

Sheet Piles Walls Effect on Seepage Characteristics under Low Concrete Gravity Dams

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Abstract:- The current study dealt with the hydraulic analysis of sheet piles walls under low concrete gravity dam constructed over tow isotropic soil layers with different permeability and thickness.

The uplift pressure force (pore water pressure) under dam, seepage discharges, and exit gradients through the complex foundation soil with two layers and different permeability with sheet piles at the upstream and the downstream of the floor numerically investigated. The investigation carried out on 54 models of assumed dams contained sheet piles of various depths and at variable angles with the horizontal axis, as well as at variable locations below the dam floor. Finite element technique with aid of (Geo-Studio - SEEP/W model) software was used to solve numerically seepage flow condition through pervious foundation soil.

Results shose that minimum value of uplift pressure force is for the case that sheet pile is at upstream and the maximum is at the end of the dam. So that, it can be expressed that the best place for sheet pile in order to decrease uplift pressure force is at upstream (heel) of the dam. In the other words, the upstream sheet pile causes decrement 75% in uplift pressure forces respect to the case that no sheet pile used.

It was also clear that changing the depth of the walls is the most influential factor on the seepage characteristics with considerable proportions for each of the seepage discharge, pore water pressure and exit gradient, except for increasing the depth with respect to the downstream sheet pile, which causes a significant increase in pore water pressure. As for the location of the walls (their distance from the two ends of the dam floor), they increase the seepage discharge, pore water pressure, and exit gradient with respect to the upstream sheet pile in little to medium proportions, and increase the seepage discharge and decrease both the pore water pressure and exit gradient with respect to the downstream sheet pile in small proportions as well. Finally, increasing inclination angle from the vertical axis with respect to the downstream sheet pile causes a moderate increase in all seepage characteristics, while increasing inclination angle of the downstream sheet pile causes a small increase in seepage discharge and a moderate to big decrease in both pore water pressure and exit gradient, respectively.

Keywords: Dam, Sheet pile, Seepage, Uplift pressure, Exit gradient.

تأثير جدران الركائز الصفائحية على خصائص النضح تحت السدود الخرسانية الثقيلة المنخفضة

الخلاصة

تناولت الدراسة الحالية التحليل الهيدروليكي لجدران الركائز الصفائحية تحت سد ثقلي الخرساني المنخفض المقام فوق طبقات تربة متماثلة ذات نفاذية وسمك مختلفين. تم فحص قوة ضغط الرفع (ضغط الماء المسامي) تحت السد ، وتصريفات النضح ، وتدرجات المخرج من خلال تربة الأساس المعقدة بطبقتين ونفاذية مختلفة مع ركائز صفائحية عند المنبع والمصب للأرضية التي تم فحصها عددياً. تم إجراء البحث على 54 نموذجاً من السدود المحتوية على ركائز صفائحية بأعماق مختلفة وبزوايا متغيرة مع المحور الأفقي ، وكذلك في مواقع متغيرة أسفل أرضية السد. تم استخدام تقنية العناصر المحدودة بمساعدة برنامج (Geo-Studio - SEEP / W model) لحل حالة التدفق للنضح من خلال تربة الأساس النفاذة عددياً.

تشير النتائج إلى أن القيمة الدنيا لقوة ضغط الماء المسامي هي في حالة أن تكون الركائز الصفائحية عند المنبع وأن الحد الأقصى عند المصب. لذلك، يمكن التعبير عن أن أفضل مكان للركائز الصفائحية من أجل تقليل قوة ضغط الرفع هو عند منبع (كعب) السد. بعبارة أخرى، تنسب الركائز الصفائحية للمنبع في انخفاض بنسبة 75٪ في قوى ضغط الرفع مقارنة بالحالة التي لا تستخدم فيها الركائز الصفائحية. كان من الواضح أيضاً أن تغيير عمق الركائز الصفائحية هو العامل الأكثر تأثيراً على خصائص النضح بنسب كبيرة لكل من تصريف النضح وضغط المياه المسامي وتدرج المخرج، باستثناء زيادة العمق فيما يتعلق بركيزة الصفائح في المصب، مما يؤدي إلى زيادة كبيرة في ضغط الماء المسامي. أما بالنسبة إلى موقع الجدران (المسافة من طرفي أرضية السد)، فإنها تزيد من تصريف النضح، وضغط الماء المسامي، وتدرج المخرج بالنسبة إلى ركيزة الصفائح المنبع بنسب قليلة إلى متوسطة، وتزيد من تصريف النضح وتخفض كل من ضغط الماء المسامي والانحدار للخروج فيما يتعلق بركيزة الصفائح في المصب بنسب صغيرة أيضاً. أخيراً، تؤدي زيادة زاوية الميل من المحور الرأسي فيما يتعلق بركيزة الصفائح في المصب إلى زيادة معتدلة في جميع خصائص النضح، بينما تؤدي زيادة زاوية ميل ركيزة الصفائح للمصب إلى زيادة طفيفة في تصريف النضح وانخفاض معتدل إلى كبير في كل من ضغط الماء المسامي وتدرج المخرج، على التوالي.

INTRODUCTION

Foundation of any hydraulic structure should be given the greatest importance in analysis and design as compared with other parts of the structure, because failure in the foundation would destroy the whole structure. One of the most important problems that cause damage to hydraulic structures is seepage under the foundations, which occurs due to the difference in water level between the upstream and downstream sides of the structures. The water seeping underneath the hydraulic structure endangers the stability of the structure and may cause failure. Hydraulic structures may be found either on an impervious solid rock foundation or on pervious foundation. The problem of seepage becomes more serious with the latter case, particularly when the pervious foundation is of a fine texture. Water seeping under the base of a hydraulic structure starts from the upstream side and tries to emerge at the downstream end of the impervious floor. If the exit gradient is greater than the critical value for the

foundation, a phenomenon called piping may occur due to the progressive washing and removal of the fines of the subsoil, *Terzaghi and Peck (1967)*.

Solutions for various problems of seepage under dams with embedded vertical sheet piles and a flat bottom dam with one or more vertical sheet piles were given using different approaches by *Khosla (1936)*, *Harr (1962)*, *Leliavsky (1965)*, *Terzaghi and Peck (1967)*, *Rushton and Redshaw (1978)*, *Griffiths and Fenton in (1993)* and others. However, limited literature is available for seepage through pervious medium beneath dams.

There are different methods to find the piezometric head distribution under hydraulic structures from which the hydraulic gradient is computed. Examples of such methods are empirical, analytical, and numerical methods.

In 1934, Professor Lane introduced his empirical “weighted – creep” theory. In this theory, it is assumed that the line of flow will follow the line of contact between a dam and its foundation, *Leliavsky (1979)*.

According to Bligh’s creep method, the percolating water follows the outline of the base of the foundation of the hydraulic structure. In other words, water creeps along the bottom contour of the structure, *Garg (1998)*.

Khosla proved that seeping water through permeable soils follows parabolic streamlines and not along the underside profile of the impervious floor as envisaged by Bligh. He proved that the flow of seeping water takes place according to Laplace equation, *Grishin (1982)*. Khosla solved the actual profile of the hydraulic structure by an empirical method known as the method of independent variables. According to this method, the actual complex profile is broken into a number of simple profiles known as elementary profiles. Each elementary profile is independently amenable to mathematical treatment and, thus, it treated independently.

Polubarinove-Kochina (1962), obtained the complete solution for an impervious structure resting on the surface of a flow domain of infinite depth with a horizontal floor, by using the velocity components and complex velocity transformation at the boundaries of the flow region.

There are many methods in which a derived relationship to calculate the magnitude of the hydraulic gradient can be obtained; however, their applications are limited because of the complexity and limitations involved. Some of these methods have been presented in detail in, *Harr (1962)*.

