Effect of Steel Sheet Piles Defects on Seepage and Contamination Transport through the Soil

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Abstract: **Hydraulic control is a popular method for control contaminant transport through groundwater. Sheet piles are perfectly used for control and delaying seepage and contaminant transport through soil. Due to imperfections of sealing, corrosion, or due to accidental damage, a horizontal slot is present in the sheet pile at depth below the ground. The gap allows water and contaminant to pass through it. The present paper investigates the effect of defects in steel sheet pile on seepage and contaminant transport whenever the slots at various distances from the ground happened. To solve the seepage and contaminant transport through groundwater, a numerical model (Geo-Studio) based on the Finite Element Method was utilized. The current study is two-dimensional flow for the effect of slot place and sheet pile depths and other parameters as, soil hydraulic conductivity, head difference between upstream and downstream pile, breadth of the gap, and distance between the contamination source and the sheet pile. In the present study a suggested equations is used for calculating total seepage discharge and seepage under sheet pile with slot for known depth of slot with maximum error 5.78 % and 1.922 % respectively. Also, an empirical equation for calculating the traveling time of contaminant through the slot in polynomial correlation formula has coefficients of determination values vary between 0.9385 and 0.9903 are presented.**

Keywords— **Defects; Finite Elements; Gap; Groundwater Protection; Hydraulic Control; Numerical Model; Sheet pile; Slot.**

1. INTRODUCTION

In 1856 Henry Darcy [1] deduced a law, which became one of the most fundamental physical connections in the field of porous-media hydrodynamics. For percolation through a cylinder with outflow under atmospheric pressure, he derived his well-known formula:

$$Q = KAi \quad (1)$$

Where Q = volumetric flow rate, percolation flux, K = hydraulic conductivity, A = a gross area, and i = hydraulic gradient

Anderson and Mesa [2], investigated the effect of vertical barrier walls or /and well on the hydraulic control of contaminated groundwater. They used impermeable circular arc wall with finite length where the center of curvature is downstream the arc. The domain is infinite and homogenous and the flow is steady and uniform. Basha et al. [3, 4] used sheet piles to control and delay the spread of contamination in two dimensions. The contamination source is located upstream sheet pile where the water table is higher than downstream. They used sand box model to verify numerical model GEOSTUDIO 2004 software. Eltarabily and Negm [5], presented an application of numerical models to analyze the mechanism of Nitrate migration through the sand. The behavior of Nitrate transport through sand is tested when vertical wall of sheet pile is used as a barrier. Two software products, SEEP/W and CTRAN/W are used for evaluating the transport of pollutants. Armanyous et al. [6] studied control the contaminant transport through soil by using equal double sheet piles. They used physical sand box model to examine the effect of depths of double sheet piles, distance between them and distance of contaminant upstream the sheet piles. Also, the regional contaminated porous field is studied numerically using simulation software MODEFLOW and M3DMS. Design charts are presented by them for quantifying the effects of equal double sheet piles on the hydraulic control of the groundwater flow field.

Shaeshaa et al. [7] numerically investigated the use of vertical sheet piles as a means of controlling the transport of contaminants through various horizontal layers of soil. Two finite elements software SEEP/W and CTRAN/W are used for the numerical study. Results demonstrate that the time of arrival increases to decrease the difference in head between the sheet piles upstream and downstream and to increase the lower layer's permeability coefficient. Mansour et al. [8] presented a numerical and experimental examination of the transport of solvents in porous media through the use of unequal double sheet piles and surface horizontal impermeable flooring. The results concluded that making use of unequal double sheet piles may increase the time of arrival by twice as compared to the single sheet pile. Armanuos et al. [9] proved a valid of using a combination of flow barrier and freshwater injection in unconfined coastal aquifer systems, when simulated by using the sand box.

Allam et al. [10] used a numerical model (Geo-Studio) containing two modules (SEEP/W and CTRAN/W) to simulate contaminant migration through the porous media using inclined barrier. Their study aims to assess the abilities of inclined barrier walls to retard the migration of contaminants through porous media. Four cases of barrier walls arrangements were considered. Mostafa et al. [11, 12] presented research insights from the numerical (SEEP/W and CTRAN/W) and the experimental (sand box model) analyses of the use of unequal double sheet piles for groundwater protection. Mei [13], solved a two-dimensional problem involving a narrow horizontal slot in a heavily driven sheet pile that separates a dry foundation from a swimming pool analytically. He demonstrated that a tiny crack allows for enough water to enter to significantly wetting the protected side of the foundation. Rowe [14], submitted a new analytical solution for modeling leakage through holes in a geo-membrane. He showed that the existence of holes in wrinkles may explain the magnitude of leakage observed in field applications with a system for detecting leaks when consolidation water arising from pressed clay liners also being considered. Niranjan et al. [15], investigated the consequences of leakage through a barrage's sheet piles on the barrage floor's uplift pressures. The Finite Element Method was utilized to resolve two-dimensional problems. Their results were given as a ratio between the sheet piles' permeability and the soil's permeability.

Melchers and Jeffrey [16], showed that steel piling corrosion is accelerated in low water at seawater harbors throughout the United Kingdom, Europe, and elsewhere to be primarily because of water pollution. Taylor [17], discovered that the river wall's sheet pile section was in a reasonable condition, although the beam of concrete capping above had observed multiple hairline cracks. Rowe and AbdelRazek [18], calculated leakage through a hole in a geomembrane wrinkle utilizing a closed-form solution procedure, and comparisons between the outcomes of those derived from 2D Finite Element Modeling. Kim et al. [19], presented the application of the wavelet packet transform for efficient noise suppression, identification of feature parameters, and detection of defects in pile stability testing by the impact echo testing method. Six data sets were used to validate the proposed scheme and were compiled from the nine defective pile cases. Dhutti et al. [20], concentrated on the numerical modeling of defect and wave propagation identification in U-shaped piles to illustrate the potential of guided wave testing for the assessment of inaccessible steel sheet pile.

