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DESIGNING GABION STRUCTURES UNDER MULTI-CRITERIA OBJECTIVES WITH GOAL PROGRAMMING

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ABSTRACT: Gabion structure is a set of stacked prefabricated cages filled with rocks. These gabion cages are made of steel wire, polypropylene, polyethylene, or nylon. Constructing these gabion cages usually follows supplier guidelines or governmental agency design standards. Designing this gabion structure, at a minimum, must satisfy many design criteria in passing external stability in sliding, overturning, and bearing capacity of the foundation. Good gabion design requires a balance of the toe bearing stress and heel bearing stress. With this requirement for the design of gabion structures to meet multi-criteria objectives, goal programming, which is a multi-criteria optimization technique, is used in this study. A 3-meter gabion example is used as a based design. Then, mixed integer nonlinear programming is introduced to rearrange a set of varying sized gabion cages to minimize the gabion weight and passing external stability criteria. Two goal programming models are introduced to meet the two design criteria in minimizing gabion weight and balancing the vertical stresses. The two goal programming models give the same optimum solution with the minimum weight of 48 kN/m and eccentricity of 0.002 meter. In contrast, the original example gives the weight of 61.92 kN/m and eccentricity of 0.086 meter.

Keywords: Gabion, Goal programming, Multi-criteria decision making, Retaining wall

1. INTRODUCTION

1.1 Gabions

Gabions are large cages or baskets usually of steel wire or square welded mesh, rectangular in shape, filled with stone. These cages or boxes are widely used in construction works as a retaining structure, erosion protection, coastal protection, pipe protection, and other usages such as protecting buried pipes [1]. Gabion retaining systems are gravity structures that use their self-weight to resist the lateral earth pressure behind it and to support any vertical surcharge resting on top of the gabion structure.

The gabion cages typically are 2 meters long, 1-meter-wide, and 1-meter-high shown in Fig 1. ASTM A975 [2] provides gabion sizes with 1 meter in width, varying lengths of 2, 3, 4 meters, and varying heights of 1, 0.5, 0.3 meters. BS8002 [3] also gives gabion shapes of 2 to 6 meters in lengths, 1 to 2 meters in widths, and 0.3, 0.5, 1 meter in depths.

1.2 Gabion Structures

Arranging different sizes of gabions can facilitate the design of a gabion wall. The gabion wall can be shaped in front slope, rear slope, or trapezoidal shape shown in Fig.2. Flexibility in gabion shapes and sizes leaves room for improvement to utilize optimization techniques in setting gabion walls.

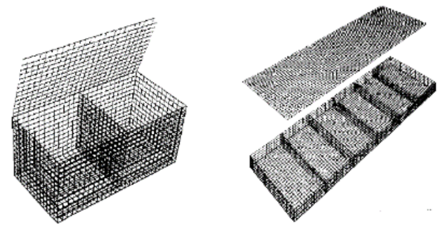

Fig. 1 Gabion (left) and mattress (right) from BS8002 [3]

Front Slope Rear Slope Trapezoidal

Fig. 2 Gabion wall shapes from BS8002 [3]

1.3 Designing Gabion Structures

Designing a gabion structure as a gravity wall shown in Fig. 2 needs to meet external stability in sliding, bearing, and overturning. There is no need for internal stability checking except using gabions as a facing unit and combined with other reinforcements. The reinforcement can be geogrid or even anchors shown in Fig. 3. Global stability checking is also omitted since the global stability depends on the actual site location and the global stability can be checked either using limit equilibrium method (LEM) or finite difference method (FEM) by using the software. Some studies illustrate LEM and FEM analysis such as [4].

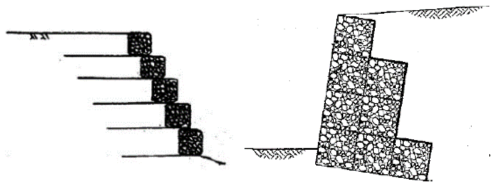

Fig. 3 Gabion facing with geogrid reinforcement (left) from FHWA-NHI-10024 [5] compared with traditional gabion gravity wall (right) from FHWA-SA-96-038 [6]

1.4 Optimization Techniques Used in Designing Gabion Structures

Designing a gabion structure is a constrained optimization problem since the design needs to be the most economical as possible while still needs to satisfy all stability constraints. Also, designing a gabion structure faces many multi-criteria by nature as aforementioned. Of course, the first objective is to design the most economic and safe solution. Another objective, for example, is to equalize the vertical stress at the toe and the vertical stress at the heel of the gabion structure as recommended by Enviromesh [7].

