Stability of Shallow Circular Tunnels in Makkah Rocks

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Abstract: The stability and safety at the excavation face, heading, work area and lifeline out of the sallow circular tunnel has always been of great concern in tunneling. The support pressure needed at the face of shallow tunnel can be determined by using approximate solution. The current method for stability of shallow circular tunnel face has been applied on a homogeneous rock formation of Makkah, KSA. This paper investigates the influence of the surcharge pressure at the ground surface, the height of rocks above the crown of circular tunnel, the radius of tunnel, and the types of rocks characteristics on the support pressure of the shallow circular tunnel face. The stability safety factor of the shallow circular tunnel is determined by using suggested formula, the proposed formula is illustrated from the approximate equation used in this investigation for determination of the support pressure. The previous mentioned factors have significant effect on the support pressure of the shallow circular tunnel face and on the stability safety factor of shallow circular tunnel in rocks. The results of this investigation are considered as a guidance for choosing the suitable type of shallow circular tunnel constructions in Makkah rocks.

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Key Words: Stability, Sallow Circular tunnel, Support Pressure, Surcharge Pressure, Factor of Safety.

1. Introduction

The stability of the shallow tunnel is one of the most important subjects in the tunnel constructions, especially in urban areas. The important aspects of the tunnel boring process is the control of tunnel face during shallow tunnel construction. To prevent the tunnel face from collapsing a minimal pressure at crown of tunnel is required. For that, the estimation of the support pressure (pressure at crown of tunnel) is very important to determine the suitable methods for tunnel boring, face protection method and tunnel design. Many attempts have been made to estimate the support pressure of tunnel face and to evaluate the tunnel face stability on soils and rocks by using numerical analysis or physical models. **Leca and Dormieux [13]** used the limit analysis concept to evaluate the stability of a tunnel face driven in frictional soil and compared these results with centrifuge tests performed by **Chambon and Corte [4].** Chambon and Corte [4] carried out centrifuge tests to study the face stability of tunnel in sands. **Karaca, et al.,[11]** used model tests and numerical solution to study the mechanics of failure around shallow tunnel in jonted rock. **Bauman, [2]** studied the face stability of tunnels in soils and soft rocks by using finite element method in combination with elastic-plastic Mohr-Coulomb constitutive model. **Strenath and Baumann [16]** used Horn model for assessing the stability under drained condition to analyze NATM-Tunneling. **Ikumaet al, [9]** studied the tunnel face stability in altered granite ground by tests models and numerical analysis method. **Vermeer,et al.,** used finite element technique to study the stability number for cohesion and surcharge for tunnel heading stability of closed-face tunneling and also factor of safety for open-face tunneling in soils and soft rocks. **Ikuma, et al.,[10]** presented geophysical investigation a head of tunnel face and actual excavation results in weak rock zone**. Konishi [12]** studied the method to evaluate the conditions for face stability through model tests and numerical analysis by the rigid plasticity finite element method. **Qin [14]** used wedge model to calculate the support pressure of tunnel face. **Shulin, et al.,[15]** devised an extensive field instrumentation programme to monitor the relationship between the maximum vertical settlement and the actual support pressure induced by tunneling. A lot of surface settlement points were installed to detect the verticle settlement profiles along/across tunnel axis. The field results were compared with numerical analysis. The ANSYS program was used for three dimentional and axi-symmetric FEM analysis. **Wei et al., [19]** modified the wedge model and assumed the up side of sliding block as a trapezoid prism, using the Terzaghi Loose earth pressure theory to calculate limited support pressure of tunnel face based on the principle sliding block entire force balance. **Hisatake and Ohno [8]** conducted a series of centrifuge tests to clarify the effect of pipe roof supports and excavation method on the displacement above a tunnel face. The model tests indicate that the maximum settlement of ground excavated by the full-face excavation method with pipe roof supports is one fourth of that without them. **Wang and Jia [18]** investigated the mechanical behavior of pipe roof reinforcement based on pastermak elastic foundation beam theory**. Hatitao and Jimging [7]** established the three dimensional model for expressing the tunnel face stability with pipe roof reinforcement, based on the kinematic method of limit analysis and shear strength reduction. The solutions computed by the proposed approach were compared with the results given by wedge model, Trapezoid wedge model, and centrifugal model test. This research study investigated the effect of various parameters on the support pressure of the shallow circular tunnel face in the construction of tunnel in Makkah region. The parametric study includes the surcharge pressure at the ground surface, overburden head, rock characteristic, and the radius of tunnel. Moreover, the stability safety factor of the shallow circular tunnel is determined by proposed by **Dimitrios** equation [6].

2. Collapse Mechanism of Tunnel - Face:

assessment of face stability is often accomplished, following a collapse mechanism originally proposed by Horn as mention in [6] as shown in Fig.1. To take into account the 3D, character of the collapse mechanism, the front ABCD of the sliding wedge is taken of equal area as the one of the tunnel cross section. On the side BDI and ACJ is set cohesion and friction (in accordance with the geostatic stress distribution $\sigma_x = K\gamma Z$). The vertical force vs. computed according the silo formula. The necessary support force S is determined by equilibrium consideration of the sliding wedge. Whereby the inclinations angle θ is varied until S becomes maximum. From the consideration of the relative displacements, the horizontal force H acts at the sliding wedge as shown in Fig. (1- c), which is omitted by the most authors [6]. The silo equation proposes a full mobilization of the shear strength at the circumference of the prism sliding downward, which implies substantial settlement at the surface.

3. Estimation Methods for Calculation of the Support Pressure:

There have been many methods to estimate the pressure required for the support of the circular shallow tunnel face, these methods could be summarized as follows:

3. 1 Approximate Solution (Dimitrios's Method):

The distribution of vertical stress between the ground surface and the crown of circular shallow tunnel is a quadratic parabola and assume that the material strength is fully mobilized at the crown. The necessary support pressure (p_c) at the crown of circle tunnel lining in rock formation can be determined from the following equation [6].

$$P_c = [q - \{(h\ c\ \cos\Phi)/(r\ (1-\sin\Phi)\} + \gamma\ h]/[1 + \{(h\ \sin\Phi)/(r\ (1-\sin\Phi)\}] \quad (1)$$

Negative sign Pc is meaning the support at least crown of shallow circular tunnel is not necessary. By experimental model tested in the laboratory has been shown that equation (1) supplies a safe estimation of the necessary support pressure [6].

Where:
P_c = support pressure at the crown.
q = surcharge pressure at ground surface.
h = height of soil above the crown of tunnel.
c = cohesion of soil.
Φ = angle of internal friction.
r = radius of circular tunnel.
γ = unit weight of soil.

