University Online Lecture Series

Geosynthetics for Reinforcement

Pietro Rimoldi, Yoshihisa Miyata, Ivan Puig Damians
IGS TC-Soil Reinforcement

INTERNATIONAL GEOSYNTHETICS SOCIETY

www.geosyntheticssociety.org

About the lecturer

Pietro Rimoldi

- Degree in Civil Engineer in 1984, he started to work in the Geosynthetics sector in 1986.
- He has been involved in the development of new products and in many research projects related to geosynthetics.
- He has designed several important projects around the world, for soil reinforcement and stabilization, landfills, hydraulic applications and erosion control.
- He is the author of more than 250 national and international publications and he has written books and design manuals for reinforced slopes and walls, basal reinforcement, veneer reinforcement, road and railway base stabilization, geosynthetic drainage systems and erosion control.
- He is Member of the International Council of the IGS, and he is presently the Chair of IGS Technical Committee on Reinforcement (TC-R).

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About the lecturer

Yoshihisa Miyata

- Dr. Miyata is Prof. of Civil Eng. Dept at the National Defense Academy of Japan.
- He received his D.Eng from Kyushu Univ in 1999. He has published more than 230 technical papers on soil reinforcement, geosynthetics engineering and ground improvement, etc.
- He is a council member, co-chair of TC-R of IGS, and vice chair of Japan chapter of IGS. He is also a board member of Geosynthetics International.
- He has received many awards from CGS, ICE, IGS, and JGS. https://www.researchgate.net/profile/Yoshihisa-Miyata

miyata@geotech-research.jp

About the lecturer

Ivan Puig Damians

- Dr. Damians (B.Eng., B.A., M.Eng., M.A., Ph.D.) is a *Researcher* at the International Centre for Numerical Methods in Engineering (CIMNE®), *Geotechnical Engineer* at VSL International Ltd (a member of Bouygues Construction Group), and *Ass.Prof.* of the Civil and Environmental Eng. Dept. at the Universitat Politècnica de Catalunya · BarcelonaTech (UPC) with teaching activity regarding Soil Mechanics, Geotech. Eng., and Sustainability assessment fields.
- He participates in research projects funded by national and international programs and agencies (e.g., DECOVALEX-2023 by ANDRA, FE-Experiment by NAGRA) as well as research projects from industry (e.g., GECO).
- He is member of several national and international technical committees and societies (TC250-SC7 developing Eurocode7, TC218 and TC307 from the ISSMGE, CTN 140/SC7, SEMSIG, CGS) and is currently Secretary of IGS Technical Committee on Reinforcement (TC-R).

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Outline

1. Introduction
2. Sustainability of reinforced soil structures
3. Soil reinforcement conceptual mechanism
4. Reinforced soil walls and slopes
5. Veneer reinforcement
6. Basal reinforcement
7. Seismic resistance of reinforced soil structures
8. Summary

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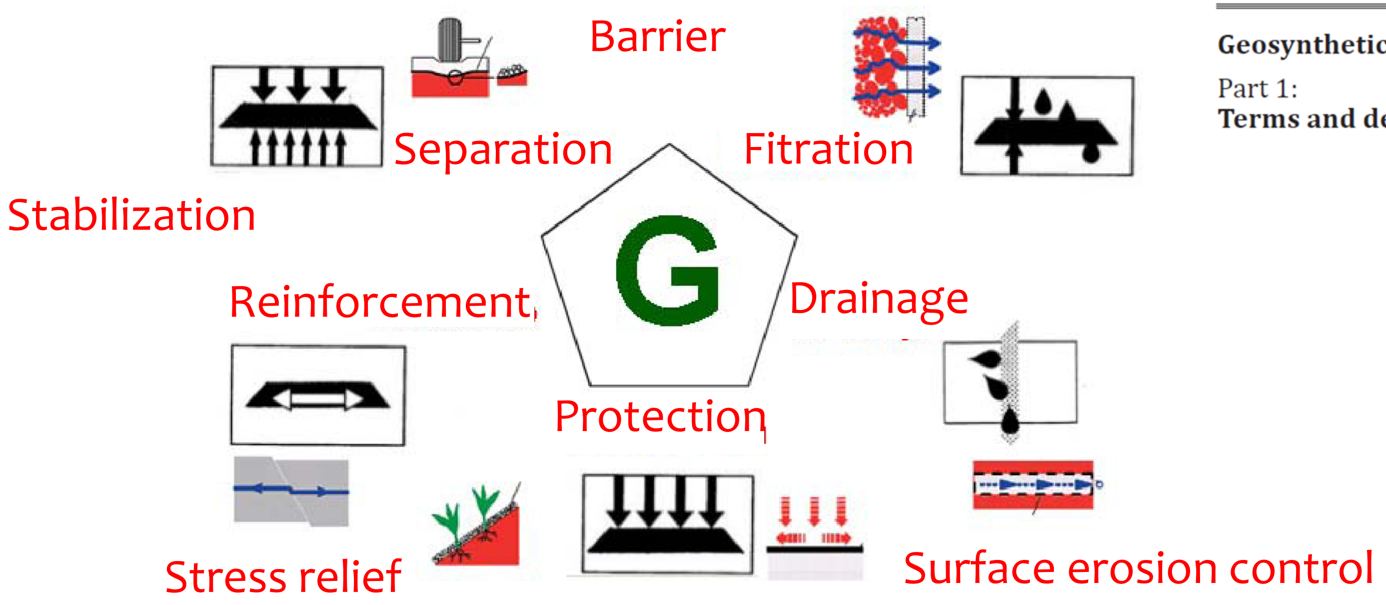
Introduction

INTERNATIONAL STANDARD **ISO 10318-1**

Geosynthetics —

Part 1:
Terms and definitions



Introduction

INTERNATIONAL STANDARD ISO 10318-1

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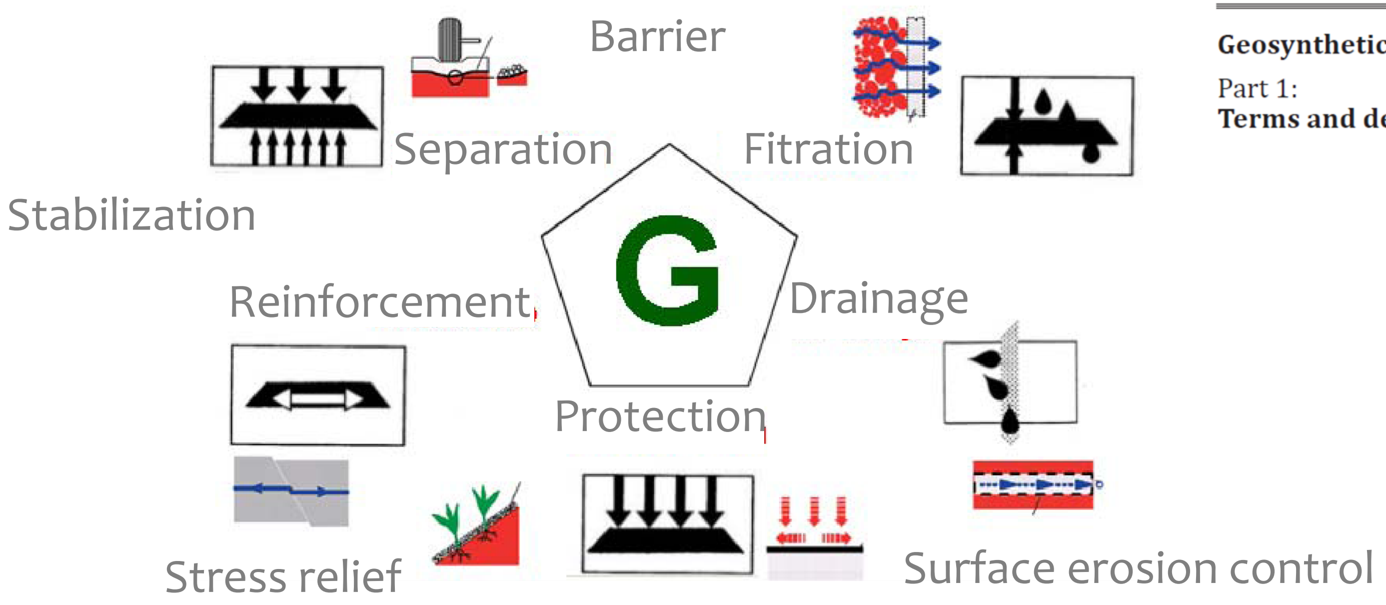

International Geosynthetics Society

IGS Technical Committees

- Barrier Systems
- Hydraulics
- Soil Reinforcement
- Stabilization

Introduction

INTERNATIONAL STANDARD **ISO 10318-1**

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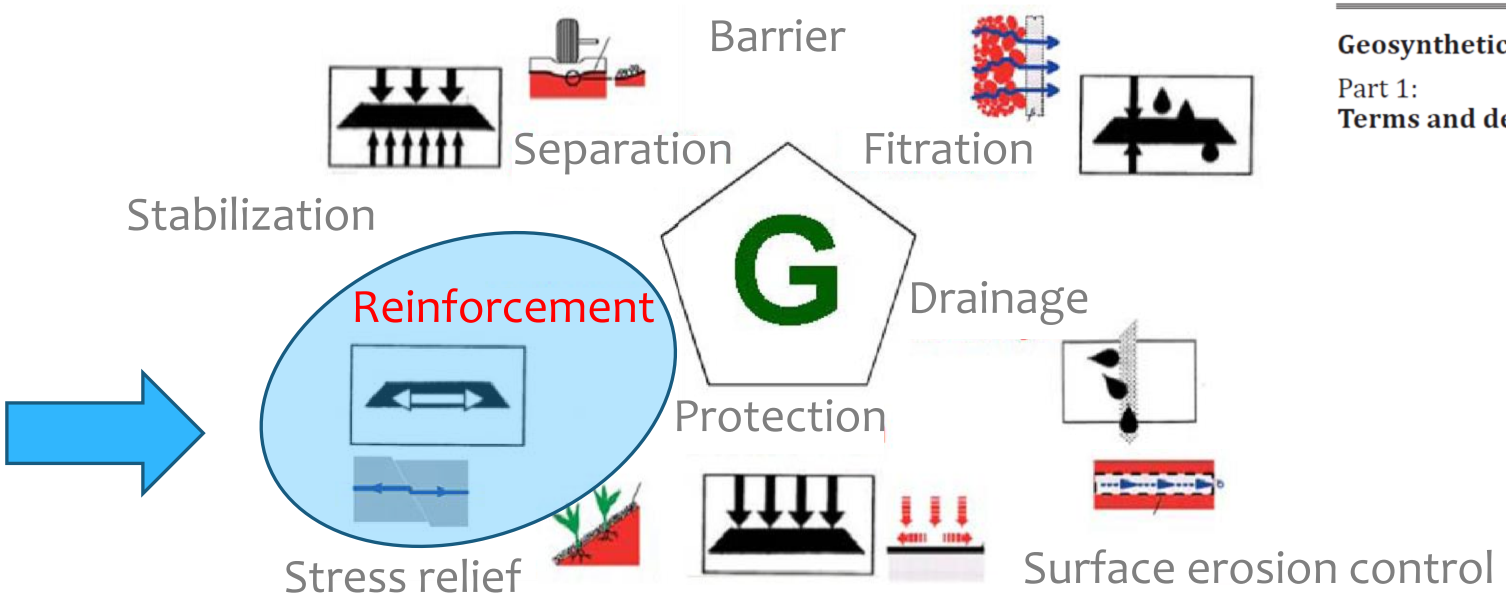

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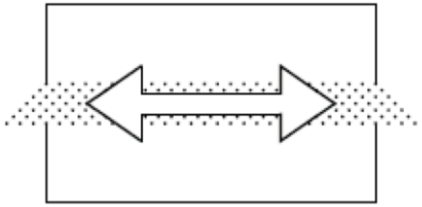
Introduction

- ✓Geosynthetics include a variety of polymeric materials that are specially fabricated to be used in geotechnical, environmental, hydraulic and transportation engineering applications.
- ✓**In this presentation we will illustrate the use of geosynthetics for the function of Reinforcement**
- ✓ISO 10318-1 definition of the function of Reinforcement:
- ✓Use of the stress-strain behaviour of a geosynthetic material to improve the mechanical properties of soil or other construction materials.
- ✓ISO 10318-2 pictogram of the Reinforcement function



- ✓In practical terms, the geosynthetic acts as a reinforcement element within a soil mass to produce a composite that has improved mechanical performance over the unreinforced soil.

Main applications

Geosynthetics fulfill the function of **reinforcement** in the following main application areas:

- **Reinforced soil walls**
- **Reinforced soil slopes**
- **Basal reinforcement of embankments:**
    - over soft soil
    - over piles
    - over voids
- **Soil veneer reinforcement**

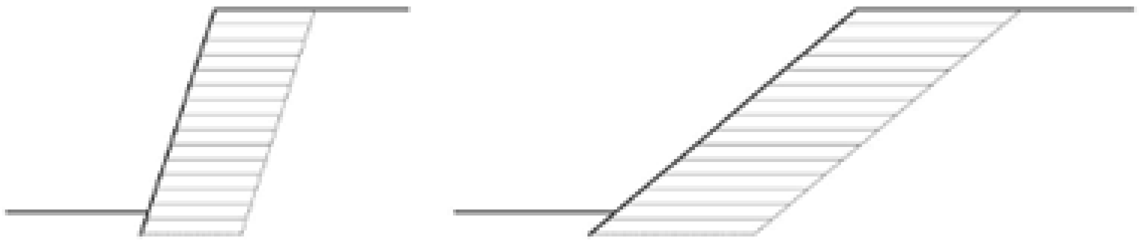
Applications

ISO/TR 18228-7
Design using geosynthetics — Part 7: Reinforcement

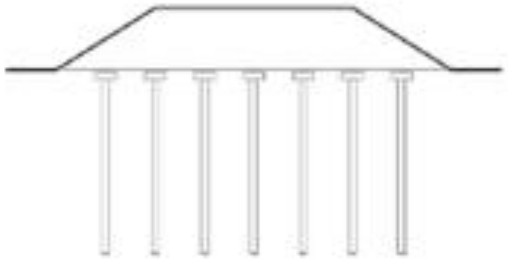
Walls and Abutments

Basal Reinforcement

Basal Mattress

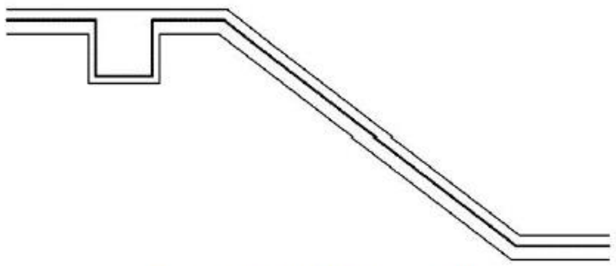


Reinforced Slopes



Piled Embankments

Reinforcement over areas prone to subsidence

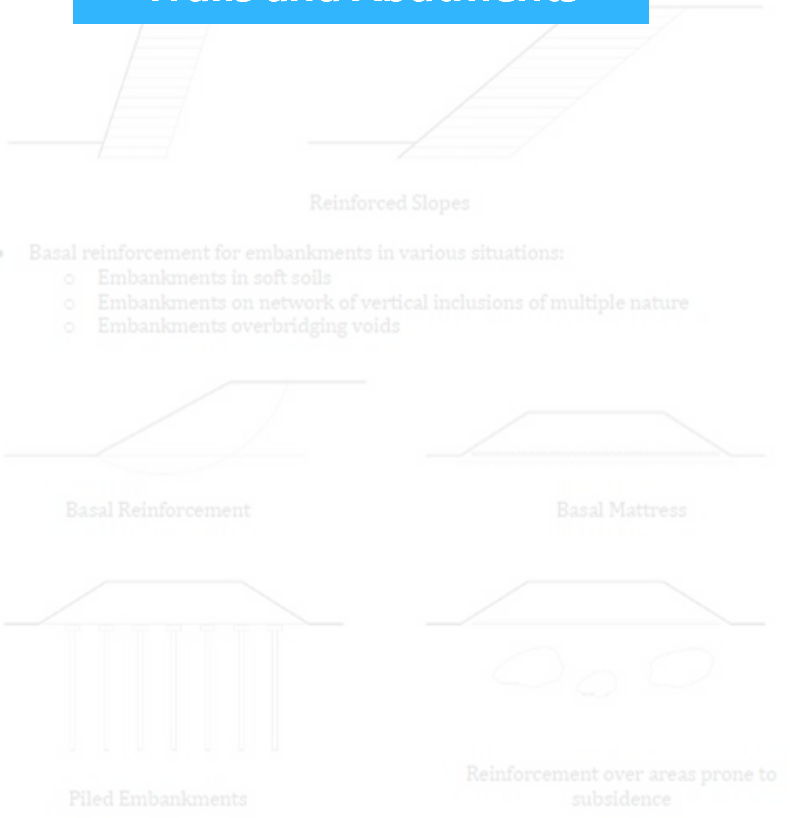


Veneer Reinforcement

Applications

ISO/TR 18228-7:2021

Walls and Abutments



Reinforced Slopes

- Basal reinforcement for embankments in various situations:
  - Embankments in soft soils
  - Embankments on network of vertical inclusions of multiple nature
  - Embankments overbridging voids

Basal Reinforcement

Basal Mattress

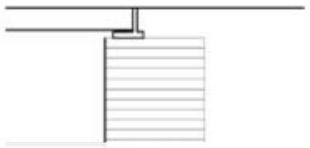
Piled Embankments

Reinforcement over areas prone to subsidence

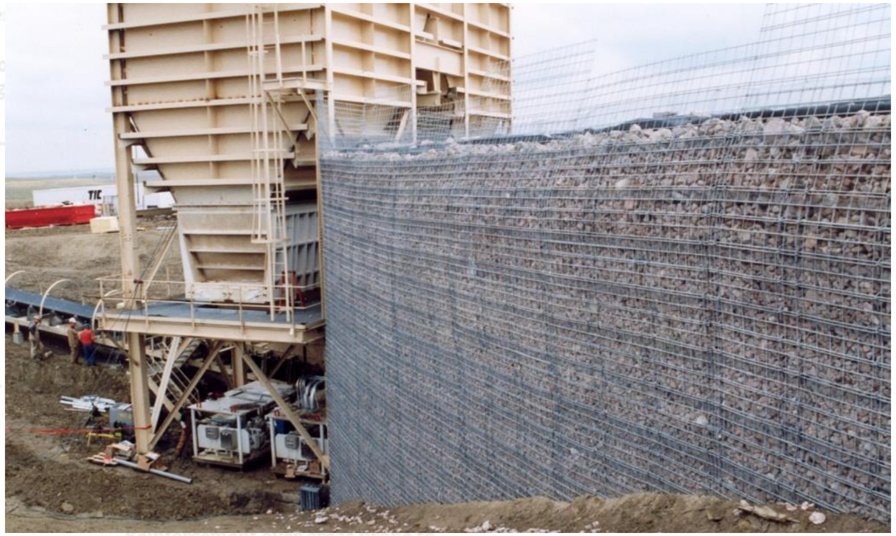
- Veneer reinforcement:
  - Landfill closures
  - Shallow slope remediation

