3D Seepage under Hydraulic Structures Provided with Intermediate Filters

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Abstract

Seepage flow under hydraulic structures provided with intermediate filters has been investigated. The flow through the banks of the canal has been included in the model. Different combinations of intermediate filter and canal width were studied. Different lengths of the floor, differential heads, and depths of the sheetpile driven beneath the floor were also investigated. It was found that the introduction of an intermediate filter to the floor of hydraulic structures reduced the uplift force acting on the downstream floor by up to 72%. The maximum uplift reduction occurred when the distance of filter location downstream the cutoff to the differential head ratio was 1. Introducing a second filter in the downstream side resulted in a further reduction in the exit hydraulic gradient and in the uplift force, which reached 90%. The optimum locations of the two filters occurred when the first filter was placed just downstream the cutoff wall and the second filter was placed nearly at the mid-distance between the cutoff and the end toe of the floor. The results showed significant differences between the three-dimensional (3D) and the two-dimensional (2D) analyses.

Keywords: Weirs; Regulators; Dams; Control structures; Mathematical modeling; Intermediate filters

Introduction

Hydraulic structures are used to control the flow of water in rivers and canals. It is necessary to minimize the uplift pressures and hydraulic gradients beneath such structures to prevent flotation, to ensure their structural stability, and to design against soil piping and consequent undermining of the structure. It is common to install cutoff walls beneath the floors of hydraulic strictures to reduce the seepage flow. In addition, intermediate filters are often provided in the floor of the structure as a further measure to reduce the uplift forces and exit hydraulic gradients. The effectiveness of these filters in reducing uplift forces has been analyzed using analytical methods.

Conformal mapping has been used to produce exact solutions for the problem of 2D seepage beneath a hydraulic structure with a flat floor having two end cutoffs and a filter located at various positions in the floor (Chawla 1975; Kumar et al. 1986). Elganainy (1986) presented a solution for the problem of seepage beneath two structures with intermediate filter built on two pervious strata. Hathoot (1986) used the Schwartz-Christoffel transformation to solve the problem of seepage beneath a concrete dam with a downstream filter.

The case of 2D seepage flow beneath a hydraulic structure provided with two intermediate filters was also studied using conformal mapping (Farouk and smith 2000). Salem et al. (2001) used the Schwartz-Christoffel transformation to examine the stability of two consecutive floors with intermediate filter. The two consecutive floors represent a subsidiary weir constructed downstream of a barrage, a scheme which is equivalent to a physical situation resulting from the construction of subsidiary weirs downstream of barrages on the Nile river in Egypt.

Several studies conducted 3D numerical analysis to analyse the problem of seepage under hydraulic structures. Griffiths and Fenton (1997) studied 3D seepage through spatially random soil. The 3D results compared favorably with the 2D results for the same structure. More recently, Ahmed et al. (2007) studied the problem of 3D seepage under hydraulic structures with leakage through the sheetpiles. A limitation in these studies was that they have not considered the seepage flow through the canal banks. Studies carried out by Ahmed and Bazaraa (2009) and Ahmed (2011) showed that neglecting the seepage flow through the banks of a canal resulted in errors in the seepage calculations.

The problem of 3D seepage beneath a hydraulic structure with a floor provided with an intermediate filter has not been investigated before. In this study, the effect of one and two intermediate filters on the development of uplift forces and exit hydraulic gradients at the downstream edge of a hydraulic structure has been analyzed. A number of analyses were carried out to investigate the effect of filter length, filter location and the introduction of a second filter on the development of uplift forces and exit hydraulic gradients. The analysis was carried out for various canal widths. Seepage through the canal banks was taken into account and the unsaturated flow above the free surface was considered.

The Finite Element Model and the Analysis procedure

The model deals with both confined and free surface flow problems. A detailed presentation of this computer program, and its validation and applications can be found in Ahmed (2008, 2009). The program uses the model of van Genuchten (1980) to include the unsaturated flow.

Fig 1 illustrates an isometric view of the configuration studied; a hydraulic structure constructed upon a pervious homogeneous isotropic soil of depth 6m and hydraulic conductivity k=3 x 10^{-5} m/s. The van Genuchten curve fitting parameters were taken $\alpha = 14.5$ m^{-1} and n=2.68. The structure includes the floor, the side retaining walls and the structure built above the floor, all of which are considered to be impervious. A sheetpile cutoff driven to a depth of 4 m under the structure was represented. Different sheetpile depths were also investigated. The length of the modeled zone was 60 m and the upstream and downstream edges of the zone were considered to be impermeable. A differential head of H=1 m between the upstream and downstream sides of the structure produced the seepage flow. The ratio of the floor length to differential head L/H was 16. Other ratios of L/H=20 and 24 were also investigated. The top of the banks was 2 m above the bed of the canal.

The finite element mesh used for the problem has a total of 10878 nodes and 9184 brick elements. Only one half of the problem was simulated because of its symmetry about the canal centerline. A 2D analysis was carried out on each case and the values of uplift forces and the exit hydraulic gradient acting on the downstream side of the structure were calculated. The problem was then studied in 3D for varying ratios of canal width to differential head W/H from 2 to 14. For each W/H ratio, scenarios of no filter, one filter, and two filters were analyzed. If *x* denotes the distance from the cutoff to the filter location (see Fig 1), the problem was studied for the ratio *x/H* varying from 1 to 6 for both the one and two filters scenarios. A comparison of the 2D and 3D results was carried out for each case.