Because of the difficulties, which met through empirical and analytical methods, it was resorted to numerical methods. Such methods provide obtaining the required results with a good accuracy such that they are well comparable to the results of the analytical solutions. The two common numerical methods applied to flow through porous media are the finite-differences method and the finite – elements method. Complex problems, the finite element method is preferable to the finite difference method for the following reasons, *Khsaf (1998)*:

1. In the finite-element method, anisotropy and non-homogeneity taken into account quite easily in comparison with the finite-difference method.
2. The boundary conditions easily handled by the finite element method whereas special formulas must be developed for each condition with the finite difference method.
3. In the finite element, method there is no restriction for the mesh size where the size of each element can be varied independent of other elements. For example, small elements may be used in areas of rapid changes whereas large elements may be used where these changes are less severe.

Therefore, considering accuracy and simplicity at the same time, the finite element method considered the best in solving different real-life problems.

LITERATURES REVIEW

Conner and Brebbia (1976) solved the seepage problem under a hydraulic structure with two piles resisting on isotropic soil by using finite element method in order to find the distribution of pressure under the base of the structure.

Cechi and Mancino (1978), and *Zienkiewicz (1982)* have given application examples of simple cases for seepage under hydraulic structures by using triangular grid of finite element to find the head distribution under the structures.

Chawla (1986) has also obtained an exact solution using conformal mapping for seepage below a flat floor with two cut-offs and a horizontal intermediate filter (the depth equal to zero) located anywhere between the two cut-offs. His results indicate that the uplift pressure and the exit gradient decrease with decrease in the depth of pervious strata, and the filter increases the stability of the structure and increases the stability of soil particles against piping.

Ijam and Nassir (1988) used the finite element method to study seepage under hydraulic structures for isotropic soil with two cut-offs. Their results presented a set of uplift pressure distribution curves, whereas the efficiency of the cut-offs was defined. Another relationship also obtained to calculate the factor of safety against failure due to heave.

Khsaf (1998) used the finite element method to analyze seepage in isotropic, anisotropic, homogeneous and non-homogeneous soil foundations underneath hydraulic structures provided with flow control devices. He studied a hydraulic structure with an upstream and / or downstream cut-off(s) with various permeable-layer thickness and various depths and locations of cut-offs. He found that the location, number and depth of the cut-offs have a noticeable effect in reduction the uplift pressure.

Salah I., Hayder T., and Hadeel Ch. (2011) made numerical investigations on the effect of cut-off inclination angle on exit gradient, uplift pressure head under hydraulic structure, and determine the optimum location and angle of inclination of cut-off. They solved this problem using the finite element method by using (ANSYS 11.0). They concluded that using downstream cut-off inclined towards the downstream side with θ less than 120° is beneficial in increasing the safety factor against the piping phenomenon.

Behnam M., Farzin S., and Behrooz O. (2014) compared the efficiency of cut off wall on some design parameters in an assumed diversion dam cross-section. They used different placements of cut off wall with various angle of inclination in the dam foundation. Results showed that minimum uplift pressure happens when cut off wall is in the heel (upstream) of the dam. They indicated to the effect of inclination of cutoff wall in upstream of the dam; respect to vertical position, in reducing of uplift pressure is very high.

M. Yousefi, M. Parvizi, M. Sedghi-Asl (2015) built a laboratory apparatus to simulate seepage and its controlling measures under sheet piles. The effect of position and depth of the sheet pile on the seepage flow and exit gradient have been demonstrated in form of dimensionless curves. The results show that the depth of the sheet piles $d/D=0.46$ with the maximum upstream water level $h/h_m=1.0$ boiling phenomenon does not occur and the seepage rate and hydraulic gradient in the area are favorable.

Nassralla T.H., and Rabea A.R.M.A (2015) study the effect of sheet pile on seepage characteristics under the hydraulic structure floor through soil consists of two layers that for convergence to exact case similar to studying case in nature. The effect of changing each of the effective water head, the sheet pile location under the floor of hydraulic structure, the sheet pile penetration depth in the soil layers and the arrangement of soil layers done.

Asmaa A. J. (2016) studied the effect of using intermediate sheet pile under the apron of hydraulic structure besides the upstream and downstream piles rest on non-homogeneous soil layer to show how it affect the uplift pressure, exit gradient and seepage discharge at toe of hydraulic structure by using computer program SEEP/W Package. She developed empirical equations to determine the quantity of uplift pressure, exit gradient and discharge at toe of hydraulic structure.

THE BASIC EQUATION OF FLOW THROUGH A POROUS MEDIA

The flow medium for seeping water under hydraulic structures is a saturated porous soil. Groundwater flow depends on many factors such as soil properties, fluid characteristics, flow geometry, time, and boundary conditions. The most important properties for such a medium to be taken into consideration are porosity and permeability. It is possible to analyze groundwater flow from knowing the flow properties, which represented by the velocity, pressure, and temperature; these properties represent the dependent variables, which vary with both space and time.

In study the flow of groundwater through porous media, two matters concerning the problem must be specified in advance. The first is the type of flow through the porous media; the second is the boundary conditions of the flow domain. Seepage beneath hydraulic structures can be considered as a steady confined flow, Harr and Deen (1961).

Flow through saturated porous media is generally governed by Darcy's law, Harr (1962):

$$V_s = K i \quad (1)$$

Where:

V_s = discharge velocity through the porous medium; (L/T);

K = hydraulic conductivity, ($L^3/L^2.T=L/T$);

i = hydraulic gradient = $-dh/ds$;

h = peizometric head = $(p/\gamma_w) + z$, (L);

p = hydrostatic pressure, (F / L²);

γ_w = unit weight of water, (F/L³);

z = elevation head, (L);

S = distance along the flow line, (L).

Equation (2) represented the linear relationship between the discharge velocity and the hydraulic gradient.

Darcy's law is valid when the special form of the Reynolds number (Re) for sub-surface flow is equal to or less than unity, Harr (1962). That is:

$$Re = \frac{Vdp}{\mu} \quad (2)$$

Where:

V = flow velocity; (L/T);

d = average diameter of soil particles, (L);

ρ = fluid density, (F T² / L⁴);

μ = coefficient of viscosity, (FT / L²).

Fortunately, most of practical seepage under hydraulic structures is laminar, (i.e., ($Re < 1$), Grishin (1987).

The components of the seepage velocity through porous media according to the general form of Darcy's Law for three-dimensional flow are, Freeze and Cherry, (1979):

$$u = -k_x \frac{\partial h}{\partial x} \quad (3a)$$

$$v = -k_y \frac{\partial h}{\partial y} \quad (3b)$$

$$w = -k_z \frac{\partial h}{\partial z} \quad (3c)$$

Where:

u, v, w = velocity components in the x-, y-, and z-direction, respectively, (L/T);

k_x, k_y, k_z = hydraulic conductivity in the x-, y-, and z- directions, respectively; (L/T).

The continuity equation for three-dimensional and incompressible flow is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

Substituting Darcy's Law, Eq. (4), in Eq. (5) results in:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial h}{\partial z} \right) = 0 \quad (5)$$

For a homogenous and isotropic soil, the hydraulic conductivity is equal in all directions, that is: $k_x = k_y = k_z = k$

Thus, Eq. (6) written as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad (6)$$

Equation (6) is the Laplace equation; it is similar to Laplace equation of velocity potential for ideal fluid flow.

Most of the problems of seepage control analysis beneath hydraulic structures represent two-dimensional flow. Hence, Eq. (6) for two-dimensional flow becomes:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad (7)$$

Consequently, for conditions of steady state, laminar flow, the seepage pattern can be completely determined by solving Eq. (8), subject to the boundary conditions of the flow domain.

