OPTIMUM DESIGN OF TRAPIZOIDAL COMBINED FOOTINGS

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ABSTRACT

This study is an application of one of the non-linear programming methods ; Hooke & Jeeves method to the structural design of the trapezoidal combined footings , considering the total cost of the footing as an objective function . The cost function was formulated in terms of the following design variables : Smaller and larger footing width, footing width, thickness, depth of embedment and left and right projections A computer program was developed to solve this design problem using the conventional structural design approach in conjunction with Hooke & Jeeves method.

A simple study was performed to detect the sensitivity of the objective function to its design variables.A further parametric study was performed regarding the distance between columns and loading conditions.

It has been proved that the minimum cost of the trapezoidal combined footing increases with the increase of the distance between columns and loading ratio.

NOTATIONS

As	Area of steel
$\bar{B}$	Footing width at several sections
B11	Effective base width beneath column 1
B12	Effective base width beneath column 2
C	Width of column 2
c	Cohesion of base soil
c1	Concrete cover
Ccon	Cost of concrete
Cex	Cost of excavation
Cf	Cost of backfilling works
Cst	Cost of reinforcing steel
D	Width of column 1
d1	Effective depth of footing base in long direction
d2	Effective depth of footing base in short direction
db	Diameter of steel bar
DF	Embedment depth of footing
DFP	Davidon- Fletcher- Powell method
Dw	Maximum required depth for wide beam action
dc,dq, $d\gamma$	Depth factors for the Hansen's bearing capacity equation

NOTATIONS-Continued

$e\ell$	Eccentricity of the resultant parallel to long direction
ES	Stress- Strain modulus of soil
ESS	Stress- Strain modulus of footing
F( )	Objective function
Fc`	Compressive strength of concrete
FE	Number of function evaluations
Fy	Yield strength of steel
HJ	Hooke & Jeeves method
HZ	Step length
II	Influence factor which used in settlement computations
KS	Modulus of subgrade reaction
L	Footing length
$\bar{L}$	Effective length of footing base
L11	Effective length beneath column 1
L12	Effective length beneath column 2
Lb	Required length of reinforcing steel
LE	Left projection
LF	Load factor
M	Bending moment

NOTATIONS-continued

m	Equivalent term
M1	Larger width of footing
N1	Smaller width of footing
Nc,Nq,Nγ	Bearing capacity factors for the Hansen's bearing capacity equation
P1	Working applied load on column 1
P2	Working applied load on column 2
Pc	Price of concrete
Pex	Price of excavations
Pf	Price of backfilling works
Pst	Price of reinforcing steel
$\bar{q}$	Effective overburden pressure at base level
q1	Ultimate applied pressure at the left end of the footing
q2	Ultimate applied pressure at the right end of the footing
q3	Ultimate applied pressure at column 1
q4	Ultimate applied pressure at column 2
qall	Allowable soil pressure
qav	Average soil pressure
qmax	The maximum applied pressure

NOTATIONS-continued

qo	Intensity of contact pressure
qu	Hansen's ultimate bearing capacity of base soil
R	Resultant force of the applied loads on the footing
RE	Right projection
r_γ	Reduction factor for limited influence of base width
XL	Distance between columns
Sc,Sq,Sγ	Shape factors for the Hansen's bearing capacity equation
Scd	Maximum deformation beneath the footing base
Sd	Differential settlement beneath the footing base
SF	Safety factor against bearing capacity failure
Si	Maximum total settlement
S_ℓ	The slope of the pressure line
T	Footing thickness
TC	Total thickness of soil layer
TH	Thickness of soil layer beneath footing base
UR	Ultimate ratio
V	Actual shear force
Vst	Volume of reinforcing steel

NOTATIONS-continued

w1	Half width of column 1
w2	Half width of column 2
X	Design vector
x	Design variable
$\overline{X}$	The location from the footing end of the resultant force on the footing base
x1	The distance from the left footing edge to the point of zero shear
xc1	The distance from the left footing edge to the centre of column 1
xc2	The distance from the right footing edge to the centre of column 2
$x\ell$	The distance from the left footing edge to the first point of zero bending moment
xn1	Distance from the left footing edge to the critical section for wide beam action near column 1
xn2	Distance from the right footing edge to the critical section for wide beam action near column 2
xr	The distance from the right footing edge to the second point of zero bending moment
Z	Total cost of the trapizoidal combined footing
γ	Unit weight of the base soil

NOTATIONS-continued

γ_C	Unit weight of the concrete
ϕ	Angle of internal friction of soil
ρ	Reinforcement ratio
ρ_S	Unit mass of steel
υ	Poisson's ratio

INTRODUCTION

The combined footing is a footing that supports two or more columns. It is the most practical solution for some conditions when a column or a load-bearing wall is so close to a property line that a footing would be eccentrically loaded or when column loads are such that the resulting spread footings may be so close together or may interfere .Trapizoidal combined footing is used when the column, which has too limited space for a spread footing, carries the larger load.

It is evident that, for any engineering design problem, engineers have to take many decisions at several stages to either minimize the effort required or maximize the desired benefit. This decision-making problem can be rectified through the use of available facilities in the field of " Operations Research " to help the designer in choosing the appropriate criterion to achieve the best results satisfying design restrictions .Mathematical programming techniques are generally studied as a part of operations research[1,9].

PURPOSE OF STUDY

The principal purpose of this research is to detect the capabilities of optimization method to handle the structural design problem of a trapezoidal combined footing and to detect the sensitivity of the objective function to its design variables in order to achieve a safe, economical design**.**

RELATED PREVIOUS STUDIES

Naaman (1982) presented minimum cost design of prestressed concrete tensile member . The cost function includes the material costs of concrete and the prestressed steel [5]. Desai et.al (1984) formulated the problem of designing an isolated sloped square footing resting on dry granular medium.It was observed from study that the saving in cost is large in dense medium when compared to the cost obtained using the conventional design approach[7].