Optimization techniques has been used in geotechnical area. Dungca [8] applies linear programming of soil mixes in the design vertical cut-off walls. Some studies apply optimization techniques in designing retaining walls, such as Saribas [9] that uses a nonlinear optimization model in designing reinforced concrete-cantilever retaining walls. Basudhar [10] applies a nonlinear cost optimization model in designing mechanically stabilized earth (MSE) walls by using sequential unconstrained minimization technique (SUMT) instead of directly solving a nonlinear optimization model, which may not guarantee the exact solution. There is no paper directly using optimization techniques in designing a gabion wall.

This paper first proposes a mixed integer nonlinear programming model (MINLP) to design a gabion wall in which MINLP is frequently used in engineering such as [11]. MINLP are also applied to civil engineering [12] such in structural design [13], construction management [14], etc. Less complicate optimization techniques such as mixed integer linear programming (MIP) is also used in transportation such as maritime logistic network [15]. After applying MINP to the proposed gabion design optimization models, this paper then applies the goal programming approach to the proposed MINP models. This goal programming approach is suitable to handle multiple objectives in designing a gabion wall. Using goal programming is well described in [16].

1.5 Aims and Scope

This paper aims to introduce an optimization approach to rearrange gabion cages as a retaining wall to achieve minimum weight and balanced vertical stresses. Achieving these two objectives using a manually calculated spreadsheet will involve many trial and error in inputting the numbers to stack the varying sized gabion cages. The optimization models proposed in designing this gabion wall are goal programming applied to mixed integer nonlinear programming model using GAMS software with MINLP solver. The flow chart outlining the key steps in this paper is shown in Fig. 4.

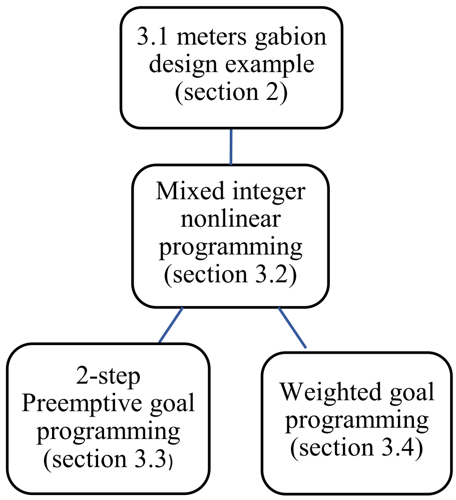

Fig. 4 Flow chart outlining the key steps

The paper begins with a design example from [7] that exemplifies the two models (27 system and 39 system) suggested by [7]. The paper then proposes a one-step mixed integer nonlinear programming optimization model that tries to minimize the gabion weight by rearranging the varying sized gabion cages. The set of constraints is only the external stability in sliding, overturning, and bearing. Both internal stability and global stability are not considered in this paper. Then two goal programming models are introduced, which are the preemptive goal programming model and the weighted goal programming. These goal programming models are used to make a design that meets two objectives in minimizing weights and balance vertical stress. Issues in handling local optimality and convergence problems of mixed integer nonlinear programming are also addressed.

Due to space limitations, this paper is scoped only one example of a 3 meters gabion wall provided by Enviromesh [7]. The results of optimization models are also compared with the example from [7]. However, this approach can be applied to design a gabion wall with any height or with more design criteria.

1.6 Research Significance

This paper applies two goal programming models: the preemptive goal programming and the weighted goal programming, to a mixed integer nonlinear programming (MINP) model to redesign an original 3.1 meters gabion wall. The proposed models can achieve minimum weight and balanced vertical stresses while passing external stability in sliding, overturning, and bearing. Using MINP can make the most economical and safe design, which is difficult to calculate haphazardly via a spreadsheet. Goal programming approach is also helpful if there is more than one objective to achieve in the design while MINP alone can achieve only one objective.

2. DESIGN EXAMPLE

Enviromesh [7] gives a design example of 3.1 meters gabion wall with a total cross-section area of 3.87 m^2 shown in Fig. 5.

2.1 Design Parameters

From Enviromesh [7] example, the design parameters are as follows.

2.1.1 Geometry

Wall height, H = 3.1 meters where y_1 = 1.0 meter, $y_2 = y_3 = y_4$ = 0.7 meter and b_w = 1.7, b_2 = 1.4 , b_3 = 1.0 , b_4 = 0.7 meters.

The slope angle of the retained soil, ε, is 15 degrees.

Wall inclination, α, is 10 degrees.

2.1.2 Materials

Soil friction angle, ϕ, is 28 degrees.

Soil density, γ = 19 kN/m^3.

Gabion density, γ_g= 16 kN/m^3.

Foundation soil density, γ_f= 19 kN/m^3.

Foundation soil internal friction angle, $\emptyset_f$, is 30 degrees.

