Hydraulic structures with defective sheet pile walls

Ahmed, A. A., Johnston, H. T., & Oyedele, L. (2013). Hydraulic structures with defective sheet pile walls. Dams and Reservoirs, 23(1), 29-37. DOI: 10.1680/dare.13.00017

Published in:
Dams and Reservoirs

Document Version:
Publisher's PDF, also known as Version of record

Dams and Reservoirs
Volume 23 Issue 1

Dams and Reservoirs 2013 **23**(1), 29–37
http://dx.doi.org/10.1680/dare.13.00017
Keywords: dams, barrages & reservoirs/mathematical modelling/waterways & canals

ice
Institution of Civil Engineers
publishing

Hydraulic structures with defective sheet pile walls

Ashraf A. Ahmed MSc, PhD, FHEA
Lecturer, School of Planning, Architecture and Civil Engineering, Queen's University Belfast, UK

Harold T. Johnston PhD, CEng, MICE, FHEA
Senior Lecturer, School of Planning, Architecture and Civil Engineering, Queen's University Belfast, UK

Lukumon Oyedele MSc, PhD
Professor, University of Lincoln, UK

A sheet pile wall driven to form a barrier wall below the floor of a hydraulic structure is frequently assumed to be watertight. Although the leakage through the interlocks of the sheet piles is usually small, damage and other factors can result in significant leakage. Consequently, this assumption is rarely, if ever, satisfied in reality. The present study used a finite-element model to investigate the effect of leaks through sheet piles driven under the floor of a hydraulic structure on seepage losses, on the uplift force and on the exit hydraulic gradient. Flow through the channel banks was considered to obtain accurate and robust calculations. The study indicated that when the leak existed in a sheet pile wall, driven centrally below the floor of the hydraulic structure, it has a small impact on seepage losses, the exit hydraulic gradients and the uplift force. However, when the leak existed at a sheet pile wall driven at the downstream end of the floor, its impact was significant, particularly on the exit hydraulic gradient with consequent risk to the stability against piping and undercutting of the structure. A combination of both cut-off walls did not provide a significant benefit, should leakage occur.

Notation

d	depth of sheet pile
E_Q	flow efficiency
$\mathbf{g}$	gravitational acceleration
H	differential water head applied on the structure
h	matric potential or pressure head
$[K_s]$	overall hydraulic conductivity matrix
k	hydraulic conductivity of porous medium
$[k_{us}]$	unsaturated hydraulic conductivity matrix
n	van Genuchten curve fitting parameter
P	fluid pressure
$\{q\}$	vector of nodal fluid heads
Q	flow with cut-off in place
$\{Q_r\}$	residual flow vector
Q_0	flow with no cut-off
$\{r\}$	overall nodal fluid head vector
$\{R_r\}$	overall residual flow vector
Z	elevation head
α	van Genuchten curve fitting parameter
γ	unit weight of fluid
θ_r	residual water content
θ_s	saturated water content
ϕ	total head of fluid

1. Introduction

Hydraulic structures, such as weirs, barrages and dams, are frequently founded on permeable soils. Flow through this permeable material below the structure needs to be controlled to prevent piping and consequent undermining (Leliavsky, 1965; Swamee *et al.*, 1997). The rate of such flow can be determined using Darcy's equation and is directly related to the local hydraulic gradient. In addition, flow beneath the structure can increase the uplift forces on its floor. To minimise groundwater flow, cut-off barrier walls are usually provided using sheet pile, concrete, soil–bentonite or cement–bentonite walls. Bentonite-based walls are more frequently used when containment is required. Rapid installation and the local availability of necessary equipment mean that driven sheet pile walls are favoured as cut-off walls in small hydraulic structures. Although there is likely to be some leakage through the joints of a well-constructed sheet pile wall, they and other barrier walls are often assumed to be impervious for design purposes. This assumption is rarely, if ever, correct in reality. In spite of the advances made in the field of geotechnical engineering, in most circumstances it is not possible to guarantee completely water-tight structures (Panthulu *et al.*, 2001). In extreme cases, the interlocking of driven sheet piles can fail as a consequence of twisting, allowing leakage to occur.