This paper integrates the numerical model (Geo-Studio) technique into a new approach to solving the steady state seepage and containment transport problems for defects steel sheet pile. The work carried out using the module (SEEP/W) to solve groundwater movement, and with the help of the results of (SEEP/W), the module (CTRAN/W) solves contamination time of travelling and concentration distribution.

2. NUMERICAL MODEL

For many reasons as demonstrated in previous introduction a gap (slot) due to a defect in steel sheet piles is occurred and allows water and contaminant to pass through the slot and underneath the sheet pile. Due to imperfections of sealing, corrosion, or due to accidental damage, a horizontal gap is present at the depth below the ground. The seepage quantities through the hole and contaminant concentration and path depend on many variables.

Figure 1 shows the schematic of the modeling of the problem under study. From the figure the study case has many variables as the soil hydraulic conductivity K , the head difference between upstream and downstream of the steel sheet pile H , and the breadth of the slot a , the depth of the centerline of the slot below the ground h , the depth of the sheet pile d , and the distance between the contamination source and the sheet pile L_s . Other parameters used in the solution are the total and effective porosity, contamination density, volumetric water content, and longitudinal and transverse dispersivity.

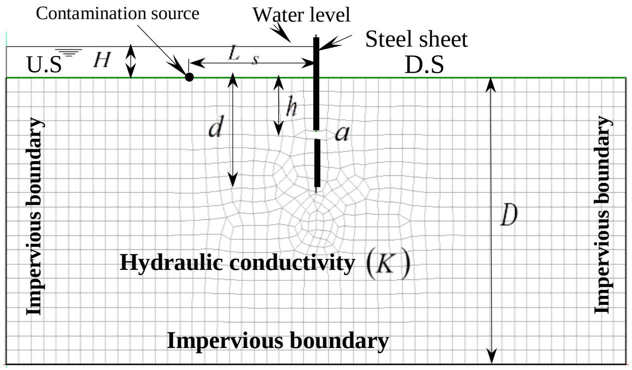

Figure 1. Dimensions of the model with slot in the sheet pile and boundary conditions

The domain under study is 100.0m long, 40.0m deep, and 1.0m wide, with impervious boundaries on the bottom, left, and right sides. The mesh is divided into elements, with approximate size of 2.0m×2.0m and refined at the hole and under the sheet pile as shown in Figure 1. The vertical sheet pile with a thickness of 10.0mm that is immersed to various depths and is positioned at a distance of 50.0m from the domain's left impervious boundary, as illustrated in Figure 1.

To solve the problem, there are many numerical solution methods and software products. SEEP/W is a finite element software product for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock. It utilizes the SEEP/W flow velocities to compute the movement of dissolved constituents in the pore-water. CTRAN/W is a finite element software product that can be used to model the movement of contaminants through porous materials. With the help of the results of (SEEP/W), the module (CTRAN/W) solves contamination distribution. The equations of contaminant transport through advection, diffusion, dispersion, and adsorption were integrated with the groundwater flow equations to determine the contamination distribution as a function of soil, contaminant type, and fluid parameters. The particle tracking analysis gives an idea of the contaminant travel distances and travel times. The Advection refers to the process by which solutes are transported by the bulk motion of flowing groundwater. Dispersion refers to the phenomenon of contaminant spreading from the path that it would be expected to follow according to the advective hydraulics of the flow system.

Considered parameters are listed in Table 1. For a steel sheet pile with slot, the solution is carried out for head difference value H of 1.0m, hydraulic conductivity value K of 1×10^{-7} m/s, slot breadth a of 0.1m. The steel sheet pile depth values d are 8.0, 10.0, 12.0, 14.0, and 16.0m, the depth of the center of the slot below the ground h equals 2.0m, 3.0m, 4.0m, 5.0m, 6.0m and 7.0m for the sheet pile with 8.0m depth and so on for the other sheet pile depths, and distances from the contamination source to the sheet pile L_s of 10.0m. The concentration of contamination at the source point is constant and equals 10000 g/m^3.

Table 1. Parameters of the model

Parameters	Values
Coefficient of Conductivity, (K), m/sec	1×10^{-7}
K_x/K_y	1.0
Sheet Pile Depth , (d) , m	8.0, 10.0, 12.0, 14.0, and 16.0 m
Head Difference ,(H), m	1.0
Breadth of the Slot, (a), m	0.1
The Depth of the Center of the Slot Below the Ground, (h), m	2.0m, 3.0m, 4.0m and so on
Distances from the Contamination Source to the Sheet Pile, (L_s), m	10
Porosity (n)	0.5
Storage Coefficient of Contamination (S)	0.0
Longitudinal Dispersivity (D_L) / Transverse Dispersivity (D_T)	2.0 / 1.0
Diffusion Coefficient, m^2/sec	1×10^{-9}
Volumetric Water Content	0.45

3. VERIFICATION OF THE MODEL

It is required to verify the accuracy of the model results. It will be applied to the solution of Basha et al. [3], and compare the results to make sure the solution is accurate. The area under consideration in Basha et al. [3] has the following parameters: 32.0m in depth, 60.0m in length, and 1.0m thickness. Water content in volume is equivalent to 0.50. The molecular coefficient is set to zero and the dispersivity is equal to 100mm. For a certain values of the head difference H equals 2.0m between the sheet piles' upstream and downstream sides is a concern for the left side of the sheet piles, hydraulic conductivity of 5×10^{-7} m/s, the domain has an impervious vertical sheet pile inserted to depth equals 13.4m at a distance of 32.0m from the left side, and the distance between the sheet pile and the contamination source L_s equals 6.0m. The longitudinal dispersivity equals transverse dispersivity =1m. The domain's bottom and two sides form an impermeable barrier. The right, left, and bottom boundary conditions are also set to a constant concentration boundary with concentration equal to zero. The flow system's starting concentration is set to zero. The concentration of contamination at the source point is constant and equals 1.0 unit/mm^3. The time steps sequence has 100 steps. Time begins at zero seconds and ends at 7.884×10^8 seconds (20 years).

