Optimum Design Of Silo Structures

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Abstract:

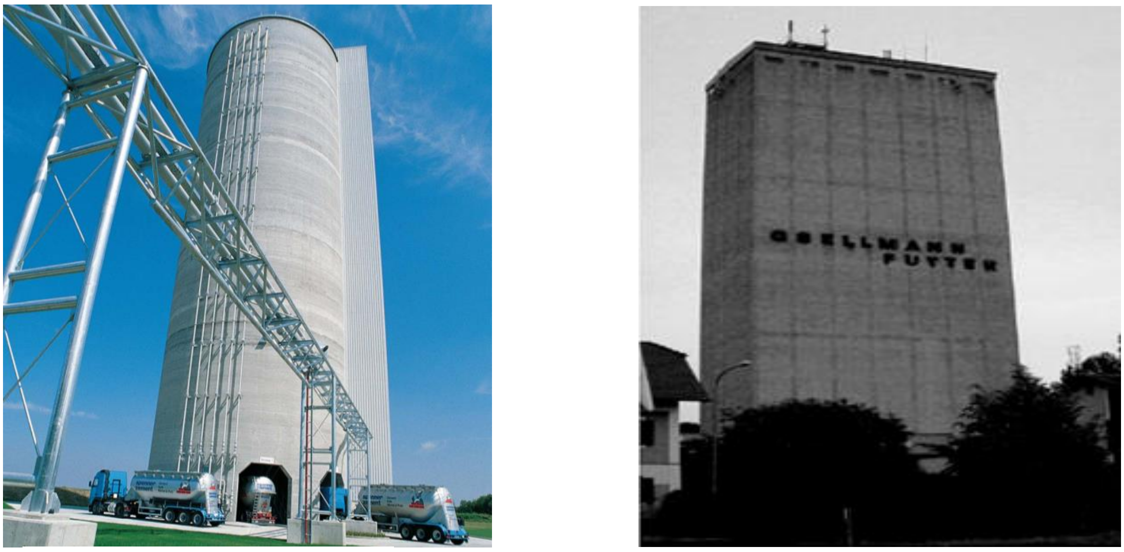
This paper deals with the problem of optimal design of reinforced concrete silos using genetic algorithms and minimizing the maximum objective method. The study provides two types of concrete silos circular and rectangular. Janssen theory method is used to analyze the structure design of silos. The cost function represents the cost of concrete, steel, and formwork for the silos. The design variables are taken such as diameter, long wall, short wall, height of cylinder and box for circular & rectangular silo respectively with free board, depth of the hopper, thickness of the wall, dimensions of ring beam, thickness of slab, angles of incline of the hopper and the amounts of reinforcement for silos. The formulation of the problem is according to ACI (313-97) code and is carried out by using a toolbox of MATLAB program. The change of design capacity related to total cost approximately linearly. The effect of the change of the concrete grade, unit price of steel and concrete, and finally the unit cost of formwork leads to increasing the total cost, while changing the steel grade leads to decreasing the total cost of both types of silo.

هذا البحث يتناول مسألة التصميم الأمثل للصوامع الخرسانة المسلحة باستخدام الخوارزميات الوراثية وتقليل الحد الأقصى. تقدم هذه الدراسة نوعين من الصوامع الخرسانية الدائرية والمستطيلة. نظرية جانسن تستخدم طريقة لتحليل وتصميم هياكل الصومعة. دالة الهدف تمثل تكاليف للكل من الخرسانة وحديد التسليح والقالب للصومعة. يتم أخذ متغيرات التصميم مثل قطر، جدار طويل، الجدار القصير، ارتفاع اسطوانة ومربع للصومعة دائرية ومستطيلة على التوالي مع مسافة الحرة، عمق القادوس، سمك الجدار، أبعاد الجسر، سمك السقف، زوايا انحدر القادوس وكميات حديد التسليح لصوامع. صياغة المسألة وفقا لقانون الكود الامريكي (٣١٣-٩٧) ونفذت باستخدام مجموعة أدوات برنامج ماتلاب. التغيير من الطاقة التصميمية المتعلقة بالتكلفة الإجمالية يكون تقريبا خطيا. تأثير التغير في مقاومة الخرسانة، وسعر الوحدة من الحديد التسليح والخرسانة، وأخيرا تكلفة الوحدة من تكلفة قالب يؤدي إلى زيادة التكلفة الإجمالية، في حين أن تغيير مقاومة حديد التسليح يؤدي إلى خفض التكلفة الإجمالية لكلا النوعين من صومعة.

Keywords: Optimization, Janssen theory, Design, ACI code, MATLAB

1. Introduction

Bins are classified into two major types deep bins or silos and shallow bins or bunkers that usually used to store granular materials. Behavior of pressures are the important difference between these two types. The difference of behavior is affected in each by the properties of the stored material and bin geometry [1]. Silo is the term used generally for a structure for storing dry granular materials where the size of the silo range from a few tones to hundreds or thousands of tones[2], these structures are usually elevated above the ground. Commonly silos used for the storage of flour, wheat, cement, coal and other granular materials [3]. Silos are generally classified according to cross-section such as a circular, rectangular, square and polygonal silos (Fig. 1), and also according to the material of construction such as concrete, steel, aluminum, and presstressed concrete [1]. The most frequently material used concrete. Concrete can provide the necessary protection to the stored material and usually lower cost than steel silo, requires little maintenance, aesthetically pleasing, high resistance to corrosion, which may be found in silos of thinner materials[1]. Mainly aims to solve the optimization problem to achieve the minimum cost function of the circular and rectangular silos.



