GEOSYNTHETICS SOLUTIONS

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Basal Geosynthetic Reinforcement Spanning Piles and Columns

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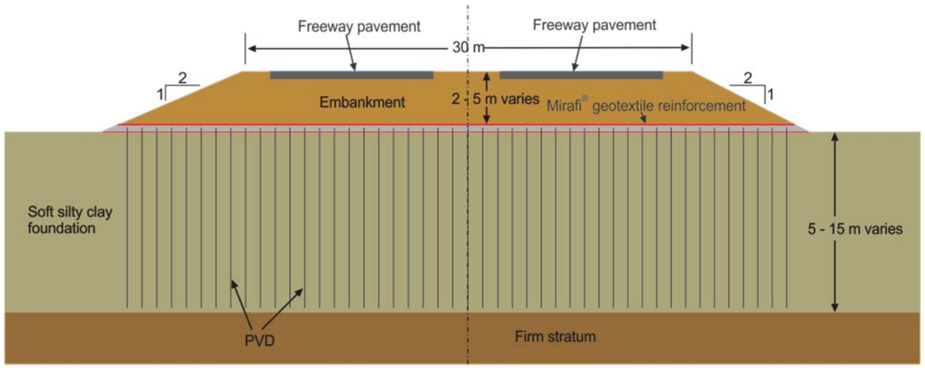
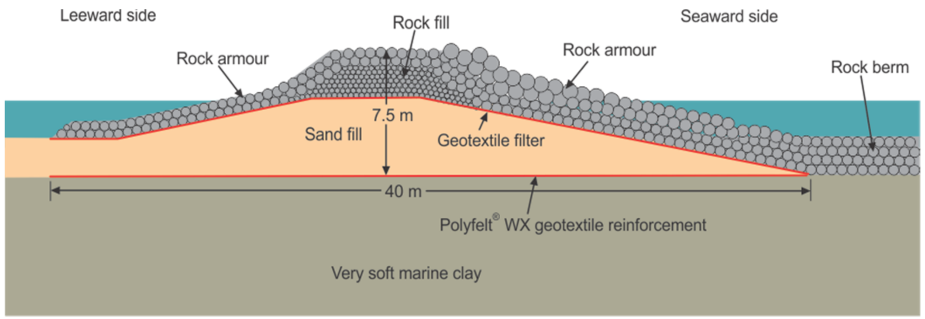
Introduction – basal geosynthetic reinforcement

- Basal geosynthetic reinforcement is used to provide stability when constructing fills over soft foundations
  - Technique has been in use for 40 years in terrestrial (i.e. on-land) environments
  - Technique has been in use for 25 years in marine environments
- Now standard practice
- Variations of this technique have also been applied
  - Basal reinforcement alone
  - Basal reinforcement with PVD's
  - Basal reinforcement supported by piles and columns

Terrestrial basal reinforcement



Marine basal reinforcement

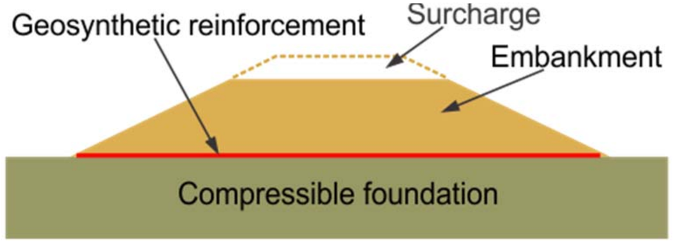


Difference in installation scale between terrestrial and marine construction

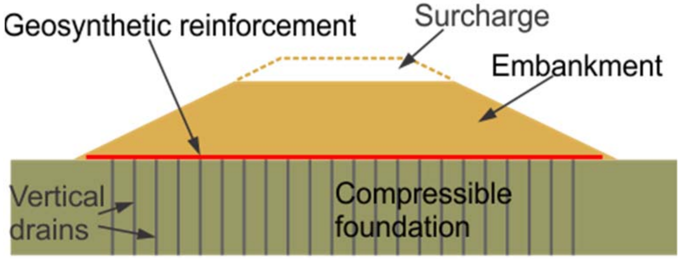
Terrestrial construction

Marine construction

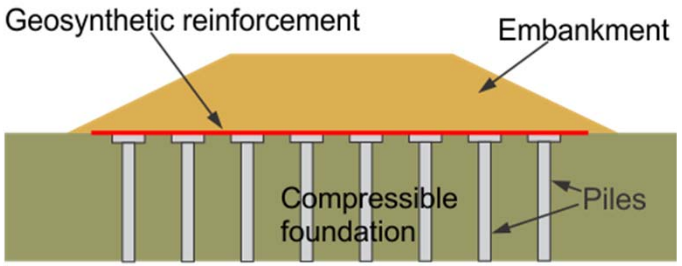
Embankment/fill construction to control foundation compressibility and low shear strength



Construct embankment and wait for settlement



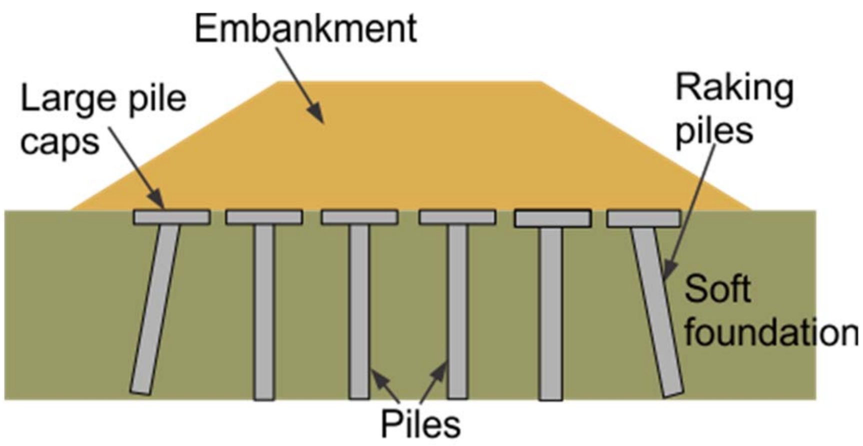
Use vertical drains to accelerate settlement



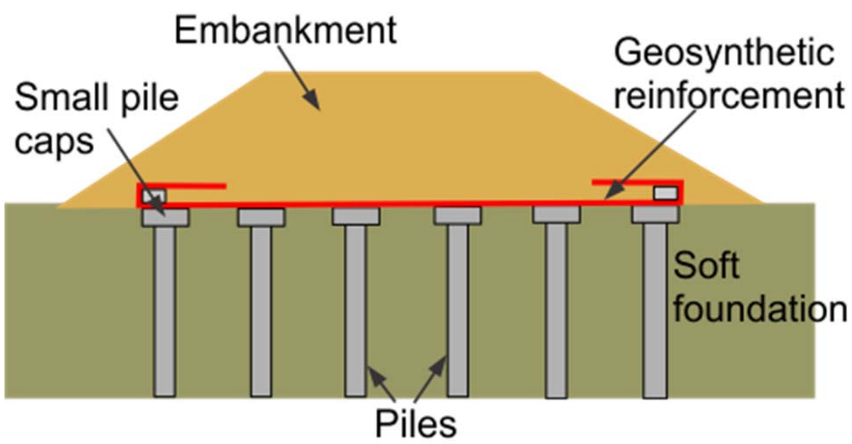
Use foundation treatment (piling) to prevent settlement