MODEL FORMULATION

The general schematic section geometry of a low concrete gravity dam with boundary condition shown in Figure (1) below:

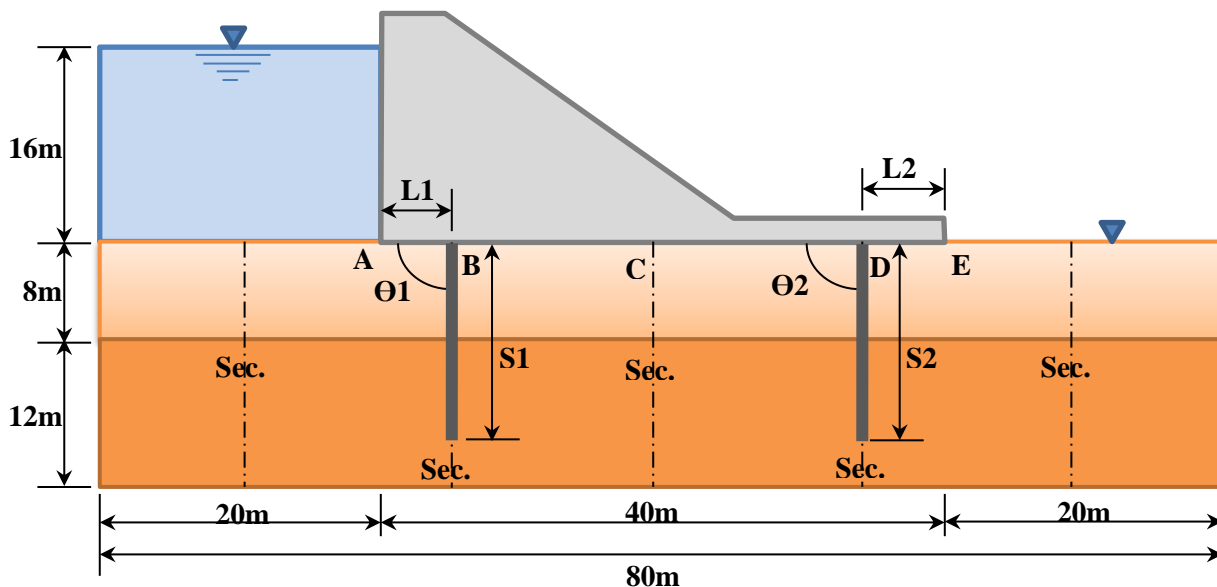


Fig. 1: Schematic presentation of the dam-foundation system and parameters model analyzed using SEEP/W Software.

Where,

S1: upstream sheet pile depth.

S2: downstream sheet pile depth.

L1: upstream sheet pile distance from the upstream end.

L2: downstream sheet pile distance from the downstream end.

Θ1: upstream sheet pile inclination angle.

Θ2: downstream sheet pile inclination angle.

As shown in Figure (1) the boundary condition on the upstream side of the dam is a total head value equal to the elevation of the water in the reservoir, which used as (16m). On the downstream side, the boundary condition is set to a value of pressure equal to zero – which indicates full saturation downstream with no tail water head. So difference between upstream and downstream total head level is ($H = 16m$). The total length of soil section is (80m) and the depth of the soil section for the first upper layer is (8m) and (12m) for the second layer. Dam floor of (40m) length used with two cutoff sheet piles installed under the dam floor.

A fifty four dams models were made using three various dimension (8m, 12m, and 16m) for the upstream and the downstream sheet pile depth (S1 & S2), four various distances (0m, 2m, 3m, and 4m) from upstream and downstream ends (L1 & L2), and three various inclinations angles (90° , 120° , and 135°) ($\Theta 1$ & $\Theta 2$) changing with each others parameters. Also two different permeability ($k_1 = 3 \times 10^{-5}$ & $k_2 = 1 \times 10^{-5} \text{ cm/sec}$) were used for the two layer beneath the dam in models.

SEEP/W MODEL APPLICATION

Aim of this study is the analysis of sheet piles under low concrete gravity dam by investigate and evaluate the effects of sheet piles depth, inclination angle, and upstream and downstream locations on the amount of uplift pressure force, seepage amount, and exit gradient for the dams constructed over pervious isotropic multiple layer foundation. Geo Studio software and SEEP/W model is a 32-bit Windows graphics program which operates on the basis of finite element relationships, and has the capability of groundwater semi-saturated and saturated conditions modeling. This model, also, simulates the moisture content and pore water pressure as a continuous function of pore water pressure. SEEP/W model is capable to calculate the hydraulic gradient and seepage flow of body and foundation of concrete dams. Also, calculates the excess pore pressure at some point from upstream to downstream and plots of velocity vectors, in addition to other plots such as potential lines, total water lines etc.

Geo Studio software and SEEP/W model was applied for the 54 cases of models to achieve this objective and calculate the total head, pore water pressure, and hydraulic gradient for five specified points beneath dam floor (A, B, C, D, and E) shown in Figure (1). In addition, the amounts of seepage discharges at five vertical sections shown in Figure (1) along the pervious soil under the dam calculated also. Each case drawn and inputs its data and start software analysis to obtained the required results. Some of the SEEP/W model results shown in Figures (2 to 12).

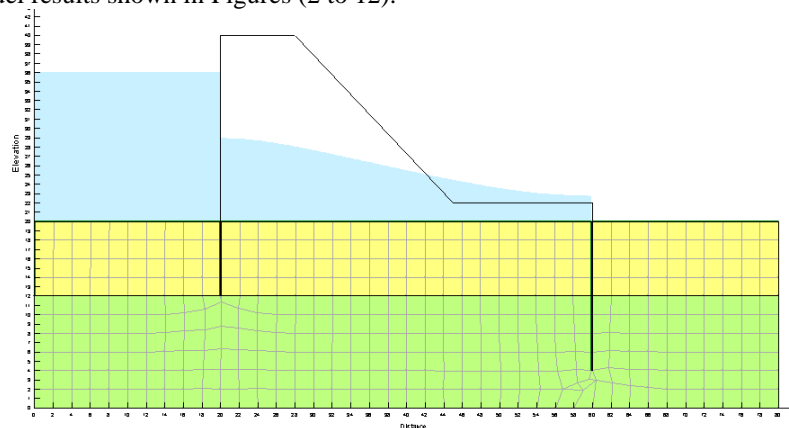


Fig. 2: Finite element mesh for the dam-foundation model.

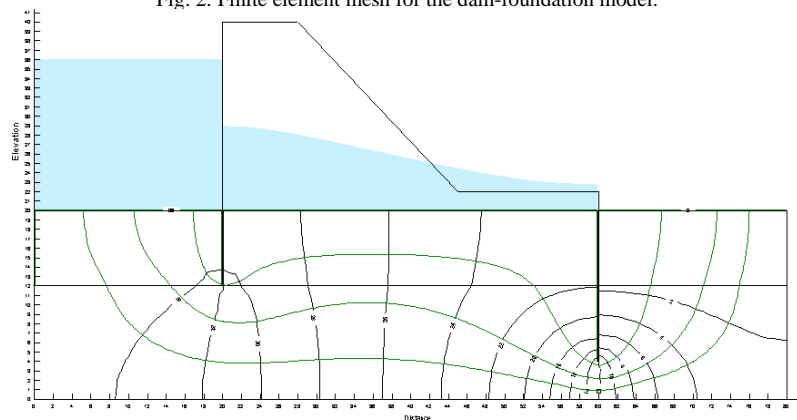


Fig. 3: Flow net for the dam-foundation model.

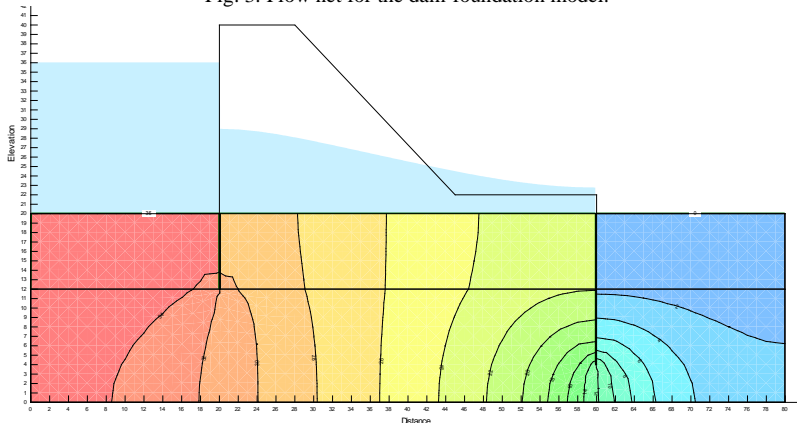


Fig. 4: Total head contours for the dam-foundation model.