3.2. Estimation Based on the Bound Theorems:

3.2.1. Lower bound of the support pressure:

Safe estimation of the support pressure (P) in a cohesive ground ($c > 0$, $\Phi = 0$) is suggested by **Davis et al., [5]** in the following equation:

$$(P_c - q)/c = (\gamma\ r/c - 1)\ (h/\ r) \quad (2)$$

3.2.2. Upper bound of the support pressure:-

Unsafe estimation of the support pressure (p) in cohesionless soil is suggested by **Atkinson and Polts [1]** for $h/r \geq 1/\sin\Phi - 1$:-

$$P_c/\gamma\ r = 1/2\cos\Phi\ (1/\tan\Phi + \Phi - \pi/2) \quad (3)$$

3.3. Numerical solutions:

From numerical results obtained with the Finite Element code PLAXIS, **Vermeer,et al, 17]** deduced the following approximation for the limit support pressure and the case $\Phi > 20^\circ$:

$$P_c = c/\tan\Phi + 2\gamma r\ (1/9\tan\Phi - 0.05) \quad (4)$$

4. Forces acting upon and within the lining of tunnel:

The tunnel lining can be regarded as a beam with initial curvature and width of 1m as shown in Fig. 2. From equilibrium considerations at a beam element with length ds, the following relations can be deduced [6]:

$$Q - N = -\ p\ r$$
$$N + Q = -\ q'\ r \quad (5)$$
$$M = r\ Q$$

Where:-
q' = distributed force tangential to the beam.
N = normal force.
Q = transverse force.
M = bending moment.

Which represent a coupled system of differential equations. The resultant force (R) exerted from the support to the rock must be considered by suitable constructions e.g. enlarged footings of the crown arc (so called elephant feet) or micro piles. It is proved that the compressive stress in the sprayed concrete within permissible limit. If β is the compressive strength and d the thickness of the sprayed concrete lining, their

$$d > P_c\ r/\beta\ ,\quad d > P_i\ r_i/\beta \quad (6)$$

Where:-
d= the thickness of sprayed concrete lining
P_i = pressure at the invert

β= the compressive stress in the sprayed concrete (shot concrete)
r_i = curvature radius of the invert

5. Surface Circular Tunnel Parameters:

In this investigation various parameter and factor were considered to study its effect and their influence on the stability of shallow circular tunnel; cover depth above the crown of the tunnel (overburden head) (5, 10, 15 and 20 m); the surcharge pressure at the ground surface (0, 100, 150, 200, 400 and 600 kN/m^2); the radius of tunnel (2, 4, 6, 8 and 10 m) and the rock characteristics (very good, good, fair and poor).

6.Rock Mass Parameters:

The majority rocks encountered in Makka region are Granodiorite. The classification, characteristics and shear strength parameters of Granodiorite rocks are determined and accordingly the Rock Mass Rating System (RMR) **[3]** are studied. The various rocks parameters have been used in this study are given in Table 1.

Table 1: Rock Parameters

Rock type	Cohesesion (c) Kpa	Angle of internal friction (ϕ)	Unit weight (kN/m3)
Very good	400	> 45	29
Good	300	35	28
Fair	200	25	26
Poor	100	15	24

7. Results and Discussion:

7.1. Pressure at crown of tunnel:

In this investigation, the pressures at crown of circular tunnel (support pressure at tunnel face) (P_c) were calculated by using approximate Dimitrios's Method (1). The various observation were made by interpreting the results shown graphically Figs (3 to 9). The relationship between radius of tunnel and pressure at crown of tunnel at various types of granodiorite rock characteristics, various overburden head, various surcharge pressure at ground surface obtained are shown in Figs (3 to 7). The negative sign of (P_c) is meaning the support at least at crown of shallow circle surface tunnel is not necessary. It is clearly observed that the support pressure has great effect by the tunnel radius, the surcharge pressure, the overburden head and the type of rock characteristics. It is observed from Figs (3 to 7) that the support pressure increases with increasing the radius of tunnel. Figs (3 to 7) and Fig. 8 shown indicates the support pressure decreases by increasing the overburden head and with improving the rock mass characteristics. It is clearly shown from Fig. 9 that the support pressure decreases with decreasing the surcharge pressure at ground surface and with improving the rock mass characteristics.

7.2. Factor of safety for tunnel face stability:

The factor of safety for the shallow circular tunnel face stability is calculated by using the following equation (7) which is illustrated from **Dimitrios [6]** equation (1):

$$Fs = h\ c \cos\Phi / r\ (1-\sin\Phi)\ (q+\gamma\ h) \qquad (7)$$

Where:
r = radius of tunnel.
c = cohesion.
Φ = angle of internal friction.

It can be observed from Fig. 15 that the factor of safety of the tunnel face (F) increases with increasing the overburden head and with improving of the rock mass characteristics. This also notices that from Fig. 16 the factor of safety increases by decreasing the radius of tunnel and with decreasing the surcharge pressure. Similar kind of conclusion is well supported by the results of kinematic method of limit analysis and the shear strength reduction technique by the three dimensional model reported by **Haitao and Jinging [7]** and also well supported by the results of centrifuge tests reported by **Chambon and Corte [4].** But it is clearly shown in Fig. 16 for surcharge pressure equal to zero that the factor of safety has been not affected by overburden head. If the factor of safety is more than one, the face of tunnel have not required any support during the period time, which is proposed in Table 2.

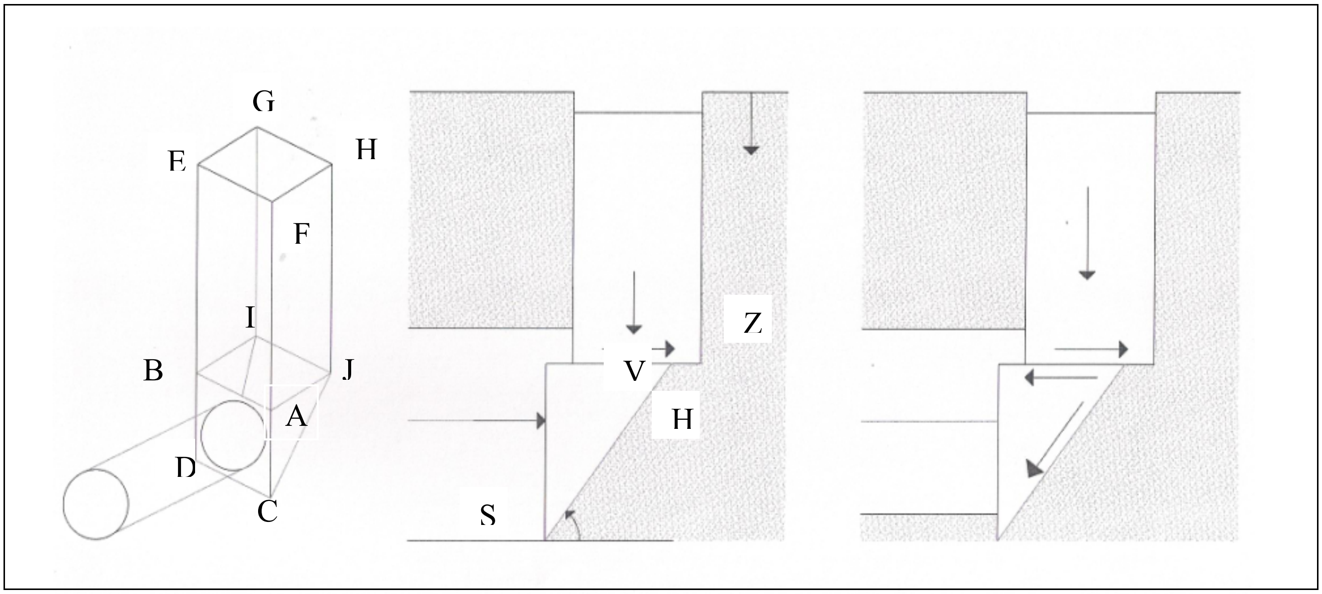
Table 2: Factor of Safety and Period of Time

