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Geotechnical Stability of Gabion Walls

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ABSTRACT

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Abstract

The geotechnical stability of the Frontface and the Backface gabion retaining walls under different soil and loading conditions is compared based on the factor of safety achieved using different Eurocode 7 design approaches. The wall is treated as a single gravity entity and a parametric study is performed by varying its breadth-to-height ratio, degree of inclination, surcharge, and soil parameters, which include unit weight and internal friction angle. Factors that significantly influence the geotechnical stability at the Ultimate Limit State (GEO) were found to be the internal friction angle of the backfill and the breadth-to-height ratio of the wall. The eccentricity of the Frontface gabion wall renders it more effective, in terms of the factor of safety achieved with respect to the number of gabion baskets used. At small breadth-to-height ratio, the failure criterion is overturning and at large values of this ratio, the structure is more prone to sliding failure. The choice of a sufficiently conservative design approach therefore depends on the design loads and design material properties involved.

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1. Introduction

Gabion walls are cellular gravity retaining structures consisting of rectangular cages, fabricated from a welded mesh or woven steel wire, filled with ballasted materials of appropriate size and characteristics (British Standards Institution, 1995). As compared to a conventional concrete retaining structure, a gabion wall is significantly less expensive, and can be rapidly constructed by stacking individual units onto each other when quick interventions are needed without the need of specialized skills or equipment (Jayasree, 2008). Eurocode 7 (British Standards Institution, 2004) is used for the design of gravity-retaining structures at Ultimate Limit State (GEO). However, unlike BS 8002 (British Standards Institute, 1994), EC7 does not detail the design of gabion retaining walls. The ULS design involves the application of partial factors from EN1997-1 to typical soil parameters or resistances and to characteristic actions or action effects so as to achieve a certain target reliability (Bauduin et al., 2005; Orr, 2000). Although it was the original aim of EC7 to ensure a unified design approach throughout

Europe, different design approaches have been developed to accommodate varying conditions. The choice of the different design approaches has a substantial effect on the design of geotechnical structures since their corresponding partial factors may not always lead to a level of safety comparable with the conventional global safety concept (López, 2011; Smith & Gilbert, 2011). Furthermore, the application of the partial factors at different levels of calculation yields different results and can have a significant influence on the final design even when the same design approach is being used (Orr et al., 2005). T.L.L. Orr et al. (2005) found that, for gravity retaining structures, the most conservative design approach varies and this is thought to be mainly a result of the way eccentricity and inclination of the surcharge are calculated.

According to BS 8002, (BS, 1994), a gabion wall can be categorized as a permanent structure and should be designed to have a high structural reliability and corrosion-resistant wire-meshes. Gabions are flexible structures which are able to withstand deflections from undercutting or land

slides (Highland & Bobrowsky, 2008). However, Ramli et al. (2013) found out, through a scaled experiment, that the lateral deformation induced by the various loading stages is – irreversible for the walls. This suggests that gabions, regardless of shape or configuration, behave as inelastic structures. According to Jayasree (2008), who carried out finite element analysis on gabion structures, the facing width has negligible effect on the lateral forces developed in the backfill and, therefore, the base is modelled as a strip footing having a constant friction factor with respect to the ground. (Amato et al., 2014) stated that minor design modifications to the gabion baskets would not alter the structural stiffness or strength of the wall. Therefore, the gabion wall has been modelled as a rigid trapezoidal gravity block (Figure 2) under active earth pressures, and verified only at the Ultimate Limit States(GEO). Lahmadiet et al. (2015) highlighted the impact that different of soil parameters in design such as the soil friction angle, unit weight of materials, and geometric ratio and these are varied in this study. Selective results have been plotted and evaluated accordingly in order to determine the parameters that govern the stability of the gravity retaining structure. A spreadsheet was developed and used to reduce repetitive hand calculation and a parametric study was performed to find out the most conservative design approach based on different soil parameters, wall geometry and loading conditions.

2. ULTIMATE LIMIT STATE (ULS) DESIGN ACCORDING TO EN 1997-1

2.1 METHODOLOGY:

According to Eurocode 7, (9.2(2) P), the following failure criteria need to be considered in ULS design:

- Failure by topping,(overturning)
- Failure by sliding on the base,

- Bearing capacity failure of the soil below the base.