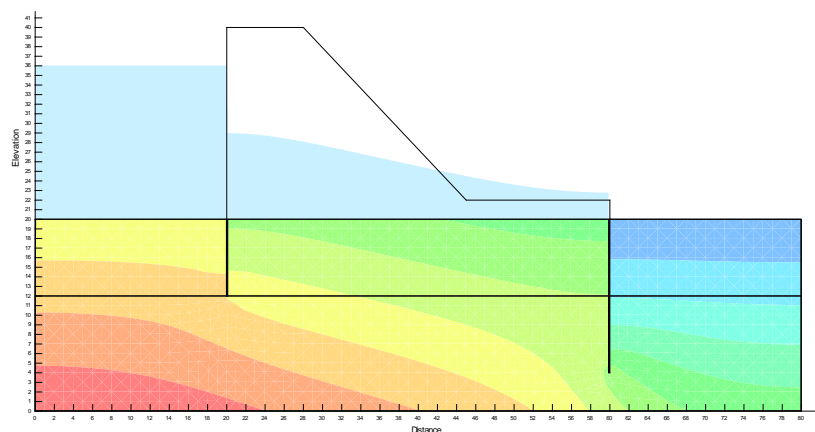


Fig. 5: Pore water pressure contours for the dam-foundation model.

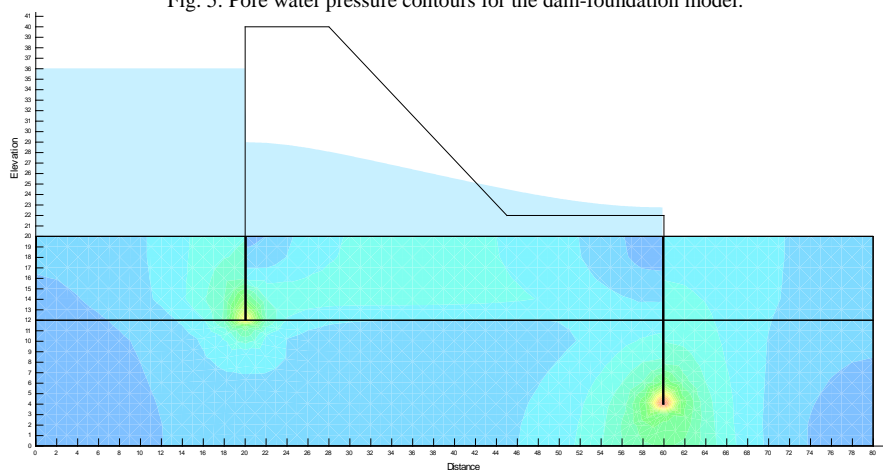


Fig. 6: Water flow (x-y) velocity for the dam-foundation model.

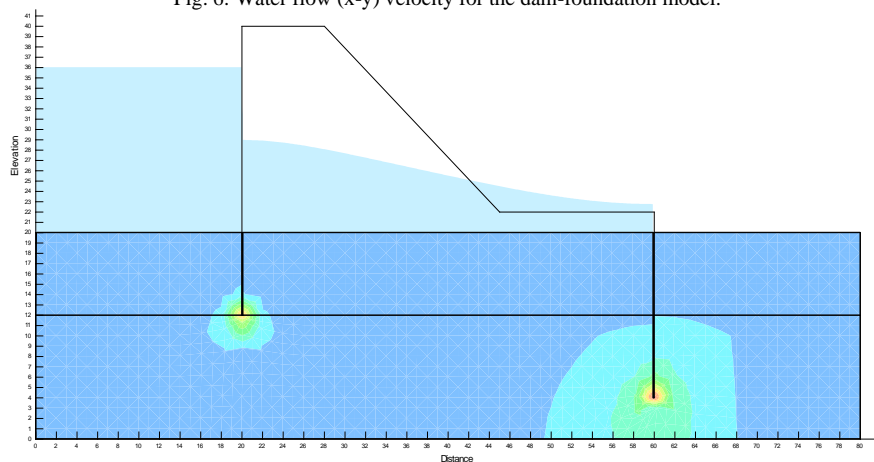


Fig. 7: Water flow (x-y) gradient for the dam-foundation model.

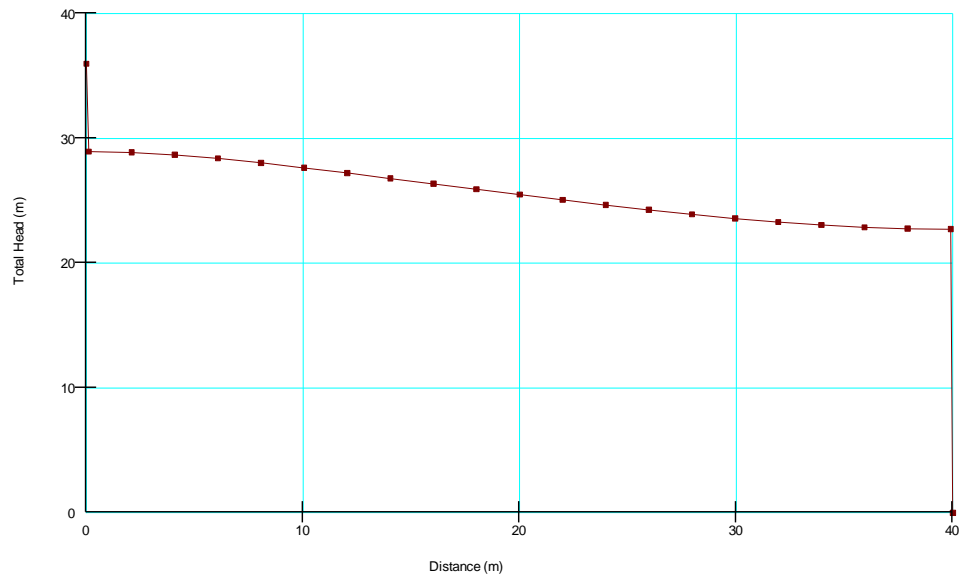


Fig. 8: Total head vs. distance along the dam floor for the model.

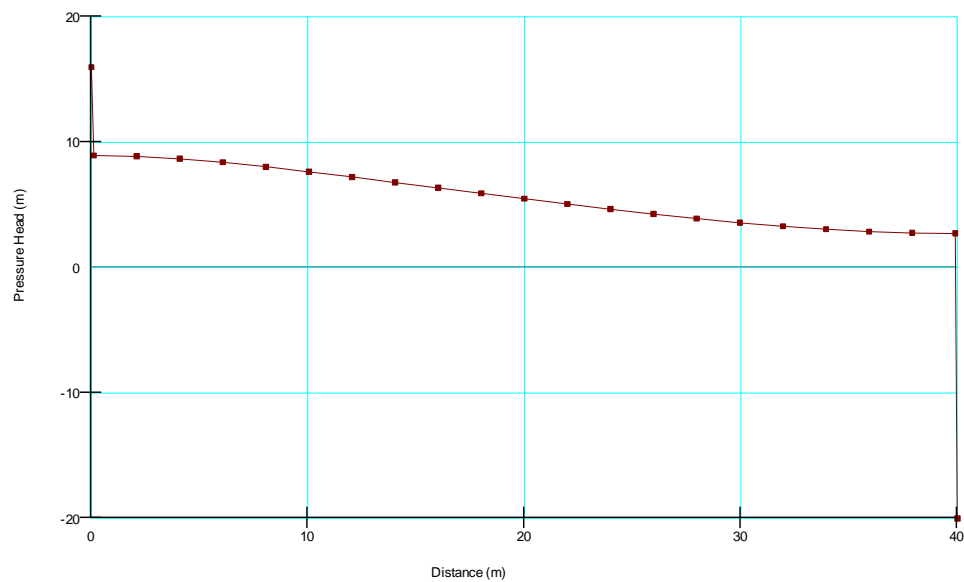


Fig. 9: Pressure head vs. distance along the dam floor for the model.

