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FINITE ELEMENT ANALYSIS OF REINFORCED EARTH WALLS

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Abstract

Reinforced earth has been applied for different types of load supporting and retaining structures in more confidence throughout the world.

In this study, the finite element method is implemented and used to analyze reinforced earth walls. The computer program SIGMA/W is used in the analysis of plane strain problems. Eight node isoparametric elements are used to model the soil while structural elements having nodes that match with the surrounding elements, are used to model the reinforcement material.

A parametric study is carried out to investigatethe effect of different parameters on the general behaviour of reinforced earth walls. These parameters include: the height of the wall (H), length of reinforcement (L) and external loads (static and cyclic). Three different heights were tried (3, 5, 7) m and three value of load (q) were used (5, 20, 50) kN/m².

It was found that the wall with small height (3 m) tends to translate and overturn about its foundation to the out, while the walls with greater heights (≥ 5 m), translate to the out, and the horizontal displacement increases with depth. It was also found that for all cases, the maximum horizontal displacement is about (0.005 m) for each 1 m height of the wall.

It was also concluded that the distribution of lateral earth pressure in reinforced embankments is always non-linear for all heights and under different loads applied at different positions. For the wall of small height (3m), the maximum value of lateral pressure is at the base of the wall as in Coulomb's theory, while at greater heights (5 and 7) m, the maximum value takes place at about (0.1H) from the base of the wall.

الخلاصـــــة

أستعمل التراب المسلح في أنواع مختلفة من المنشآت الساندة و الحاملة للأثقال بثقة عالية في معظم أنحاء العالم.

في هذه الدراسة طبقت طريقة العناصر المحددة في تحليل الجدران الترابية المسلحة و أستعمل برنامج الحاسبة SIGMA/W في تحليل مسائل الانفعال المستوي. و أستعملت العناصر ثمانية العقد لتمثيل التربة بينما أستعملت العناصر الانشائية التي لها عقد مناظرة في التربة المحيطة لتمثيل مادة التسليح. وأجريت دراسة معاملات للتحري عن تأثير عدة معاملات على السلوك العام للجدران الترابية المسلحة. و تتضمن هذه المعاملات: ارتفاع الجدار (H) و طول التسليح (L) و الأحمال الخارجية. و قد جربت ثلاثة ارتفاعات للجدار هي (3 و 5 و 7) م و ثلاث قيم للحمل (q) هي (5 و 20 و 50) كيلونيوتن/م2.

و قد وجد أن الجدار قليل الارتفاع (3 م) يميل الى الانتقال و الدوران حول قاعدته و الى الخارج بينما الجدران ذات الارتفاعات الأعلى (≤5 م) تنتقل الى الخارج، و تتزايد الازاحة الجانبية مع العمق. كما وجد أيضا أنه في جميع الحالات تكون الازاحة الجانبية القصوى بحدود (0.005 م) لكل (1) م من ارتفاع الجدار. كما تم التوصل أيضا الى أن توزيع الضغط الترابي الجانبي في السداد المسلحة يكون دائما غير خطي و لجميع الارتفاعات و تحت تأثير أحمال مختلفة و مسلطة في مواقع مختلفة. و للجدار بارتفاع (3) م وجد أن القيمة القصوى لضغط التراب الجانبي تقع عند القاعدة كما في نظرية كولومب بينما للارتفاعات الأكبر (5 و 7) م، تكون القيمة القصوى عند ارتفاع بحدود (0.1 H) من قاعدة الجدار.

1. Introduction

Reinforced earth in its modern phase, can be defined as a construction material, composed of a soil fill limited to cohesionless free drainage materials, that is strong in compression but weak in tension, and the reinforcing element which is relatively high tensile strength material, placed at stipulated spacings, which supply the mass with the necessary tension. Lastly, the facing element is usually non-structural element, acting as an outer membrane to prevent the soil from sloughing (Change and Forsyth, 1977). The soil and reinforcing element will interact by means of frictional resistance, and this results into stable mass, that behaves monolithically and can be used as earth retention and load supporting structure. The simplicity of the construction of reinforced earth was the reason of its rapid spread and application with increasing confidence throughout the wourld (Mckittrick and Darbin, 1979), the last decade has seen the rapid development in reinforced earth and its use in civil engineering. Reinforced earth is really an attractive and economical answer to many earth retention problems, associated with highway construction, such as retaining walls, bridge abutments, platform supporting structures, foundation slabs, under water quay and sea walls, dams sedimentation basins and tunnel linings...etc.

The best benefits of reinforced earth may be summarized, as follows:

1. A significant saving in cost can be achieved, compared with a conventional structure, especially when pile foundation would otherwise be required.
2. The construction of reinforced earth structures can possibly take any desired shape, and can be stopped at any stage in both horizontal and vertical directions.

3. More favourable distribution of load and differential settlements can bring about as a result of flexibility of reinforced earth (Barclay, 1972).
4. It is quick and easy to construct, as well as repair and destroy.

The soil used in mechanically stabilized earth (MSE) structures is most often a granular material referred to as “Select Granular Backfill” with a maximum of 15% fines and a maximum size of four inches (100 mm), (Brabant, 2001).

Extensible geosynthetic reinforcements come in many different forms. The major types include uniaxial and biaxial,, geogrids and woven and non-woven geotextiles. Extensile reinforcements, by definition stretch, very often to the extent that the strain in the reinforcement is greater than or equal to the soil mass, thus there is considerable, lateral movement when extensible soil reinforcement are used, (Das et al., 2004).

Burke et al., (2004) conducted numerical simulation by using finite element procedure on a full-scale model of geosynthetic reinforced soil structure. It was 2.8 m high and constructed on a 20 cm thick soil foundation. It was subjected to Kobe earthquake motions that were scaled to an acceleration amplitude of 0.4 g. In the analysis, the block facing and at the boundaries were modelled as linear elastic materials. The geosynthetic reinforcement was modelled using a bounding surface model of power hardening functions, and the backfill and foundation soil were modelled using a generalized plasticity model. The analysis was conducted under two-dimensional plane strain conditions using a modified version of Diana-Swandyne-II software. The analysis results were very close to the experimental results, although the displacement of bottom blocks at the end of shaking seems to give a higher value than the experimental results, and it was concluded that the largest settlement in the analysis occurs behined the reinforced zone.

2. REINFORCED EARTH WALLS - PARAMETRIC STUDY

In this paper, some parameters are varied through their reasonable ranges in order to establish their importance and effect on the horizontal displacement and lateral pressure of reinforced earth walls. The aim of this paper is to investigate the effect of height of the wall (H), length of reinforcement (L) and external loads on both the horizontal displacement and lateral earth pressure and to find the suitable distance to subject these loads from the wall.

3. Description of the Numerical Model

In order to investigate the effect of height of wall, length of reinforcement and external loads, the problem is analyzed numerically using the finite element computer program (SIGMA/W). The geometry of the model and the properties of the materials used are described in the next paragraphs.

4. Features and Capabilities of the Finite Element Program Used

GEO-SLOPE provides several geotechnical and geo-environmental engineering software products. One of these products is "SIGMA/W" that is used in this work.

SIGMA/W is a general finite element software product for stress and deformation analyses of geotechnical engineering structures. The followings are some typical cases that can be analyzed using SIGMA/W.

- Deformation Analysis

The most common application of SIGMA/W is to compute deformations caused by earthworks such as foundations, embankments, excavations and tunnels.

- Embankment / Excavation Construction

In this program, finite elements can be added or removed from the finite element mesh to simulate the construction of fill placement or excavation. Elements to be activated or deactivated can be identified at various stages, making it possible to simulate the process over time.

- Excess Pore-Water Pressures

The effect of excess pore-water pressures generated during fill placement or foundation construction is often a major consideration in slope stability during construction. SIGMA/W can be used to estimate these types of pore-water pressures.

- Constitutive Relations

SIGMA/W is formulated for several elastic and elasto-plastic constitutive soil models. All models may be applied to two-dimensional plane strain and ax symmetric problems. The supported constitutive models are: Linear-elastic, Anisotropic Linear-Elastic, Nonlinear Elastic (hyperbolic), Elastic-Plastic (Mohr-Coulomb or Tresca), Strain Softening, Slip-Surface, Cam-Clay and Modified Cam-Clay. Effective stress parameters for analyses of drained soils can be used, or total stress parameters for undrained soils, can be used.

The isoparametric quadrilateral and triangular finite elements are not the only type of elements that the program has supported, an infinite element and structural elements can also be used. The elements can be added or removed in stages in order to simulate the construction and excavation of embankment, (SIGMA/W, Version 5, 2002).

Model Geometry

The geometry of the model problem is shown in Figure (1), while the typical finite element mesh utilized to discretize the model of reinforced earth wall is shown in Figure (2). The mesh consists of two-dimensional 8-noded isoparametric quadrilateral plane strain elements. The reinforcement material is modelled using structural elements having nodes that match with the surrounding elements.

The depth of the soil foundation (Hc) is kept equal to (6 m) and the level of water table is kept at the surface of the soil foundation. Due to symmetry, only one half of the problem is modelled, (Salim, 2007).