- Embankments can be constructed using basal geosynthetic reinforcement to provide short term shear resistance and then wait for settlement to occur before completion
  - Surcharging can help
  - Settlement times can be 5 to 20 years
- Prefabricated vertical drains (PVD's) may be inserted in the soft foundation to accelerate consolidation
  - Surcharging can help
  - Reduce settlement times to 1 to 2 years
- Piles or columns used to prevent (or limit) settlement from occurring
  - Basal reinforced piled embankments (load transfer platforms)
- Excavate the soft foundation soil
  - Can be expensive
- These same techniques are also being used in marine environments
  - However, marine structures have to be designed hydraulically as well as structurally

Terrestrial evolution of basal reinforced piled embankments



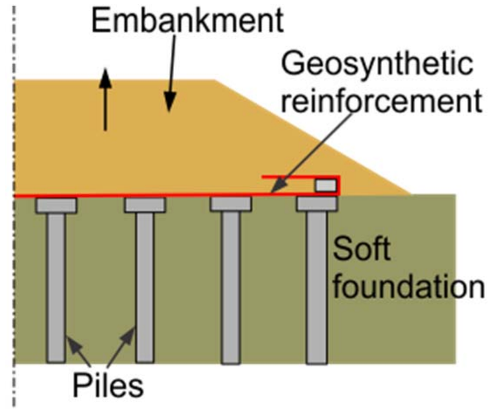
Conventional (old-style) piled embankment

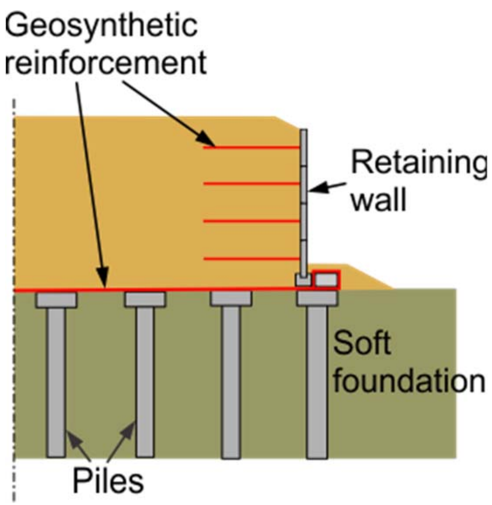


Basal reinforced piled embankment

- In late 1920's piled embankments started to be used in Scandinavia
  - Large pile caps
  - Raking piles on outside of embankment
- In early 1980's basal reinforced piled embankments started to be used in UK
  - Included geosynthetic reinforcement
  - Small pile caps
  - No raking piles on outside of embankment
- The basal reinforcement:
  - Transfers un-arched embankment loads to adjacent pile caps
  - Counteracts outward horizontal thrust of embankment fill in direction across the embankment

Advantages of the basal reinforced piled embankment technique





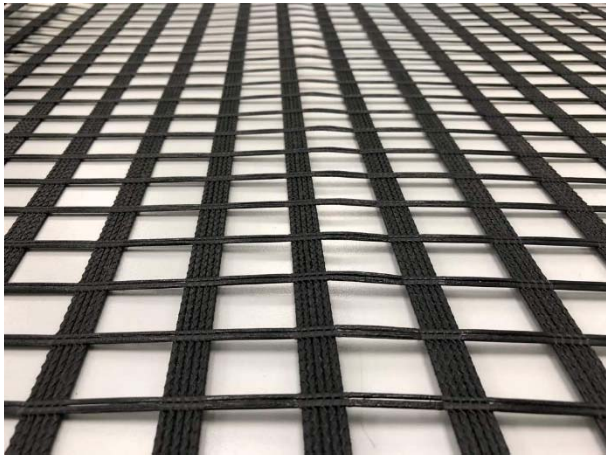
- ***Terrestrial:***
  - Differential settlements between piled embankment and other piled or existing structures are minimized
  - Embankments can be constructed to heights and at rates independent of the foundation strength
  - Embankment side slopes can be constructed at angles independent of foundation strength
- ***Marine:***
  - Structures can be raised to required design levels relatively quickly
  - Surface design levels are maintained
    - Depends on compressibility of columns used
  - Shear stability governed by composite shear resistance of foundation and not by soft foundation alone

Basal geosynthetic reinforcement used

- Basal geosynthetic reinforcement consists of woven geotextiles or geogrids
  - Using high modulus polyester yarns
- These provide high tensile strengths at low strains, excellent durability and form a good bond with the adjacent soil
- However, it must be remembered that these ultimate initial strengths are not the design strengths that are calculated to support engineering structures
  - Can be 30% to 50% of ultimate initial strengths

Polyester woven geotextiles

Polyester geogrids



High strength reinforcement properties

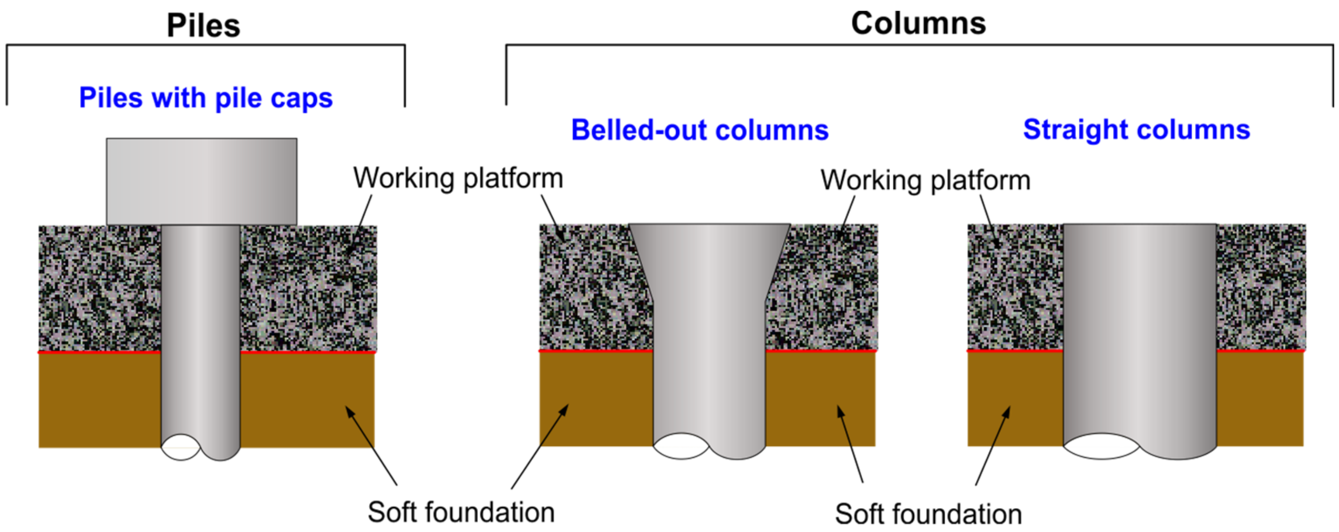
Property	Woven geotextiles	Geogrids
Ultimate tensile strengths	200 - 2,000 kN/m	200 - 800 kN/m
Strain at maximum load	10 - 15%	10 - 15%
Bond coefficients	0.8 - 0.95	0.8 - 0.95