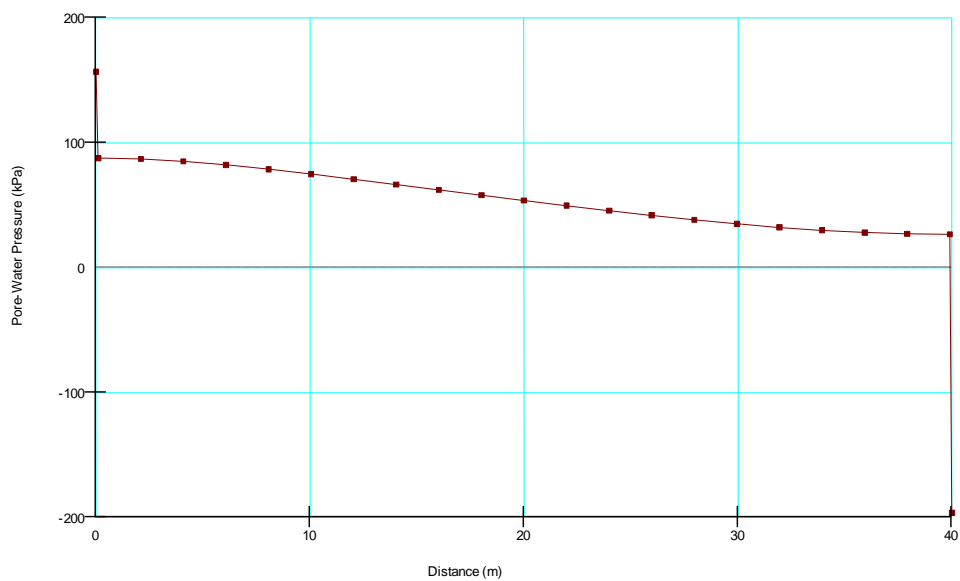


Fig. 10: Pore water pressure vs. distance along the dam floor for the model.

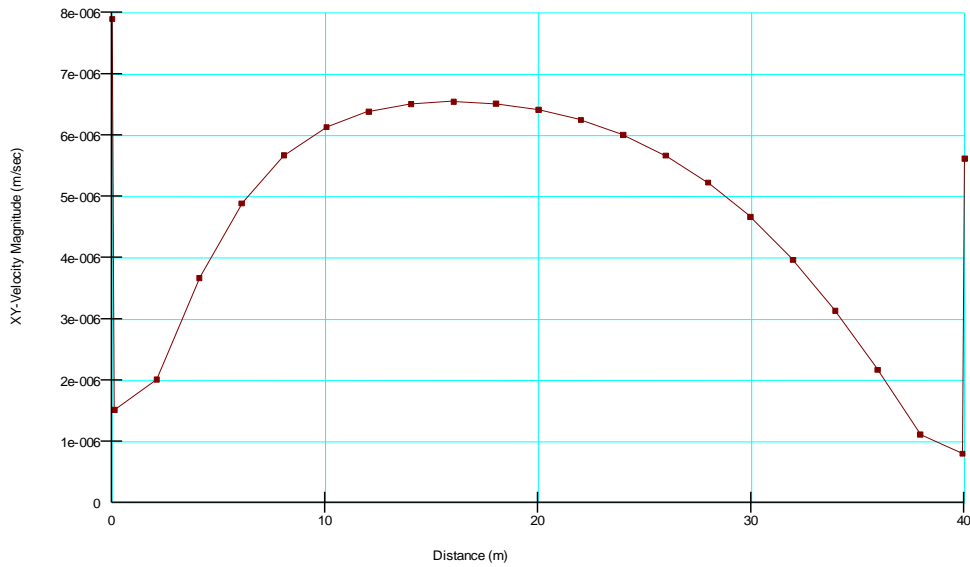


Fig. 11: Water flow (x-y) velocity vs. distance along the dam floor for the model.

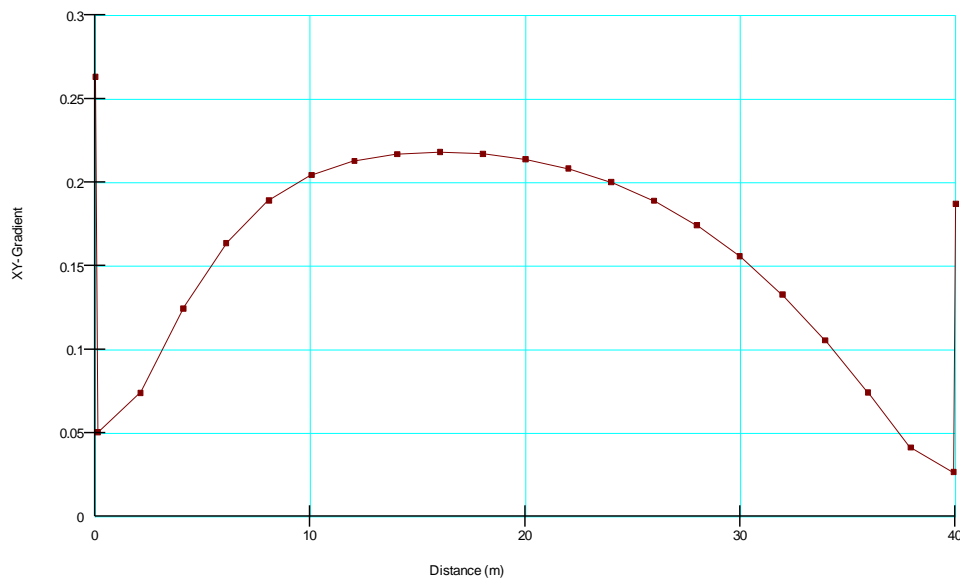


Fig. 12: Water flow (x-y) gradient vs. distance along the dam floor for the model.

ILLUSTRATION OF RESULTS

The effect of changing the dimensions of both sheet piles upstream and downstream under the dam in terms of their depths, locations and internal inclination angles for each of them on the change in the amount of seepage discharge in the permeable foundation soil beneath the dam are shown in Figures (13-30).

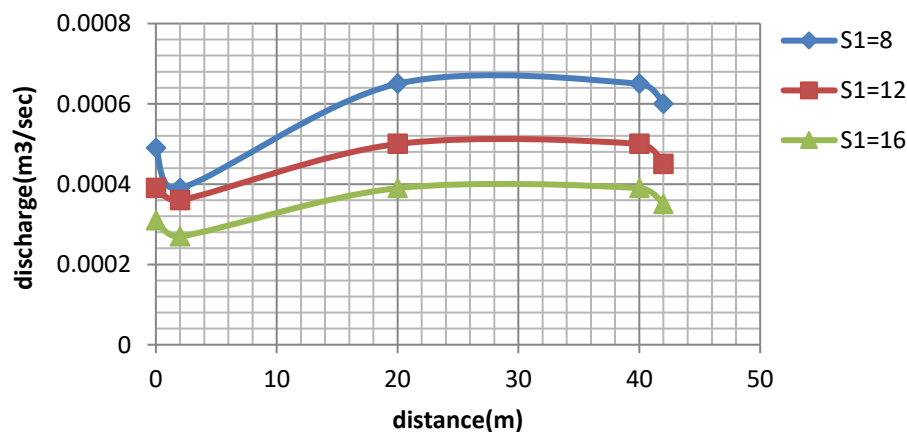


Fig. 13: Effect of upstream sheet pile depth (S1) on seepage discharge.

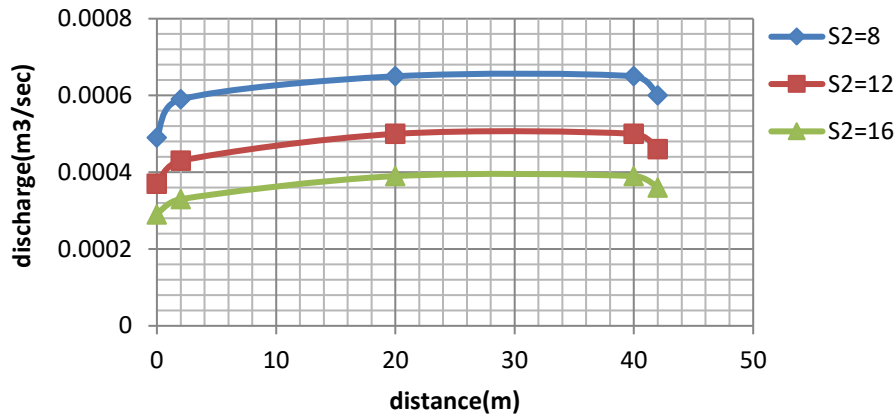


Fig. 14: Effect of downstream sheet pile depth (S2) on seepage discharge.