(a) Circular Silo **(b) Rectangular Silo**

Figure (1) Silo Structure Types

Cost optimum design of reinforced concrete structures is receiving more and more attention from the researchers. Hasan Al-Badri (2008)[4] studied optimum design of reinforced concrete circular silo. Design variables were taken as diameter, cylinder height, height of hopper, angle of inclination of hopper, and unit weight of stored materials. These constraints were formulated in accordance with ACI code using FORTRAN-77. Increasing number of supporting columns lead to increase diameter and total cost of silo. Increasing the angle of internal friction and coefficient of friction cause an increasing, the total cost, diameter, height, hopper height and angle of inclination of the hopper. Suvarna D. D. and Rathod S. T.(2013)[5] presented a comparison of design and seismic behavior of silo. Industrial silo used to store cement. The capacity flat bottom silo a 450 m^3 designed and analyzed according to ACI code (ACI 313) also by referring the Indian Standards and Euro code using the STAAD Pro program. The area of reinforcement was found to differ along the depth of the wall. The difference of value (μ and ϕ) leads to differ pressure calculations. The ACI code was found to be more safety in pressure calculation than other codes. Dharmendra H. Pambhar et al. (2015)[6] studied design and analysis of the circular silo for storing bulk materials and comparison between net programming and manual design of circular silo for different material and calculate the pressure and reinforcement of the silo. The requirements and assessment of the silo for design and load criteria using the Indian Standards. The stress and area of reinforcement were the same result when comparison of Visual Basic programming and manual design, thickness of wall decreasing when height and diameter ratio increased.

2. Optimization

Optimization is the process of getting the best or optimal results under given circumstances. The idea of the optimization is to select the best solution from many available solutions that satisfy the problem requirement. The goal of all such decisions is either to minimize the effort or maximize the desired benefit. The effort or the benefit can be commonly expressed as a function of certain design variables. There are many ways for solving all optimization problems efficiently[7]. Optimization problems can be classified into several ways, such as classification based on the existence of constraints, the nature of the design variables, the permissible values of the design variables, the deterministic nature of the variables, and the number of objective functions[8]. Optimization problems can be classified according to the number of objective functions as single and multi-objective programming problems. Constraints cannot be selected randomly. Two types of constraints might be identified side and behavior constraints (Fig. 2). In civil design, the objective is commonly taken as the decrease of the cost or weight if more than one criterion has to be satisfied[7].

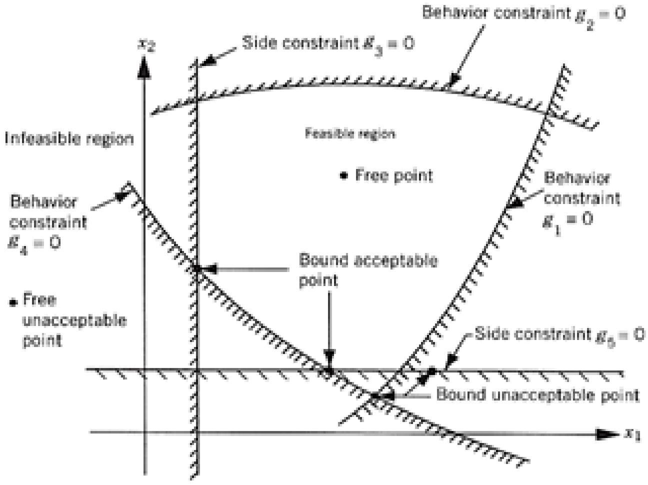


Figure (2) Constraint Surfaces in a Hypothetical Two Dimensional Design Space [7]

2.1 Genetic Algorithm

Genetic algorithms (GA) are random search methods that mimic some of the process of natural biological evolution. The major purpose of using genetic algorithms is to reach the best solution. Genetic algorithms are working with a population of possibility solutions applying the principle of (GA) are based on Darwin’s theory of "survival of the fittest" to produce the best approximations to a solution[8]. Genetic algorithm differ from other methods of optimization in starting the procedure, the points population (the trial of design vectors) are used instead of single design point, used the values of objective function only without using the derivatives in search procedure, and the design variables are in the form of strings of the binary variables that same the chromosomes in the natural genetics, In each new generation, new strings are produced by using crossover of randomized parents and selection from old generation (old strings) [7]:

1. Reproduction:

is a process aim to allow the genetic information stored in the best fitness artificial string, to survive the next generation [9]. It is known as the first operation (Fig. 3) that applied in the population to choose good designs strings of the population to compose a mating pool [7].

2. Crossover: after reproduction process, the crossover is a process implemented. Through which a string is divided into segments (Fig. 3), which are exchanged with the segments corresponding to another string. The aim of crossover process is to generate new strings through the exchange of information between the strings of mating pool [7].

3. Mutation: is applied to the new strings with a specific small mutation probability. The mutation operator varies the binary digit (1 to 0) or (0 to 1) (Fig. 3). In the single point mutation, a mutation location is chosen at random along the string length [7].

2.2 Minimizing the Maximum Objective Method

Minimizing the Maximum Objective (fminimax) method uses a goal attainment method. It is assumed goals equal to (0) and the vector of weighting coefficients equal to (1). The formulation of the goal attainment problem is as follows [10]:

$$\min \max f_i(x) = \left(\frac{f_i(x)-goal_i}{weight_i}\right) \quad (1)$$

More clearly, it can be expected fminimax to convert the multi-objective function into a single objective.

f(x) = max(F1(x),...Fj(x))

The objective function is a single with minimize. Hence, optimization objectives toolbox are wanted to be smooth. Therefore, the objective function of fminimax problem is formulated as a smooth of goal attainment problem[10].

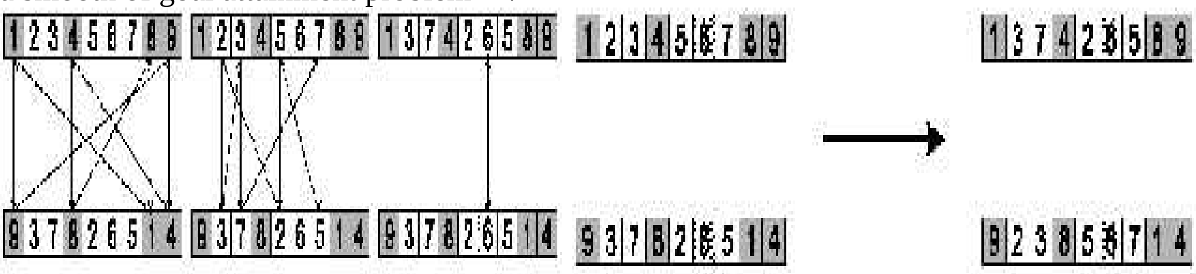


Figure (3) Processes Reproduction, Crossover, and Mutation

3. Janssen Theory

In 1895 Janssen has been published a logical procedure to calculate wall pressures in a silo. The conventional grain pressure theory was the first to take into account the phenomenon of wall friction. The Janssen theory appears very popularity because simplicity [11]. Some assumptions of Janssen horizontal pressures are uniform over the perimeter of a cross-section. The vertical stresses are zero at the free surface. The stored material is isotropic and uniform in weight, coefficient of friction is constant, ratio of horizontal to vertical pressures K is constant[12]. It can be concluded the following equations by assuming the equilibrium of a horizontal slice of material in the silo.