The right edge and the center line of the mesh are prevented from horizontal movement by means of horizontal rollers, while the bottom edge is prevented from both horizontal and vertical movements.

Material Properties

The modified Cam clay model is used to describe the behaviour of the soil foundation (clay), and the hyperbolic model is used to describe the behaviour of the soil behind the wall (sand), while the reinforcement material is assumed to behave elastically which has elastic modulus (E) = 4000000 kPa and thickness = 4 mm, (Giannelis, 1996).

The material properties required for the constitutive relationship of the foundation soil and granular soil of the wall are given in Table (1).

The properties of the cohesive soil of the foundation are adopted from the work of Kamal, et al., (2005), while the properties of the wall granular material are adopted from the work of Ketchart and Wu (2001).

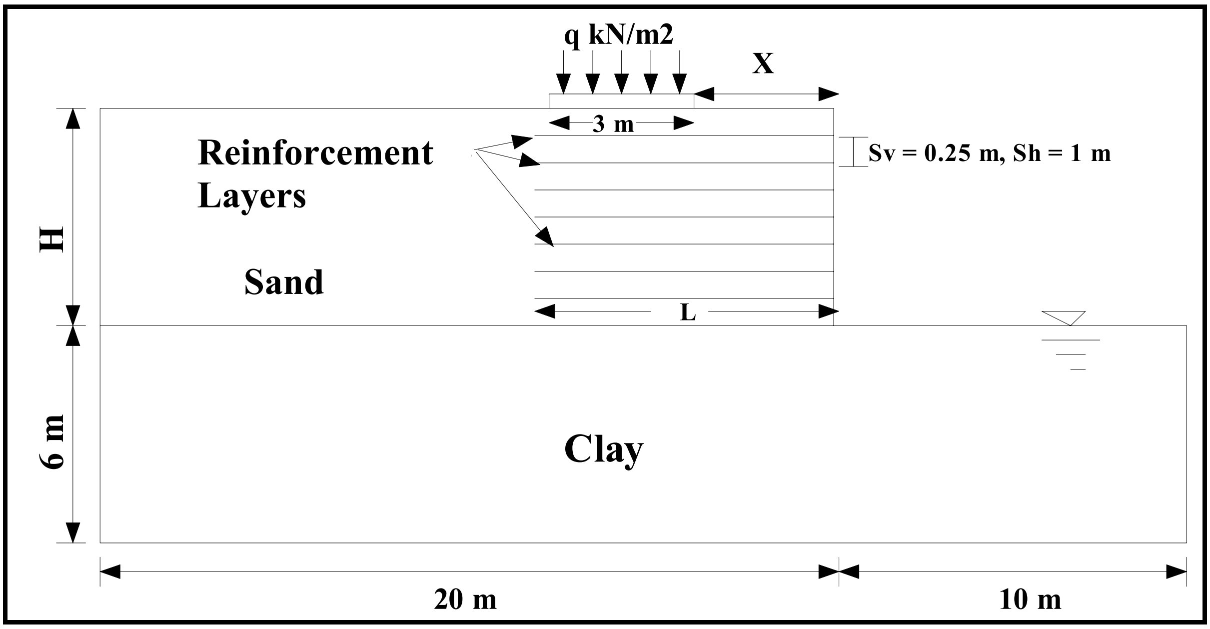

Figure (1): Model Geometry of Reinforced Earth Wall.

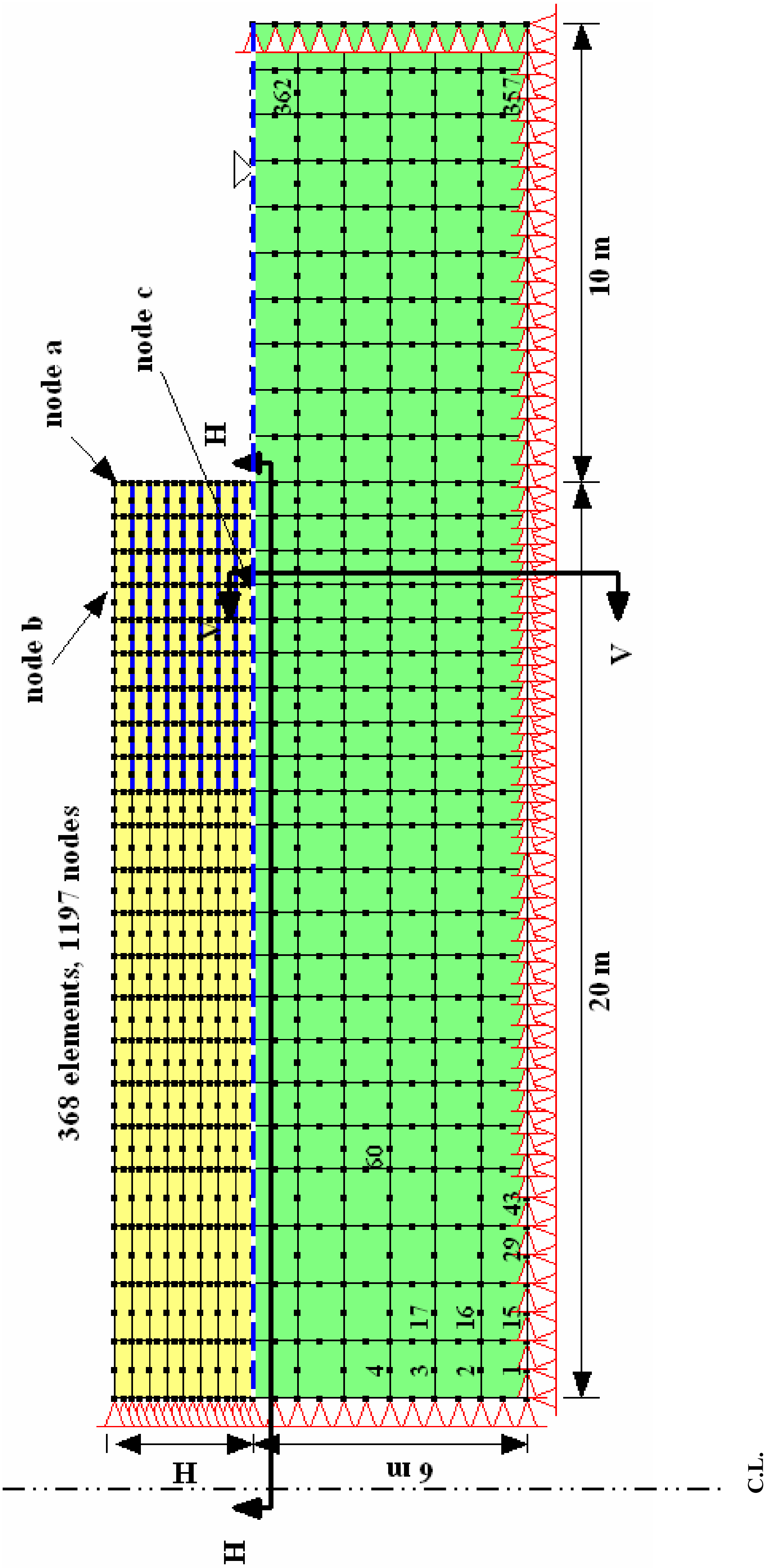

Figure (2): Typical Finite Element Mesh of Reinforced Earth Wall.

Table (1): Material Properties for the Foundation Soil and Soil of the Earth Wall.

Material Properties of Sand (from Ketchart and Wu, 2001)		Material Properties of Clay (from Kamal et al., 2005)	
Soil Property	**Value**	**Soil Property**	**Value**
γ (kN/m)^3	16.8	λ	0.25
Ø (degree)	40	κ	0.05
c (kN/m^2)	0	e_{CS}	2.44
E (kPa)	60000	M_{CS}	0.9
K	350	γ (kN/m^3)	15.5
N	0.5	k_h (m/day)	1.728×10^{-4}
N	0.35	k_V (m/day)	1.728×10^{-4}
R_f	0.7	_	_

where:

λ = Slope of the normal consolidation line,

κ = Slope of the swelling line,

e_{CS} = Specific volume when p' is equal to 1.0,

M_{CS} = Slope of the critical state line,

k_h = Horizontal coefficient of permeability,

k_V = Vertical coefficient of permeability.

5. Results and Discussion

Effect of the Height of the Wall (H)

In this study, three different heights of the wall are used, (3, 5, 7) m. Figure (3) shows the relationship between the displacement ratio (S/H) (horizontal displacement over the height of the wall) and the elevation of the wall. In these figures, the length of reinforcement is considered to be equal to height of the wall. It can be noticed from this figure that the maximum value of S/H is (0.564 %) at the height of 7 m, and it can be said that the maximum horizontal displacement is approximately (0.005) m for each 1 meter from the wall. The maximum values of S/H for (5 and 7) m height take place at the toe of the wall, while at 3 m height, it is noticed that the maximum displacement occurs at the top of the wall. This means that the wall with small height (3 m) tends to translate and overturn about its foundation to the right, while the walls with greater heights translate to the right and the displacement increases linearly with depth due to the increase of the active earth pressure. Table (2) gives the maximum value of S/H for each height.