2.1.3 Bearing capacity parameters

The bearing capacity parameters are defined by the following equations from Meyerhof [17].

$$N_q = e^{\pi tan\emptyset} tan^2(45 + \emptyset/2) = 18.4 \quad (1.1)$$

$$N_c = cot\emptyset(N_q - 1) = 30.1 \quad (1.2)$$

$$N_\gamma = (N_q - 1)tan1.4\emptyset = 15 \quad (1.3)$$

2.1.4 Other parameters

Surcharge, P_0 = 10 kN/m^2.

The Inclination angle to the vertical plane, β, is 94.46 degrees.

The retained wall friction reduction by geotextile, δ, is 28 degrees where $\delta = \phi$ if no geotextile or 0.9ϕ with geotextile.

Active earth pressure coefficient [17], K_a = 0.364 where

$$K_a = \frac{sin^2(\beta+\phi)}{sin^2\beta \sin(\beta-\delta)\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\varepsilon)}{\sin(\beta-\delta)\sin(\beta+\varepsilon)}}\right]} \quad (2.1)$$

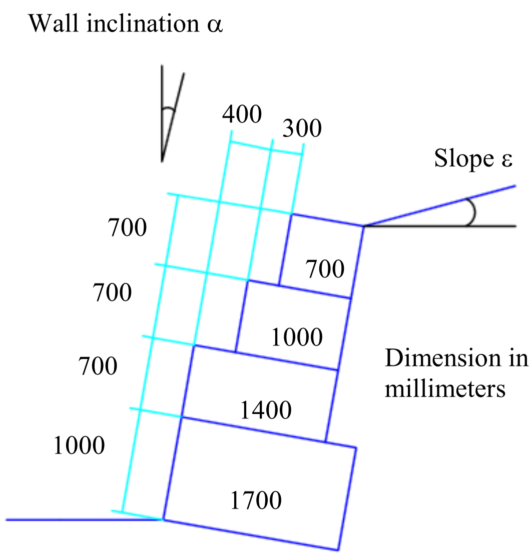

Fig. 5. The dimension of gabion structure from Enviromesh designed example [7]

The triangular pressure acting on the wall, P_a = 43.4 kN shown in Fig. 6 where

$$P_a = 0.5K_a\gamma H^2 + P_0K_aH \quad (2.2)$$

Horizontal component P_h = 39.8 kN where

$$P_h = P_a\cos(90 - \beta + \delta) \quad (2.3)$$

Vertical component P_v = 17.3 kN where

$$P_v = P_a\sin(90 - \beta + \delta) \quad (2.4)$$

2.2 Variables

The variables are as the followings.

Vertical distance to P_a, d_h = 0.852 meter. From

$$d_h = \frac{H}{3}(H + \frac{3P_0}{\gamma})/(H + \frac{2P_0}{\gamma}) - b_w sin\alpha \quad (3.1)$$

$$d_h = d_h^{\prime} - b_w sin\alpha \quad (3.2)$$

as shown in Fig 7, from the moment equivalent

$$\left(\frac{1}{2}\gamma_s H + P_0\right) d_h^{\prime} = \frac{1}{2}\gamma_s H \frac{H}{3} + P_0 \frac{H}{2}.$$

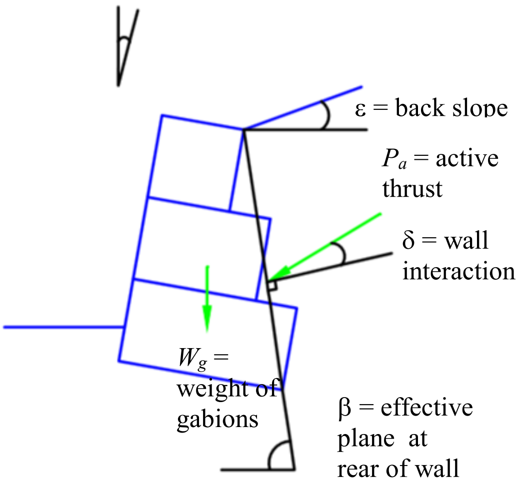

Fig. 6 Coulomb active earth pressure from Enviromesh [7]

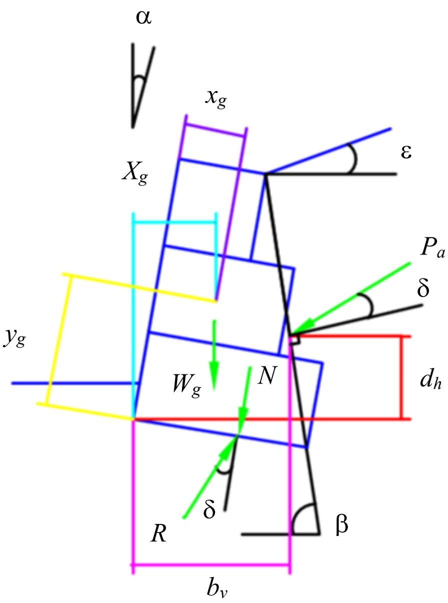

Fig. 7. d_h and b_v from Enviromesh [7]