The new results for contamination concentration distribution showed a good agreement with the numerical results for Basha et al. [3] as shown in Figure 2 and Figure 3. This means that the computer program can be used to study the present problem for any boundary conditions taking in account the error percentage.

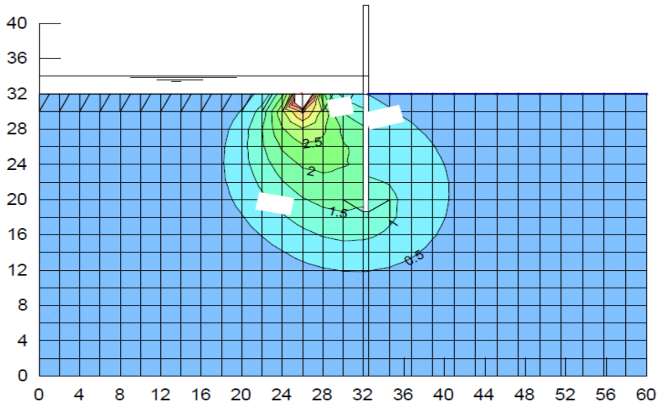

Figure 2. Contamination concentration distribution at H = 2m, L_S = 6.0m, and t = 15. 0 years, after Basha et al. [3]

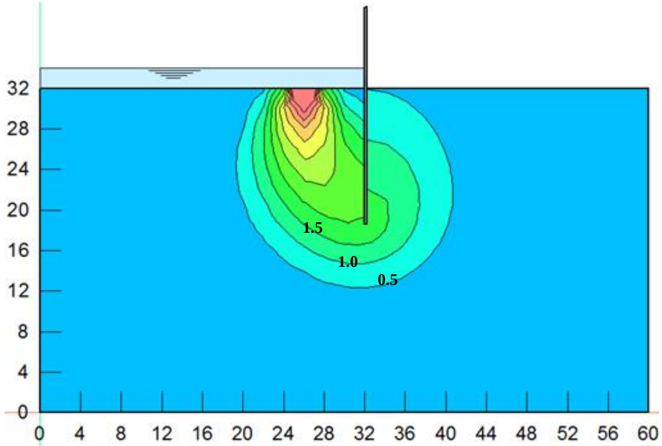

Figure 3. Contamination concentration distribution at H = 2m, L_S = 6.0m, and t = 15.0 years, present study

4. RESULTS, ANALYSIS AND DISCUSSIONS

Placing impermeable vertical sheet piles in the flow path is one of the most widely used techniques for slowing the transport of groundwater seepage and contaminants. Due to defects of steel sheet pile due to accidental damage or any other reasons, a horizontal slot is present at the depth below the ground. The seepage quantities through the gap and contaminant concentration and path are studied and

5. SEEPAGE THROUGH STEEL SHEET PILE WITHOUT DEFECTS

For impermeable steel sheet pile, the solution is carried out for head difference value H of 1.0m, hydraulic conductivity value of 1×10^{-7} m/s, sheet pile depth values of 8.0, 10.0, 12.0, 14.0, and 16.0m. After set the geometry and generate the grid as shown in Figure 1, input data are: coefficient of permeability, water content (as reported in Table 1). Boundary conditions were specified as total head H and impervious boundary, Figure 1.

To model the contaminant migration in saturated soil, SEEP/W was firstly run. The SEEP/W contour function allows one to graphically view the results by displaying the flow net for solid steel sheet pile as shown in Figure 4.

The seepage flow discharge, q computed from SEEP/W are listed in the Table 2. Table 2 declared that the seepage flow discharge decrease with increase the depth of sheet pile.

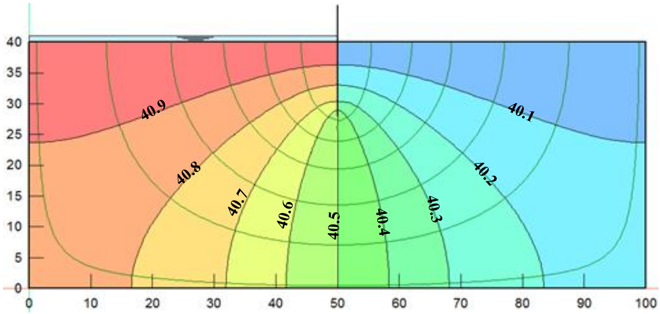

Figure 4. Flow net distribution at H =1.0m, K = 1×10^{-7} m/sec, d =12.0m for solid sheet pile

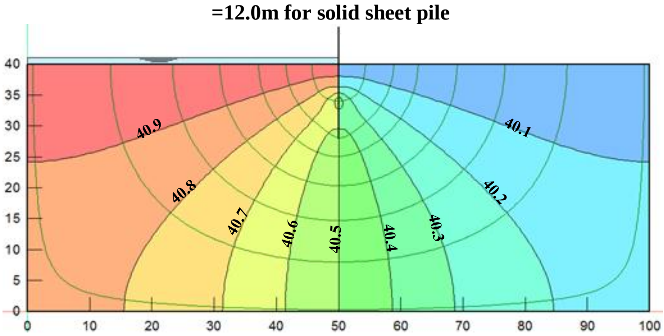

Figure 5. Flow net distribution at H =1.0 m, K = 1×10^{-7} m/sec, d =12.0m, a =0.1m, and h =6.0m for sheet pile with slot