Results and Discussion of One Intermediate Filter

The Effect of the Filter Location

Fig 2 presents different sections perpendicular to the canal centerline showing the free surface positions both upstream and downstream sides of the floor. As expected, the water flows out from the canal into the banks in the upstream side and then flows from the banks into the canal on the downstream side. It is therefore important to take the flow through the banks into consideration. Modelling this problem in 2D (e.g. Chawla 1975, Farouk and smith 2000) or in 3D without considering the flow through the banks has not provided accurate analysis that can be used in the design of the structure. The free surface at a distance of 10 m upstream and downstream of the structure was nearly flat.

Fig 3 presents the average uplift forces on the floor, when there was one filter, for different ratios of *W/H*. The filter location was measured from the sheet pile cutoff to the upstream edge of the filter. The uplift force shown in the figure is normalized relative to the case of no filter in place. The introduction of a filter to the floor of the structure, regardless of its location, significantly reduced the uplift force developed under the floor. The smallest reduction in uplift force occurred when *W/H*= 2 where the reductions varied from 56% to 33% as *x/H* varied from 1 to 6, respectively. As the ratio *W/H* increased, the potential for uplift reduction also increased. For *W/H*=14, the reduction in uplift force varied from 72% to 35% as the ratio *x/H* varied from 1 to 6, respectively. For *x/H* =1 to 2, only slight or no change was observed in the uplift force.

The greatest reduction in the uplift force occurred when *x/H*=1. This is because the uplift pressure is higher just downstream the cutoff than at any other point in the downstream side. The filter intercepts some of the streamlines and hence breaks the development of the uplift pressure. The above results in Fig 3 mean that placing a filter at this position will have a greater impact than at any other position.

Fig 4 presents the exit hydraulic gradients along the canal width for different filter locations. The exit hydraulic gradient calculated at the center of the canal was smaller than its value at the canal edge because of the water seepage through the banks. The water flows through the banks at a faster rate than below the structure. This is attributed to the existence of sheet pile below the floor that increases the travelling distance of the flowing water. Fig 4 shows again the importance of undertaking a 3D analysis of seepage problems since the exit hydraulic gradient obtained from the 2D analysis is that for the canal center. The 2D analysis also disregards seepage through the canal banks.

Fig 5 illustrates the impact the filter location had on the exit hydraulic gradient observed at the edge and at the centerline of the canal. All filter locations with *x/H*= 1 to 5 had little effect on the exit hydraulic gradient. A filter placed with *x/H* = 6 was found to further reduce the exit gradient. This happened both at the edge and at the center of the canal. However, the exit hydraulic gradient for all of these locations was reduced compared to the case of no filter in place. The main reason for this reduction in exit gradient is because the filter intercepts some streamlines. Both the central and edge exit hydraulic gradients calculated using the 3D model were greater than the value obtained from the 2D model. As the W/H ratio increased from 2 to 14, the central exit hydraulic gradient decreased and became comparable to the results of the 2D model.

The Effect of Filter Length

The effect of the filter length on the uplift pressure developed beneath the floor was analyzed using W/H ratios of 8 and 12. The filter length is taken as the dimension in the longitudinal direction of the canal. The results of this analysis are shown in Fig. 6. Increasing the length of the filter reduced the uplift force further; however the magnitude of this reduction was not significant when compared with the reduction produced from placing the filter in the downstream side.

Obviously, the existence of a filter, even with small length, is still able to break the development of the uplift pressure on the downstream floor. Hence, the increase in the filter length did not lead to a significant further reduction in the uplift force. These findings confirm those of Chawla (1975), and Farouk and Smith (2000). Increasing the filter length caused a small reduction in the exit hydraulic gradient at the edge and at the center of the canal.

Different Depths of Sheetpile

In addition to the 4 m deep sheetpile presented in Figs 3, and 5, a depth of the sheetpile cutoff of 2 m was tested for different locations of the intermediate filter. The percentage reductions in the exit gradient, and uplift force made by the filter for this case were similar to the percentage reductions made by the 4 m sheetpile. The only difference was that the absolute values of the uplift force and the exit gradient obtained were slightly greater than the values obtained for 4 m deep sheetpile.

Results and Discussion of Two Intermediate Filters

The provision of a second filter to the floor of the structure reduced the uplift force beneath the floor significantly (Fig 7). The greatest reduction in the uplift force occurred when the two filters were located at *x/H* =1 and 4. For these two filter locations, the maximum reduction in the uplift force was 80% when *W/H* =2. Increasing *W/H* to 14 led to reduction in the uplift force by 90%.

The optimum position of the filters downstream of the sheet pile cutoff changed as the floor length to differential head ratio *L/H* varied (Fig 8). When *L/H* was increased to 24, the optimum locations of the filters occurred at ratios of *x/H* of 1 and 5.

The downstream floor can be considered as three sections for analysis. Pore water pressure develops on the first section between the cutoff and the first filter. The first filter then intercepts some of the flow lines preventing the build-up of pore pressure along its length. Pore water pressure increases on the second section of the floor between the two filters. The second filter reduces the pore water pressure along its length and the pore water pressure increases again over the third section of the floor between the second filter and the downstream edge. The total pressure on the floor is less than the total pressure that is developed with either one or no filter in place.

Comparison with 2D Results

The uplift force calculated using the 3D model was comparable to its 2D value when W/H > 10 as shown in Fig 7. When W/H <10, the uplift force resulting from the 3D model was greater than that obtained from the 2D solution. When W/H <10, the seepage flow through the banks is significant compared to the flow beneath the floor, which is always reduced by one or more rows of cutoff walls that are usually driven below the floor. This may be the reason behind the increased 3D uplift force for narrow canals.