The following principle needs to be satisfied (2.4.7.3.1(1)P): $E_d \leq R_d$

Where E_d and R_d are the design values of the ‘effect of actions’ and ‘resistance to the actions’ respectively, both calculated by applying the partial factors given in Table A.3, Table A.4 and Table A.13 in EN1997-1. Different designers have suggested varying methods of applying partial factors in design (Orr et al., 2005; Orr, 2000). The calculation methodology illustrated in Figure 1 has been developed and general equations (Modular Gabion Systems, 2004) have been modified by incorporating partial factors in the equations ((2)-(14)).

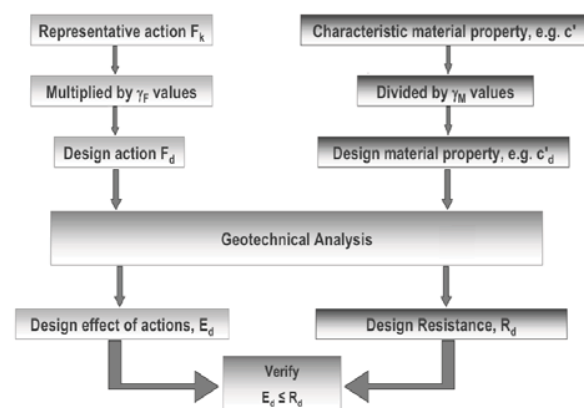


Figure 1: The methodology for the geotechnical analysis at ULS according to EC7.

2.2 MODEL

Rock-filled gabions are gravity structures designed using the same methodology as that employed for gravity walls, which rely on their weight to achieve stability against lateral forces caused by retained soil and surcharge. Igneous rocks, $\gamma_{avg} = 30\text{kN/m}^3$, are most appropriate for gabion fills since they exhibit similar behaviour when used for this purpose (Jayasree, 2008). Water pressure is neglected because of the high void ratio (30-40%) of the gabions.

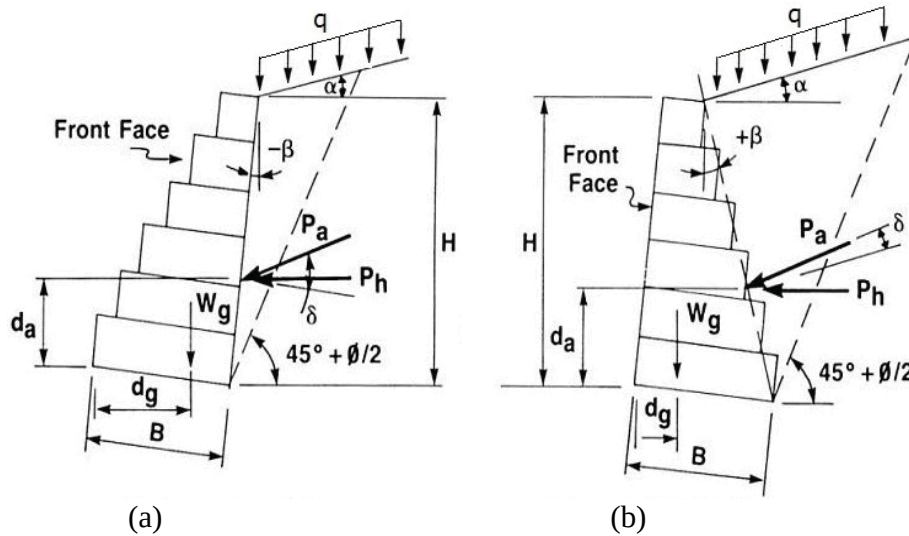


Figure 2: Gabion retaining wall models) (a) Frontface gabion wall, (b) Backface gabion wall.