Table 2. Discharge under the steel sheet pile without slot

d (m)	q (×10^{-7}) (m^3/s/m)
8.0	0.80
10.0	0.72
12.0	0.66
14.0	0.61
16.0	0.56

Table 3. Discharge through slot and under the steel sheet pile with slot

d (m)	h (m)	q_{in} (×10^{-7}) (m^3/s/m)	q_{und} (×10^{-7}) (m^3/s/m)	q_{tot} (×10^{-7}) (m^3/s/m)
8.0	2.0	0.42	0.72	1.14
	3.0	0.37	0.70	1.07
	4.0	0.30	0.69	0.99
	5.0	0.27	0.68	0.95
	6.0	0.21	0.68	0.89
	7.0	0.17	0.68	0.85
10.0	2.0	0.44	0.66	1.10
	3.0	0.40	0.64	1.04
	4.0	0.32	0.64	0.96
	5.0	0.29	0.62	0.91
	6.0	0.25	0.62	0.87
	7.0	0.23	0.61	0.84
	8.0	0.18	0.61	0.79
	9.0	0.14	0.62	0.76
12.0	2.0	0.45	0.61	1.06
	3.0	0.40	0.59	0.99
	4.0	0.34	0.59	0.93
	5.0	0.31	0.58	0.89
	6.0	0.27	0.57	0.84
	7.0	0.25	0.56	0.81
	8.0	0.22	0.56	0.78
	9.0	0.20	0.56	0.76
	10.0	0.16	0.56	0.72
	11.0	0.13	0.56	0.69
14.0	2.0	0.45	0.57	1.02
	3.0	0.41	0.55	0.96
	4.0	0.34	0.54	0.88
	5.0	0.32	0.53	0.85
	6.0	0.28	0.53	0.81
	7.0	0.27	0.52	0.79
	8.0	0.24	0.52	0.76
	9.0	0.22	0.51	0.73
	10.0	0.19	0.51	0.70
	11.0	0.18	0.51	0.69
	12.0	0.15	0.51	0.66
	13.0	0.12	0.52	0.64
16.0	2.0	0.46	0.53	0.99
	3.0	0.42	0.51	0.93
	4.0	0.35	0.51	0.86
	5.0	0.33	0.50	0.83
	6.0	0.29	0.49	0.78
	7.0	0.28	0.48	0.76
	8.0	0.25	0.48	0.73
	9.0	0.24	0.47	0.71
	10.0	0.21	0.47	0.68
	11.0	0.20	0.47	0.67
	12.0	0.18	0.47	0.65
	13.0	0.17	0.47	0.64
	14.0	0.14	0.47	0.61
	15.0	0.11	0.48	0.59

6. SEEPAGE THROUGH STEEL SHEET PILE WITH SLOT

The effects of sheet pile defects on seepage quantities are calculated and analyzed. The SEEP/W contour function allows one to graphically view the results by displaying flow net that represent the equipotential lines and streamlines, as shown in Figure 5. Figure 5 presents the equipotential and streamlines with a head difference of 1.0m, hydraulic conductivity equals 1×10^{-7} m/sec, and the depth of the sheet pile equals 12.0m in SEEP/W module, whereas the breadth of the slot is 0.1m and the center of the slot at a depth equals 6.0m below the ground.

The discharge through the slot q_{in} and the discharge under the sheet pile q_{und} are determined from the SEEP/W module then it can be calculated the total discharge q_{tot}. Whereas the total discharge equals the sum of the discharge through the slot and the discharge flow under the sheet pile. The discharge through the slot q_{in}, the discharge under the sheet pile q_{und} and the total discharge q_{tot} are listed in Table 3.

7. COMPRISON BETWEEN SEEPAGE THROUGH STEEL SHEET PILE WITH AND WITHOUT SLOT

The discharge through the slot q_{in} and the discharge under the sheet pile q_{und} are determined from the SEEP/W module then it compared with the discharge for the case without slot. The seepage flow discharge, q computed from SEEP/W for steel sheet pile without slot is less than the total discharge in case of presented slot.

Figure 6 shows the correlation between the relative depth ($h^* = h/d$) and the relative total discharge ($q^*_{tot} = q_{tot}/q$) at a constant head value H of 1.0m, hydraulic conductivity K equals 1×10^{-7} m/s, and slot dimensions 1.0m × 0.1m for varied relative sheet pile depth ($d^* = d/D$).

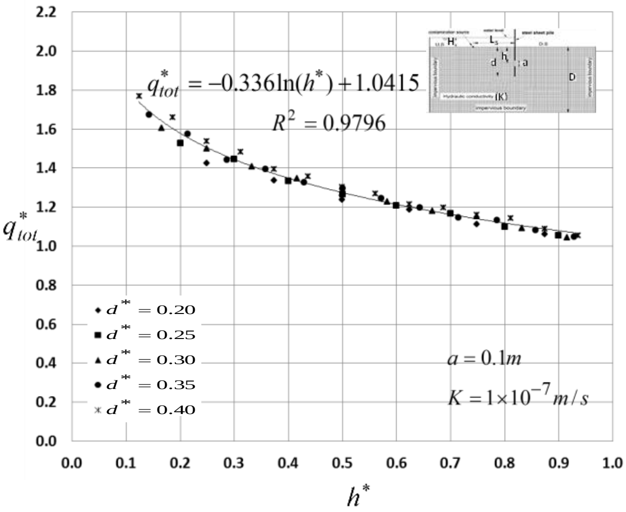

Figure 6. Correlation between the relative depth h^* and the relative total discharge q^*_{tot} for H =1.0m

From the results it can be noticed the presence of the slot leads to an increased in the seepage flow for a specified both of breadth of the slot, difference head, and hydraulic conductivity with any depth of the sheet pile. Figure 6 shows that, for a given value of the hydraulic conductivity and slot breadth, the relative total discharge increases with the decrease of the relative depth for slot. When the slot is near to the ground surface, the seepage is increasing by approximately 80%. While the slot depth from the ground surface approximate to 0.8, the seepage is increasing by approximately 10%. The correlation between the relative total discharge and relative depth of the slot from the ground surface is a polynomial with a correlation coefficient 0.9796 and can be expressed as:

$$q^*_{tot} = -0.336\ln(h^*) + 1.0415 \quad (2)$$

Where q^*_{tot} = the relative total discharge, and h^* = relative depth.