There have been only a few attempts to investigate the effects of leakage through sheet piles driven to form barrier walls beneath hydraulic structures. One of the early studies was by Karadi *et al.* (1980) who investigated a leaking barrier wall as a two-dimensional problem using the finite-difference technique.

A limitation in their study was that they assumed the leakage to be uniformly distributed over the entire barrier wall. Obviously, such an assumption does not reflect what happens in practice. Krizek and Karadi (1969) also carried out an experimental study to test the effectiveness of leaking sheet piles.

More recently, Ahmed *et al.* (2007) investigated the effect of leakage through sheet piles driven under hydraulic structures on exit hydraulic gradients, seepage losses and uplift force. Although their study used a three-dimensional model, it suffered from a limitation by not including the flow through the surrounding banks in their calculations. Ignoring the seepage through the banks was found to produce erroneous results (Ahmed and Bazaraa, 2009).

The main purpose of the current research was to study the effect of leakage through a sheet pile wall beneath a hydraulic structure on its effectiveness by considering seepage losses, uplift forces and exit hydraulic gradients. Seepage through the surrounding banks of the channel has been included in the calculations to obtain more accurate and reliable results (Ahmed and Bazaraa, 2009). Unsaturated flow above the free surface has been taken into consideration. Knowing the increase in the uplift force and exit hydraulic gradient resulting from sheet pile leakage is important in assessing the stability of hydraulic structures.

2. Mathematical background

A computer model developed by Ahmed (2008) was used. The model calculates the seepage in both confined and unconfined aquifers, considering the unsaturated flow above the free surface. The residual flow procedure presented herein, which is used to locate the free surface, follows closely Desai and Baseghi (1988).

The partial differential equation governing steady incompressible fluid flow through a porous medium can be written as

1. $$\mathrm{div}(k\,\boldsymbol{g}\mathrm{rad}\phi) = 0.0$$

where k represents hydraulic conductivity of the medium, $\boldsymbol{g}$ is gravitational acceleration, $\phi = P/\gamma + Z$ = total fluid potential or head, P/γ is the pressure head, Z is the elevation head and γ is unit weight of fluid. The pseudo-functional, U for the steady-state flow can be expressed as

2. $$U = \frac{1}{2}\iiint_v k\left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial y}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2\right]\mathrm{d}x\mathrm{d}y\mathrm{d}z$$

Applying the residual flow procedure (Desai and Baseghi, 1988) yields the element equations

3. $$[k_\mathrm{s}]^e\{q\} = \{Q_\mathrm{r}\}^e$$

where $[k_\mathrm{s}]^e$ is the element hydraulic conductivity matrix at saturation, $\{q\}$ is the vector of nodal fluid heads of element and $\{Q_\mathrm{r}\}^e$ is the element residual flow vector composed as

4. $$\{Q_\mathrm{r}\}^e = [k_\mathrm{us}]^e\{q\}$$

where $[k_\mathrm{us}]^e$ is the unsaturated hydraulic conductivity matrix. The assembly over the elements on the entire domain yields

5. $$[K_\mathrm{s}]\{r\} = \{R_\mathrm{r}\}$$

where $[K_\mathrm{s}]$ is the overall hydraulic conductivity matrix at saturation, $\{r\}$ is the overall nodal fluid head vector and $\{R_\mathrm{r}\}$ is the overall residual flow vector. Equation 5 is a system of non-linear equations.

The model of van Genuchten (1980) was adopted to consider the unsaturated flow

6. $$\theta = \theta_\mathrm{r} + \frac{(\theta_\mathrm{s} - \theta_\mathrm{r})}{[1 + (\alpha h)^n]^m}$$

7. $$k_\mathrm{us}(S_\mathrm{e}) = k_\mathrm{s}{S_\mathrm{e}}^{1/2}\left[1 - (1 - S_\mathrm{e}^{1/m})^m\right]^2$$

where $S_\mathrm{e} = (\theta - \theta_\mathrm{r})/(\theta_\mathrm{s} - \theta_\mathrm{r})$, h is the pressure head in cm, θ_r and θ_s are the residual and saturated water contents respectively, α and n are van Genuchten curve fitting parameters, and $m = 1 - 1/n$.

