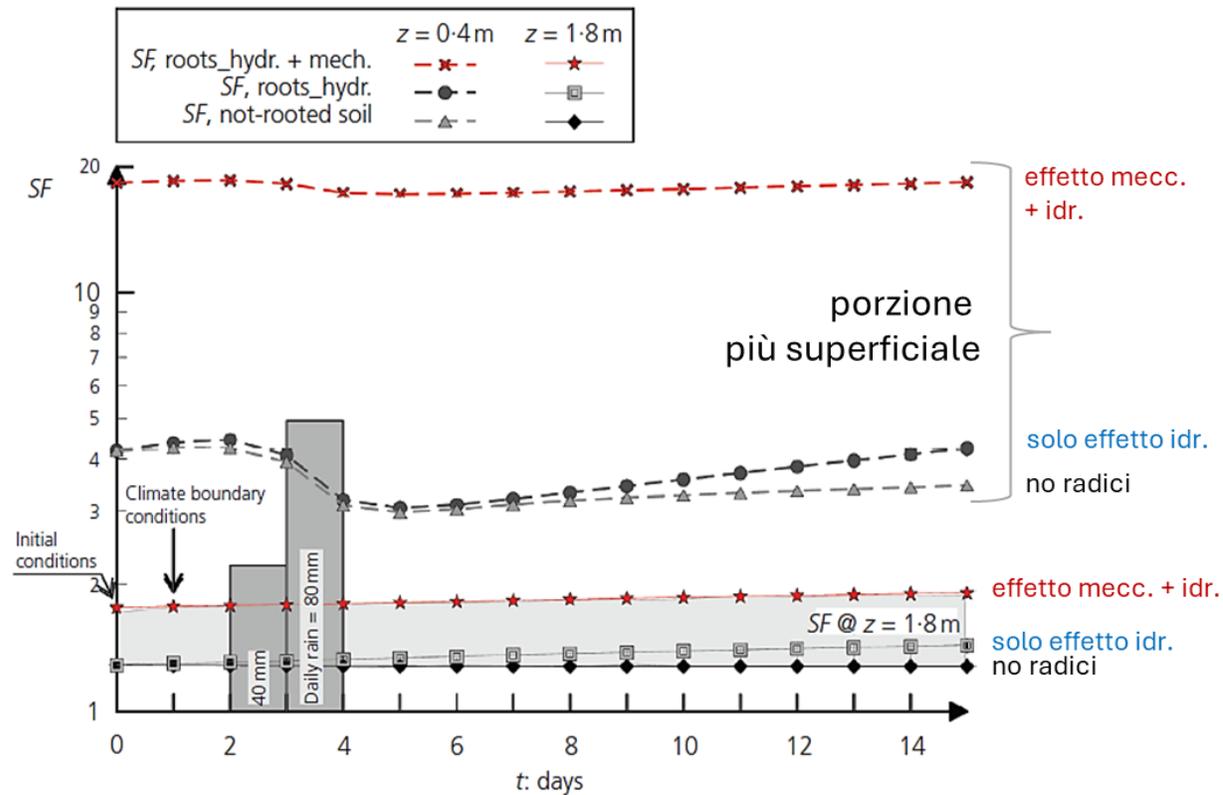
(CECCONI ET AL., 2015)