2.3 SOIL PARAMETERS

According to Simpson (2000), partial factors should be applied as directly as possible rather than to quantities derived later in the calculation. The variation of active earth pressure by the depth of the wall in cohesive-frictional soils has a non-linear distribution. However, the point of application of the pressure always acts at the lower one third of the wall height (Ahmadabadi & Ghanbari, 2009). Applying partial factors, the resultant force of the triangular pressure distribution modifies to:

$$P_a = \frac{K_a \gamma_s H^2}{2 \gamma_G} \gamma_\gamma \quad (2)$$

If a uniformly distributed load, q , is acts vertically on the backfill. Equation (2) is modified to:

$$P_h = K_a \cos \beta \left[\frac{\gamma_s H^2}{2} \gamma_\gamma + q H \gamma_Q \right] \quad (3)$$

The lateral earth pressure coefficient, K_a is given by Coulomb's equation since the values of K_a agree closely to the charts given in the Eurocode (Valsson, 2011).

$$K_a = \frac{\cos^2(\phi_d - \beta)}{\cos^2 \beta \cos(\delta + \beta) \left[1 + \sqrt{\frac{\sin(\phi_d + \delta) \sin(\phi_d - \alpha)}{\cos(\delta + \beta) \cos(\alpha - \beta)}} \right]^2} \quad (4)$$

2.4 OVERTURNING MOMENT CHECK

Taking moment about the toe of the wall yields:

$$M_r \geq SF_o M_o \quad (5)$$

Each moment is calculated from the product of the net force and its perpendicular. If

surcharge is present, the distance from the base at which the P_h acts is:

$$d_a = \frac{H \left[H + \frac{3q}{\gamma_s} \left(\frac{\gamma_\gamma}{\gamma_G} \right) \right]}{3 \left[H + \frac{2q}{\gamma_s} \left(\frac{\gamma_\gamma}{\gamma_G} \right) \right]} + B \sin \beta \quad (6)$$

The overturning moment is:

$$M_o = d_a P_h \quad (7)$$

The resisting moment is:

$$M_r = d_g W_g \quad (8)$$

2.5 SLIDING RESISTANCE CHECK

The lateral earth pressure and the frictional resistance at the base of the wall are related by:

$$\frac{\mu W}{\gamma_{G, fav} \gamma_{RH}} \geq SF_s P_h \quad (9)$$

The soil and gabion friction factor, μ , is approximately $\tan 35^\circ$ (NAVFAC, 1986).

2.6 BEARING PRESSURE CHECK

Owing to their flexibility, gabion walls are appropriate for soil with poor bearing capacity and saturated retained material. According to Lin, Yang, Li, & Zhao, (2009), who observed the behaviour of gabion walls in the laboratory, the

vertical pressure spreads nearly uniformly and is always less than theoretical values. Thus, the Terzaghi bearing-capacity equation can be used, and the need for passive pressure is not essential since there is negligible settlement. The eccentricity, e , of the resultant vertical force from the midwidth of the base, $B/2$ is:

$$e = \frac{B}{2} - \frac{(M_r - M_o)}{W_v / \gamma_{G, fav}} \quad (10)$$

For the resultant force to lie in the middle third:

$$-\frac{B}{6} \leq e \leq \frac{B}{6} \quad (11)$$

The maximum pressure under the base, Q , is then

$$Q = \left[\frac{w_v}{B \gamma_G} \right] \left[1 + \frac{6e}{B} \right] \quad (12)$$

The maximum pressure must not exceed the allowable soil bearing pressure, Q_{ult} :

$$Q \gamma_{RV} \leq S F b Q_{ult} \quad (13)$$

Where Q_{ult} is given by Terzaghi's bearing-capacity equation.

$$Q_{ult} = \gamma_c N_c c' + \gamma_q N_q q + 0.5 \gamma_r N_r B \gamma \quad (14)$$

3. RESULTS AND DISCUSSION

This is performed by analyzing at least 3 graphs per external stability checks for every parameter varied listed below. The results are plotted in graphs showing the factor of safety against various wall heights for every fixed geometric ratio, B/H .