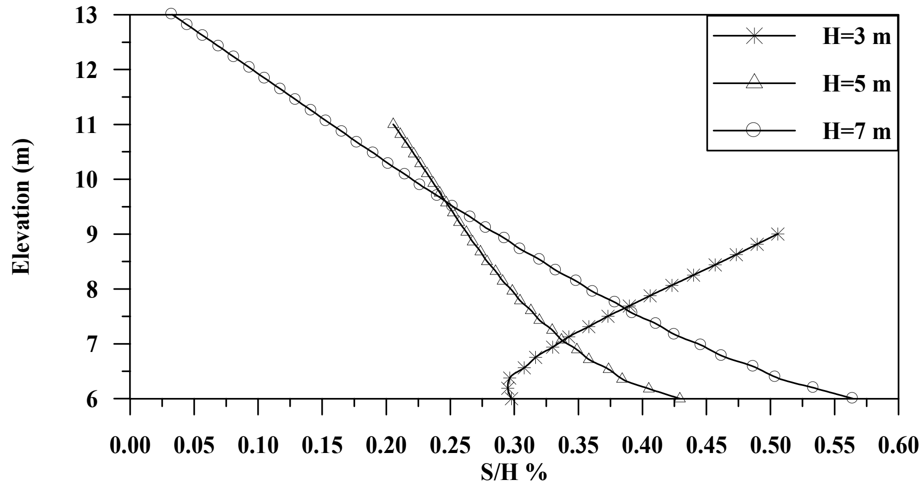

Figure (3): Effect of Wall Height on the Horizontal Displacement.

Table (2): Maximum Horizontal Displacement for Different Heights of the Wall.

Wall Height (m)	Max. Value of S/H %
3	0.505
5	0.429
7	0.564

Figure (4) shows the relationship between the lateral stress ratio (LSR) (lateral earth pressure (Pa)/γ×H) and the elevation of the wall. It can be noticed that the distribution of the lateral pressure is non-linear for all heights, the pressure increases with depth. The maximum lateral earth pressure for walls with (H >3m) does not take place at the base of the wall, as indicated by Rankine and Coulomb theories, but at an elevation of about (0.1H). This conclusion agrees with that found by Salman (2006) for cantilever retaining walls.

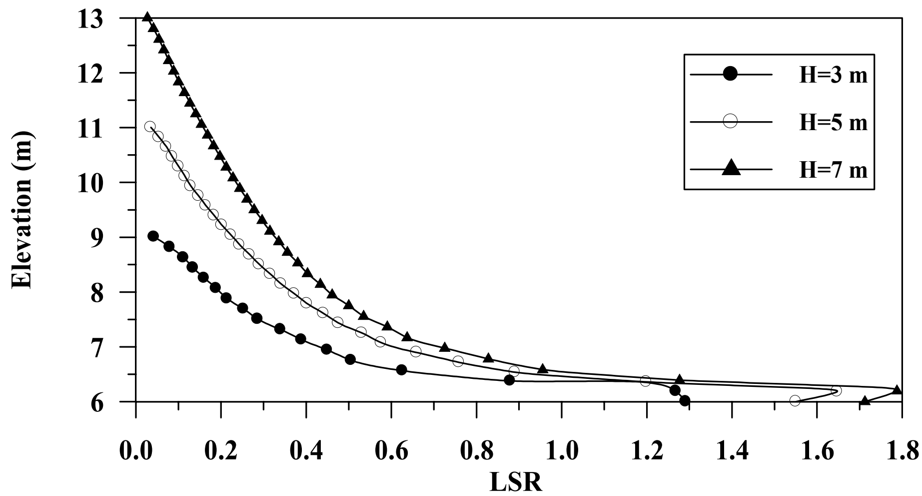

Figure (4): Effect of Wall Height on the Distripution of Pressure behined the Wall.

Effect of the Length of the Reinforcement Strips (L)

To study the effect of length of the strips (L) on horizontal displacement and lateral earth pressure of the wall, three values of length are used, as below:

- $L = H \cot(45 + \frac{\phi}{2}) = 0.47H$ at $\phi = 40^{o}$.
- L = 0.8 H
- L = H

According to the classical theories of soil mechanics, the failure plane is assumed to be inclined at (θ = 45+Ø/2) to the horizontal (Terzaghi, Peck and Mesri, 1996), therefore the distance between the wall and the intersection of the slip surface with the ground is equal to (Distance = H cot (45+Ø/2)). At Ø=40^{o}, Distance = 0.47H, as taken in this section.

The effect of strip length on S/H and LSR can be observed in Figures (5) to (10). It is noticed that S/H decreases as the length of the strip is increased and the best function of the wall can be obtained when L=H. These results are similar to those obtained by Smith and Pole (1980) (Length of reinforcing elements ≥ 0.8H). It can be noticed that increasing the length of reinforcement bar from (L=0.47H to L=H), decreases the value of the maximum lateral displacement for each height in the order of about 18% at the base of the wall because the reinforcement will carry greater values of the pressure. Figures (8) to (10) show the relationship between the LSR and the extension of reinforcement. It is noticed that the length of strip has limited effect on the values of lateral stresses.

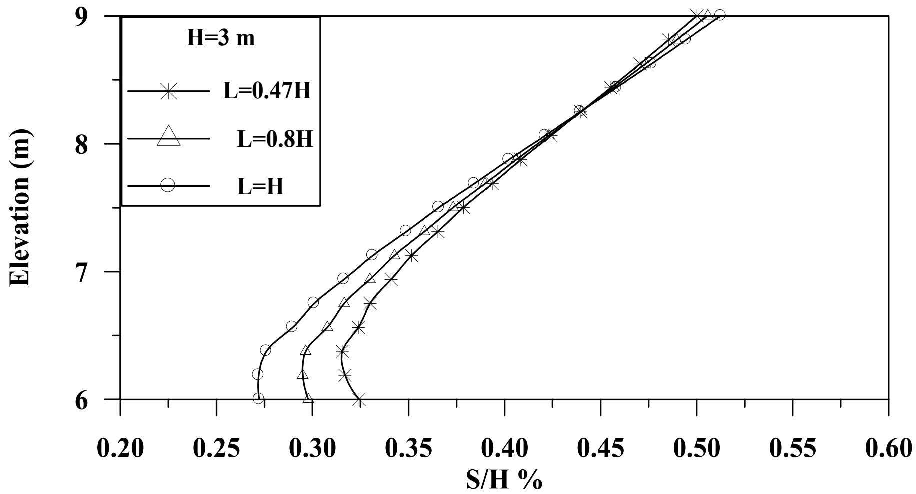

Figure (5): Effect of Reinforcement Bar Length on Distribution of Displacement along the Wall, (H = 3 m).

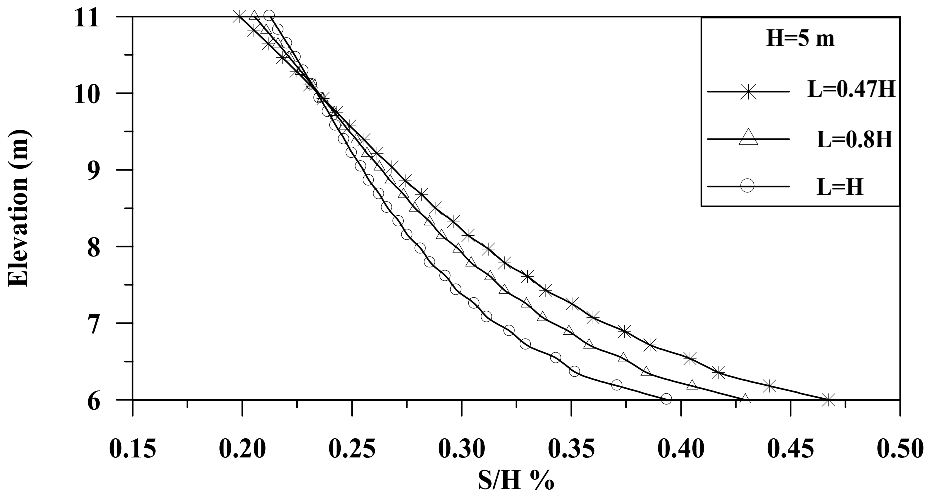

Figure (6): Effect of Reinforcement Bar Length on Distribution of Displacement along the Wall, (H = 5 m).