The vertical pressures at depth z below the surface of the stored material is following [1,13]:

$$q = \frac{\gamma R}{\mu k}\left(1 - e^{-\frac{\mu k z}{R}}\right) \quad (2)$$

The horizontal pressure at depth z below the surface of the stored material is following [1,13]:

$$p = qk$$

$$p = \frac{R\gamma}{\mu}\left(1 - e^{-\frac{\mu k z}{R}}\right) \quad (3)$$

The friction pressure at depth (z) below the surface of the stored material is following [1]:

$$p_w = \gamma R\left(1 - e^{-\frac{\mu k z}{R}}\right) \quad (4)$$

The lateral pressure ratio k shall be calculated by:

$$k = 1 - sin\,\emptyset \quad (5)$$

4. Design of Silo

Any procedure of pressure estimation may be applied to design that gives vertical, horizontal and frictional design pressures compare to those given by Sections 4.4.2 and 4.4.3 of the ACI code (313_97)[13]. For silos with a discharge opening at center design pressures due to stored material are:

$$q_{des} = C_d\, q \quad (6)$$

$$P_{des} = C_d\, \mathrm{P} \quad (7)$$

$$q_{\alpha,des} = p_{des} \sin\alpha^2 + q_{des}\cos\alpha^2 \quad (8)$$

$$V_{des} = V \quad (9)$$

4.1 Design Circular Silo

The circular silos were assumed to subject the tension force only because the radial pressure from stored material is known to be symmetric (uniform) along the inside perimeter at any depth. The ultimate hoop tensile force per unit height is [1].

$$F_u = K_l P_{des}\frac{D}{2} \quad (10)$$

The required steel area per unit height is ($K_l = 1.7$)

$$A_s = \frac{F_u}{\emptyset F_y} \quad (11)$$

Vertical compressive stresses must also be checked. Suggested limits for circular silo is[1,13].

$$F_{vert} = 0.385\, \mathrm{f_{c'}}\, \mathrm{b\ t} \quad (12)$$

$$f_{vert} = \frac{p_{vert}}{t*1} \quad (13)$$

$$p_{vert} = 1.7\ (\text{live load}) + 1.4\ (\text{dead load}) \quad (14)$$

4.2 Design Rectangular Silo

The silo is a rigid frame subject to pressure (P_{des}) differing with height. The resultant moment diagram will be as shown in (Fig. 4) any wall having bending moment, shear and axial tension[1]. The ultimate horizontal tensile force at the depth Y per unit height is[1]:

$$\mathrm{F_{a,u}} = \mathrm{K_l P_{b,des}}\frac{\mathrm{b}}{2} \qquad (\text{for wall } \text{"a"}) \quad (15)$$

$$\mathrm{F_{b,u}} = \mathrm{K_l P_{a,des}}\frac{\mathrm{a}}{2} \qquad (\text{for wall } \text{"b"}) \quad (16)$$

The silo walls resist tension force and bending moment. The combination can be replaced by an eccentric tension with $e = M_u/F_u$. The eccentric force (F_u) can locate in the space between the layers of steel (Fig. 5) or external of space (Fig. 6).

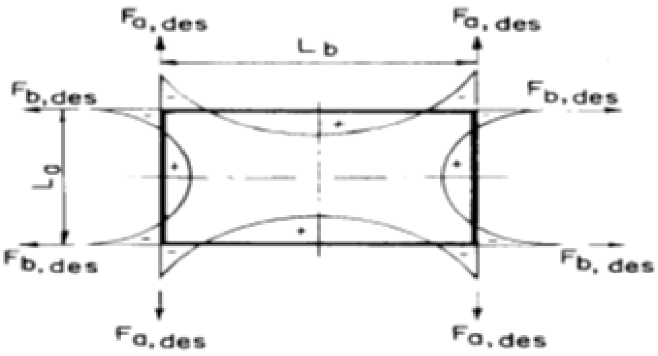


Figure (4) Design Loads, Axial Load and Bending Moment of Rectangular Silo [1]

Case I: Small eccentricity[1] (Fig. 5)

$e \leq \frac{t}{2} - d''$

with taking moment about each layer of steel and neglect the strength of concrete [1,14].

$$Reqd\ A_s = \frac{f_u e'}{\emptyset f_y (d-d')} \quad (17)$$

$$Reqd\ A_{s'} = \frac{f_u e''}{\emptyset f_y (d-d')} \quad (18)$$

Case II: Large eccentricity[1] (Fig. 6)

$e > \frac{t}{2} - d''$

$$f_{s'\ effective} = 87\left(\frac{yL-\beta_1 d'}{yL}\right) - 0.85 f_{c'} \quad (19)$$

If the value of the effective compressive steel stress ($f_{s'\ effective}$) is a negative compression steel in this case will not be effective. There are two solutions either depth should be increased or effective compressive steel ($A_{s'}$) moved to a location where compression steel will be effective[1].

$$Reqd\ A_{s'} = \frac{F_u\left(e''/\emptyset\right) - 0.85 f_{c'} b y_L (d - \frac{y_L}{2})}{f_{s'eff}(d-d')} \quad (20)$$

If Eq.(20) gives a positive value of compressive steel, ($A_{s'}$) is necessary. In this case addition, tensile steel is required:

$$Reqd\ A_s = \frac{F_u/_{\emptyset} + 0.85 f_{c'} b y_L + A_{s'} f_{s'eff}}{f_{s'eff}(d-d')} \quad (21)$$

The code limit is determined for ratio y/d from Table (1) and find value y_L. Where limiting depth of the compression zone to determine the effective compressive steel stress.