Table 1: Parameters studied

Parameter	Graph						
	1	2	3	4	5	6	7
Height, H (m)	2 - 10	2 - 10	2	2	2	2	2
Width, B (m)	0.5H	0.5H	0.4 - 4	1	1	0.2 - 4	0.2 - 4
Horizontal inclination, α ($^\circ$)	5	5	5	0-10	5	5	5
Vertical inclination, β ($^\circ$)	-5	+5	± 5	-10 - 10	± 5	0	0
Surcharge, q (kN/m 2)	10	10	10	0 - 10	10	10	10
Cohesion, c (kN/m 2)	0	0	0	0	0	0	0
Unit Weight of basket, γ_b (kN/m 3)	21	21	21	21	21	21	21
Unit Weight of soil, γ_s (kN/m 3)	14	14	14	14	14 - 24	14	14
Friction angle, ϕ ($^\circ$)	35	35	35	35	35	20 - 50	20 - 50
Friction factor, δ ($^\circ$)	35	35	35	35	35	35	35

3.1. EFFECT OF USING DIFFERENT DA FOR CALCULATION

—◆— B-EQU LIMIT	—■— B-DA1C1	—▲— B-DA1C2	—✕— B-DA2	—✱— B-DA3C1	—●— B-DA3C2
—◆— O-EQU LIMIT	—■— O-DA1C1	—▲— O-DA1C2	—✕— O-DA2	—✱— O-DA3C1	—●— O-DA3C2
—◆— S-EQU LIMIT	—■— S-DA1C1	—▲— S-DA1C2	—✕— S-DA2	—✱— S-DA3C1	—●— S-DA3C2

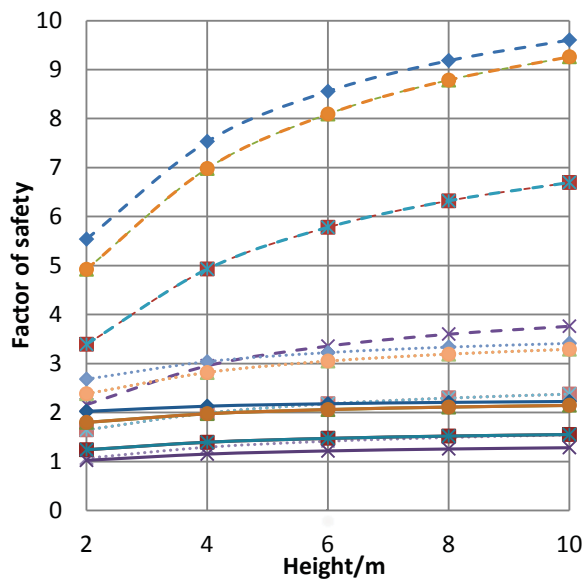


Figure 4: Effect of varying height on Front face wall for different design approaches

Graphs show that the Frontface gabions walls provide a higher factor of safety and are more effective than Backface gabions walls for the same number of baskets used and subjected to the same conditions. It is suggested that DA1C2, which overlaps with DA3C2, is the least conservative followed by DA1C1, DA3C1 and finally DA2, which is the most conservative design approach for all the three external stability checks. Even though the geometric ratio, B/H was kept constant at 0.5, the factor of safety achieved increased with increased height

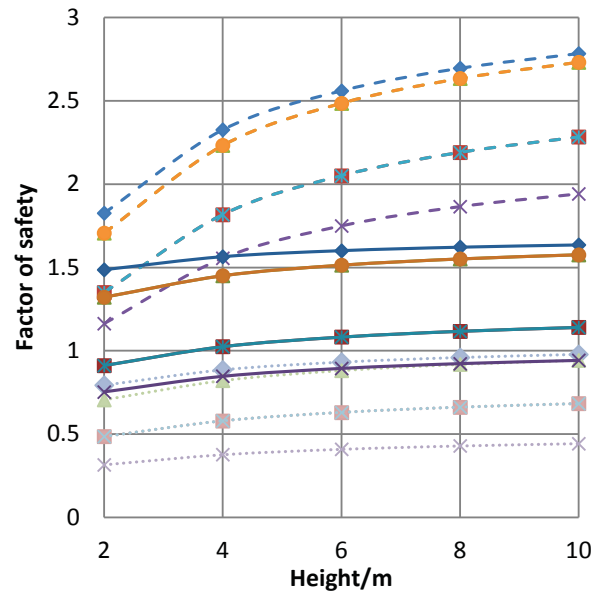


Figure 5: Effect of varying height on Back face wall for different design approaches

in both cases. Thus even if the height, H , increase is compensated by the same amount in terms of base width, B , the factor of safety still increases for overturning and bearing failure. Frontface gabion walls are expected to fail by sliding whereas Backface gabion walls are more prone to overturning. Bearing failure is less likely to happen in both cases. The similarity of both graphs suggests that the geometric ratio affects both of the walls.

