Anchorage length of geosynthetic reinforcement in embankments supported on piles

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ABSTRACT
Anchorage length is an integral part of the design of embankments on piles over soft foundation soils, as part of a foundation system to control stability and prevent or limit settlement of the embankment. In these projects high strength geosynthetic reinforcement is placed at the base of the embankment, directly over the pile caps, where they support all or part of the vertical stress applied on the foundation soil through the tensioned membrane mechanism. The geosynthetic reinforcement has to carry high tensile forces, which can occur only if the geosynthetic reinforcement is properly anchored at the extremities of the embankment. Hence there is a need to design and construct adequate anchorage lengths. The anchorage length can be provided as a straight length, or more commonly by wrapping the geosynthetic reinforcement around gabions placed at the toe of the embankment. This paper presents a new, more rigorous, design method for determining the anchorage length of geosynthetic reinforcement in embankments with basal reinforcement supported on piles. The required anchorage length for the geosynthetic reinforcement is calculated considering the long-term (unfactored) tensile strength in the geosynthetic reinforcement, and all the resisting forces (pullout force on pile cap, pullout force between gabion and first pile cap, pullout forces over and below gabions, pullout force along anchorage length). The long-term (unfactored) tensile strength in the geosynthetic reinforcement, the load on piles and the load under arching between piles must be calculated in advance, using either Marston's or the Hewlett & Randolph methods (BS 8006-1:2010+A1 (2016)). A new Factor of Safety for anchorage length can be defined as the ratio of the total pullout resisting force mobilized along the full length of the geosynthetic reinforcement beyond the outer pile cap to the long-term (unfactored) tensile strength required in the geosynthetic reinforcement. In the proposed method the anchorage length is determined by trial and error until the calculated Factor of Safety for anchorage exceeds the minimum required value. A design example is provided to show the potential of the method.

1. INTRODUCTION

The design of geosynthetic reinforcement used as a component to control embankment stability and settlement, that is the design of geosynthetic reinforcement on piles, can be carried out using the method in BS 8006-1:2010+A1(2016). This method affords to calculate first the load shedding due to soil arching generated between pile caps, that is the vertical load V_p on piles (kN) and the uniform load W_T under the arching between pile caps (kPa); then the required (long-term, unfactored) tensile strength of the geosynthetic reinforcement can be calculated, considering the geosynthetic reinforcement as a tensioned membrane spanning the distance between adjacent pile caps, where the load on the tensioned membrane is given by W_T; the tensile strength in the geosynthetic reinforcement produced by the tensioned membrane mechanism depends on the tensile strain set for the geosynthetic reinforcement, which in turn depends on the deflection of the geosynthetic reinforcement between adjacent pile caps. Usually an upper strain of 6 % is used in design. This value typically takes account of both the short- and long-term (creep) effects in the geosynthetic reinforcement. This method has been used for long time, producing so far satisfactory results.
What is still lacking in the BS 8006-1:2010+A1 (2016) standard is a proper method for calculating the required anchorage length of the geosynthetic reinforcement beyond the outer pile cap, considering all the pullout shear stresses and forces that are generated along the various segments of the anchorage length.
While construction details of a typical anchorage option of wrapping the geosynthetic reinforcement around a gabion (placed on top of the outer pile cap) is provided in BS 8006-1:2010+A1 (2016), there is actually no

guidance for calculating the so called bond length, that is the anchorage length L_a inside the embankment after wrapping the geosynthetic reinforcement around the gabion.
To overcome this issue, this paper proposes a method for calculating the anchorage length of geosynthetic reinforcement over piles, for the most common solution of wrapping the geosynthetic reinforcement around a gabion placed at or close to the toe of the embankment, thus avoiding the need to increase the width of the embankment to provide an adequate anchorage length.