If Eq.(20) gives a negative value of compressive steel (A's), in this case this is no need to put the steel in the negative zone. The wall will be designed as singly reinforced, and value of the tensile steel is as in Eq.(22)[1].

$$Reqd\ A_s = \frac{F_u/_{\emptyset} + 0.85 f_{c'} b y}{f_y} \quad (22)$$

$$y \cong d - \sqrt{d^2 - \frac{2 f_u e''}{0.85 \emptyset f_{c'} b}} \quad (23)$$

Table (1) Code Limit of y_L

Concrete strength $f_{c'}$ (psi)	Steel yield strength (psi)		
	40,000	**50,000**	**60,000**
Up to 4,000	0.436	0.405	0.378
5,000	0.411	0.381	0.355
6,000	0.386	0.357	0.333

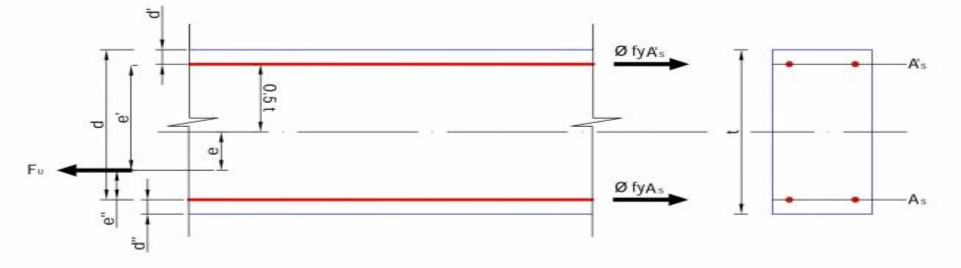


Figure (5) Case I: Small Eccentricity

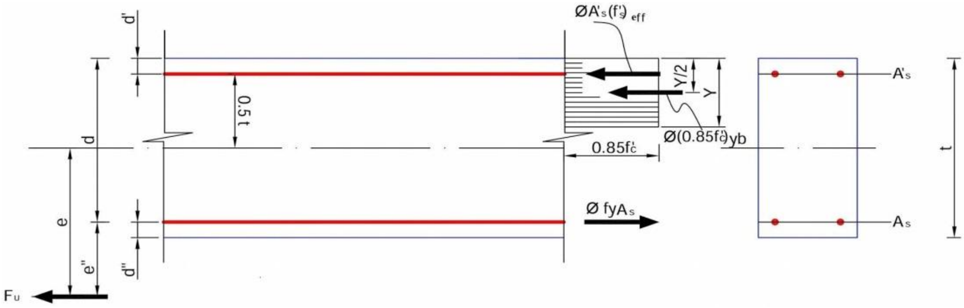


Figure (6) Case II: Large Eccentricity

4.3 Conical Hopper

The conical hopper is located under the influence of two tensile membrane forces. The meridional force (F_m) is parallel to the original line of the cone and the tangential force (F_t) is in the plane of hopper and horizontal. These loads shown in (Fig. 7) are resulting from vertical pressures q_{des} (at depth Y) and W the composite weights of the self-weight of the hopper and material stored under depth Y plus all machines supported by the hopper [1].

$$F_{mu} = K_l \left[\frac{q_{des} D}{4 \sin \alpha} + \frac{W_l}{\pi D \sin \alpha}\right] + K_g \left[\frac{W_g}{\pi D \sin \alpha}\right] \quad (24)$$

$$F_{tu} = K_l \left[\frac{q_{\propto,des} D}{2 \sin\propto}\right] \quad (25)$$

The reinforcement area per unit width of conical hopper for both forces is [1]:

$$\text{Reqd } As_{mh} = \frac{F_{mu}}{\emptyset f_y} \quad \text{(meridional direction)} \quad (26)$$

$$\text{Reqd } As_{th} = \frac{F_{tu}}{\emptyset f_y} \quad \text{(horizontal direction)} \quad (27)$$

4.4 Pyramidal Hoppers

Load for pyramidal hopper is similar for conical hopper (Fig. 8). Wall of this hopper is pyramidal wall. The walls are influenced by the bending moment and tensile forces. The angles of slope for walls (a) and (b) are (α_a and α_b) respectively. The tensile forces in the sloping walls are consisted of meridional forces (F_m) and horizontal forces (F_t) [1].

$$F_{ma,u} = \frac{K_l(c_a W_l + A_a q_{a,des}) + K_g c_a W_g}{a \sin \alpha_a} \quad (28)$$

$$F_{mb,u} = \frac{K_l(c_b W_l + A_b q_{b,des}) + K_g c_b W_g}{b \sin \alpha_b} \quad (29)$$

$$F_{ta,u} = K_l \left[\frac{b}{2}\right] q_{\alpha b,des} \sin \alpha_a \quad (30)$$

$$\boldsymbol{F_{tb,u} = K_l \left[\frac{a}{2}\right] q_{\alpha a,des}} \quad (31)$$

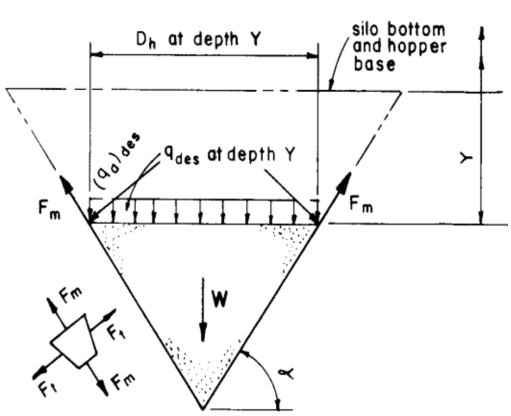


Figure (7) Conical Hopper

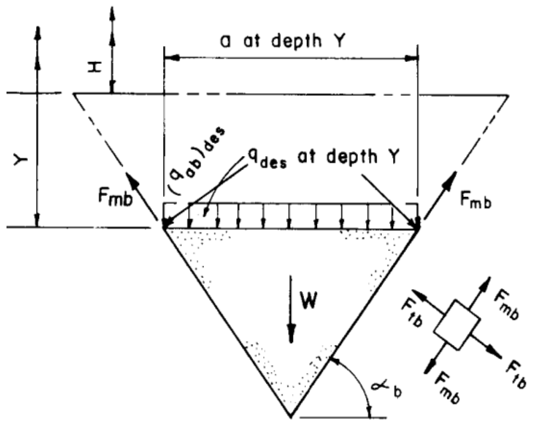


Figure (8) Pyramidal Hopper

5. Formulation of Optimization Problem

The cost of materials concrete, steel reinforcement and formwork is considered. The objective function which should be minimized the total cost of the silos can be stated:

$$C = C_c\ (Q_{cT}) + C_S\ (W_{ST}) + C_F\ (A_{FT}) \quad (32)$$

$$Q_{cT} = Q_w + Q_h + Q_R + Q_s \quad (33)$$

$$W_{cT} = W_w + W_h + W_R + W_s \quad (34)$$

$$A_{cT} = A_w + A_h + A_R + A_s \quad (35)$$

5.1 Constraints for Circular or Rectangular Silo

1. The height shall be more than 1.5 (diameter for circular or short wall for rectangular)[1].

$$H \geq 1.5\ (D \text{ or } a)$$

$$g_1 = 1.5(D \text{ or } a) - H \leq 0 \quad (36)$$

2. The crack width shall not exceed 0.25 mm[2].

$$W_c = 0.0001 f_s [dc\ A]^{1/3}\ (0.145) \leq 0.25mm$$

$$g_2 = 0.0001 f_s [dc\ A]^{1/3} (0.145) - 0.25 \leq 0 \quad (37)$$

3. The thickness of wall shall be more than the minimum thickness 6 in (150mm)[1,13].

$$t_{min} \geq \frac{mE_s + f_s - nf_{c'}}{f_s f_{c,ten}} PD/2$$

$$g_3 = \frac{mE_s + f_s - nf_{c'}}{f_s f_{c,ten}} PD/2 - t_{min} \leq 0 \quad (38)$$

4. The static vertical pressure shall be less than the design vertical pressure of short wall[1]

$$q_{a,b} \leq q_{(a,b)des}$$

$$g_4 = q_{a,b} - q_{(a,b)des} \leq 0 \quad (39)$$

5. The static horizontal pressure shall be less than the design horizontal pressure of short wall (a) [1].

$$p_{a,b} \leq p_{(a,b)des}$$

$$g_5 = p_{a,b} - p_{(a,b)des} \leq 0 \quad (40)$$

6. Static pressure normal inclined at angle α shall be less than the design pressure[1].

$$q_{\alpha,b} \leq q_{\alpha,b,des}$$

$$g_6 = q_{\alpha,b} - q_{\alpha,b,des} \leq 0 \quad (41)$$

6. Results and Discussion

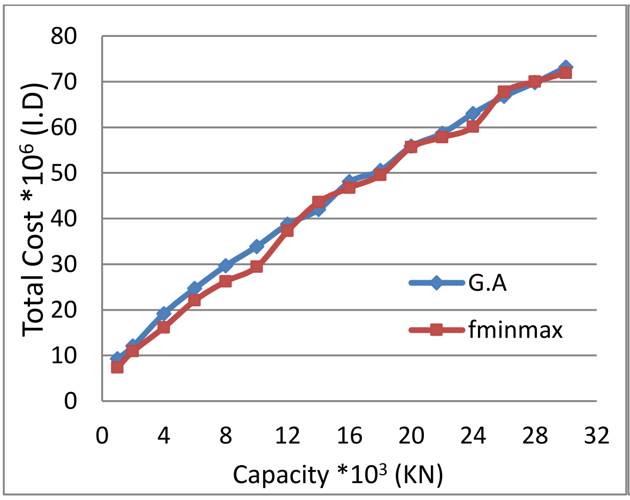
The applications include solving many numerical examples in order to show the effects of various design variables and different parameters on the optimal design. These examples are concerned as the following: effect of the design capacity of the silo, the effect of the materials properties (concrete and reinforcing steel), the effect of the unit price of concrete, steel, and formwork.

6.1 Effect of the Design Capacity of Silos

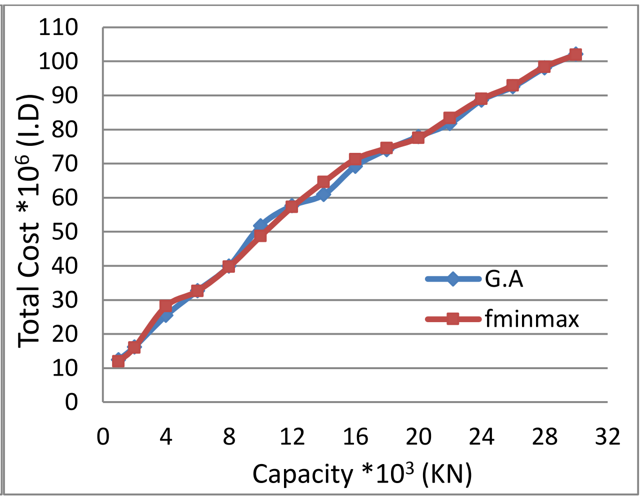
Different design capacities are considered to investigate the effect of the design capacity of the silo on the optimum solution as shown in (Fig. 9). The parameters shown in Table (2) are used for each value of the optimum dimensions. The optimal solution has been summarized using genetic algorithms (GA) and minimizing the maximum objective (fminimax) respectively. The relation between the total cost and the design capacity of the silos are shown in (Fig. 9) and it is found approximately a linear relationship of both types of silo. The steel reinforcement of the wall of the silo, the wall of hopper and ring beam are found to increase with increasing the design capacity.