Types of piles/columns used

- A number of different pile/column types have been used in piled embankments
- Piles:
  - Pre-cast concrete piles – these have high capacity, therefore greater pile spacings and larger pile caps
  - Timber piles – with constant groundwater conditions
- Columns:
  - Larger diameter - don’t have pile caps
  - Stone columns and grout injected SC
  - Confined stone columns
  - Concrete columns
  - “Controlled modulus” columns
  - Deep cement mixed (DCM) columns
- Piles/columns are designed to support the full fill loading with minimal or controlled settlements
  - End-bearing design

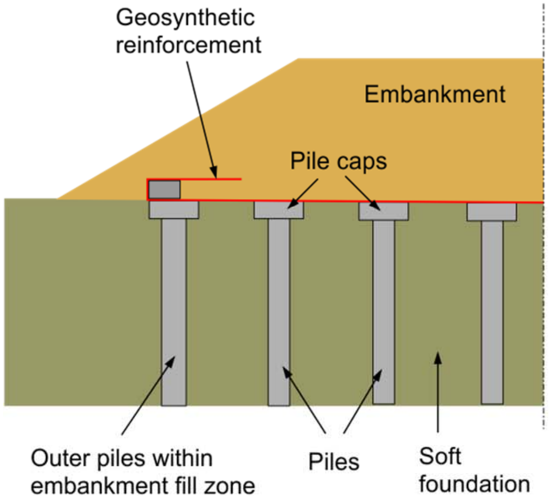
Piles and columns

- ***Piles:***
  - Most commonly pre-cast concrete piles
    - High load capacity
    - Maximum spacings
  - Necessitates the use of pile caps
    - Also concrete
    - Cast in place or pre-cast
- ***Columns:***
  - Formed insitu
  - Wide variety of column techniques
  - Most commonly unreinforced
    - Limited shear and horizontal load resistance
  - Maybe formed by mixing cement with soft foundation soil
    - Limited load and shear capacity



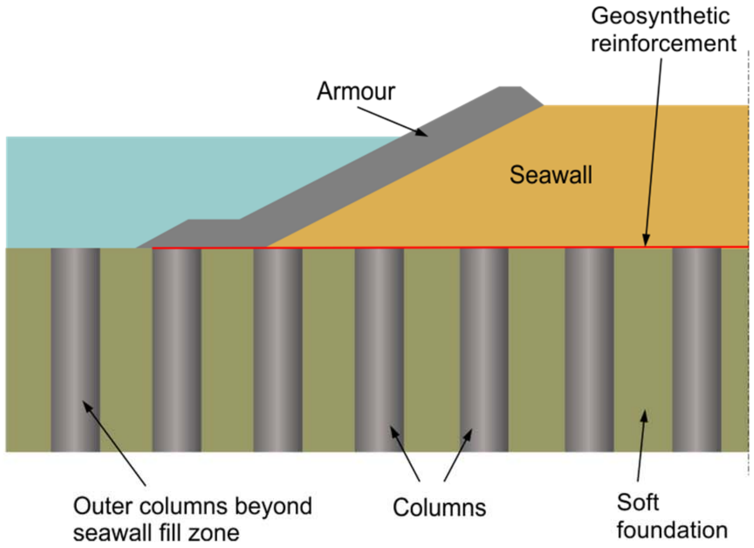
Terrestrial versus marine configuration

Terrestrial



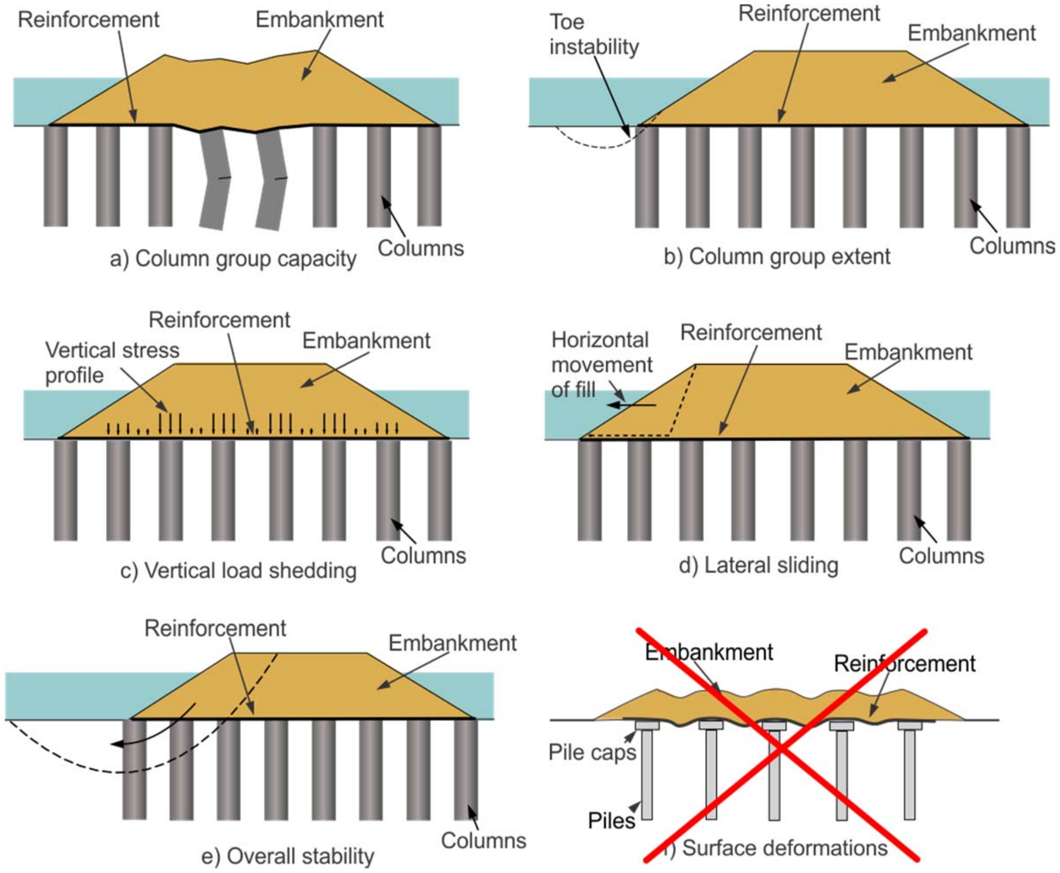
- Geometry:
  - Height and crest width requirements to meet alignment requirements
  - Side-slope to meet internal stability requirements
- Fill:
  - Coarse base layer, then can be fine granular fill
- Foundation:
  - Pile group extent to provide stability at crest