Namiq and Al-Ani (1985) minimized the cost of spread footings subjected to double eccentricity by using graphical method as well as Rosenbrock' s method .The results showed that the optimum ratio of footing length to its width (L/B) is directly proportional to the ratio of the difference between the eccentricities in both directions to the eccentricity in short direction (e_L-e_B/e_B) .It was also shown that the ratio of the price of steel to the price of concrete which was defined as cost ratio does not affect the optimum (L/B)[8].

Al-Douri (1999) minimized the cost of rectangular combined footings by using several methods.She concluded that the minimum cost of the footing decreases with increasing the distance between the columns for a constant length [14].

Al-Jubair (1994) minimized the cost of ring foundations by using simplex method of Nelder and Mead.The results obtained supported the efficiency of optimization techniques in selecting the most economical design of ring foundations for given conditions [13].

Al-Jubori (2001) minimized the cost design of mat foundations. He showed that the minimum cost of the raft foundation decreases with increasing of the angle of internal friction of soil and increases with increasing the column spacing in both directions as well as with increasing the difference between the loads of adjacent columns[15].

FORMULATION OF THE PROBLEM

In every optimization problem, there are two main features namely; the objective function and the constraints. Referring to Fig.(1) six independent design variables were selected namely; larger footing width(M1), smaller footing width(N1), thickness (T), embedment depth (DF), left projection (LE) and right projection (RE).Soil properties were treated as constant quantities.

PROGRAMME USER'S MANUAL

The programme for the design of trapezoidal combined footing has been written in " QUICK-BASIC". Optimization programme carrying out the minimization process were defined as main programme with termination accuracy of the step length less than 1.0 E-8.A subroutine was linked to the main programme. It contains the necessary computations for structural analysis using the conventional approach.

OBJECTIVE FUNCTION

The total cost of the trapezoidal combined footing was considered as the objective function. It can be, calculated as follows:

$Cost(U.P.) = C_{con} + C_{ex} + C_f + C_s$ ……………………………..…(1)

Where:

Cost(U.P.) = total cost (unit price) .

C_{con} = cost of concrete (unit price) .

C_{ex} = cost of excavations (unit price) .

C_f = cost of backfilling works (unit price) .

C_s = cost of steel reinforcement (unit price) .

A. Cost of Concrete

C_{con} = Vol. of Concrete * Pc

= B_{av}.* T * L * Pc …………………………………...…(2)

where:

B_{av}. = average footing width (m) = (n1+m1)/2 .

L = footing length (m) .

T = footing thickness (m).

Pc = price of concrete, materials & labours (unit price per cubic metre).

B. Cost of Excavation Works

$C_{ex} = B_{av}. * L * DF * P_{ex}$ ……………………………………(3)

Where:

DF = embedment depth of footing (m) .

Pex = price of excavation works, labour (unit price per cubic metre).

C. Cost of Backfilling works

$C_f = B_{av.} * L * (DF – T). P_f$ ……………………………………(4)

Where:

P_f = price of backfilling works, materials & labours (unit price per cubic metre).

D. Cost of Reinforcing Steel

C_{st} = Vol. of steel * density * Pst …………………………..(5)

$= V_{st} . \rho s. P_{st}$

Where:

Vst = total volume of reinforcing steel (m^3)

$= \sum Vsti$

ρs = unit weight of steel (ton/ m^3)

Pst = price of steel, materials & labours (unit price per ton) .

CONSTRAINTS

In this research two main types of constraint were considered; the geotechnical and structural constraints .Each type is discussed for the trapezoidal combined footing problem in the following sections.

A. Geotechnical Constraints

1. Stability against base failure

i.) The maximum applied pressure under-the footing base (q_{max}) should not exceed the allowable bearing capacity (q_{all})

$$\frac{qu}{qmax} \geq SF \qquad (6)$$

where:

qmax = The maximum applied pressure (kN/m^2) .

$$= \frac{P1 + P2}{\bar{B}.\bar{L}}$$

$\bar{B}$ = $(B_1+B_2)/2$

P1,P2 = working applied loads on column 1 and column 2, respectively (kN).

qu = Hansen's ultimate bearing capacity of base soil (kN/m^2).

= c Nc sc dc + q Nq sq dq + 0.5γ Nγ Nγ sγdγ rγ , ref.[12]

c = the cohesion of the base soil (kN/m^2).

q = effective overburden pressure at footing base level (kN/m^2).

$= \gamma .DF$

γ = unit weight of the base soil (kN/m^2).

Nc,Nq,Nγ = bearing capacity factors for the Hansen's bearing capacity equation which depends on φ only.

$$Nq = (\exp(\pi \tan\varphi)).\tan^2(45 + \frac{\varphi}{2})$$

$$Nc = \frac{Nq - 1}{\tan\varphi}$$

$$N\gamma = 1.5\,(Nq\text{-}l)\tan\varphi$$

φ = angle of internal friction of the base soil (degrees).

sc,sq,sγ = shape factors for the Hansen's bearing capacity equation.

$$Sc = 1 + \frac{Nq}{Nc} . \frac{N1}{\bar{L}}$$

$$Sq = 1 + \frac{N1}{\bar{L}}\tan\varphi$$

$$S\gamma = 1 - 0.4 \frac{N1}{\bar{L}}$$

$$\bar{L} = L - 2e\gamma$$

$dc, dq, d\gamma$ = depth factors for the Hansen's bearing capacity equation.