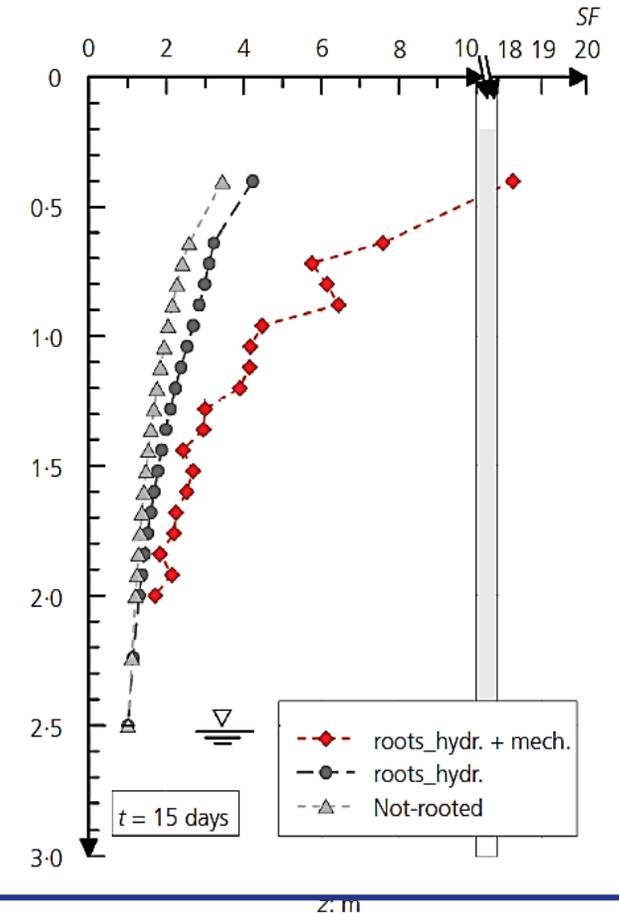
Analisi numeriche Vadose/W

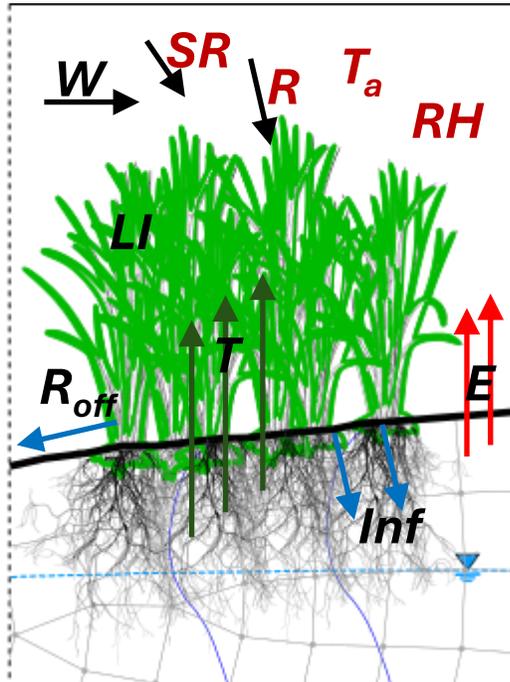
Esempio di calcolo (ancora molto semplice!):

pendio : $\alpha = 30^\circ$
 sabbia fine : $\phi' = 30^\circ, c' = 0$
 specie erbacea: Eragrass



(CECCONI ET AL., 2015)





W wind;
SR solar radiation;
R rainfall rate;
T_a atmospheric temperature;
RH relative humidity;
E evaporation rate;
T transpiration rate;
LI leaf interception;
R_{off} runoff;
Inf infiltration rate.

(adattata from COTECCHIA ET AL., 2024)

Water balance

$$Inf = R - (R_{off} + ET + LI)$$

Interazione terreno (non saturo)/radice:

Water uptake

Modifiche suzione e conducibilità idraulica



Variazione **resistenza a taglio terreno radicato**



ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

A BioGeoT H M coupled system

Hydraulic balance
 $Inf = R - (R_{off} + ET + LI)$

Energy balance
 $G_0 = SR_{net} - (H + \lambda ET)$

(Elio et al., 2017)

Balance equations	Nodal variables	Physical laws - constitutive properties	Boundary conditions
Mass balance of liquid	P_l	<ul style="list-style-type: none"> Darcy's law Fick's law Henry's law Psychrometric law Ideal gas law 	Pressures/Fluxes / Meteorological factors
Mass balance of gas	P_g	<ul style="list-style-type: none"> Retention curve Conductivity functions Diffusion/Dispersion coefficients 	
Internal energy balance	T	<ul style="list-style-type: none"> Fourier's law Heat conductivity Specific and latent heat Density variation with T 	Temperatures / Fluxes
Momentum balance	u	Soil constitutive model and mechanical parameters	Displacements / Forces

W wind;
SR solar radiation;
R rainfall rate;
T_a atmospheric temperature;
RH relative humidity;
E evaporation rate;
T transpiration rate;
LI leaf interception;
R_{off} runoff;
Inf infiltration rate.

(Stasi et al., 2024) (Ng et al., 2016) (Fraccica et al., 2022)

F. Cotecchia, M. Cecconi, V. Tagarelli, 25 August 2024, ECSMGE24, Workshop TC106

Latent Heat λE **Sensible Heat** H

SELLERS ET AL. 1986
(J. OF THE ATMOSPHERIC SCIENCES)

Bare soil **With canopy**

Saturated surface Unsaturated surface Saturated surface Unsaturated surface

Air **Canopy** **Soil**

(Samat & Vaunat, 2018)
(Vaunat et al., 2024)
(Badakhshan et al. 2024)

CODE BRIGHT
A 3D program for thermo-hydro-mechanical analysis in geologic media
(Olivella et al., 1994)

SVA

interaction

COMPLEXITY INCREASE

1° LEVEL



2° LEVEL



3° LEVEL

ROOTED/VEGETATED SOILS

DRY / SAT

UNSAT

M only

τ_f
 E', G

M not coupled with **H**

τ_f
 E', G

M - H

τ_f SWRC: $s = f(\vartheta)$
 E', G HCF: $k_{rel} = f(s)$

M - H - T

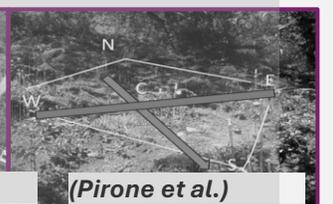
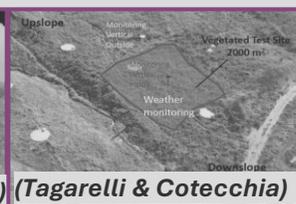
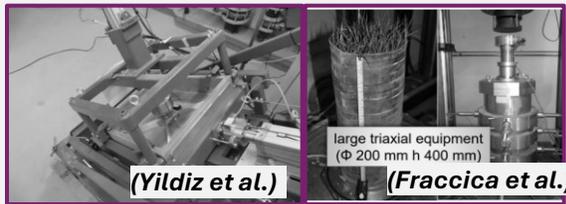
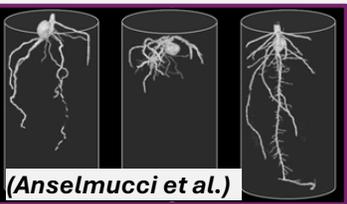
τ_f SWRC: $s = f(\vartheta)$ λ_s
 E', G HCF: $k_{rel} = f(s)$ α_s, C_s