2. ANCHORAGE LENGTH OF GEOSYNTHETIC REINFORCEMENT ON PILES

2.1 Outline of the design method

The required anchorage length for geosynthetic reinforcement is calculated considering the long-term (unfactored) tensile strength in the geosynthetic reinforcement, and all the resisting forces (pullout force on pile cap, pullout force between gabion and first pile cap, pullout forces over and below gabions, pullout force along anchorage length). The long-term (unfactored) tensile strength in the geosynthetic reinforcement, the load on piles, and the load under arching between piles has to be calculated in advance using the Marston's or Hewlett & Randolph methods given in BS 8006-1:2010+A1 (2016). A Factor of Safety for anchorage can be defined as the ratio of the total pullout resisting force mobilized along the full length of the geosynthetic reinforcement beyond the outer pile cap to the long-term (unfactored) tensile strength required in the geosynthetic reinforcement. In the proposed method the anchorage length is determined by trial and error until the calculated Factor of Safety for anchorage exceeds the minimum required value. The method proposed in this paper is readily programmable in a spreadsheet to aid routine design.

2.2 Geometrical values

The model geometry for an embankment of height, H, with a side slope, β, is shown in Fig. 1. The gabion thrust block has a width B_g and a height H_g. The geometric distances shown in Fig. 1 are defined here.

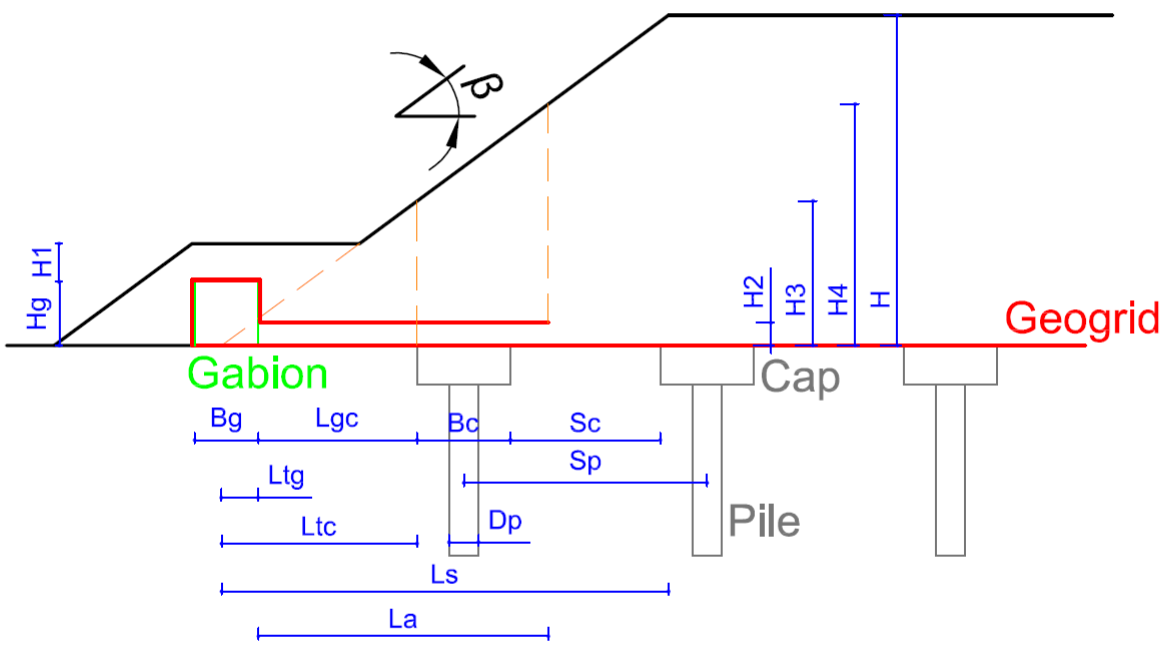

Figure 1. Scheme with geometrical parameters

Horizontal length of embankment slope not including a toe berm (m):

$$L_s = H/tan\beta \quad [1]$$

Horizontal distance between the inner face of the gabion thrust block and outer most edge of the pile cap (m):

$$L_{gc} = L_{tc} - L_{tg} \quad [2]$$

Horizontal distance between gabion and embankment toe (m):

$$L_{tc} = L_{gc} + \mathrm{B_g} - L_s \quad [3]$$

Embankment height over the edge of the outer most pile cap (m):

If $L_{tc} < L_s$: $H_3 = L_{tc}/tan\beta$ [4]

If $L_{tc} \geq L_s$: $H_3 = H$ [5]

Embankment height over the length of the geosynthetic reinforcement, from the inner edge of the gabion to the end of the returned geosynthetic reinforcement La (m):

