OPTIMUM DESIGN OF TUNNELS

Hasan Jasim Mohammad **Amar Salem Khazal**

Lecturer **Assistant Lecturer**

Civil Eng. Dept. - University of Tikrit

ABSTRACT

This study is an application of optimization method to the structural design of tunnels, considering the total cost of the tunnels as an objective function with the properties of the tunnel and soil unit weight, height of soil above tunnel, height of water above tunnel and tunnel radius, as design variables.

A computer program has been developed to solve numerical examples using the ACI code equations , requirements and criteria in concrete design.

The results shown that the minimum total cost of the tunnel increases with the increase of the soil unit weight and tunnel radius, and decreases with the increase of the height of water above tunnel.

KEY WORDS

Tunnels , optimization , design

NOTATIONS

E modulus of elasticity.

I moment of inertia.

g weigh per unit volume along the lining.

k coefficient of subgrad reaction.

M total bending moment.

Mv bending moment due to vertical load.

Mh bending moment due to horizontal load.

Mt bending moment due to horizontal triangle load.

Mr bending moment due to subgrad reaction load.

Ms bending moment due to self load.

Pe1 vertical effective soil pressure.

Pw1 vertical water pressure.

qe1 horizontal effective soil pressure (tunnel top).

qw1 horizontal water pressure (tunnel top).

qe2 horizontal effective soil pressure (tunnel bottom).

qw2 horizontal water pressure (tunnel bottom).

Rc centroid tunnel radius.

θ the angle from the top of tunnel.

δ the horizontal displacement of segment ring at horizontal diameter point.

INTRODUCTION

TechSpan consists of segmental precast arches forming a three-hinged arch structure (Figure 1). The hinge points are at the crown of the arch and the two bottoms of the arch .The span of the arches ranges from about 5 m to 20 m and the height of the arch ranges from about 30% to 70% of the span (Figure 2). The TechSpan arches used in lieu of bridges typically can be in the range of 30% to 40% of height to Span because of the small amount of soil over the crown of the arch (usually 1 m to 2 m).Arches used for industrial applications usually have larger amount of soil over the crown, (usually 25 m to 35 m), and tend to have a height to span ratio of 60% to 70%[1].

The main benefits of the TechSpan Technology are the rapid and simple method of construction. Rapid construction is a benefit for fast turnaround projects, which means that the on site construction time would be reduced. TechSpan can also be built with 2 crane operators and 3 laborers i.e., no highly skilled workers are necessary. Another advantageous use of a TechSpan bridge occurs when culvert construction requires the disturbance of environmentally sensitive waterways. In these cases, TechSpan can cross the waterway without temporary channel relocation[1].

The appearance of the selected arch and wall system met the aesthetic needs of the planned development (Figure's 3 and 4).The span of the arches was 4.9 m with a height of 3.2 m. The two outer arches provided a lighted walkway tunnel for the park on both sides of the creek[1].

Torres et al., (1966),as reported by Al-Jubori (2001) presented the minimum cost design of prestressed concrete highway bridges subjected to AASHTO loading by using piecewise LP (load program) method [2].

Kirsch (1972) presented a minimum cost of a continuos two-span prestressed concrete beam .The cost function included only the cost of concrete and the cost of prestressing steel [3].

Namman (1982) presented a minimum cost design of prestressed concrete tension member based on the ACI-Code 1977 .The cost function included the material costs of concrete and the prestressing steel [4].

Al-Jubair (1994) minimized the cost of ring foundations by using the 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 [5].

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 [6].

Al-Jubori (2001) minimized the cost design of mat foundations. He proved that the minimum cost of the raft foundation decreases with increasing of the angle of internal friction of the soil and increases with increasing the column spacings in both directions as well as with increasing the difference between the loads of adjacent columns[2].

