Effects of Sand Density and Reinforcement on the Behavior of Buried Tunnel

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Abstract

This paper aim to study the effects of earth reinforcement on the stresses generated within a semicircular cross-section tunnel lining buried in sandy soil due to surface loading. The effect of position and number of reinforcement layers was studied. Also, the relative density of soil was investigated. The depth of soil above the tunnel crown was fixed to be three times the tunnel radius. Two relative densities for soil were used, 55.3% and 73.3%. One layer of reinforcement that was used located at distance equal to the radius or two times the radius above tunnel crown. Also, two layers of reinforcement were located at distance equal to radius and two times radius above the tunnel crown. The results show that the use of earth reinforcement will reduce the stresses generated in the tunnel lining due to application of surface loading.

Keywords: Tunnel, earth reinforcement, relative density, sand.

1-Introduction

Tunnels are one of the common practices in civil engineering. They are used for different projects such as highways, rail ways, transporting of water, main sanitary pipes, metro........etc. The design of tunnels depends mainly on the type of soil or rock through which it is constructed. Due to the importance of these projects, the factors affecting the behavior of tunnels especially the stresses generated within tunnel lining should be studied. These factors including type of soil, depth of soil above tunnel crown, type of external applied stresses(static or dynamic), the shape of cross-sectional area of the tunnel, depth of ground water ………etc.

Many researchers have investigated this subject. Majid [1], investigated the best one of three possible geometric shapes of underground shelter, semi-circular, elliptical, and parabolic. The study utilized the finite element method and more realistic material properties representation such as non-linear stress-strain relation for soil. The results showed that the parabolic shape is the best for underground shelters to carry the applied loads for the conditions presented in the study.

Shafiqu, et al. [2], studied the finite element analysis of tunnels in saturated porous medium using the elastoplastic-viscoplastic bounding surface model. A comparison of the finite element results with field measurements demonstrate the ability of the bounding surface model to solve problems of tunneling in saturated porous medium.

Toma [3], investigated the behavior of tunnel lining in sandy soil. The testing program comprised different factors such as sand depth, soil density with and without the effect of surface loading. The results showed that the generated stresses for different surface loading types decreased with the increasing of sand density for all regions within tunnel lining and they increased as the sand depth increases.

Marto [4], studied the effects of tunnel depth and relative density of sand on surface settlement induced by tunneling by means of parametric study through finite element modeling. Tunnel excavation in sand with two different relative densities of 30% and 75% was investigated. Also, the effect of tunnel depth was analyzed. The results showed that increasing the relative density of sand reduces the ground movements induced by tunneling. In addition, shallow tunneling in loose sand produced remarkable movements around the tunnel and on the ground surface.

Soil reinforcement is one of the available methods used to improve the bearing capacity and decrease the settlement of foundation resting on weak soil. Reinforced soil is a construction material that consists of soil fill strengthened by a variety of tensile inclusions. These tensile inclusions come in many forms ranging from strips and grids to discrete fibers and woven and non-woven fabrics. The soil and reinforcing element will interact by means of frictional resistance. Geogrids reinforce the soil through confinement of the particles, stiffening the granular layer for improved load distribution, Stephen [5].

Appropriate selection of the type and location of the reinforcement material is essential in order to achieve optimum improvement. Al-Murshdi [10], carried out several laboratory model tests to study the effect of reinforced and non-reinforced granular trench in improving the ultimate bearing capacity of a strip footing resting on soft clay. One of the main conclusion of the study is the reinforcement of the sloped trenches has a beneficial effect on increasing the ultimate bearing capacity.

Shamsher [6], studied the behavior of large triaxial specimen of sand reinforced with different percentage of geogrid micro-mesh under drained condition. The results showed that the reinforcement increases the deviator stress developed at any strain including peak and residual level. Also, the peak stresses of the reinforced samples occurred at higher axial strain than the non-reinforced samples at lower cell pressure.

AbdulJabar [7], investigate the feasibility of using randomly reinforced granular trench with geogrid micro mesh to achieve further improvement in terms of bearing capacity ratio and settlement reduction percentage as compared to the same trench systematically reinforced with geogrid layers. The results indicate that high level of improvement was gained when the random reinforcement method is used as compared with the systematic reinforcement method.