Resisting moment,The horizontal distance from the toe to P_a, b_v = 1.741 meters shown in Fig. 7,

$$b_v = b_w cos\alpha - d_h / tan\beta \quad (3.3)$$

Horizontal distance to W_g shown in Fig. 7,

$$X_g = x_g cos\alpha + y_g sin\alpha \quad (3.4)$$

$$M_r = P_v b_v + W_g X_g \quad (3.5)$$

Overturning moment,

$$M_o = P_h d_h \quad (3.6)$$

Safety factor against overturning,

$$FS_O = M_r / M_O \quad (3.7)$$

Normal force on the plane of sliding,

$$N = W_g + P_v \quad (3.8)$$

Tangential force,

$$T = P_h \quad (3.9)$$

Sliding resistance,

$$F_r = (N cos\alpha + T sin\alpha) tan\phi \quad (3.10)$$

Driving force,

$$F_d = T cos\alpha - N sin\alpha \quad (3.11)$$

Safety factor against sliding,

$$FS_s = F_d / F_r \quad (3.12)$$

Reaction eccentricity,

$$e = \frac{b_w}{2} - \frac{M_r - M_o}{N} \quad (3.13)$$

where e is a free variable that is unrestricted in sign. Note that negative eccentricity causes reverse overturning to the backside (earth-filled) of the wall. Vertical stress at the toe,

$$\sigma_t = \frac{N}{b_w}\left(1 + \frac{6e}{b_w}\right) \quad (3.14)$$

where vertical stress at the heel,

$$\sigma_h = \frac{N}{b_w}\left(1 - \frac{6e}{b_w}\right) \quad (3.15)$$

Allowable soil bearing stress,

$$q_a = P_0 N_q + 0.5\gamma_s b_w N_\gamma \quad (3.16)$$

Safety factor against the bearing,

$$F_b = \sigma_t / q_a \tag{3.17}$$

2.3 Design Output

Enviromesh [7] provides two approaches to design gabion systems. One is called "gabion 27 system". Another is called "gabion 39 system". For this 3-meter height gabion structure example. The 27 system has four layers, and the 39 system has three layers. The gabion 27 system with four layers is already illustrated in the calculation previously. The output for these two systems is compared and later shown in Table 2.

3. OPTIMIZATION MODELS

Optimization techniques are applied here. Three models are proposed. The first model is a mixed integer nonlinear programming (MINP) model. The other two models are goal programming models. One is a preemptive goal programming model. Another is a weighted goal programming model.

The design parameters for the three models are as follows:

3.1 Design Parameters

The 3.1-meter design example from Enviromesh [7] is borrowed here. The geometrical parameters, soil parameters, and calculated constants are shown in Table 1.

From Table 1, Instead of using the original Enviromesh example with four layers of gabions as mentioned before, this model uses 6 gabion layers with $y_1 = y_2 = y_3 = y_4 = y_5 = y_6 = 0.5$ meter. The vertical centroids for the six gabion layers are calculated as follow:

Height direction centroid

$$yy_1 = y_1/2 = 0.25 \tag{4.1}$$

$$yy_2 = y_1 + y_2/2 = 0.75 \tag{4.2}$$

$$yy_3 = y_1 + y_2 + y_3/2 = 1.25 \tag{4.3}$$

$$yy_4 = y_1 + y_2 + y_3 + y_4/2 = 1.75 \tag{4.4}$$

$$yy_5 = y_1 + y_2 + y_3 + y_4 + y_5/2 = 2.25 \tag{4.5}$$

$$yy_6 = y_1 + y_2 + y_3 + y_4 + y_5 + y_6/2 = 2.75 \tag{4.6}$$

3.2 Mixed Integer Nonlinear Programming

Mixed integer nonlinear programming (MINP) model minimizes the minimum gabion weight while satisfying the external stability constraints in sliding, overturning, and bearing stability. This is done by adjusting the decision variables

Table 1 Geometrical parameters, soil parameters, and calculated constants

Description	Symbol	Value	Unit
Slope angle of the retained soil	ε	15	degrees
Inclination angle to the vertical plane	β	94.46	degrees
Soil cohesion	c	0	kPa
Soil internal friction angle	ϕ	28	degrees
Soil density	γ	19	kN/m^3
Retained wall friction reduction by geotextile	δ	28	degrees
Wall inclination	α	10	degrees
Surcharge	P_0	10	kPa
Base layer height	y_1	0.5	meter
2nd layer height	y_2	0.5	meter
3rd layer height	y_3	0.5	meter
4th layer height	y_4	0.5	meter
5th layer geight	y_5	0.5	meter
6th layer height	y_6	0.5	meter
Active earth pressure coefficient	K_a	0.364	
Triangular pressure acting on the wall	P_a	43.4	kN
Horizontal component	P_h	39.8	kN
Vertical component	P_v	17.3	kN
Bearing capacity depth factor	N_q	18.4	
Bearing capacity shape factor	N_c	30.1	
Bearing capacity inclination factor	N_γ	15.7	