3.2. EFFECT OF B/H RATIO

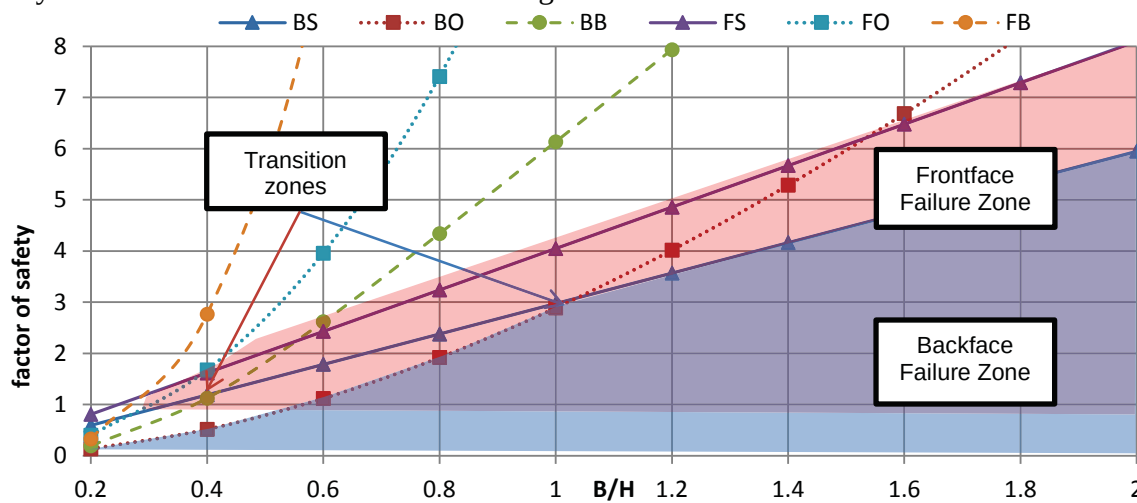


Figure 6: Effect of varying breadth-height ratio of retaining walls

An increase in B/H ratio increases the factor of safety for all cases. The increase in bearing capacity was found to be most significant. The curves for both cases are similar and as the geometric ratio increases, failure starts by overturning failure followed by sliding. This confirms that the stability of the walls is not affected by height, but by the B/H ratio. To find this changing point the equation of

overturning(5) is equated to the equation for sliding(9). This gives:

$$d_g = \mu d_a \quad (15)$$

Hence, the centroid of the gabion wall is the determining factor since μ and d_a were constant in both cases. Apart from the eccentricity, the inclination angle, β , of the gabion is the only difference in both cases.