VEG

- ROOTS TYPE AND STATE
- R.A.R
- LEAF AREA INDEX
- COVER FRACTION
- ROOT TENSILE STRENGTH
- LIFE CYCLE
- SPATIAL VARIABILITY
-

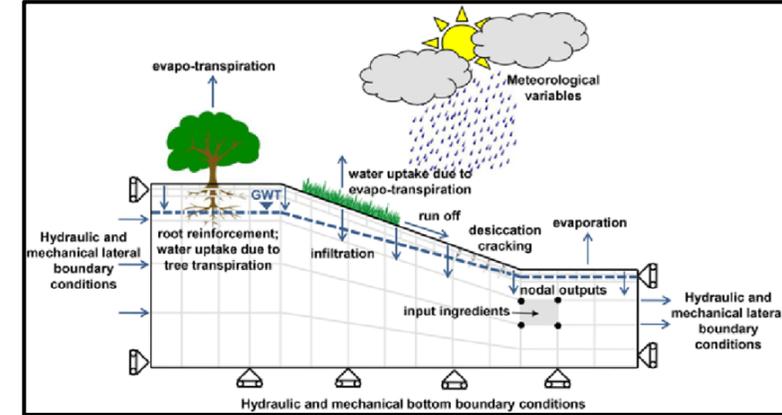
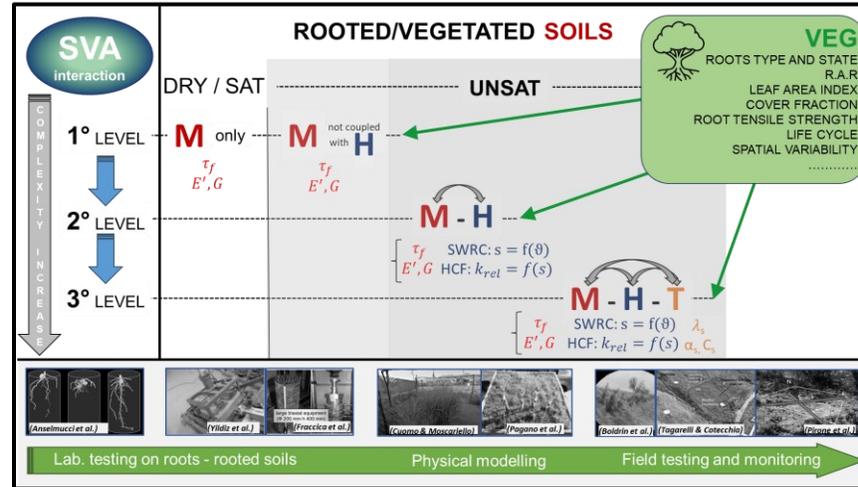
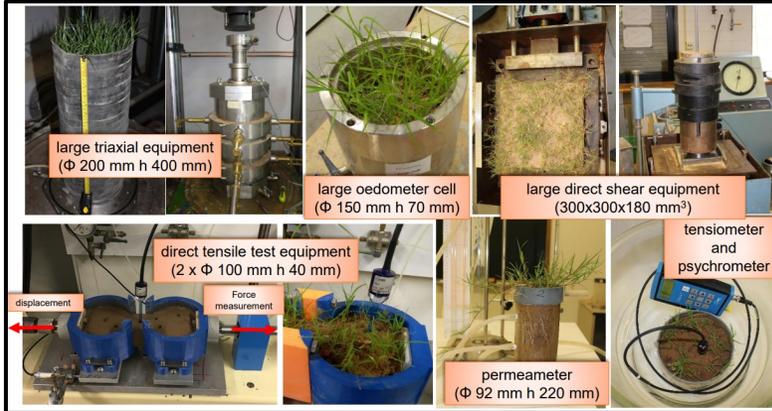
(CECCONI ET AL. 2024, SUBMITTED)



Lab. testing on roots - rooted soils

Physical modelling

Field testing and monitoring



from experimental analysis



to conceptual modelling



to numerical modelling



BGTHM assessment of **SVA** interaction
for any geotechnical system (not only slopes)

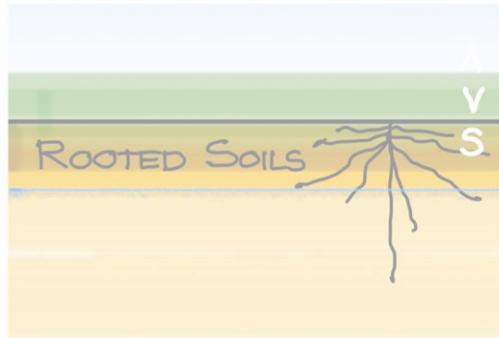
(adattata from COTECCHIA ET AL., 2024)



SHORT TERM GOAL:

Assessment of SVA INTERACTION

- Proper understanding of mechanisms/processes involving all the “environmental compartments” and their mutual interaction,
- Investigation of SVA interaction through experimental, analytical and numerical studies.



LONG TERM GOAL:

Design of NBS - Support to the planning of earth use

Key activities for disaster risk reduction:

- structural + non-structural measures into natural resources management approaches,

through strategies for the reduction of disaster risk and adaptation to climate change (e.g.: UNISDR, 2015)

(geotechnical) systems' resilience 
for natural hazard risk reduction 

- Support to the planning of land use. Reducing deforestation and soil consumption represent critical issues to meet the 2030 global goals.



Scaletta

Introduzione

Posizione del problema

Un po' di storia...