In the 3D flow, the unsaturated flow through the banks may play a role in the difference between 2D and 3D results. For the 2D analysis of this problem, the flow is confined, and hence only saturated flow is considered. However, for the problem investigated in this research, the unsaturated flow was minimal. This may be attributed to the soil type used in the current analysis, or the fact that the free surface was only 1 m below the top level of the bank. The effect of unsaturated flow in 3D flow problems under hydraulic structures needs further investigations for different soil types, and different structures configurations.

Comparison between One- and Two-Intermediate Filters

Table 1 shows the reduction in total uplift pressure for the one- and two-filters scenarios. When one filter was used, the total uplift force acting on the downstream floor was reduced by between 56% and 72% compared with the uplift experienced when no filter was provided. As the W/H ratio increased the potential for uplift reduction increased. The introduction of a second filter to the floor reduced the uplift forces further. When both filters were positioned at their optimum locations the total uplift force acting on the downstream side of the floor was reduced by between 80% and 90% of the uplift forces calculated in the ‘no-filter’ scenario. This represents a further 25% decrease in uplift force when compared with the ‘one-filter’ scenario.

The edge and central exit hydraulic gradient from the one- and two-filters scenarios are compared in Fig 9. The maximum reduction in the exit hydraulic gradient occurred when the filters were located at x/H =2 and 6. When one filter was introduced, the exit gradient was reduced by between 41% and 45% at the canal edge, and by 50% to 65% at the center of canal for W/H ratios of 2 to 14, respectively. The introduction of a second filter reduced the edge exit hydraulic gradient by 50% to 73% for W/H ratios of 2 to 14, respectively. The central exit hydraulic gradient was reduced by between 57% and 81% when two intermediate filters were introduced to the floor of the structure. The reduction in exit gradient at the canal center is greater than the reduction at the canal edge. This can be attributed to the flow through the canal banks that makes the exit gradient at the canal edge less sensitive to the provision of intermediate filter in the floor, particularly when the ratio W/H was small, i.e. for narrower canals.

Differential Heads

The previous results were based on the differential head H= 1 m. A second value of the differential head H= 2 m was tested for the case of 'one-filter' when W/H=10. The results are presented in Table 2, which shows both the uplift force and the exit hydraulic gradient at the canal edge. The effect of different filter locations for H=2 m on uplift force and exit hydraulic gradient remained the same as in the case H=1 m. A small increase of about 3% in the exit hydraulic gradient occurred when H=2 m compared to when H=1 m. This may be attributed to the nonlinearity of the problem caused by the unconfined flow through the banks. However, the influence of the filter location remained the same for different values of H.

Conclusions

2D and 3D analyses were carried out to study the effect of intermediate filters on the development of downstream uplift force and exit hydraulic gradient beneath floors of hydraulic structures. A number of variables were investigated including filter location, filter length, and the number of filters introduced to the floor of the structure. Results have been obtained for varying ratios of canal width to differential head, and different ratios of floor length to differential head.

The use of one filter reduced the uplift forces developed beneath the floor of the structure. The optimum location of the filter occurred when *x/H*=1, and reductions in uplift force of between 55% and 72% were recorded. The reduction in uplift force increased as the canal width increased. Increasing the length of the filter reduced the uplift force; however, this was small in comparison to the reduction experienced due to the introduction of an intermediate filter.

The introduction of a second intermediate filter in the floor of the structure decreased both the uplift pressure and exit hydraulic gradients. When the two filters were positioned such that *x/H*=1 and 4, maximum reductions in uplift force of between 80% and 90% were obtained. It is recommended that to maximize the reduction of the uplift force, the first filter should be located just downstream of the cutoff and the second should be positioned half way between the cutoff and the downstream end of the floor.

The maximum reduction in exit hydraulic gradient occurred when the two filters were located at *x/H* =2 and 6. The introduction of a second filter reduced the edge exit hydraulic gradient by 50% to 73% for W/H ratios of 2 to 14, respectively. The central exit hydraulic gradient was reduced by between 57% and 81% when two intermediate filters were introduced to the floor of the structure.

Differences between the results calculated using the 2D and 3D analyses were identified. These differences occur because the 2D analysis does not consider seepage flow through the canal banks. If the increases in uplift pressure and exit hydraulic gradients are neglected at the design stage, it may result in the structure being under-designed and unstable. Results of the 2D and 3D models were found to be comparable only when the canal width to differential head ratio was greater than 10.

Acknowledgments

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Figures Captions

Fig 1. 3D view and cross section of the configuration studied

Fig 2. Free surface at different sections perpendicular to the canal centerline (W/H=10)

Fig 3. Effect of filter location on the downstream uplift force for different widths of the canal. The uplift force is normalized to the case of no filter in place.

Fig 4 Change of the exit gradient along the canal width. The exit hydraulic gradient is normalized to the case of no filter in place (W/H=10).