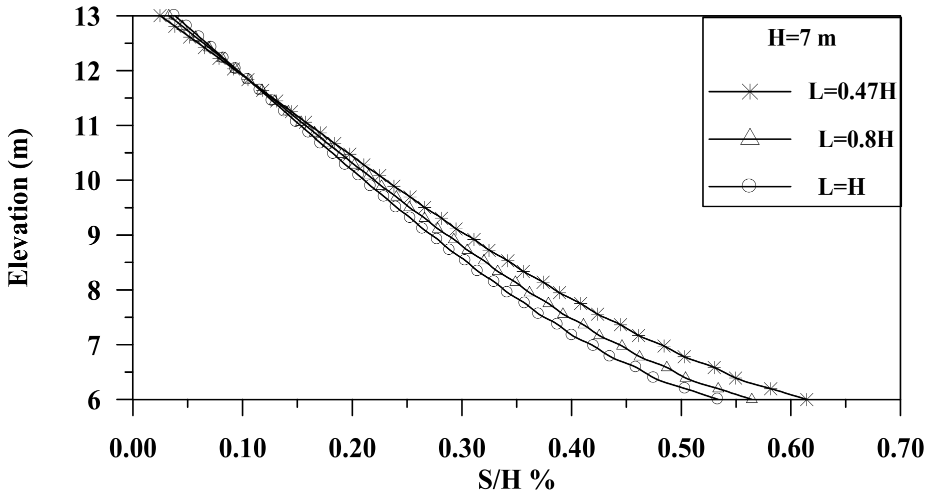

Figure (7): Effect of Reinforcement Bar Length on Distribution of Displacement along the Wall, (H = 7 m).

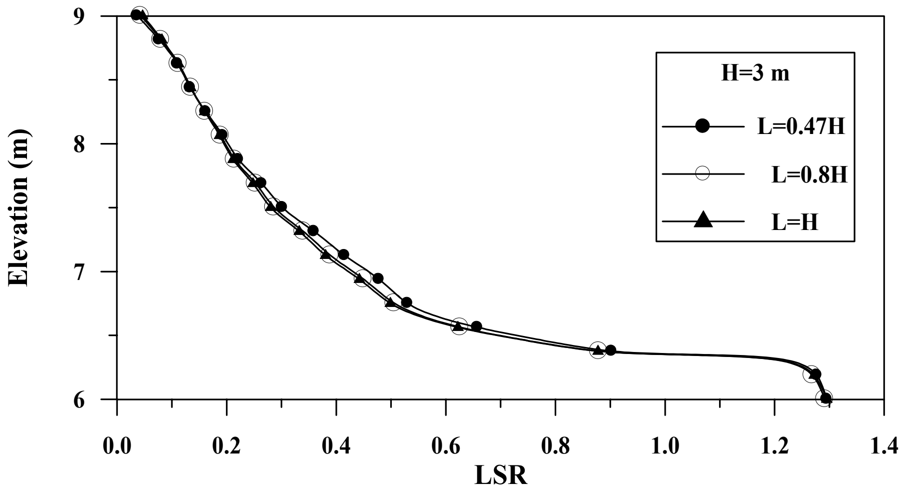

Figure (8): Effect of Reinforcement Bar Length on Distribution of Lateral Stress behind the Wall, (H = 3 m).

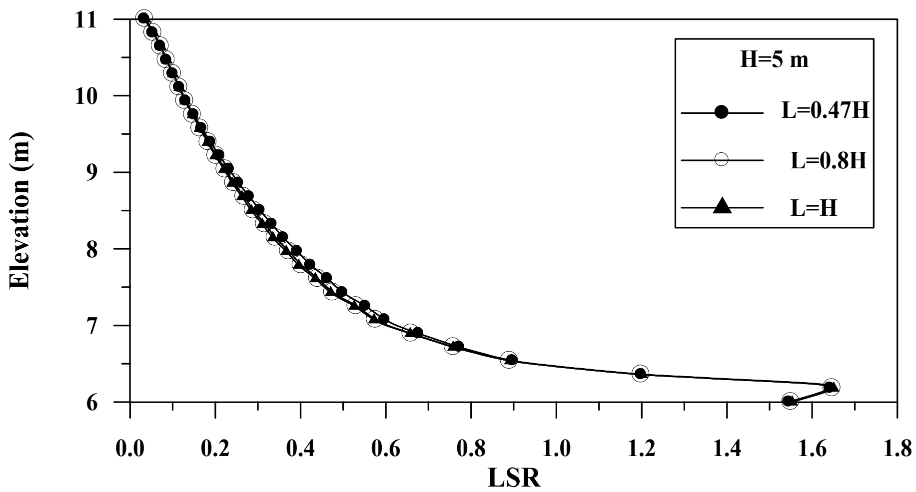

Figure (9): Effect of Reinforcement Bar Length on Distribution of Lateral Stress behind the Wall, (H = 5 m).

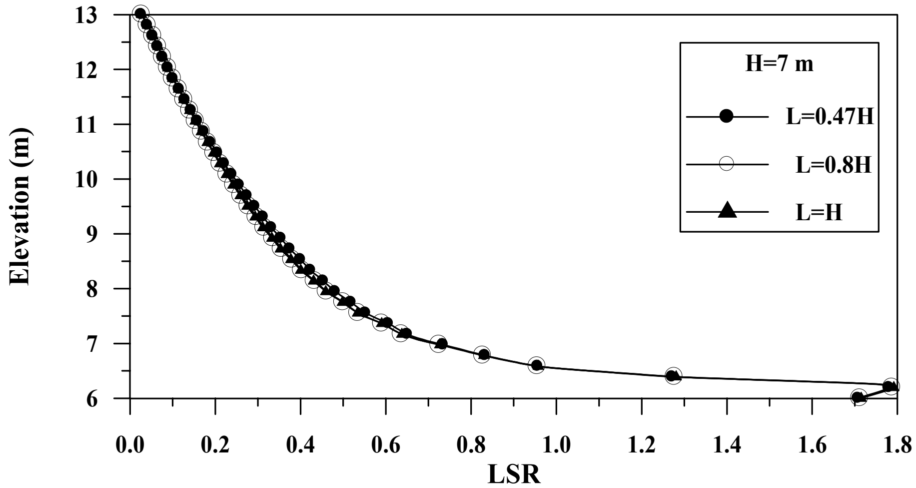

Figure (10): Effect of Reinforcement Bar Length on Distribution of Lateral Stress behind the Wall, (H = 7 m).

Effect of External Loads

a. Distributed Load (q)

In order to study the effect of static load, three different values of load (5, 20, and 50) kN/m^2 are distributed over 3 m and applied at different distances from the wall (X) which is chosen as below, the length of reinforcement (L) is chosen as equal to 0.8H.

- X=0
- X=H/3
- X=H/2
- X=H

I. The Effect of (q) on the Lateral Displacement

All the figures in this section draw the relationship between S/H and the elevation of wall for four values of (X) and for each load applied.

Figures (11) to (13) show the relationships for the wall of 3 m height. It can be noticed from these figures that S/H at top of the wall decreases as the load is applied far away from the wall. When the load is applied directly behind the wall (X=0), the wall tends to rotate about a point. This rotation decreases as the location of the load from the wall (X) increases. The rotation of the wall is found to be about a point located approximately at mid height of the wall. The rotation increases due to the increase of the moment about the base because the arm of the force increases as the load is applied far away from the wall.

The same behaviour is noticed for all values of the load (q), but as the load decreases the wall rotation increases. Figures (14) to (16) show the relationship for the wall of 5 m height. In this case, the behaviour differs from that of (3 m) height wall. When the applied load is small (q=5 kN/m^2), the wall also rotates, but towards the backfill behined it. The rotation increases as the distance of the load (X) decreases. The point of rotation is also located at the wall's mid height.

When the applied load is increased to (q=20 and 50 kN/m^2), the wall rotation tends to be outward the wall, and this rotation decreases as (X) increases.

Figures (17) to (19) show the relationship for the wall of 7 m height. When q=5 kN/m^2, as shown in Figure (17), it can be noticed that the behaviour is similar to that of Figure (14), but without overturning for any value of (X), and with simple difference between the values of S/H, the wall rotates about a point located at a point 3.5m from the base of wall (i.e. at H/2).

When the load is equal to 20 kN/m^2 as in Figure (18), S/H increases as (X) increases with clear difference between the values of S/H, and the wall rotates about a point located at height 3.5 m from the base of the wall (i.e. H/2).

When a load of 50 kN/m^2 is applied behind the wall, as shown in Figure (19), it can be seen that the load at distance X=H gives the maximum value of S/H at the toe of the wall whereas when the load is applied at other distances (X=0, H/3, H/2), S/H increases as the distance increases and the wall tends to change its failure form at a point which is located at 3.5 m from the base of the wall. Table (3) gives the maximum values of S/H at each load applied with different heights of the wall, and it can be noticed that the maximum effect of the load on (S/H) occurs when a load of 50 kN/m^2 is applied at (X=0) from the wall (3 m) height. The minimum effect occurs when a load of 5 kN/m^2 is at a distance (X=H) from the wall (5 m) height. In the next figures, the positive sign for horizontal displacement means movement to the right (out of the wall).