Purpose Of Study

The purpose of this study is to detect the capabilities of optimization method to handle the economical structural design of a tunnel. Giving a safe design with minimum cost based on considering the effects of different parameters on the tunnel and giving the designer the relationships and curves between design variables, the design of a tunnel can be more economical, reliable and simple.

Objective Function

The total cost of a tunnel can be represented by:

ZT=CSRE+CSFW+CSCO ....(1)

where:

ZT= Total cost (unit price).

CSRE= Cost of tunnel reinforcement (unit price).

CSFW= Cost of tunnel formwork (unit price).

CSCO= Cost of tunnel concrete (unit price).

CSRE= [π *Rc*No.]*COR ...(2)

CSFW= [π *Rc] *COFW ...(3)

CSCO= [π *Rc*0.20]*COCO ...(4)

and where:

COR= Price of reinforcement (unit price/ton)

COFW= Price of formwork (unit price/m2)

COCO= Price of concrete (unit price/m3)

Rc = Radius of tunnel .

No. = Number of reinforcement bars per meter length .

Structural Formulations

The design approach used for TechSpan is aimed at determining the most ecomomic efficient arch shape meeting the project specifications. The project specifications include the clearance box required inside the arch and the geometry of the surrounding soil. (Figure 5) .

In order to achieve an economical design, TechSpan utilizes the concept of a funicular curve. The term funicular is defined as "imitating a rope and its tension" (Figure 6).Since "rope" cannot support compression or bending loads, it takes its entire load in tension. However, if the "rope" could be modified, say by dipping it in concrete and bending it into a curve or arch, then it could be maintained in its exact shape. If the vertical and horizontal forces were then applied to the same points as they were within the rope, then this new structure would support its load completely in compression (Brock bank and Segrestin 1995, as listed) [1].

The Bending moment , M, in Ring model (Figure 7) at the angle of θ from the top of tunnel can be given by[7]

$$M=M_v+M_h+M_t+M_r+M_s \qquad \ldots(5)$$

Where M_v , M_h , M_t , M_r , M_s are the bending moments due to vertical load, horizontal load, horizontal triangle load, subgrad reaction and self load, and they are defined as follows :

$$M_v= 1/4\ (1-2\sin^2\theta)(p_{e1}+p_{w1}).R_c^2 \qquad \ldots(6)$$

$$M_h=1/4(1-2\cos^2\theta)(q_{e1}+q_{w1}).R_c^2 \qquad \ldots(7)$$

$$M_t=1/48(6-3\cos\theta-12\cos^2\theta+4\cos^3\theta)(q_{e2}+q_{w2}-q_{e1}-q_{w1}).R_c^2 \qquad \ldots(8)$$

$$M_r=(0.2346-0.3536\cos\theta)k.\delta.R_c^2 \qquad (0°\leq\theta\leq45°) \qquad \ldots(9)$$

$$M_r=(-0.3487+0.5\sin^2\theta+0.2357\cos^3\theta)k.\delta.R_c^2 \qquad (45°\leq\theta\leq90°) \qquad \ldots(10)$$

$$M_s=(3/8\pi-\theta.\sin\theta-5/6\cos\theta).g.R_c^2 \qquad (0°\leq\theta\leq90°) \qquad \ldots(11)$$

Where k is the coefficient of subgrad reaction , R_c is the centroid radius of tunnel , g is weight per unit volume along the lining and δ is the horizontal displacement of segment ring at horizontal diameter point and given by:

$$\delta=\frac{\{2(p_{e1}+p_{w1})-(q_{e1}+q_{w1})-(q_{e2}+q_{w2})+\pi.\ g\}.R_c^4}{24(EI+0.0454k.R_c^4)} \qquad ...(12)$$

Computer Program

The main program, utilized to perform the necessary calculations for optimization, was drawn from Bundy (1984) [8] and translated to FORTRAN-77.Hooke and Jeeves method was used to performed the minimization process utilizing this method of solution. Followings, are the required input parameters for this program.