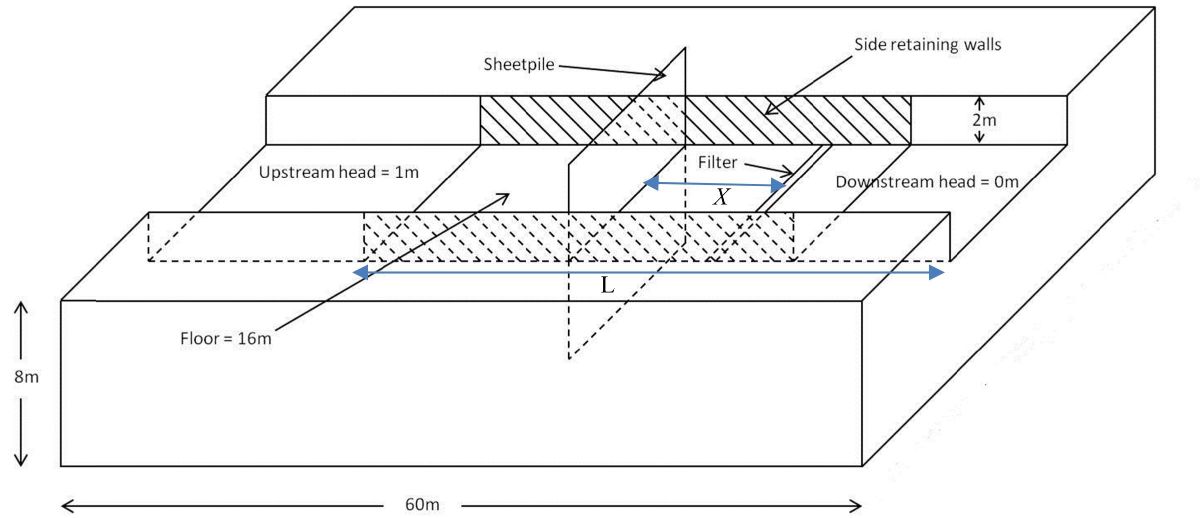
Fig. 5. Effect of filter location on the exit hydraulic gradient for different widths of the canal. The exit gradient is normalized to the case of no filter in place.

Fig. 6. Effect of filter length on uplift force. The uplift force is normalized to the case of no filter in place.

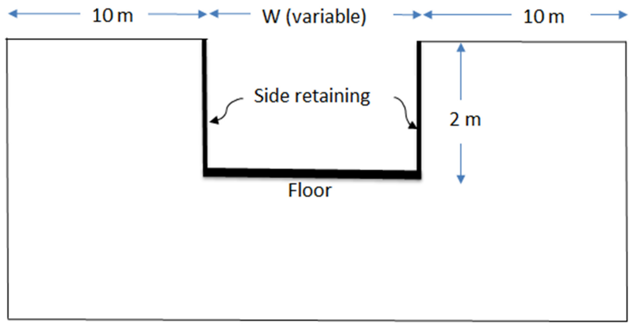
Fig. 7. Effect of introducing a second filter on uplift force developed beneath the floor of the structure.

Fig. 8. Reduction in uplift force for various filters locations and varying floor length.

Fig.9. Reduction in the exit hydraulic gradient for one- and two-filter scenarios (one filter x/H=6; two filters x/H= 2& 6).