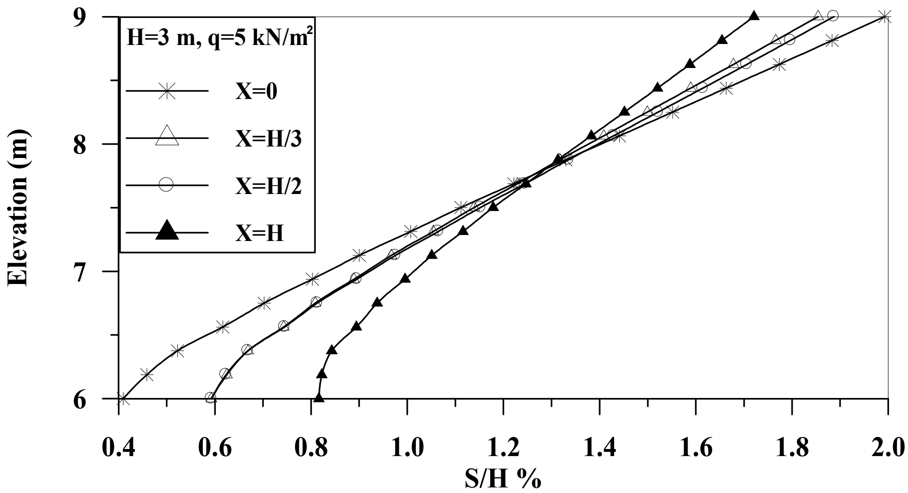

Figure (11): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=3 m, q=5 kN/m^2).

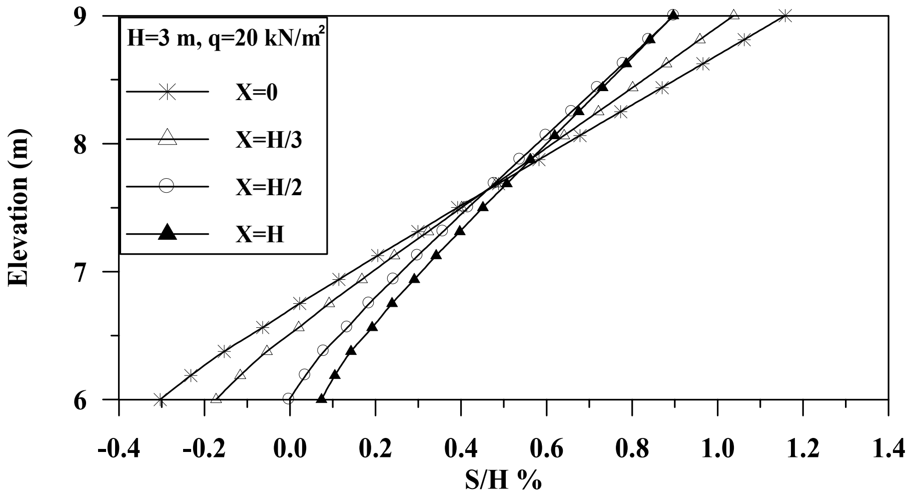

Figure (12): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=3 m, q=20 kN/m^2).

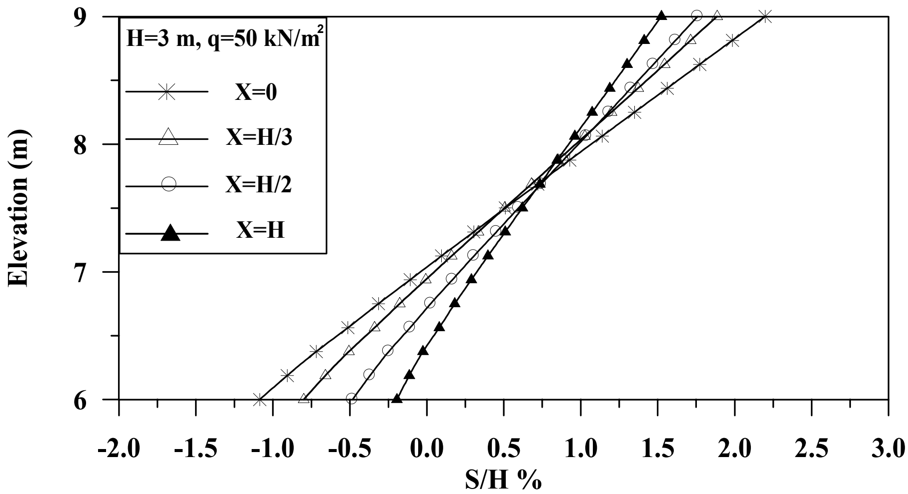

Figure (13): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=3 m, q=50 kN/m^2).

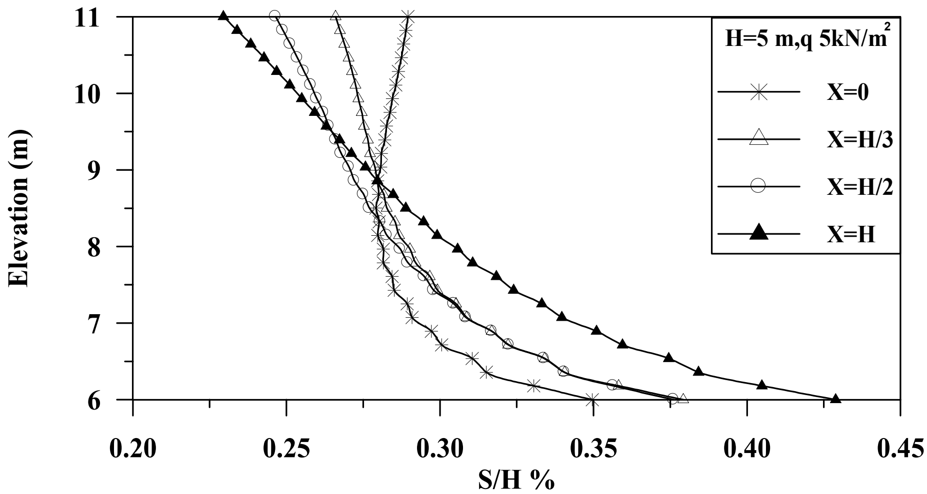

Figure (14): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=5 m, q=5 kN/m^2).

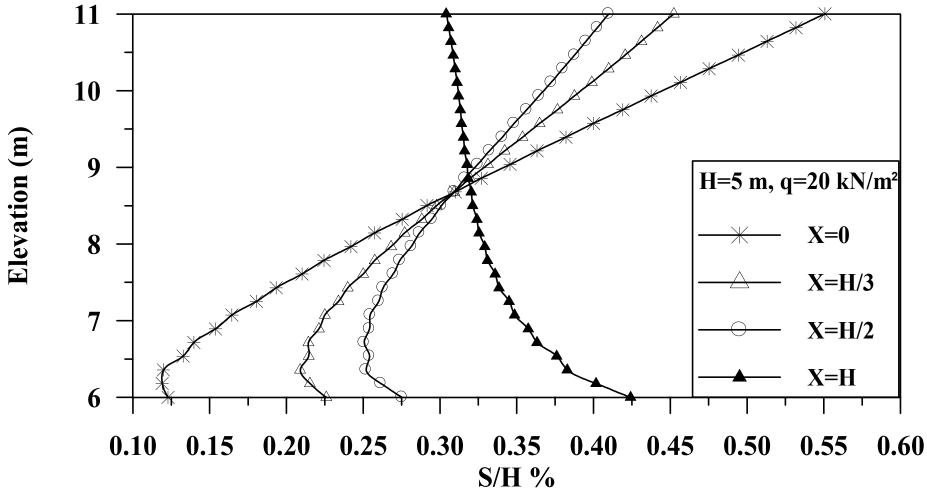

Figure (15): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=5 m, q=20 kN/m^2).

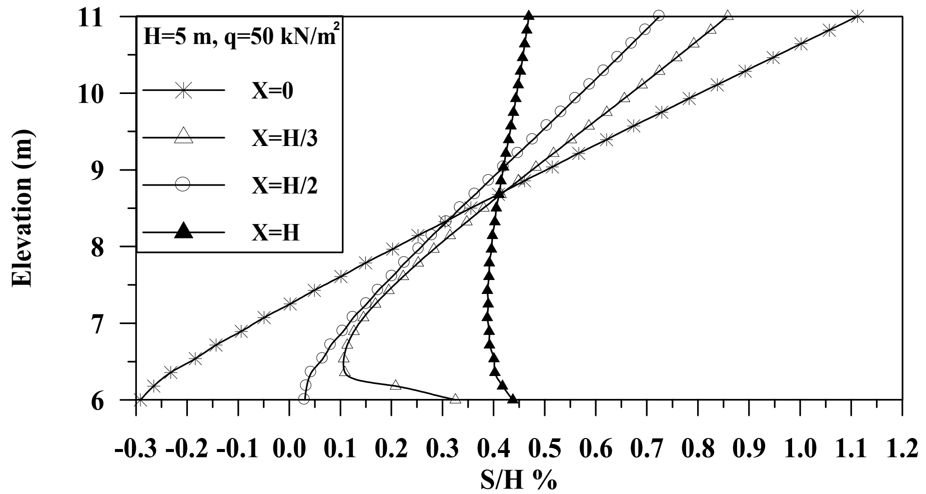

Figure (16): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=5 m, q=50 kN/m^2).