Modelli - RR

Esempi di calcolo: coltri superficiali

Evidenza sperimentale

Interazione SVA

Condizioni sismiche: cenni



Studio degli effetti sul contenimento di movimenti superficiali

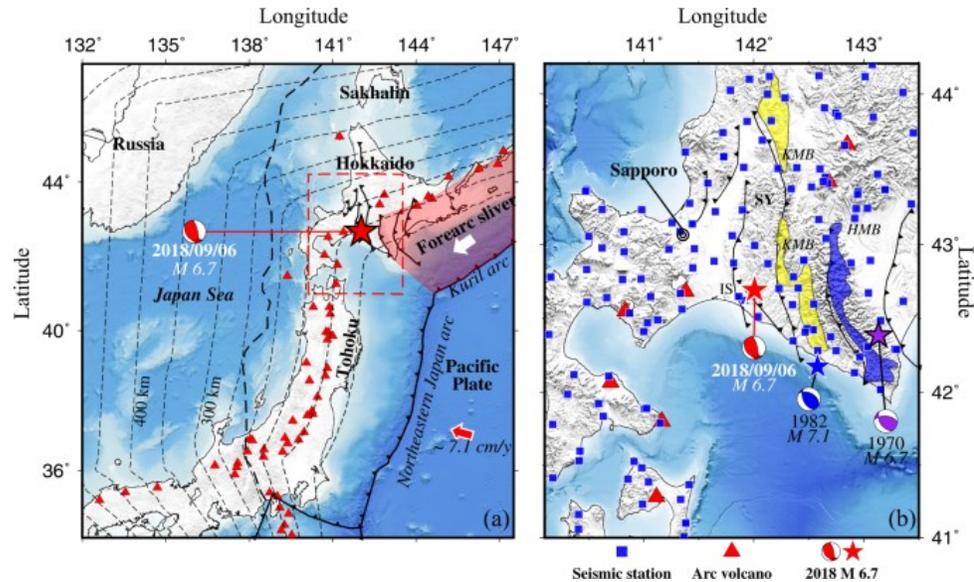
- **in atto o riattivati:**

- azioni ‘aggiuntive’ di natura sismica (aggravio)
- problema pratico: valutazione della sicurezza e prestazione sismica
- Interazione terreno-radici

- **indotti:**

- sisma → fattore di innesco
- problema pratico: scelta della specie → prestazione sismica
- ✓ interazione ‘**meccanica**’ terreno-radice come si modifica ?
- ✓ effetti ‘**idraulici**’: variazione w_n e S_r → comportamento ciclico

Come affrontare il problema ?



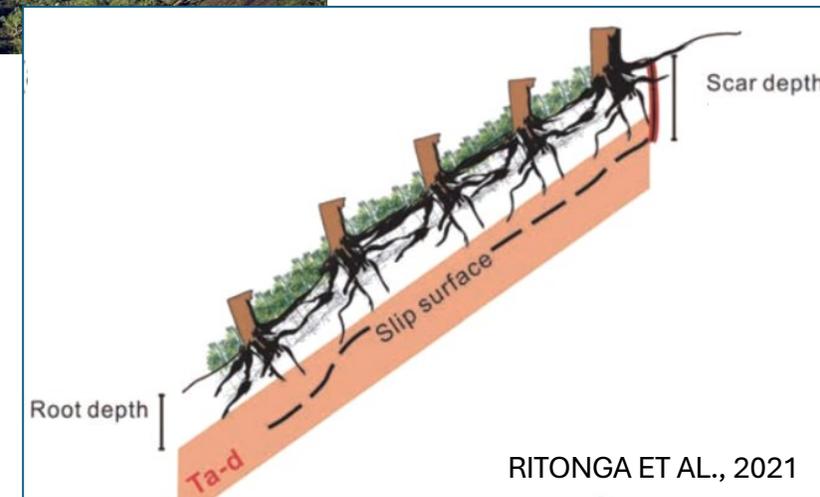
2018 ($M_w = 6.7$) Hokkaido Earthquake

Osservazioni post-evento

geometria e dimensioni delle s.d.s

s.d.s a profondità superiore della zona radicata

approfondimento s.d.s





Sperimentazione

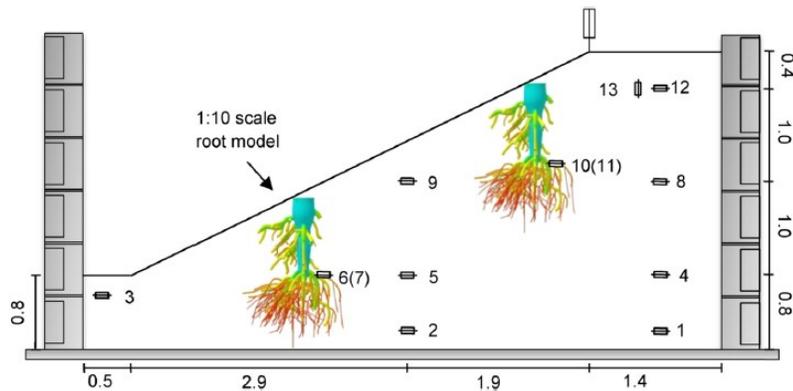
approccio: modellazione fisica in scala ridotta

problema: riprodurre elementi con proprietà meccaniche (rigidezza, resistenza) e geometria note delle radici

elementi "radice" in ABS (acrylonitrile butadiene styrene) stampante 3D, scala 1:10, ripetibili, *'rappresentativi'*

prove in centrifuga: modello di pendio, radici 'sospese', deposizione pluviale, input sismico)