If $(L_a + L_{tg}) < L_s$: $H_4 = (L_a + \mathrm{L_{tg}})/tan\beta$ [6]

If $(L_a + L_{tg}) \geq L_s$: $H_4 = H$ [7]

Embankment height H_5 over internal inner edge of the gabion (m):

$$H_5 = \mathrm{L_{tg}} \cdot \tan\beta \quad [8]$$

Area of pile cap per unit width A_c (m^2/m), assuming that the center to center spacing of the piles $S_p \geq 1.0$ m:

For circular pile cap: $A_c = \left(\frac{\pi}{4} \cdot B_c^2\right) \cdot \left(\frac{\mathrm{B_c}}{\mathrm{S_p}}\right)$ [9]

For square pile cap: $A_c = (B_c^2) \cdot \left(\frac{\mathrm{B_c}}{\mathrm{S_p}}\right)$ [10]

2.3 Vertical stresses

From the scheme presented in Fig. 2 the vertical stresses acting on the anchor length, between adjacent pile caps and on the piles themselves are defined.

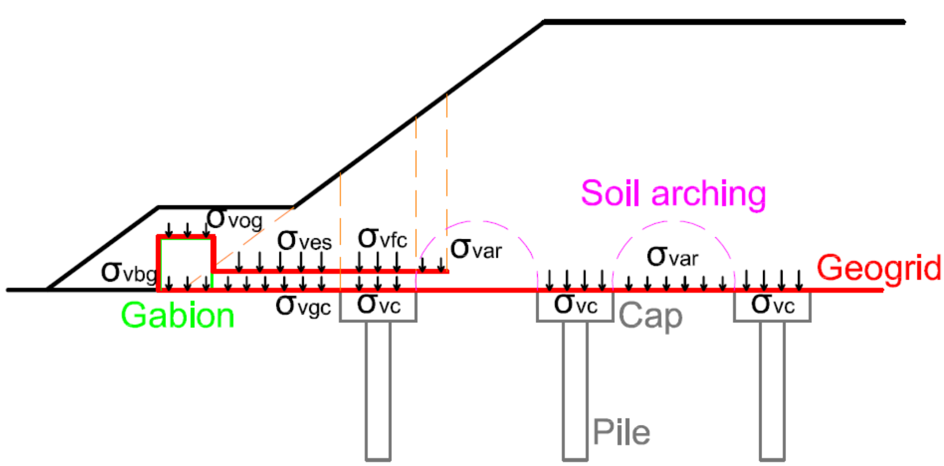

Figure 2. Scheme with vertical stresses

The average vertical stress on pile cap σ_{vc} (kPa):

$$\sigma_{vc} = \left(\frac{V_p}{A_c}\right) \cdot \left(\frac{B_c}{S_p}\right) \quad [11]$$

The average vertical stress between gabions and first pile cap σ_{vgc} (kPa):

$$\sigma_{vgc} = 0.5 \cdot \gamma_f \cdot (H_3 - H_5) \quad [12]$$

where γ_f is the unit weight of fill (kN/m^3).

The vertical stress below gabions σ_{vbg} (kPa):

$$\sigma_{vbg} = \left(\gamma_g \cdot H_g + \gamma_f \cdot H_1\right) \quad [13]$$

where γ_g is the unit weight of the gabion filled with stones (kN/m^3).

The vertical stress over gabions σ_{vog} (kPa):

$$\sigma_{vog} = \left(\gamma_f \cdot H_1\right) \quad [14]$$

The average vertical stress τ_{ves} along anchorage length below embankment slope (kPa):

$$\sigma_{ves} = 0.5 \cdot \gamma_f \cdot \left(H_3 + H_g - 2 \cdot H_2\right) \quad [15]$$

The vertical stress σ_{vfc} along anchorage length above first pile cap (kPa):

$$\sigma_{vfc} = \sigma_{vc} \quad [16]$$

The vertical stress σ_{var} under arching between piles (kPa):

$$\sigma_{var} = W_T \quad [17]$$

2.4 Pullout shear stresses

From the scheme presented in Fig. 3 the shear stresses involved in anchoring the geosynthetic reinforcement can be defined as follows.