3.2.1 Objective function

$$Min\ W_g \qquad \text{(O1: MINP)}$$

3.2.2 Decision variables

b_w: gabion width (m) at the base layer

b_i : gabion width (m) at layer i, i = 2, 3, 4, 5, 6

x_{Fi}: offset (m) of gabion at the front at layer i, i = 2, 3, 4, 5, 6
x_{Bi}: offset (m) of gabion at the back at layer i, i = 2, 3, 4, 5, 6
i_w: positive integer variable of gabion wall width at the base.
i_i: positive integer variable of gabion wall width at layer i, i = 2, 3, 4, 5, 6

3.2.3 Constraints
Widths

$b_2 = b_w - x_{2F} - x_{2B}$ (C1.1: layer 2)

$b_3 = b_2 - x_{3F} - x_{3B}$ (C1.2: layer 3)

$b_4 = b_3 - x_{4F} - x_{4B}$ (C1.3: layer 4)

$b_5 = b_4 - x_{5F} - x_{5B}$ (C1.4: layer 5)

$b_6 = b_5 - x_{6F} - x_{6B}$ (C1.5: layer 6)

Integer widths

$b_w = 0.5 i_w$ (C2.1: base)

$b_2 = 0.5 i_2$ (C2.2: layer 2)

$b_3 = 0.5 i_3$ (C2.3: layer 3)

$b_4 = 0.5 i_4$ (C2.4: layer 4)

$b_5 = 0.5 i_5$ (C2.5: layer 5)

$b_6 = 0.5 i_6$ (C2.6: layer 6)

At least one integer widths

$b_w \geq 1, b_2 \geq 1, b_3 \geq 1, b_4 \geq 1, b_5 \geq 1, b_6 \geq 1$

(C3.1 - C3.6: $\geq$ 1 integer width)

Gabion weight

$W_g = \gamma_g(y_1 b_w + y_2 b_2 + y_3 b_3 + y_4 b_4 + y_5 b_5 + y_6 b_6)$ (C4: gabion weight)

Base direction centroids

$xx_1 = b_w/2$ (C5.1: base)

$xx_2 = x_{2F} + b_2/2$ (C5.2: layer 2)

$xx_3 = x_{2F} + x_{3F} + b_3/2$ (C5.3: layer 3)

$xx_4 = x_{2F} + x_{3F} + x_{4F} + b_4/2$ (C5.4: layer 4)

$xx_5 = x_{2F} + x_{3F} + x_{4F} + x_{5F} + b_5/2$ (C5.5: layer 5)

$xx_6 = x_{2F} + x_{3F} + x_{4F} + x_{5F} + x_{6F} + b_6/2$ (C5.6: layer 6)

Base direction moments

$xxm_1 = y_1 b_w xx_1$ (C6.1: base)

$xxm_2 = y_2 b_2 xx_2$ (C6.2: layer 2)

$xxm_3 = y_3 b_3 xx_3$ (C6.3: layer 3)

$xxm_4 = y_4 b_4 xx_4$ (C6.4: layer 4)

$xxm_5 = y_5 b_5 xx_5$ (C6.5: layer 5)

$xxm_6 = y_6 b_6 xx_6$ (C6.6: layer 6)

Height direction moments

$yym_1 = y_1 b_w yy_1$ (C7.1: base)

$yym_2 = y_2 b_2 yy_2$ (C7.2: layer 2)

$yym_3 = y_3 b_3 yy_3$ (C7.3: layer 3)

$yym_4 = y_4 b_4 yy_4$ (C7.4: layer 4)

$yym_5 = y_5 b_5 yy_5$ (C7.5: layer 5)

$yym_6 = y_6 b_6 yy_6$ (C7.6: layer 6)

Center of gravity

$$x_g = \frac{y_1 b_1 xx_1 + y_2 b_2 xx_2 + y_3 b_3 xx_3 + y_4 b_4 xx_4}{y_1 b_w + y_2 b_2 + y_3 b_3 + y_4 b_4}$$

(C8.1: horizontal)

$$y_g = \frac{y_1 b_1 yy_1 + y_2 b_2 yy_2 + y_3 b_3 yy_3 + y_4 b_4 yy_4}{y_1 b_w + y_2 b_2 + y_3 b_3 + y_4 b_4}$$

(C8.2: vertical)

$xx_g = x_g cos\alpha + y_g sin\alpha$ (C8.3: level)

Sliding stability

$N = W_g + P_v$ (C9.1: reaction)

$$\frac{(Ncos\alpha + P_h sin\alpha)tan\phi}{P_h cos\alpha - Nsin\alpha} \geq 1.5$$