Applications

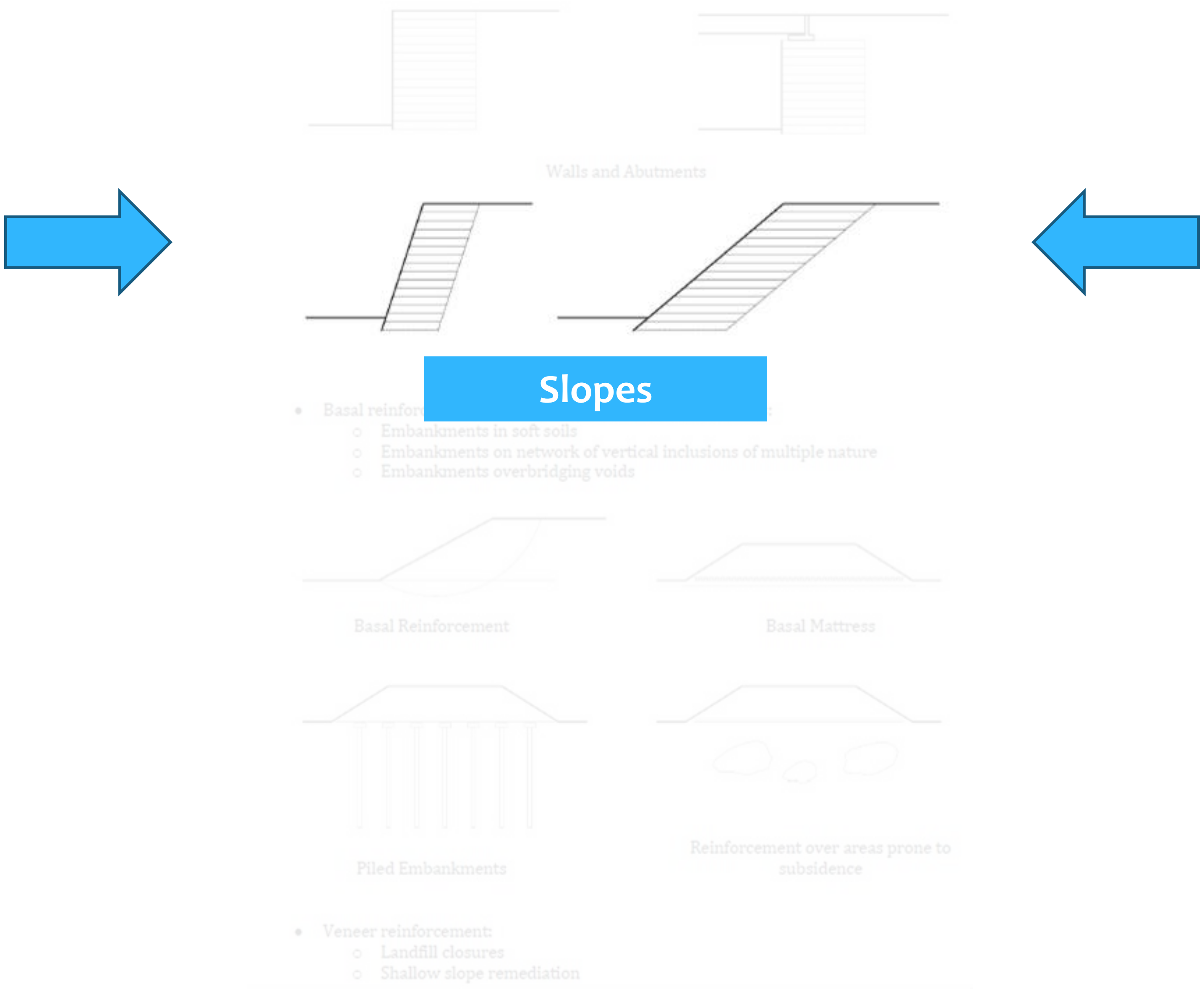
ISO/TR 18228-7:2021



Walls and Abutments

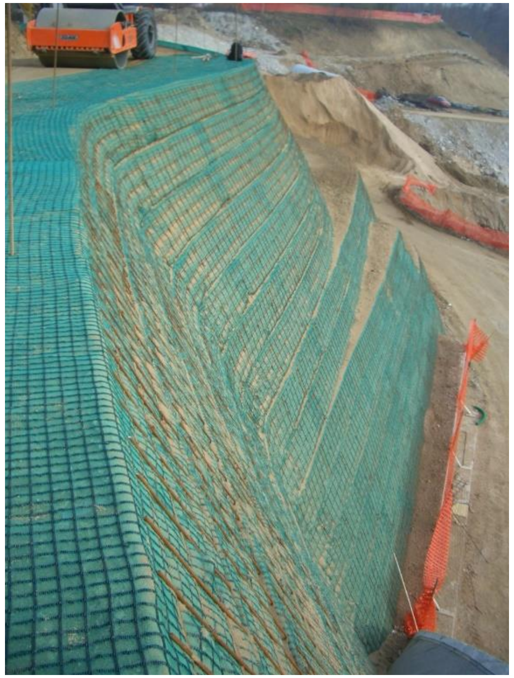


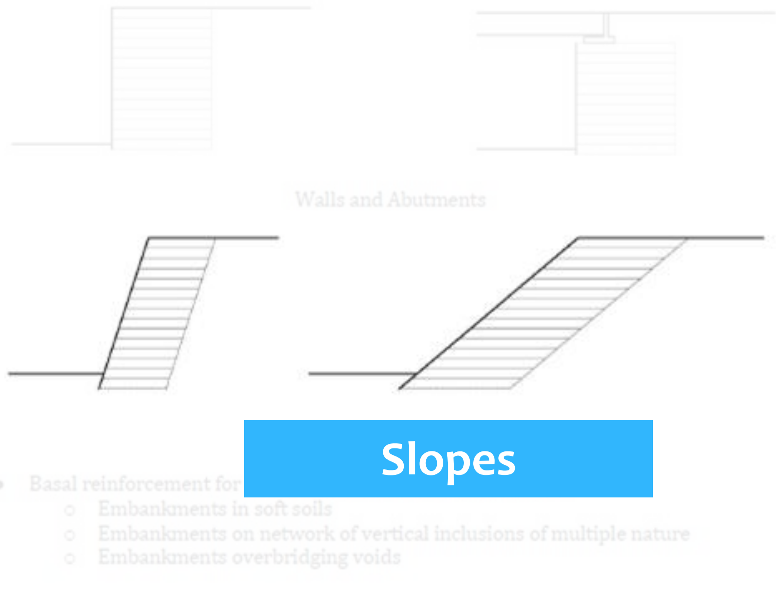
Applications



Applications

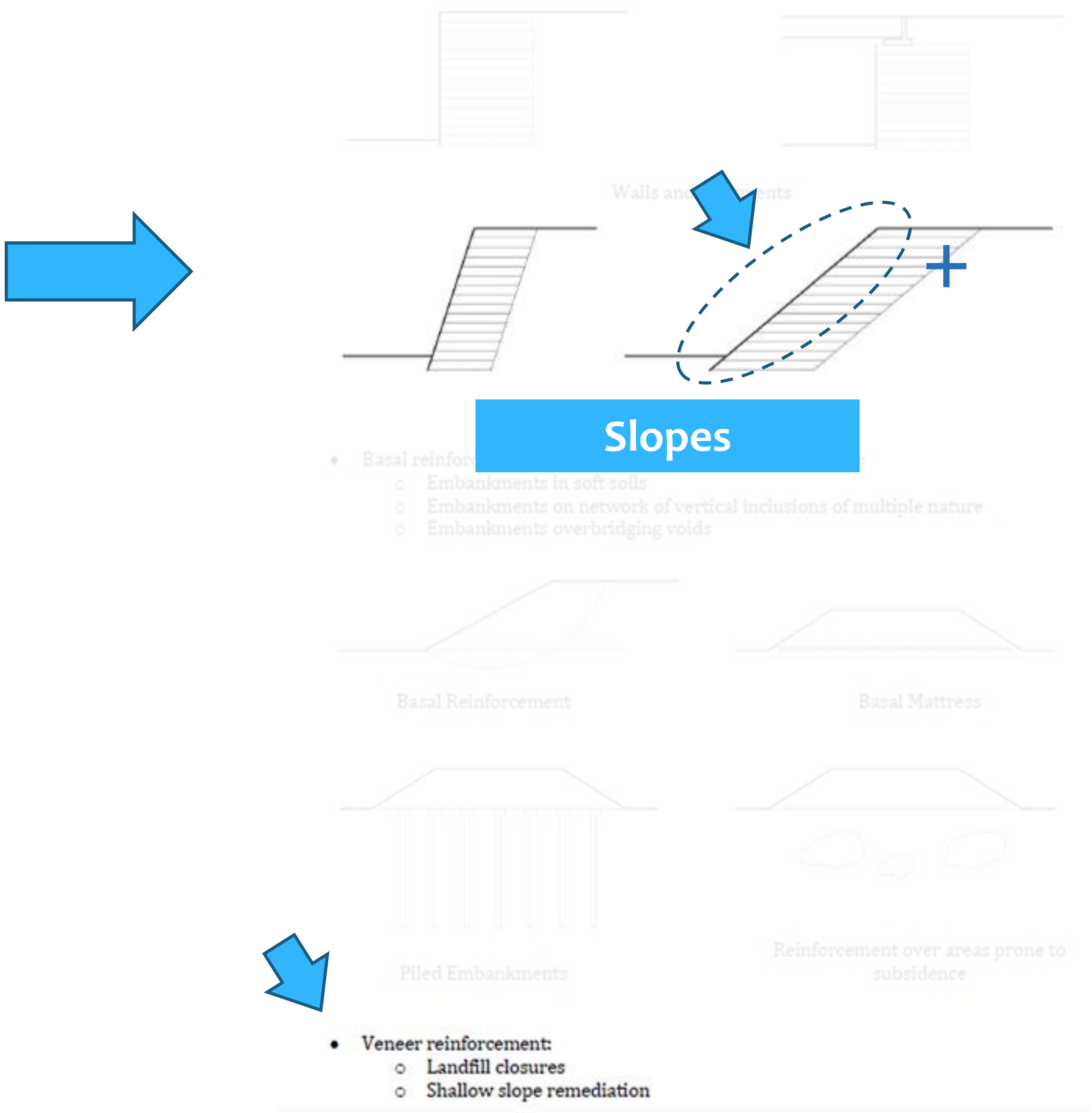
ISO/TR 18228-7:2021





Applications

ISO/TR 18228-7:2021



Applications

…+

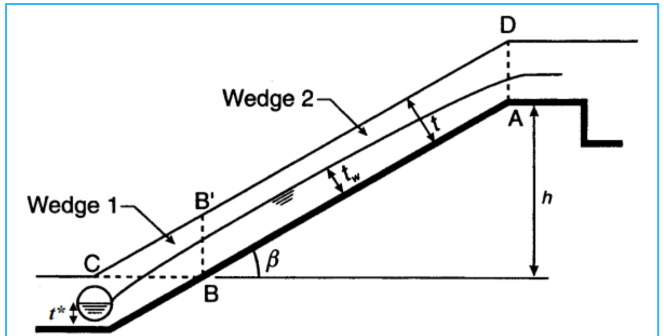
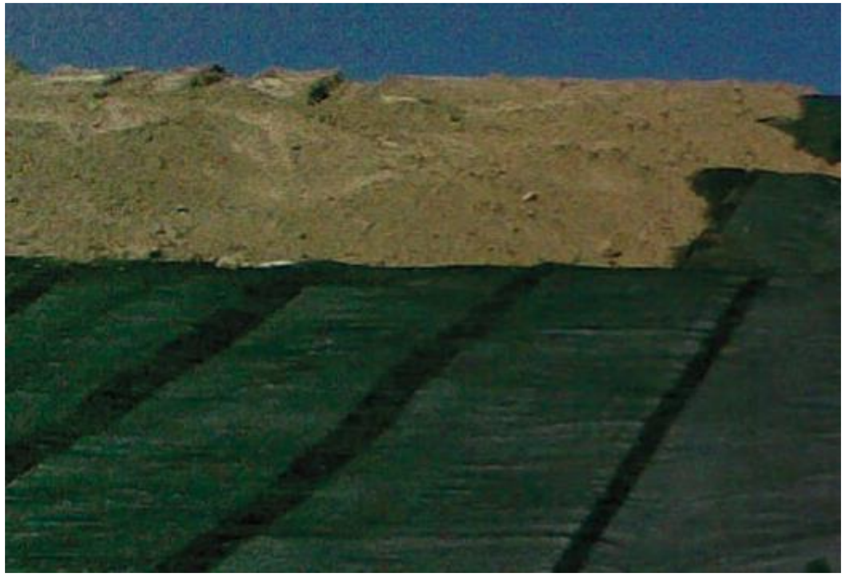


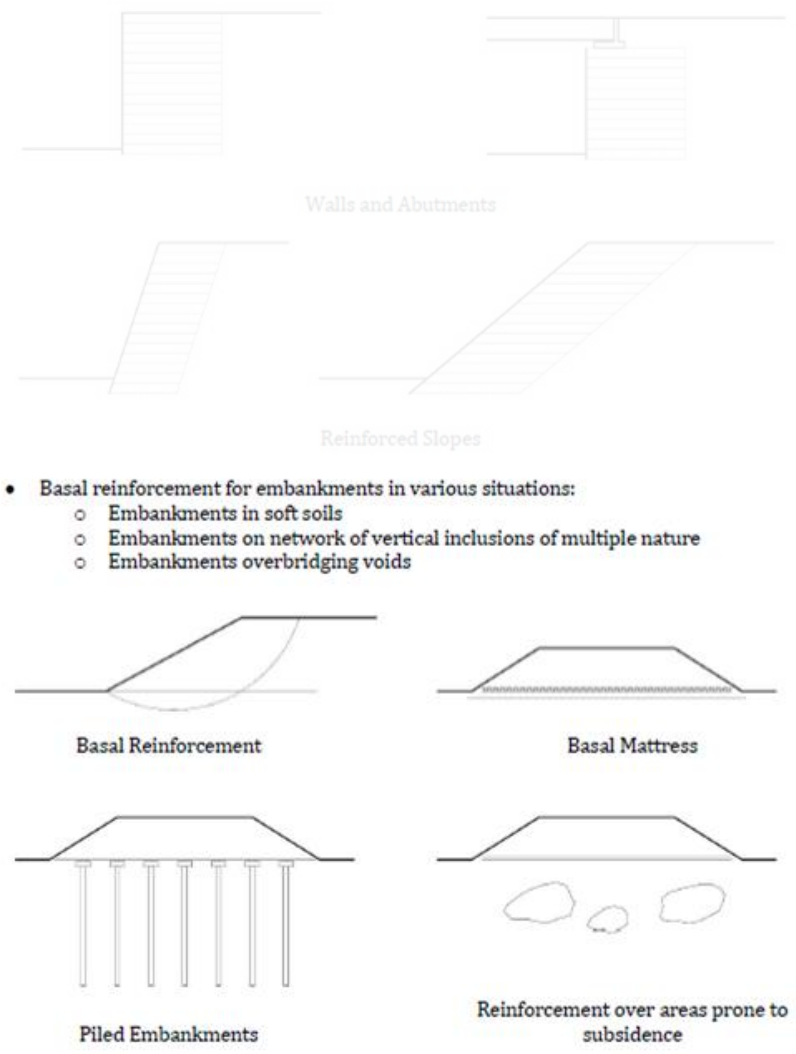
Figure 1. Slope Geometry used to derive Veneer Finite Slope Stability Equation [Giroud et al, 1995]

Veneer reinforcement



Applications

ISO/TR 18228-7:2021



- Basal reinforcement for embankments in various situations:
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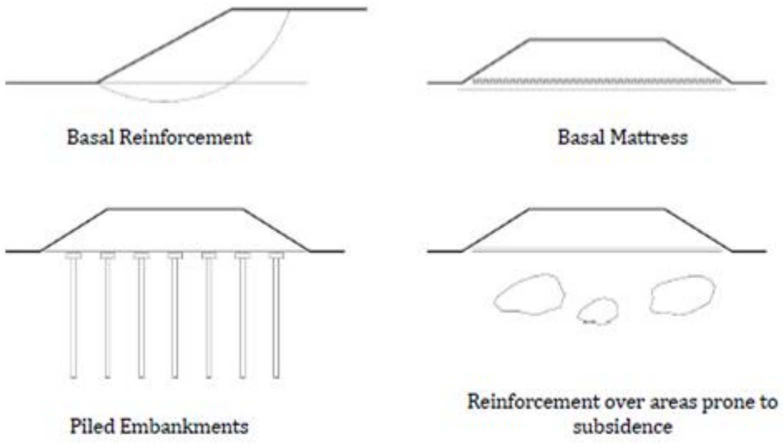
Basal reinforcement

Applications



Basal reinforcement

Applications

ISO/TR 18228-7:2021

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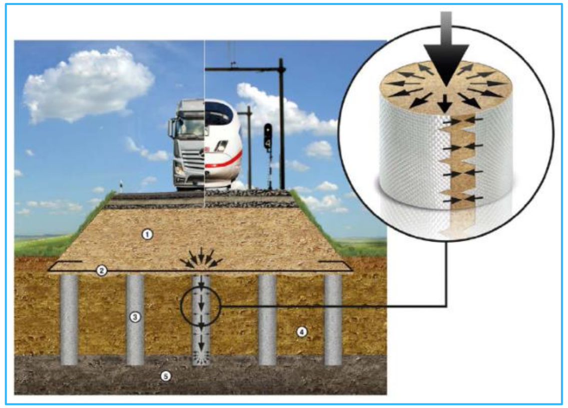
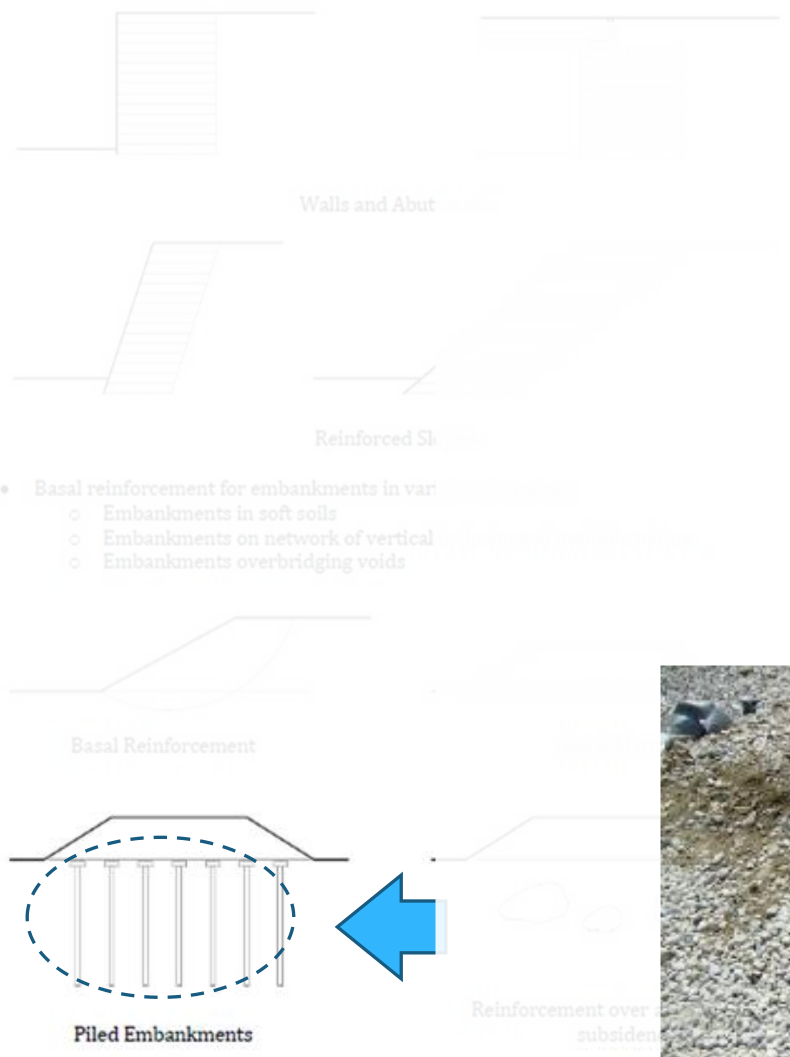


Geosynthetic encased columns (GEC)



Basal reinforcement

General/brief history of soil reinforcement

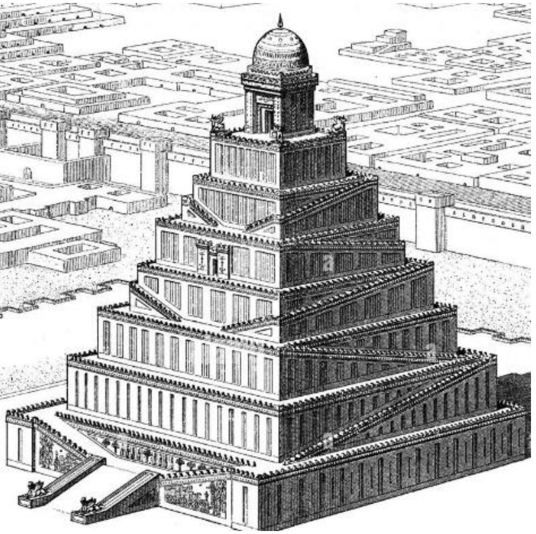
- Soil reinforcement is an ancient concept, examples are the Ziqqurat in Mesopotamia and the Great Wall in China
- Only the advent of geosynthetics allowed to engineer the concept of soil reinforcement, thanks to the availability of industrialized products with constant and predictable technical characteristics
- 40 years of successful projects and positive experiences, extensive testing and research, development and validation of design methods, have demonstrated the superior performance of reinforced soil structures subjected to all types of permanent and accidental loads
- Structures built in highly seismic areas have demonstrated the superior resistance of reinforced soil structures that sustained extremely strong earthquake without major damages

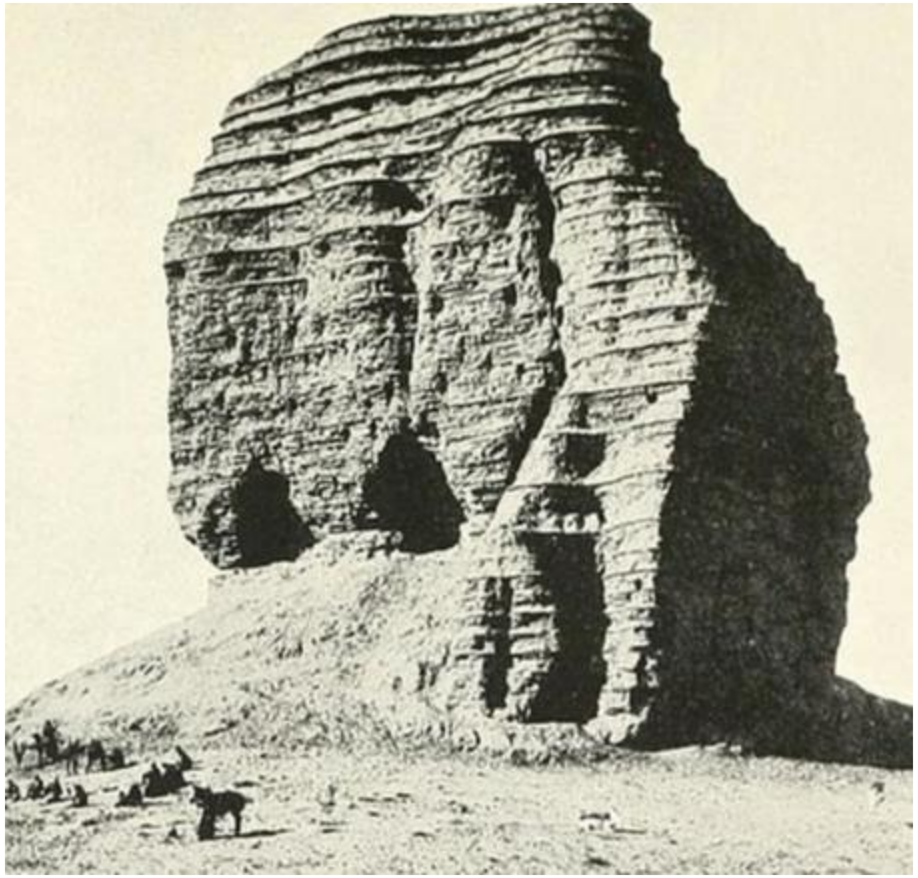
General/brief history of soil reinforcement

Ziggurat of Dur-Kurigalzu at Aqar Quf, Iraq

built in the 14th century BC by the Kassite King Kurigalzu

60 m high, built with sand and clay reinforced with reeds placed in horizontal lines



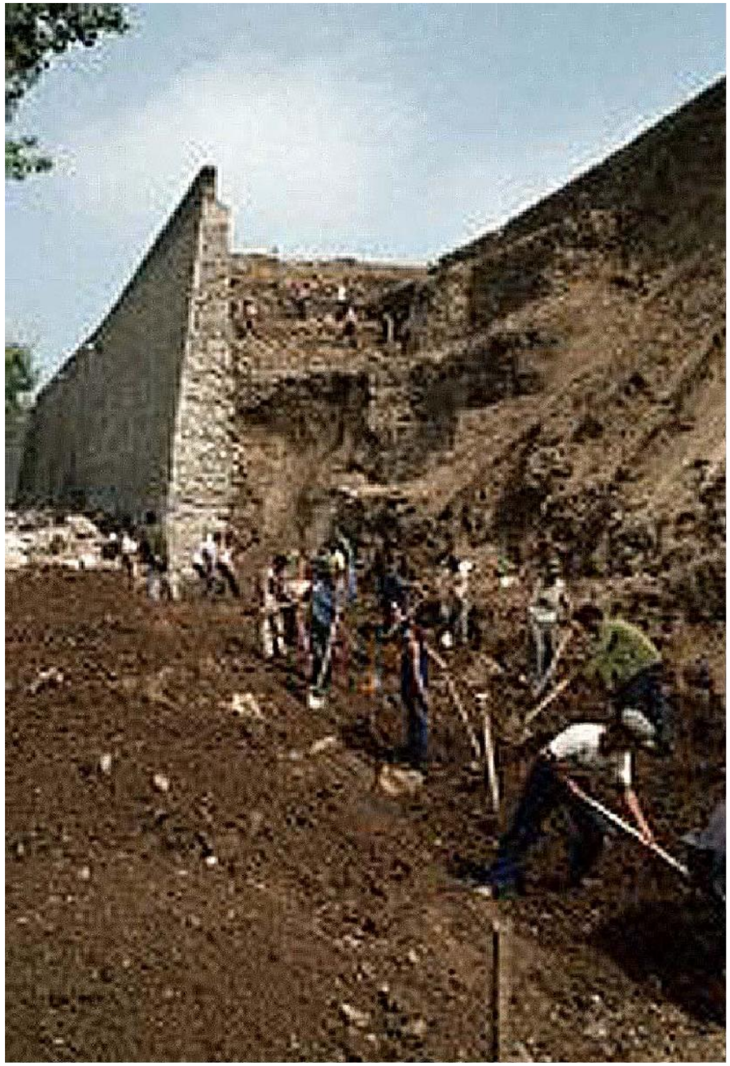


General/brief history of soil reinforcement

GREAT WALL OF CHINA (200 B.C.)

8.5 m high, 8,800 km long

Sand and clay reinforced with dried branches of red willow



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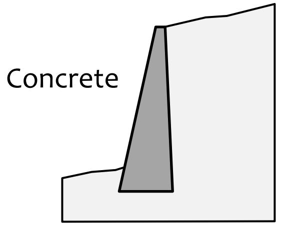
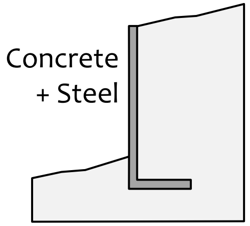
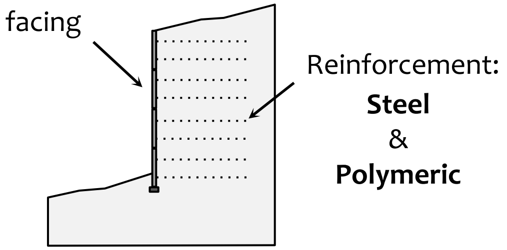
Sustainability of reinforced soil structures



Gravity

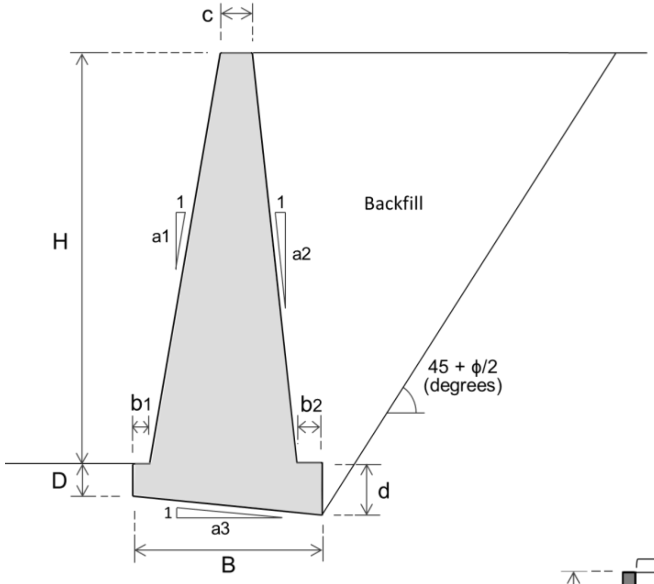


Cantilever

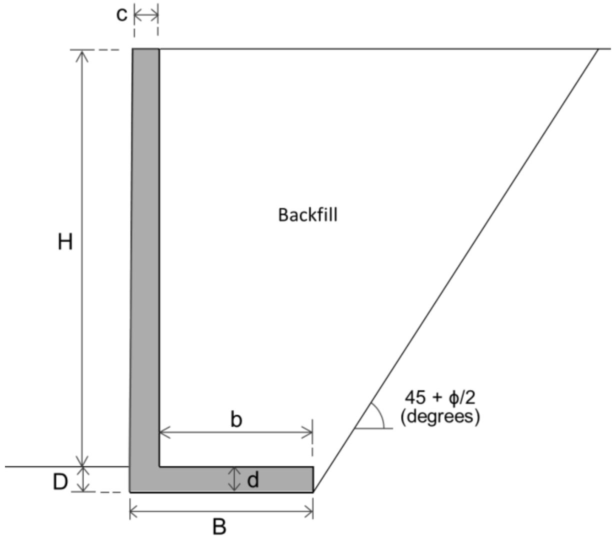


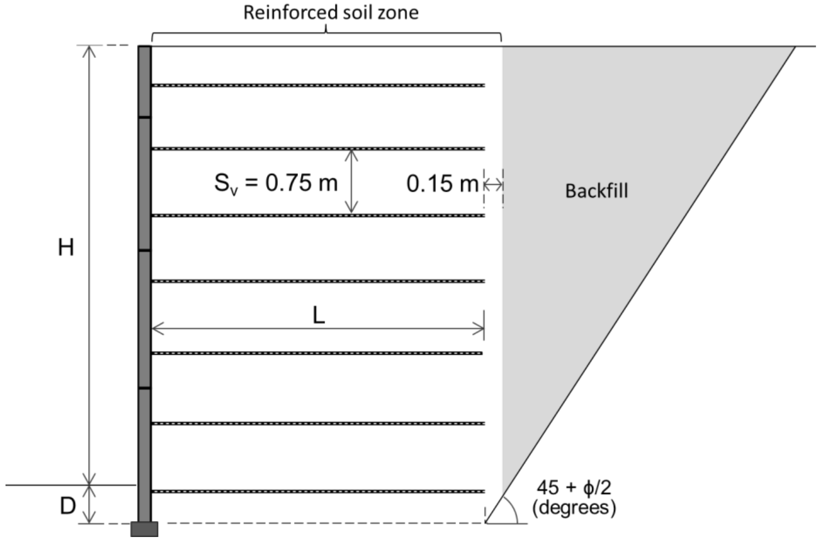
Reinforced soil

Sustainability of reinforced soil structures

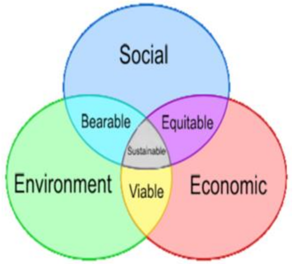


¿optimal?