Ns- number of independent (design) variables.

X(Iz)-initial estimate of the design variables [Iz=1,2,3,……Ns]

Hz-step length.

The program (Tunnel.For) in FORTRAN-77 was written by using the design procedure of ACI-Code with code [9] improvement in load factors. This program gave good results with code requirements .

The program (Tunnel .For) uses a subroutine with the program (H & J. For). Input data symbols and other parameters used in subroutine (Tunnel .For) is listed in Table (1) and results shown in Table (2).

Numerical Example

The problem was solved by using four sets of initial trial values for design variables vector X=[γs, H, hw, Rc] .The input data is: Ns=4. The first initial trial values: X(1)=18.30 , X(2)=22.93 , X(3)=13.99 , X(4)=7.95. The second initial trial values: X(1)=19.50 , X(2)=21.50 , X(3)=12.0 , X(4)=7.80.The third initial trial values: X(1)=19.50, X(2)=18.0 , X(3)=13.0 , X(4)=8.20 . The fourth initial trial values: X(1)=19.0, X(2)=17.0 , X(3)=12.50 , X(4)=8.0 . Hz=0.01

The results obtained are shown in Table (3). Figs (8) to (11) show the convergence rate towards the minimum cost design of Tunnel.

DISCUSSION OF RESULTS

A parametric study was done to the soil unit weight, height of soil above tunnel, height of water above tunnel, and tunnel radius for the fourth initial trial point. The results are listed in Tables (4),(5),(6) and (7).

It can be observed from Table (4) and Figs. (12) to (14) that as the soil unit weight increases; the minimum total cost is increased ,as shown in Fig (12), the minimum total cost is at 17 kN/m3.Also the optimum moment and steel area are rapidly increased with increment of soil weight , Figs. (13) and (14) . But the height of soil above tunnel, the height of water above tunnel, and tunnel radius dose not change with soil unit weight change Table(4).

It can be observed from Table (5) and Figs (15) to (20) that as the height of soil above tunnel increases; the minimum total cost decreases then increases, Fig. (15).The minimum total cost occure at 16.5m height. The optimum soil unit weight is decreased, Fig. (16)and still constant after 16 m height. The optimum height of water above tunnel is increased Fig. (17) and became constant after 16m height. The optimum tunnel radius decreases and stay constant after 16m height Fig(18). But optimum moment and steel area are decreased and then increased Figs.(19)and(20), the optimum value between 16-17m height.

It can be realized from Table (6) and Figs. (21) to (25) that as the height of water above tunnel increases; the minimum total cost decreases then increase and then decreased Fig.(21). The minimum total cost is at 13m height. The optimum soil unit weight and height of soil above tunnel have values constant then increased after 14m height of water Figs.(22) and (23). The optimum moment and steel area are also have a constant values but they decreased after 13m height Figs.(24) and (25).

It can be noticed from Table(7) and Figs(26) to (28) that as the tunnel radius increased ; the minimum total cost increased Fig(26) . The optimum moment and steel area are increased then decreased Figs(27) and (28). From Table (7), soil unit weight, height of soil above tunnel, and height of water above tunnel are dose not change with increased tunnel radius .

CONCLUSIONS

1-The minimum total cost is more sensitive to the changes in soil unit weight and tunnel radius .

2-Increase in soil unit weight leads to increase in minimum total cost, moment and steel area.

3-Increase in height of soil above tunnel leads to increase in minimum total cost. So , increases are obtained in height of water above tunnel, moment and steel area, but decreased are obtained in soil unit weight and tunnel radius .

4-Increase in height of water above tunnel leads to decreases in total cost, moment and steel area, and increases in soil unit weight and height of soil above tunnel .

5- Increase in tunnel radius leads to increase in total cost and decreases in moment and steel area , but doesn't affect by the height of soil and water above tunnel and soil unit weight.