(C9.2: the sliding factor of safety)

Overturning stability

$d_h = \frac{H}{3}(H + \frac{3P_0}{\gamma})/(H + \frac{2P_0}{\gamma}) - b_w sin\alpha$

(C10.1: d_h)

$b_v = b_w cos\alpha - d_h/tan\beta$ (C10.2: b_v)

$M_r = P_v b_v + W_g x x_g$

(C10.3: resisting moment)

$M_o = P_h d_h$ (C10.4: overturning moment)

$M_r/M_O \geq 2$

(C10.5: moment factor of safety)

Eccentricity

$e = \frac{b_w}{2} - \frac{M_r - M_O}{N}$ (C11.1: eccentricity)

$|e| \leq b_w/6$ (C11.2: eccentricity limit)

By replacing *e*, which is a free variable, with e^+ and e^- which are positive variables by using the relationship $e = e^+ - e^-$. This constraint (C11.2) is converted to $e^+ - e^- \leq b_w/6$
where
e^+ : positive eccentricity. In this case, the wall will lean toward facing.
e^- : negative eccentricity. In this case, the wall will lean toward the retained soil.

Bearing
$\sigma_t = \frac{N}{b_w}\left(1 + \frac{6e}{b_w}\right)$

(C12.1: vertical bearing stress at the toe)

$q_a = P_0 N_q + 0.5\gamma_s b_w N_\gamma$

(C12.2: soil bearing capacity)

$\sigma_t/q_a \geq 2.5$ (C12.3.: bearing factor of safety)

3.2.4 Width/Height ratio

As suggested by Ortigo and Sayao [18] that the base width (*b*) should occupy about 0.4*H* to 0.6H, where *H* is the wall height. Hence, *b/H* lower bound for all six layers is set at 0.4 in constraints (C13.1) to (C13.6), while the *b/H* upper bound is set at 0.6 in constraint (C14) as follows.

$b_w/H \geq 0.4$

(C13.1: base layer minimum width)

$b_2/(H - y_1) \geq 0.4$

(C13.2: 2nd layer minimum width)

$b_3/(H - y_1 - y_2) \geq 0.4$

(C13.3: 3rd layer minimum width)

$b_4/(H - y_1 - y_2 - y_3) \geq 0.4$

(C13.4: 4th layer minimum width)

$b_5/(H - y_1 - y_2 - y_3 - y_4) \geq 0.4$

(C13.5: 5th layer minimum width)

$b_6/(H - y_1 - y_2 - y_3 - y_4 - y_5) \geq 0.4$

(C13.6: 6th layer minimum width)

$b_w/H \leq 0.6$ (C14: maximum width)

3.2.5 MINP solution

By mainly adjusting the decision variables in the gabion layer widths b_w, i_w, b_i, i_i, *i* = 2, 3, 4, 5, 6, the solution of this mixed integer nonlinear programming model gives the minimum weight W_g^* = 48 kN/m. The eccentricity *e* = 0.233 meter as shown in Table 2.

Table 2 Comparison of the designs from Enviromesh and mixed integer nonlinear programming

Model	27	39	MINP
H, m	3.1	3.0	3.0
Wg,, kN/m	61.92	72.0	48.0
e, m	0.086	0.172	0.233
FSO	2.72	2.87	2.00
FSS	1.87	1.83	1.52
FSB	7.14	6.18	4.89

Note: 27 is Enviromesh 27 system design. 39 is Enviromesh 39 system design. MINP is mixed integer nonlinear programming. *H* is wall height in m. W_g is gabion weight in kN/m, *e* is eccentricity in m. *FSO* is overturning factor of safety. *FSS* is sliding factor of safety. *FSB* is bearing factor of safety.

3.3 Preemptive Goal Programming

Preemptive goal programming is used in this model by sequential assign the two goals, as shown below.

Goal 1: minimum gabion weight, W_g

Goal 2: minimum eccentricity, e

Preemptive goal programming model will solve two optimization models sequentially. The first model will try to solve goal 1, which is the first priority objective. The second model will sequentially solve goal 2, which is the second priority objective, while setting the satisfied objective goal 1 as a constraint. Details of the two steps preemptive goal programming are as follows.

The first preemptive goal is done by assigning the first objective function that is the first priority, as follows.

Min W_g (O2.1: preemptive goal 1)

The set of constraints is the same as in MINP model.

Hence, the first preemptive goal programming model is exactly the same as MINP model. The solution of the first preemptive goal has the minimum weight W_g = 48 kN/m where the eccentricity e = 0.233 meter as shown in Table 3.