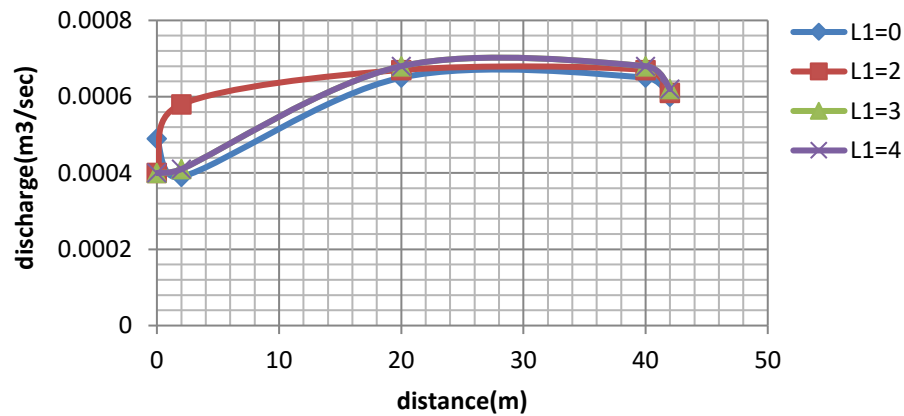


Fig. 15: Effect of upstream sheet pile location (L1) on seepage discharge.

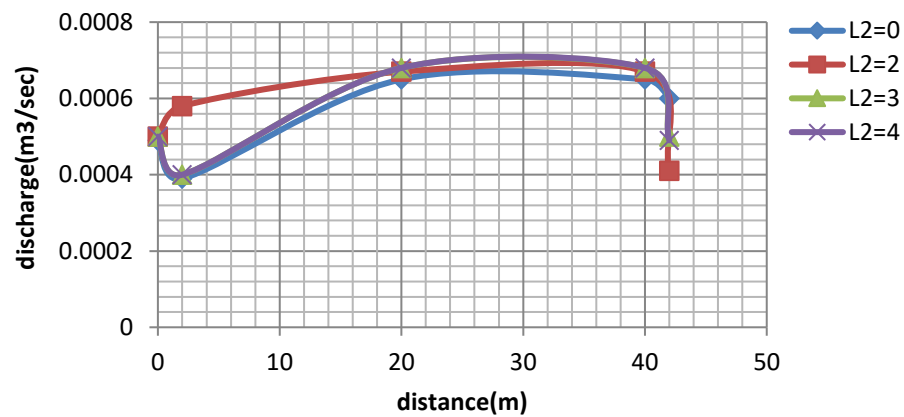


Fig. 16: Effect of downstream sheet pile location (L2) on seepage discharge.

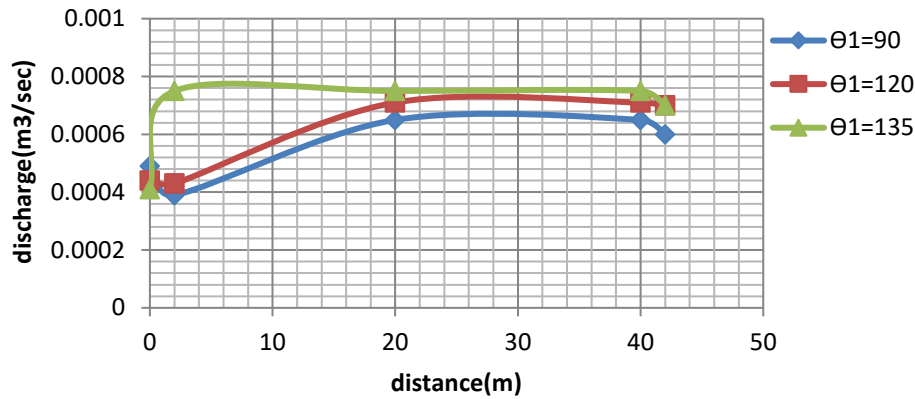


Fig. 17: Effect of upstream sheet pile inclination angle (Θ_1) on seepage discharge.

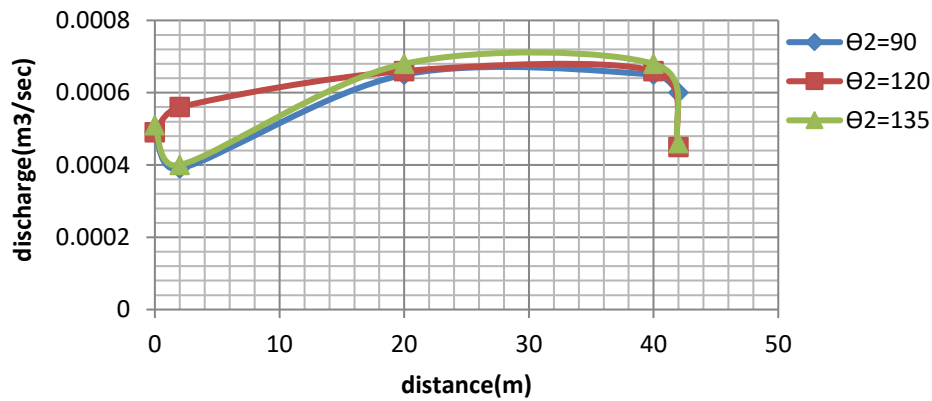


Fig. 18: Effect of downstream sheet pile inclination angle (Θ_2) on seepage discharge.

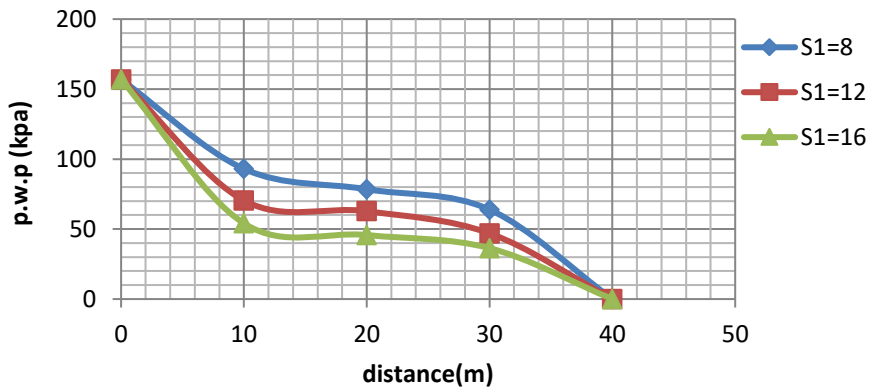


Fig. 19: Effect of upstream sheet pile depth (S_1) on pore water pressure.

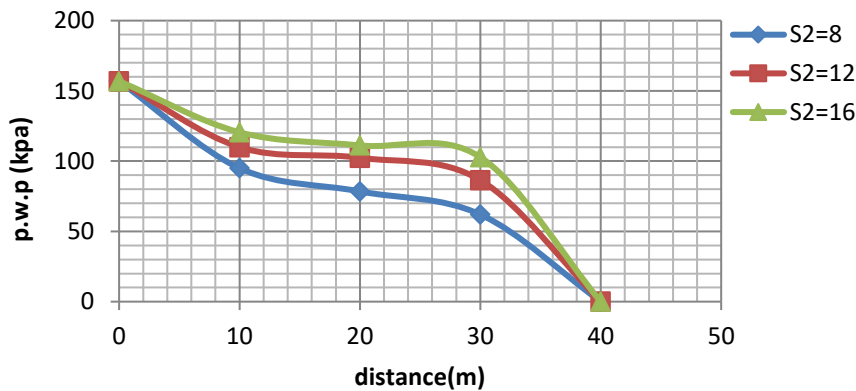


Fig. 20: Effect of downstream sheet pile depth (S_2) on pore water pressure.