These equations were used to develop a computer program. A detailed presentation of this program, its validation and applications can be found in Ahmed (2008, 2009).

3. Description of the application problem and the analysis procedure

The problem represented in the numerical model was a hydraulic structure founded on a permeable homogenous isotropic soil of depth 6 m and having a hydraulic conductivity of 3×10^{-5} m/s, representing a silty sand. The length of the modelled zone was 60 m, and the channel width was 10 m. The banks of the channel extended 10 m each side and its top level was 2 m above the bed level of the channel. The impermeable floor of the structure was 16 m in length and extended across the channel width with retaining walls at both sides up to the top bank level as shown in Figure 1(a). The seepage flow occurred owing to a differential head H of 1 m between the upstream and the downstream sides of the structure. Figure 1(b) shows the finite-element mesh used for one of the

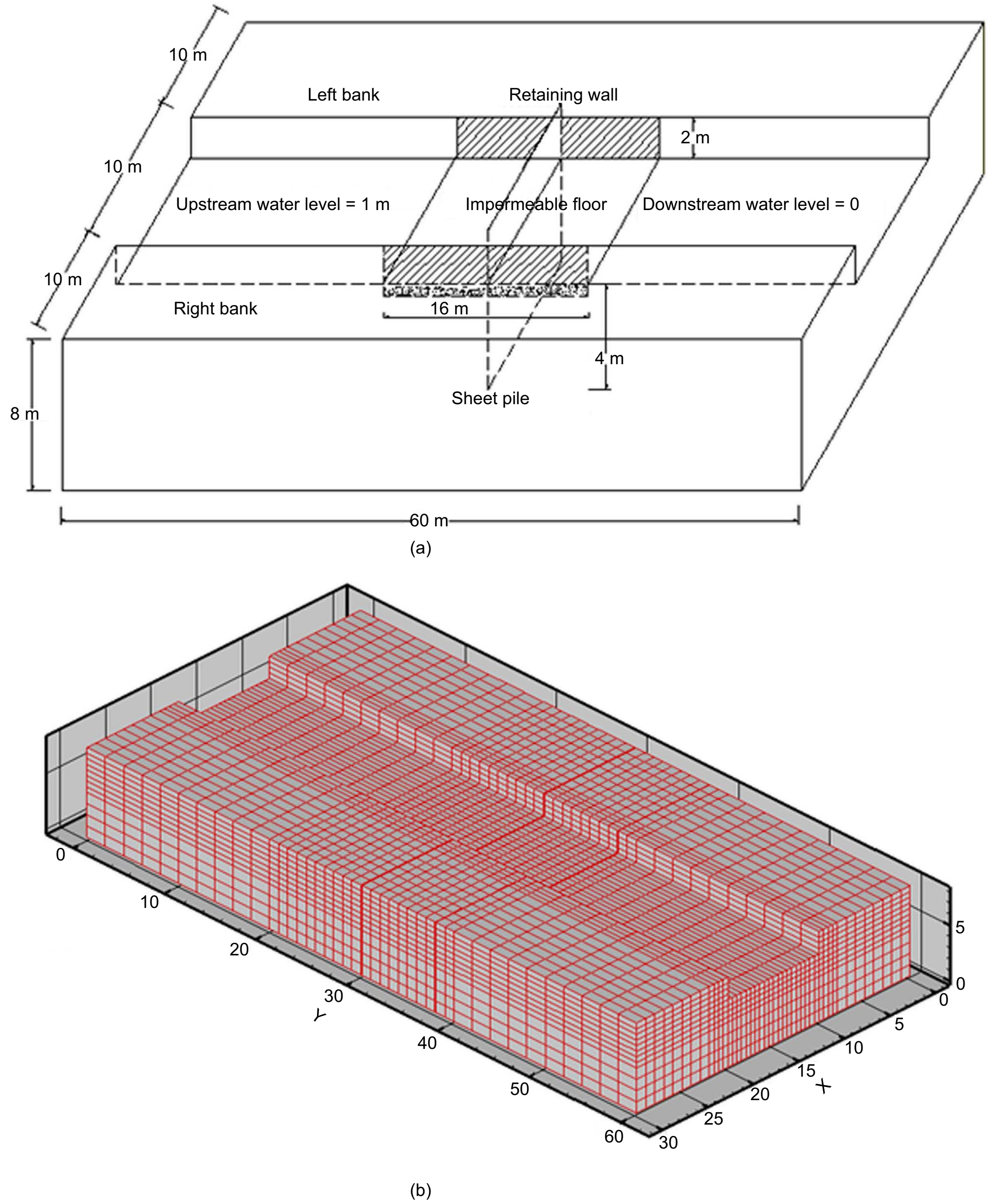

Figure 1. (a) Schematic of the modelled problem showing a single sheet pile wall in the central location; (b) dimensions and finite-element mesh of the analysed problem

simulations. The total number of nodes was 21 887 and a total of 18 816 brick elements were used.

In the current investigation, the problem was studied for the situation in which no cut-off wall was installed. Two positions of a sheet pile cut-off wall were then studied; at the middle and at the end of the floor of the hydraulic structure. A combination of middle and end walls was also studied. In the two wall configuration, leakage was assumed to occur in one of the walls. Ahmed (2011) found that the combination of middle and end sheet pile walls had a significant effect in reducing the exit hydraulic gradient and seepage losses below hydraulic structures.

4. Model results

4.1 Effect of location of leakage

A single sheet pile wall of penetration depth 4 m was represented under the structure as shown in Figure 1(a). For this configuration the effect of leakage through a hole in the sheet pile wall having an area of 2·5% of the wall area was investigated. The results are shown in Table 1. It can be seen that the worst case was when the leakage occurred in the upper central area. This is because the flow path beneath the structure will be less, and the seepage larger, if the leakage occurs in the upper region of the barrier wall. All further simulations used this location.