3.3. INCLINATION ANGLE AND SURCHARGE

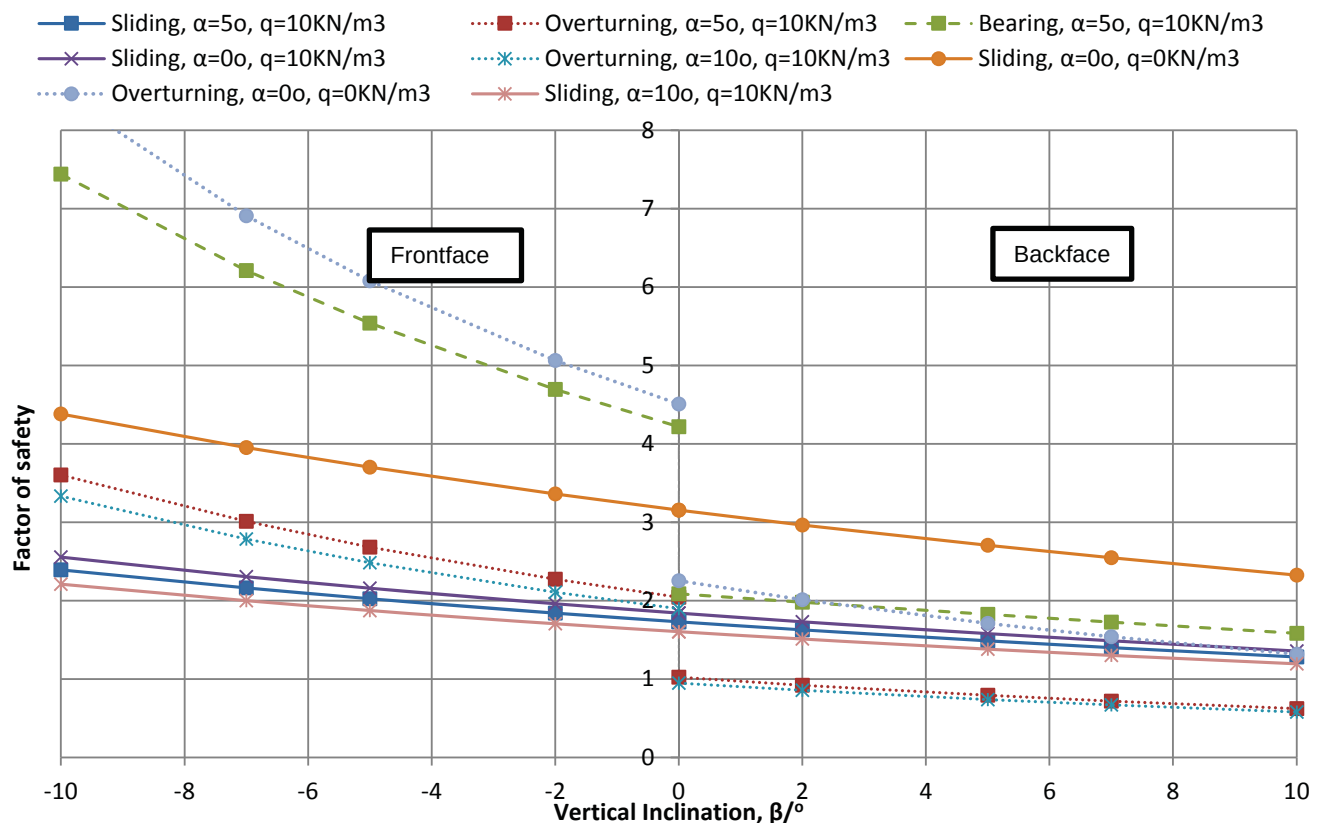


Figure 7: Effect of inclination angles

For a Frontface gabion, increasing the angle from the vertical increases the factor of safety against failure whereas for a Backface gabion, a greater inclination lowers the stability as the eccentricity decreases. Increasing surcharge decreases the factor of safety and this effect was found to be very significant as far as overturning failure is concerned. Surcharge has a maximum effect when the angle of horizontal inclination, α is 0° . When there is no inclination, the factor of safety against sliding is the same for both walls.

It can be concluded that surcharge and the angle of inclination from the horizontal affect both walls equally. The factor of safety against overturning is significantly higher in Frontface and suggests that Frontface is more resistant to topping failure.