In this study, the effect of using geogrid reinforcement on the generated stresses within tunnel lining is investigated. The effect of number of geogrid reinforcement layer used and its location relative to tunnel crown are considered.

2-Theoretical approach

Bolton [11], suggests adopting Rankine's technique of making Mohr's Circles to touch the envelopes of limiting strength to have simplified analytical method to reveal the collapse mechanism of soil arches.

Figure (1a) shows that if the soil and surcharge pressure σ_0 are uniform then there is no shear stress along the vertical plane AB, because of symmetry.

Interfering frictionless radial planes CD and EF on both sides of vertical, the effect of analysis of wedge CDEF will be concentrated into the crown of cavity.

The radii CD and EF are frictionless and both surcharge σ_0 and the internal cavity pressure σ_a are normal to circumferences DF and CE respectively, therefor the principal stresses in the wedge can be radial and circumferential. The radial stress σ_r should be so small at any radius when the tangential stress σ_θ can generate passive collapse for each circular wedge elements illustrated by VWYX in Figure (1b).

To calculate the forces on a wedge element conducted by summing the stresses over the length of the element is the unit weight of soil multiplied by the volume of the element.

$$(\sigma_r + d\sigma_r)(r + dr) - d\theta - \sigma_r r d\theta - 2\sigma_\theta dr \frac{d\theta}{2} + \gamma r d\theta dr = 0$$

$$\sigma_r dr d\theta - \sigma_\theta dr d\theta + r d\sigma_r d\theta - \gamma r d\theta dr = 0$$

$$\frac{d\sigma_r}{dr} = \frac{\sigma_\theta - \sigma_r}{r} - \gamma$$

The friction model were used with zero pore water pressures, the criterion of the collapse for the element would be

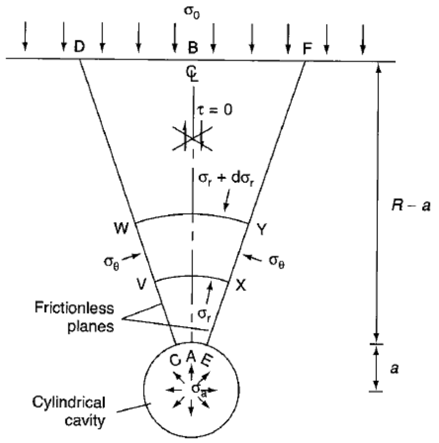
$$\sigma'_\theta = K'_p \sigma'_r$$

Since $\sigma'_\theta = \sigma_\theta$ and $\sigma'_r = \sigma_r$ and because the pore pressure is zero

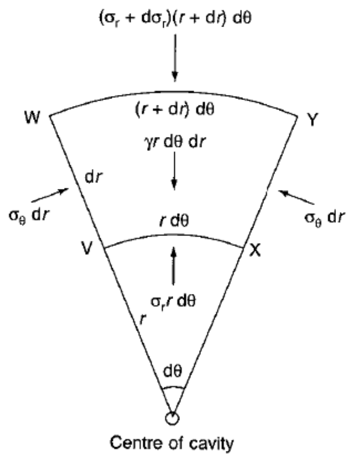
$$\sigma_\theta = K'_p \sigma_r$$

Substituting this into equation (3.1), we obtain

$$\frac{d\sigma_r}{dr} = \frac{(K'_p - 1)\sigma_r}{r} - \gamma$$



(a) Disposition of element



(b) Forces on element

Figure: 1: cross-section through overburden above the crown of a cylindrical cavity (after Bolton, 1979)

This is most easily integrated by substituting $\psi = \sigma_r / r$ from which

$$d\sigma_r = r d\psi + \psi dr$$

So that by Equation

$$r\frac{d\psi}{dr} + \psi = (K'_p - 1)\psi - \gamma$$

$$r\frac{d\psi}{dr} = (K'_p - 2)\psi - \gamma$$

$$\int_{\sigma_a/a}^{\sigma_0/R} \frac{d\psi}{(K'_p - 2)\psi - \gamma} = \int_a^R \frac{dr}{r}$$

$$\frac{\frac{\sigma_0}{\gamma R}(K'_p - 2) - 1}{\frac{\sigma_a}{\gamma a}(K'_p - 2) - 1} = (\frac{R}{a})^{K'_p - 2}$$