$dc = 1 + 0.4\, K_1.$

$dq = 1 + 2 \tan\varphi\ (1 - \sin\varphi)^2 .\ K_1.$

$d\gamma = 1.0.$

$K_1 = DF/N1$ when $DF/N1 \le 1$

$K_1 = \tan^{-1}(DF/N1)$ (radians) when $DF/N1 > 1$

$r\gamma$ = reduction factor for limited influence of footing width.

= 1.0 for $N1 \le 2m$.

= 1-0.25 log (N1/2) for N1 > 2m .

SF = reduction factor against bearing capacity failure.

= 2

ii.) The location of the resultant force on the footing base ($\bar{x}$) must be within the middle- third part of the base.

$L/3 \le \bar{X} \le L/2$ ....(7)

where:

$\bar{x} = xc_1 + xb$

2. Footing settlement

The maximum total (S_i) and differential (Sd) settlement must be within the allowable limits[4].

$S_i \leq 3.81$ cm (1.5 in) ....(8)

Sd $\leq$ 2.54 cm (1 in) ....(9)

3.Protection Against Eenvironmental Effects

The footing should be constructed below the zone of seasonal volume changes. Thus, the following constraint will be introduced

$2\text{ m} \geq DF \geq 0.9\text{m}$ ....(10)

B. Structural Constraints

1. Shear failure

i.) Wide-beam shear

The maximum shear stress due to wide-beam shear $(v_c)_w$ must be within concrete strength [11].

$(v_c)_W = 0.17 \times 0.85 \times \sqrt{f'c}$ ....………..............(11)

ii.) Punching shear

The maximum shear stress due to punching shear (diagonal tension) $(v_u)_p$ must be within the concrete strength

$(v_u)_P \leq 0.33 \times 0.85 \times \sqrt{f'c}$ ………………………...........……(12)

2. Reinforcement Ratio for Bending,Moment

The reinforcing ratio for bending moment at any section should not be less than (ρ_{min}) and it should not be more than (ρ_{max}) [10].

$\rho_{min} \leq \rho_i \leq \rho_{max}$ ……………………………………………..(13)

Where:

ρ_i = reinforcement ratio for bending moment at any section.

ρ_{min} = minimum reinforcement ratio.

$= \frac{1.4}{Fy}$ (for beams)

Fy = yield strength of steel (MPa)

ρ_{max} = maximum reinforcement ratio.

$= 0.75 \frac{0.85fc}{Fy} \beta_1 \frac{600}{600 + Fy}$

β_1 = 0.85 when $f'c \leq 28$ N/mm²

= 0.85 - 0.0275 (f′c - 28) when f′c > 28 N/mm²

C- Side Constraints

The upper and lower limits of footing breadth (N1&M1), footing depth of embedment (DF), the distance from the footing left edge to the left face of column 1 (LE), and the lower limit of footing thickness (T) are governed by practical considerations.

$XL \geq N1, M1 \geq \max(3D, 3C)$ ……………………………….(14)

$2m \geq DF \geq \max(T, 0.9m)$ ……………………………….(15)

$T \geq 0.25m$ ……………………………………………….(16)

$XL/2 \geq LE \geq 0$ ………………………………………….(17)

$XL/2 \geq RE \geq 0$ ………………………………………….(18)

It should be noted that, there is no need for an upper limit for footing thickness since any large value of (T) will be discarded in favour of cost minimization. Hence, the optimization problem can be stated as:

Find $X = [\ N1\ \ M1\ \ T\ \ DF\ \ LE\ \ RE]^T$ that minimizes eq. (1) subject to the constrains defined by equations (6) to (18). The problem of a trapezoidal combined footing design can be solved as an unconstrained minimization problem by giving the cost function a high value upon violation of any constraint in order to discard the point (i.e., values of design variables)generated this situation.

NUMERICAL EXAMPLE

This numerical example illustrates the application of the used optimization methods to the trapezoidal combined footing design problem and confirming their utility to reach the optimum solution., for more details, the reader is referred to (1,3,6). The following values were assigned to the input parameters of the subroutine " CON ".

P_1 = 950 KN , P_2 = 750 KN   LF = 1.6

w_1 = w_2 = 0.25 m   XL = 5.0 m

φ = 30 Deg.   c = 0.0 kN/m^2

υ = 0.3[2])

ES = stress – strain modulus of soil (kN/m^2

= KS. Bav $(1-\upsilon^2) I_S . I_f$.

KS = modulus of subgrade reaction (kN/m^3)

$$I_s = I_1 + \left(\frac{1-2\upsilon}{1-\upsilon}\right) I_2$$

I_i = influence factors which depend on (L/B),thickness of stratum, Poission ' s ratio (υ) and embedment depth (DF).

I_f = 1 γ_{soil} = 17 kN/m^3

$\gamma_{con.}$ = 24 kN/m^3 f'_C = 21 N/mm^2

FY = 375 N/mm^2 ρ_s = 7.85 ton/m^3

PC = 100 (unit price per ton)

P_{st} = 600 (unit price per cubic metre)

P_{ex} = 2 (unit price per cubic metre)

P_f = 1.0 (unit price per cubic metre)

The above sample problem was solved by using the Hooke & Jeeves optimization method using three initial trial points.The following are the required input data for each one.

N = number of design variables =6, Hz = step length= 0.05

X(1) = N1, X(2) = M1, X(3) = DF, X(4) = T, X(5) = LE, X(6) = RE

The first initial trial values :

X(1)=2.15, X(2)= 4.27, X(3)=1.0, X(4)=0.9, X(5)= 0.5, X(6)= 0.5

The second initial trial values :

X(1)=2. 5, X(2)= 4.0, X(3)=1.5, X(4)=0.8, X(5)= 0.5, X(6)= 0.5

The third initial trial values :

X(1)=2.0, X(2)= 4.5, X(3)=1.0, X(4)=0.75, X(5)=0.5, X(6)=0.5

The results obtained are shown in Table (1). Figs.(3,4,5) show the convergence rate towards the minimum cost design of trapezoidal combined footing.