Marine



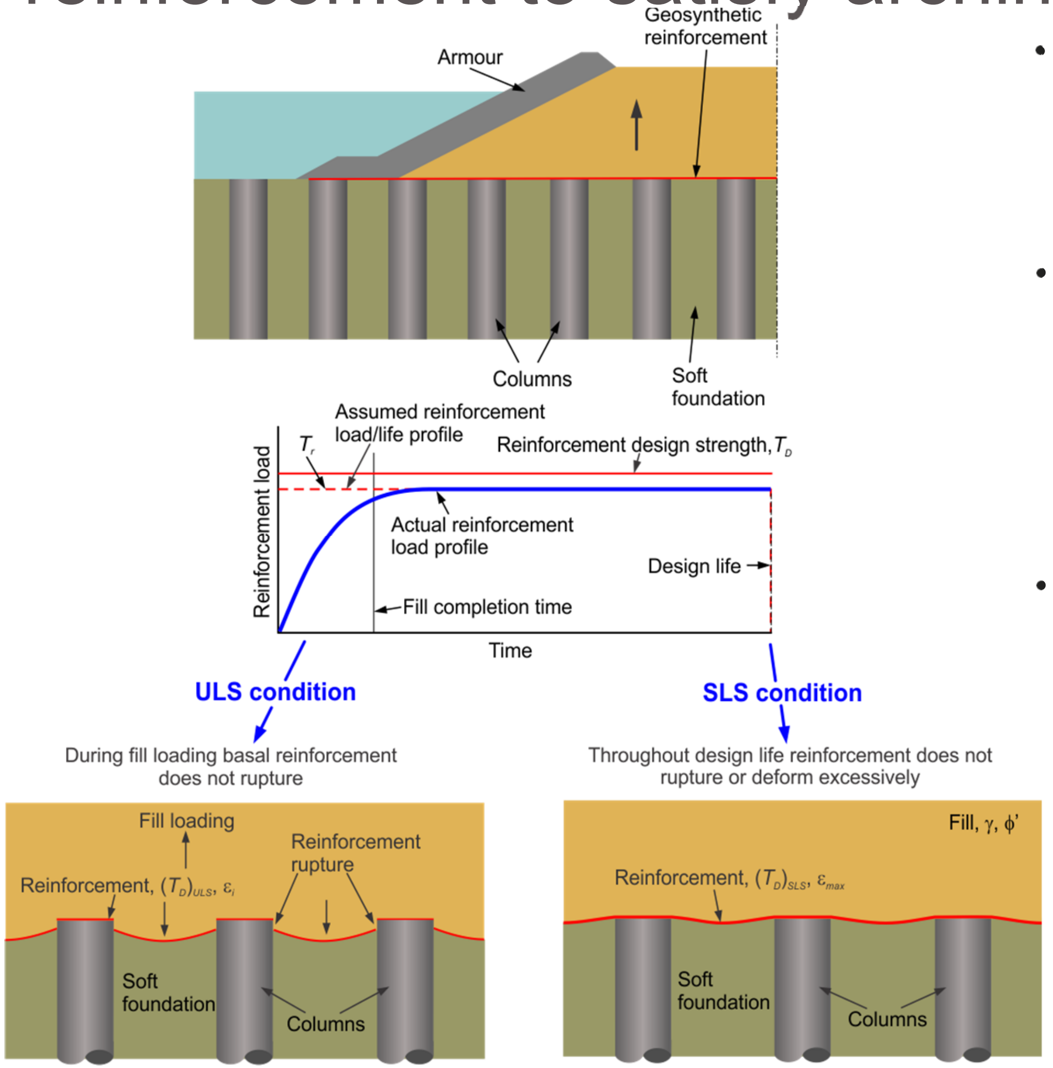
- Geometry:
  - Height and side-slope to meet hydraulic stability requirements
- Fill:
  - Coarse granular fill, stable to construct a mound
  - Outer armour layers for hydraulic stability requirements
- Foundation:
  - Column group extent to provide stability at toe

BS8006 adaptation to column supported marine structures – structural limit states



- To begin with the structure must be hydraulically stable
- The 1st case is to ensure the column group capacity can support the marine structure within prescribed stability and deformation limits
- The 2nd case is to ensure no toe instability occurs
- The 3rd case is to ensure the vertical load shedding is supported and distributed by the basal reinforcement
- The 4th case is to ensure the horizontal outward thrust is supported by the basal reinforcement or the column foundation treatment
- The 5th case is to ensure adequate overall stability
- The 6th case deals with terrestrial low-height basal reinforced piled embankments
  - Not applicable for marine structures

BS8006 ULS and SLS conditions for basal reinforcement to satisfy arching



- As the fill height is increased the tensile load increases in the basal reinforcement until an equilibrium point is reached
  - Then remains constant with time
- ***ULS condition:***
  - Short term reinforcement strength (taken as initial strength) does not allow rupture on loading of fill
  - BS8006, Cl 8.3.3.14 requires reinforcement initial strain $\varepsilon_i \leq 6\%$ in calculation
- ***SLS condition:***
  - Long term reinforcement strength maintains arched loads at defined reinforcement strain
    - Initial strain for PET reinforcement in this calculation should be $\varepsilon_i \leq 4\%$
  - BS8006, Cl 8.3.3.14 requires reinforcement creep-strain over design life $\varepsilon_{cs} \leq 2\%$ in calculation

BS8006 approach to determine arching and resulting basal reinforcement loads

Analytical model to determine amount of arching at base of pile or column supported fill

↓

Vertical stress acting on basal reinforcement between pile caps or columns, p_f'

↓

Evenly distributed load acting on basal reinforcement between pile caps or columns, W_T