Pullout shear stress on first pile cap (contact geosynthetic reinforcement - fill) (kPa) :

$$\tau_1 = f_{pof} \cdot \sigma_{vc} \cdot \tan \varphi_f \quad [18]$$

where f_{pof} is the pullout factor for the contact geosynthetic reinforcement - fill.

Pullout shear stress on first pile cap (contact geosynthetic reinforcement - pile cap) (kPa):

$$\tau_2 = f_{poc} \cdot \sigma_{vc} \cdot \tan \varphi_c \quad [19]$$

where f_{poc} is the pullout factor for the contact geosynthetic reinforcement – pile cap.
Pullout shear stress between gabion and first pile cap (contact geosynthetic reinforcement - subsoil) (kPa):

$$\tau_3 = f_{pos} \cdot \sigma_{vgc} \cdot \tan \varphi_s \quad [20]$$

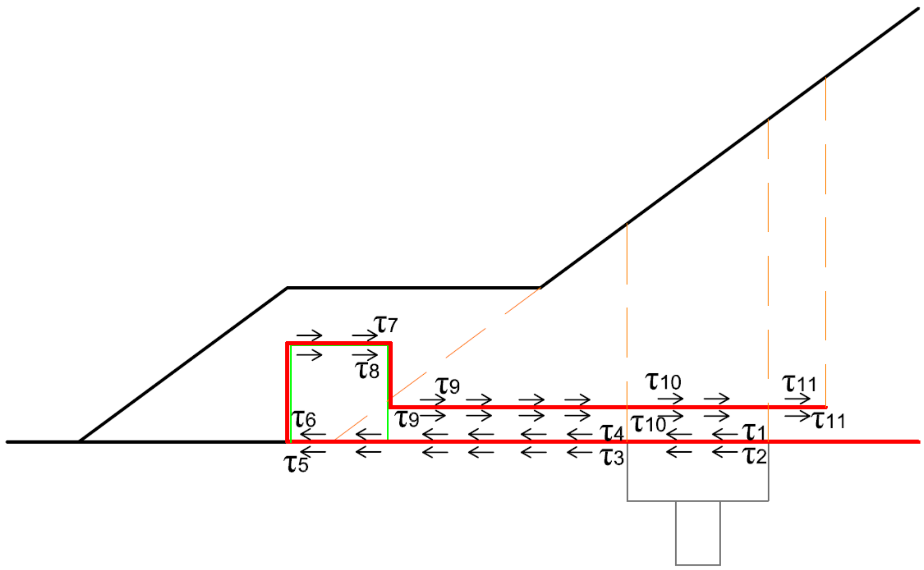

Figure 3. Scheme with shear stresses

where f_{pos} is the pullout factor for the contact geosynthetic reinforcement - subsoil.

Pullout shear stress between gabion and first pile cap (contact geosynthetic reinforcement - fill) (kPa):

$$\tau_4 = f_{pof} \cdot \sigma_{vgc} \cdot \tan \varphi_f \qquad [21]$$

Pullout shear stress below gabions (contact geosynthetic reinforcement - subsoil) (kPa):

$$\tau_5 = f_{pos} \cdot \sigma_{vbg} \cdot \tan \varphi_s \qquad [22]$$

Pullout shear stress below gabions (contact geosynthetic reinforcement - gabion) (kPa):

$$\tau_6 = f_{pog} \cdot \sigma_{vbg} \cdot \tan \varphi_g \qquad [23]$$

where f_{pog} is the pullout factor for the contact geosynthetic reinforcement - gabion.

Pullout shear stress over gabions (contact geosynthetic reinforcement - fill) (kPa):

$$\tau_7 = f_{pof} \cdot \sigma_{vog} \cdot \tan \varphi_f \qquad [24]$$

Pullout shear stress over gabions (contact geosynthetic reinforcement - gabion) (kPa):

$$\tau_8 = f_{pog} \cdot \sigma_{vog} \cdot \tan \varphi_g \qquad [25]$$

Pullout shear stress along anchorage length below embankment slope (contact geosynthetic reinforcement - fill) (kPa):

$$\tau_9 = f_{pof} \cdot \sigma_{ves} \cdot \tan \varphi_f \qquad [27]$$

Pullout shear stress along anchorage length above first pile cap (contact geosynthetic reinforcement- fill) (kPa):