Factor of safety (F)	Period time of no need support
> 1.50	Long
1.25 -1.50	Medium
1.00 – 1.25	Short
<1.00	------

8. Conclusion:

This investigation has been studied the effect of the surcharge pressure at the ground surface, the height of rocks above the crown of circular tunnel (overburden head), the radius of tunnel and the types of rocks characteristics on the support pressure and the factor of safety of the shallow circular tunnel face. The results obtained from this study have led to the following conclusion:

- The support pressure at the crown of the shallow circular tunnel decreases and the stability safety factor of tunnel increases with increasing the overburden head and with improving the rock mass characteristics.
- The support pressure decreases at the crown of tunnel and the factor of safety increases with decreasing both of the radius of tunnel as well as the surcharge pressure at the ground surface.
- The results obtained from this investigation can be considered as a guidance for choose the suitable type of shallow circular tunnel constructions in Makkah region.



θ

(a) (b) (c)

Fig. 1(a-c) Collapse Mechanism of Horn to analyses Tunnel Face stability

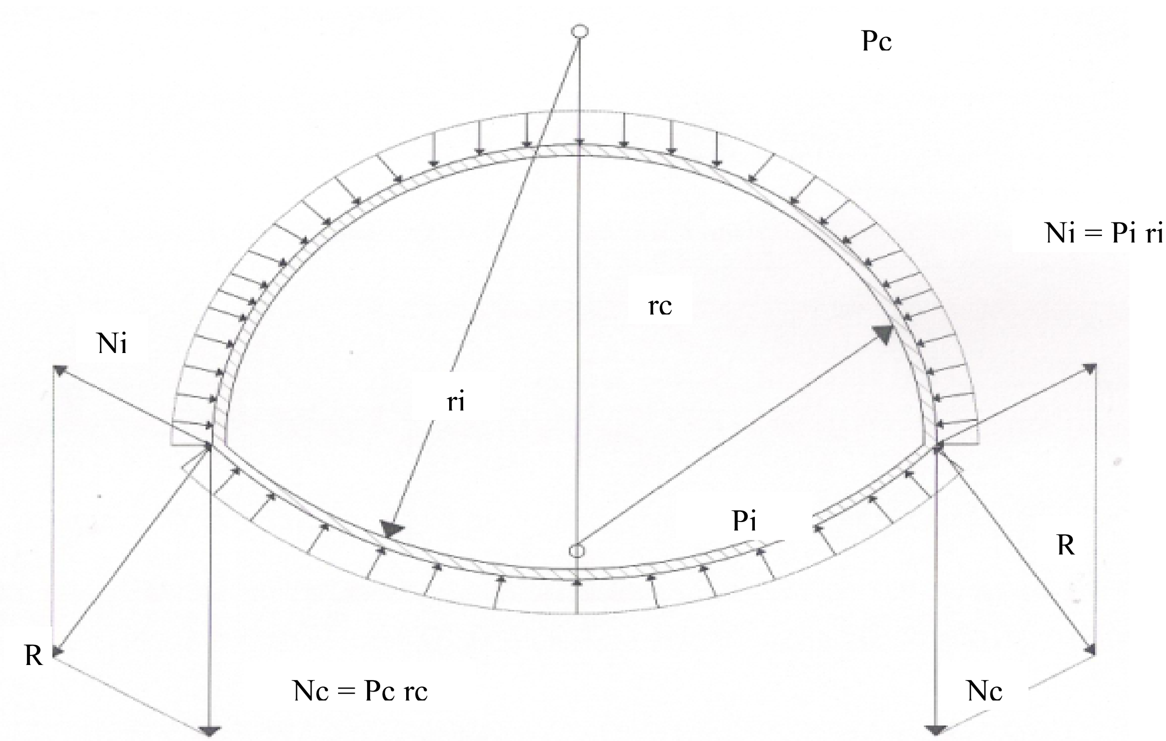
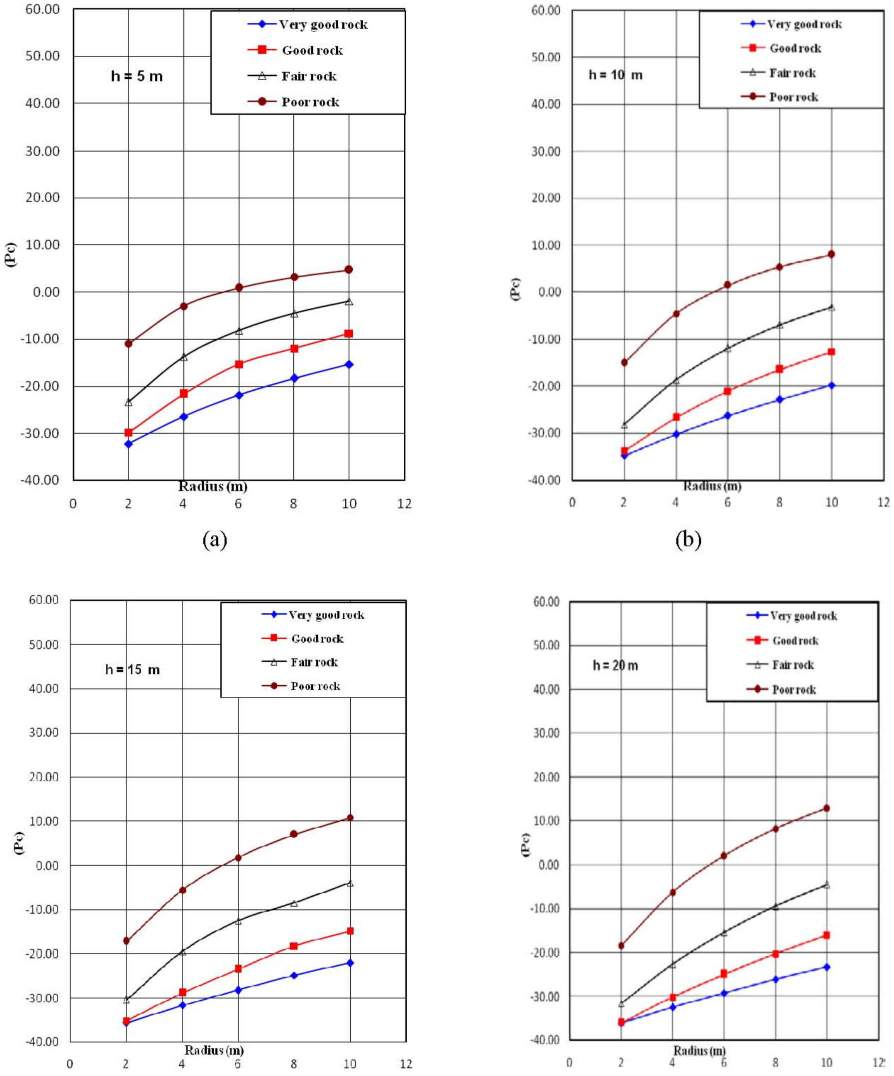