↓

Deflected shape of basal reinforcement is parabolic

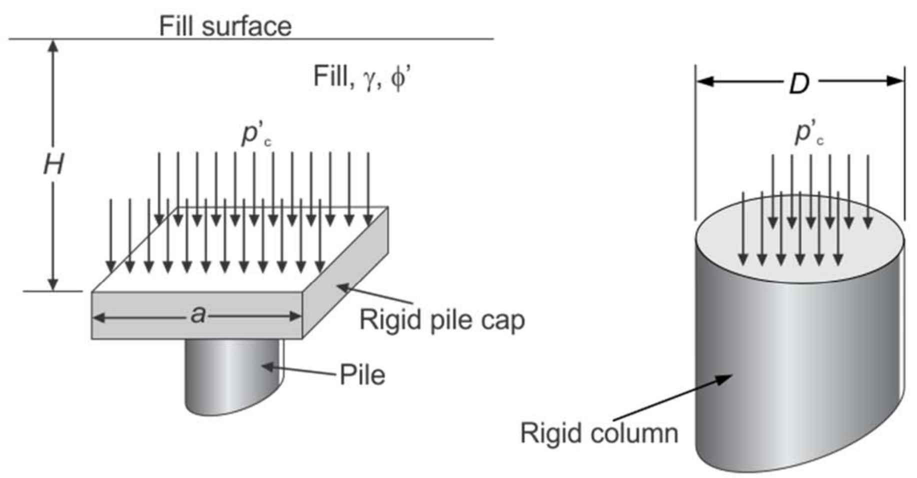
↓

Tensile load in basal reinforcement, T_{rp}

BS8006 "positive projecting conduits" analytical model

Square caps

Circular columns

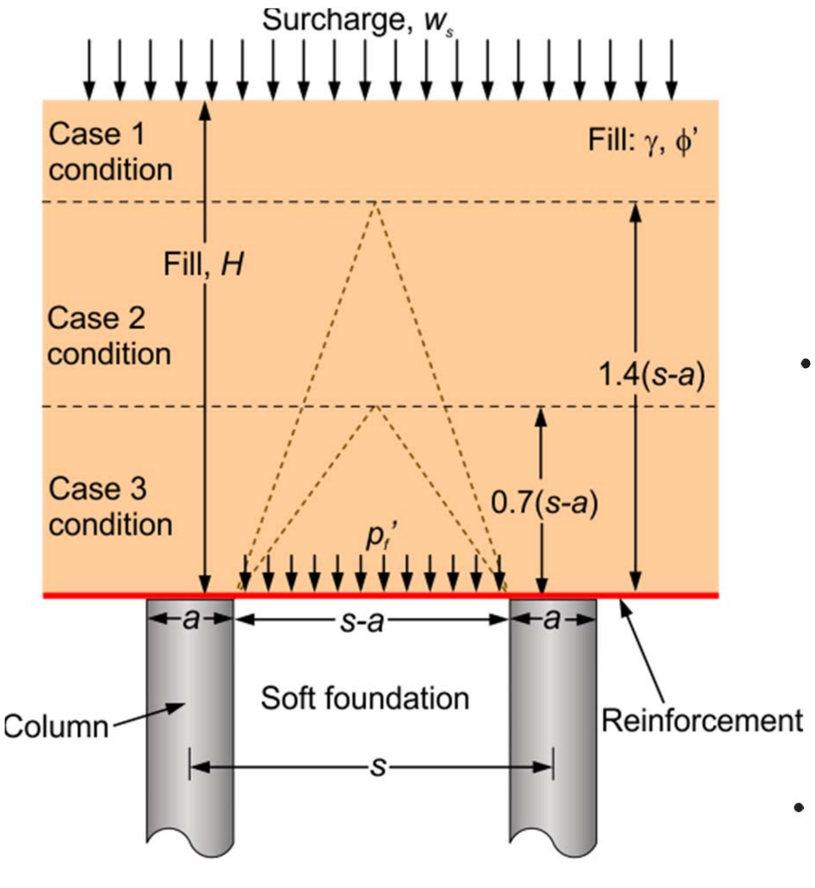


$a = 0.89D$

Arching on top of rigid pile cap or circular column:

$$\frac{p'_c}{\sigma'_v} = \left(\frac{C_c\, a}{H}\right)^2 \qquad \sigma'_v = \gamma H$$

BS8006 'projecting conduits' approach to pile cap/column arching



p_f' = vertical stress acting on reinforcement

- ***Case 1 condition:*** $H \geq 1.4(s\text{-}a)$
  - Fully arched condition - high column supported fills
    - Corresponds to an arching angle of 70º
  - Load from increased fill height transferred fully to columns only
    - Vertical stress on basal reinforcement p_f' does not change with increasing height

$$p_f' = \frac{1.4 f_{fs}\gamma(s-a)}{s^2-a^2}\left[s^2 - a^2\left\{1.95 - \frac{0.13a}{s-a}\right\}^2\right]$$

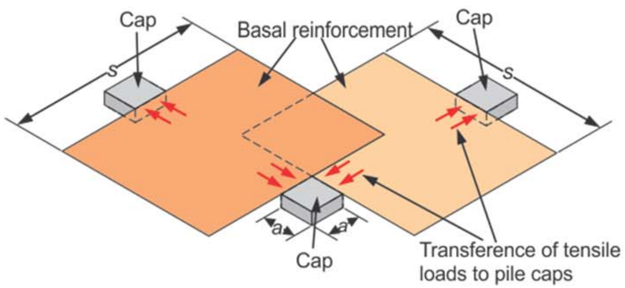
- ***Case 2 condition:*** $1.4(s\text{-}a) > H \geq 0.7(s\text{-}a)$
  - Partially arched condition
    - Corresponds to arching angles 55º to 70º
  - Load from increased fill height transferred to both columns and basal reinforcement
    - Vertical stress on basal reinforcement p_f' changes with height

$$p_f' = \frac{f_{fs}\gamma H + f_q w_s}{s^2-a^2}\left[s^2 - a^s\left\{1.95 - \frac{0.18a}{H}\right\}^2\right]$$

- ***Case 3 condition:*** $H < 0.7(s\text{-}a)$
  - Limited arching - shallow height
  - This BS8006 procedure is not recommended for these geometries
  - Also not relevant for marine structures

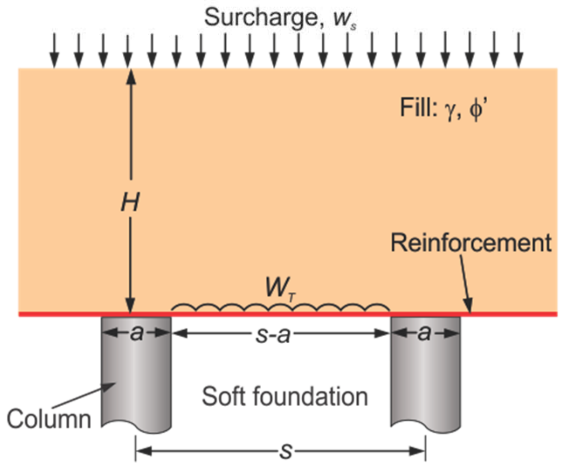
BS8006 approach to determine evenly distributed load acting between individual pile caps/columns

BS8006 conventional - 2-D reinforcement area coverage

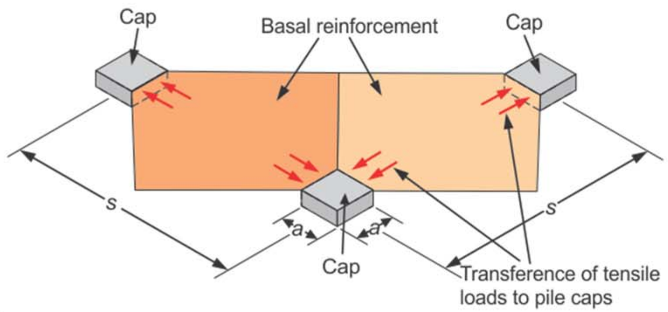


$$(A_c)_{BS} = s(s-a)$$

$$W_T = \frac{p_f'(A_c)_{BS}}{a(s-a)} = \frac{s\,p_f'}{a}$$



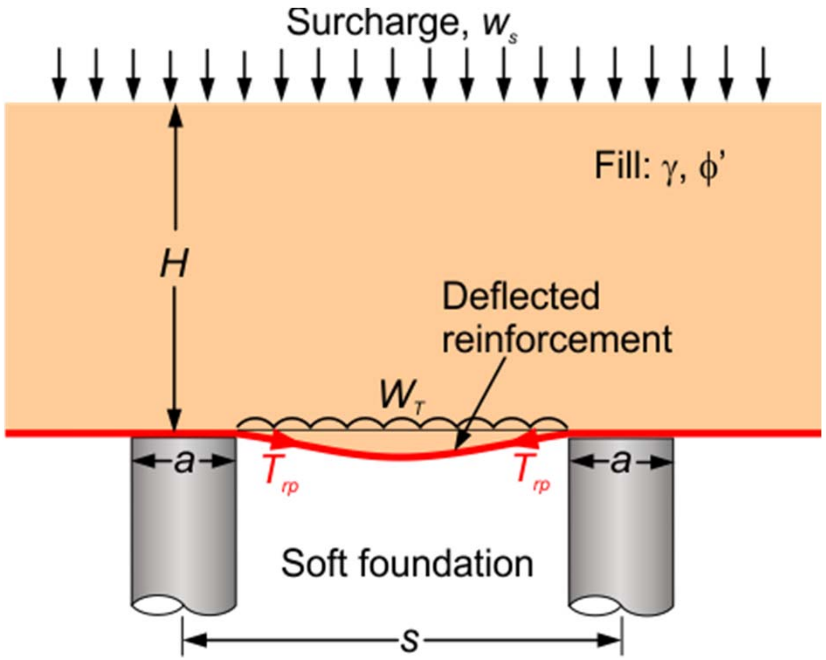
BS8006 **modified** - 3-D reinforcement area coverage