Table (2) The Constant Parameters Used Throughout This Study

No.	Parameter Type	Value	No.	Parameter Type	Value
1	F.B (free board)	0.3 m	**6**	f_y (yield strength of steel)	275 MPa
2	E_s (modulus of elasticity for steel)	20 GPa	**7**	$f_{c'}$ (strength of concrete)	35 MPa
3	γ_c (unit weight of concrete)	24 KN/m^3	**8**	C_c (concrete cost)	175000 I.D
4	γ_m(unit weight of storage material)	8.3 KN/m^3	**9**	C_s (steel cost)	1250000 I.D
5	γ_s (unit weight of steel)	7.85 ton/m^3	**10**	C_F (formwork cost)	10000 I.D



(a) Circular Silo

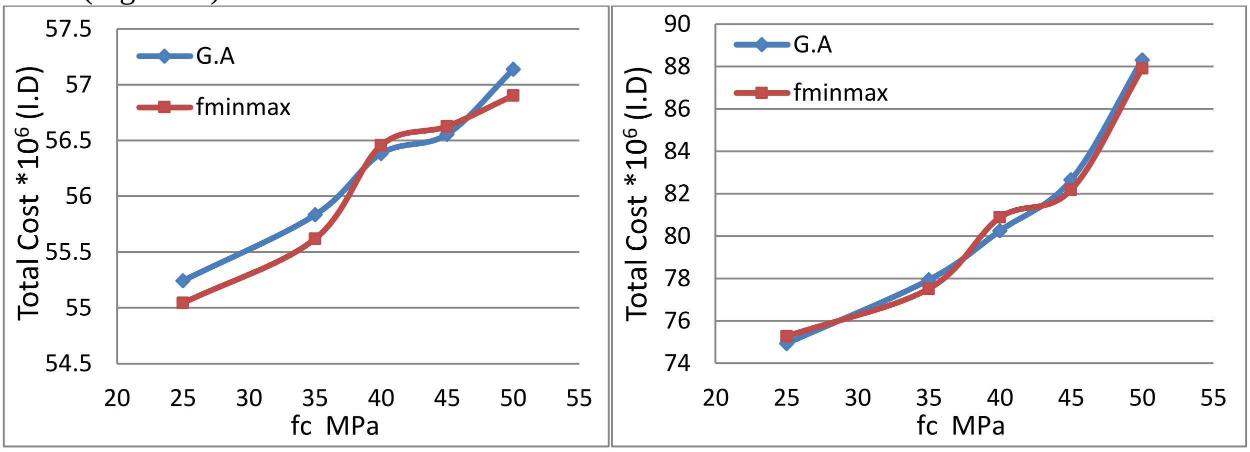


(b) Rectangular Silo

Figure (9) Optimum Design of Silos by G.A and fminmax for Different Capacity

6.2 Effect of the Concrete Properties

For concrete, grades (25, 35, 40, 45 and 50 MPa) are investigated which indicate the cube compression strength. Some parameters are considered constant throughout the study as in Table (2) with the exception of changing the cube compression strength and constant capacity (20000 KN). Since practically the increasing in grade of concrete leads to increase the total cost circular silo slightly (Fig. 10-a) but in rectangular silo leads to a greatly increasing of the total cost (Fig. 10-b).

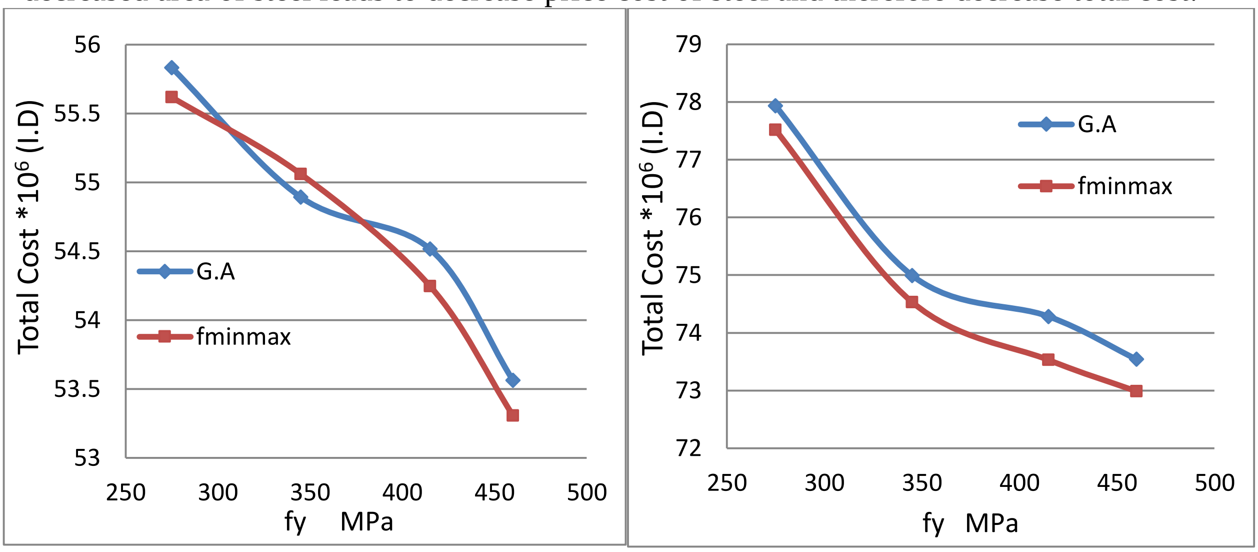


(a) Circular Silo **(b) Rectangular Silo**

Figure (10) Optimum Design of Silos by G.A and fminmax Different Concrete Compressive Strength

6.3 Effect of the Steel Properties

For steel reinforcement yield strength (275, 345, 415, and 460 MPa) are used. Some parameters are considered constant throughout the study as in Table (2) with the exception of changing the steel reinforcement yield strength and constant capacity (20000 KN). Since practically the increase in grade of steel leads to decrease of total cost of circular silo (Fig. 11-a). And the same behavior of rectangular silo shown in (Fig. 11-b) as a result is effect change grade of steel. Due to the inverse relationship between grade of steel and area of steel, when decreased area of steel leads to decrease price cost of steel and therefore decrease total cost.