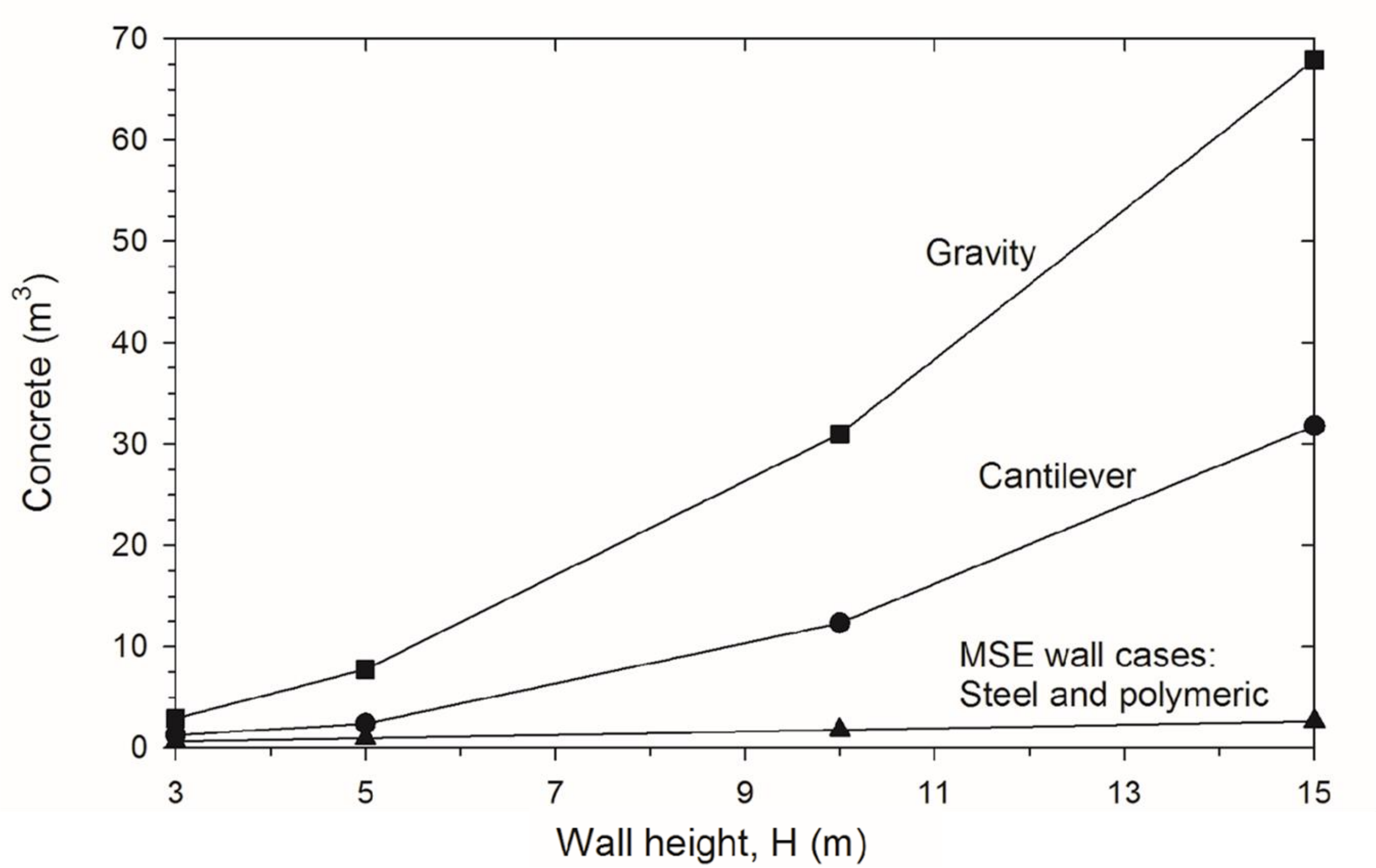
… in terms of
Sustainability!



Sustainability of reinforced soil structures

Construction material required for each wall option (for unit length of the wall)

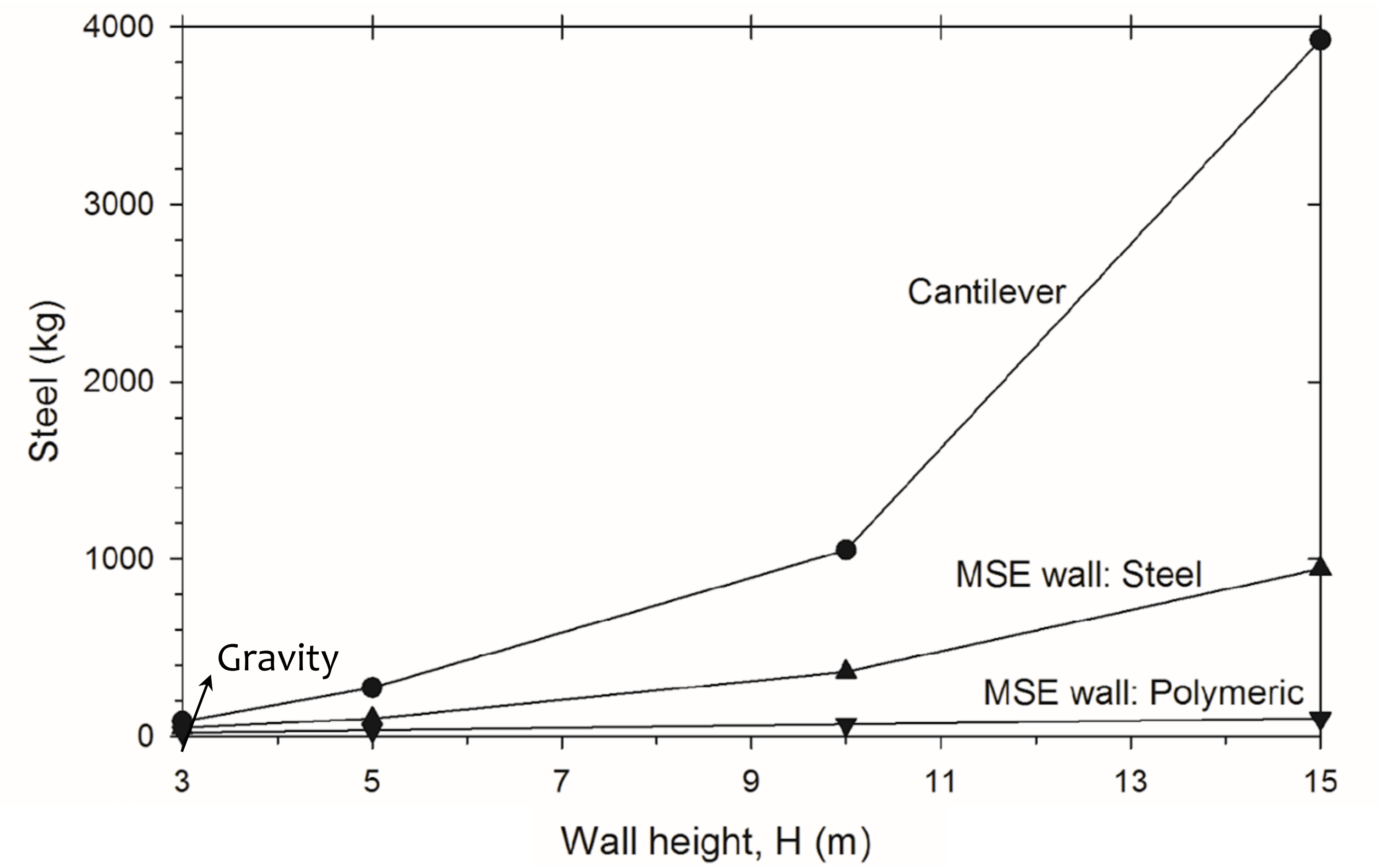
Concrete



Sustainability of reinforced soil structures

Construction material required for each wall option (for unit length of the wall)

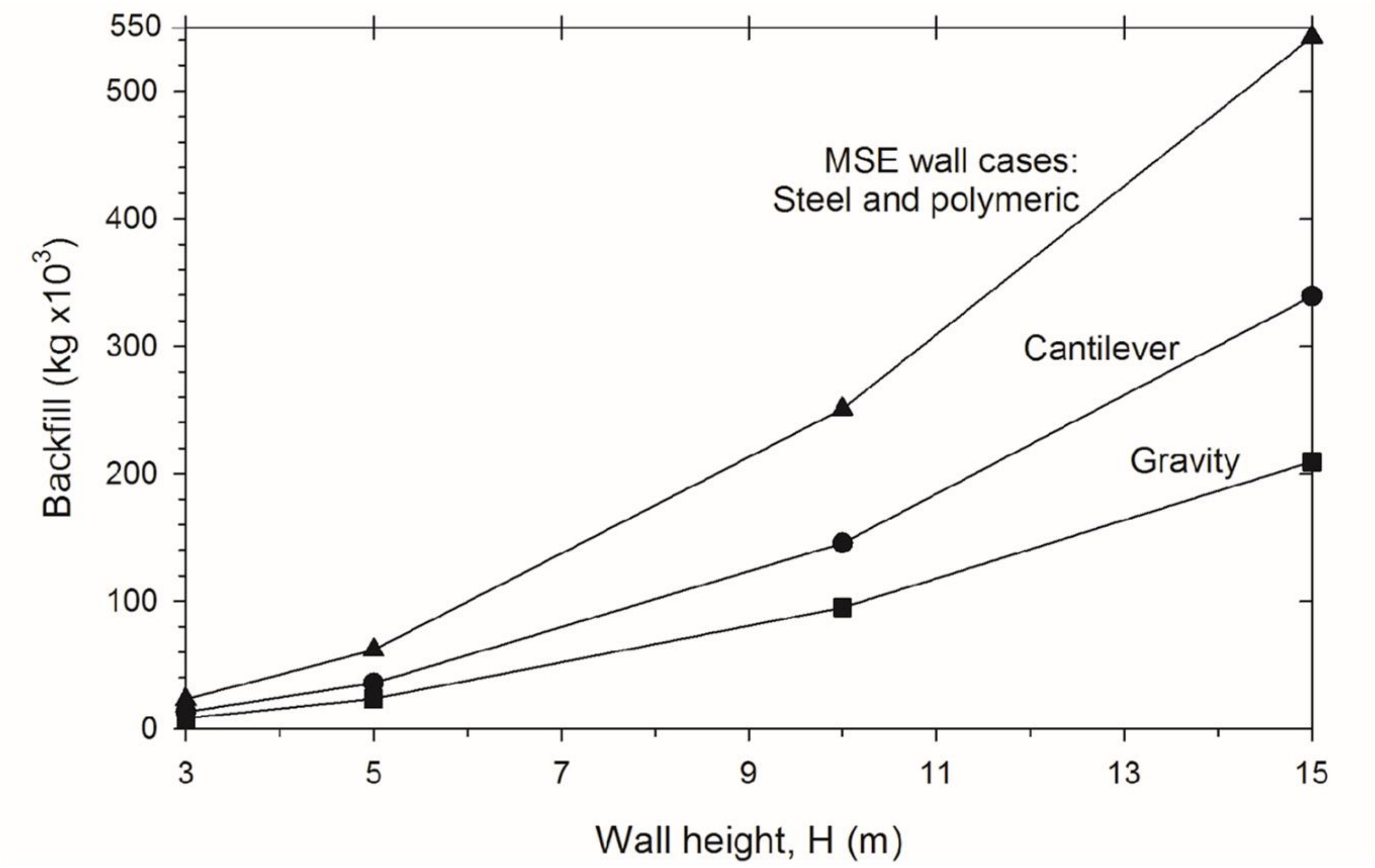
Steel



Sustainability of reinforced soil structures

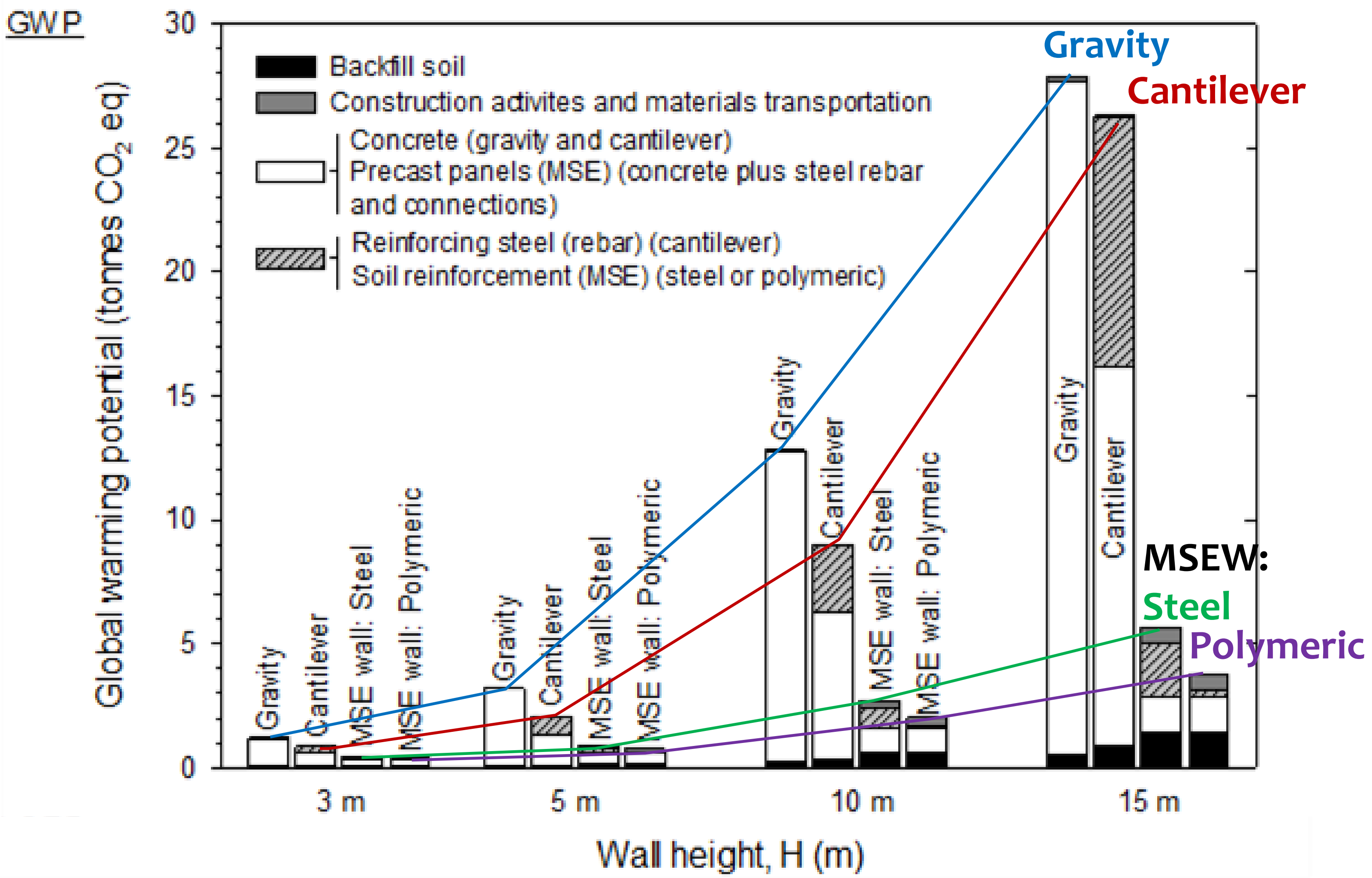
Construction material required for each wall option (for unit length of the wall)

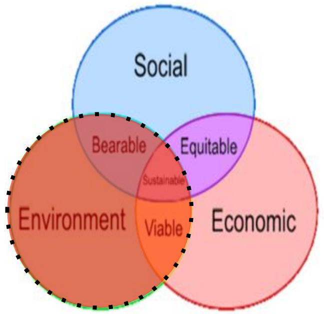
Backfill



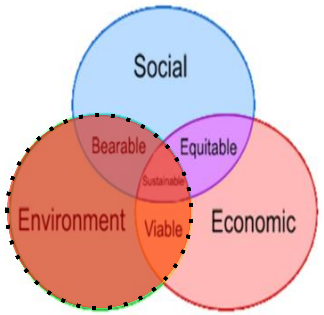
Sustainability of reinforced soil structures

Global warming potential (CO_2 equivalent), for unit length of the wall:

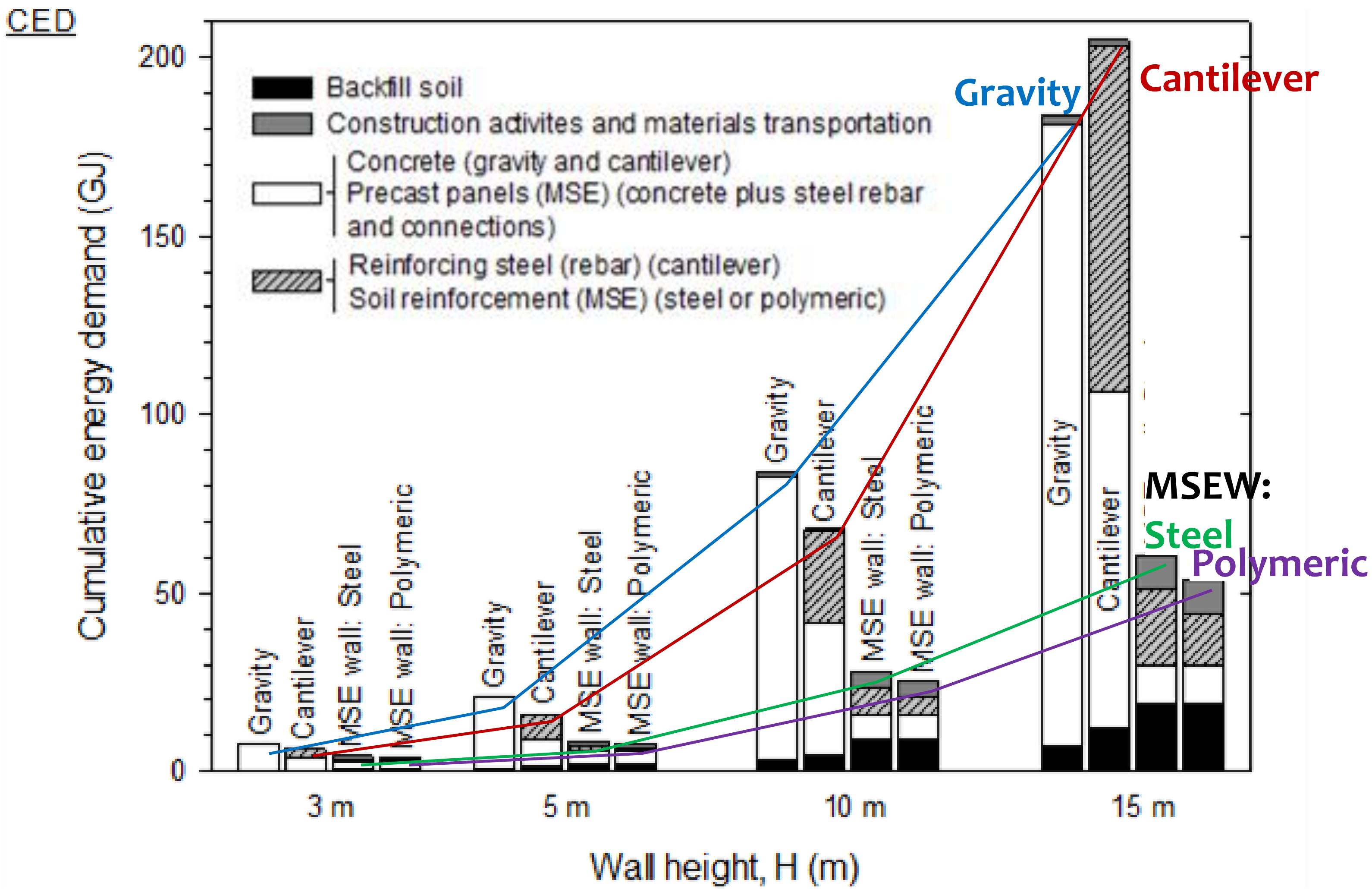




Sustainability of reinforced soil structures

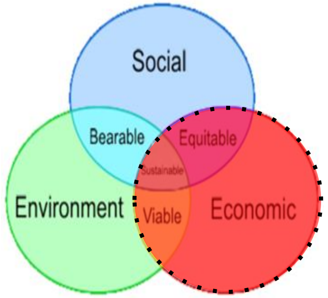


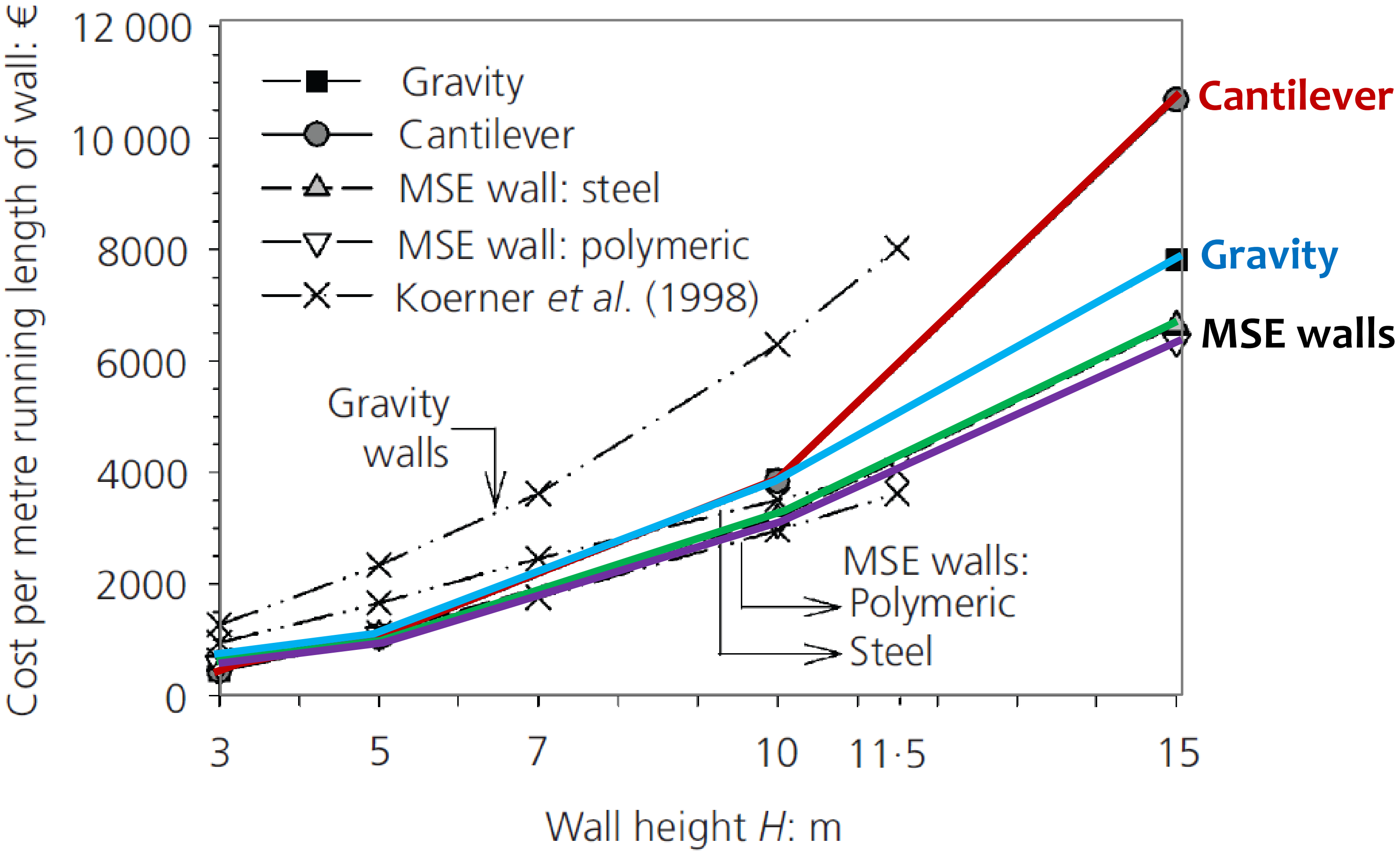
Cumulative energy demand (G Joules), for unit length of the wall:



Sustainability of reinforced soil structures

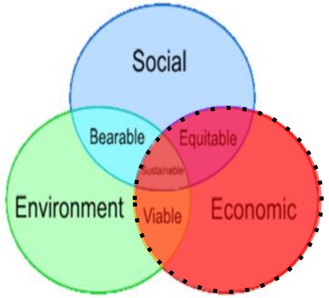
Total cost of each wall option:

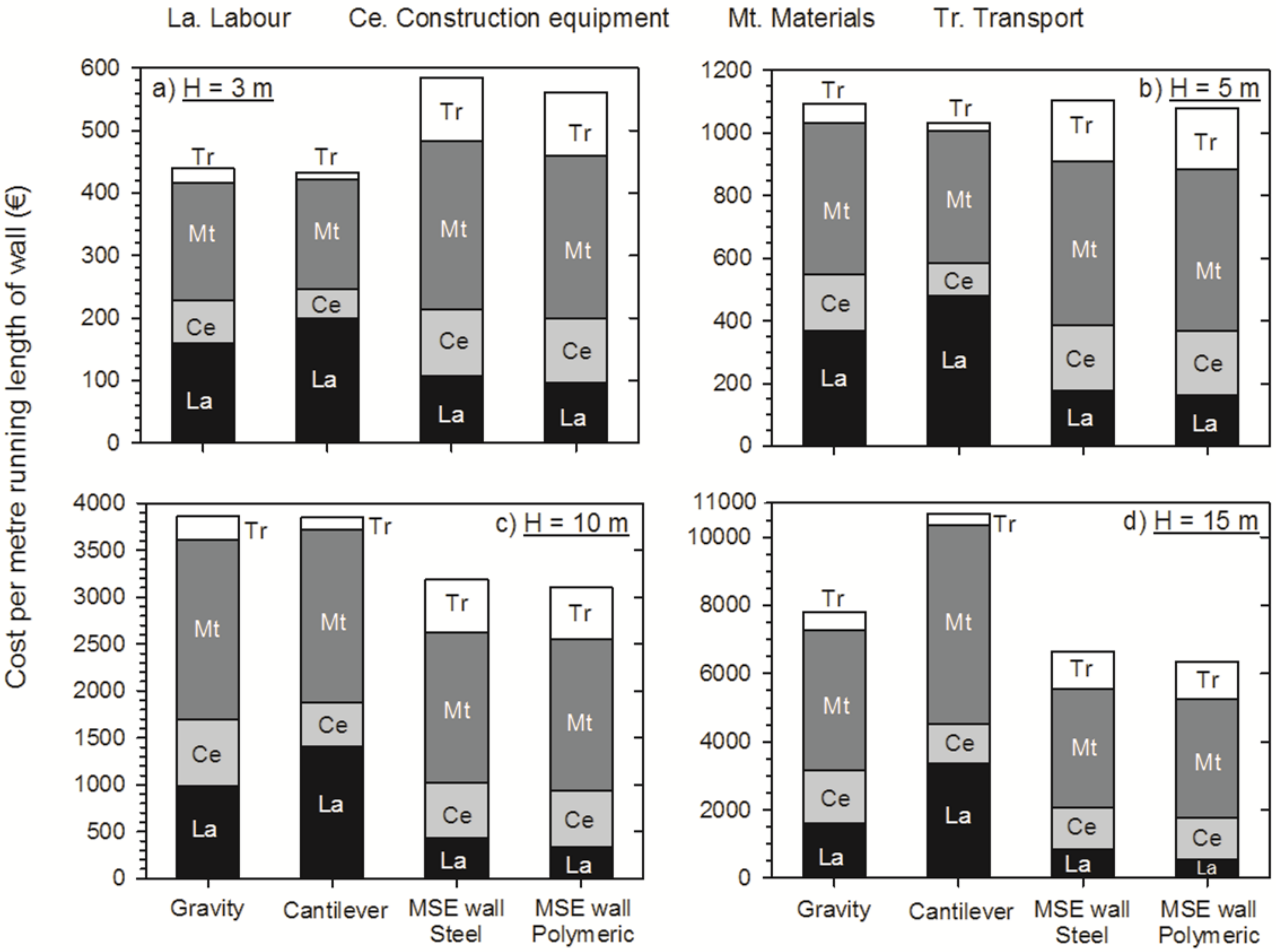




Sustainability of reinforced soil structures

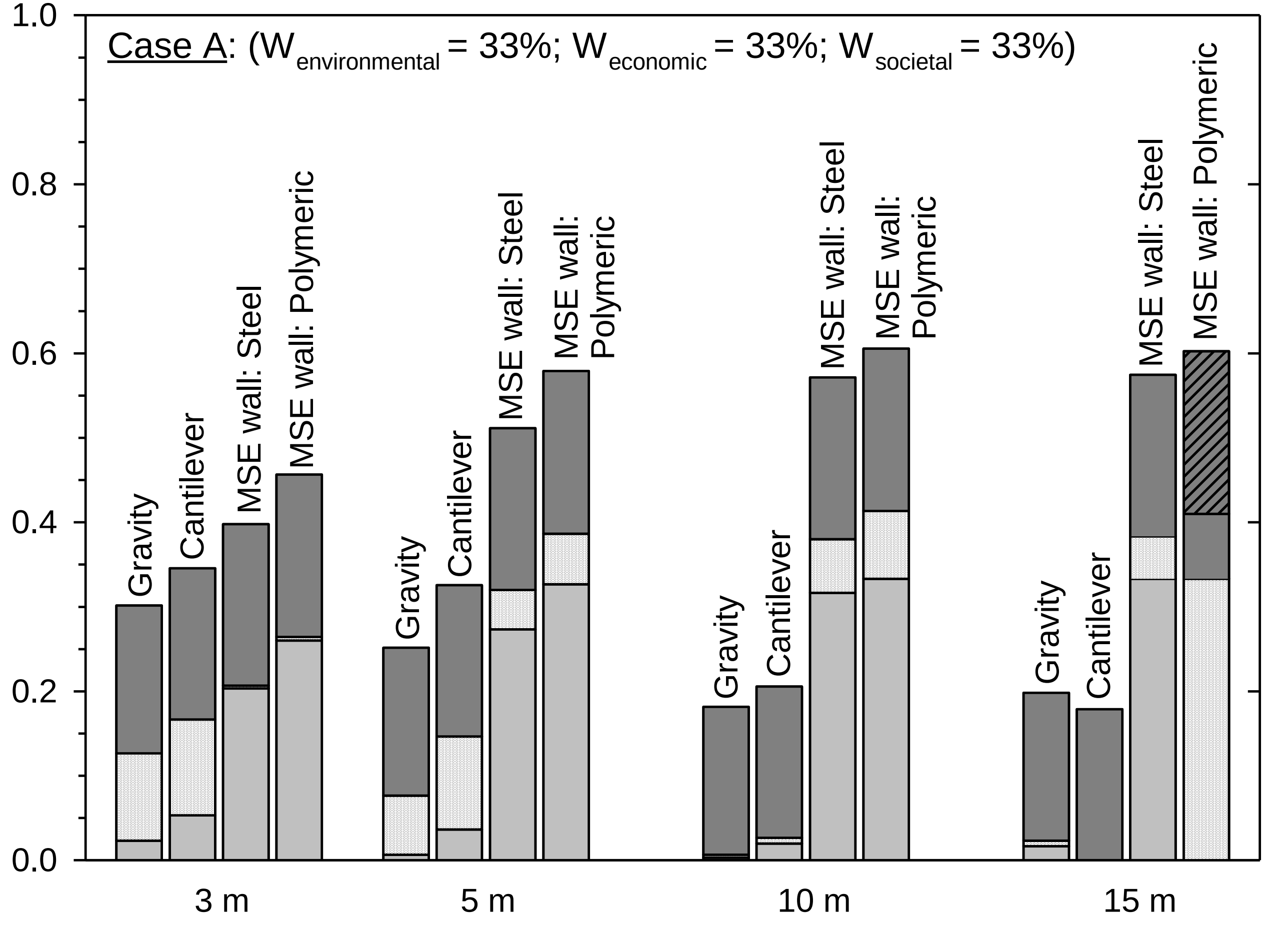
Economic inventory of materials and construction/fabrication processes

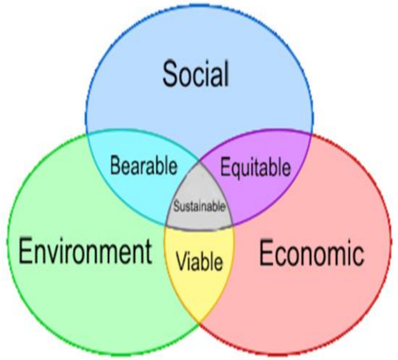




Sustainability of reinforced soil structures

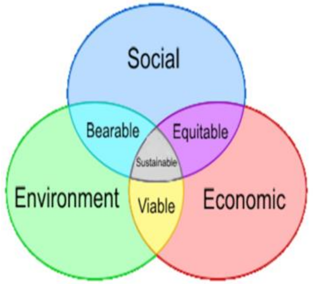
SUSTAINABILITY ASSESSMENT RESULTS:

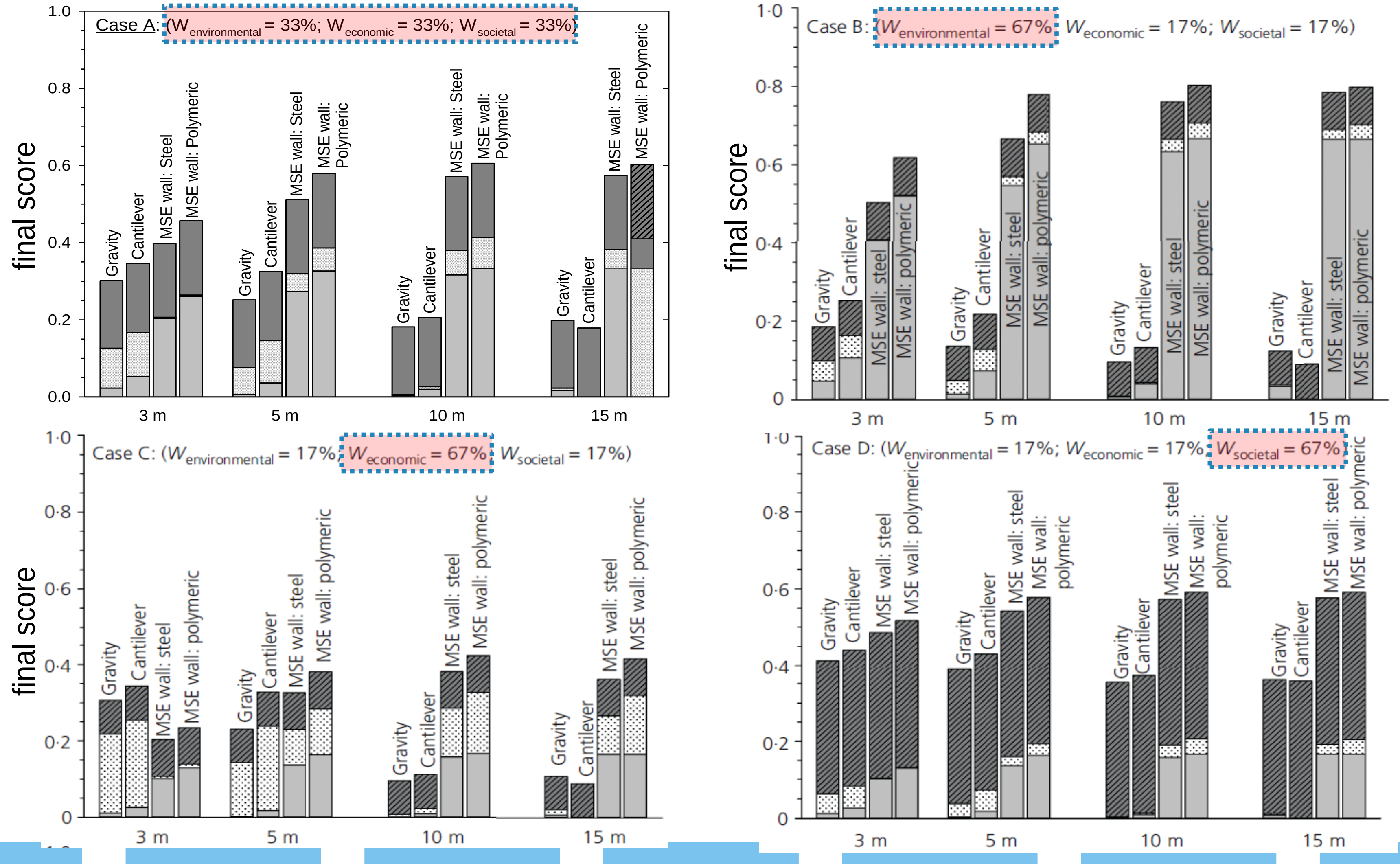




Sustainability of reinforced soil structures

SUSTAINABILITY
ASSESSMENT RESULTS:





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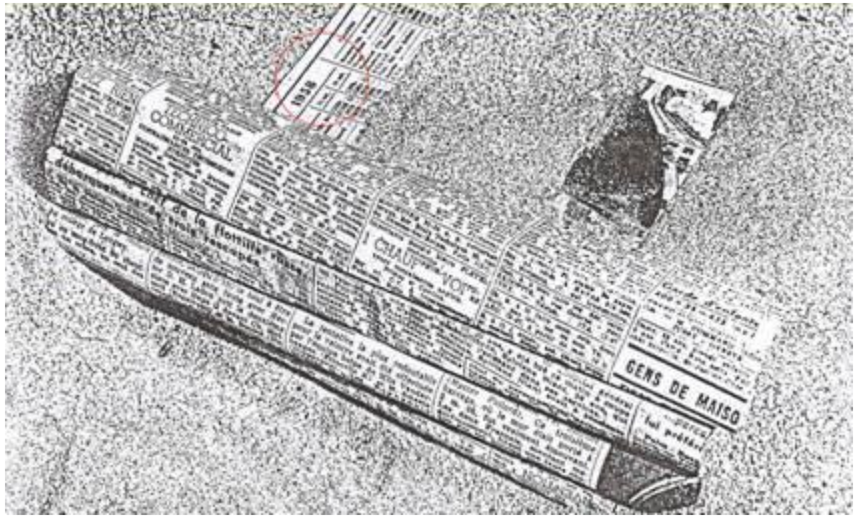
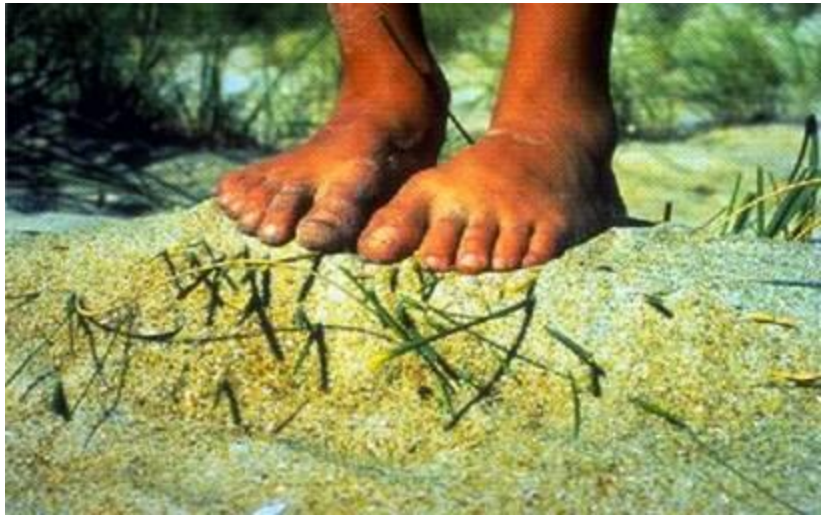
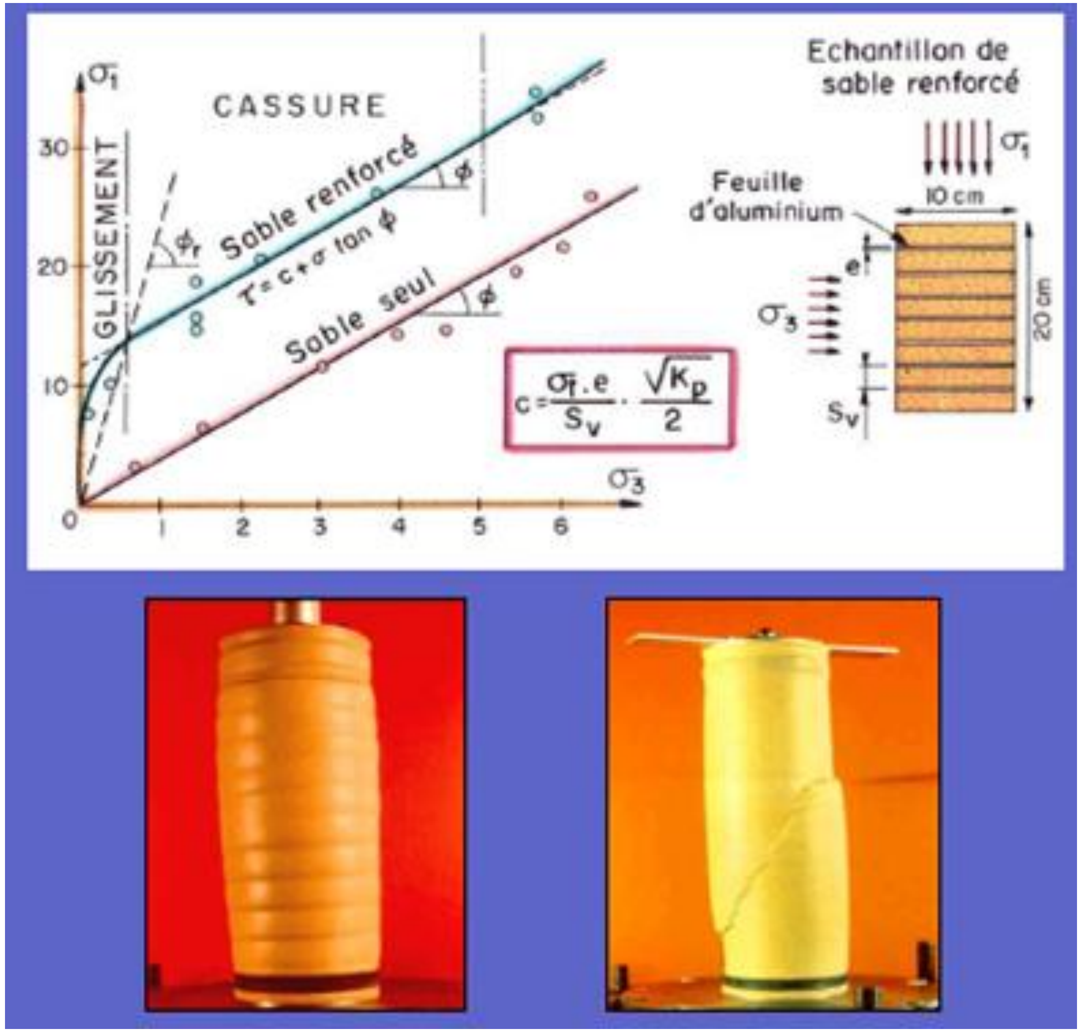
Soil reinforcement conceptual mechanism

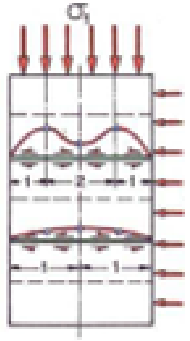




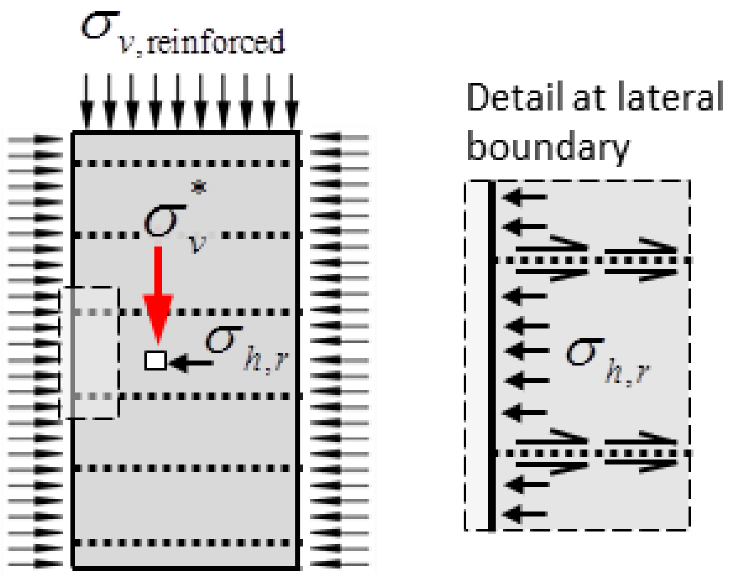
Soil reinforcement conceptual mechanism

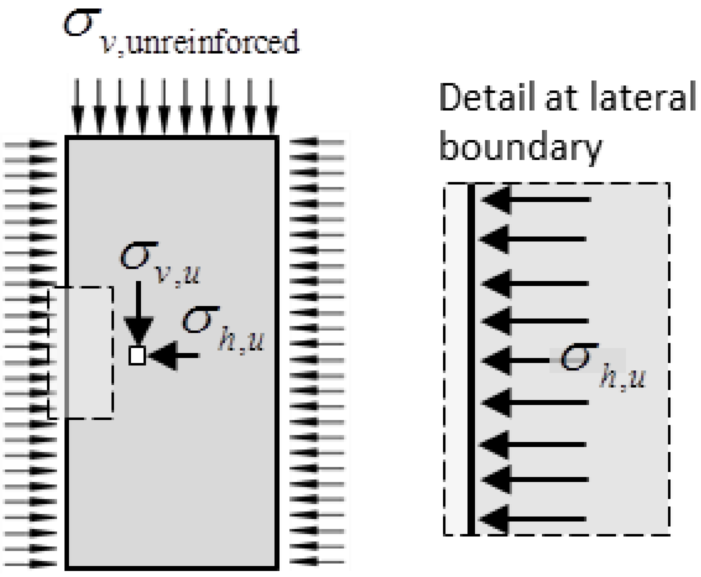
Vidal (1963)



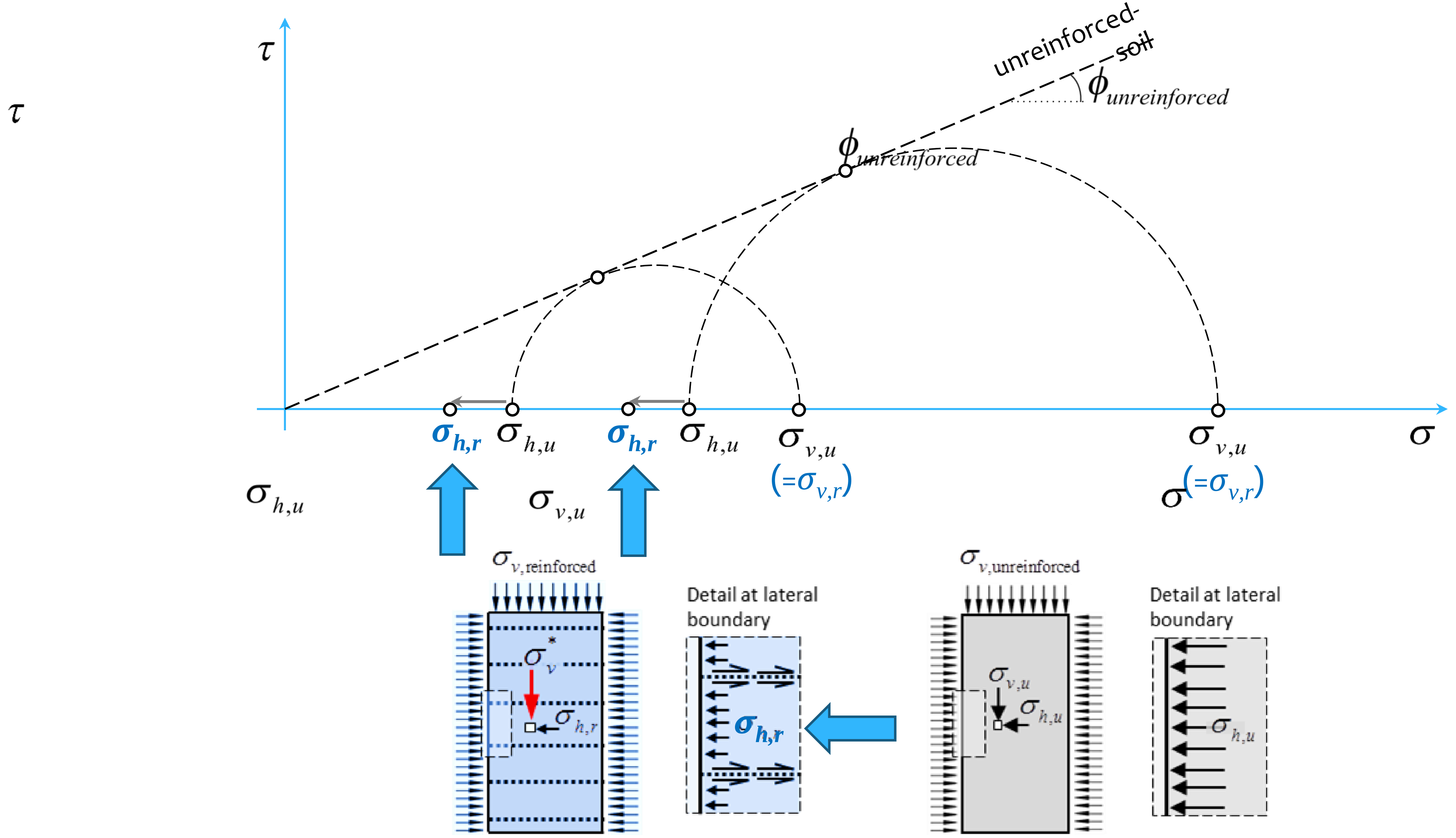


Soil reinforcement conceptual mechanism





Soil reinforcement conceptual mechanism



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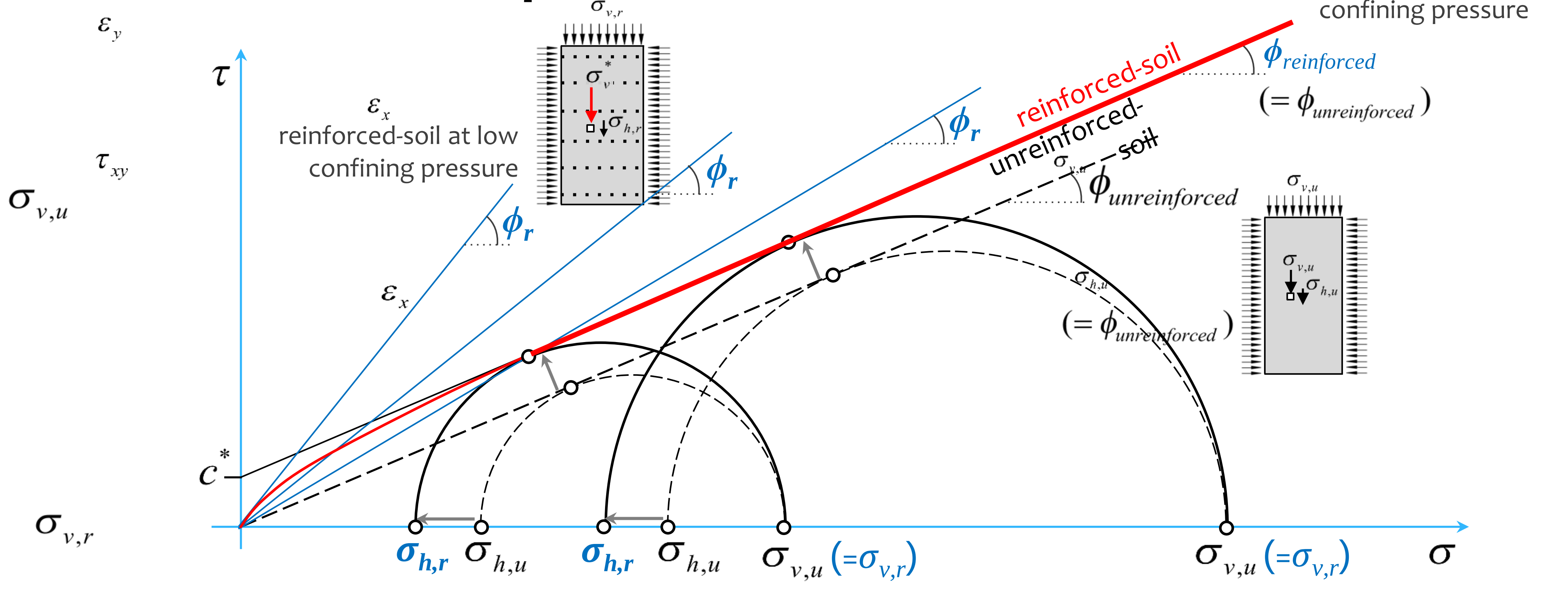
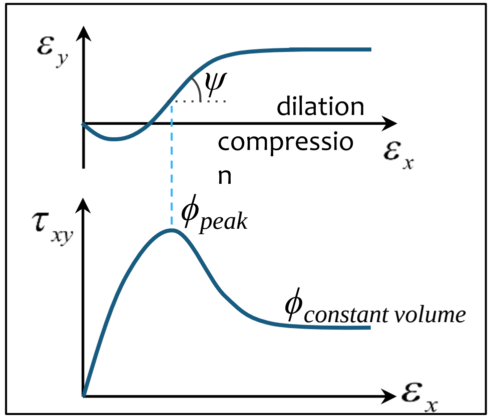
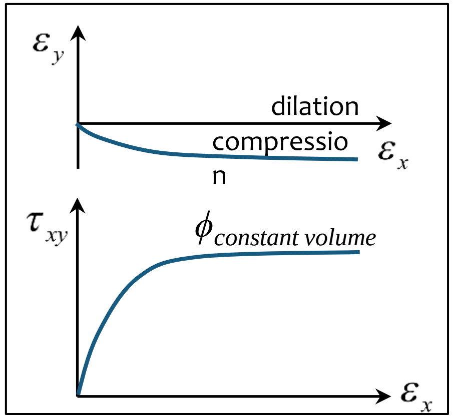