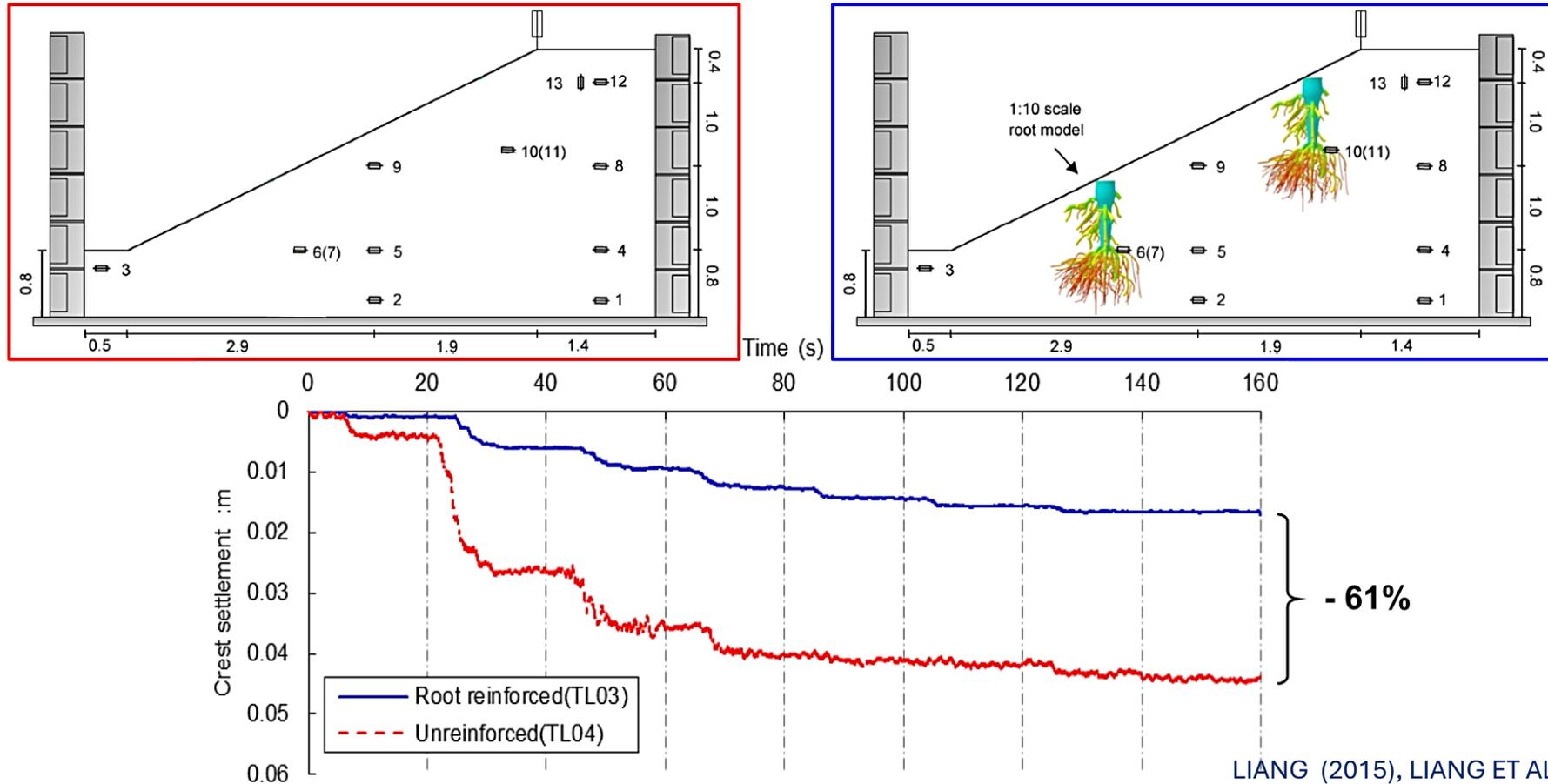
risposta : $a(t)$, $s(t)$



KNAPPETT & CO-WORKERS: LIANG (2015), LIANG ET AL. (2015, 2017)