SENSITIVITY TO THE DESIGN VARIABLES

In order to specify the first order parameter among the design variables, a simple study was performed on the cost function via changing the values of the design variables one at a time.

It can be deduced from Figs.(6) through (9) that , the cost of footing is more sensitive to the changes in the values of the larger footing width ,depth of embedment , left and right projections.

The results demonstrate the minor effect of footing thickness, T as shown in Table(1).

PARAMETRIC STUDY

A parametric study was carried out regarding column spacing, and loading conditions .The results are shown in Tables (2) and (3).

DISCUSSION

It can be observed from Table (1) and Figs.(3) through (5) that , Hooke and Jeeves method handled the optimization problem sucssesfully for the three initial trial points.

It is evident from Table (1) and Figs.(6) through (9) that the minimum cost is more sensitive to the changes in the larger footing width, embedment depth, left and right projections compared to the variations in footing thickness.

It can be deduced from Table (2) and Fig.(10) that the minimum cost increases as the column spacing increase. This increase in the minimum cost in general is due to the increase in the optimum footing width (N1 and M1).

It can be realized from Fig. (12) that, at a ratio of the column spacing to the footing length equals (76.9 %) , the maximum footing width , begins to increase.

It is clear from Figs.(13) through (15) that, at a ratio of the column spacing to the footing length equals (73%), the optimum footing thickness begins to decrease whereas left and right footing projections begin to increase.

It can be observed from Table (3) and Fig.(16) that , the minimum cost increases as the load ratio increase. This increase in the minimum cost is due to the increase in the optimum footing width and thickness.

Fig.(18) and Figs.(20) and (21) show that, at a rate of the load ratio equals (33.3%) of the load increase, the maximum footing width decreases, then it begins to increase at a rate of the load ratio equals (66.7%) of the load increase, as well as footing left projection, whereas footing right projection ,begins to increase beyond a rate of (33.3%)of the load increase.

CONCLUSIONS

1. The achievement of an economical foundation design can be handled as a problem of mathematical programming.
2. Optimization technique was successfully applied to the problem of the trapezoidal footing design.
3. The accuracy required for terminating the procedure has a great effect on the results, that is any unsuitable accuracy will either lengthens the procedure or gives local minima.
4. The minimum cost was more sensitive to the changes in load ratio than to the changes in column spacing .

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Table (1) The Design Results (initial trial points)

Variables	Distance Between Columns,XL				
	4.5	4.75	5	5.25	5.5
N1(m)	1.5	1.52	2.0	2.005	1.92
M1(m)	3.99	3.715	3.199	3.945	4.329
DF(m)	0.9	0.9	0.9	0.9	0.9
T(m)	0.65	0.8	0.75	0.685	0.7
LE(m)	0.299	0.0249	0.05	0.19	0.005
RE(m)	0.299	0.125	0.199	0.24	0.25
Cost (U.P)	1760.875	1809.967	1870.842	2188.607	2307.479
FE*	360	320	312	312	137
SF	4.839	4.347	4.98	6.252	6.309
SET(m)	$4.221*10^{-05}$	$4.100*10^{-05}$	$4.429*10^{-05}$	$4.598*10^{-05}$	$4.510*10^{-05}$
SCD(m)	$5.517*10^{-06}$	$5.349*10^{-06}$	$4.886*10^{-06}$	$5.105*10^{-06}$	$5.974*10^{-06}$
MM**(kN.m)	-7484.561	-6655.69	-7025.121	-7899.083	-7408.571

Variables	First trial point	Second trial point	Third trial point
N1(m)	1.82	2.143	2.0
M1(m)	3.915	3.644	3.199
DF(m)	0.9	0.90	0.9
T(m)	0.769	0.701	0.75
LE(m)	$5.0*10^{-03}$	$9.75*10^{-02}$	$4.99*10^{-02}$
RE(m)	0.14	0.199	0.199
Cost (U.P)	2020.795	2003.781	1870.842
FE*	313	320	312
SF	5.219	5.791	4.98
SET(m)	$4.146*10^{-05}$	$4.278*10^{-05}$	$4.429*10^{-05}$
SCD(m)	$5.517*10^{-06}$	$5.349*10^{-06}$	$4.886*10^{-06}$
MM(kN.m)**	-6838.868	-7225.098	-7025.121