Dense sand at low confining pressure



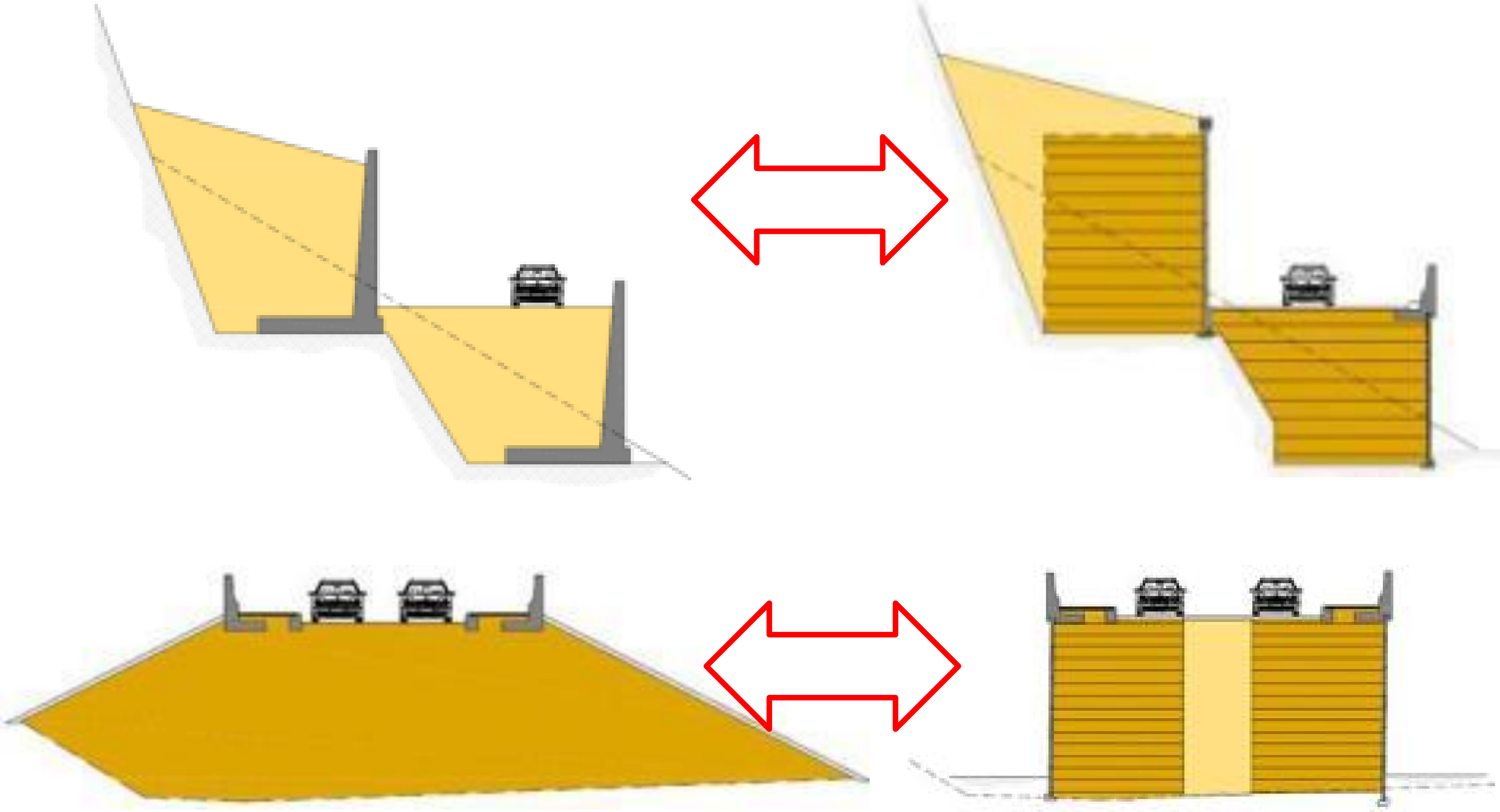


Dense sand at high confining pressure

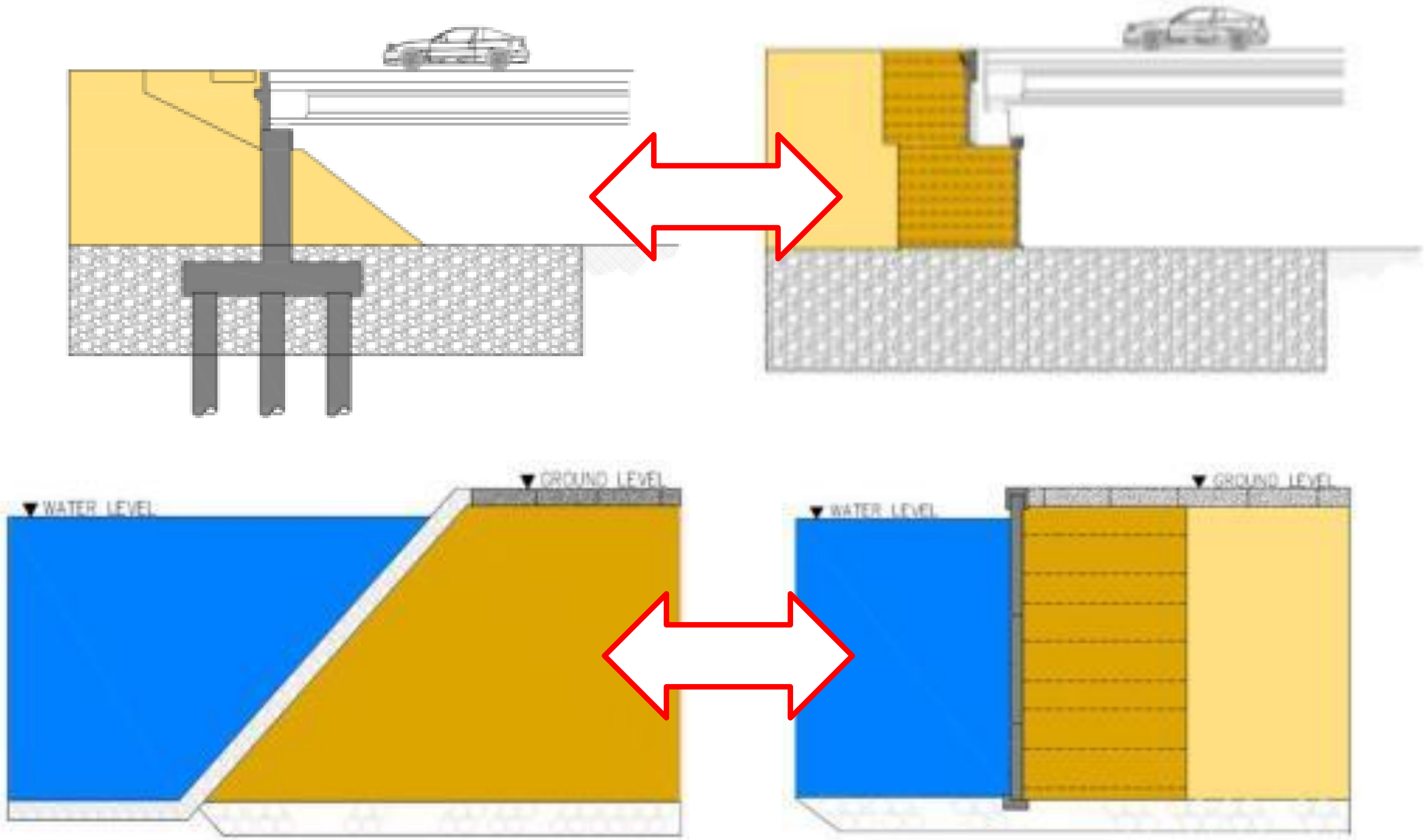
Outline

1. Introduction
2. Sustainability of reinforced soil structures
3. Soil reinforcement conceptual mechanism
4. **Reinforced soil walls and slopes**
5. Veneer reinforcement
6. Basal reinforcement
7. Seismic resistance of reinforced soil structures
8. Summary

Reinforced soil walls



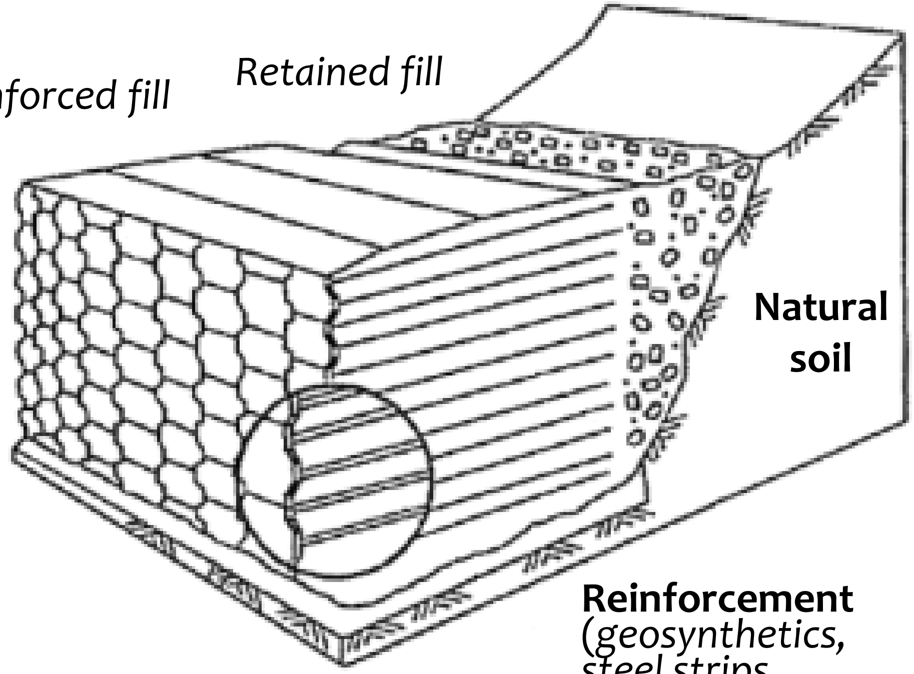
Reinforced soil walls



Reinforced soil walls

Generalities of the Reinforced soil walls

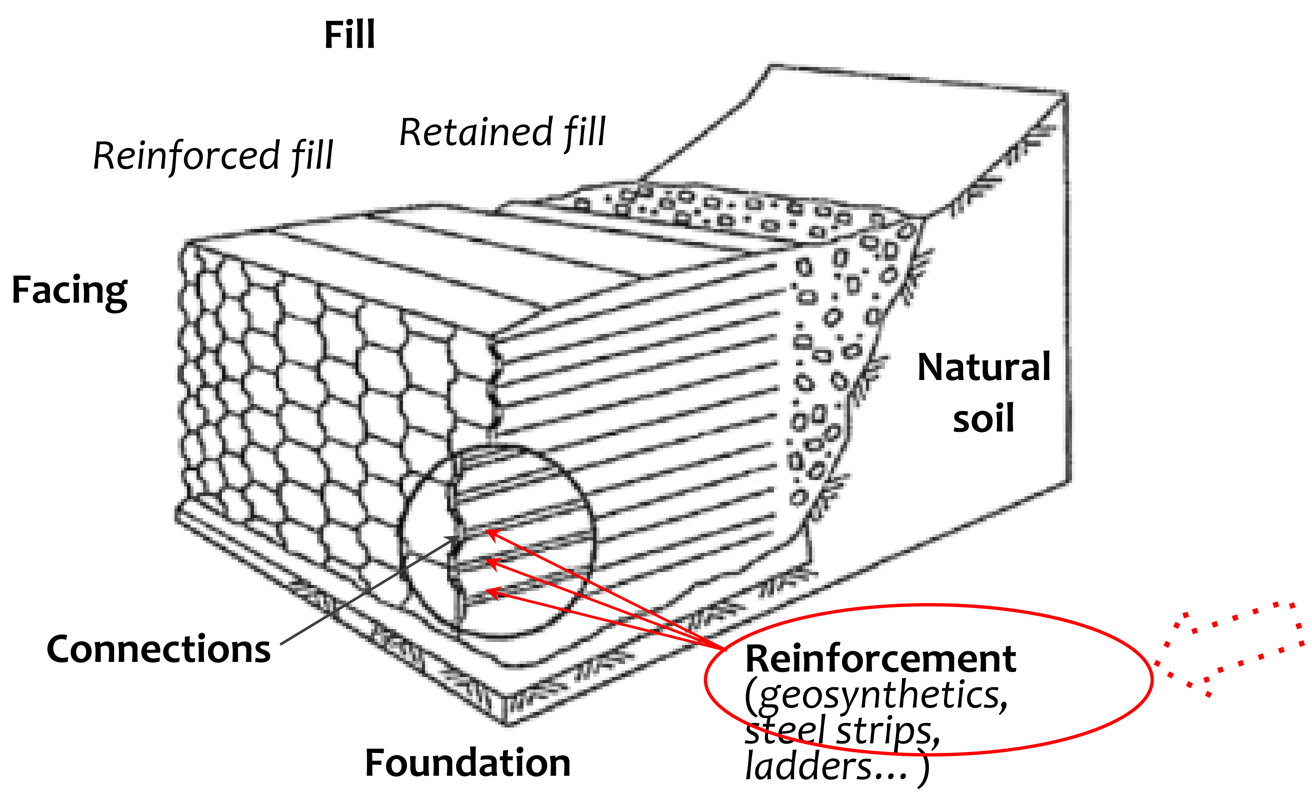
Main components



Reinforced soil walls

Generalities of the Reinforced soil walls

Main components

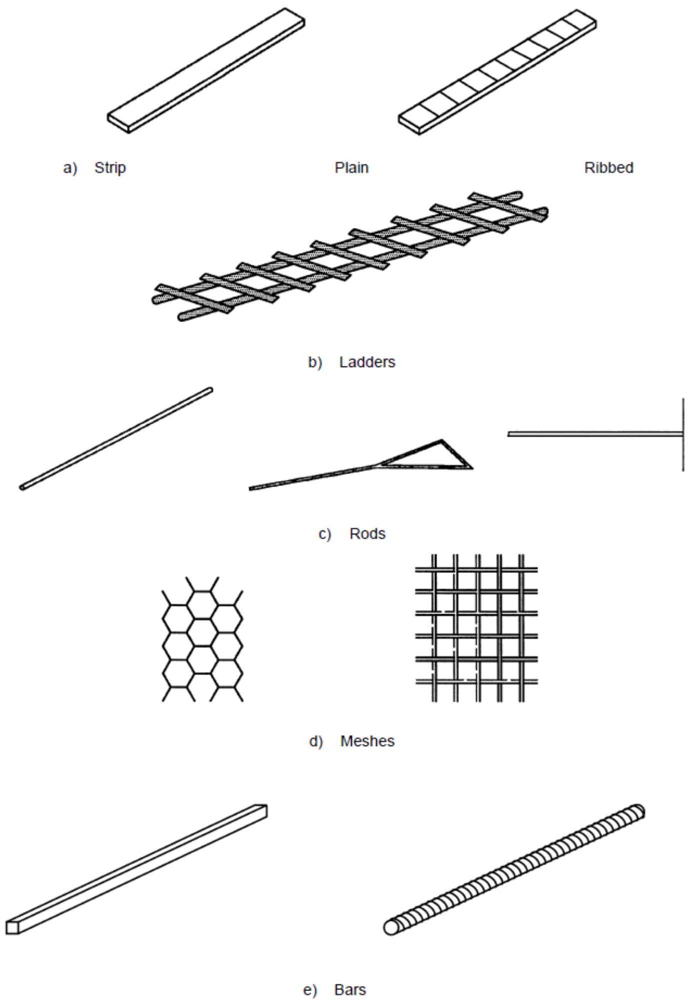


Reinforced soil walls: types of reinforcement

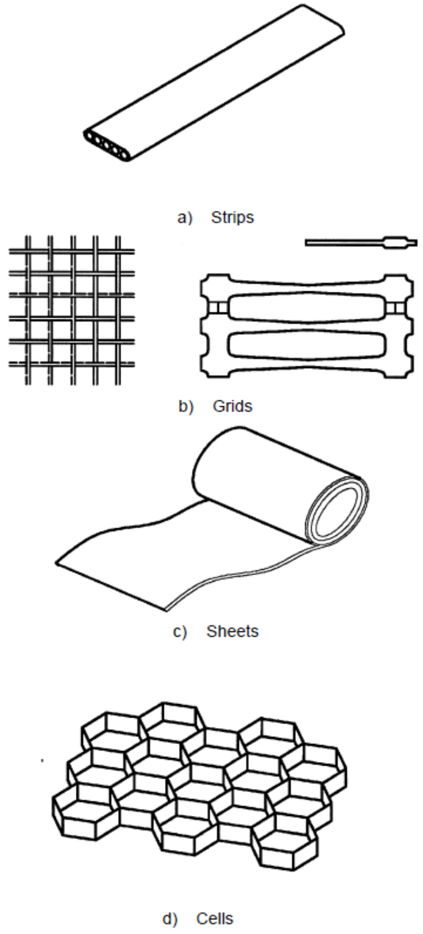
EN 14475:2006
Execution of special geotechnical works - Reinforced fill

EN 14475:2006

Steel reinforcements



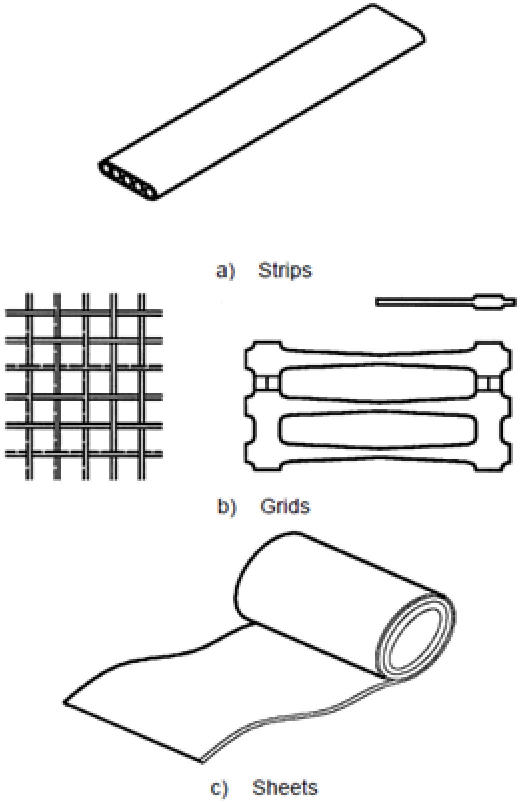
Polymeric reinforcements



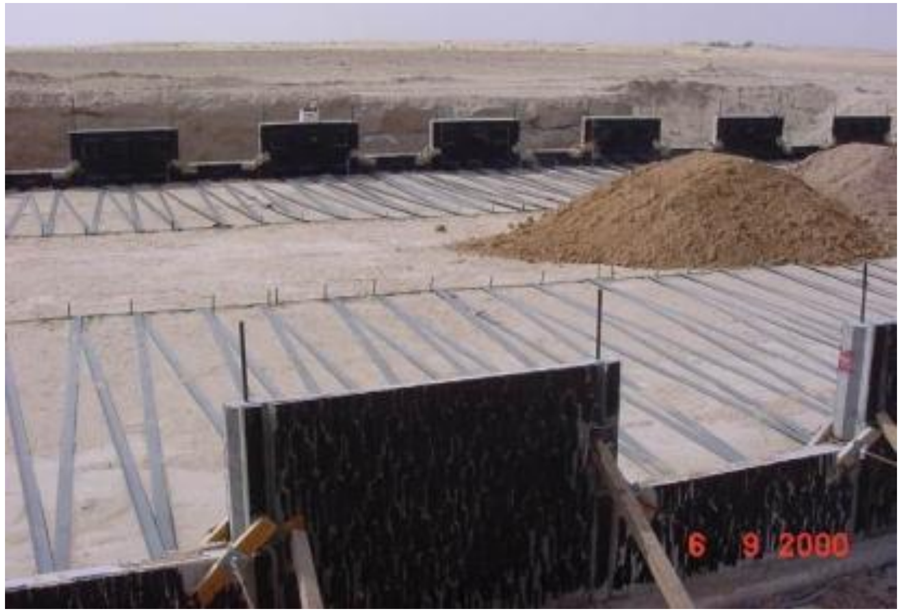
Reinforced soil walls

EN 14475:2006

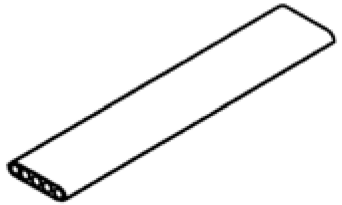
Polymeric reinforcements

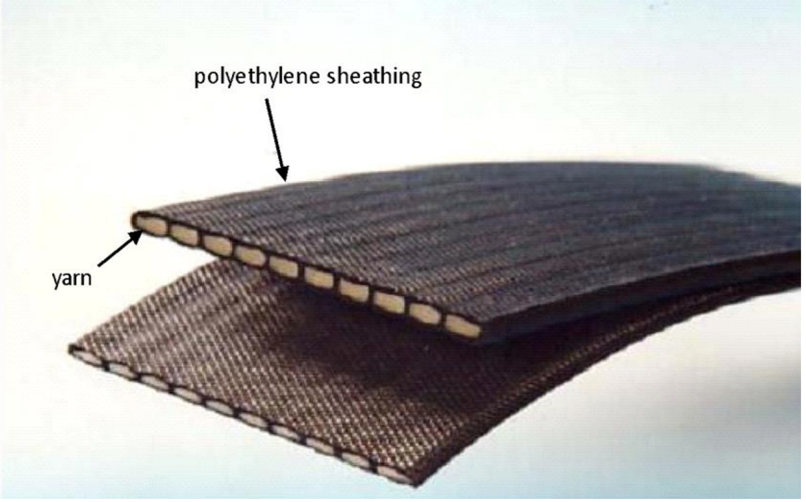


Reinforced soil walls



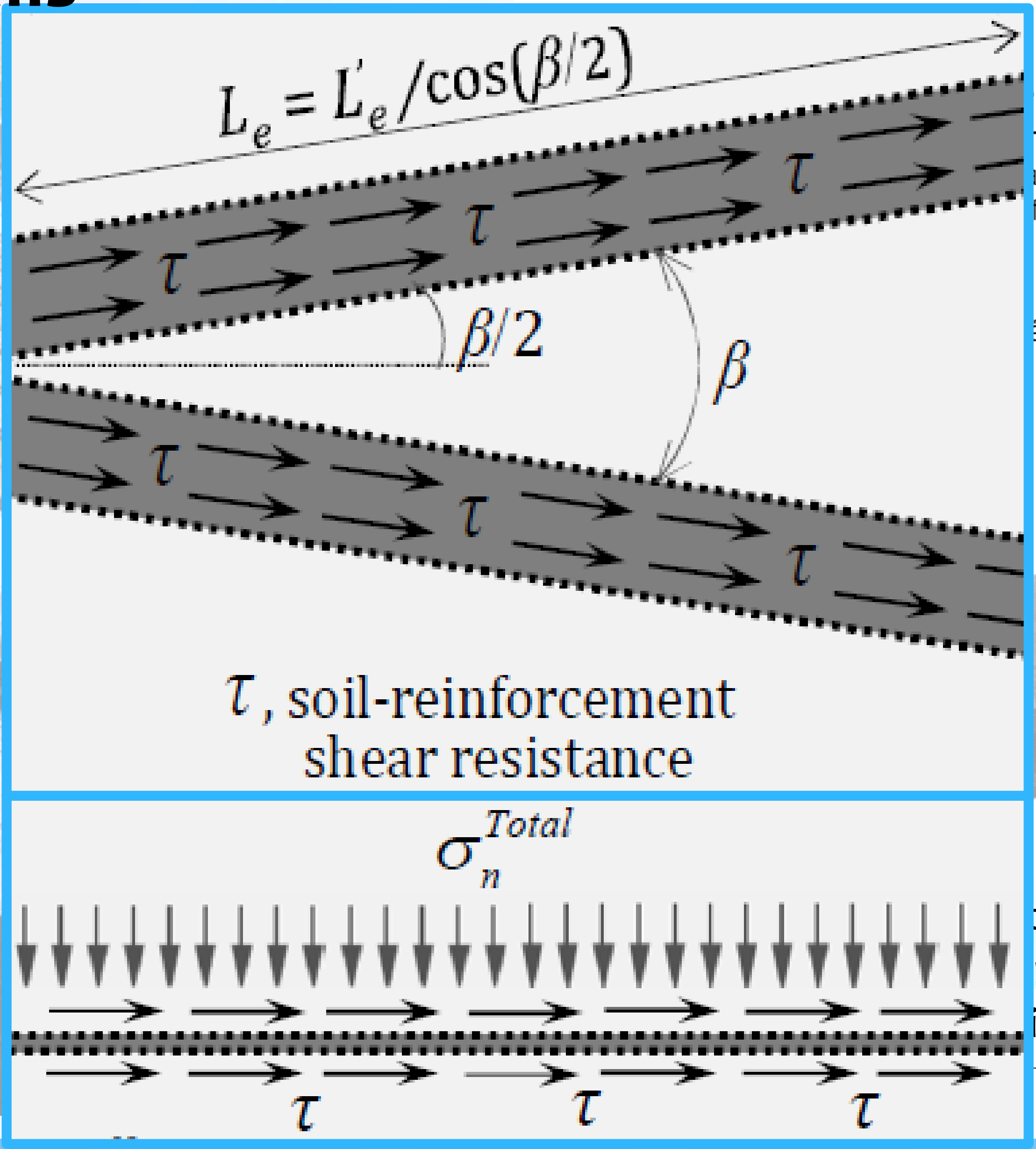
Polymeric reinforcements
Geostrips





Example: Polyester yarns core, encased in polyethylene sheating

Reinforced soil walls



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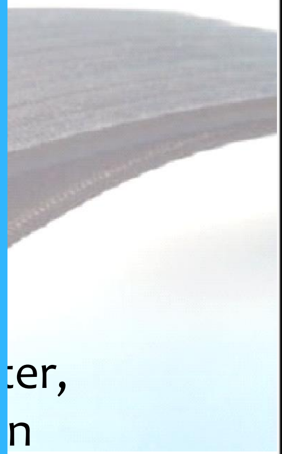