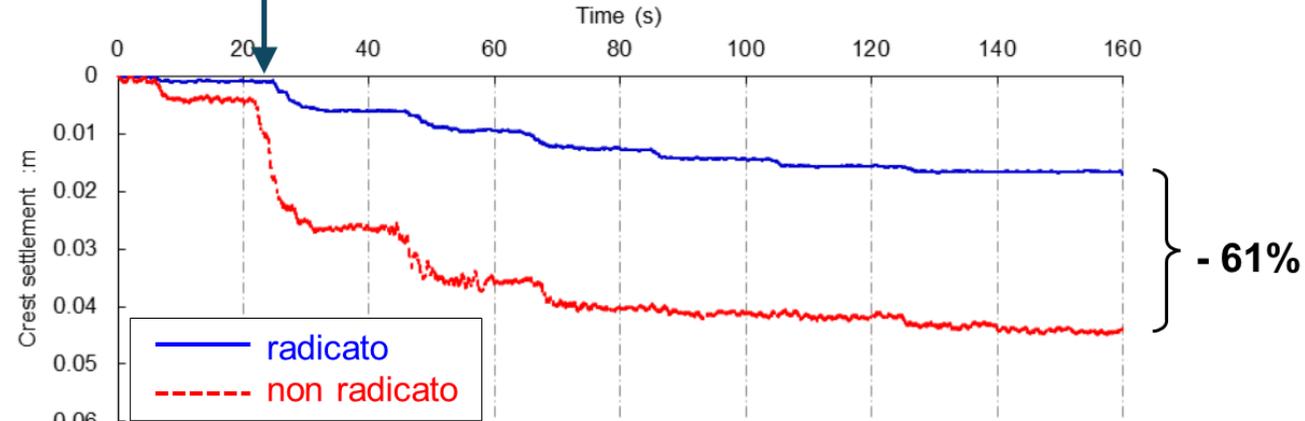
Evidenza sperimentale



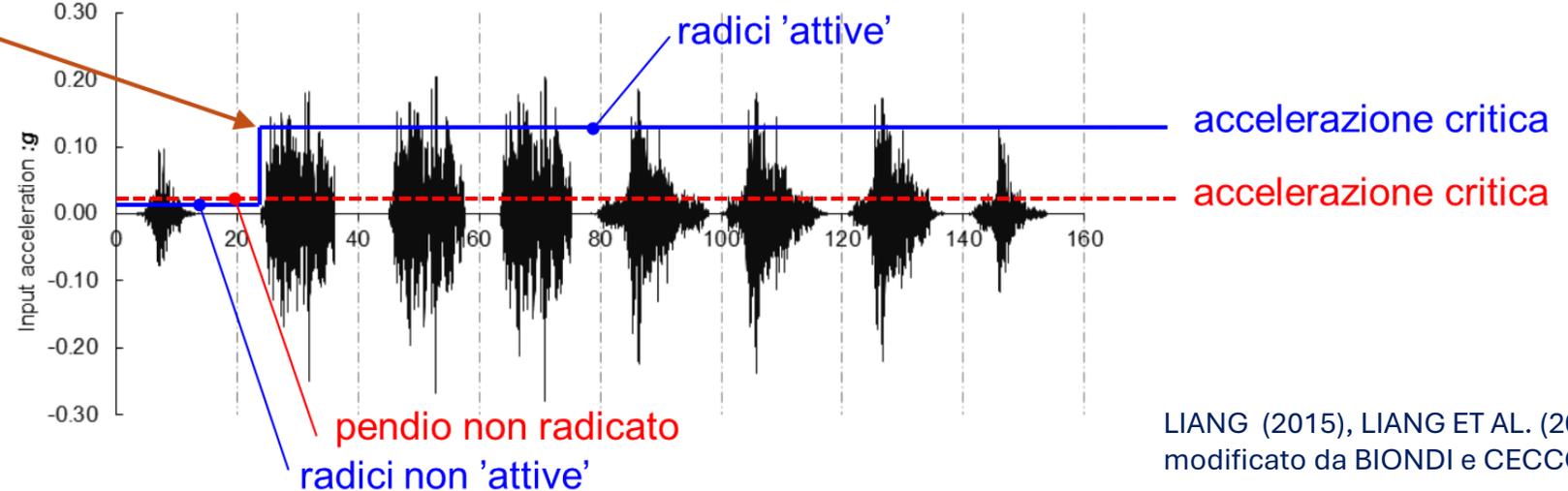
LIANG (2015), LIANG ET AL. (2015, 2017)- modificato



Attivazione
meccanismo
plastico



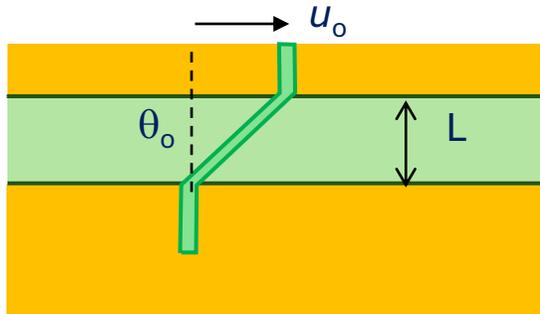
interazione



LIANG (2015), LIANG ET AL. (2015, 2017)
modificato da BIONDI e CECCONI, 2023



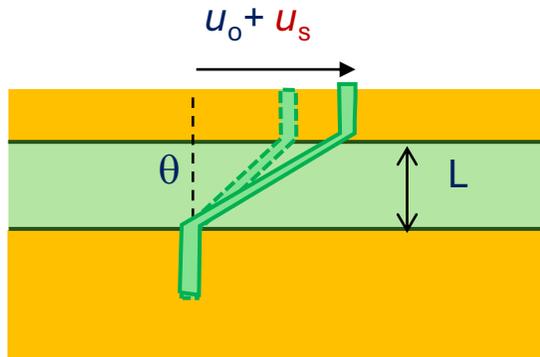
Approccio al problema



condizioni statiche (**RR, WWF – models**)

$$\gamma \approx \frac{\partial u}{\partial z}$$

$$\Delta\tau = \frac{A_r}{A_s} \cdot t_r \cdot (\sin \theta + \cos \theta \tan \varphi) \approx \frac{A_r}{A_s} \cdot t_r \cdot (1 \div 1.3)$$



condizioni sismiche: ulteriori spostamenti u_s , interazione (dinamica),
variazione sforzo di trazione
 $u_s = f(z, t, w, V_s,)$