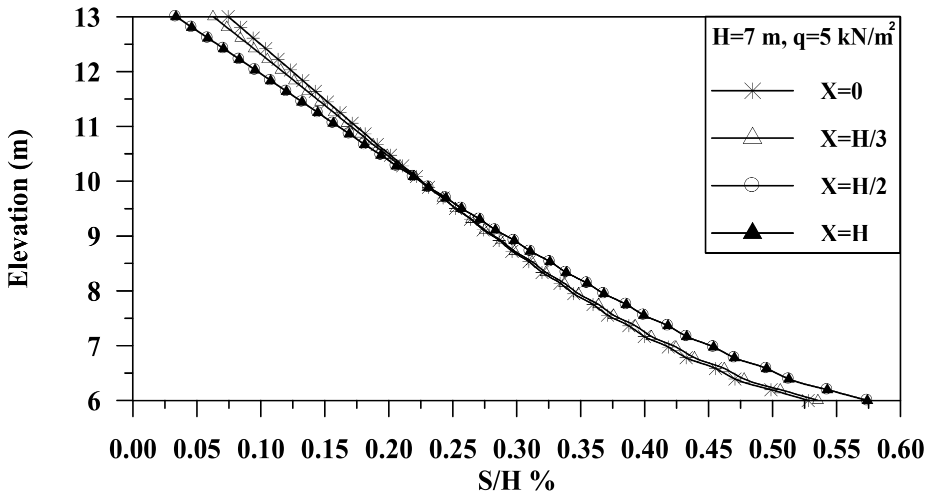

Figure (17): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=7m, q=5 kN/m ^{2}).

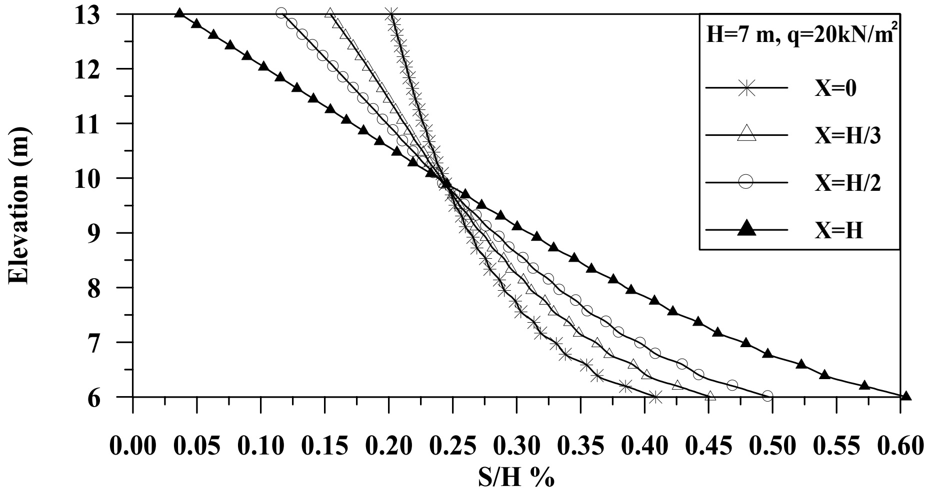

Figure (18): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=7m, q=20 kN/m ^{2}).

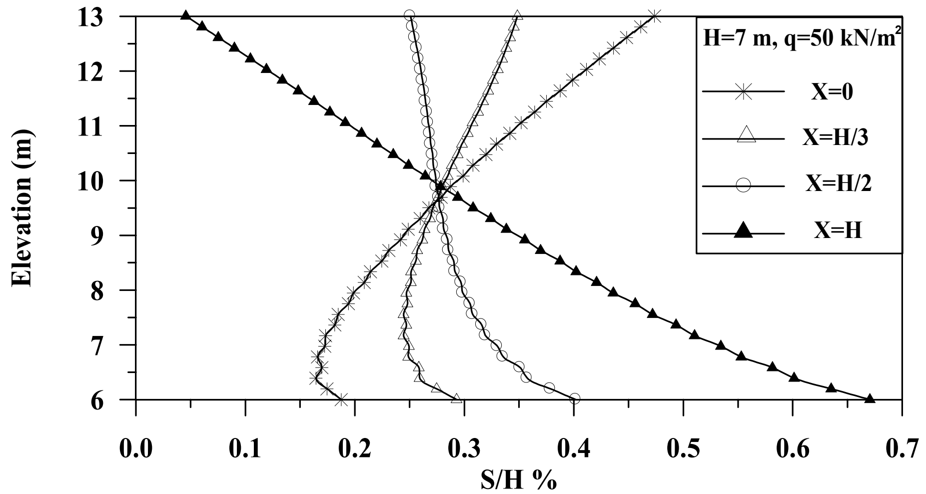

Figure (19): Effect of External Load Applied at Different Distances from the Wall on Distribution of Displacement, (H=7m, q=50 kN/m ^{2}).

Table (3): Values of the Maximum Displacement under Different Loads Applied at Different Positions.

	Height of wall (m)			Load (q) kN/m^2
S/H %	3	5	7	
	1.93 at X=0	0.428 at X=H	0.574 at X=H	**5**
	1.158 at X=0	0.551 at X=0	0.604 at X=H	**20**
	2.19 at X=0	1.112 at X=0	0.671 at X=H	**50**

II. The Effect of (q) on the Lateral Pressure

The figures in this section draw the relationship between LSR and the elevation of the wall. Figures (20) to (23) show the distribution of the lateral stress ratio along the wall height under external surcharge loads applied at different positions from the wall back when (H=3m). Figures (24) to (27) and Figures (28) to (31) show the distribution of stresses when the heights of the wall are 5 m and 7 m, respectively.

It can be noticed that the distribution of the lateral earth pressure in reinforced embankments is always non-linear for all heights and under different loads applied at different positions.

The maximum value of LSR for small walls (H=3m) decreases as the load is applied at larger distance (X). When the load (q) is applied at (X=0) for the wall of (H=3m), it is found that when (q=20 kN/m^2), the maximum LSR is obtained and even greater than the case when (q=50 kN/m^2), as shown in Figure (20). This can be understood when the wall rotation argued in the previous section is studied which affects considerably the values of LSR.

For the case of (H=5 m), and the load located at (X=H/3), the greater surcharge load (q=50 kN/m^2) reveals the minimum LSR, as shown in Figure (25), for the same reason discussed above.

When the height of the wall becomes (H=7 m), the effect of the external load value or its position becomes unimportant. This is because the lateral pressure caused by the backfill soil is greater than that caused by the surcharge.

Table (4) summarizes the maximum values of LSR with the value of (X) for walls of different heights, and it is noticed from this table the critical value is (2.38) at X=0 and q=20 kN/m^2 for 3 m height, minimum value is (1.42) at X=H/3 and q=5 kN/m^2 for 3m height.

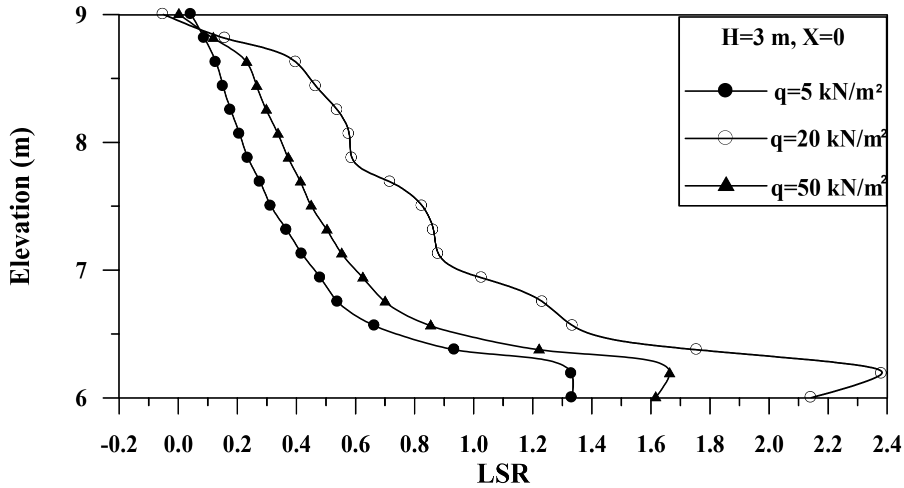

Figure (20): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 3 m, X = 0).