Consider what internal supporting stress $\sigma'_a = \sigma_a$ would be required in an otherwise unlined tunnel through dry sand with zero surcharge. From Equation (3.4) with $\sigma_0 = 0$

$$\sigma_a = \frac{\gamma a}{K'_p - 2}[1 - \left(\frac{R}{a}\right)^{K'_p - 2}]$$

This is remarkable in that the effect of increasing depth R is swiftly reduced to zero so that

$$\sigma_a \to \frac{\gamma a}{K'_p - 2} \text{ as } \frac{a}{R} \to 0$$

Table 1: Properties of sand used

Parameter	Value	Test Method
Shape	Sub rounded	Binocular Microscope
Mineral composition	>87.5% Quartz	Energy Dispersive Spectroscopy
Particle size, D10	0.183	ASTM D6913
Particle size, D30	0.32 ,	ASTM D6913
Mean particle size, D50	0.403	ASTM D6913
Particle size, D60	0.457	ASTM D6913
Uniformity Coefficient , C_u	2.497	ASTM D6913
Curvature Coefficient , C_c	1.224	ASTM D6913
Specific gravity, G_s	2.7	ASTM D854-10
Minimum void ratio, e_{min}	0.588	ASTM D4253
Maximum void ratio, e_{max}	0.857	ASTM D4254
Internal friction angle, φ	33.5°-37.4°	ASTM D3080
Classification of sand	S-P	ASTM D2487, USCS

3- Materials Used

Sandy soil brought from local market is used as a soil bed. Different tests were conducted on sand including gradation test, specific gravity, minimum and maximum void ratio, particle shape and mineral compassion, direct shear test, and confined compression test. The results of these tests are presented in Table 1.

Tin plate of 0.35 mm thickness is used to manufacture a semicircular cross-sectional tunnel model with radius equal to 50 mm and length equal to 290 mm. The tunnel model fixed on a base of steel plate of 2 mm thickness. The tunnel model plate has a modulus of elasticity equal to 128 Gpa and poisons ratio equal to 0.25.

Tensor CE121 is the commercial name of the earth reinforcement used in this study. The dimensions of the layer are equal to (300x290) mm located at the center line of the tunnel. The main properties of the reinforcement are presented in Table 2.

Table 2: Properties of the reinforcement

Grid dimensions aperture (mm)	8x6
Thickness (mm)	3.3
Grid weight (kg/m^2)	0.73
Polymer	HDPE*
Maximum tensile strength (kN/m)	7.68
Extension at maximum load (%)	20.2
Load at 10% extension (kN/m)	6.8
Extension at 50% maximum load (%)	3.2

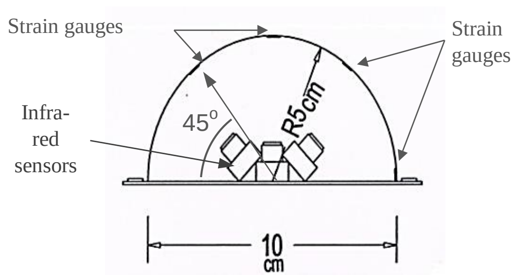
* High Density Polyethylene

4- Test setup

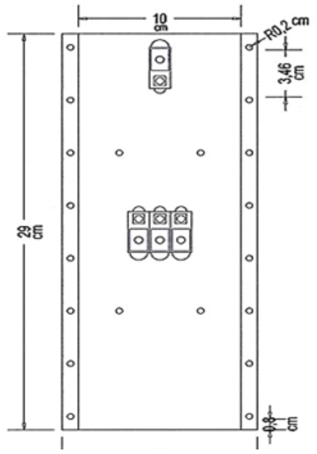
A steel box with dimensions equal to (600x300x700) mm is used to carry out the tests required to perform the experimental program. The box is made of a steel plate of 5 mm thickness for the side walls except the front side made of 10 mm tempered glass. The base of the box is made of steel plate with thickness equal to 10 mm. The sand raining technique is used to prepare the sand bed at two different relative densities (55.3% and 73.3%). This technique is used before by many researchers among them Rad and Tumay [8], and Creswell et al. [9]. The relative density achieved is depending on sieve opening used and on drop distance of sand particle. Many tests were conducted to investigate the effect of these two variables to get the required relative density mentioned above.