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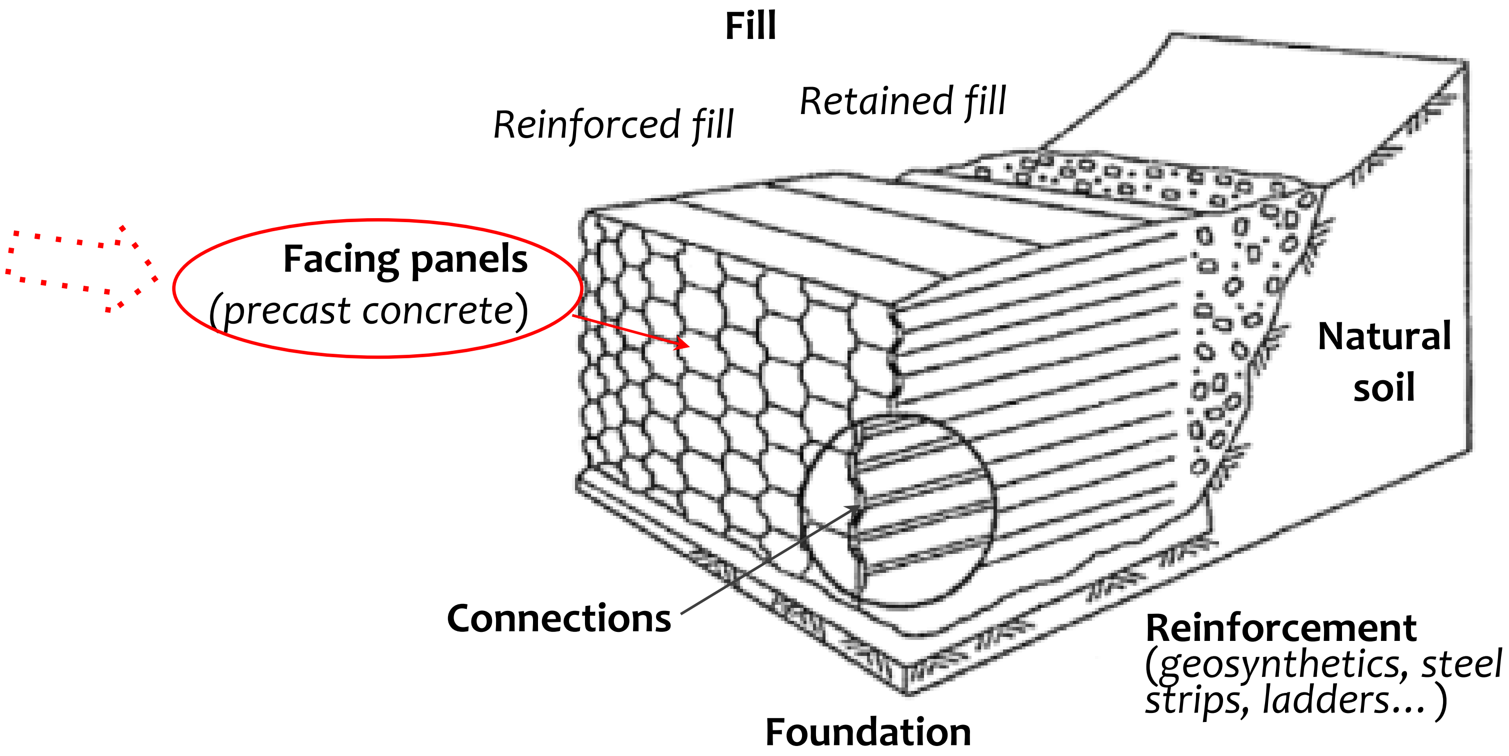
Reinforced soil walls

Generalities of the Reinforced soil walls

Main components

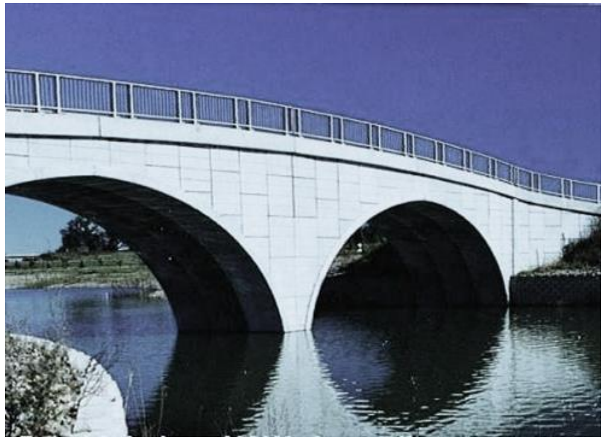


Reinforced soil walls

Precast concrete panels (partial or full-height panels)

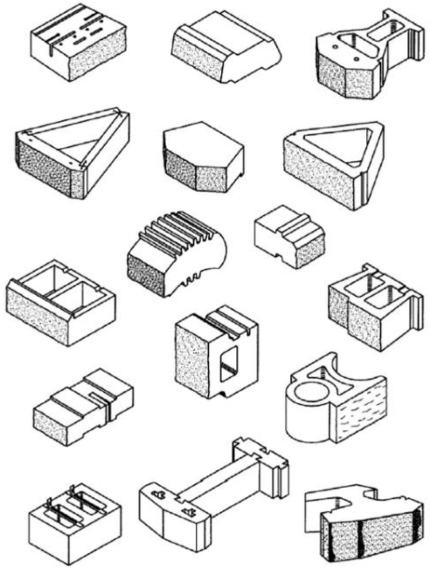
Reinforced soil walls

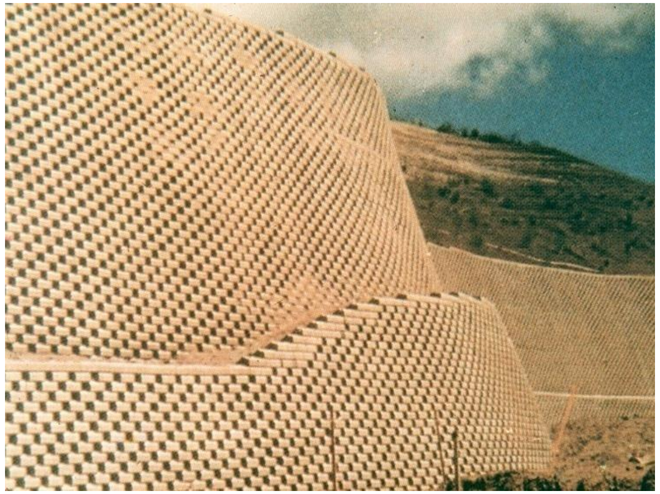
Precast concrete panels (partial or full-height panels)



Reinforced soil walls

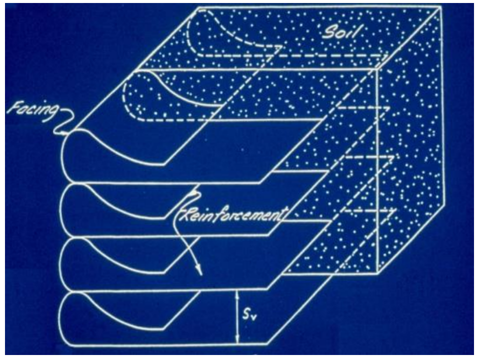
Segmental masonry blocks facing

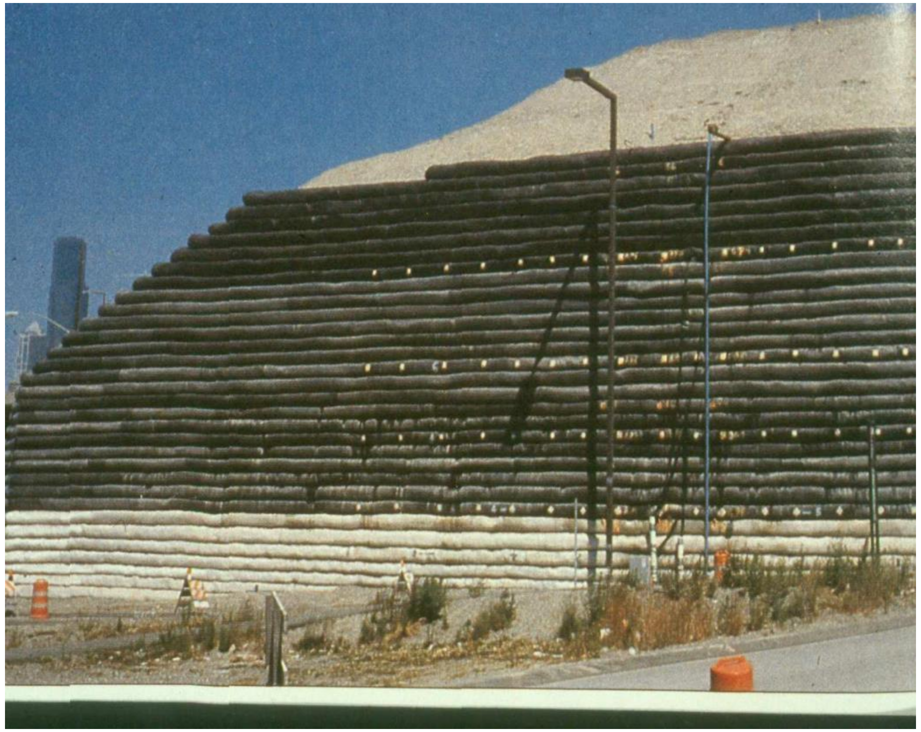




Reinforced soil walls

Wrapped facing (geotextile sheets)





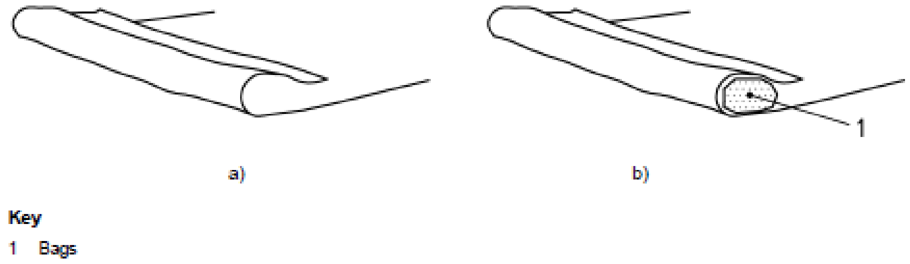
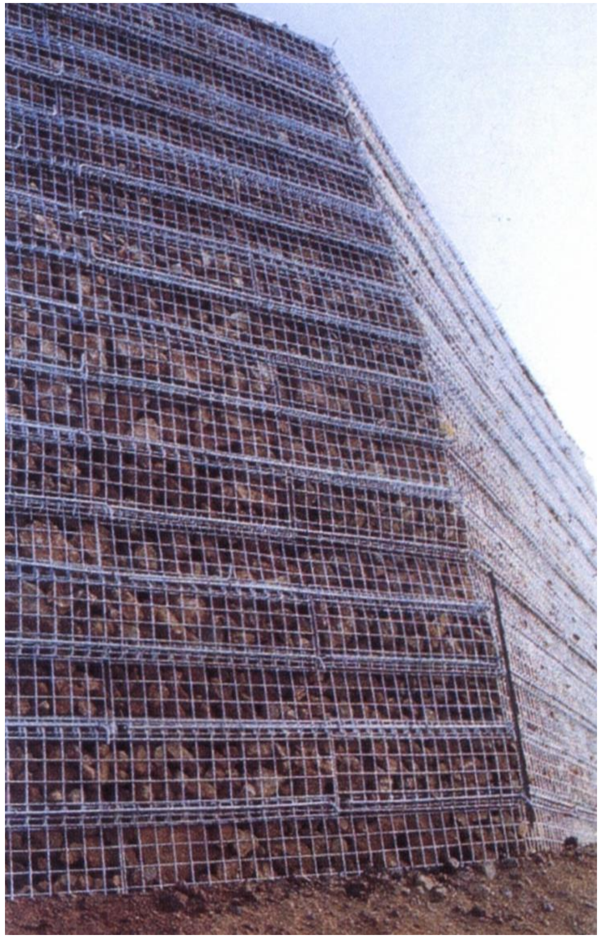


Figure C.12 - Soft facing units

Reinforced soil walls

Woven and Welded
wire mesh (WWM)
facing



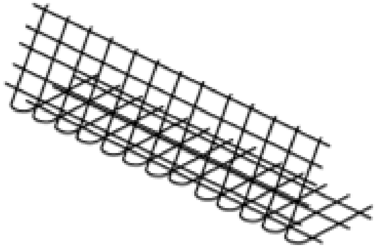


Figure C.10 - Steel welded wire mesh

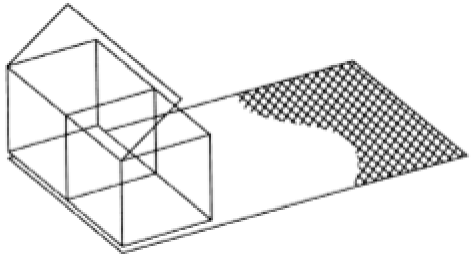
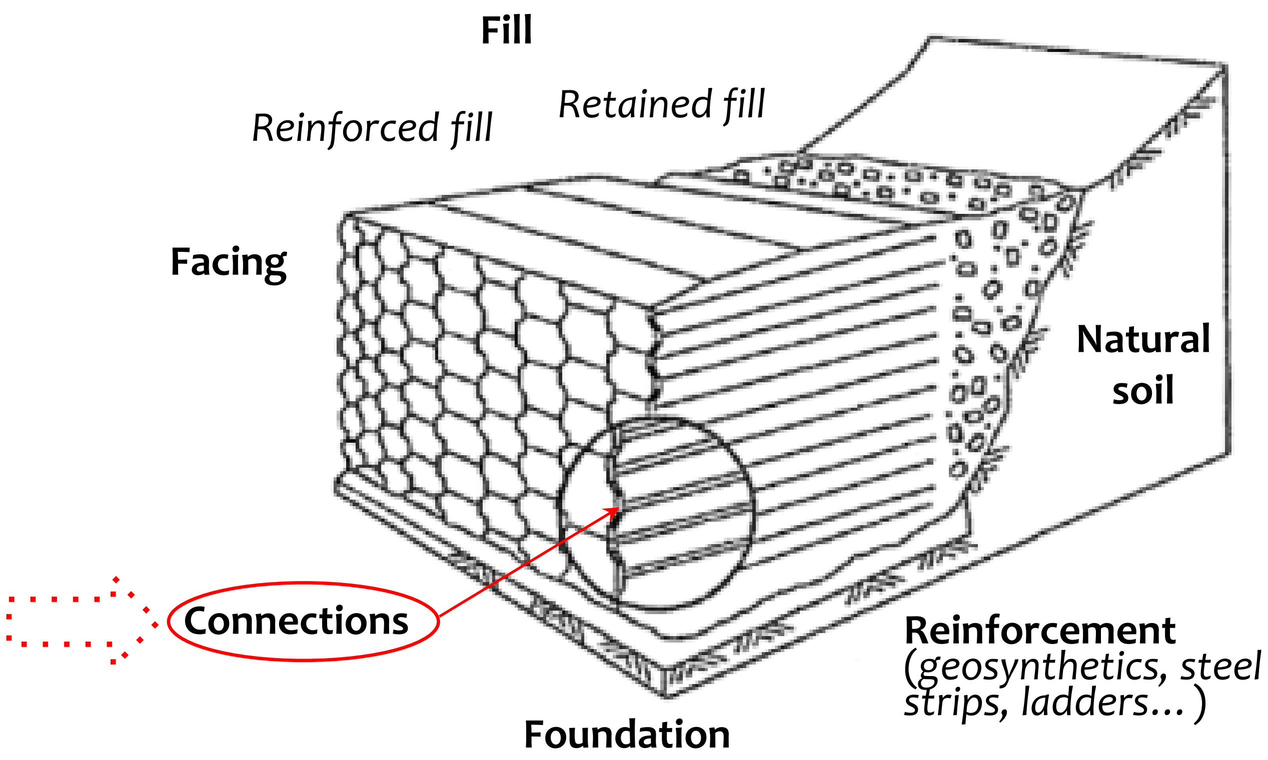


Figure C.11 - Gabion baskets

Reinforced soil walls

Generalities of the Reinforced soil walls

Main components



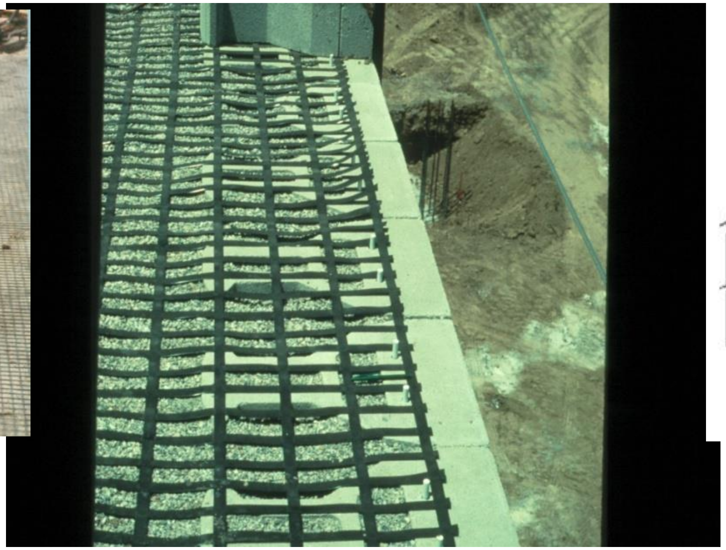
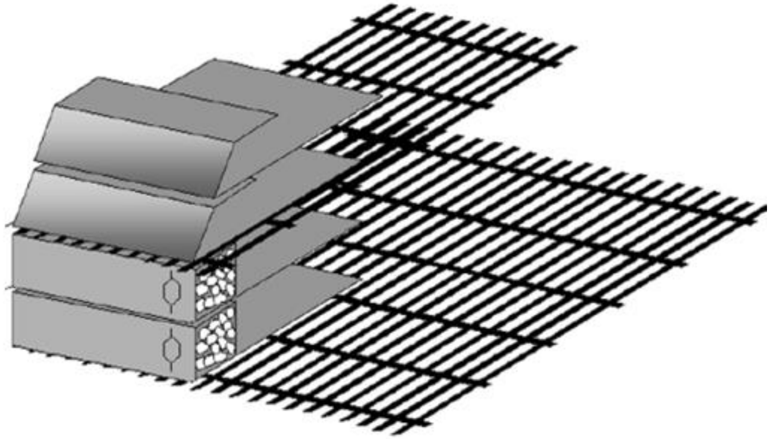
Reinforced soil walls

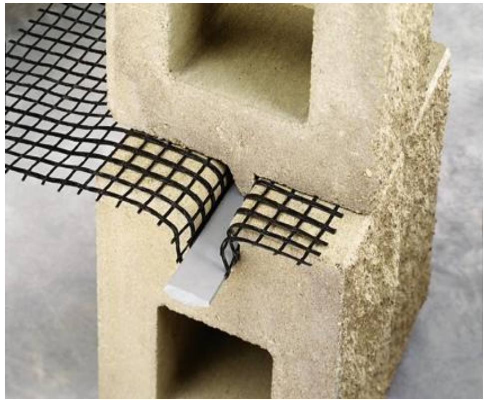
Connection types depend on facing and reinforcement system




Reinforced soil walls

Connection types depend on facing and reinforcement system



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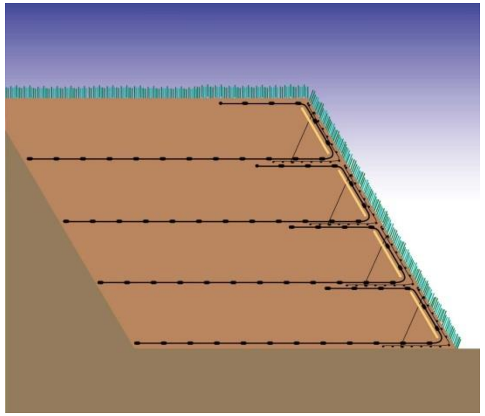
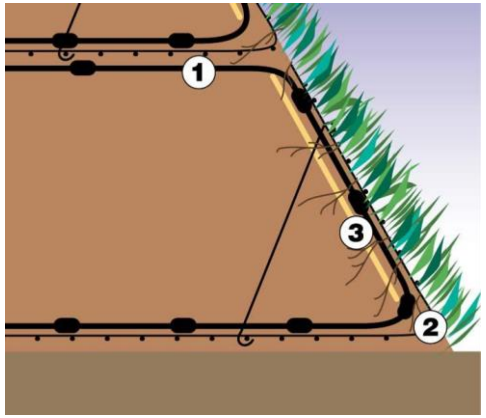
Reinforced soil slopes - Applications

Reinforced soil slopes are retaining structures with non-vertical facing.