From this optimum solution in goal 1, the second preemptive goal is assigned with this second priority objective function. This second goal is to try to equalize the vertical stress at the toe to be the same as the heel vertical stress. In other words, this objective function is trying to minimize the eccentricity to be zero. Since the vertical stress at the toe is $\sigma_t = \frac{N}{b_w}\left(1 + \frac{6e}{b_w}\right)$ and the vertical stress at the heel is $\sigma_h = \frac{N}{b_w}\left(1 - \frac{6e}{b_w}\right)$, Equalizing $\sigma_t = \sigma_h$ implies that $e = 0$. This is done by adjusting the decision variables of the offsets x_{Fi} and x_{Bi} , i = 2, 3, 4, 5, 6 of the gabion layers.

The second objective function is as follows.

Min $e^+ - e^-$ (O2.2: preemptive goal 2)

Except one constraint is added to satisfy the first goal, the other constraints are the same as in model 1. The added constraint is as follows:

$W_g = 48$ (C15: satisfying the first goal)

The solution of the second goal, which is the optimum solution of this preemptive goal programming model, gives the minimum eccentricity e = 0.002 meters, which is less than the eccentricity in the previous first preemptive goal model at e = 0.233 meters. Of course, the minimum weight W_g = 48 kN/m, which is the same as the previous first preemptive goal model since this minimum weight is enforced as a constraint (C15) in the second preemptive goal model. Table 3 shows the comparison of preemptive goal programming with Enviromesh 27 system and 39 system.

Table 3 Comparison of the designs from Enviromesh and preemptive goal programming

Model	27	39	GP1	GP2
H, m	3.1	3.0	3.0	3.0
W_g, kN/m	61.92	72.0	48.0	48.0
e, m	0.086	0.172	0.233	0.002
FSO	2.72	2.87	2.00	2.45
FSS	1.87	1.83	1.52	1.52
FSB	7.14	6.18	4.89	9.37

Note: GP1 is step 1 preemptive goal programming using goal 1. GP2 is step 2 preemptive goal programming from using goal 2 while setting goal 1 as a constraint. Other notations are the same as aforementioned in Table 2.

3.4 Weighted Goal Programming

Weighted goal programming is done by assigning a set of weights to handle the same objectives as preemptive goal programming in minimizing gabion weight (W_g) and eccentricity (e). Hence, the objective function is:

Min $w_g W_g + w_e(e^+ + e^-)$ (O3: weighted goal)

The set of constraints is the same as in MINP model.

Table 4 Comparison of the designs from all models

Model	27	39	MINP	Goal
H, m	3.1	3.0	3.0	3.0
W_g, kN/m	61.92	72.0	48.0	48.0
e, m	0.086	0.172	0.233	0.002
FSO	2.72	2.87	2.00	2.45
FSS	1.87	1.83	1.52	1.52
FSB	7.14	6.18	4.89	9.37

Note: 27 is Enviromesh 27 system design. 39 is Enviromesh 39 system design. MINP is mixed integer nonlinear programming. Goal is both preemptive goal programming and weighted goal programming that give the same optimum solution.

Assigning values to w_g and w_e is based on the level of importance of each goal [19] in which the first goal should gain greater weight than the second goal.

By subjectively assigning $w_g = 2$ and $w_e = 1$, the optimal solution for the weighted goal programming is the same as the preemptive goal programming in which the minimum weight W_g =

48 kN/m and the eccentricity e = 0.002 meter, same as those in GP2 in Table 3.

By experimentally changing the weights, the optimum solution is invariant that achieves the same optimum solution. Trial weights assigned are a pair of $w_g = 3$ and $w_e = 2$, a pair of $w_g = 1$ and $w_e = 1$, and a pair of $w_g = 1$ and $w_e = 2$.

The optimum solutions from all models are shown in Table 4. The calculation details, including the widths and offsets of all models, are shown in Table 5.

4. FINDINGS AND DISCUSSION

4.1 Comparison of Optimum Solutions from All Models

From Table 4, the optimal solution of MINP is the same as those in preemptive goal step 1 that tries to achieve goal 1 in minimizing gabion weight. By setting another goal in balancing vertical stress at the heel and vertical stress at the toe in goal 2, the preemptive goal model (Goal in Table 4) achieves less eccentricity at 0.002 meters, compared with 0.233 meters when using MINP. Weighted goal programming gives the same optimum solution as those in preemptive goal programming (Goal in Table 4). Table 4 is exactly the same as Table 3, except for the changes in the column description.

4.2 Model Validation and Optimization Issues

The solutions of the three optimization models (MINP, preemptive goal programming, and weighted goal programming) are obtained using GAMS (General Algebraic Modeling Software). GAMS can integrate many third-party optimization solvers. The solver chosen in GAMS for these three models is MINLP solver. This MINLP (Mixed Integer Nonlinear Program) can solve the model that is mixed with both nonlinear terms and discrete variables [20].