Fig. 2 Forces at points where the curvature of liming change



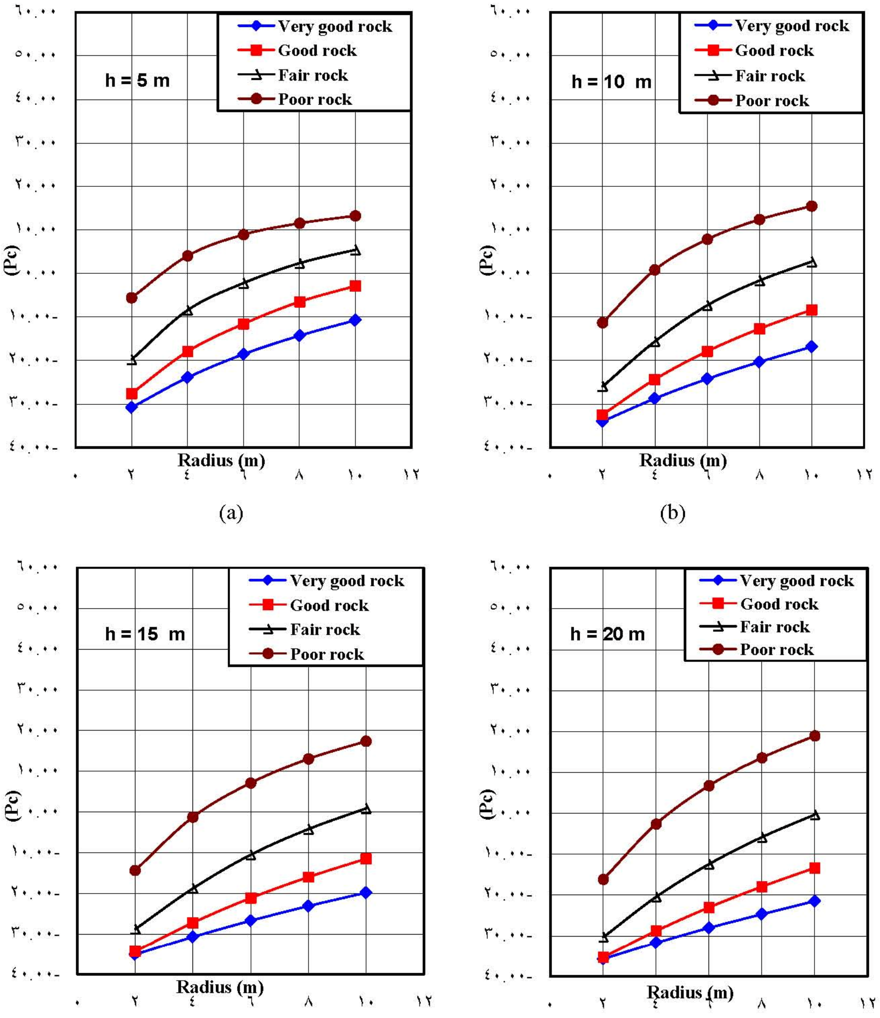
(a)

(b)

(c)

(d)

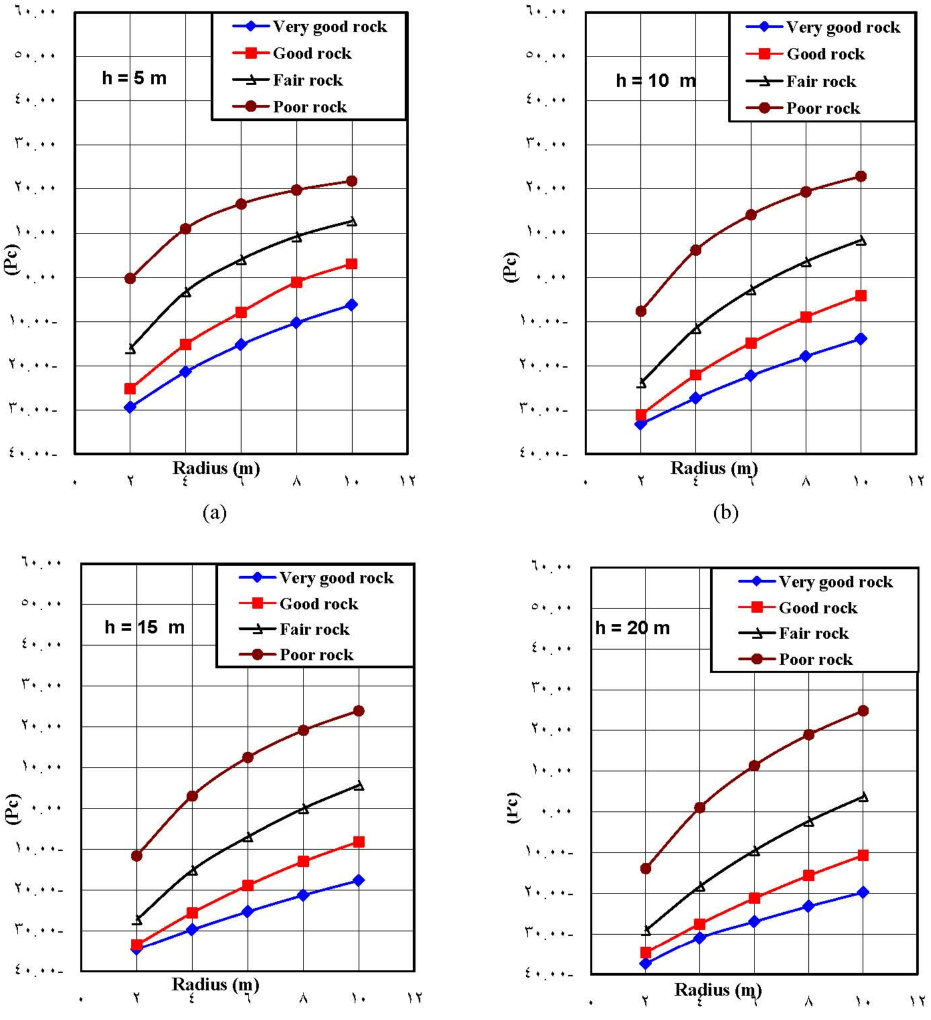
Fig 3 (a-d):- Relationships between radius of tunnel and pressure at crown at various types of rocks and heights (q = 0.00 t/m^2)