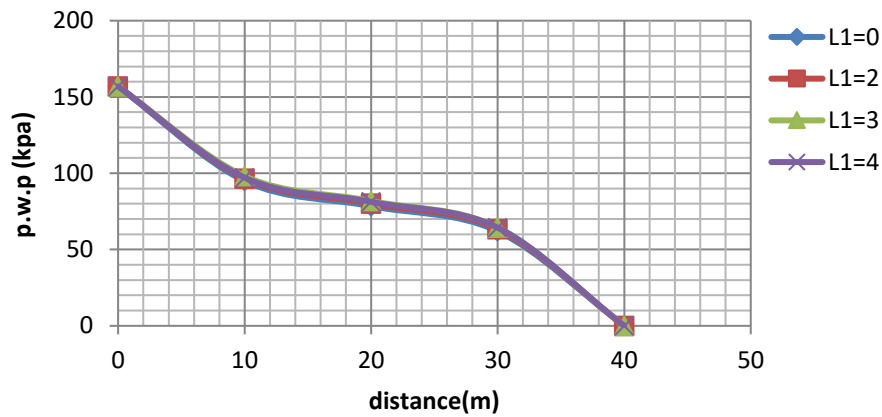


Fig. 21: Effect of upstream sheet pile location (L1) on pore water pressure.

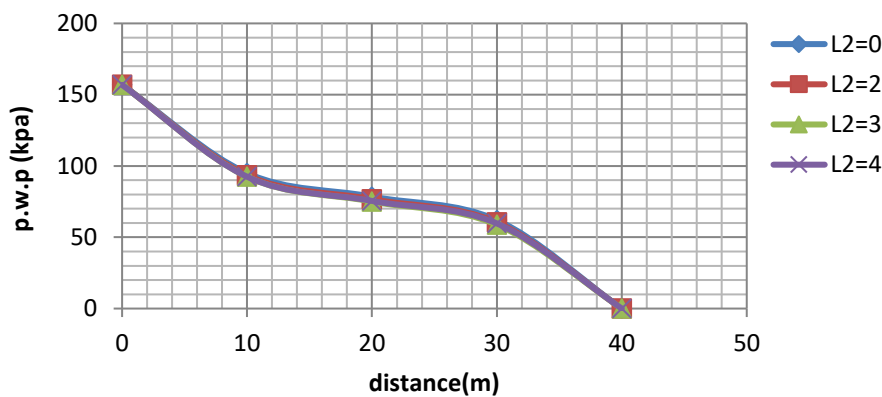


Fig. 22: Effect of downstream sheet pile location (L2) on pore water pressure.

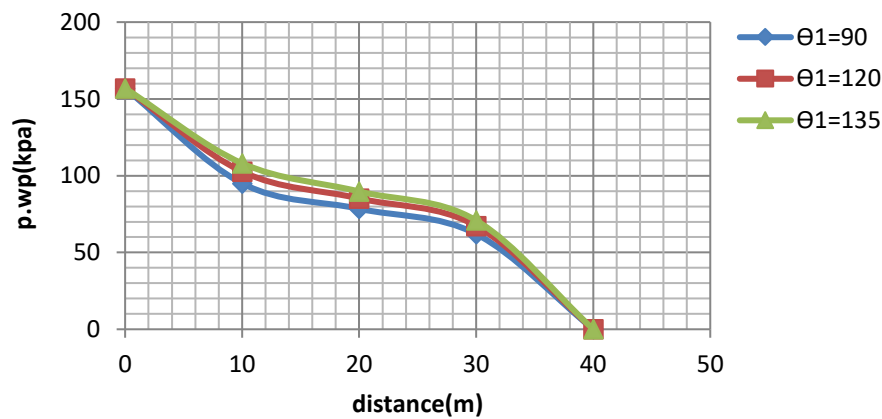


Fig. 23: Effect of upstream sheet pile inclination angle (Θ_1) on pore water pressure.

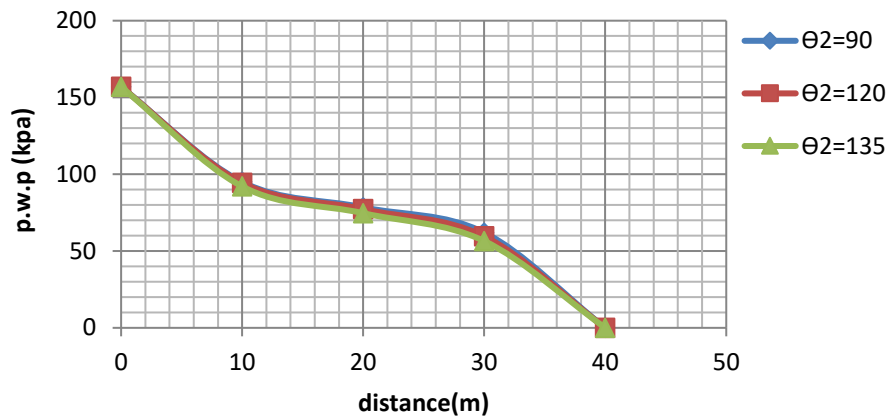


Fig. 24: Effect of downstream sheet pile inclination angle (Θ_2) on pore water pressure.

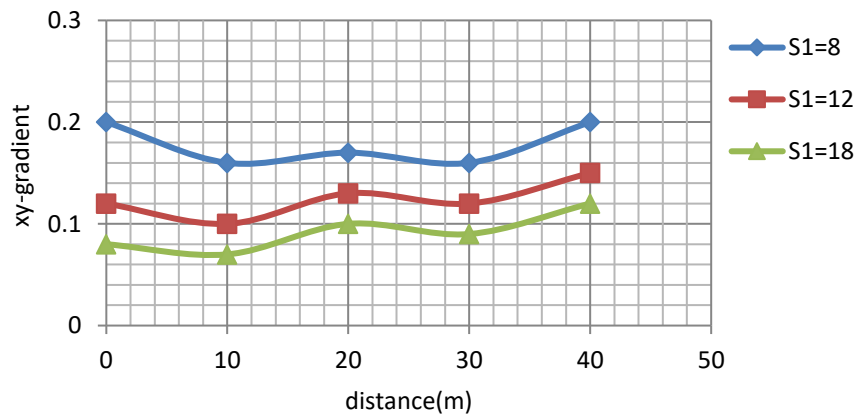


Fig. 25: Effect of upstream sheet pile depth (S1) on x-y gradient.

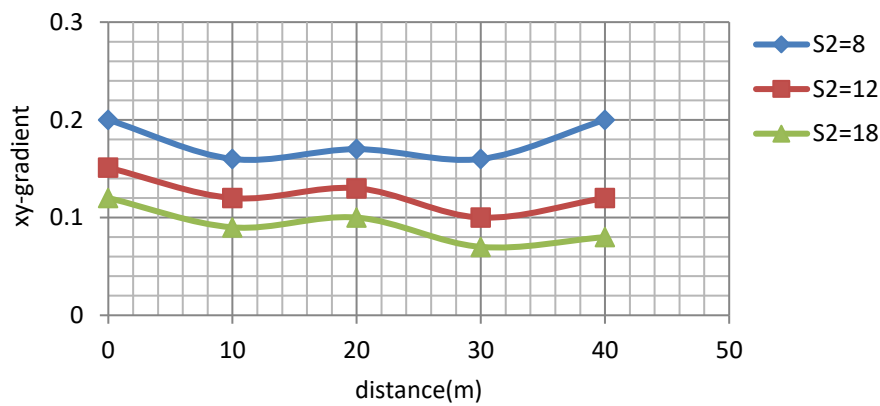


Fig. 26: Effect of downstream sheet pile depth (S2) on x-y gradient.