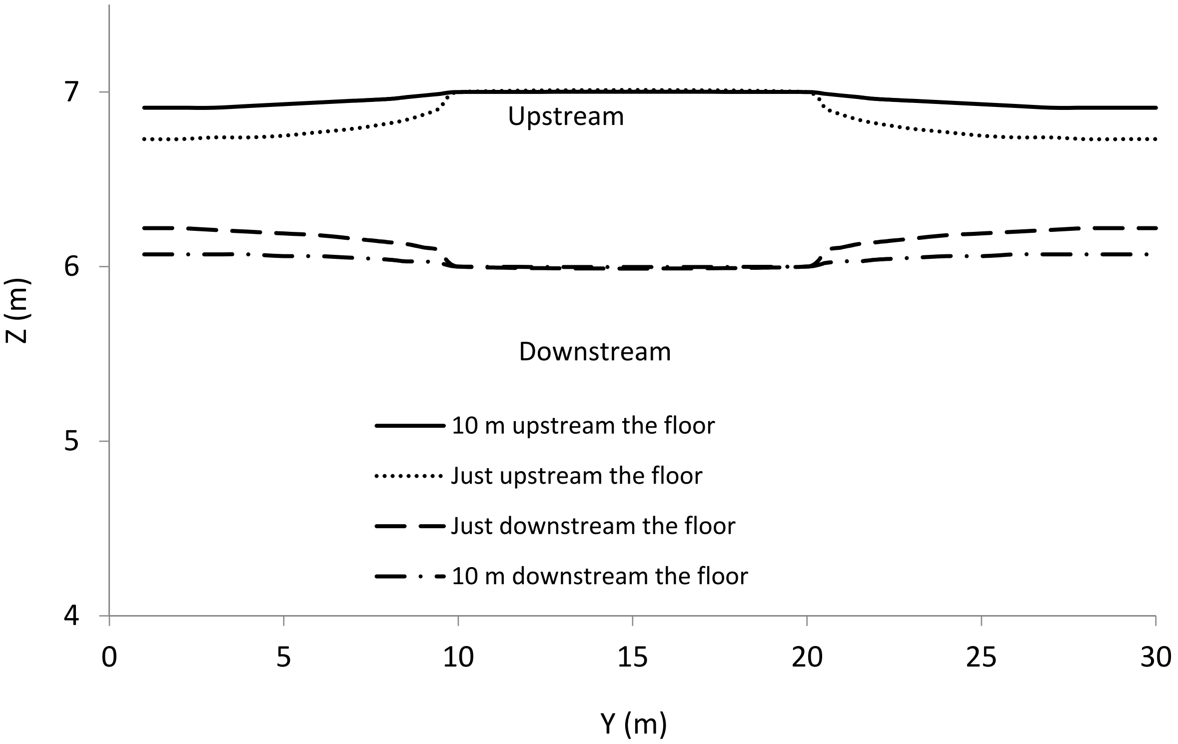


3D view



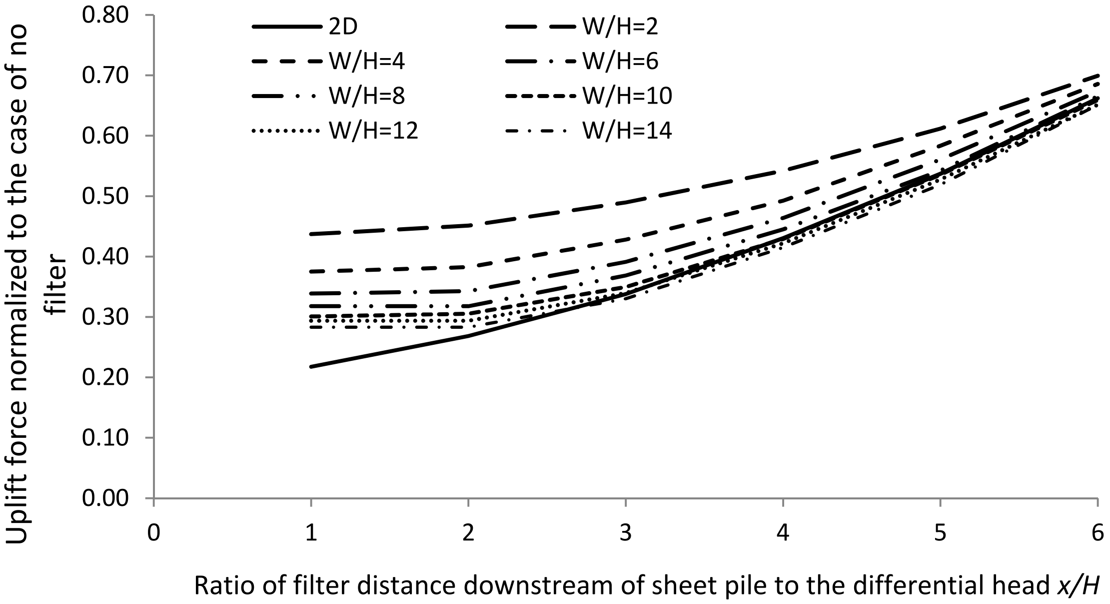
Cross section through the canal

Fig 1



7
6
5
4
Z (m)
0
5
10
15
20
25
30
Y (m)
Upstream
Downstream
10 m upstream the floor
Just upstream the floor
Just downstream the floor
10 m downstream the floor

Fig 2



0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
2D
W/H=2
W/H=4
W/H=6
W/H=8
W/H=10
W/H=12
W/H=14
Uplift force normalized to the case of no filter
Ratio of filter distance downstream of sheet pile to the differential head *x/H*

Fig 3

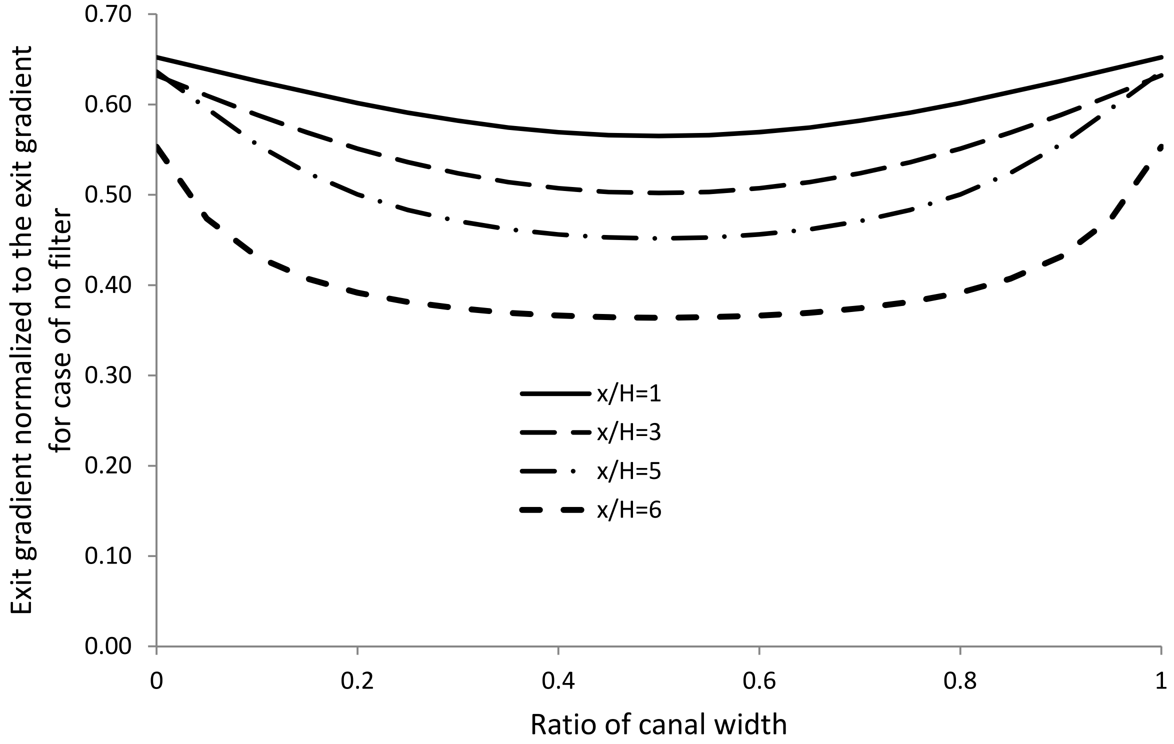

0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
0.2
0.4
0.6
0.8
1
Exit gradient normalized to the exit gradient for case of no filter
Ratio of canal width
x/H=1
x/H=3
x/H=5
x/H=6