(a) (b)

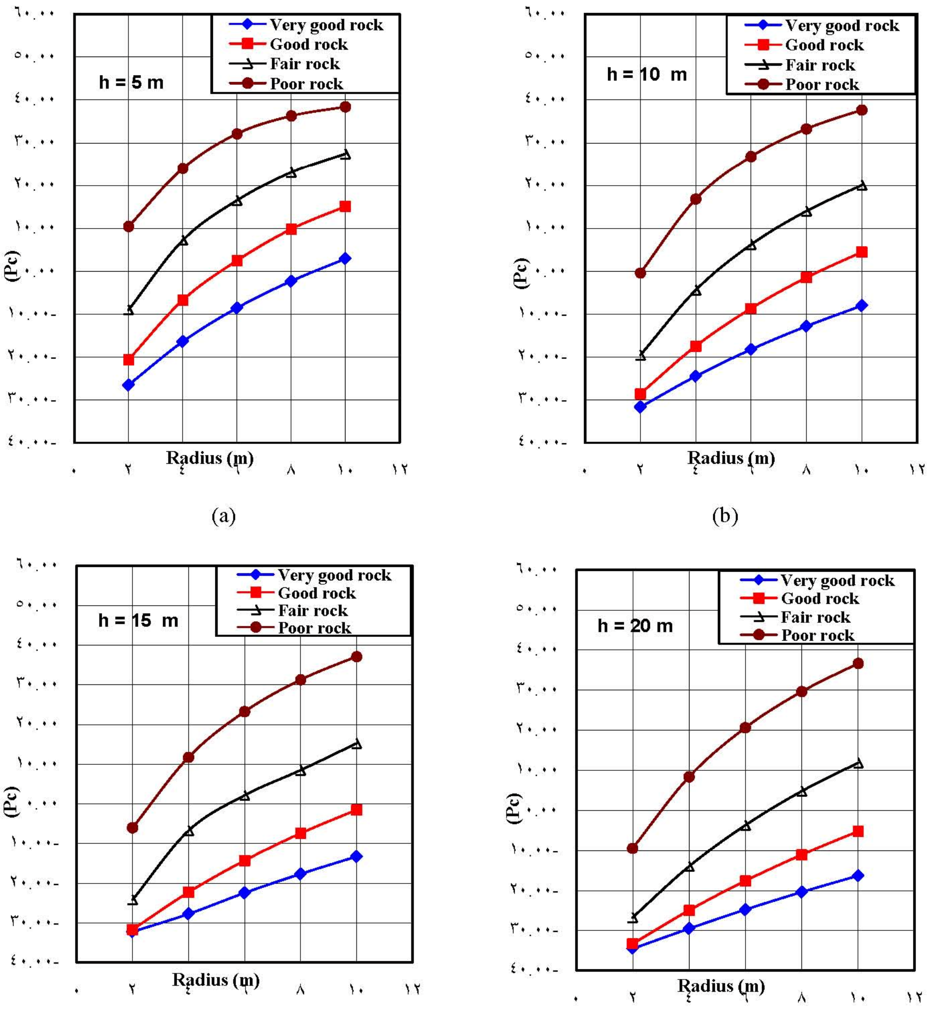
(c) (d)

Fig 4(a-d):- Relationships between radius of tunnel and pressure at crown at various types of rocks and heights (q = 10.00 t/m^2)



(c) (d)

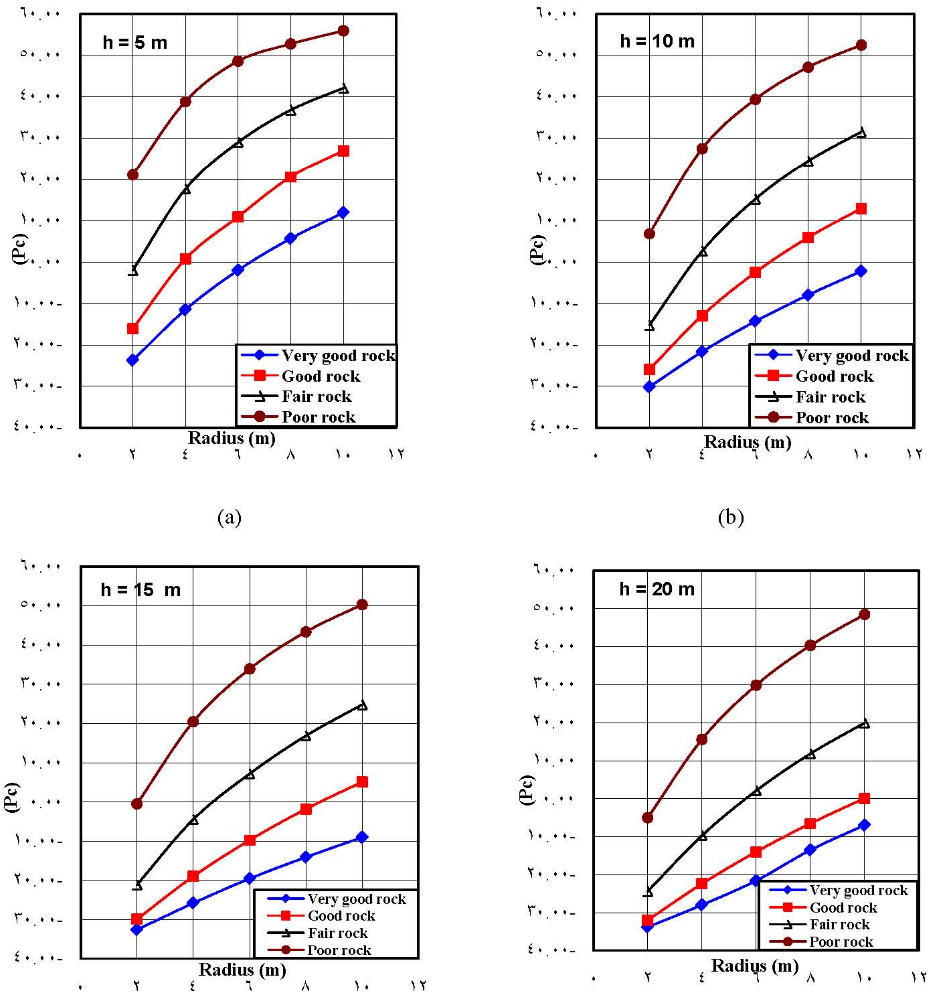
Fig 5(a-d):- Relationships between radius of tunnel and pressure at crown at various types of rocks and heights (q = 20.00 t/m^2)



(a) (b)

(c) (d)

Fig 6(a-d):- Relationships between radius of tunnel and pressure at crown at various types of rocks and heights (q = 40.00 t/m^2)



(a) (b)

(c) (d)

Fig 7(a-d):- Relationships between radius of tunnel and pressure at crown at various types of rocks and heights (q = 60.00 t/m^2)