3.4. EFFECT OF UNIT WEIGHT OF SOIL TO WALL STABILITY

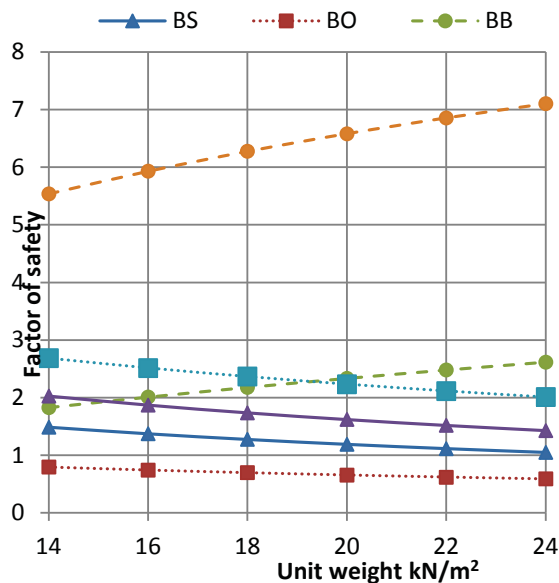


Figure 8: Effect of increasing unit weight of backfill

Variations in the unit weight of the backfill do not significantly affect the factor of safety achieved. The factors of safety for sliding and overturning are related to the unit weight of ballast and the unit weight of soil. It was observed that when the unit weight of soil is approximately equal to the unit weight of the gabion, the factor of safety did not change with increase in height at constant B/H. Increasing the unit weight of soil decreases the factor of safety in both cases since the lateral force acting on the gabion increases. The increase of weight of the ballast provides more stability since the normal force is increased. Lowering the value of the unit weights has the reverse effect. i.e decreasing the ballast unit weight will lower the factor of safety against sliding and overturning. However, a significant increase in the unit weight of the ballast leads to bearing capacity failure. The bearing capacity increased when the unit weight of the backfill was increased.

3.5. EFFECT OF FRICTION ANGLE



The previous section leads to the conclusion that the failure criterion of all design approaches starts from overturning failure followed by sliding failure. Figure 9 and 10 serve to verify if the choice of the design approaches has an effect on the failure criterion.

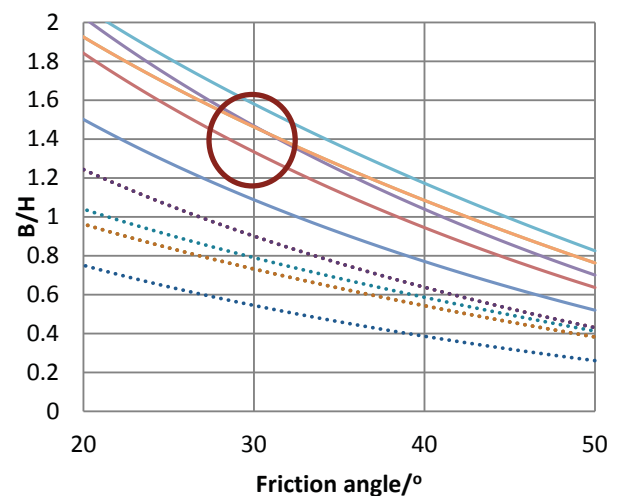
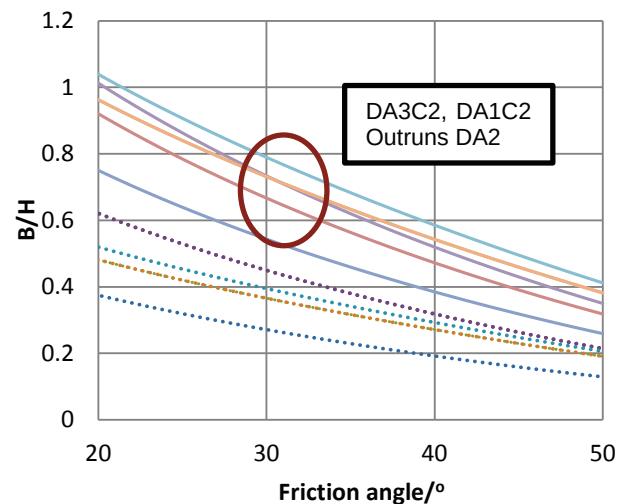


Figure 9: B/H vs ϕ for Frontface wall

Figure 10: B/H vs ϕ for Backface wall

With an increase in the friction angle of the retained soil, the B/H ratio increases because the lateral force acting on the wall decreases with a decrease in the active pressure coefficient. DA3C1 is the most conservative design followed by DA1C2, which is overlapped, by DA3C2, followed by DA2 and DA1C1 for sliding. However, as the friction angle increases, DA1C1 outruns DA2. For overturning DA3C2 and

DA1C2 are most conservative, followed by DA3C1, DA2, and then DA1C1. Therefore, the choice of the design approach for the most conservative design varies according to the material that is retained and the breadth-to-height ratio of the retaining structure. This final graph confirms that the Frontface gabion is the best choice for a gabion retaining structure. Therefore, it is believed that at large friction angles, DA1C1 and DA3C2 are more sensitive to the friction angle than to the unit weight of soil.