$$\tau_{10} = f_{pof} \cdot \sigma_{vfc} \cdot \tan \varphi_f \qquad [28]$$

Pullout shear stress along anchorage length below arching between piles (contact geosynthetic reinforcement - fill) (kPa):

$$\tau_{11} = f_{pof} \cdot \sigma_{var} \cdot \tan \varphi_f \qquad [29]$$

Where f_{pof}, f_{poc}, f_{pos}, f_{pog} are pullout factors accounting for the interaction between the fill, pile caps, subsoil, gabion and the geosynthetic reinforcement respectively. It has to be noted that the pullout factors are specific to each geosynthetic reinforcement and should be determined by testing or using safe default values.
Note that shear stresses along the vertical faces of the gabion has not been considered, both in favour of safety and due to the very small horizontal stresses that usually occurs against the vertical faces, which prevents the development of significant shear stresses.

2.5 Pullout forces

From the scheme in Fig. 4, and with reference to the shear stresses defined in Fig 3, the pullout forces involved in calculations are defined as follows.

Pullout force on pile cap (kN/m):

$$S_c = (\tau_1 + \tau_2) \cdot A_c \qquad [30]$$

Pullout force between gabions and first pile cap (kN/m):

$$S_{gc} = (\tau_3 + \tau_4) \cdot L_{gc} \cdot 1 \qquad [31]$$

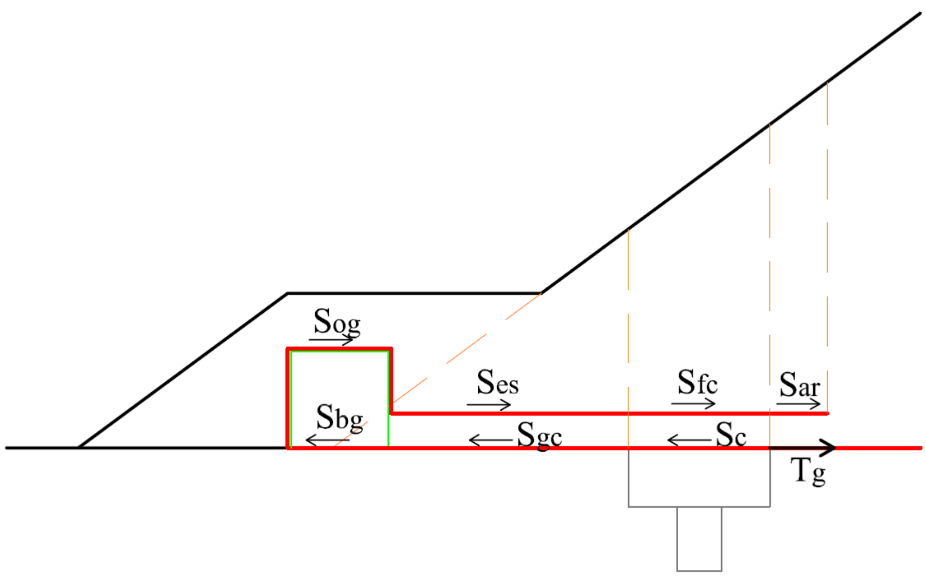

Figure 4. Scheme with tensile and shear forces

Pullout force below gabions (kN/m):

$$S_{bg} = (\tau_5 + \tau_6) \cdot B_g \cdot 1 \qquad [32]$$

Pullout force over gabions(kN/m):

$$S_{og} = (\tau_7 + \tau_8) \cdot B_g \cdot 1 \qquad [33]$$

Pullout force along anchorage length below embankment slope(kN/m):

If $L_a \geq L_{gc}$: $S_{es} = 2 \cdot \tau_9 \cdot L_{gc}$ [34]

If $L_a < L_{gc}$: $S_{es} = 2 \cdot \tau_9 \cdot L_a$ [35]

Pullout force along anchorage length above first pile cap(kN/m):

If $L_a \leq L_{gc}$: $S_{fc} = 0$ [36]

If $L_a \geq (L_{gc} + B_c)$: $S_{fc} = 2 \cdot \tau_{10} \cdot A_c$ [37]