Equation (2) is a suitable equation for correlation between relative total discharges versus the relative depth of the slot below the ground, for different values of the sheet pile depths, constant head value H of 1.0m, hydraulic conductivity K equals 1×10^{-7} m/sec and slot dimensions 1.0m × 0.1m. The comparison between the related total discharge computed from Eq. (2) with the determined from the SEEP/W program are listed in Table 4 according to the values of the relative total discharge obtained from the program and the values calculated from Equation (2). The error percentage was calculated in the following equation:

$$error\% = \frac{(q^*_{tot})_{pro} - (q^*_{tot})_{cal}}{(q^*_{tot})_{pro}} \times 100 \quad (3)$$

Where $(q^*_{tot})_{pro}$ = the relative total discharge determined from the SEEP/W module, and $(q^*_{tot})_{cal}$ = the relative total discharge calculated using Eq. (2).

With the known of the depth of the center of the slot below the ground h and slot dimensions 1.0m × 0.1m, the value of relative total discharge can be calculated by using Eq. (2) with maximum error 5.78% than the relative total discharge computed by the SEEP/W program, Table 4.

Figure 7 presents the correlation between the relative depth, h^* versus the ratio of slot discharge to total discharge ($q^*_{in} = q_{in}/q_{tot}$) for hydraulic conductivity, K equals 1×10^{-7} m/s, slot dimensions 1.0m × 0.1m and difference head between upstream and downstream, H equals 1.0m for different values of relative sheet pile depth, d^*. Figure 7 shows that as the relative depth increases, the ratio of slot discharge to total discharge decreases at a constant value of both hydraulic conductivity and slot breadth.

Table 4. Comparison of relative total discharge between the values from the program and values from the derived equation

(d^*)	(h^*)	$(q^*_{tot})_{pro}$	$(q^*_{tot})_{cal}$ **Eq. (2)**	**Error percentage (%)**
0.20	0.25	1.43	1.507	-5.775
	0.38	1.34	1.371	-2.509
	0.50	1.24	1.274	-2.982
	0.63	1.19	1.199	-1.004
	0.75	1.11	1.138	-2.307
	0.88	1.06	1.086	-2.246
0.25	0.20	1.53	1.582	-3.567
	0.30	1.44	1.446	-0.110
	0.40	1.33	1.349	-1.203
	0.50	1.26	1.274	-0.831
	0.60	1.21	1.213	-0.398
	0.70	1.17	1.161	0.456
	0.80	1.10	1.116	-1.755
	0.90	1.06	1.077	-2.022
0.30	0.17	1.61	1.644	-2.333
	0.25	1.50	1.507	-0.486
	0.33	1.41	1.411	-0.109
	0.42	1.35	1.336	0.951
	0.50	1.27	1.274	-0.131
	0.58	1.23	1.223	0.381
	0.67	1.18	1.178	0.345
	0.75	1.15	1.138	1.160
	0.83	1.09	1.103	-1.086
	0.92	1.05	1.071	-2.418
0.35	0.14	1.67	1.695	-1.387
	0.21	1.57	1.559	0.933
	0.29	1.44	1.462	-1.373
	0.36	1.39	1.387	0.430
	0.43	1.33	1.326	0.126
	0.50	1.30	1.274	1.597
	0.57	1.25	1.230	1.314
	0.64	1.20	1.190	0.565
	0.71	1.15	1.155	-0.611
	0.79	1.13	1.123	0.762
	0.86	1.08	1.093	-1.047
	0.93	1.05	1.066	-1.641
0.40	0.13	1.77	1.740	1.565
	0.19	1.66	1.604	3.418
	0.25	1.54	1.507	1.851
	0.31	1.48	1.432	3.362
	0.38	1.39	1.371	1.565
	0.44	1.36	1.319	2.791
	0.50	1.30	1.274	2.238
	0.56	1.27	1.235	2.606
	0.63	1.21	1.199	1.224
	0.69	1.20	1.167	2.427
	0.75	1.16	1.138	1.943
	0.81	1.14	1.111	2.764
	0.88	1.09	1.086	0.268
	0.94	1.05	1.063	-0.912

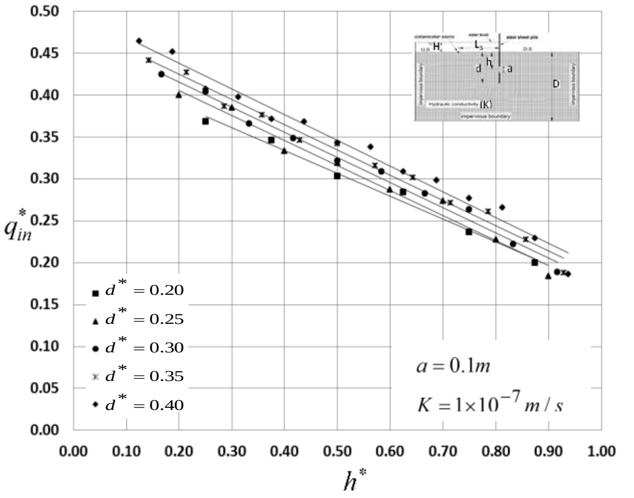

Figure 7. Correlation between the relative depth h^* and ratio of slot discharge to total discharge q^*_{in} for H =1.0m

When the relative sheet pile depth, d^* increase while maintaining a constant value for the slot breadth, a , the ratio of slot discharge to total discharge increases. If the slot gets closer to bottom of the sheet pile, the discharge passes through the slot decrease and the under discharge get the maximum flow. The best fit for the curve between the relative depth and the ratio of slot discharge to total discharge is linear form. When the relative depths of the sheet pile are 0.20, 0.25, 0.30, 0.35, and 0.40, the correlation coefficient (R^2) values vary from 0.9796 to 0.9893 as shown in Table 5. The linear form for the curve between the relative depth and the ratio of slot discharge to total discharge can be written as:

$q^*_{in} = a_1.h^* + b_1$ …………………………….…………..…… (4)

Where q^*_{in} = ratio of slot discharge to total discharge, a_1 and b_1 = constants

From Figure 7, it can be seen that with the increase in the relative depth, the ratio of slot discharge to total discharge, q^*_{in} decrease, until the relative depth, h^* reaches 0.9, the ratio of slot discharge to total discharge remain constant.