5-Instrumantation and measurement

Electrical strain gauges are used to measure the strain induced in the tunnel lining due to the applied surface loading and sand layer weight. The strain gauges are fixed on the inner surface of the tunnel at four selected points which represent (crown, left shoulder, right shoulder, and sprig line) as shown in Figure (2a). In addition four infra-red sensors are used to measure the deformation in tunnel surface due to applied loading as shown in Figure (2b).



(a) Front view for the tunnel with IR sensors positions and strain gauges locations.



(b) Top view for the tunnel base with IR sensors positions.

Figure 2: Infra-red sensors and strain gauges fixation positions on the tunnel model.

6-Test procedure

After fixing the tunnel model, with its base, on the steel box base, a sand layer of thickness equal to 150 mm above the crown level is prepared using the sand rainier with preselected sieve size and drop distance to achieve the relative densities equal to 55.3% and 73.3%.

Layer of earth reinforcement is installed at its designed positions at 50 mm or/and 100 mm above the tunnel crown level during the preparation of the sand bed. A schematic set-up of testing procedure is shown in Figure 3.

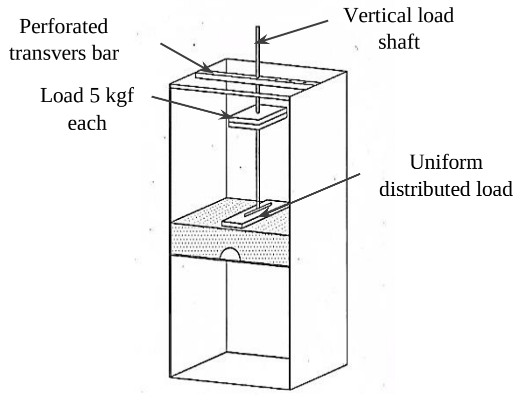


Figure 3: applied load on the surface of sand layer

Uniform distributed load on a strip area equal to (100x270) mm is applied at the surface of the sand through a rigid steel plate. The load is applied incrementally. Each increment is equal to 5 kgf until reaching 150 kgf. The failure load in this study is defined as the load which produces excessive settlement at the surface equal to 10% of plate width or slightly more.

7-Testing program

Eight tests were conducted, four for each relative density. One without reinforcement, two with single reinforcement layer located at 50 mm or 100 mm above the crown level, and one with double reinforcement layer located at 50 mm and 100 mm above the crown level.

8-Results and discussion

Soil-structure interaction problem aimed to analyze the stresses generated and the way by which it was distributed between the soil and structure. The design of the structure depends on the amount and type of stresses generated in the structure due to application of external loading. The aim of this study is to investigate the effect of earth reinforcement on stresses generated in buried tunnel due to application of surface loading. The problem studied is plain strain problem. There are three types of stresses generated in tunnel lining. The first is the tangential stress (σ_θ), the second is the longitudinal stress (σ_ℓ), and the third is the shear stress (τ) as shown in Figure (3).

Eight tests were conducted to investigate the effect of number of reinforcement layer and its position within soil bed and the effect of relative density of sand bed. It was noticed that the tangential stress has the highest value among the other two types in all test. Due to that, it was considered as an indicator to measure the effect of the variable studied on behavior of the tunnel. The depth of soil above crown level of the tunnel was fixed to three times the radius of the tunnel. Two positions of reinforcement were selected. The first is at distance equal to radius of tunnel above the crown level while the second is equal to two times the radius of the tunnel above the crown level. Tables (3) & (4) present the values of tangential stresses in tunnel lining at crown region for all tests carried out in this study.

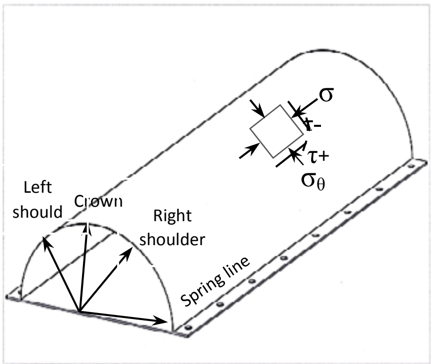


Figure 4: types of stresses generated within tunnel lining

Table 3: values of tangential stresses (σ_θ) in kPa at crown region due to applied surface load for soil relative density 55.3% for non-reinforced and reinforced soil at distance equal to 1R and 2R above the crown region.