If $L_{gc} < L_a < (L_a - L_{gc})$: $S_{fc} = 2 \cdot \tau_{10} \cdot A_c \cdot \frac{(L_a - L_{gc})}{B_c}$ [38]

Pullout force along anchorage length below arching between piles(kN/m):

If $L_a \leq (L_{gc} + B_c)$: $S_{ar} = 0$ [39]

If $L_a > (L_{gc} + B_c)$: $S_{ar} = 2 \cdot \tau_{11} \cdot [L_a - (L_{gc} + B_c)]$ [40]

The total pullout force(kN/m) is:

$S_{tot} = S_c + S_{gc} + S_{bg} + S_{og} + S_{es} + S_{fc} + S_{ar}$ [41]

2.6 Factor of Safety for anchorage

The Factor of Safety for anchorage can be defined as the ratio of the total pullout resisting force mobilized along the full length of the geosynthetic reinforcement beyond the inner edge of the first pile cap to the long-term (unfactored) tensile strength required in the geosynthetic reinforcement:

$FS_a = S_{tot} / T_g$ [42]

The check is satisfied if:

$FS_a \geq FS_{a,min}$ [43]

where the minimum required Factor of Safety $FS_{a,min}$ is set by the Designer; its suggested value is in the range 1.30 – 1.50.

If the above condition is not satisfied, the anchorage length L_a (m), that is the length beyond the gabion (see Fig. 1), has to be increased by trial and error until a satisfactory Factor of Safety is achieved.

2.7 Total anchorage length

The total length for anchorage (including wrapping length around gabions) $L_{a\text{-}tot}$ (m) is:

$L_{a\text{-}tot} = L_a + 2 \cdot B_g + 2 \cdot H_g - H_2 + L_{gc}$ [44]

3. EXAMPLE

Let's design the anchorage length for the shallow embankment on piles shown in Fig. 5, where the pile load and the ultimate strengths (across embankment and parallel to embankment) of the geosynthetic reinforcement are shown, which has been calculated according to Hewlett & Randolph method (2012), based on the tensile properties, at short and long term, of a family of bonded polyester geosynthetic reinforcement with polyethylene protective coating, commercially known as Maccaferri ParaLink. The input data for this example is summarized in Table 1, while Table 2 presents a summary of the calculation outputs.