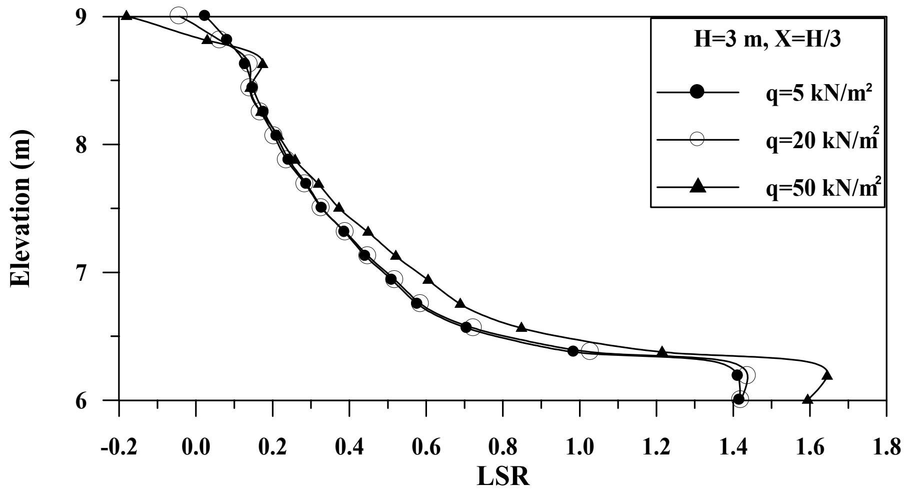

Figure (21): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 3 m, X = H/3).

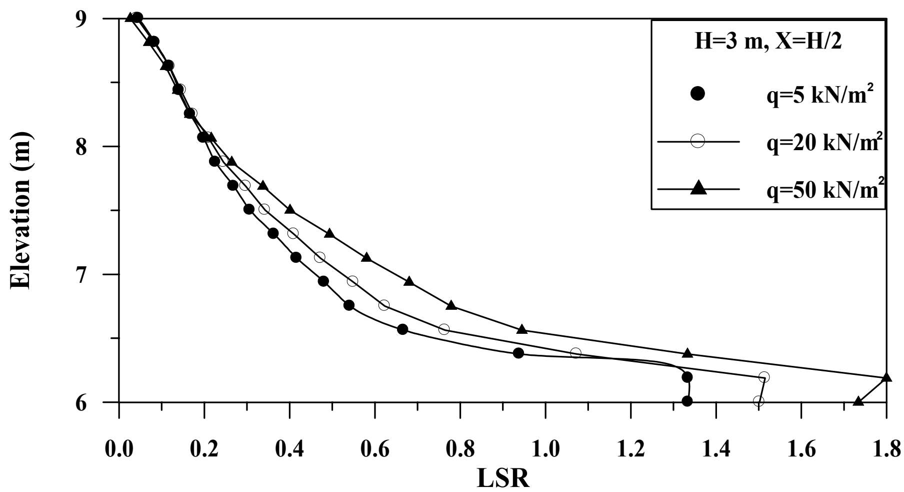

Figure (22): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 3 m, X = H/2).

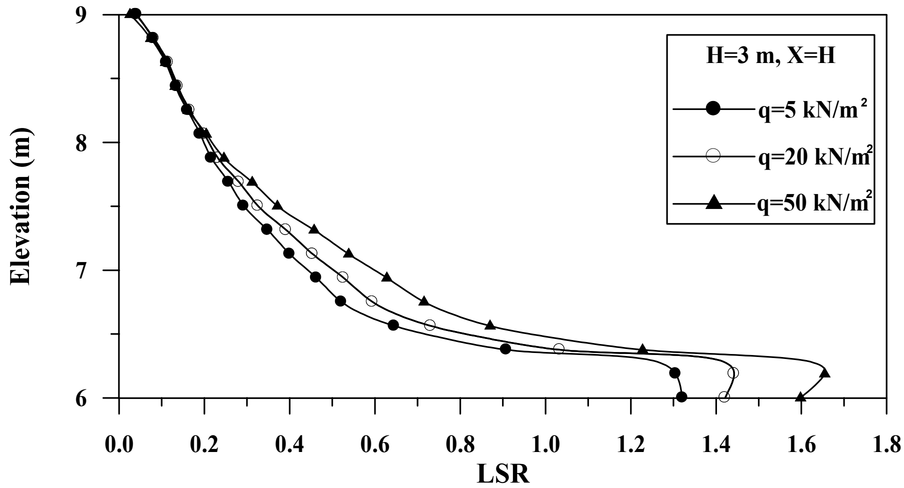

Figure (23): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 3 m, X = H).

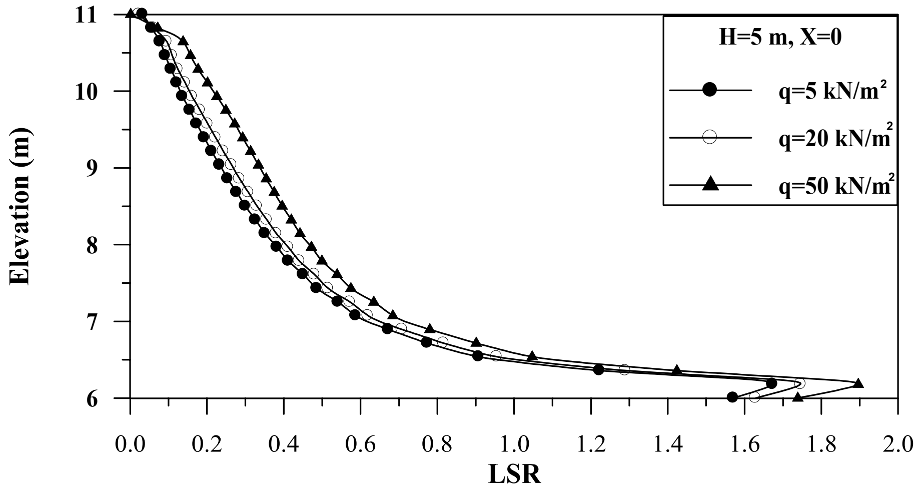

Figure (24): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 5 m, X = 0).

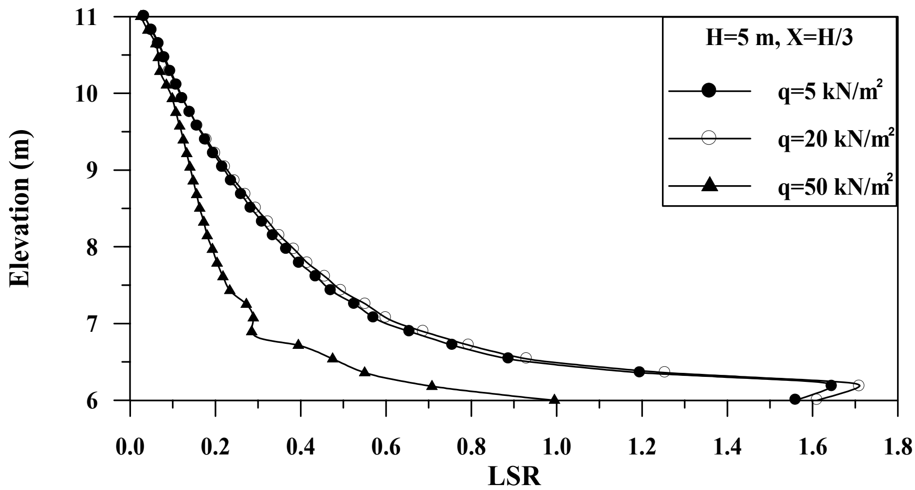

Figure (25): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 5 m, X = H/3).

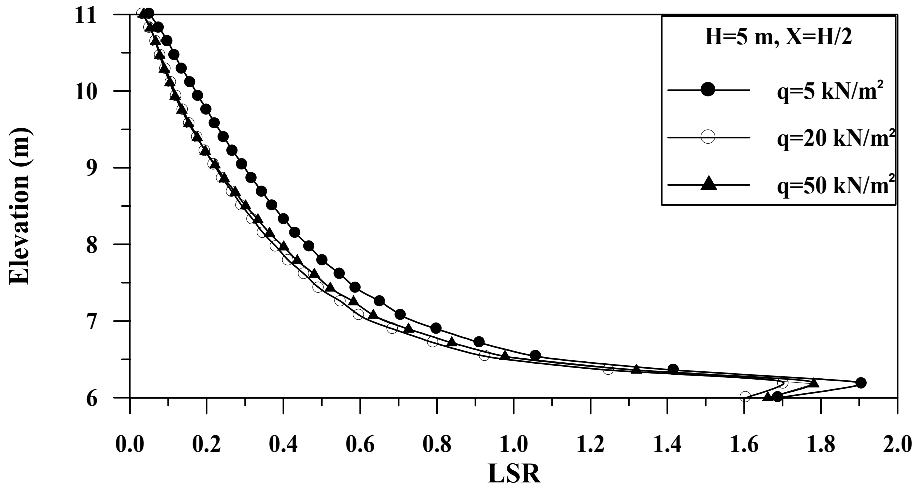

Figure (26): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 5 m, X = H/2).