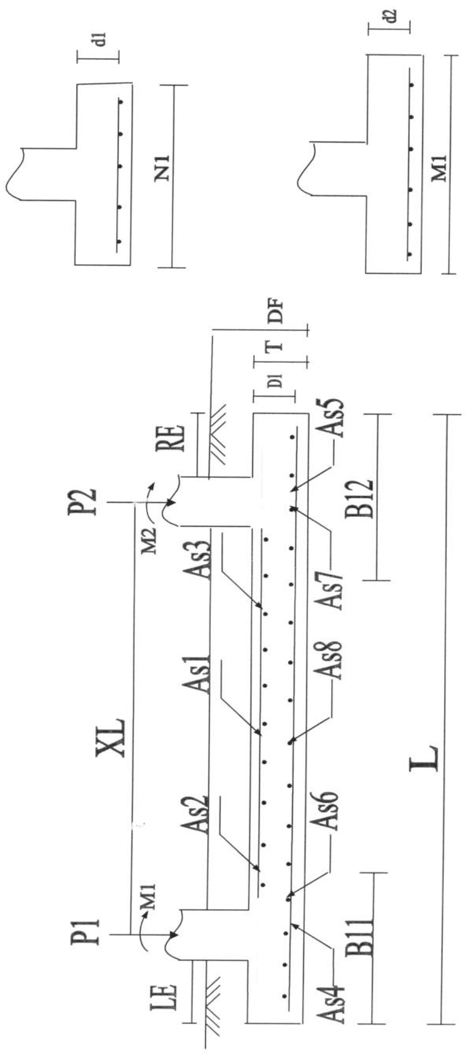


Fig. (1) Typical section trapezoidal combined footing

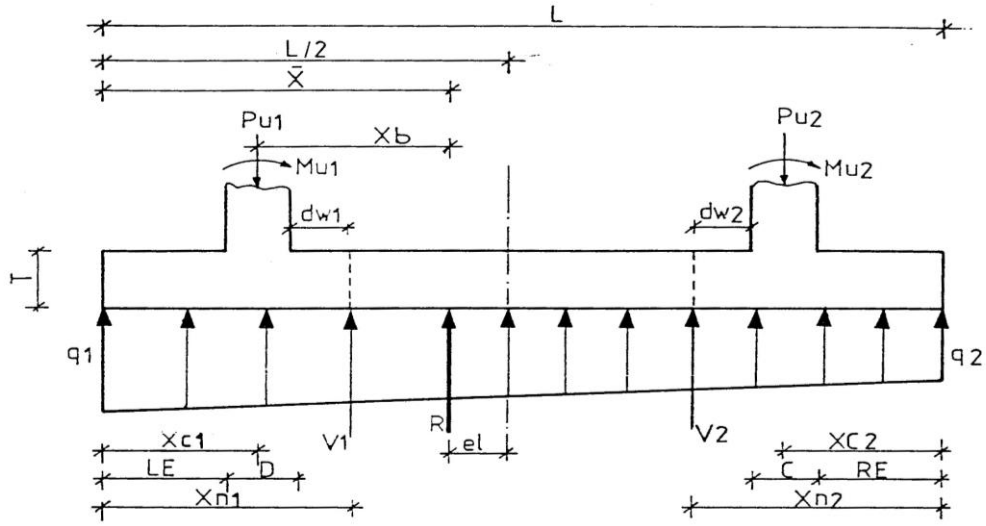
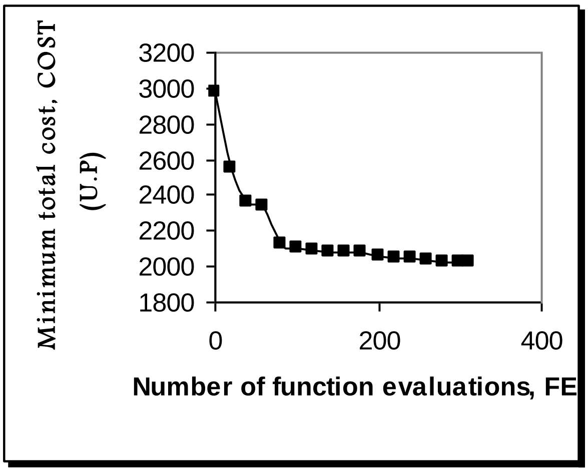
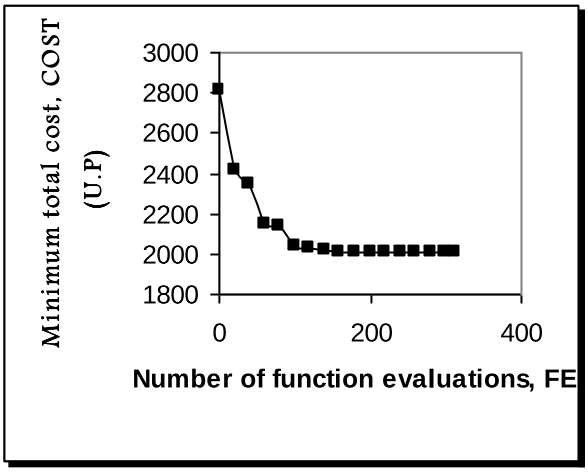


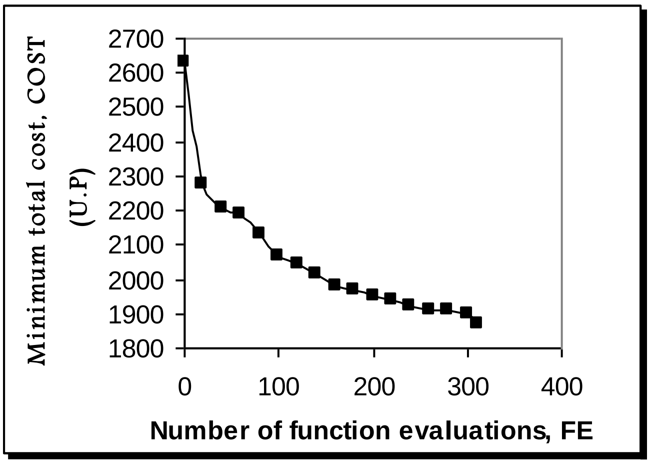
Fig (2) Forces on a Trapezoidal Combined Footing