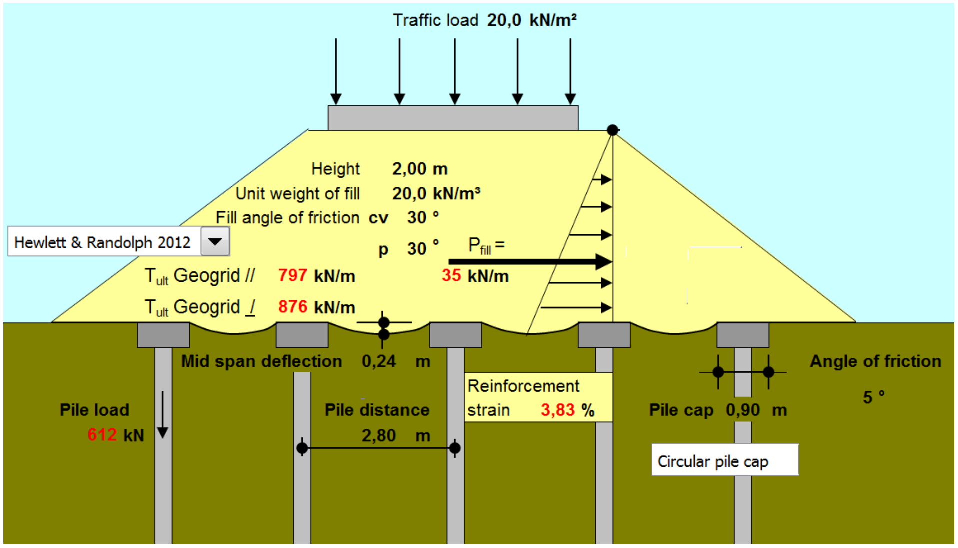

Figure 5. Scheme of the embankment on piles for the Example

Table 1. Input data for Example

PILES GEOMETRY AND LOADS	SYMBOL	VALUE	UNIT
Diameter	D_p	0,50	m
Pile cap size	B_c	0,90	m
Circular pile cap = 1; square pile cap = 2		1	
Pile spacing	S_p	2,80	m
Spacing between pile caps	S_c	1,90	m
Distance toe - first pile cap	L_{tc}	3,00	m
Load on pile caps (from Marston or H&P calculations)	V_p	612,00	kN
Vertical stress under arching between piles (from Marston or H&P calculations)	W_T	121,00	kPa
EMBANKMENT GEOMETRY	**SYMBOL**	**VALUE**	**UNIT**
Height	H	2,00	m
Lateral slope	β	30,00	deg
Moist unit weight of fill	γ_f	20,00	kN/m^3
Friction angle of fill	φ_f	30,00	deg
FOUNDATION SOIL	**SYMBOL**	**VALUE**	**UNIT**
Friction angle (undrained conditions)	φ_{su}	5,00	deg
GABIONS FOR ANCHORAGE	**SYMBOL**	**VALUE**	**UNIT**
Height	H_g	1,00	m
Width	B_g	1,00	m
Unit weight when filled	γ_g	17,00	kN/m^3
Average height of fill on gabions	H_1	0,30	m
Distance toe - inner hedge of gabion	L_{tg}	0,50	m
GEOGRIDS	**SYMBOL**	**VALUE**	**UNIT**
Ultimate tensile strength	T_u	900,00	kN/m
Unfactored tensile strength in geogrids between piles (from Marston or H&P calculations)	T_g	385,00	m
Height of anchorage length on embankment base	H_2	0,20	m
Friction angle geogrid - pile cap	φ_c	30,00	deg
Friction angle geogrid - gabions	φ_g	25,00	deg
PULLOUT FACTORS	**SYMBOL**	**VALUE**	**UNIT**
Pullout Factor contact geogrid - subsoil	f_{pos}	0,60	m
Pullout Factor contact geogrid - gabion	f_{pog}	0,80	m
Pullout Factor contact geogrid - fill	f_{pof}	0,90	m
Pullout Factor contact geogrid - pile cap	f_{poc}	0,80	deg
FACTOR OF SAFETY FOR ANCHORAGE	**SYMBOL**	**VALUE**	**UNIT**
Minimum required Factor of Safety for anchorage	$FS_{a,min}$	1,50	0,00

Table 2. Calculation results for the Example

CALCULATED VALUES	**SYMBOL**	**VALUE**	**UNIT**
Selected anchorage length (length beyond gabion)	L_a	3,70	**m**
GEOMETRICAL VALUES	**SYMBOL**	**VALUE**	**UNIT**
Horizontal length of embankment slope	L_s	3,46	kPa
Horizontal distance between gabion and first pile cap	L_{gc}	2,00	kPa
Embankment height over hedge of first pile cap	H_3	1,73	kPa
Embankment height over hedge of La	H_4	2,00	kPa
Embankment height overover internal hedge of gabion	H_5	0,18	kPa
Area of pile cap per unit width	A_c	0,20	m^2/m
VERTICAL STRESSES	**SYMBOL**	**VALUE**	**UNIT**
Average vertical stress on pile cap	σ_{vc}	962,03	kPa
Average vertical stress between gabions and first pile cap	σ_{vgc}	15,50	kPa
Vertical stress below gabions	σ_{vbg}	23,00	kPa
Vertical stress over gabions	σ_{vog}	6,00	kPa
Average vertical stress along anchorage length below embankment slope	σ_{ves}	23,32	kPa
Vertical stress along anchorage length above first pile cap	σ_{vfc}	962,03	kPa
Vertical stress under arching between piles	σ_{var}	121,00	kPa
PULLOUT SHEAR STRESSES	**SYMBOL**	**VALUE**	**UNIT**
Pullout shear stress on first pile cap (contact geogrid - fill)	τ_1	499,89	kPa
Pullout shear stress on first pile cap (contact geogrid - pile cap)	τ_2	444,34	kPa
Pullout shear stress between gabion and first pile cap (contact geogrid - subsoil)	τ_3	0,81	kPa
Pullout shear stress between gabion and first pile cap (contact geogrid - fill)	τ_4	8,05	kPa
Pullout shear stress below gabions (contact geogrid - subsoil)	τ_5	1,21	kPa
Pullout shear stress below gabions (contact geogrid - gabion)	τ_6	8,58	kPa
Pullout shear stress over gabions (contact geogrid - fill)	τ_7	3,12	kPa
Pullout shear stress over gabions (contact geogrid - gabion)	τ_8	2,24	kPa
Pullout shear stress along anchorage length below embankment slope (contact geogrid - fill)	τ_9	12,12	kPa
Pullout shear stress along anchorage length above first pile cap (contact geogrid - fill)	τ_{10}	499,89	kPa
Pullout shear stress along anchorage length below arching between piles (contact geogrid - fill)	τ_{11}	62,87	kPa
PULLOUT FORCES	**SYMBOL**	**VALUE**	**UNIT**
Pullout force on pile cap	S_c	193,07	kN/m
Pullout force between gabions and first pile cap	S_{gc}	17,74	kN/m
Pullout force below gabions	S_{bg}	9,79	kN/m
Pullout force over gabions	S_{og}	5,36	kN/m
Pullout force along anchorage length below embankment slope	S_{es}	48,47	kN/m
Pullout force along anchorage length above first pile cap	S_{fc}	204,43	kN/m
Pullout force along anchorage length below arching between piles	S_{ar}	100,60	kN/m
Total pullout force	S_{tot}	579,45	kN/m
FACTOR OF SAFETY FOR ANCHORAGE	**SYMBOL**	**VALUE**	**UNIT**
Factor of Safety for anchorage	FS_a	**1,51**	-
TOTAL ANCHORAGE LENGTH BEYOND FIRST PILE CAP	**SYMBOL**	**VALUE**	**UNIT**
Total length for anchorage (including wrapping around gabions)	$L_{a\text{-}tot}$	**9,50**	**m**