Fig 4

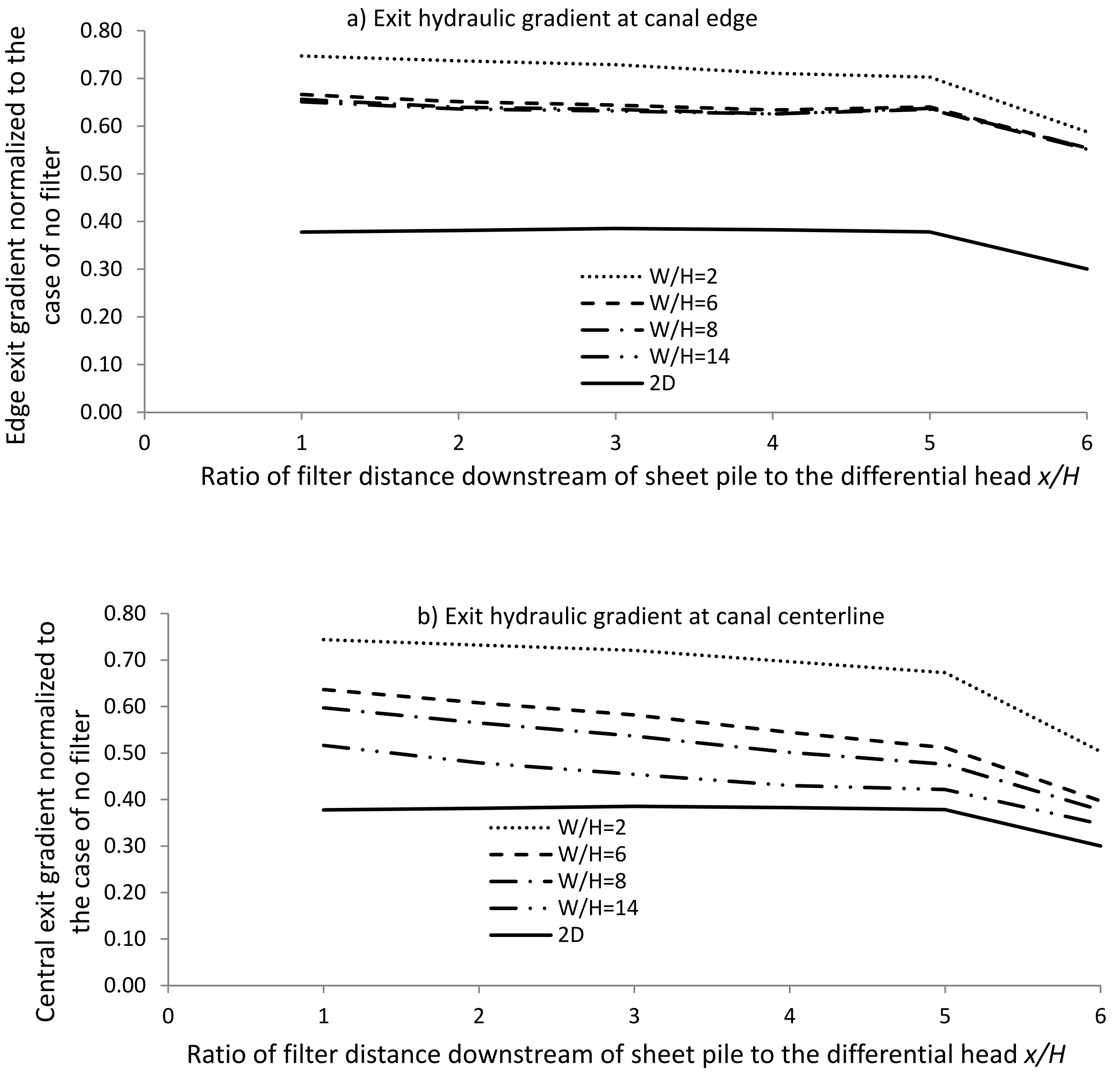

a) Exit hydraulic gradient at canal edge
Edge exit gradient normalized to the case of no filter
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
Ratio of filter distance downstream of sheet pile to the differential head x/H
W/H=2
W/H=6
W/H=8
W/H=14
2D
b) Exit hydraulic gradient at canal centerline
Central exit gradient normalized to the case of no filter
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
Ratio of filter distance downstream of sheet pile to the differential head x/H
W/H=2
W/H=6
W/H=8
W/H=14
2D

Fig 5

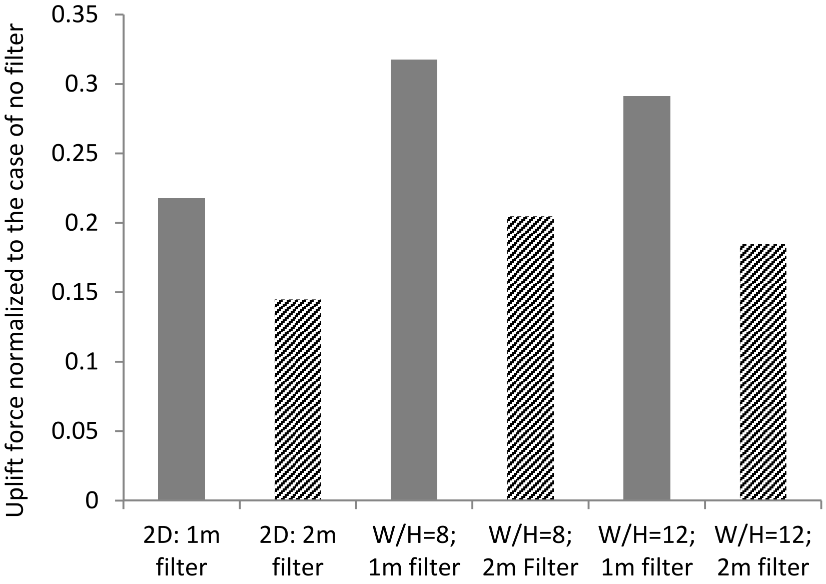

Uplift force normalized to the case of no filter
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2D: 1m filter
2D: 2m filter
W/H=8; 1m filter
W/H=8; 2m Filter
W/H=12; 1m filter
W/H=12; 2m filter