4. CONCLUSION

Backface gabions are more effective than Frontface gabions since the factor of safety against all geotechnical failure criteria achieved by the Backface gabion is higher than that achieved by the Frontface under the same soil conditions. It has been found that as the B/H ratio of the gravity walls increases, the failure criterion shifts from overturning to sliding and it is suggested that the failure mode is a function of the eccentricity of the structure. Frontface and Backface gabions are more resistant to topping failure and sliding failure respectively. The failure criterion was found to be independent of height for constant B/H ratio, inclination angles, β and α , surcharge and unit weight of soil retained by the gabion walls. An increase in the degree of inclinations of the wall from the vertical improved stability for the Frontface gabion wall while the reverse effect occurred for the Backface wall. It is found that sliding stability is the same for both walls when there is no inclination. The most conservative design approach is DA2 for low friction angles and DA1C2 when the friction angle becomes large and material parameters have greater effect. The exact point at which the choice of the most conservative design approach changes depends on the material parameters and loading conditions involved. Sliding failure was also found to be unaffected by an increase in height at constant B/H ratio and when the unit weight of the soil retained was approximately equal to the unit weight of the gabion basket. Bearing

failure is unlikely to happen in both cases except for realistically small B/H. DA2 was most affected by actions while DA1C2 by soil parameters. DA1C1 and DA3 were affected by both actions and soil parameters. Overall stability is mostly affected by the internal friction angles of the retained soil and the ratio B/H.

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Notation List

B	breadth of wall (m)	W_v	resultant vertical force (w_g) (kN)
BB	bearing capacity of Backface wall	X_i	distance to the local centroid of the area A_i (m)
BO	overturning of Backface wall	Y_i	height of section corresponding to X_i (m)
BS	sliding of Backface wall	b	width of a gabion basket (m)
B-XXX	bearing capacity of design approach xxx	c	cohesion of soil(kPa)
DA1C1	design approach 1 combination 1	d_a	distance from base to equivalent force acting (m)
DA1C2	design approach 1 combination 2	d_g	distance from to to centroid (m)
DA2	design approach 2	e	eccentricity (m)
DA3C1	design approach 3 combination 1	h	height of a gabion basket (m)
DA3C2	design approach 3 combination 2	n	number of gabion basket
EC7	Eurocode 7	p_a	active earth pressure (kN)
FB	bearing capacity of Frontface wall	p_h	horizontal component of earth pressure (kN)
FO	overturning of Frontface wall	q	surcharge (kPa)
FS	sliding of Frontface wall	α	angle from the horizontal to the slope of backfill (°)
-XXX	bearing capacity of design approach XXX	β	angle of Backface slope with vertical (°)
K_a	coefficient of active earth pressure	γ_s	unit weight of backfill (kN/m ³)
M_o	overturning moment (kN/m)	γ_b	unit weight of 1 gabion basket (kN/m ³)
M_r	resisting moment (kN/m)	γ_G	partial factor for unfav permanent actions
N_c	Terzaghi coefficient for cohesion (kPa)	$\gamma_{G,fav}$	partial factor for favourable permanent actions
N_q	Terzaghi coefficient for overburden (kPa)	γ_Q	partial factor for unfav. variable actions
N_γ	Terzaghi coefficient for self-weight (kPa)	$\gamma_{Q,fav}$	partial factor for favourable variable action
O-XXX	overturning of design approach XXX	γ_{RH}	partial factor for sliding resistance
Q_{ult}	ultimate bearing capacity (kPa)	γ_{RV}	partial factor for bearing resistance
Q	bearing capacity (kPa)	$\gamma_{c'}$	partial factor for effective cohesion
SF_b	factor of safety against bearing failure	γ_θ	partial factor for coefficient of shearing resistance
SF_o	factor of safety against overturning	γ_γ	partial factor for unit weight, γ
SF_s	factor of safety against sliding	ϕ	internal friction angle of soil (°)
S-XXX	Sliding of design approach XXX	δ	friction factor between wall and ground (°)
W_g	weight of gabion wall (kN)	μ	coefficient of the sliding friction, $\tan\phi$ (°)