Table 5 contains the constants a_1 and b_1 values in Equation (4) for relative sheet pile depth at the constant head and hydraulic conductivity. From Table 5, it is clear that the values of constant, a_1 are negative and range from -0.2721 to -0.3069, but the values of constant, b_1 are positive and vary from 0.4426 to 0.4993.

Figure 8 shows the correlation between the relative depth, h^* and the relative slot discharge ($q^{**}_{in} = q_{in}/q$) for varied relative sheet pile depth d^* with a constant head value H of 1.0m and a slot breadth a of 0.1m. From the figure it can be noticed that, for a given value of the hydraulic conductivity and slot breadth, the relative slot discharge, q^{**}_{in} decreases as the relative depth, h^* increases. When the relative sheet pile depths increase while the slot breadth remains constant, the relative slot discharge increases. From Figure 8, it can be seen that, the relation between the relative depth and the relative slot discharge is presented in the following empirical equation:

$q^{**}_{in} = a_2.\ln h^* + b_2$ ………...………………...………..… (5)

Where q^{**}_{in} = the relative slot discharge, a_2 and b_2 = constants

Based on Equation (5), when the relative sheet pile depth varies between 0.20 and 0.4, the relation between the relative slot discharge and the relative depth is logarithmic with a negative value of the constant, a_2 varying from -0.2510 to -0.2990 and positive values of the constant, b_2 ranging from 0.1975 to 0.2301. The values of constant variables a_2 and b_2 for Equation (5) and the correlation coefficients are listed in Table 6.

Table 5. Values derived from the correlation between the relative depth and the ratio of slot discharge to total discharge at relative sheet pile depths

(d^*)	(a_1)	(b_1)	(R^2)
0.20	-0.2721	0.4426	0.9882
0.25	-0.2981	0.4652	0.9806
0.30	-0.2998	0.4752	0.9893
0.35	-0.3011	0.4849	0.9859
0.40	-0.3069	0.4993	0.9796

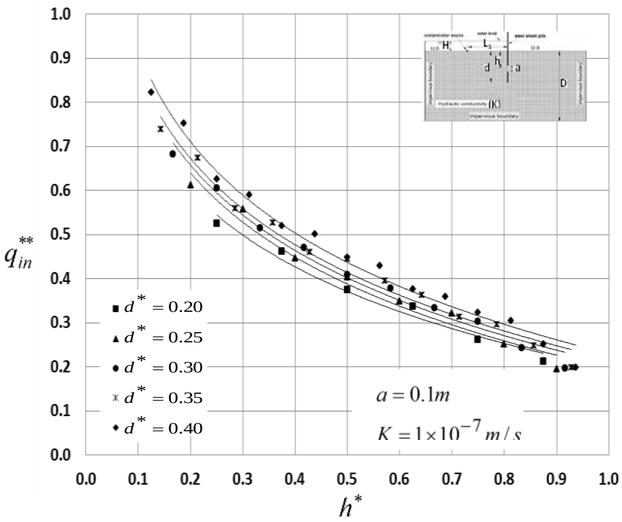

Figure 8. Correlation between the relative depth h^* and the relative slot discharge q^{**}_{in} for H =1.0m

Table 6. The results of the relation between the relative depth and the relative slot discharge with varying relative sheet pile depth

(d^*)	(a_2)	(b_2)	(R^2)
0.20	-0.2510	0.1975	0.9761
0.25	-0.2750	0.1977	0.9752
0.30	-0.2790	0.2088	0.9841
0.35	-0.2820	0.2185	0.9828
0.40	-0.2990	0.2301	0.9846

8. COMPARISON BETWEEN SEEPAGE UNDER STEEL SHEET PILE WITH AND WITHOUT SLOT

Figure 9 presents the correlation between the relative depth, h^* and the relative under discharge ($q^*_{und} = q_{und}/q$) for varied relative sheet pile depth, d^* with a constant head value

H of 1.0m and a slot breadth a of 0.1m. Figure 9 indicates that, for a given value of the hydraulic conductivity and slot breadth, the relative under discharge decreases at a very small rate as the relative depth increases and the values are pretty much the same, although the variations of the relative sheet pile depth. From Figure 9, it can be seen that, the relation between the relative depth and the relative under discharge is polynomial with a correlation coefficient 0.9386 according to the following equation:

$$q^*_{und} = 0.2474(h^*)^2 - 0.3667h^* + 0.9789 \quad \text{……………..…} \quad (6)$$

Where q^*_{und} = the relative under discharge

It is noticed that Equation (6) is suitable for each values of the sheet pile depths with the variation of the relative depth of the slot h^* at a constant head value H of 1.0m, slot breadth of 0.1m, and hydraulic conductivity equals $1{\times}10^{-7}$ m/sec by an error don't exceed 1.922 % as calculated in Table 7 according to the values of the relative under discharge obtained from the program and values calculated from Equation (6).

The error percentage was calculated in the following equation:

$$error\% = \frac{(q^*_{und})_{pro} - (q^*_{und})_{cal}}{(q^*_{und})_{pro}} \times 100 \quad \text{……………..….} \quad (7)$$

Where $(q^*_{und})_{pro}$ = the relative under discharge from the program, and $(q^*_{und})_{cal}$ = the relative under discharge calculated from Equation (6).