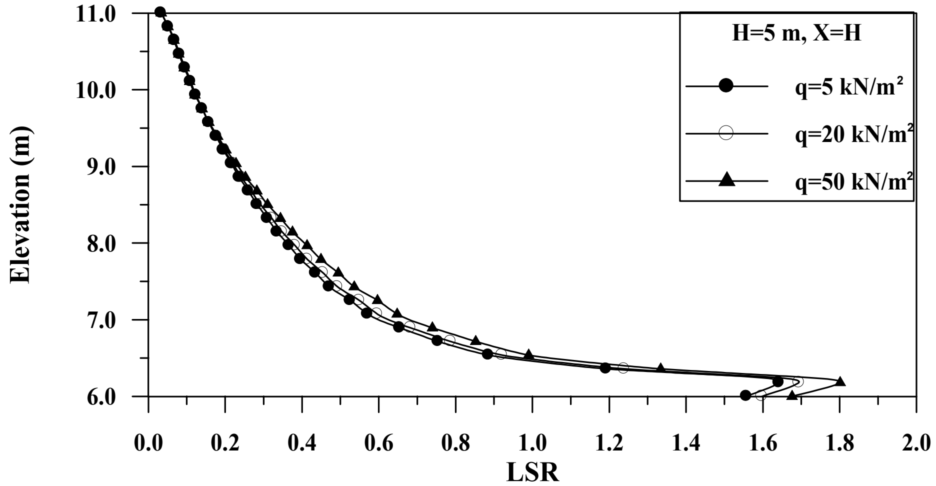

Figure (27): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 5 m, X = H).

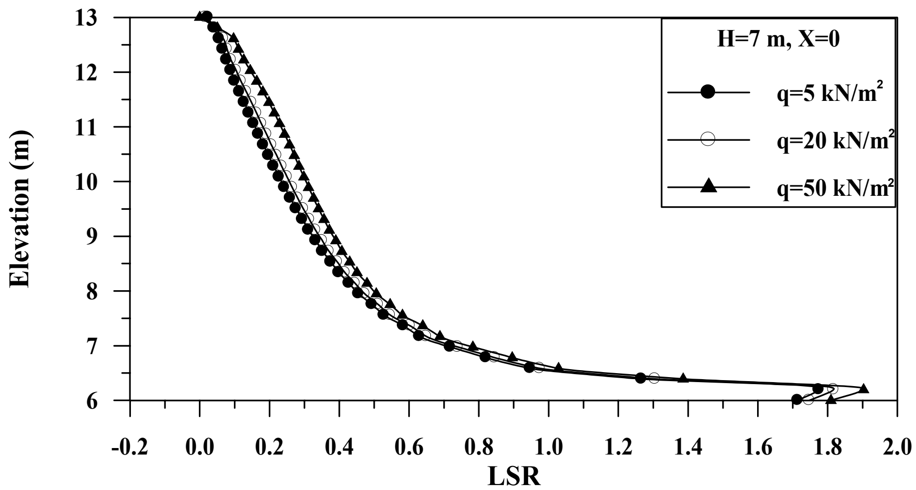

Figure (28): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 7 m, X = 0).

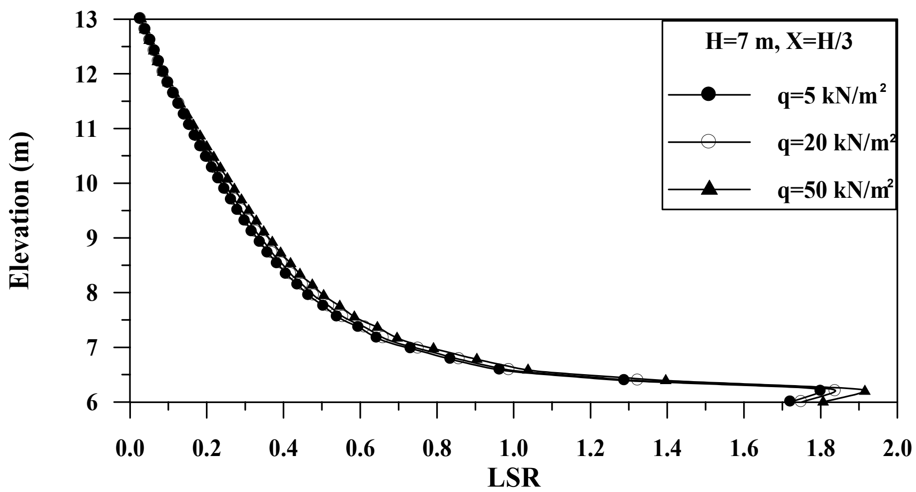

Figure (29): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 7 m, X = H/3).

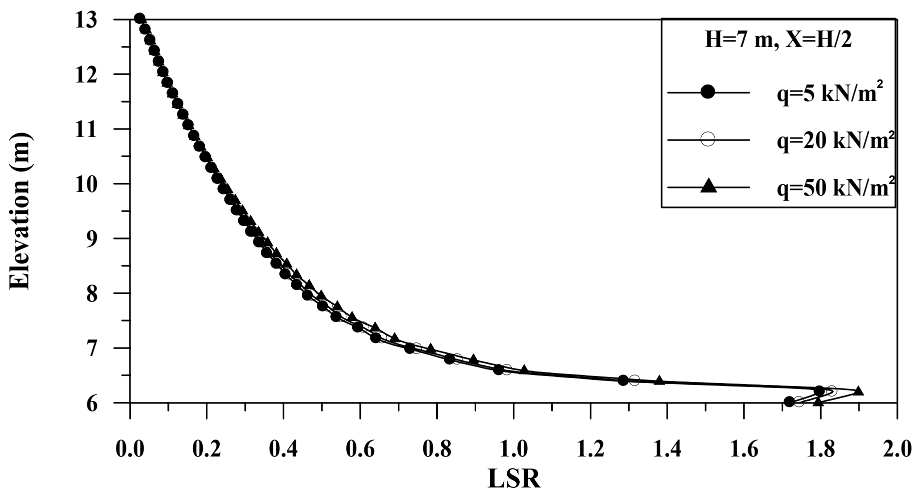

Figure (30): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 7 m, X = H/2).

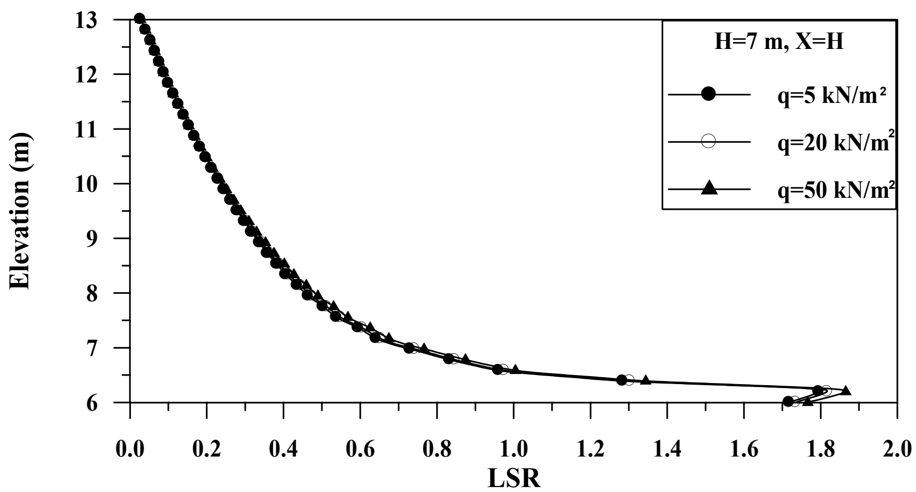

Figure (31): Effect of the Surcharge Load on Distribution of Lateral Pressure behind the Wall, (H = 7 m, X = H).

Table (4): Maximum Values of the Lateral Pressure under Different Loads Applied at Different Locations.

	The Elevation of Wall (m)			The Load q (kN/m^2)
	3	5	7	
LSR	1.42 at X=H/3	1.9 at X=H/2	1.8 at all X	**5**
	2.38 at X=0	1.75 at X=0	1.82 at all X	**20**
	1.8 at X=H/2	1.9 at X=0	1.9 at all X	**50**

6. CONCLUSIONS

Through this study, the effect of several parameters is studied. The following conclusions may be drawn:

1. The wall with small height (3 m) tends to translate and overturn about its foundation to the out, while the walls with greater heights (≥5 m), translate to the out and the horizontal displacement increases with depth. It was found that for all cases, the maximum horizontal displacement is about (0.005 m) for each 1 m height of the wall.
2. The increase in the length of reinforcement bar from (L = 0.47H to L = H) has the same effect on the maximum lateral displacement for all heights of the wall, and a decrease in the maximum value of the horizontal displacement ratio (S/H) of the order of about 18% is noticed for three cases when (L) is increased from (0.47 H to H).
3. The distribution of lateral earth pressure in reinforced embankments is always non-linear for all heights and under different loads applied at different positions. For the wall of small height (3 m), the maximum value of lateral pressure is at the base of the wall as in Coulomb's theory, while at greater heights (5 and 7) m, the maximum value takes place at about (0.1H) from the base of the wall.
4. When the height of the wall is small (3 m), and when the wall is subjected to applied loads, the horizontal displacement at the top of the wall decreases as the load is applied far away from the wall. When the load is applied directly behined the wall, the wall tends to rotate about a point located approximately at mid-height of the wall. When the height of the wall is large (≥5 m), the rotation of the wall depends on the magnitude of the applied load and the point of rotation is also located at the wall's mid-height. When the wall is high (7 m), the largest effect of the external load is when the load is applied at a distance (X=H).

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