Note that, in Fig. 5, the reinforcement strain of 3.83 % is the short term strain which affords, for the given geogrid with the Reduction Factors applicable to this specific design condition, to get the long term strain of 6.0 %, that is the strain limit suggested by BS 8006-1:2010+A1 (2016).

Table 3 reports the results of calculation of FS_a for increasing values of L_a, showing that a specific calculation of L_a is required, while generic specifications (e.g. $L_a \geq 2.0$ m) may be totally unsafe.
It has to be noted that if H is increased to 4.0 m, while all other parameters are kept the same as in Table 1, then L_a = 2.80. If H is increased to 6.0 m, while all other parameters remain constant (Table 1), then L_a = 3.60. It is evident that it is not possible to establish any general rule or any direct proportionality between the height of embankment, the input parameters, and the anchorage length.

Hence the proposed method can be considered as a proper tool for calculating the anchorage length that is required in any given design situation.

Table 3. Variation of FS_a with L_a for Example

L_a (m)	1.00	2.00	3.00	4.00
FS_a	0.65	0.71	1.28	1.60

4. CONCLUSIONS

The paper presents a new rigorous design method for determining the anchorage length of geosynthetic reinforcement on pile as basal reinforcement of embankments on soft soil.
The required anchorage length for geosynthetic reinforcement is calculated considering the long-term (unfactored) tensile strength in the geosynthetic reinforcement, and all the resisting forces (pullout force on pile cap, pullout force between gabion and first pile cap, pullout forces over and below gabions, pullout force along anchorage length).
The long-term (unfactored) tensile strength in the geosynthetic reinforcement, the load on piles and the load under arching between piles have to be calculated in advance, using available methods.
The Factor of Safety for anchorage is defined as the ratio of the total pullout resisting force mobilized along the full length of the geosynthetic reinforcement beyond the inner edge of the first pile cap to the long-term (unfactored) tensile strength required in the geosynthetic reinforcement.
Schemes and formulas for calculating geometrical parameters, vertical stresses, pullout shear stresses, and pullout forces along the various segments of the total anchorage length (including wrapping length around the gabion) have been provided.
In the proposed method the anchorage length is determined by trial and error until the calculated Factor of Safety for anchorage exceeds the minimum required value.
A design example has been provided to show the potentiality of the method.

REFERENCES

BS 8006-1:2010+A1 (2016). Code of practice for strengthened/reinforced soils and other fills. *British Standard Institution*. London, UK.