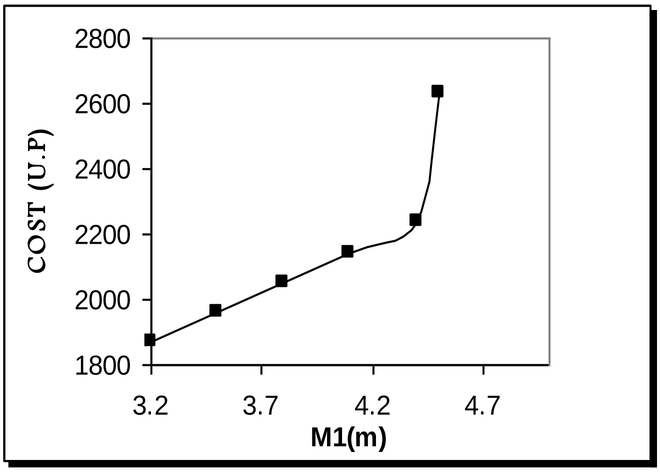
Fig(3) Convergence of The First Initial Point Towards The Minimum



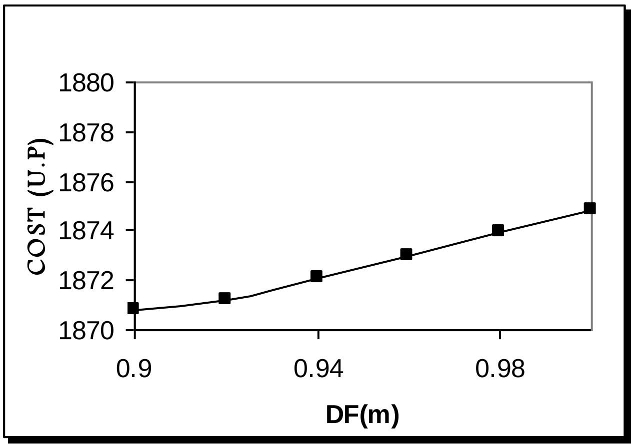
Fig(4) Convergence of The Second Initial Point Towards The Minimum



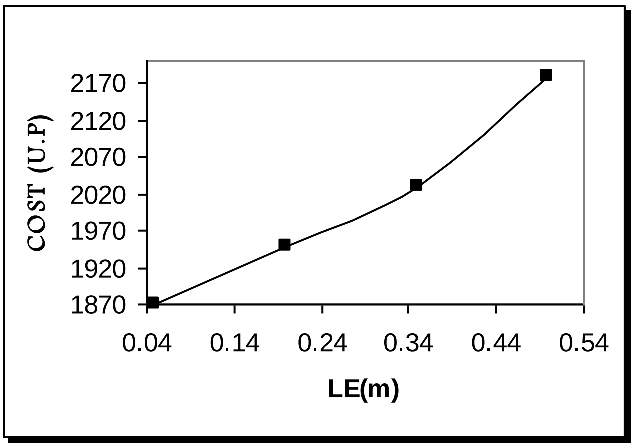
Fig(5) Convergence of The Third Initial Point Towards The Minimum



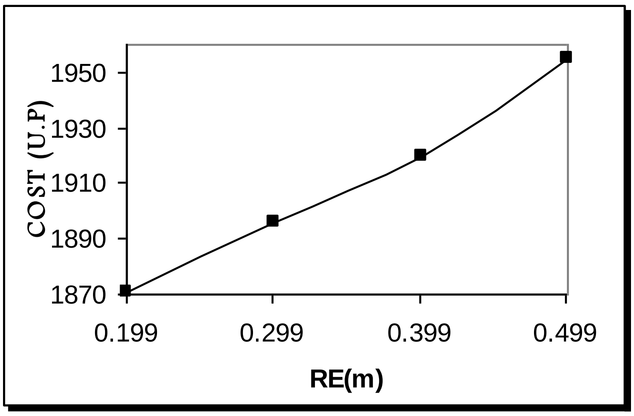
Fig(6) Minimum Total Cost,Cost vs Larger Footing Width ,M1



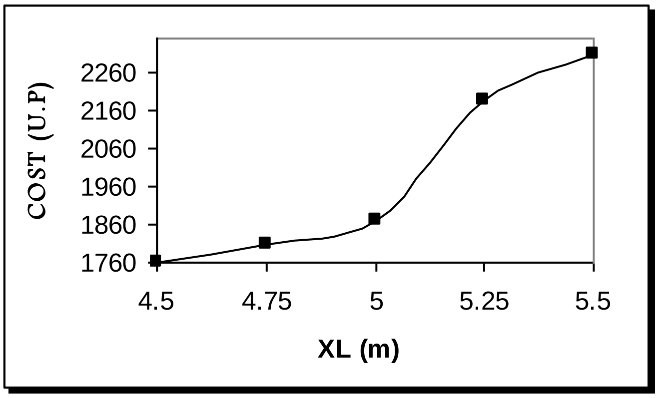
Fig(7) Minimum Total Cost,Cost vs Footing Embedment Depth ,DF



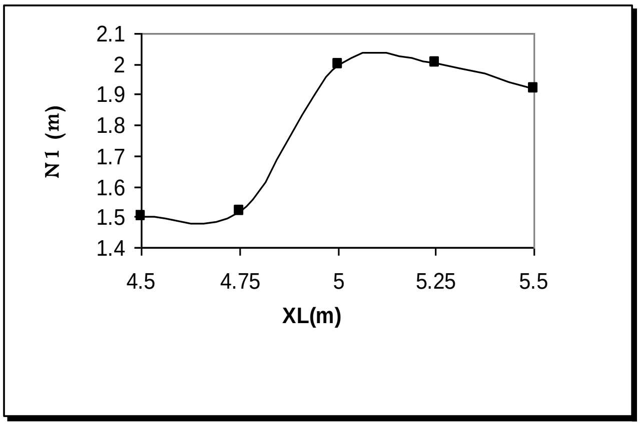
Fig(8) Minimum Total Cost,Cost vs Footing Left Projection ,LE