$$(A_c)_{trap} = \frac{s^2 - a^2}{2}$$

$$W_T = \frac{p_f'(A_c)_{trap}}{a(s-a)} = \frac{(s+a)p_f'}{2a}$$

BS8006 approach to determine reinforcement load resulting from fill arching

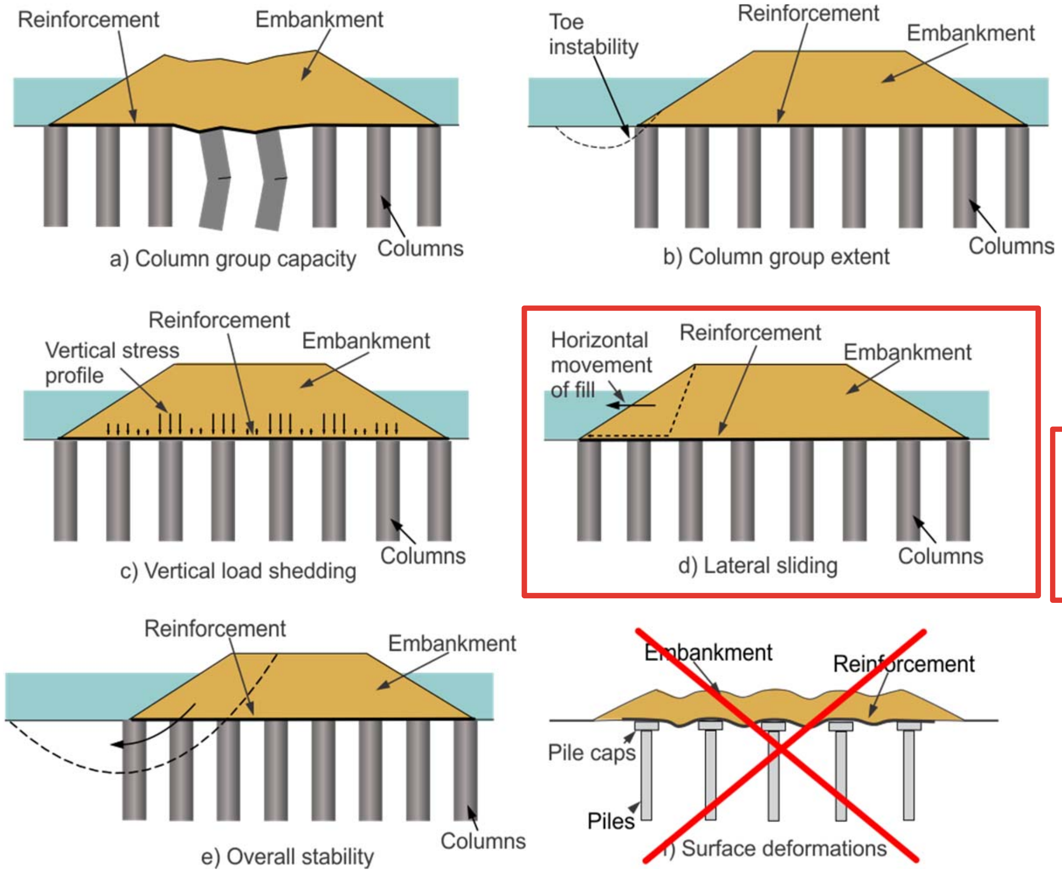


Parabolic equation:

$$T_{rp} = \frac{W_T(s-a)}{2}\sqrt{1+\frac{1}{6\varepsilon}}$$

- BS8006 does not allow for foundation support beneath reinforcement
  - Considers that it is unreliable
- Deflected reinforcement shape approximates a parabola
- BS8006, Cl8.3.3.14 – maximum initial reinforcement strain ε_{max} = 4% or 6% depending on whether SLS or ULS calculation
- T_{rp} is the calculated reinforcement load in vicinity of pile caps/columns resulting from fill arching

BS8006 adaptation to column supported marine structures – structural limit states



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- The 1st case is to ensure the column group capacity can support the marine structure within prescribed stability and deformation limits
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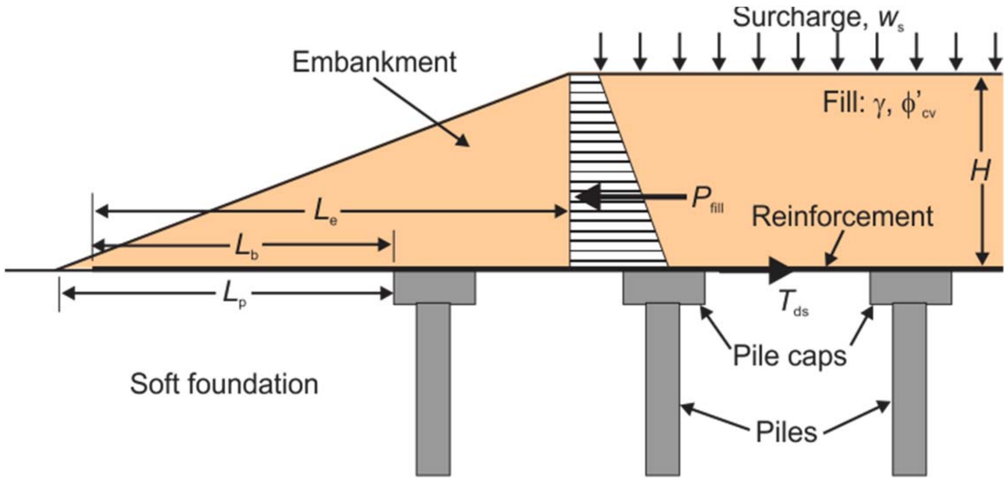
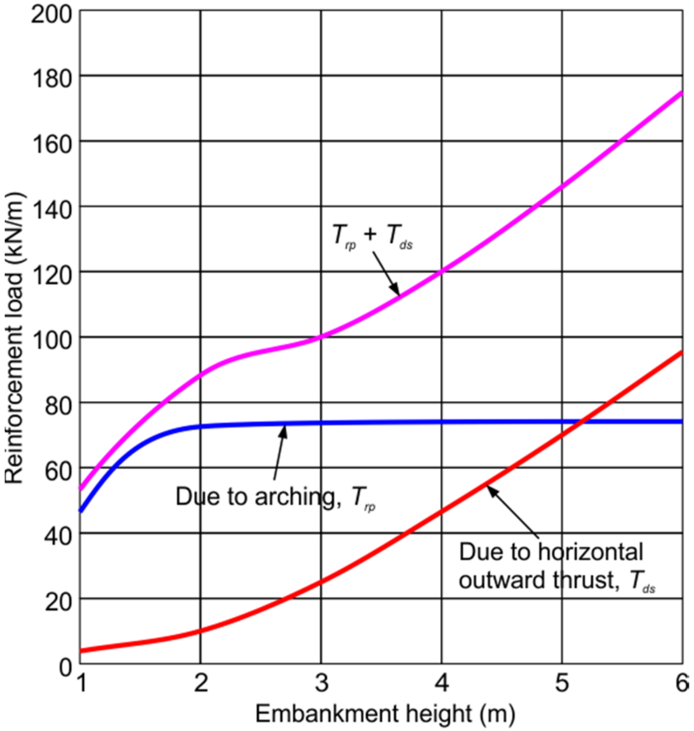
Horizontal outward thrust: reinforcement load