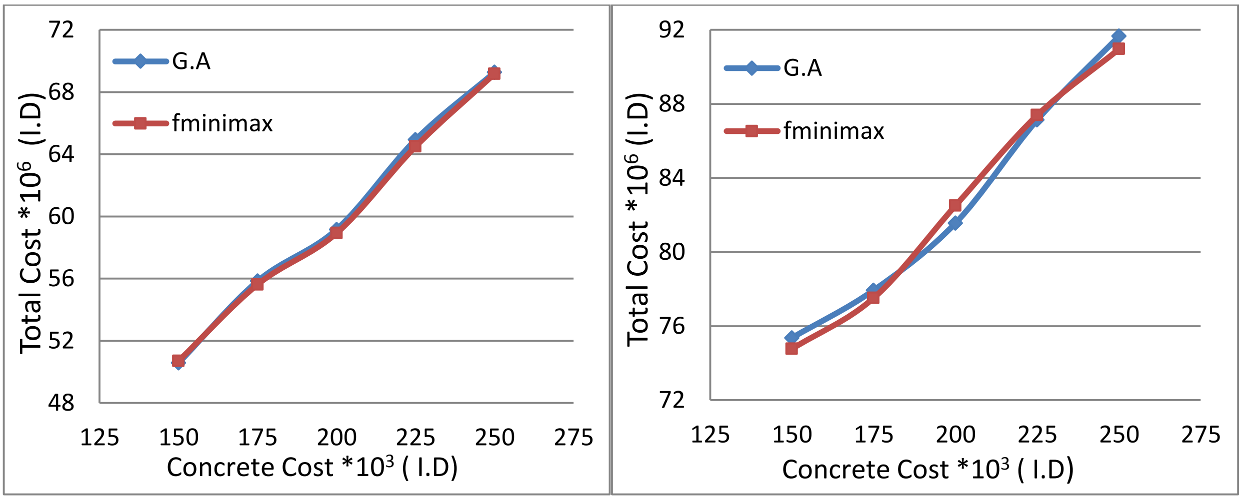


(a) Circular Silo **(b) Rectangular Silo**

Figure (11) Optimum Design of Silos by G.A and fminmax for Different Steel Yield Stress

6.4 Effect of Concrete Unit Cost

To illustrate this effect, five values of concrete unit cost (C_c) are taken as (150000, 175000 ,200000, 225000, and 250000) I.D/m^3. Some parameters are considered constant throughout the study as in Table (2). The results are given in (Fig. 12). It can be noted that the increasing of concrete unit cost has highly influenced the optimum solution by increasing the cost of silos, because of the extrusive relationship between concrete unit cost and total cost.

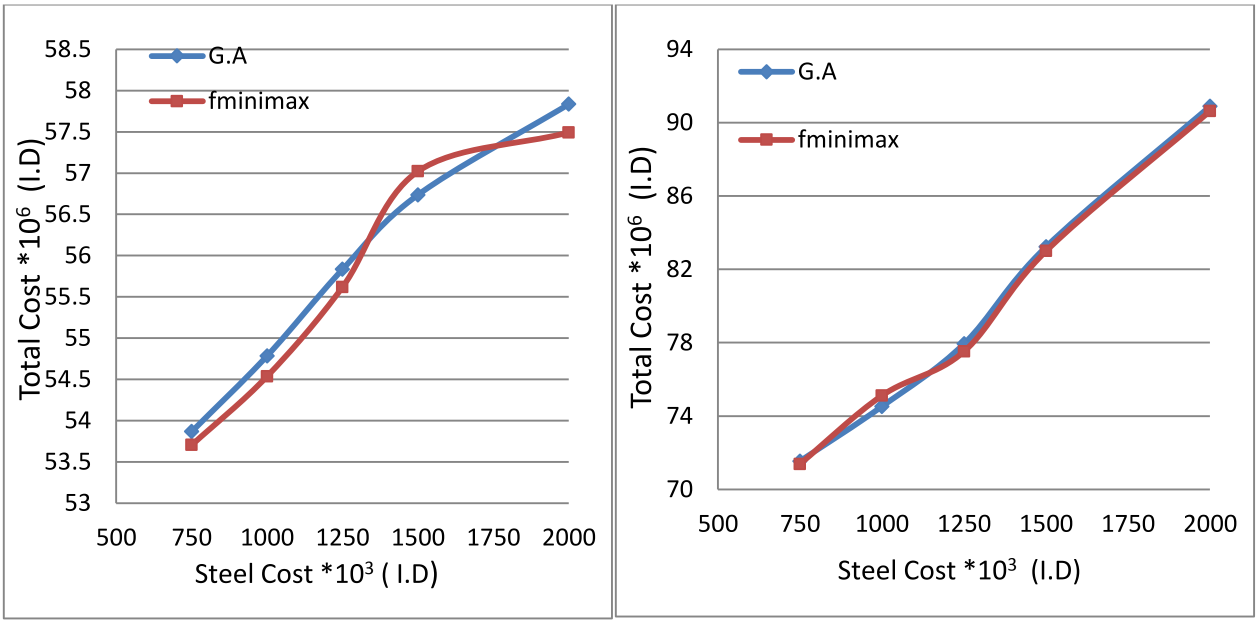


(a) Circular Silo **(b) Rectangular Silo**

Figure (12) Optimum Design of Silos by G.A and fminimax Different Concrete Cost

6.5 Effect of Steel Unit Cost

Five values of steel unit cost (C_s) are used including (750000, 1000000, 1250000, 1500000, and 2000000) I.D/ton. The results for the optimum circular silo solution are shown in (Fig. 13-a). It can be noted that the increasing of steel unit cost leads to increase the cost of circular silo, but the optimum rectangular silo solution is shown in (Fig. 13-b). It can be seen increasing steel unit cost leads to increase a greater effect of the total cost rectangular silo, because of the extrusive relationship between steel unit cost and total cost of silo.