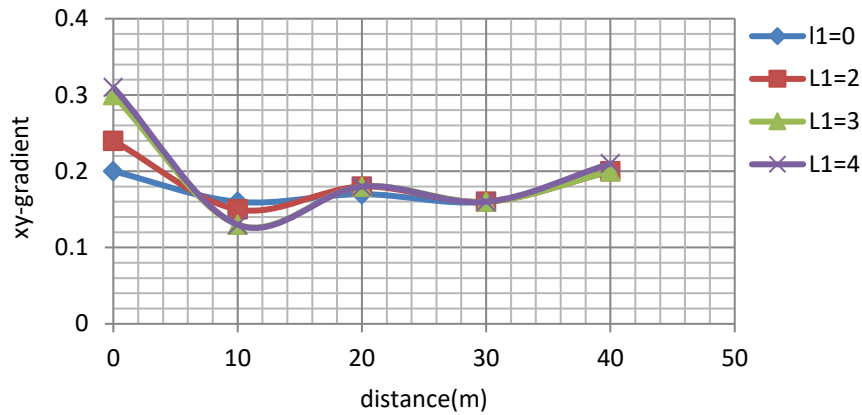


Fig. 27: Effect of upstream sheet pile location (L1) on x-y gradient.

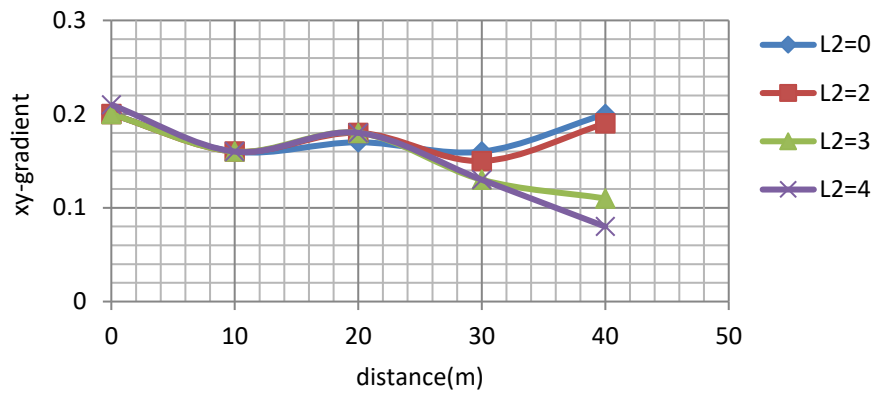


Fig. 28: Effect of downstream sheet pile location (L2) on x-y gradient.

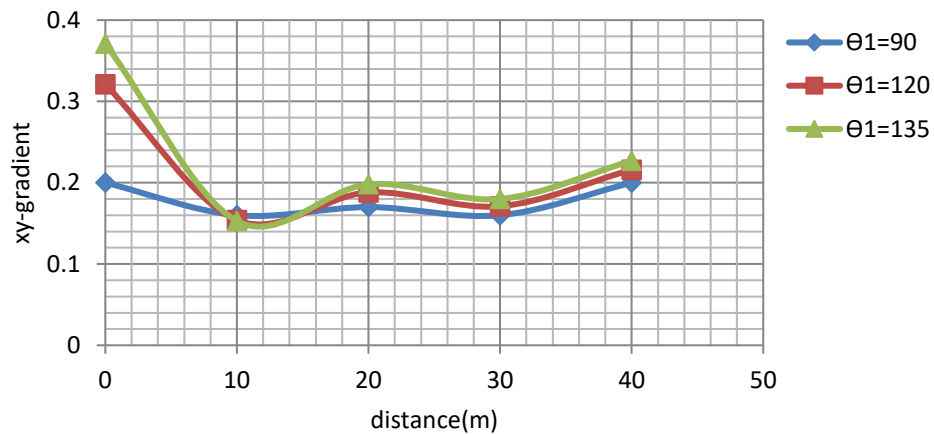


Fig. 29: Effect of upstream sheet pile inclination angle (Θ_1) on x-y gradient.

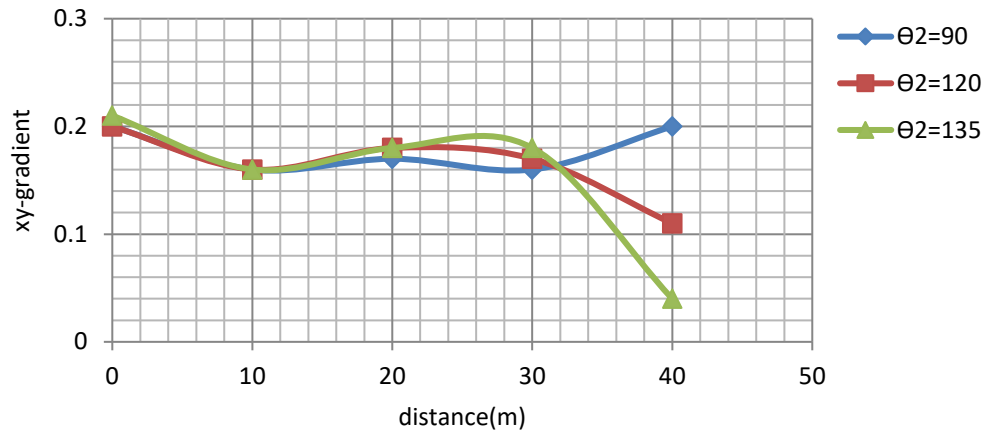


Fig. 30: Effect of downstream sheet pile inclination angle (Θ_2) on x-y gradient.

SUMMARY AND CONCLUSIONS

The major objectives of this study are to compare the efficiency of sheet pile cut off wall geometry characteristics (depth, location, and inclination angle) on some design parameters (amount of seepage discharge, total head, pore water pressure, and hydraulic gradient) in an assumed dam. Analyses based on finite elements and SEEP/W model software used to simulate seepage through soil foundation under low gravity dam for 54 assumed models. Some of selected results presented as schemes represent the relation between various parameters. Based on the obtained results and analyzes in this study, it can be said briefly that the total flow rate and outlet gradient decreases by increasing the sheet pile cut off wall depth. The minimum total uplift force and maximum exit gradient would occur when the cutoff wall places on upstream of dam.

Increasing upstream sheet pile depth up to (60%-100%) and keeping other parameter constant, amount of seepage discharge under the dam decreases to (23%-40%), pore water pressure (p.w.p) decrease to (26.5%-43%), and exit gradient decreases to (25%-40%) , Figure (13), Figure (19), and Figure (25) respectively.

Also increasing downstream sheet pile depth up to (60%-100%) and keeping other parameter constant, seepage discharge under the dam decreases to (23%-40%), pore water pressure (p.w.p) increases to (39.4%-65%), and exit gradient decreases to (48%-60%) , Figure (14), Figure (20), and Figure (26) respectively.

Increasing upstream sheet pile distance up to 4m from upstream end and keeping other parameter constant, amount of seepage discharge under the dam increases to 3.3%, pore water pressure (p.w.p) increases to 3.8%, exit gradient increases 5%, Figure (15), Figure (21), and Figure (27) respectively.

Wheres increasing downstream sheet pile distance up to 4m from downstream end and keeping other parameter constant, lead to increasing amount of seepage discharge under the dam to 18%, pore water pressure (p.w.p) decreases to 5.6% for 3m distance and retreat to 3.7% for 4m distance, and exit gradient decreases to 18.8% , Figure (16), Figure (22), and Figure (28) respectively.

Finally increasing upstream sheet pile inclination angle 33° from vertical axis and keeping other parameter constant, causes increasing seepage discharge under the dam to 15.4%, pore water pressure (p.w.p) increases to 14.3%, and exit gradient increases to 15% , Figure (17), Figure (23), and Figure (29) respectively.

Wheres increasing downstream sheet pile inclination angle 33° from vertical axis and keeping other parameter constant, causes increasing seepage discharge under the dam to 4.6%, pore water pressure (p.w.p) decreases to 8.8%, and exit gradient decreases to 80% , Figure (17), Figure (23), and Figure (29) respectively.

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