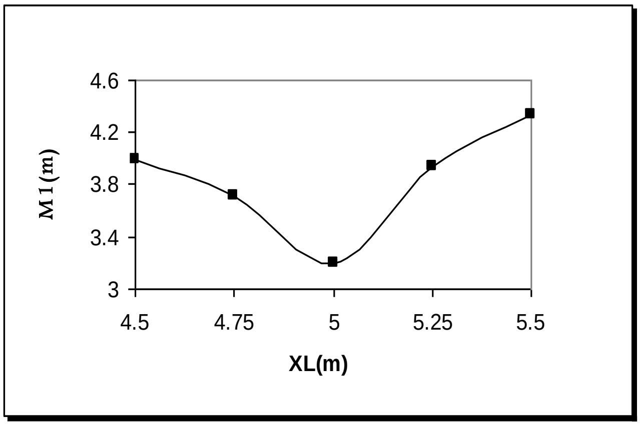
Fig(9) Minimum Total Cost,Cost vs Footing Right Projection ,RE



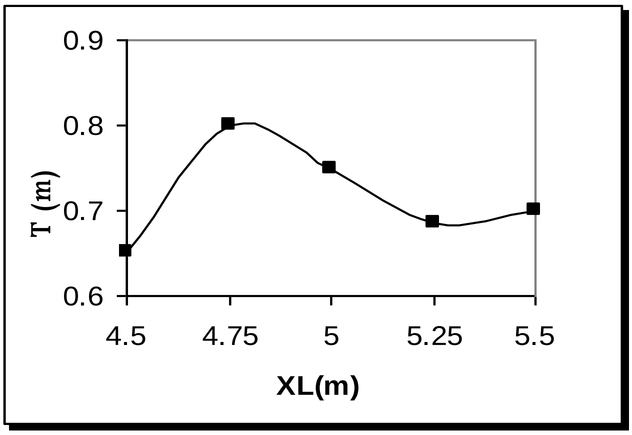
Fig(10) Minimum Total Cost,Cost vs Distance Between Columns ,XL



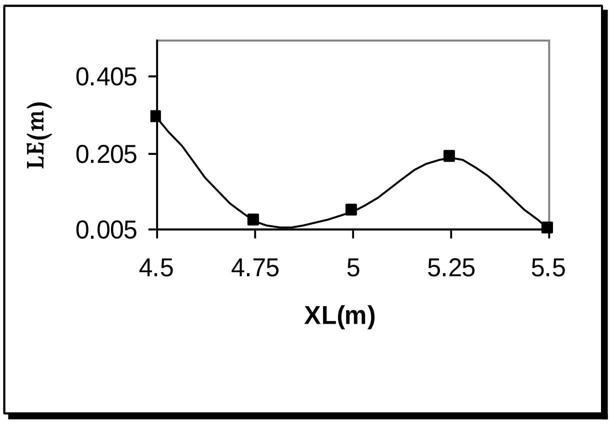
Fig(11) Smaller Footing Width,N1 vs Distance Between Columns ,XL



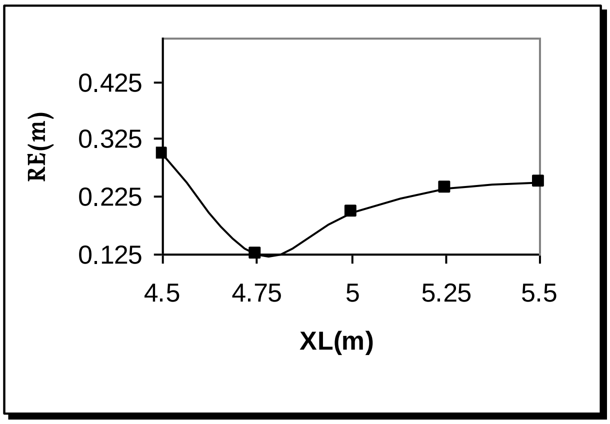
Fig(12) Larger Footing Width,M1 vs Distance Between Columns ,XL



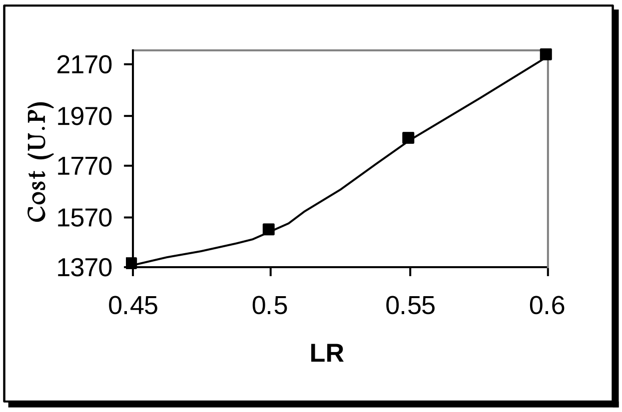
Fig(13) Minimum Footing Thickness,T vs Distance Between Columns ,XL



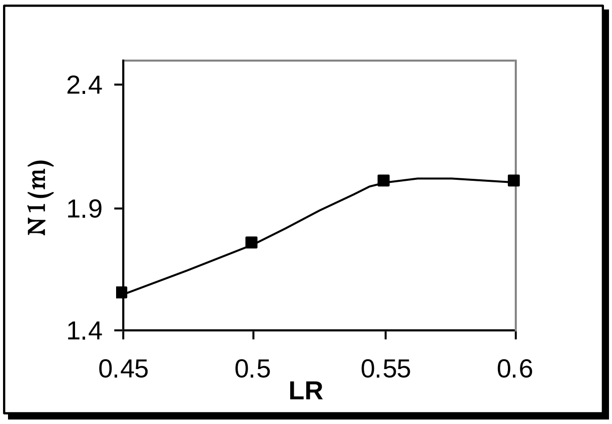
Fig(14) Minimum Footing Left Projection, LE vs Distance Between Columns ,XL