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Table (1) Some Input Data

Symbols	Value	Function
γ_s	19.0	Soil unit weight (kN/m^3)
H	17.0	Height of soil above tunnel (m)
h_w	12.50	Height of water above tunnel (m)
R_c	8.0	Tunnel radius (m)
SYS	414	Yield of steel strength (Mpa)
CS	34.5	Concrete compressive strength (Mpa)
Ws	90.0	Surcharge load (kN/m^2)

Table (2) Some Results of (Tunnel .For)

	Tunnel. For	Ref.[1]
M(kN.m)	138.3	139.4
A_s(mm^2)	185.6	188.2

Table (3) The Design Results (initial trial point)

Variables	First trial	Second trial	Third trial	Fourth trial
Cost (U.P.)	7047	7507	5133	4070
γ_s(kN/m^3)	16.77	17.97	17.97	17.47
H(m)	21.40	19.97	16.47	15.47
h_w(m)	15.51	13.52	14.52	14.02
R_c(m)	6.43	6.28	6.68	6.48
FE *	220	210	230	200

* Number of function evaluation.

Table (4) The Design Results for different soil unit weight

Variables (kN/m^3)	γ_s=17.0	γ_s=17.5	γ_s=18.0	γ_s=18.5	γ_s=19.0	γ_s=19.5	γ_s=20.0
Cost (U.P.)	2853	3101	3424	3747	4067	4393	4716
H(m)	15.47	15.47	15.47	15.47	15.47	15.47	15.47
h_w(m)	14.02	14.02	14.02	14.02	14.02	14.02	14.02
R_c(m)	6.48	6.48	6.48	6.48	6.48	6.48	6.48
M(kN.m)	102.3	138.9	186.4	233.9	281.5	329.0	376.5
A_s(mm^2)	137	186	250	314	378	441	505
FE*	221	252	215	202	208	208	241

* Number of function evaluation.

Table (5) The Design Results for different height of soil above tunnel

Variables(m)	H=15	H=16	H=17	H=18	H=19
Cost (U.P.)	3397	2878	2852	3424	4070
γ_s(kN/m^3)	16.39	15.53	15.47	15.47	15.47
h_w(m)	13.15	13.97	14.02	14.02	14.02
R_c(m)	7.40	6.48	6.48	6.48	6.48
M(kN.m)	120.8	105.4	102.3	186.4	281.5
A_s(mm^2)	162	141	137	250	378
FE*	215	254	247	245	261

* Number of function evaluation.

Table (6) The Design Results for different height of water above tunnel

Variables(m)	h_w=10	h_w=11	h_w=12	h_w=13	h_w=14	h_w=17
Cost (U.P.)	3822	3405	2987	2748	2856	2726
γ_s(kN/m^3)	15.47	15.47	15.47	15.47	15.53	16.28
H(m)	15.47	15.47	15.47	15.47	15.53	16.45
R_c(m)	6.48	6.48	6.48	6.48	6.48	6.48
M(kN.m)	245.0	183.5	122.1	86.9	84.7	83.0
A_s(mm^2)	329	246	164	117	115	111
FE*	215	218	221	220	220	224

* Number of function evaluation.

Table (7) The Design Results for different Tunnel radius

Variables(m)	R_c=7	R_c =7.5	R_c =8	R_c =8.5	R_c =9	R_c =9.5	R_c =10
Cost (U.P.)	3343	3729	4070	4346	4532	4608	4848
γ_s(kN/m^3)	17.47	17.47	17.47	17.47	17.47	17.47	17.47
H(m)	15.47	15.47	15.47	15.47	15.47	15.47	15.47
h_w(m)	14.02	14.02	14.02	14.02	14.02	14.02	14.02
M(kN.m)	264.3	277.1	281.5	276.2	260.3	233.1	223.8
A_s(mm^2)	355	372	378	371	349	313	300
FE*	215	218	221	220	220	224	215

* Number of function evaluation.