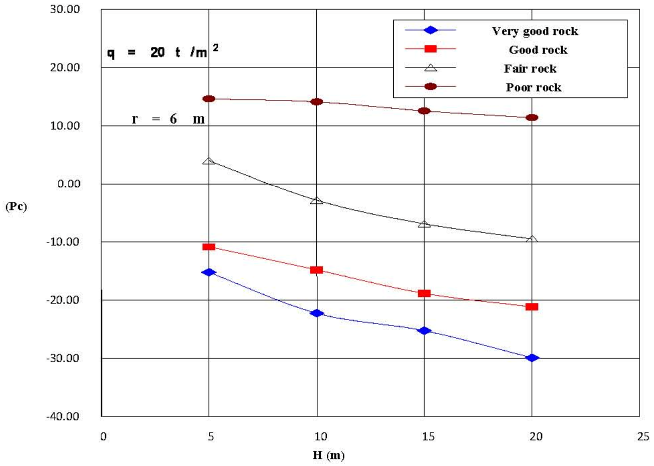


Fig 8:- Effect of overburden head on (H) support pressure
q = (20 t/m^2)

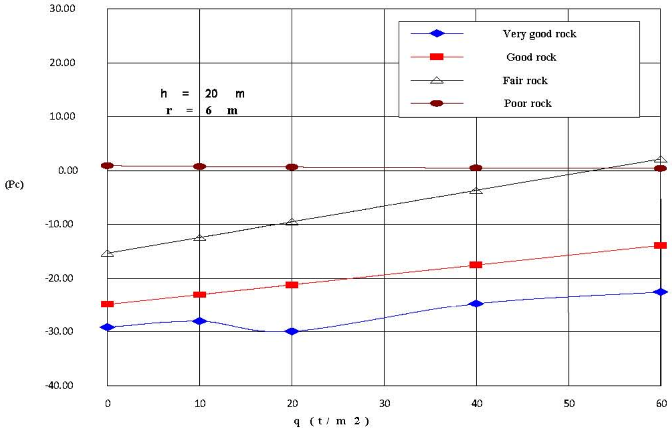
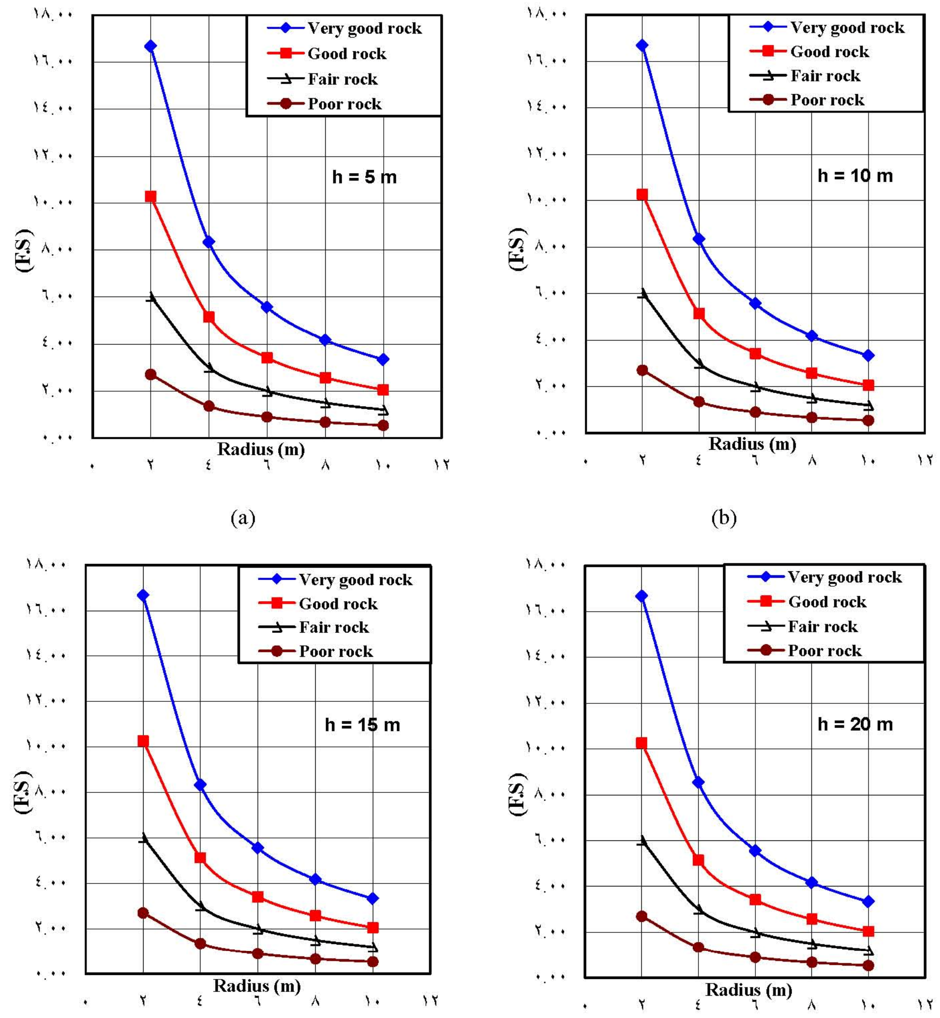


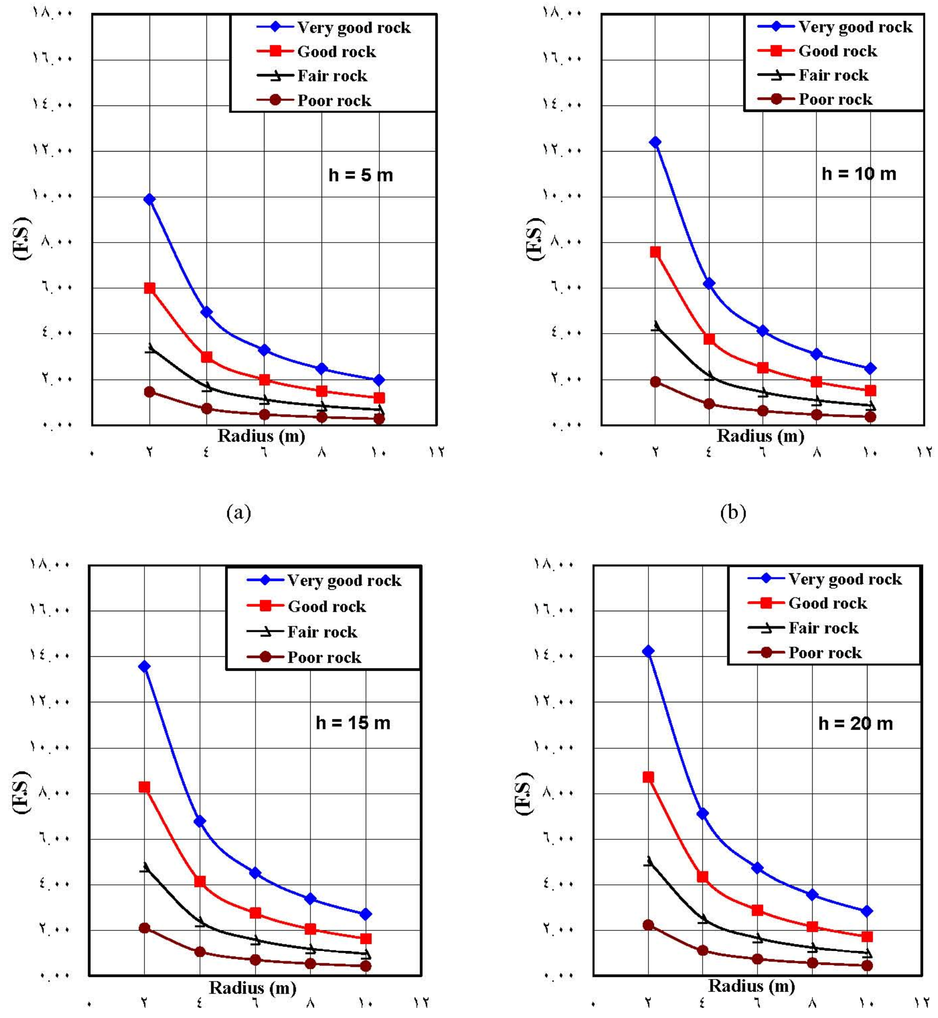
Fig 9:- Effect of surcharge pressure on support pressure
At H = (20 m)