Advantages of reinforced soil slopes:

- Superior stability compared to unreinforced slopes
- Easy and fast construction
- Machinery works inside the footprint of the structure
- the locally available / marginal soil can be used, with important environmental benefits
- Facing can be easily vegetated for good aesthetics with low environmental and visual impact

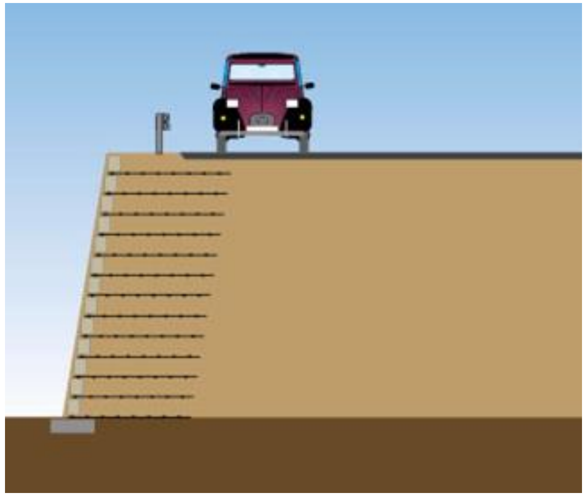


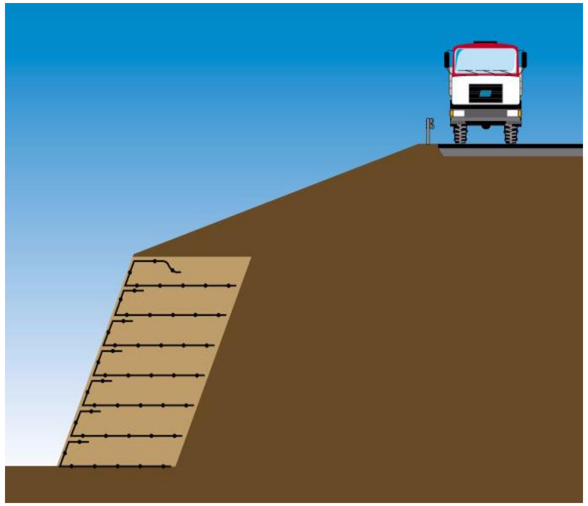


1. Geogrid
2. Geomat/Geoblanket
3. Steel mesh formwork

Reinforced soil slopes - Applications

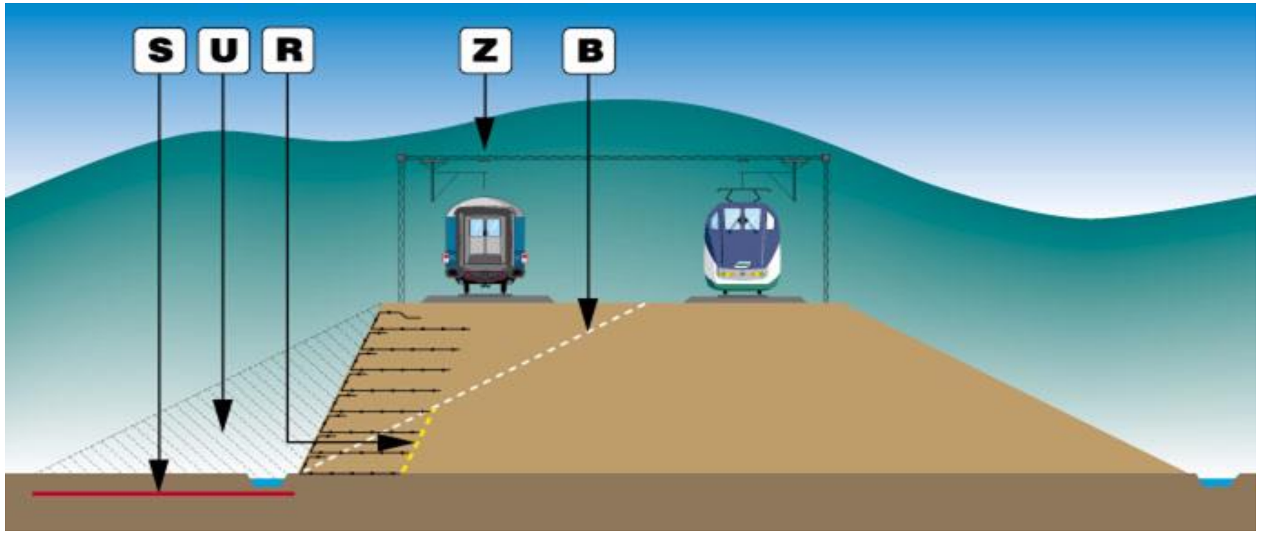
- Road support





Reinforced soil slopes - Applications

- Railway embankments

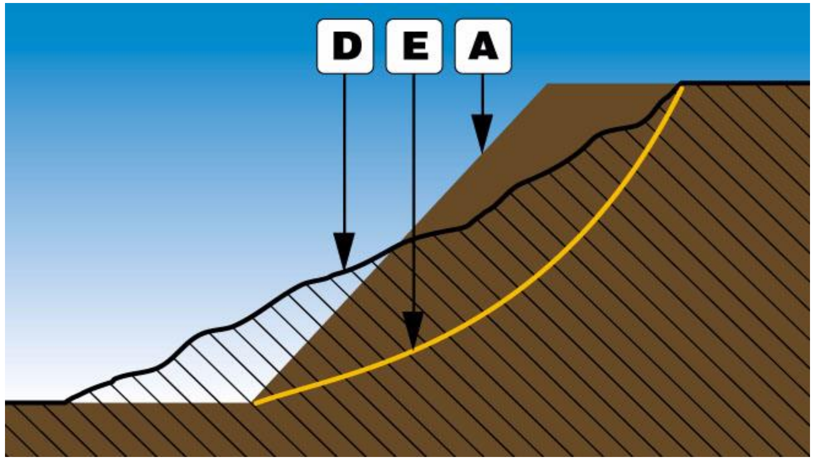


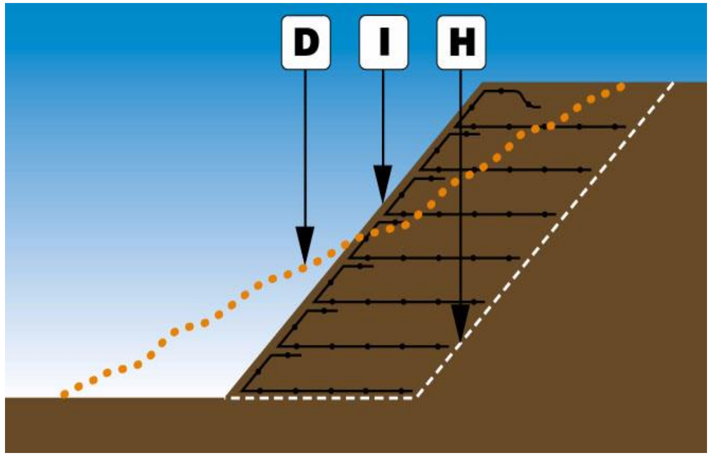
Reinforced soil slopes - Applications

- Embankments dikes

Reinforced soil slopes - Applications

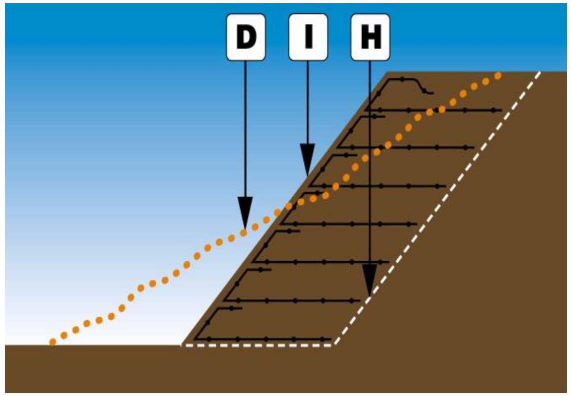
- Repair of failed slopes





Reinforced soil slopes - Applications

- Repair of failed slopes

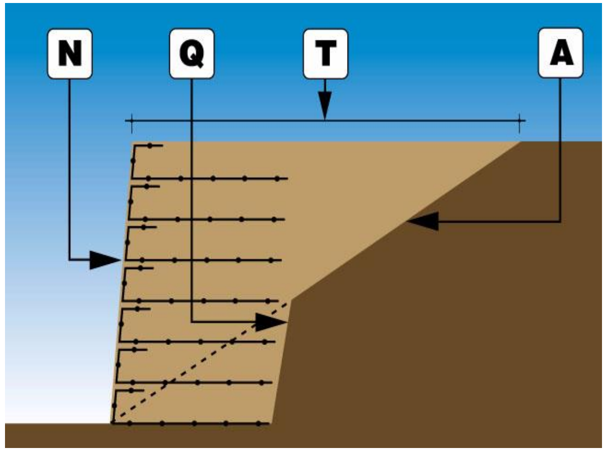


Reinforced soil slopes - Applications

- Repair of failed slopes

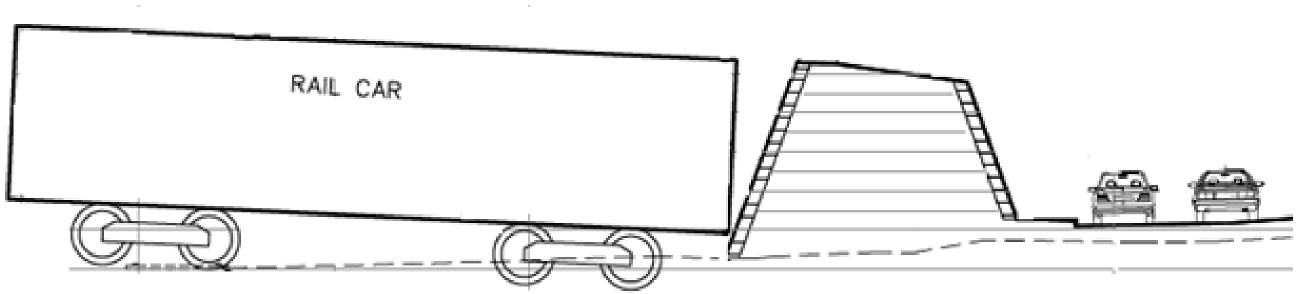
Reinforced soil slopes - Applications

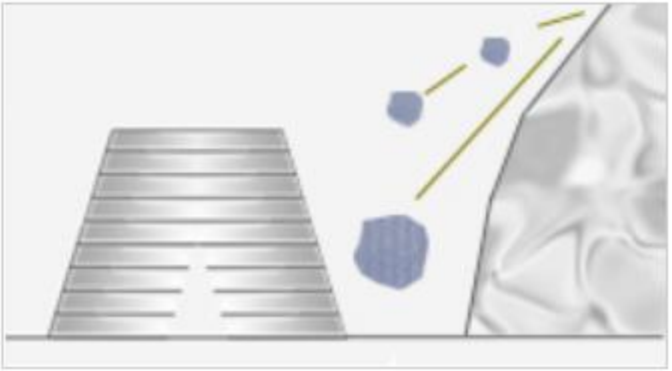
- Steepening of shallow slopes



Reinforced soil slopes - Applications

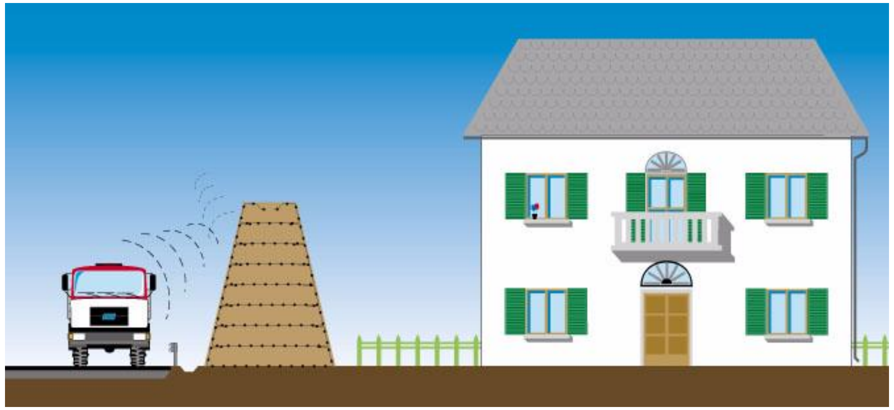
- Impact barriers





Reinforced soil slopes - Applications

- Sound barriers



Outline

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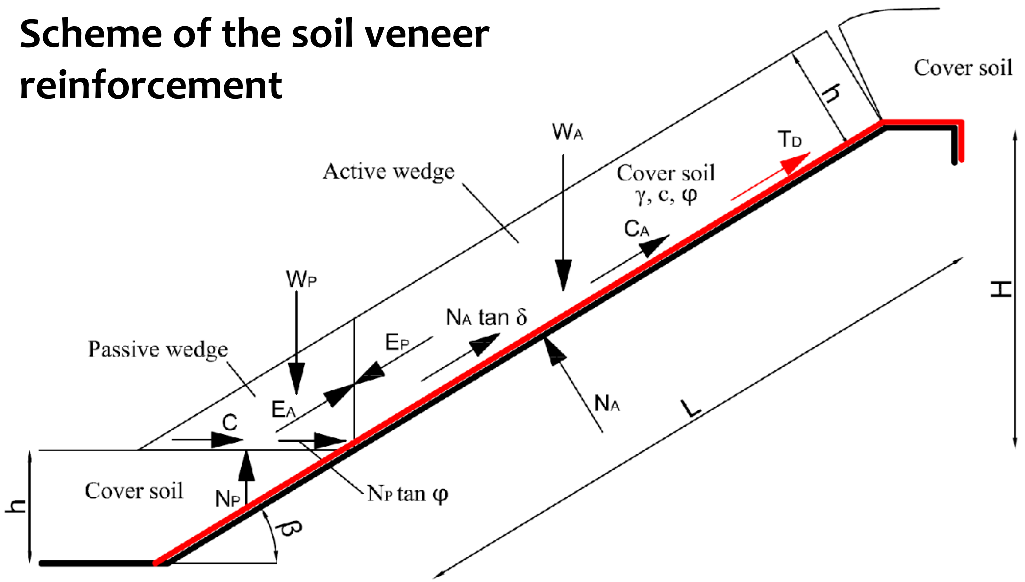
Veneer reinforcement

Veneer is intended as a relatively thin cover soil layer placed on a slope.

Soil veneer reinforcement is the only reinforcement application where reinforcement is not placed horizontally but sloping.

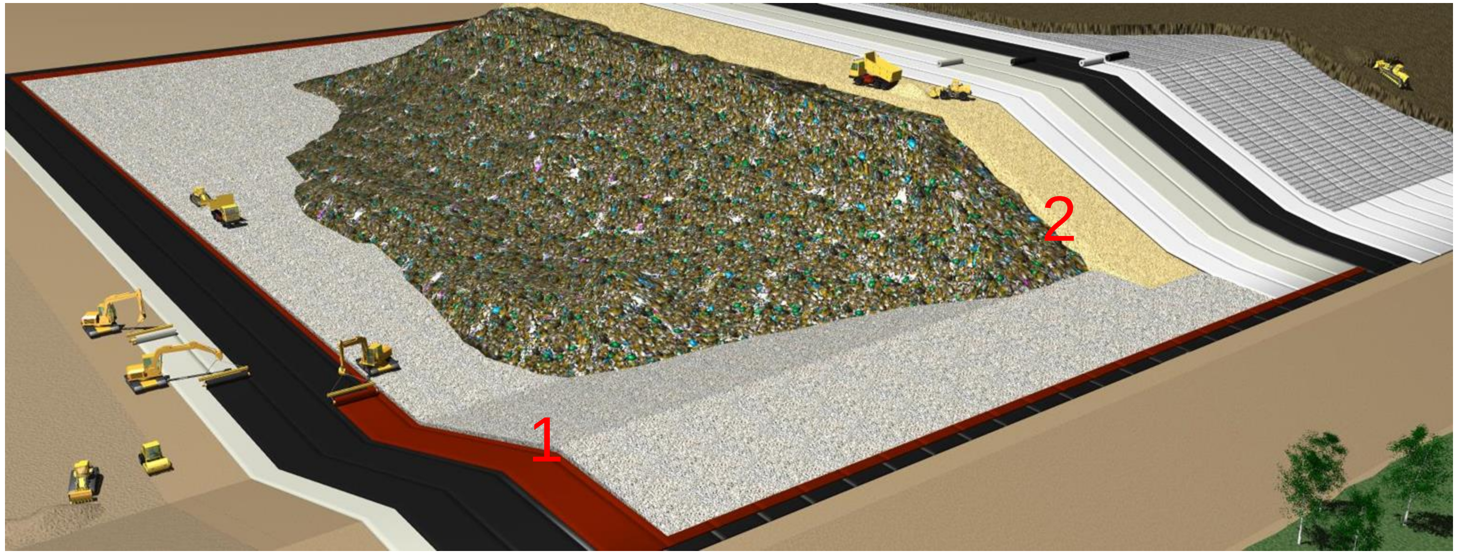
Scheme of the soil veneer reinforcement



Veneer reinforcement

There are two main applications in which cover soil stability needs to be checked:

1. Leachate collection soil placed above a Geomembrane (GBR), Geosynthetic Clay Liner (GCL) and/or Compacted Clay Liner (CCL) along the sides of a landfill or a heap leach pad before waste or ore is placed and stability achieved accordingly.
2. Final cover soil placed above a GBR, GCL and/or CCL in the cap or closure of a landfill or a heap leach pad.



Veneer reinforcement

- As the veneer layer becomes longer and steeper, the tensile strength required for the geosynthetic reinforcement becomes quickly very high, of the order of hundreds kN/m.
- Such high tensile strength have to be transferred to the veneer layer, hence the interface properties soil – geosynthetic are very important.
- Below the reinforcing geosynthetic usually there is the lining system, hence interlocking between soil and geogrid becomes very limited, while the friction angle soil – geotextile may be too small for transferring high tensile forces.
- Hence a reinforced geomat, made up by a tridimensional geomat factory bonded to a high strength geogrid or geotextile, is usually the preferred choice.

Veneer reinforcement

Main advantages of soil veneer reinforcement are:

- Superior stability compared to unreinforced veneers
- Slopes of a landfill or mining tailing capping can be designed at higher inclination, thus affording much more storage volume
- High Factors of Safety can be achieved even in highly seismic areas
- Easy and fast construction

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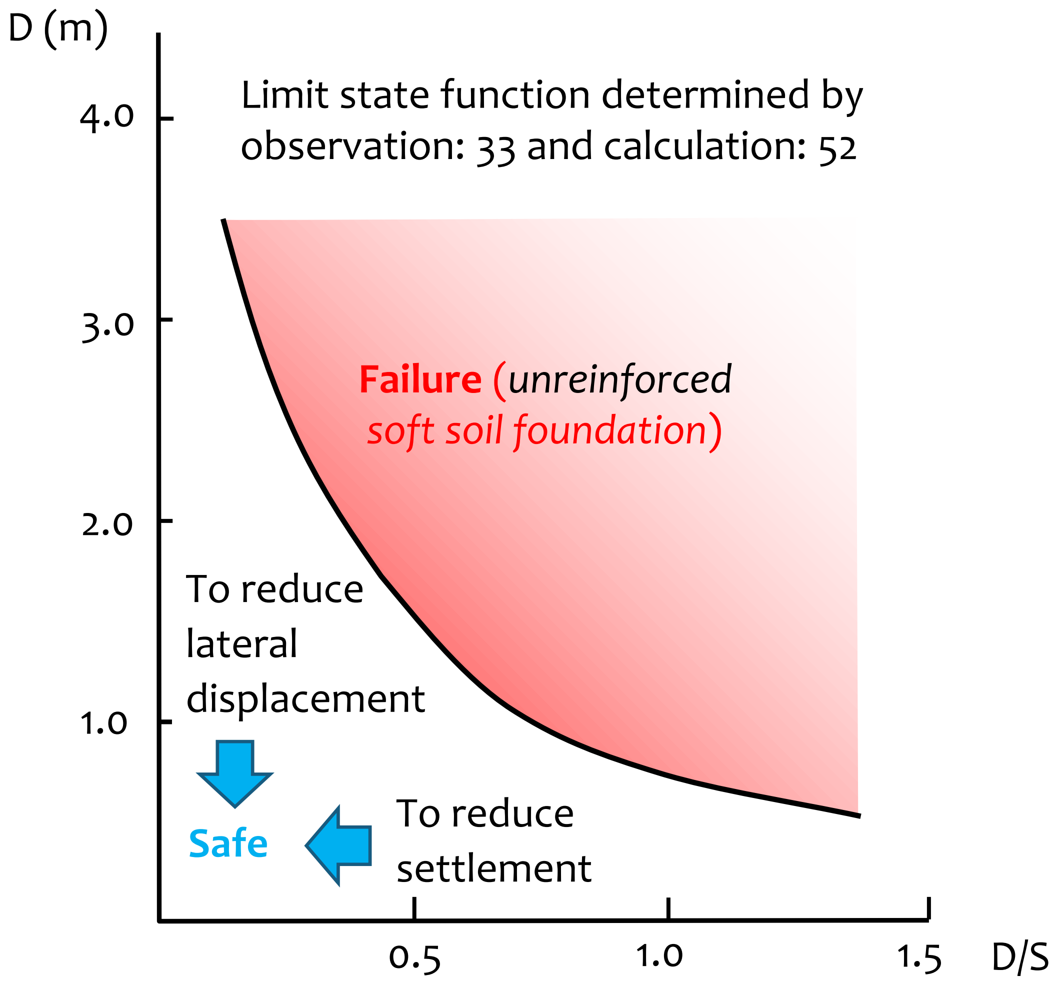
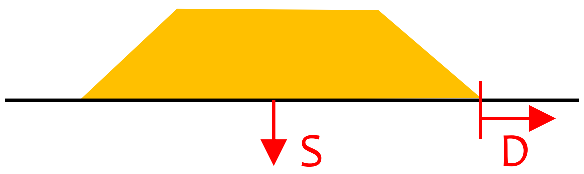
Basal reinforcement

Lessons Learn from Failures of Unreinforced Embankments on Soft Soil Foundation



Matsuo and Kawamura (S&F, 1977)

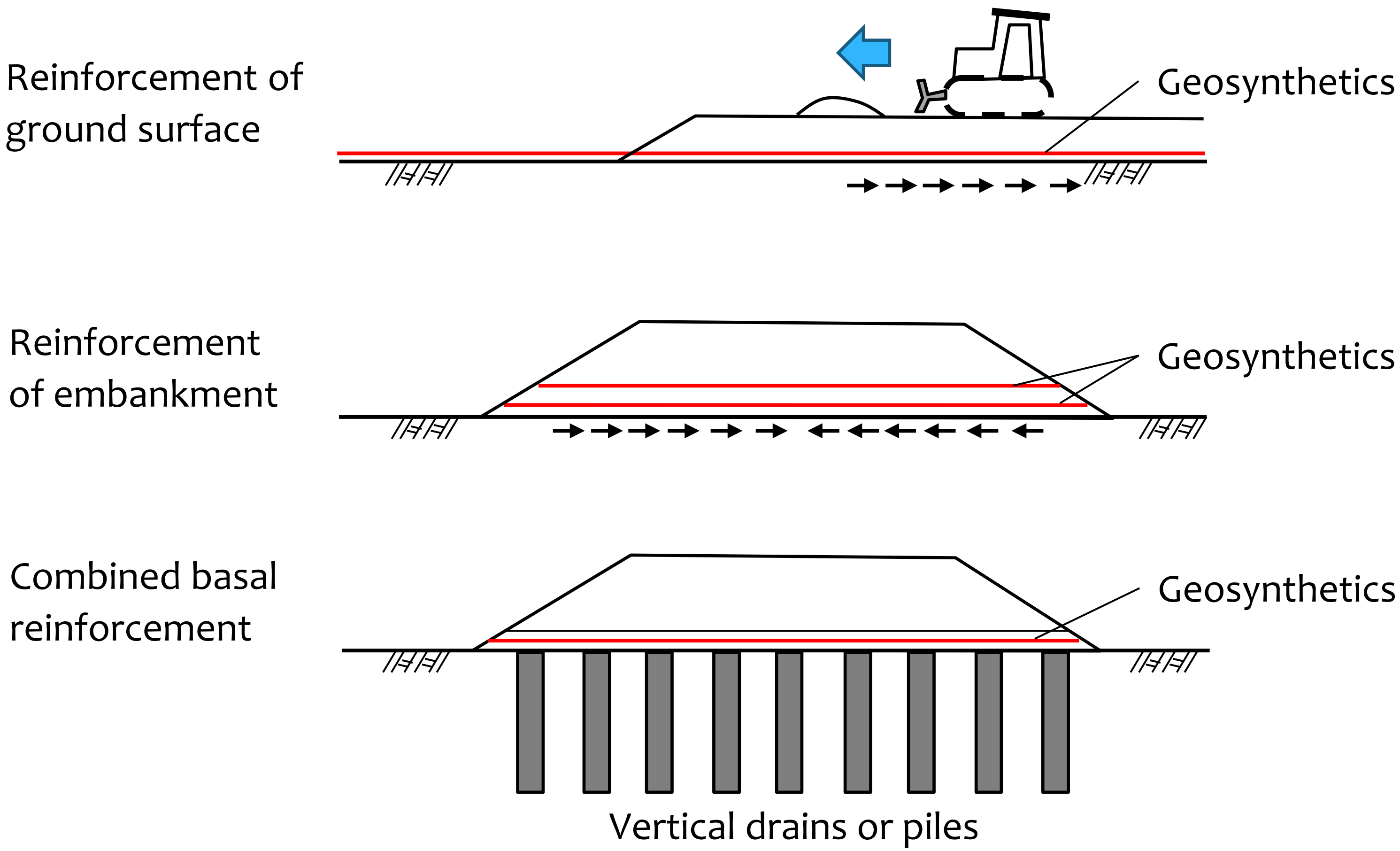


S: Settlement at the center of embankment
D: Lateral deformation of the toe

In the case of unreinforced embankment, the limit state can be shown by single function. This means that the stability of the embankment can be ensured by reducing the lateral displacement or the settlement.

Basal reinforcement

Geosynthetics Basal Reinforcement for Soft Soil Foundation

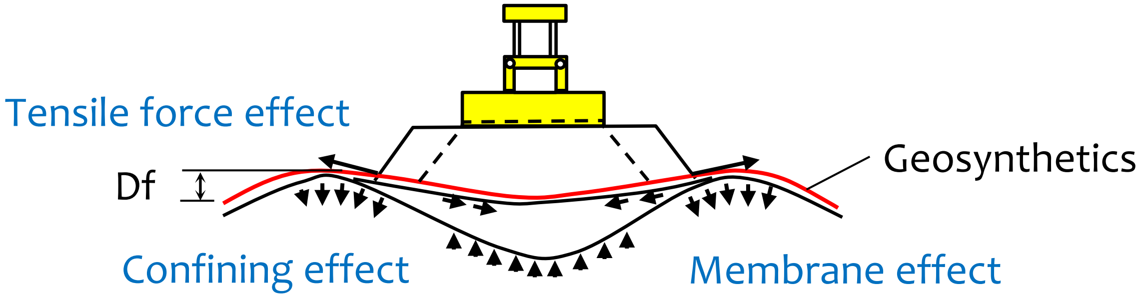


These are effective to reduce settlement and horizontal displacement.

Basal reinforcement

Reinforcement of Ground Surface of Soft Soil Foundation

by courtesy of Dr. Hironaka



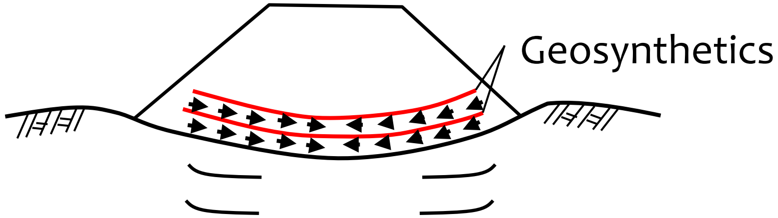
This technique enables the operation of construction machinery on soft ground.

Basal reinforcement

Reinforcement of Embankment on Soft Soil Foundation

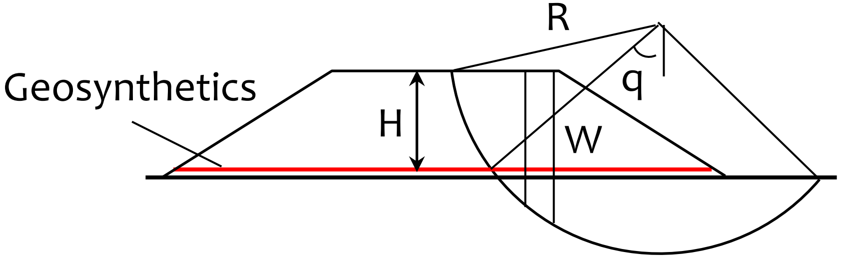
by courtesy of Dr. Hironaka

This technique is effective to construct high embankment on soft ground.