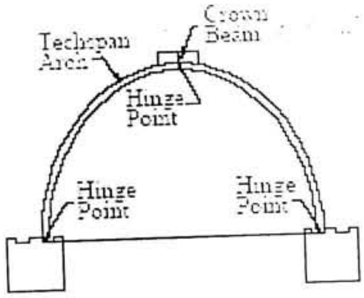


Figure No. 1
Three Hinged Arch Structure

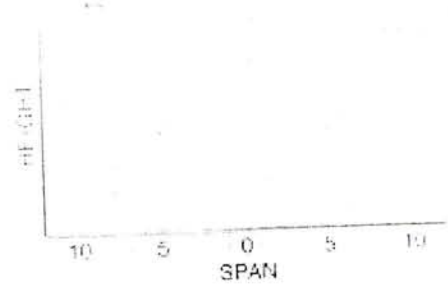


Figure No. 2
Height to Span Comparison

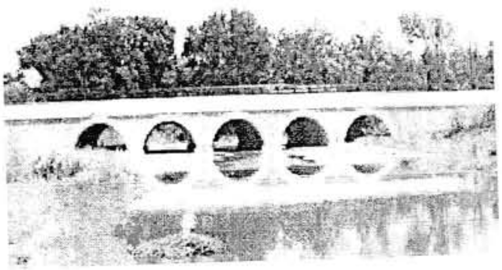


Figure No.3

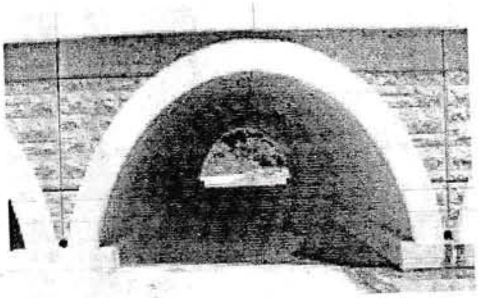


Figure No.4

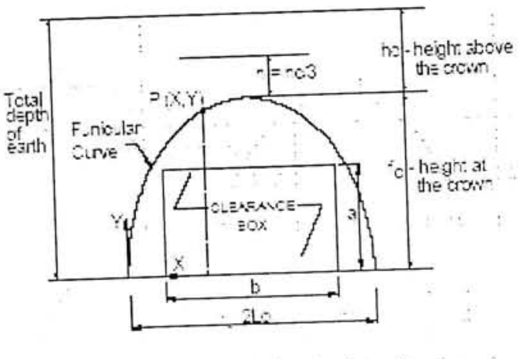


Figure No. 5 – Funicular Curve

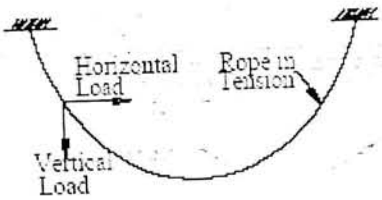


Figure No. 6 – Rope in Tension

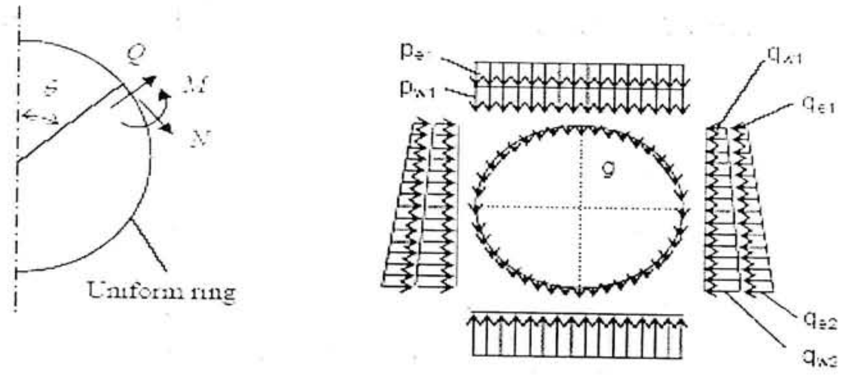
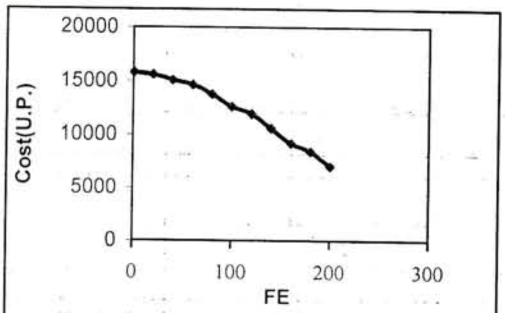