(a) (b)

(c) (d)

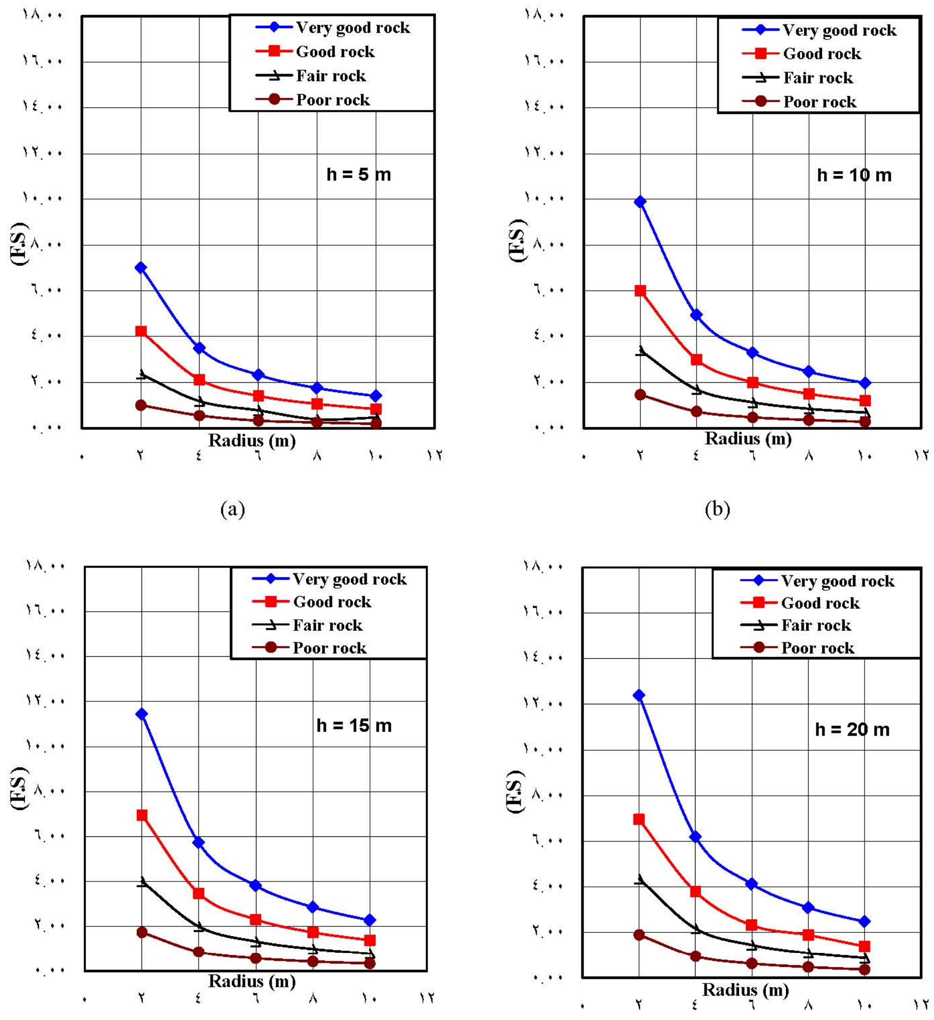
Fig 10 (a-d):- Relationships between radius of tunnel and factor at safety of tunnel face at various types of rocks ($q = 0.00\ t/m^2$)



(a) (b)

(c) (d)

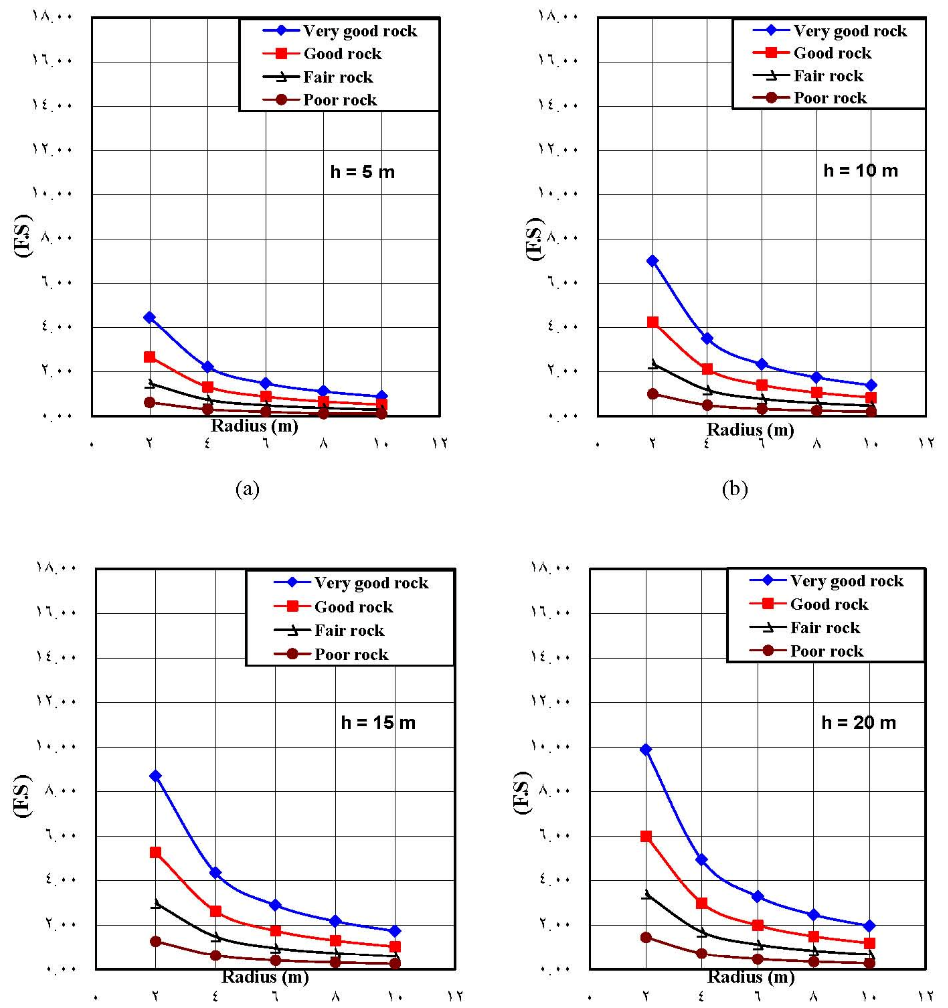
Fig 11 (a-d):- Relationships between radius of tunnel and factor at safety of tunnel face at various types of rocks (q = 10.00 t/m^2)