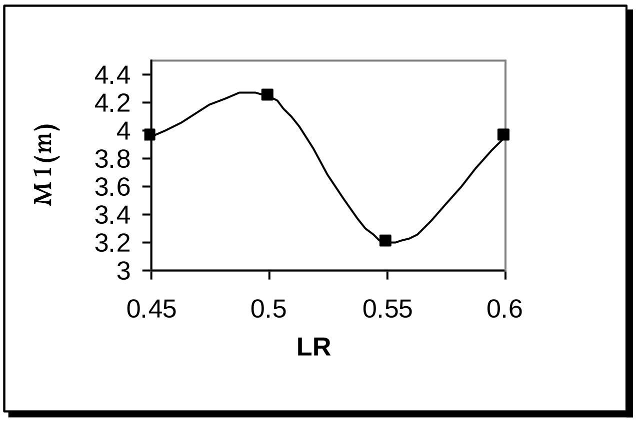
Fig(14) Minimum Footing Right Projection, RE vs Distance Between Columns ,XL



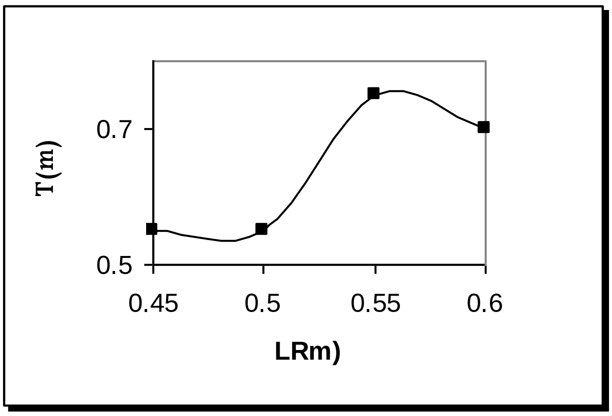
Fig(15) Minimum Total Cost, Cost vs Loading Ratio,LR



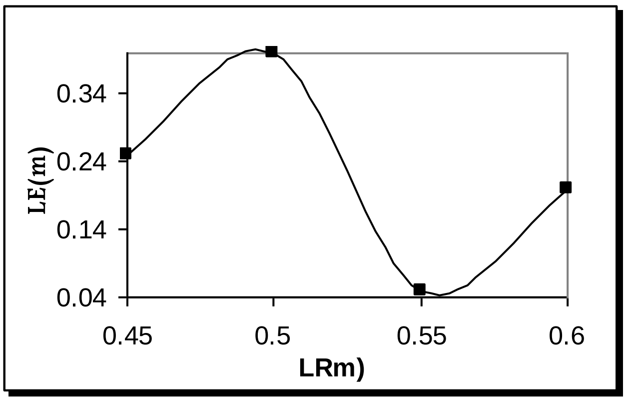
Fig(17) Smaller Footing Width,N1 vs Loading Ratio,LR



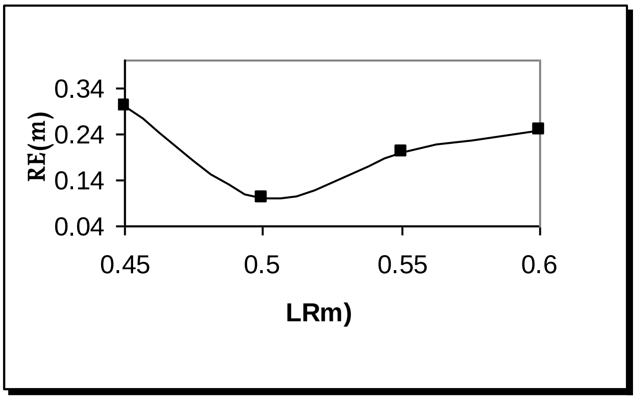
Fig(18) Larger Footing Width,M1 vs Loading Ratio,LR



Fig(19) Minimum Footing Thickness,T vs Loading Ratio,LR



Fig(20) Minimum Footing Left Projection, LE vs Loading Ratio,LR



Fig(21) Minimum Footing Right Projection,
RE vs Loading Ratio,LR

التصميم الأمثل للأسس المشتركة شبه المنحرفة

إيمان موسى فرحان

مدرس مساعد

قسم الهندسة المدنية- جامعة تكريت

الخلاصة

تتعلق هذه الدراسة بإحدى طرق البرمجة اللاخطية (Non-linear Programming Methods) وبالتحديد طريقة هوك وجيفز Hooke&Jeeves Method على مسألة التصميم الإنشائي للأسس المشتركة شبه المنحرفة,على اعتبار أن الكلفة الكلية للأساس هي دالة الهدف .صيغت دالة الهدف بدلالة المتغيرات التصميمية التالية(العرض الأصغر للأساس ,العرض الأكبر للأساس,سمك الأساس,عمق الدفن,البروز الأيسر والأيمن للأساس).

أعد برنامج حاسبة لحل هذه المسألة التصميمية باستخدام طريقة التصميم الإنشائي التقليدي (The Conventional Structural Design Approach) بالارتباط مع طريقة هوك وجيفز Hooke&Jeeves Method .

نفذت دراسة بسيطة لتحري مدى حساسية دالة الهدف إزاء متغيراتها التصميمية كما أجريت دراسة أعمق لبيان تأثير المسافة بين الأعمدة Column Spacing وظروف التحميل Loading Conditions على الكلفة الكلية.لقد برهن أن الكلفة الدنيا للأساس تتزايد مع زيادة المسافة بين الأعمدة كما تتزايد تبعاً لزيادة نسبة التحميل.