Fig 6

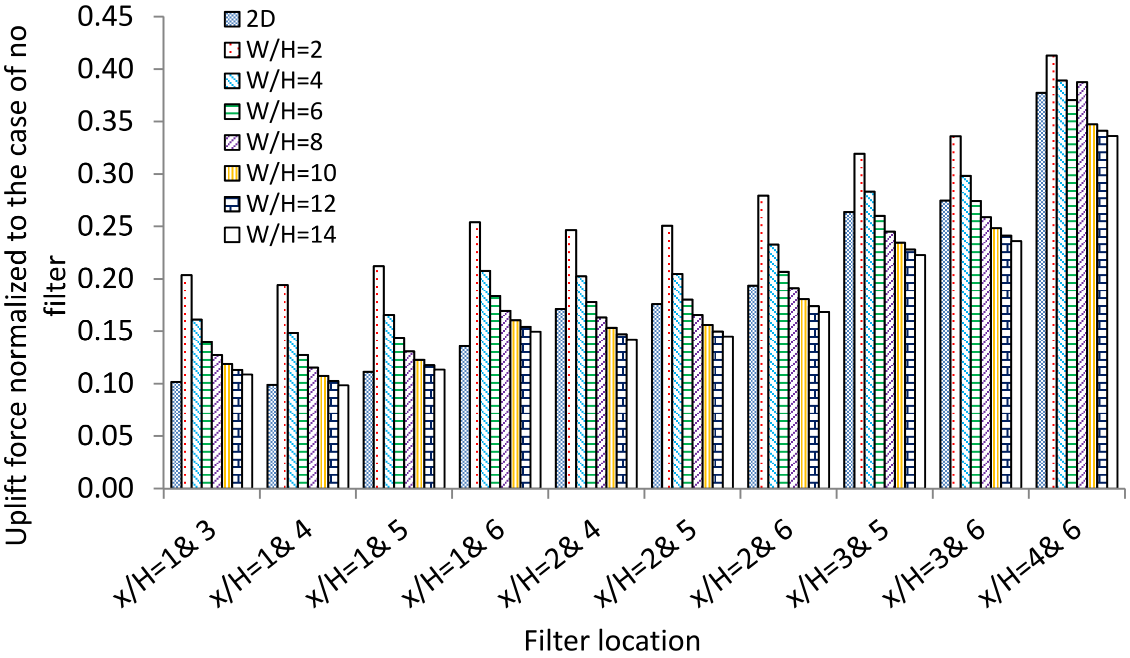

Uplift force normalized to the case of no filter
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2D
W/H=2
W/H=4
W/H=6
W/H=8
W/H=10
W/H=12
W/H=14
x/H=1& 3
x/H=1& 4
x/H=1& 5
x/H=1& 6
x/H=2& 4
x/H=2& 5
x/H=2& 6
x/H=3& 5
x/H=3& 6
x/H=4& 6
Filter location