(a) (b)

(c) (d)

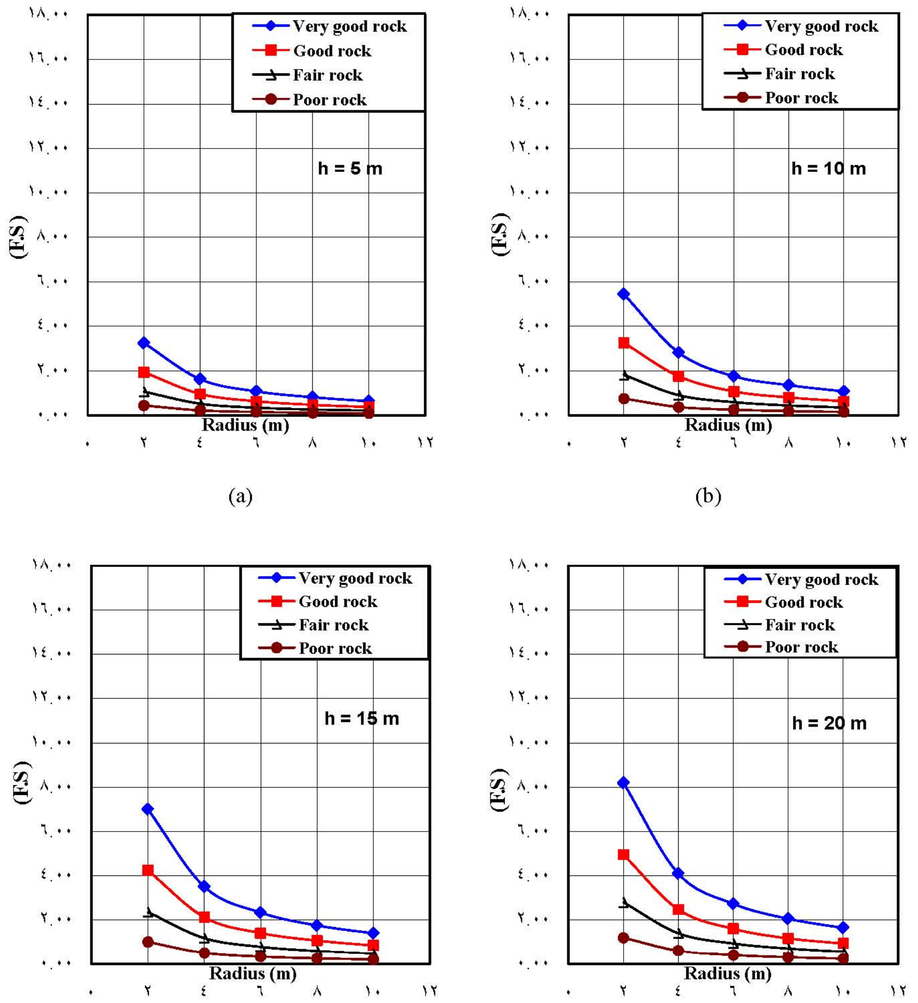
Fig 12(a-d):- Relationships between radius of tunnel and factor at safety of tunnel face at various types of rocks (q = 20.00 t/m^2)



(a) (b)

(c) (d)

Fig 13(a-d):- Relationships between radius of tunnel and factor at safety of tunnel face at various types of rocks (q = 40.00 t/m^2)



(a) (b)

(c) (d)

Fig 14(a-d):- Relationships between radius of tunnel and factor at safety of tunnel face at various types of rocks (q = 60.00 t/m^2)

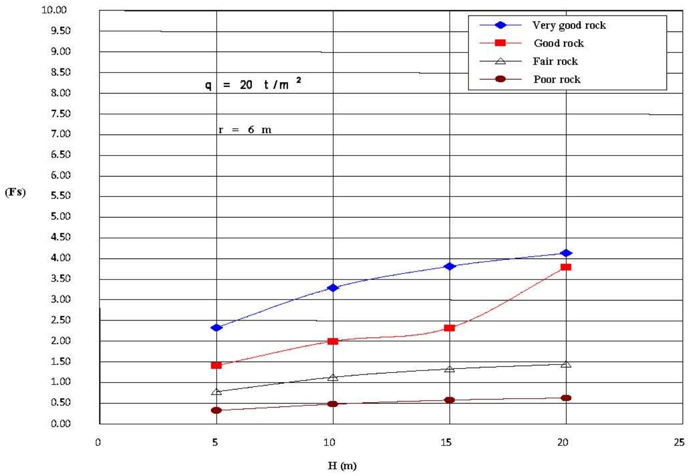


Fig 15:- Effect of overburden head on factor of safety for stability of shallow Circular tunnel at q = (20t/m^2)

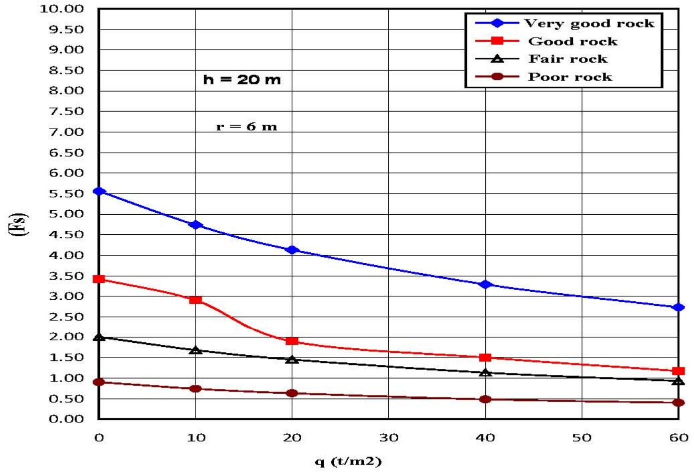


Fig 16:- Effect of surcharge pressure on the factor of safety for stability Of shallow tunnel at H = (20m)

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