Load (Kgf)	Load (N)	D_r 55.3%			
		Not reinf.	1R	2R	1R & 2R
10	**98.06**	2.198	2.418	0.879	2.198
20	**196.1**	7.473	4.396	5.714	3.956
30	**294.2**	16.703	7.912	9.451	9.231
40	**392.2**	23.516	12.088	12.527	10.989
50	**490.3**	31.648	16.484	20.000	14.945
60	**588.4**	43.956	20.440	26.154	17.802
70	**686.4**	54.945	24.396	30.549	22.198
80	**784.5**	68.791	28.352	37.143	24.396
90	**882.6**	87.912	36.044	45.495	28.791
100	**980.6**	107.4*	38.242	54.066	32.088
110	**1078.7**		41.758	64.396	36.923
120	**1176.8**		48.791	68.791	39.780
130	**1274.8**		53.846	72.747	41.538
140	**1372.9**		60.000	78.242	43.516
150	**1471**		65.714	90.989	55.604

*soil failure due to surface loading

Table 4: values of tangential stresses (σ_θ) in kPa at crown point due to applied surface load for soil relative density 73.3% % for non-reinforced and reinforced soil at distance equal to 1R and 2R above the crown point.

Load (Kgf)	Load (N)	D_r 73.3%			
		Not reinf.	1R	2R	1R &2R
10	**98.06**	1.538	0.659	2.637	2.418
20	**196.1**	3.736	5.934	8.352	5.495
30	**294.2**	9.231	10.769	15.385	10.549
40	**392.2**	18.462	13.626	25.275	13.846
50	**490.3**	23.736	17.143	27.473	19.341
60	**588.4**	30.549	21.099	37.143	20.879
70	**686.4**	42.198	25.714	37.363	24.615
80	**784.5**	53.846	31.429	38.462	27.912
90	**882.6**	69.011	35.165	39.341	29.451
100	**980.6**	83.956	39.560	42.637	33.846
110	**1078.7**	112.08	47.473	44.835	35.824
120	**1176.8**	130.54	51.648	49.011	38.681
130	**1274.8**	147.4*	58.242	50.110	40.000
140	**1372.9**		61.538	52.527	42.637
150	**1471**		69.670	54.945	44.396

*soil failure due to surface loading

Figures (5) & (6) illustrate the relation Load-Stress for the values in the table above for sandy soil at relative density 55.3% and 73.3% respectively.

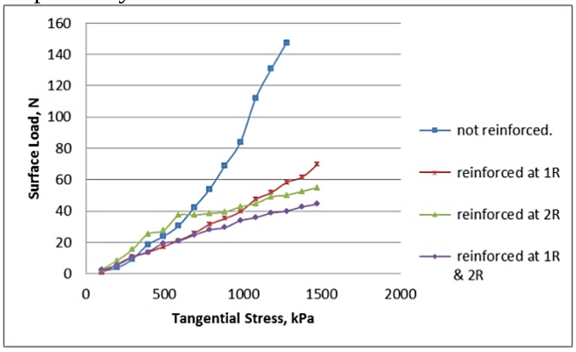


Figure 5: load-stress diagram for crown region at sand relative density 55.3% with different reinforcement levels.

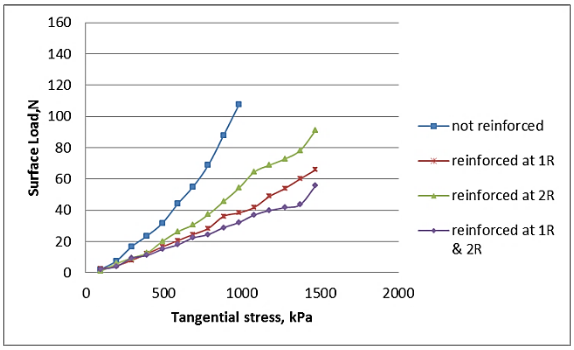


Figure 6: load-stress diagram for crown region at sand relative density 73.3% with different reinforcement levels.

The results indicate the following general points:

1- Soil without reinforcement failed due to application of surface load equal to 100kgf and 130Kgf for soils with relative density equal to 55.3% and 73.3% respectively. While soil with reinforcement does not fail at maximum applied load equal to 150kgf.