Mixed integer nonlinear programming model may lead to local optimal solutions or convergence problems [21]. Hence, GAMS coding practices are utilized to guarantee an adequate model. Those practices recommended [20] are specifying sensible initial values, setting variable bounds, scaling variables and equations, avoiding expressions in nonlinear functions, reformulating and approximating for discontinuous.

The practices utilized for this proposed model are setting variable bounds in (C13.1) – (C13.6), avoiding expressions in nonlinear functions such as in (C11.1) and (C12.1), and reformulating for discontinuous function such as absolute value function in (C11.2). Specifying sensible initial values simply uses GAMS default values setting at zeros. There is no need to scale variables and equations since all variable values are in the same scale of measurement units. Global optimal solutions cannot be guaranteed due to the nonconvex constraints involved. However, the proposed models are adequate because varying parameters successfully solve the models without convergence difficulties showing as infeasible solutions. However, due to space limitations, the trial results and GAMS coding are not shown.

Table 5 Calculation details of the designs from all models

Model	27	39	MINP	Goal
H, m	3.1	3	3	3
α, degrees	10	6	10	10
b_w, m	1.7	2.0	1.5	1.5
b_2, m	1.4	1.5	1.5	1
b_3, m	1.0	1.0	1	1
b_4, m	0.7	-	1	1
b_5, m	-	-	0.5	1
b_6, m	-	-	0.5	0.5
x_{2F}, m	0	0	0	0.5
x_{2B}, m	0.3	0.5	0	0
x_{3F}, m	0.4	-	0.145	0
x_{3B}, m	0	0.5	0.355	0
x_{4F}, m	0.3	-	0	0
x_{4B}, m	-	-	0	0
x_{5F}, m	-	-	0.048	0
x_{5B}, m	-	-	0.452	0
x_{6F}, m	-	-	0	0.5
x_{6B}, m	-	-	0	0
W_g, kN/m	61.92	72	48	48
e, m	0.086	0.172	0.233	0.002
M_r, kN-m	96.4	101.9	67.0	82.0
M_O, kN-m	35.5	35.5	33.5	33.5
FSO	2.72	2.87	2.00	2.45
F_r, kN	49.4	53.3	40.7	40.7
F_d, kN	26.4	29.1	26.7	26.7
FSS	1.87	1.83	1.52	1.52
Q_a, kPa	437.1	481.7	407.3	407.3
σ_t, kPa	61.2	78.0	83.3	43.5
FSB	7.14	6.18	4.89	9.37

Note: 27 is Enviromesh 27 system design. 39 is Enviromesh 39 system design. MINP is mixed integer nonlinear programming. Goal is both preemptive goal programming model and weighted goal programming model.

4.3 Optimization Values and Computational Cost

Both MINP, preemptive/weighted goal programming model can save the weights of this 3-

meter gabion wall down, compared with 1.29 from the 27 system and 1.5 from the 39 system. However, using MINP gives more eccentricity than the 27 system and the 39 system. Preemptive goal programming model (GP in Table 6) Both preemptive goal programming or weighted goal programming gain the same minimum weight as MINP at 48 kN/m but lower eccentricity at 0.002 meters. Hence, either preemptive goal programming or weighted goal programming may be considered an aiding tool used to design a gabion wall if the saving in gabion weights and lower eccentricity is worth its computation cost.

Table 6 Comparison of the weights and eccentricities from all models

Model	27	29	MINP	Goal
H, m	3.1	3.0	3.0	3.0
W_g, *kN/m*	61.92	72	48	48
Ratio	1.29	1.5	1	1
e, m	0.086	0.172	0.233	0.002

Note: 27 is Enviromesh 27 system design. 39 is Enviromesh 39 system design. MINP is mixed integer nonlinear programming. Goal is both preemptive goal programming model and weighted goal programming model.

When comparing the computational cost of MINP, preemptive goal programming, and weighted goal programming, MINP needs only a one-step model. Preemptive goal programming needs a two-step model, but the second preemptive goal programming for the second goal programming needs to add only one constraint to satisfying the first goal. Weighted goal programming is also a one-step model but may need experimenting to change the weights assigned to the goal objective function to avoid local optimality problems.

5. CONCLUSION AND FUTURE WORKS

Optimization techniques such as mixed integer nonlinear programming (MINP) is a tool to make a gabion wall design by choosing a combination of many decision variables that is difficult to do with a manually calculated spreadsheet. However, using MINP needs to deal with the addressed local optimality and convergence problems.

Using MINP gains a lesser weight than the original Enviromesh 27 system and 39 system, but MINP model gives a greater eccentricity than the 27 system and 39 system, as shown in Table 1. Using goal programming models, either preemptive goal programming or weighted goal programming can achieve minimum weight and minimum eccentricity.

Goal programming approach can be applied to design a gabion wall with any height or added design criteria. This goal programming approach can also be extended to other retaining wall structures that need to achieve many objectives in the design criteria.

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