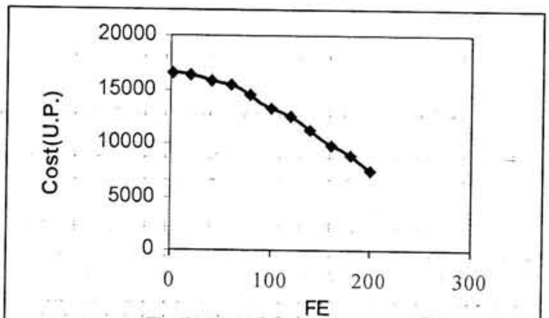


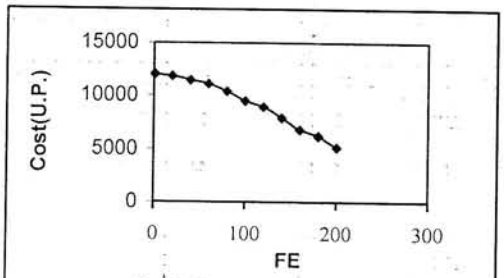
Figure No.7 Ring Model



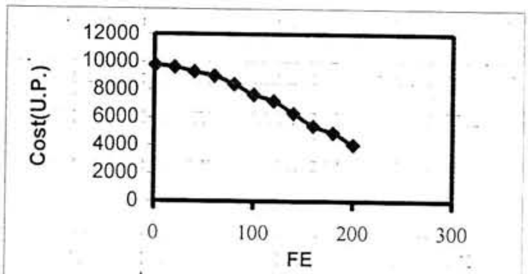
Fig(8)Convergence towards the minimum(First initial trial)



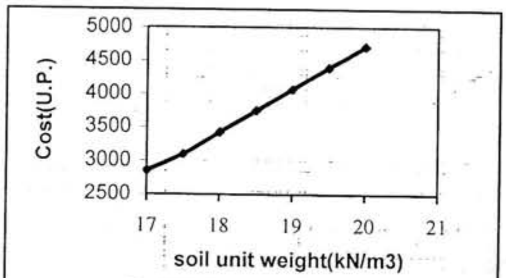
Fig(9)Convergence towards the minimum(Second initial trial)



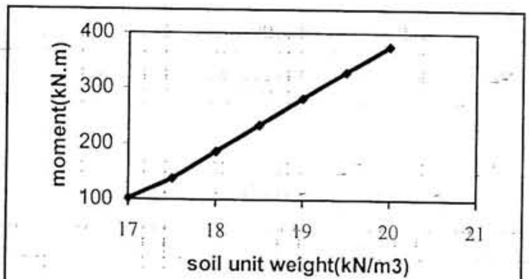
Fig(10)Convergence towards the minimum(Third initial trial)



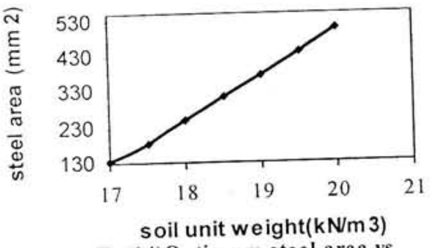
Fig(11)Convergence towards the minimum(Fourth initial trial)