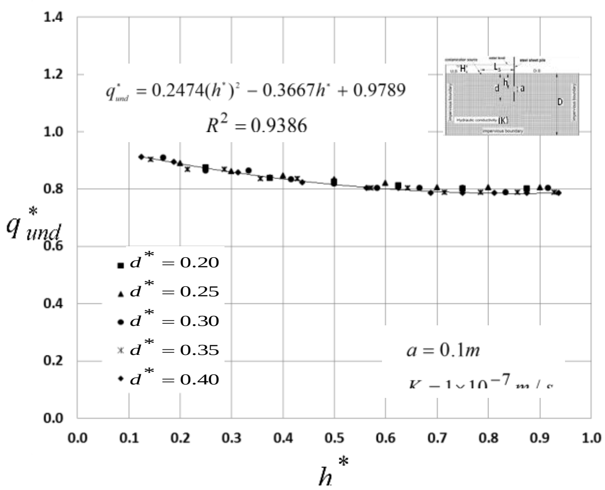

Figure 9. Correlation between the relative depth h^* and the relative under discharge q^*_{und} for H =1.0m

9. CONTAMINATION TRANSPORT THROUGH THE STEEL SHEET PILE WITHOUT SLOT

For a certain value of the head difference equals 1.0m, hydraulic conductivity equals $1{\times}10^{-7}$ m/s, the distance between the contamination source point which equals 10000 g/m^3 from the sheet pile, L_S equals 10.0m, and the sheet pile depth equals 12.0m the arrival times, t_1 are listed in Table 8. The time t_1, which is determined by iteration as the time gives a 5% of the contaminant concentration to move from the contamination source to downstream of the sheet pile without slot. The model's run duration begins at 0.0 day and ends at 90000 days, with a total of 400 steps. The longitudinal dispersivity was approximately doubled to the transverse dispersivity. The arrival time for the present case, t_1 equals 51300 days as presented in Figure 10.

Table 7. Comparison of relative under discharge between the values from the program and values from the derived equation

(d^*)	(h^*)	$(q^*_{und})_{pro}$	$(q^*_{und})_{cal}$ **Eq. (6)**	**Error percentage (%)**
0.20	0.25	0.900	0.903	-0.299
	0.38	0.875	0.876	-0.135
	0.50	0.863	0.857	0.591
	0.63	0.850	0.846	0.429
	0.75	0.850	0.843	0.819
	0.88	0.850	0.847	0.300
0.25	0.20	0.917	0.915	0.132
	0.30	0.889	0.891	-0.255
	0.40	0.889	0.872	1.922
	0.50	0.861	0.857	0.431
	0.60	0.861	0.848	1.529
	0.70	0.847	0.843	0.447
	0.80	0.847	0.844	0.395
	0.90	0.861	0.849	1.376
0.30	**0.17**	0.924	0.925	-0.045
	0.25	0.894	0.903	-0.979
	0.33	0.894	0.884	1.094
	0.42	0.879	0.869	1.107
	0.50	0.864	0.857	0.722
	0.58	0.848	0.849	-0.082
	0.67	0.848	0.844	0.483
	0.75	0.848	0.843	0.642
	0.83	0.848	0.845	0.396
	0.92	0.848	0.851	-0.254
0.35	**0.14**	0.934	0.932	0.306
	0.21	0.902	0.912	-1.114
	0.29	0.885	0.894	-1.026
	0.36	0.869	0.879	-1.225
	0.43	0.869	0.867	0.192
	0.50	0.852	0.857	-0.580
	0.57	0.852	0.850	0.272
	0.64	0.836	0.845	-1.117
	0.71	0.836	0.843	-0.853
	0.79	0.836	0.844	-0.890
	0.86	0.836	0.846	-1.230
	0.93	0.852	0.852	0.088
0.40	**0.13**	0.946	0.937	1.004
	0.19	0.911	0.919	-0.892
	0.25	0.911	0.903	0.881
	0.31	0.893	0.888	0.492
	0.38	0.875	0.876	-0.135
	0.44	0.857	0.866	-1.013
	0.50	0.857	0.857	-0.030
	0.56	0.839	0.851	-1.385
	0.63	0.839	0.846	-0.842
	0.69	0.839	0.844	-0.529

	0.75	0.839	0.843	-0.447
	0.81	0.839	0.844	-0.595
	0.88	0.839	0.847	-0.973
	0.94	0.857	0.853	0.535

Table 8. Time for contaminant to reach downstream steel sheet pile without slot

d (m)	t_1 (days)
8.0	31625
10.0	40250
12.0	51300
14.0	64575
16.0	79875

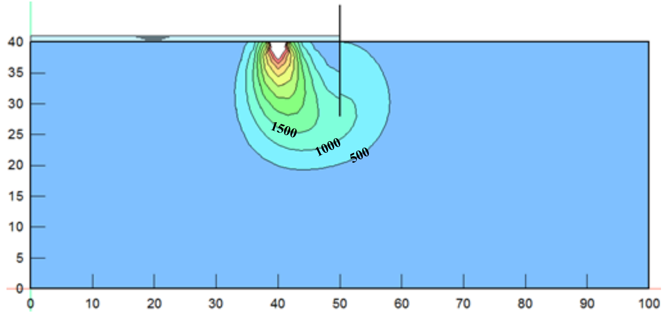

Figure 10. Contamination concentration and distribution at H = 1.0m, L_S =10.0m, d =12.0m, and t_1 = 51300 days for solid steel sheet pile

10. CONTAMINATION TRANSPORT THROUGH THE STEEL SHEET PILE WITH SLOT

Figure 11 shows the effect of the slot in the sheet pile on the contamination distribution at the finite element layout in the CTRAN/W module with a head difference, H of 1.0m, hydraulic conductivity, K equals 1×10^{-7} m/sec, the depth of the sheet pile, d equals 12.0m with the breadth of the slot, a equaling 0.10m, the center of the slot at a depth, h equals 6.0m below the ground. Distance, L_S between the contamination source points with concentration equals 10000 g/m^3 far from the sheet pile equals 10.0m. For all runs, the time of the contamination arriving downstream was calculated, which is the time of the contamination passing through the slot, t_2 are presented in Table 9 with 5.0% concentration to the soil surface downstream of the sheet pile which equals 29025 days. Figure 12 presents the correlation between the relative depth, h^* and the relative time through the slot,($t_2^* = t_2/t_1$). Also, the figure shows that the relative time through the slot, t_2^* increases with an increase in the relative depth, h^*.