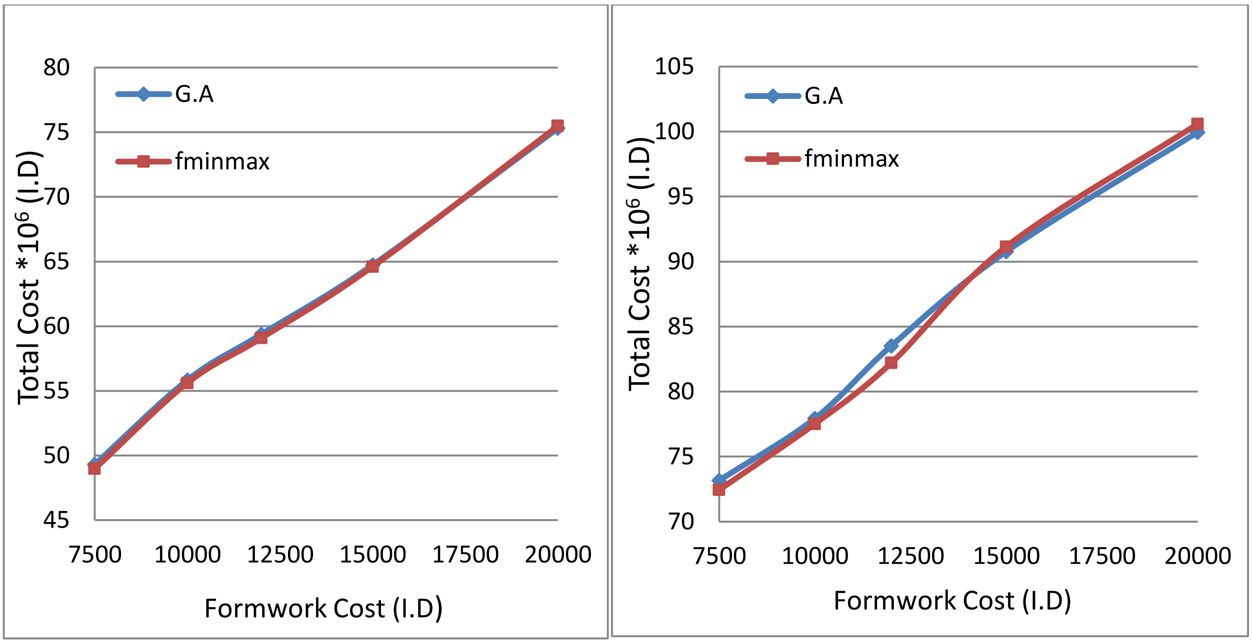


(a) Circular Silo **(b) Rectangular Silo**

Figure (13) Optimum Design of Silos by G.A and fminimax Different Steel Cost

6.6 Effect of Formwork Unit Cost

Five values of formwork unit cost (C_F) are taken as (7500,10000,12000,15000, and 20000) I.D/m^2. Some parameters are considered constant throughout the study as in Table (2) with the exception of changing the unit cost of formwork and constant capacity (20000 KN). The results for the optimum circular silo solution are shown in (Fig. 14-a). It can be seen increasing formwork unit cost leads to increase the total cost of circular silo. It can be noted from (Fig. 14-b) that the increasing of formwork unit cost leads to increase a greater effect of the total cost rectangular silo, because of the extrusive relationship between formwork unit cost and total cost.



(a) Circular Silo **(b) Rectangular Silo**

Figure (14) Optimum Design of Rectangular Silo by G.A and fminimax Different Formwork Cost

7. Conclusions

- The total cost of circular and rectangular silos linearly increases with increase the design capacity.
- It is preferable to use the lowest permissible concrete grade in the design of the circular and rectangular silos because increasing in concrete grade leads increase the total cost, take into consideration the conditions of safety in the design.
- From a cost point of view, It is preferable to use reinforcing steel of high yield strength in the design of the circular and rectangular silos because the increasing in steel grade leads to increase the total cost.
- From a cost point of view, it is preferable to use the lowest permissible formwork cost in the design of the circular silo because the increasing in formwork cost leads to increase the cost, take into consideration the quality of work.
- The circular silo is more economical than rectangular silo because of the complexities in design of rectangular silo.

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Nomenclature

A_{FT} =Total surface area of formwork (m^2)

A_w = Surface area of wall formwork (m^2)

A_h = Surface area hopper formwork (m^2)

A_R = Surface area ring beam formwork(m^2)

A_s = Surface area of slab formwork (m^2)

A_s , $A_{s'}$ = Reinforcement steel area per unit width of wall (m^2/m)

As_{th} = Area steel tangential(horizontal)for hopper of circular silo (m^2/m)

As_{mh} = Area steel meridional for hopper of circular silo (m^2/m)

a = Short wall rectangular silo (m)

b = Long wall rectangular silo (m)

C = Total cost function (I.D)

C_c = Cost of concrete per unit volume (I.D/m^3)

C_S = Cost of steel per unit volume (I.D/ton)

C_F = Cost of formwork per unit area (I.D/m^2)

D= Inside diameter of circular silo (m)

e = eccentricity

F_{mu} = The meridian force per unit width of hopper wall (KN/m)

$F_{tu=}$ The tangential force per unit width of hopper wall (KN/m)

F_h = The horizontal force per unit width of cylinder silo (KN/m)

F_a, F_b = Horizontal force per unit width of short and long wall of rectangular silo (*KN/m*)

H= Height of silo (m)

k = Coefficient of lateral pressure to the vertical pressure

P= Static horizontal pressure due to stored material for cylinder silo (KN/m^2)

α = Angle of inclined hopper (Rad)

p_a, p_b = **S**tatic horizontal pressure due to stored material for short and long wall for rectangular silo(KN/m^2)

q = Static vertical pressure due to stored material for circular silo (KN/m^2)

q_a, q_b, = Static vertical pressure due to stored material for short and long wall for rectangular silo(KN/m^2)

p_w= Vertical pressures produces friction force (KN/m^2)

q_α = Unit static pressure normal to surface inclined at angle (α) (KN/m^2)

Q_{cT} = Total Concrete volume (m^3)

Q_w= Concrete wall volume (m^3)

Q_h = Concrete hopper volume (m^3)

Q_R = Concrete Ring beam volume (m^3)

Q_s = Concrete slab volume (m^3)

R= Hydraulic radius of horizontal cross section of storage space (m)

t = Thickness of silo (m)

W_{ST} = Total Weight of steel (ton)

W_w = Weight of wall steel (ton)

W_h = Weight of hopper steel (ton)

W_R = Weight of ring beam steel (ton)

W_s =Weight of slab steel (ton)

y_L = The limiting depth of compression block (m)

$\bar{f_{s,eff}}$ = Effective steel stress (MPa)

μ = Coefficient of friction between stored material and wall

γ = The density of the stored material (KN/m^3

θ = The internal angle of friction of the granular material

$\emptyset$ = Strength reduction factor =0.9