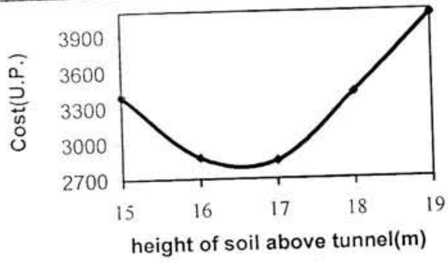
Fig(12)Minimum total cost vs. soil unit weight



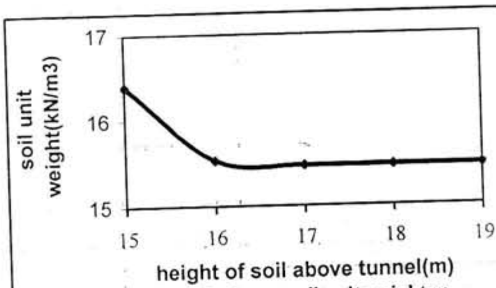
Fig(13)Optimum moment vs. soil unit weight



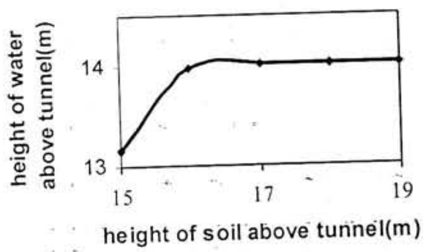
Fig(14)Optimum steel area vs. soil unit weight



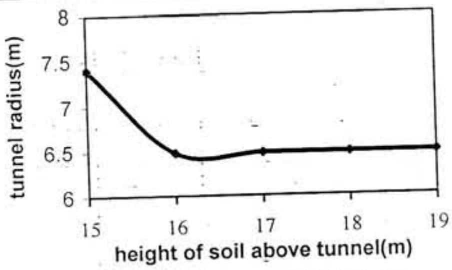
Fig(15)Minimum total cost vs. height of soil above tunnel



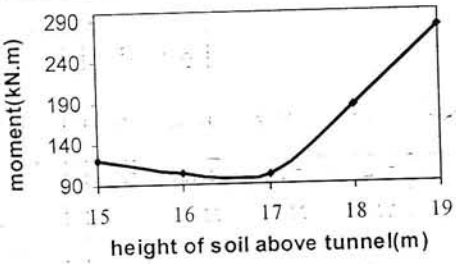
Fig(16)Optimum soil unit weight vs. height of soil above tunnel



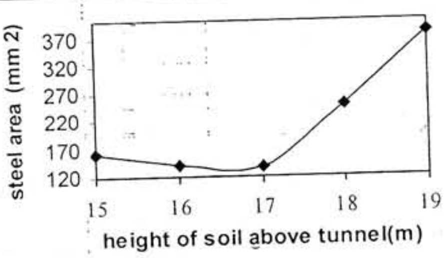
Fig(17)Optimum height of water above tunnel vs. height of soil above



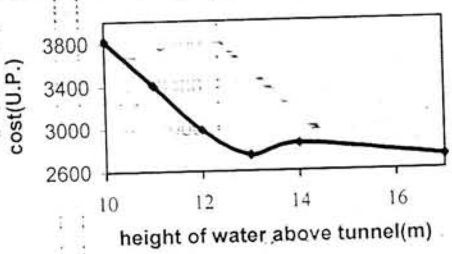
Fig(18)Optimum tunnel radius vs. height of soil above tunnel



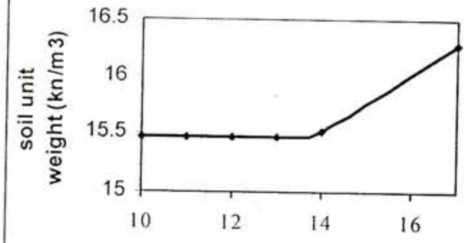
Fig(19)Optimum moment vs. height of soil above tunnel