While the slot breadth remains constant, the relative time through the slot, t_2^* decreases as the relative sheet pile depths, d^* increase. The correlation between the relative depth and the relative time through the slot, whereas minimum and maximum values for the correlation coefficient are 0.9385 and 0.9903, respectively is expressed as:

$$t_2^* = a_3.(h^*)^2 - b_3.h^* + c_3 \quad (8)$$

Where t_2^* = the relative time through the slot, and a_3, b_3, and c_3 = constants.

According to Equation (8), the correlation between the relative time through the slot and the relative depth is polynomial when the relative sheet pile depths varies between 0.20 and 0.4. The constant a_3 is a positive value varies from 1.1732 to 2.6561 and the constant b_3 is negative values ranging from -0.6463 to -3.4751, and the constant c_3 is positive value and differ from 0.4746 to 1.8901. The constant values a_3, b_3, and c_3 for Equation (8) for the constant head H and the hydraulic conductivity K for the relative sheet pile depth d^* are shown in Table 10.

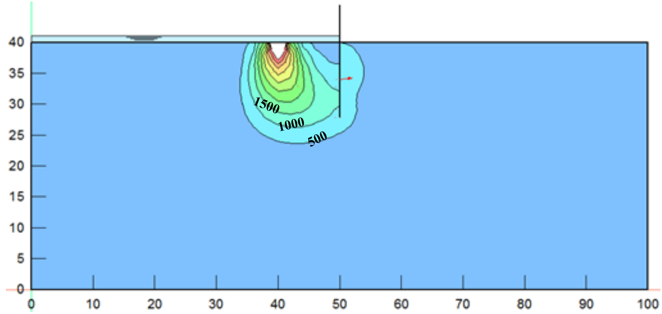

Figure 11. Contamination concentration and distribution at H = 1.0m, a = 0.10m, L_S =10.0m, d =12.0m, h = 6.0m, and t_2 = 29025 days

Table 9. Time for contaminant to reach downstream steel sheet pile with slot

d (m)	h (m)	t_2 (days)	d (m)	h (m)	t_2 (days)
8.0	2.0	38375	14.0	2.0	71325
	3.0	32250		3.0	58725
	4.0	26000		4.0	33750
	5.0	23375		5.0	28800
	6.0	25125		6.0	29925
	7.0	27750		7.0	31500
10.0	2.0	47000		8.0	34650
	3.0	38500		9.0	37575
	4.0	29750		10.0	42300
	5.0	26250		11.0	45225
	6.0	27500		12.0	51075
	7.0	28000		13.0	56925
	8.0	31375	16.0	2.0	86625
	9.0	34750		3.0	63225
12.0	2.0	58275		4.0	33750
	3.0	48600		5.0	29025
	4.0	31725		6.0	30150
	5.0	28350		7.0	31875
	6.0	29025		8.0	35500
	7.0	29875		9.0	38625
	8.0	33375		10.0	43375
	9.0	35375		11.0	47750
	10.0	39875		12.0	53200
	11.0	44875		13.0	57200
				14.0	64000
				15.0	71400

Table 10. Results of the relation between the relative depth and the relative time through the slot when the relative sheet pile depth varies at a constant distance from the sheet piles to the contamination source

(d^*)	(a_3)	(b_3)	(c_3)	(R^2)
0.20	2.6561	-3.4751	1.8901	0.9385
0.25	1.9022	-2.1827	1.2951	0.9554
0.30	1.5869	-1.5040	0.9262	0.9844
0.35	1.3607	-1.0264	0.6709	0.9827
0.40	1.1732	-0.6463	0.4746	0.9903

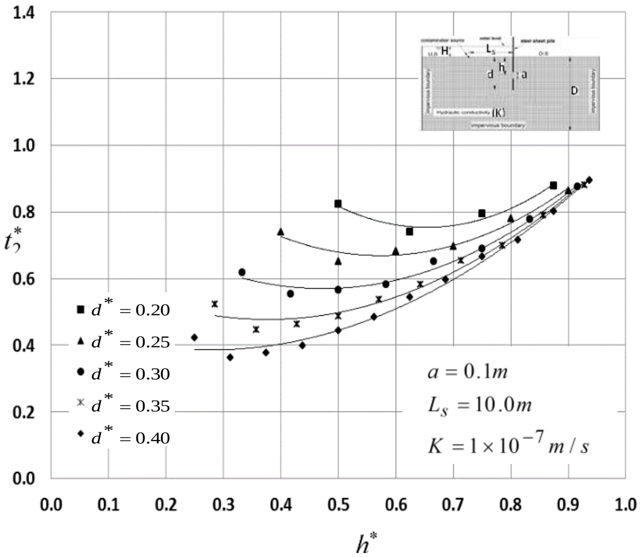

Figure 12. Correlation between the relative depth h^* and the relative time t_2^* through the slot for H =1.0m

11.CONCLUSIONS

Through the numerical analysis in the (SEEP/W) and (CTRAN/W) modules to demonstrate the effect of the defects on the seepage characteristics and contaminant concentration and distribution with using the steel sheet piles, the following conclusions are stated:

1. For a single steel sheet pile with slot, the total flux increased than the total flux for steel sheet pile without slot.
2. Flow through slot was highly dependent on the sheet pile depth and the place of the slot under the ground surface.
3. Increasing the depth of slot down the ground surface leads to reduction both values of the discharge through slot and discharge under the sheet pile.
4. Trending equation for total seepage discharge in case of various steel sheet pile depths with slot in polynomial correlation has a coefficient of determination 0.9796, Eq. (2), with maximum error 5.78 % was recommended.
5. Also, suggested equation for seepage discharge under the slot sheet pile with various depths in polynomial correlation has a coefficient of determination 0.9386, Eq. (6), with maximum error 1.922 %.
6. Comparing the state of the presence of slot with the absence of it, different behaviors with different characteristics of seepage will appear at different percentage. Also decrease the depth of the slot from ground increase seepage discharge as well as accelerate the contaminant transport to arrive the downstream ground through the slot.
7. Suggested an empirical equation for calculating the traveling time of contaminant through the slot in polynomial correlation formula has coefficients of determination values vary between 0.9385 and 0.9903, Eq. (8).

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