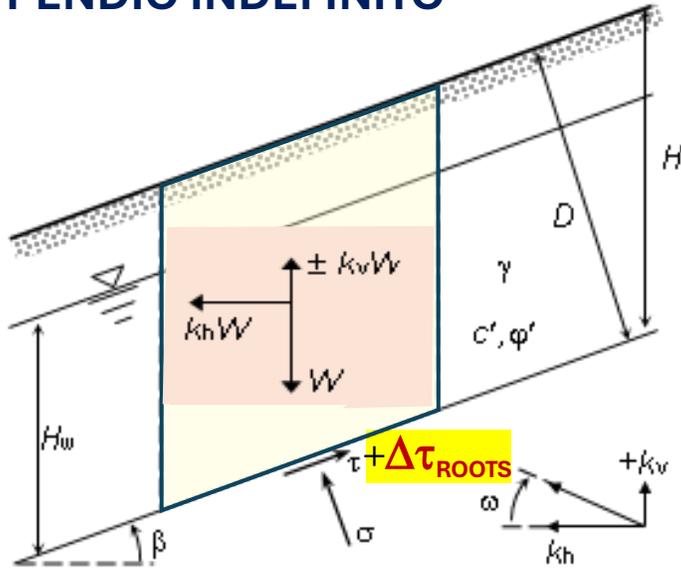
interazione dinamica: tempo, rigidzze relative, livelli def.

Approcci semplificati (**LEM**):

- approccio pseudo-statico
- metodi agli spostamenti



PENDIO INDEFINITO



FS funzione di:

- azione sismica (orizzontale, verticale)
- variazioni u
- profondità

$$FS = \frac{(c' + \Delta\tau) / (\gamma \cdot H)}{\sin \beta \cdot \cos \beta \cdot (1 - k_v) + k_h \cdot \cos^2 \beta} + \tan \varphi' \cdot \frac{\cos \beta \cdot (1 - r_u) \cdot (1 - \Delta u^*) - (k_h \cdot \sin \beta + k_v \cdot \cos \beta)}{\sin \beta \cdot (1 - k_v) + k_h \cdot \cos \beta}$$

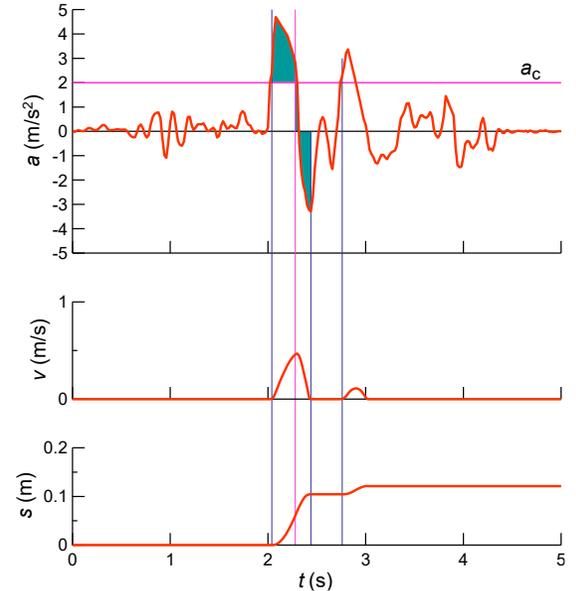


Analisi agli spostamenti (semplificata):

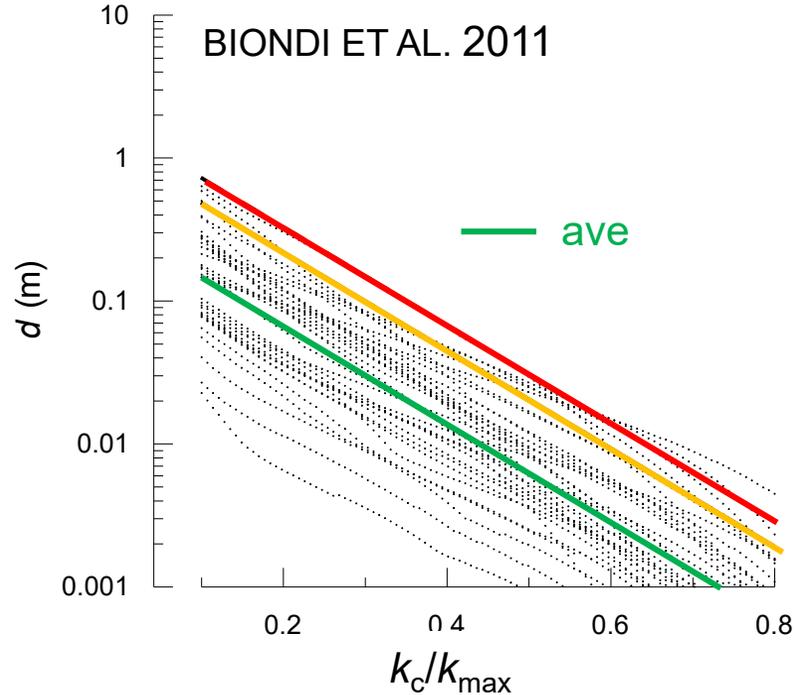
- determinazione accelerazione critica a_c (FS=1)
- scelta input sismico
- integrazione equazione del moto
→ spostamenti



$$k_c(t) = \frac{\cos \beta \cdot \tan \varphi' \cdot (1 - r_u) \cdot [1 - \Delta u^*(t)] - \sin \beta + (c' + \Delta\tau) / (\gamma \cdot H)}{(\sin \beta \pm \omega \cos \beta) \cdot \tan \varphi' + (\cos \beta \mp \omega \sin \beta)} = k_{c,0} + \Delta k_c$$