- Geosynthetic reinforcement carries outward thrust of embankment + load due to arching across embankment
- Outward thrust can be a considerable reinforcement load component for higher embankments

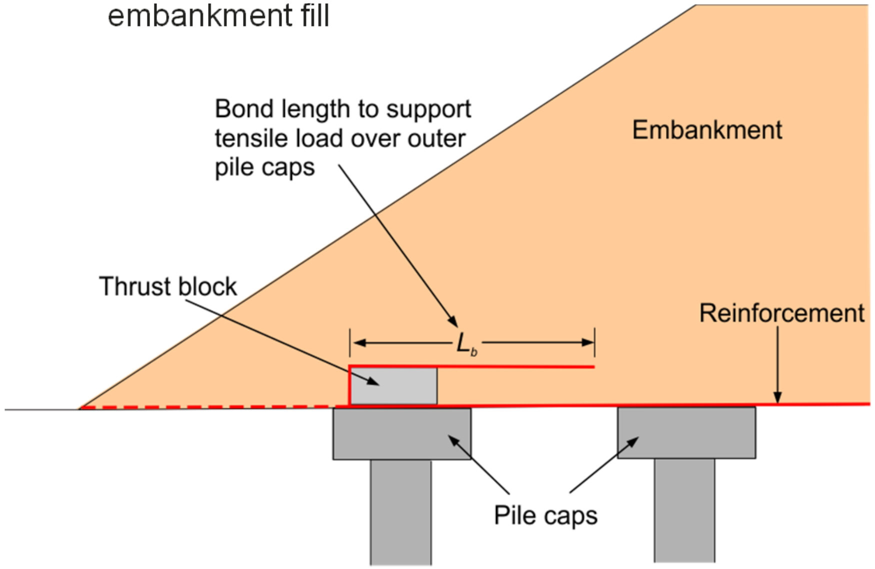


Resulting tensile load in geosynthetic reinforcement due to outward thrust of embankment:

$$T_{ds} = P_{fill} = 0.5 K_a \, f_f \, (\gamma H + 2 w_s) H$$

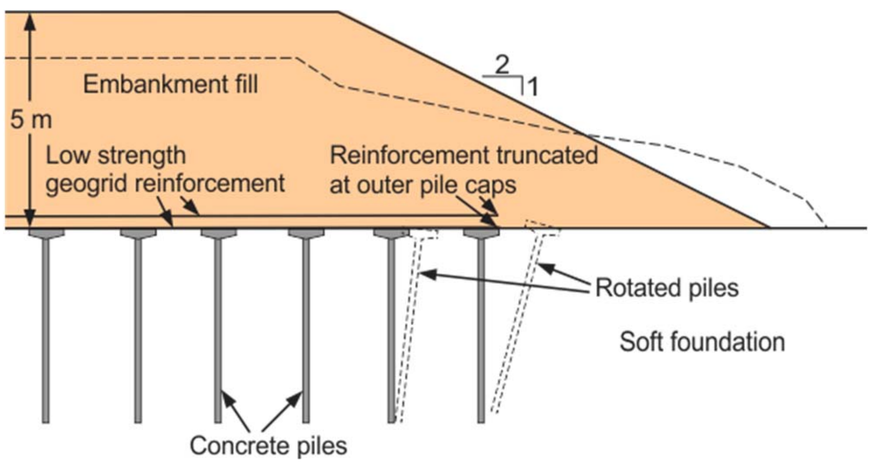
Basal reinforcement detailing at edge of piled embankment

- Tensile loads must be supported by the reinforcement over the outer row of piles
  - This requires an adequate reinforcement bond length at the embankment edge
- Thrust block provides a reaction surface for reinforcement and redirects tensile loads
  - Gabions or concrete columns have been used
- Reinforcement is returned into embankment fill to generate required bond length
  - This utilises the vertical overburden stress of the embankment fill



Consequences of ignoring the horizontal outward thrust

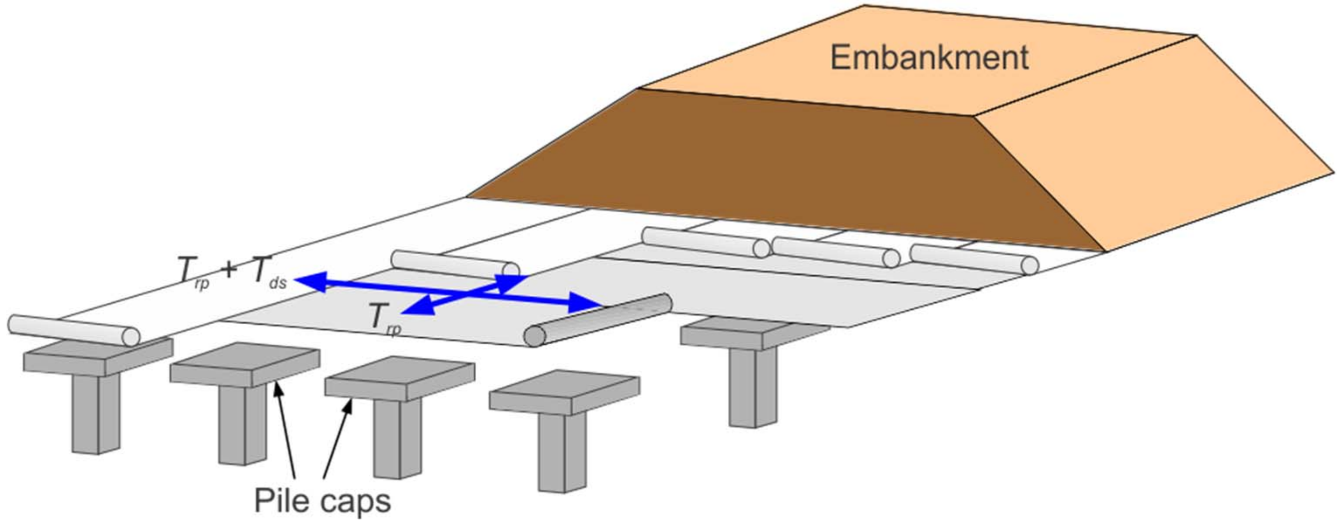
- If the horizontal outward thrust is not accounted for and/or the reinforcement is not truncated properly failure can occur in the outer zone of the piled embankment
- Case of 5 m high piled embankment founded on soft clay foundation
  - Concrete piles, 2 m spacing, with 0.75 m pile caps
  - Two layers of 20 kN/m geogrid basal reinforcement truncated at outer pile caps
- On reaching around 4 m fill height:
  - Outward failure of the embankment
  - Outward rotation of outer piles
  - Rupture and pull-out of reinforcement in outer location