2- In this study, the effectiveness of reinforcement is defined as:

For non-reinforced soil:

$$\text{Effectiveness} = \frac{\sigma_{\theta fn} - \sigma_{\theta fr}}{\sigma_{\theta fr}} \%$$

For reinforced soil:

$$\text{Effectiveness} = \frac{\sigma_{\theta 1} - \sigma_{\theta 2}}{\sigma_{\theta 2}} \%$$

Where:

$\sigma_{\theta fr}$ is the tangential stress at failure load for non-reinforced soil.

$\sigma_{\theta fn}$ is the tangential stress at failure load (100 Kgf for D_r= 55.3% and 130 Kgf for D_r=73.3%) for reinforced soil.

$\sigma_{\theta 1}$ and $\sigma_{\theta 2}$ are the largest and smallest tangential stresses at maximum applied load (150 Kgf) for certain reinforced test.

The effect of the studied variable on stresses generated in tunnel lining can be pointed out as a comparison between results of tests with reinforcement with that without reinforcement at different soil relative densities.

A) For soil with relative density (D_r %) =55.3%

1- The stresses generated in the tunnel lining at crown point due to installing reinforcement is reduced to 181% and 99% for one layer installed at distance equal to R and 2R above the crown level respectively. While it is reduced to 235% for two layer reinforcement.

2- The effectiveness of one layer reinforcement installed at distance equal to R above crown level is more than that for one layer installed at 2R above crown level by 38%.

3- The effectiveness of two layer reinforcement installed at distance equal to R and 2R above crown level is more than that for one layer installed at distance equal to R above crown level by 18%.

B) For soil with relative density (D_r %) = 73.3%

1- The stresses generated in the tunnel lining at crown point, due to installing reinforcement, is reduced to 153% and 194% for one layer installed at distance equal to R and 2R above the crown level respectively. While it is reduced to 268% for two layer reinforcement.

2- The effectiveness of one layer installed at distance equal to 2R above the crown is more than that for one layer installed at distance equal to R above crown level by 26%.

3- The effectiveness of two layer installed at distance equal to R and 2R above crown level is more than that for one layer installed at distance equal to 2R above crown level by 23%.

The results show that for non-reinforced soil, the stresses generated in tunnel lining due to surface loading is decreased with increasing the relative density of soil. It is better to install the reinforcement at distance equal to R above the crown level for soil with low relative density. While it is better to install the reinforcement at distance equal to 2R above crown level for soil with high relative density. Also, the use of two layer of reinforcement will increase the effectiveness of using reinforcement.

9-Conclusion

For the conditions presented in this study the following main conclusions can be stated:

1- For any case, the stresses generated in tunnel lining are decreased with increasing the relative density of soil.

2- The use of two layers of reinforcement increase the performance of earth reinforcing.

3- It is better to install the one layer reinforcement at greater depth for soil with low relative density.

10-Referances

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تأثير تسليح التربة على سلوك الانفاق المدفونة تحت الارض

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الخلاصة

ان الهدف من هذه الورقة البحثية هو دراسة تاثير تسليح التربة على الاجهادات المتولدة داخل بطانة النفق ذو المقطع النصف دائري والمدفون في تربة رملية نتيجة الاحمال المسلطة على سطح التربة. لقد تم دراسة موقع وعدد طبقات التسليح فوق النفق كذلك دراسة تاثير تغير الكثافة النسبية للتربة. ان عمق التربة فوق اعلى نقطة للنفق تم تثبيتة بمقدار ثلاث اضعاف قيمة نصف قطر النفق. تم استخدام قيمتين للكثافة النسبية للرمل وهي 55.3% و 73.3% . تم استخدام طبقة تسليح واحدة موضوعة على بعد نصف قطر واحد ومن ثم على بعد ضعف نصف القطر محسوب من اعلى نقطة للنفق. كذلك تم استخدام طبقتين من التسليح موضوعتين على بعد نصف قطر واحد والاخرى على بعد ضغف نصف القطر من اعلى نقطة للنفق. اظهرت النتائج ان استخدام التسليح للتربة يساهم في تقليل الاجهادات المتولدة داخل بطانة النفق نتيجة الاحمال المسلطة على سطح التربة.