BIONDI e CECCONI, 2024
(in preparation)



Analisi agli spostamenti (semplificata):

- diversi valori di $a_c = k_c g$ (diversi sistemi terreno-radice)
- database di registrazioni sismiche
- leggi previsionali dello spostamento

Effetto degli apparati radicali:

$$\Delta\tau > 0 \rightarrow \Delta k_c > 0 \rightarrow \Delta d_{\max} < 0$$

$$\log d_{\max} = C_1 \cdot (S_S \cdot S_T) - C_2 \cdot \frac{k_{c,o} + \Delta k_c}{k_{\max}}$$



$$\log (d_{\max} / d_{\max,o}) = \frac{-C_2 \cdot \Delta k_c}{k_{\max}}$$



Implicazioni pratiche - Eurocodice 7

Progetto delle azioni (2.4.6.1.(9))

Le seguenti caratteristiche, che possono influenzare le pressioni dell'acqua, devono essere considerate:

- effetto favorevole o sfavorevole del drenaggio
- variazioni nelle pressioni dell'acqua dovute alla crescita o alla rimozione di **vegetazione**.

Situazioni di progetto (11.3.(2) P) «Overall stability»

Occorre considerare l'effetto delle seguenti circostanze, ove appropriato :

- variazioni climatiche, incluse variazioni di temperatura
- **vegetazione** o la sua rimozione”.

Considerazioni progettuali e costruttive (11.4)

I pendii dovrebbero essere “sigillati”, **piantumati** o protetti artificialmente.

Pendii potenzialmente instabili possono essere stabilizzati per mezzo di gabbioni, ancoraggi, drenaggi,, **vegetazione**, o una combinazione di questi.



UNIVERSITÀ DEGLI STUDI
DI CASSINO E DEL
LAZIO MERIDIONALE



INCONTRO ANNUALE DEI RICERCATORI DI GEOTECNICA UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE GAETA, 4-6 SETTEMBRE 2024



a

Giovanni **Biondi**, Università di Messina

Federica **Cotecchia**, Vito **Tagarelli**, Politecnico di Bari

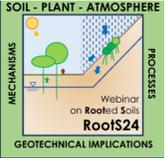
Alessandro **Fraccica**, ISPRA, Roma

Grazie,
M.

Webinar on Rooted Soils _RootS24

SOIL-PLANT-ATMOSPHERE INTERACTION: Mechanisms, Processes and Geotechnical Engineering Implications

The 2nd edition of the *Int. Workshop on Rooted Soils* will be held **online**. This will be an opportunity to share the latest updates on the active initiatives, with the aim to foster a discussion on possible joint activities of interest to the attendees



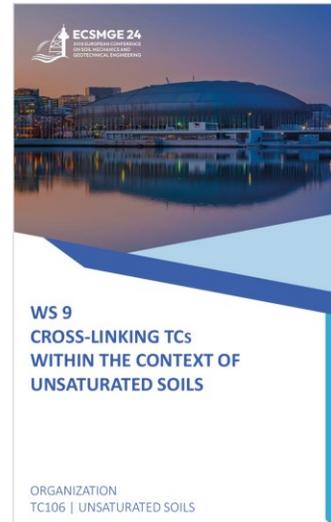
Friday 10th May 2024 at 10:00 a.m. (GMT+02:00)

- 10:00: V. Tagarelli & M. Cecconi: "1 year from RootS23: updates and initiatives"
- 10:30: V. Capobianco, G. Scaringi & A. Fraccica: "COST action proposal"
- 10:50: Open discussion

11:30: *Chair*: F. Cotecchia
Invited lecture: **The mechanics of rooted soils: recent advances**
Anthony Kwan LEUNG
 Dept. of Civil and Environmental Engineering - School of Engineering,
 Hong Kong University of Science and Technology, HKUST



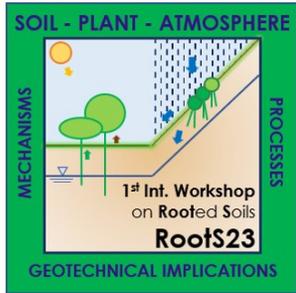
- Q&A
- 12:45: Final discussion and closing remarks



ROOTED SOILS IN PARTIALLY SATURATED CONDITIONS: SOME INSIGHTS IN THE SVA INTERACTION

Federica Cotecchia | Politecnico di Bari
Manuela Cecconi | Università degli Studi di Perugia
Vito Tagarelli | Politecnico di Bari





RootS23

SOIL-PLANT-ATMOSPHERE INTERACTION:
MECHANISMS, PROCESSES AND GEOTECHNICAL
ENGINEERING IMPLICATIONS

20th - 21st April 2023

Perugia, Department of Engineering, University of Perugia



The topic of the Workshop is broad and multidisciplinary, spanning several scientific fields, each contributing to the **investigation and modeling** of specific aspects of the **soil and plant behavior** under **variable climatic conditions**.

20 invited lectures, 2 open discussion from the floor, in 3 half days

Invited Speakers



Not only geotechnical scientists, but researchers from different several fields:

- Agriculture and agronomy science;
- Ecology science;
- Ecological Engineering;
- Forest Soil Sciences;
- Forestry Hydraulics;
- Geology;
- Soil physics and biophysics;