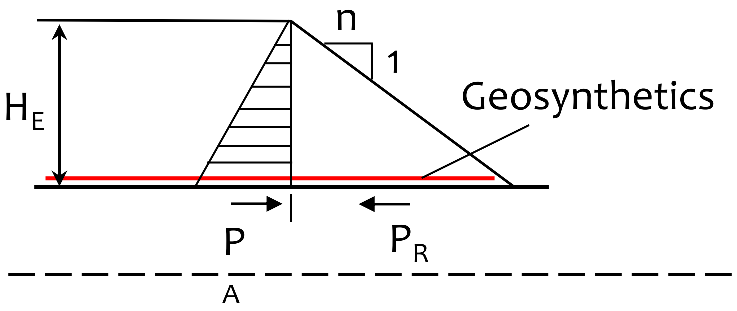


limit states considered in the design

< Overall stability analysis >



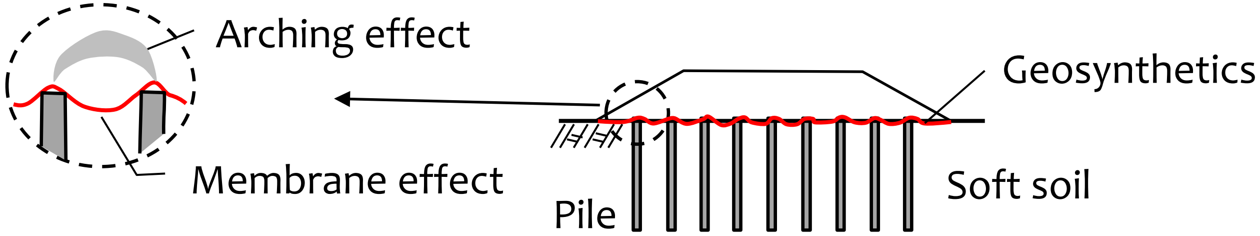
< Sliding stability analysis >



Basal reinforcement

Combined Basal Reinforcement

by courtesy of Dr. Hironaka



This technique ensures not only "stability" but also "serviceability" of embankment.

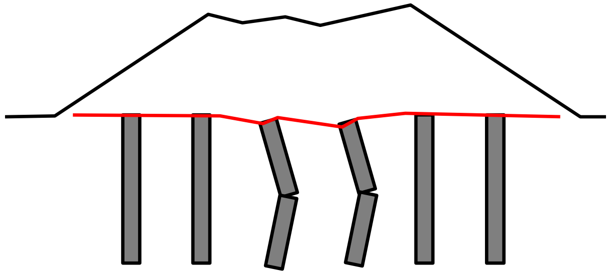
Basal reinforcement

Design of Combined Basal Reinforcement

< Limit states of basal reinforced embankment with piles and Design>

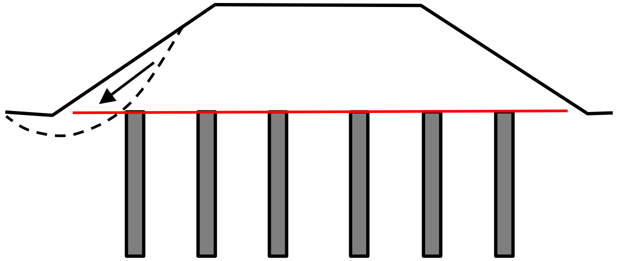
a) Pile group capacity

Design of piles



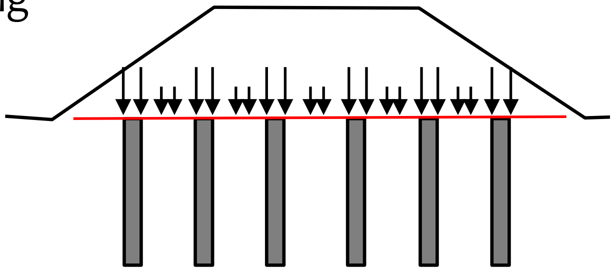
b) Pile group extent

Layout of piles



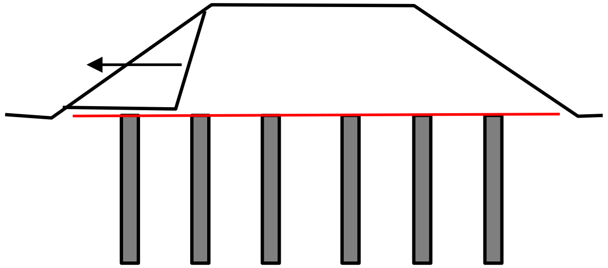
c) Vertical load shedding

Layout of piles



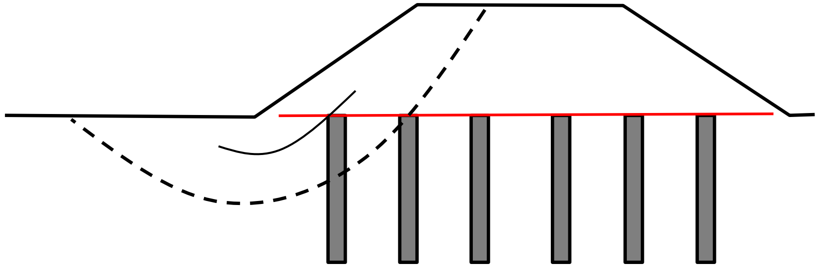
d) Lateral sliding

Geometry of embankment



e) Overall stability

Selection of geosynthetics



BSI (2010)

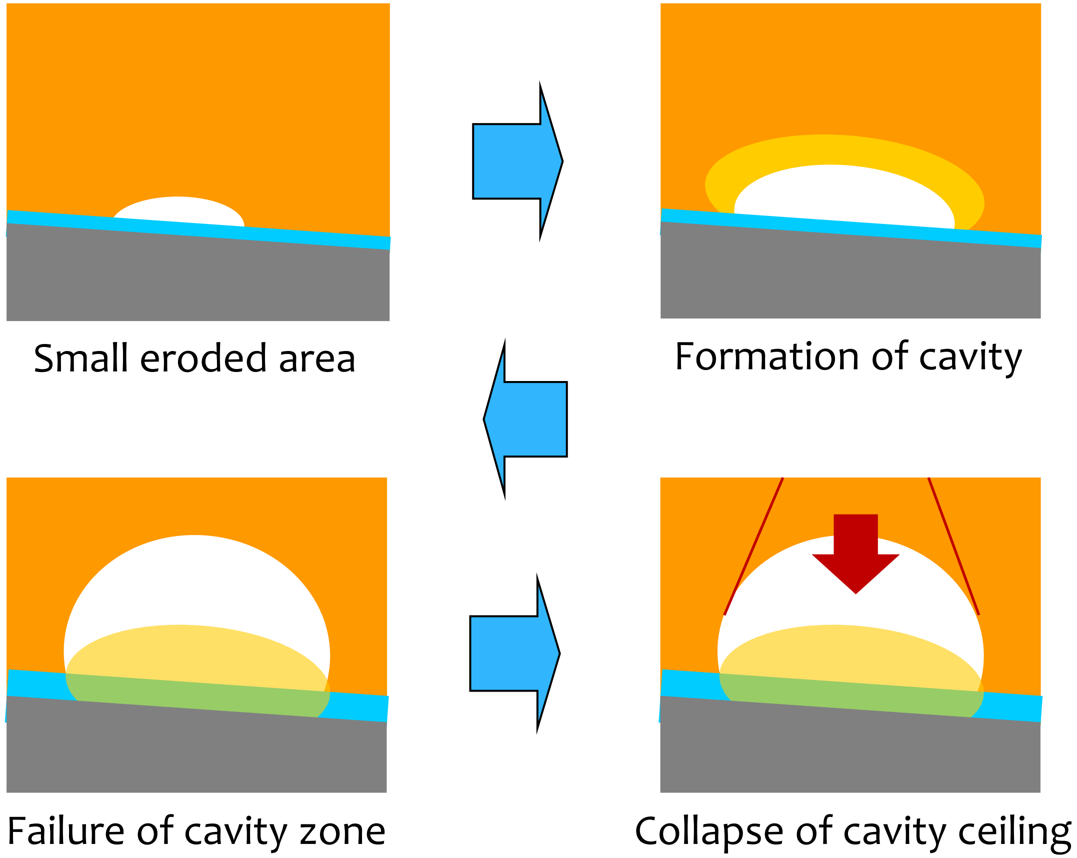
Basal reinforcement

Lessons Learn from Failures of Embankments Overlying Voids

by courtesy of Dr. Kohata

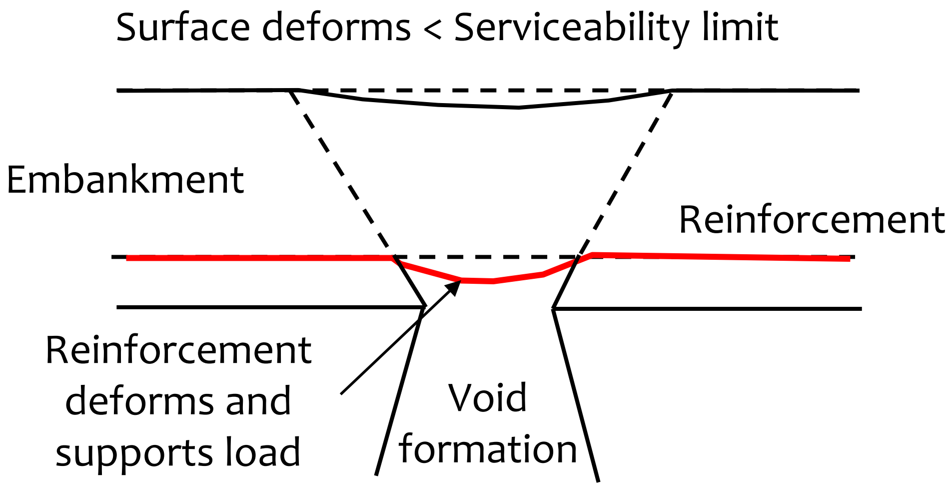
Progressive formation of void causes serious geotechnical damage in social infrastructure.

A mechanism of void formation: Internal Erosion



Basal reinforcement

Basal Reinforcement for Embankments Overlying Voids

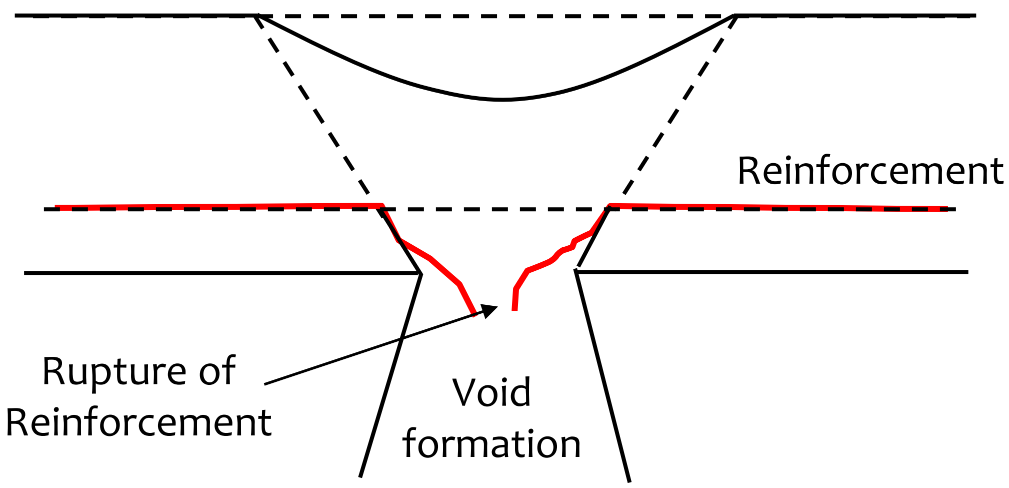


The void formation causes serious damage on roads. Applying basal reinforcement, the geosynthetic reinforcement deforms across the void and supports the fill in the embankment, then the deformation of the ground surface is maintained below the serviceability limit.

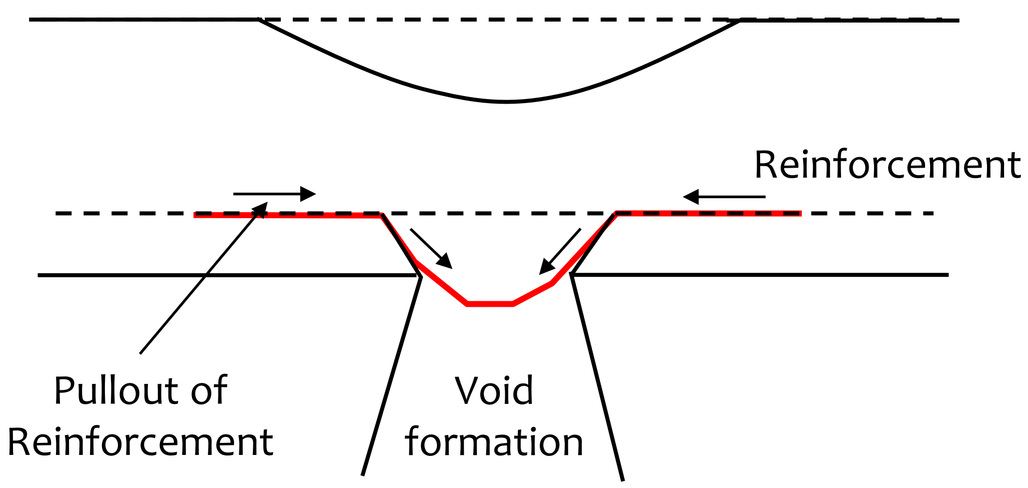
Basal reinforcement

Ultimate limit states considered in the design

< Rupture of reinforcement >



< Pullout of reinforcement >



Applying basal reinforcement, the geosynthetic reinforcement deforms across the void and supports the fill in the embankment, then the deformation of the ground surface is maintained below the serviceability limit.

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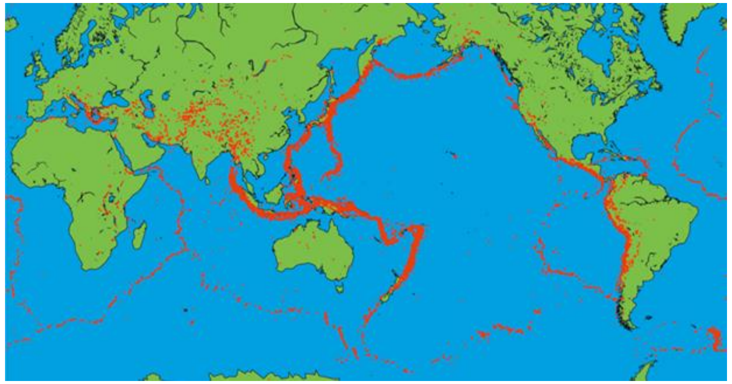
Seismic resistance of reinforced soil structures

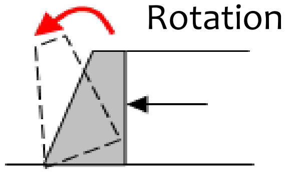
Global seismic map



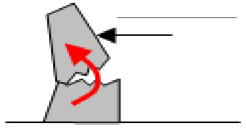
Peak Ground Acceleration in recent notable earthquakes

Earthquake	PGA
2011 Tohoku earthquake and tsunami	2.7g
2011 Christchurch earthquake	2.2g
1994 Los Angeles earthquake	1.7g
2016 Kumamoto earthquake	1.6g
1999 Jiji earthquake	1.0g
1999 Athens earthquake	0.6g

Earthquake Damage of Geotechnical Structures



Classical gravity-structures collapse by seismic actions.

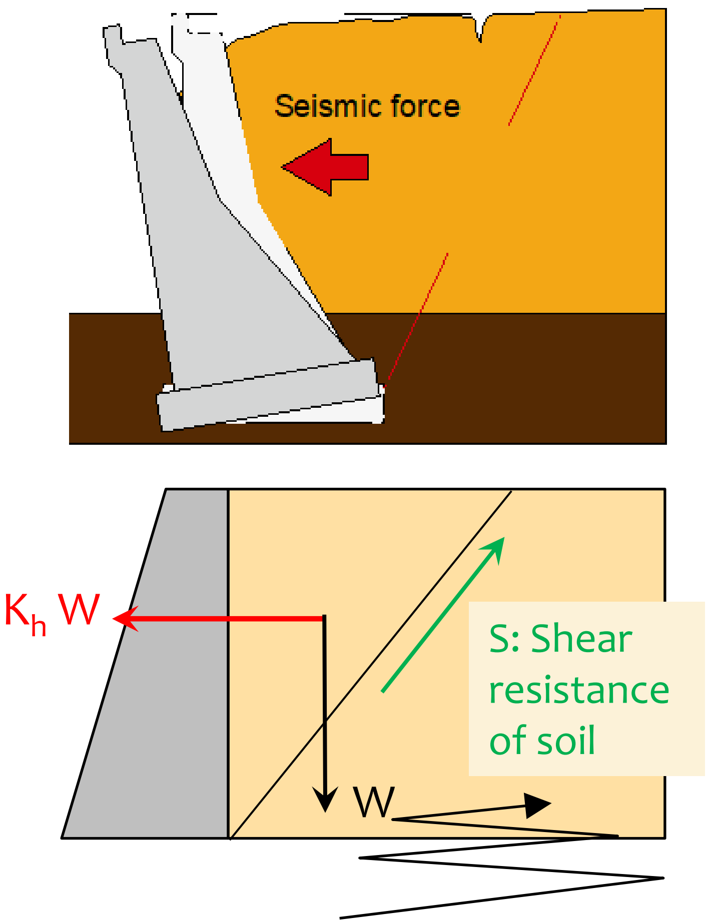


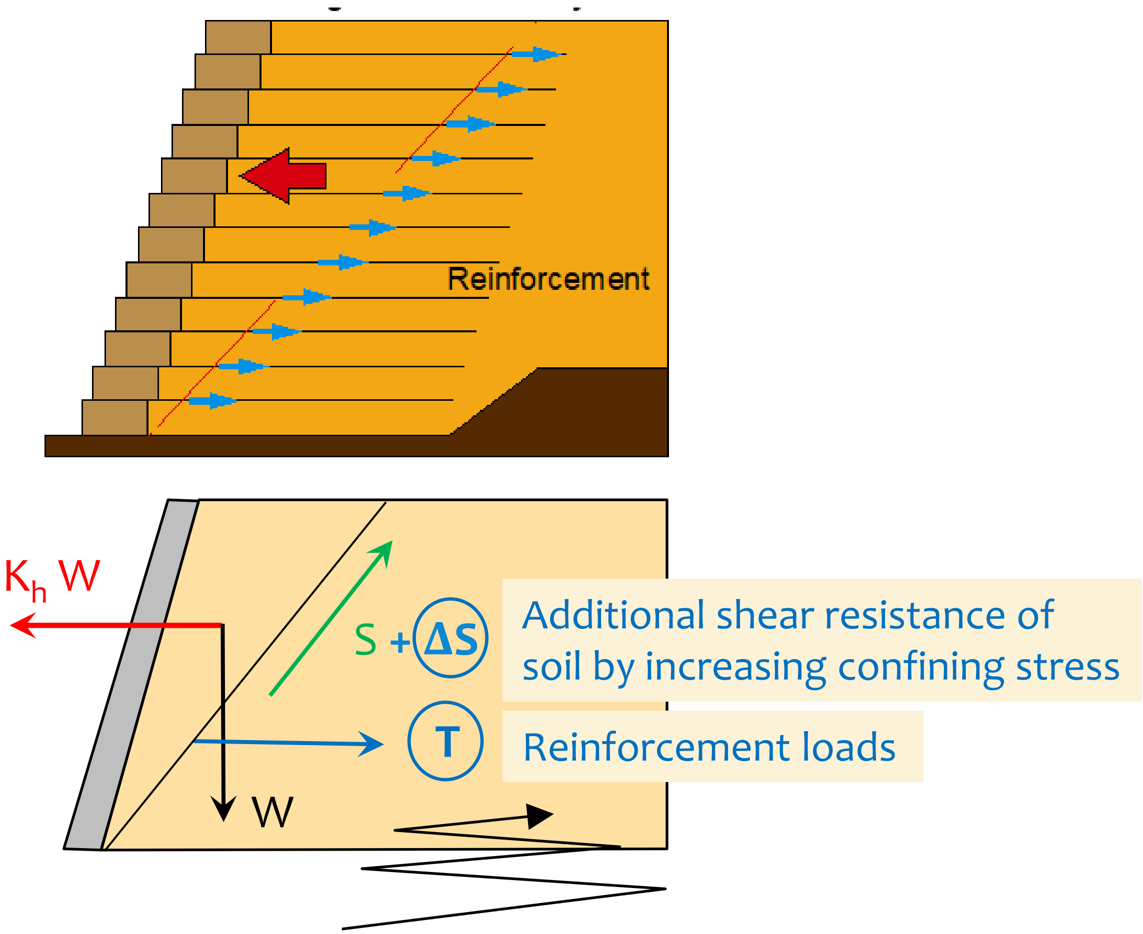
Failure of Reinforced Concrete Structure

by courtesy of Dr. Shinoda

Seismic resistance of reinforced soil structures

Seismic performance comparison of Gravity-type and Reinforced Soil walls





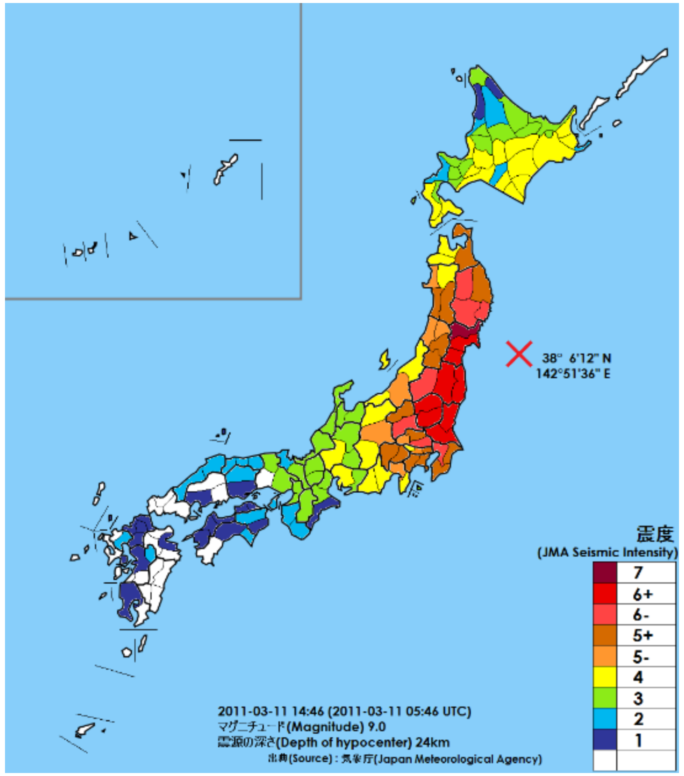
Poor performance of gravity-type walls

Excellent performance of reinforced walls

Seismic resistance of reinforced soil structures

Actual Performance of Geosynthetic-Reinforced Walls

Example of Tohoku earthquake (2011)



…how did Geosynthetic-Reinforced Walls behave during earthquakes?

Ultimate limit state

Restorability limit state

Serviceability limit State

Miyata (2012), Kuwano, Miyata and Koseki (2014)

Seismic resistance of reinforced soil structures

Actual Performance of Geosynthetic-Reinforced Walls

Summary of investigation of **1595 walls** in Tohoku earthquake (SI > 5+)

	Steel Strip walls	Geosyn walls	Multi-anchor walls
Ultimate limit state	**0.3%**	**0.7%**	**0%**
Restorability limit state	**1.0%**	**4.3%**	**0%**
Serviceability limit State	**7.0%**	**0.7%**	**3.0%**
No damage	**91.7%**	**94.3%**	**97.0%**

Miyata (2012), Kuwano, Miyata and Koseki (2014)

Actual seismic actions are much higher than design value.
However, GRWs show good performance.

Seismic resistance of reinforced soil structures

Actual Performance of Geosynthetic-Reinforced Walls

RC bridge collapsed, but Geosynthetic-reinforced wall survived.

Chilean earthquake (27 February 2010) - 8.8 Richter

Seismic resistance of reinforced soil structures

Disaster recovery and reconstruction measures by geosynthetics

Damaged geo-structures due to earthquake



Reconstructed geo-structures by soil reinforcement technology



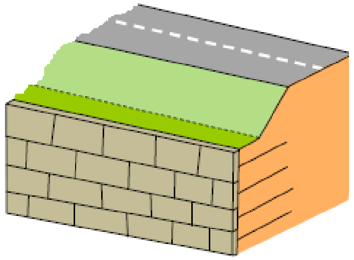
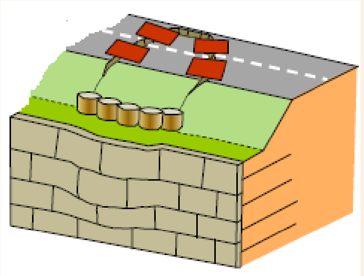
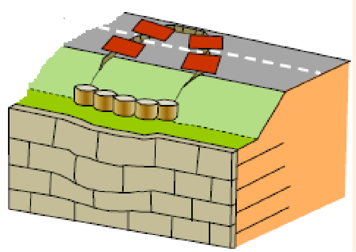
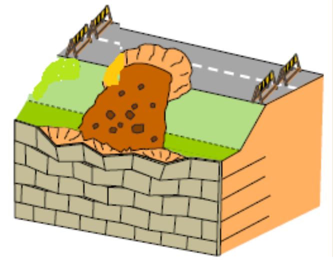
by courtesy of Dr. Hirai

Smooth and rapid recovery, and reconstruction from disaster

Seismic resistance of reinforced soil structures

Performance Based Seismic Design of Geosynthetic-Reinforced Walls

Target performance = **F** (Magnitude of actions, Importance of structure)

Actions \ Importance		High	Normal H>8m	Normal H≤8m
Permanent		Performance Level 1 To keep the normal operation 		Performance Level 2 To recover quickly 
Seismic	**L1: Frequently** (Statistics base)			
	L2: Accidental (Scenario based)	Performance Level 2 To recover quickly 	Performance Level 3 To recover using some time 	

Technical standard on road earthwork structure (Japan, 2015)

Outline

1. Introduction
2. Sustainability of reinforced soil structures
3. Soil reinforcement conceptual mechanism
4. Reinforced soil walls and slopes
5. Veneer reinforcement
6. Basal reinforcement
7. Seismic resistance of reinforced soil structures
8. **Summary**

SUMMARY

1. Geosynthetics for soil reinforcement can be used for the following applications:
   - Reinforced soil walls
   - Reinforced soil slopes
   - Veneer reinforcement
   - Basal reinforcement
2. Reliable design methods and construction procedures are available for each application
3. Reinforced soil structures provide higher sustainability and lower carbon footprint than traditional structures
4. Reinforced soil structures have shown to be stable, flexible and resilient, easy to build and construction time saving
5. Reinforced soil structures afford high seismic resistance both in ultimate and serviceability limit states

Outline

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Thanks for your attention

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