Fig. 7

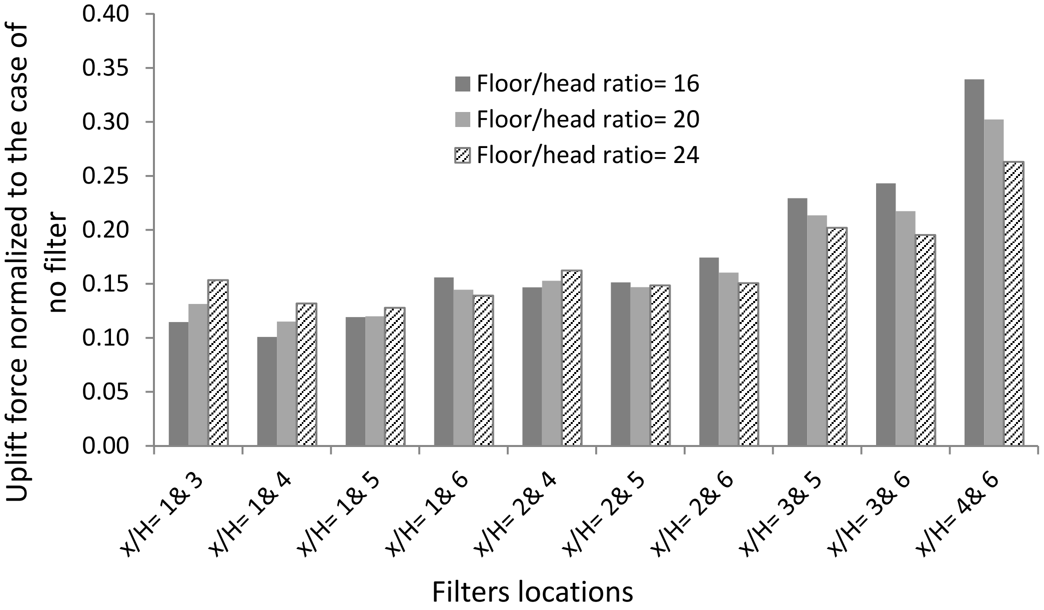
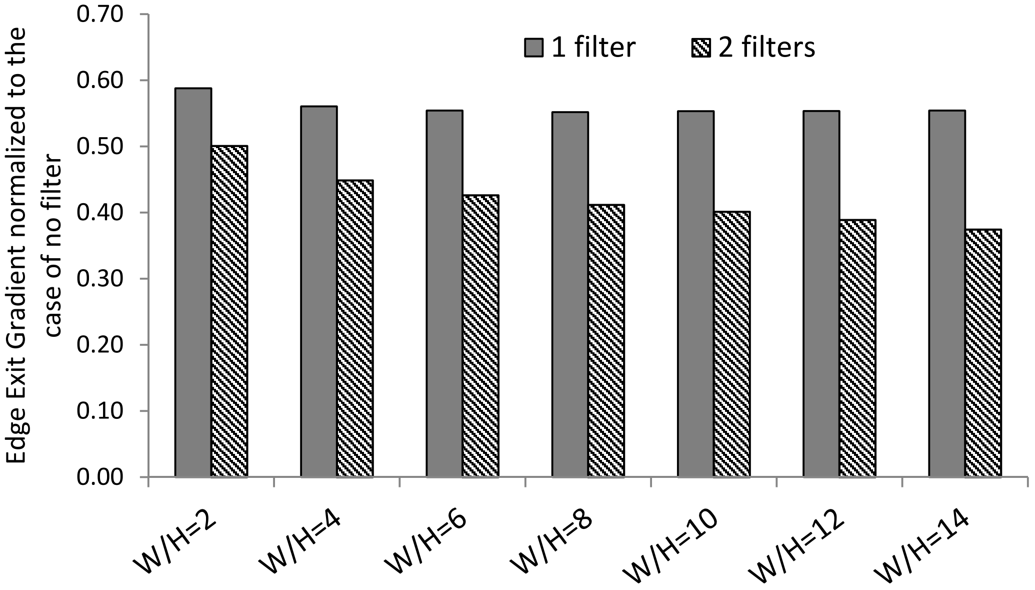
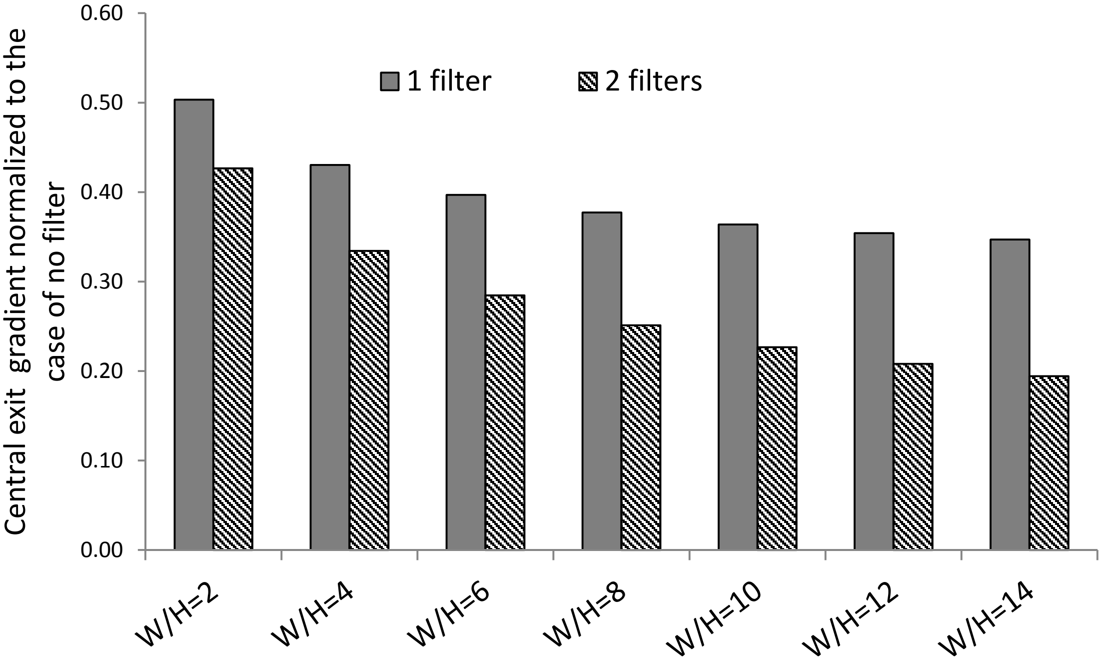

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Uplift force normalized to the case of no filter
Floor/head ratio= 16
Floor/head ratio= 20
Floor/head ratio= 24
x/H= 1& 3
x/H= 1& 4
x/H= 1& 5
x/H= 1& 6
x/H= 2& 4
x/H= 2& 5
x/H= 2& 6
x/H= 3& 5
x/H= 3& 6
x/H= 4& 6
Filters locations

Fig. 8



a) At canal edge



b) At canal centerline

Fig 9

Table 1. Downstream uplift force for cases one filter located at $x/H = 1$, and two filters located at $x/H = 1$& 4 for different ratios of W/H.

Canal width/ differential head ratio	Downstream total uplift force normalized to the case of no filter		Percentage (%) total uplift reduction using one filter	Percentage (%) total uplift reduction using two filters
	1 filter	2 filters		
W/H=2	0.44	0.20	56.3	80.4
W/H=4	0.38	0.15	62.5	85.2
W/H=6	0.34	0.13	66.1	87.1
W/H=8	0.32	0.11	68.2	88.6
W/H=10	0.30	0.11	69.9	89.4
W/H=12	0.29	0.10	70.6	89.9
W/H=14	0.28	0.10	71.7	90.1

Table 2. Uplift Force and Exit gradient at the canal edge for different filter locations and two different differential head. The uplift force and exit gradient are normalised to the case of no filter in place.

	Uplift force		Exit gradient	
Filter distance x/H	**H=1m**	**H=2m**	**H=1m**	**H=2m**
1	0.30	0.30	0.64	0.67
2	0.31	0.30	0.64	0.67
3	0.35	0.35	0.64	0.67
4	0.43	0.43	0.64	0.67
5	0.54	0.53	0.64	0.67
6	0.66	0.66	0.55	0.58