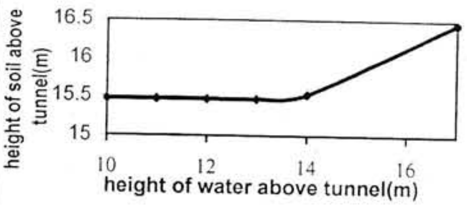
Fig(20)Optimum steel area vs. height of soil above tunnel



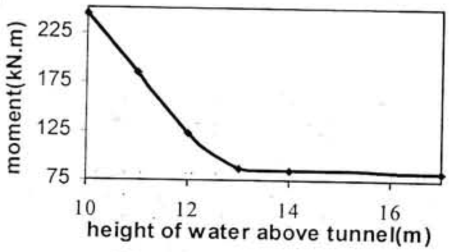
Fig(21)Minimum total cost vs. height of water above tunnel



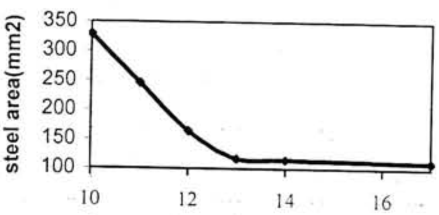
Fig(22)Optimum soil unit weight vs. height of water above tunnel



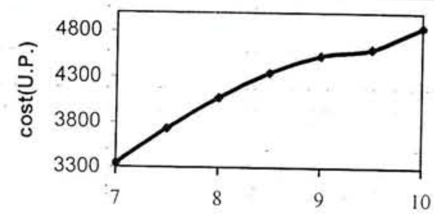
Fig(23)Optimum height of soil above tunnel vs. height of water above tunnel



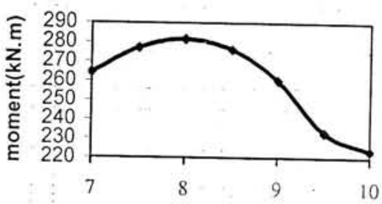
Fig(24)Optimum moment vs. height of water above tunnel



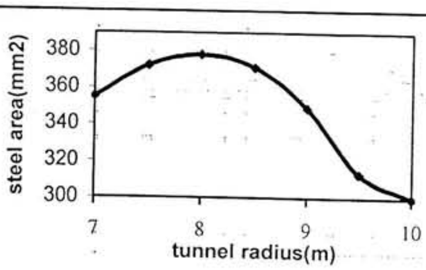
Fig(25)Optimum steel area vs. height of water above tunnel



Fig(26)Minimu total cost vs. Tunnel radius



Fig(27)Optimum moment vs. Tunnel radius



Fig(28)Optimum steel area vs. Tunnel radius

التصميم الأفضل للأنفاق

حسن جاسم محمد ألبدري — مدرس

عمار سليم خزعل — مدرس مساعد

قسم الهندسة المدنية – جامعة تكريت

الخلاصة

تمت دراسة تطبيق الطريقة المثلى على مسألة التصميم الإنشائي للأنفاق ، باعتبار الكلفة الكلية للنفق كدالة هدف وبعض الخواص الهندسية (والتي شملت وحدة وزن التربة وارتفاع التربة فوق النفق وارتفاع مستوى الماء فوق النفق ونصف قطر النفق) كمتغيرات تصميميه. تمت كتابة برنامج حاسبة لحل الأمثلة العددية بالاستناد إلى معادلات مواصفات المعهد الأمريكي للخرسانة ومتطلبات ومعايير التصاميم الخرسانية.

لقد بينت النتائج بان الكلفة الكلية للنفق تزداد بزيادة وحدة وزن التربة ونصف قطر النفق وتقل بزيادة ارتفاع مستوى الماء فوق النفق.

الكلمات الدالة

أنفاق ، أمثلية عددية ، تصميم