Basal reinforced piled embankments: bi-directional reinforcement loads

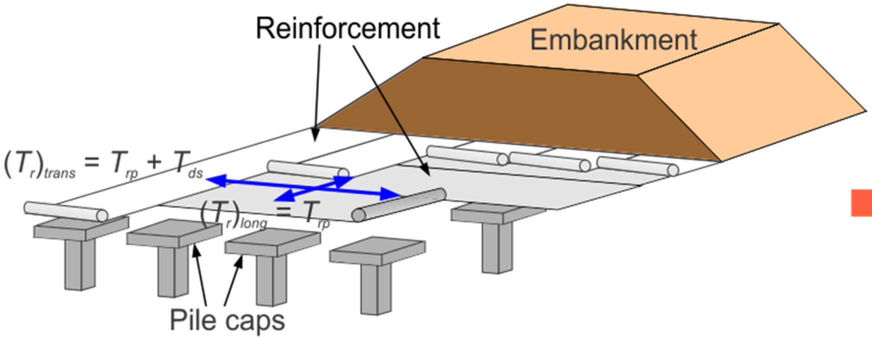
- Reinforcement loads have to be carried both along and across the basal reinforced piled embankment
  - Along: due to embankment arching (T_{rp})
  - Across: due to embankment arching plus horizontal outward thrust of embankment (T_{rp} + T_{ds})
- Also, loads must be transferred continuously across base of embankment
- The most efficient way of doing this is to use two layers of uni-axial reinforcement laid at right angles to each other

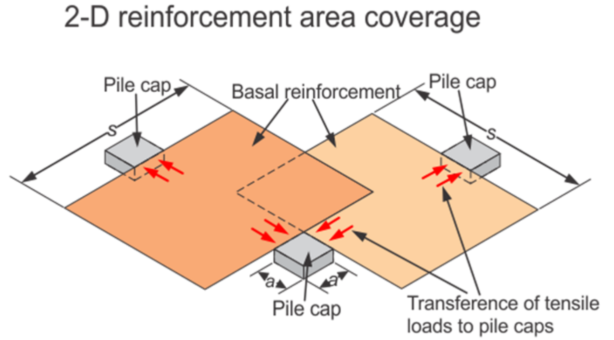
Bi-directional reinforcement loads



Two-way and one-way load transfer

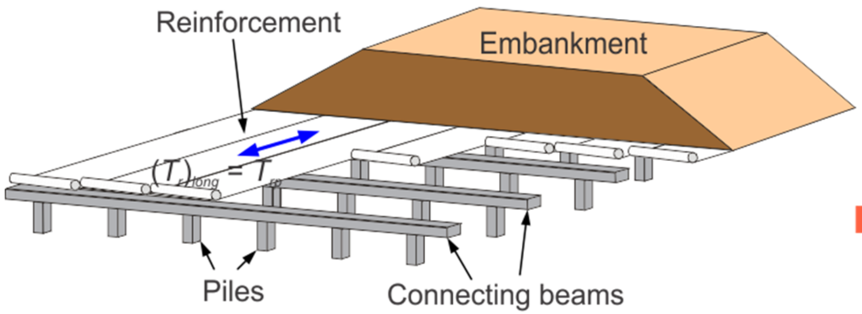
Two-way load transfer

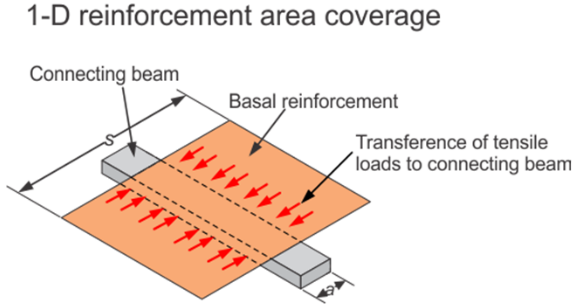




$$(A_c)_{2D} = s(s-a)$$

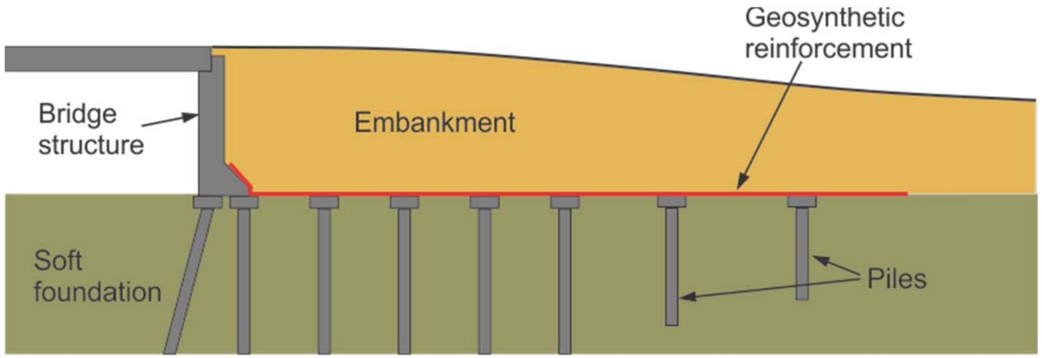
One-way load transfer





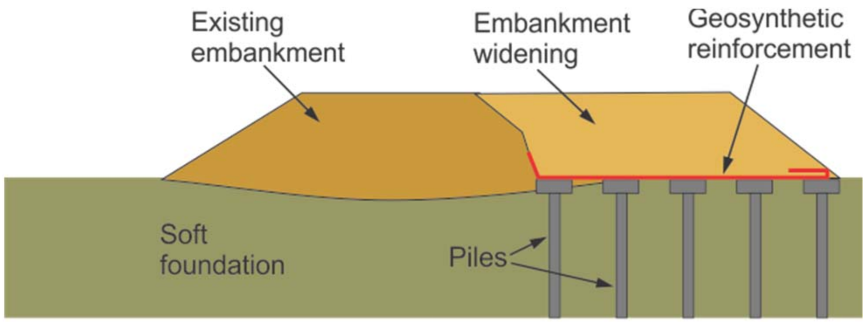
$$(A_c)_{1D} = s - a$$

Terrestrial examples of use (1)



a) Embankment approaching a piled structure

Terrestrial examples of use (2)



b) Embankment widening preventing differential settlements

Concluding remarks

- The use of basal geosynthetic reinforcement is a recognised technique when dealing with soft foundation soils in both terrestrial and marine environments
- Basal reinforcement can be used alone, in combination with PVD's or in combination with piles and columns
  - The use of piles and columns work to prevent or minimise the settlements of fills placed on top of soft foundations while providing stability
- The role of the basal reinforcement spanning piles and columns is to enable the unarched fill loads to be transferred to adjacent piles and columns and to counteract the horizontal outward thrust of the fill
- This results in a two-way load shedding system where two uni-directional reinforcement layers are placed orthogonally
  - The exception to this is where concrete connecting beams or continuous columns are placed in one direction (at right angles to the direction of the fill) and consequently a single uni-directional reinforcement layer is placed parallel to the fill direction
- Various analytical models exist to enable the determination of the tensile loads in the basal reinforcement