Leakage having different areas ranging from 2·5% to 10% of the wall area was then represented. In each case, the flow efficiency E_Q of the barrier was studied. The flow efficiency relates the flow with the barrier in place, Q, with the flow without the barrier, Q_0. It is defined as the ratio of the change in flow with the barrier in place to the flow without the barrier or

$$E_Q = \frac{(Q_0 - Q)}{Q_0}$$

The flow efficiency, uplift force and exit hydraulic gradients for each case were calculated.

4.2 Single central sheet pile wall

A centrally located single sheet pile wall was represented in the mathematical model. Leakage having different areas ranging from 2·5% to 10% of the wall area was then investigated. The model results are shown in Table 2 and in Figure 2.

4.3 Single sheet pile wall at downstream end

In the second case, the sheet pile wall was assumed to be located at the downstream end of the floor. Again leakage was assumed to occur through a hole ranging from 2·5% to 10% of the wall area in the centre of the wall. The model results are shown in Table 3.

4.4 Two sheet piles with leakage in the middle wall

In the third case two sheet pile walls were assumed to be installed located under the middle of the structure and at the downstream end of the floor. Leakage was assumed to occur in the centre of the cut-off located under the middle of the structure through an area ranging in size from 2·5% to 10% of its wall area. The results are presented in Table 4.

4.5 Two sheet piles with leakage in the end wall

In the final configuration, two sheet pile walls were assumed to be installed and located under the middle of the structure and at the downstream end of the floor. Leakage was assumed to occur in the centre of the cut-off located at the end of the structure through an area ranging in size from 2·5% to 10% of that wall area. The results are presented in Table 5.

5. Discussion

5.1 Single central sheet pile wall

The installation of a watertight sheet pile wall at the middle of the floor was shown to have reduced the flow seeping under the structure. The calculated flow efficiency, considering only flow under the structure, was 17·6% (Table 2). When flow through the canal banks was considered, it was found that the flow efficiency was much less at 3·2%. This result confirms the need to consider flow through banks as, if it is not included, seepage flows tend to be overestimated.

When leakage occurred in the sheet pile wall, it did not have significant influence on its performance as a cut-off wall. Results of this case, presented in Table 2, show that the flow efficiency, considering the total flow around and below the sheet pile wall, was about 2% owing to a leakage area of 10% of the wall area compared to about 3% for a watertight wall. This is not surprising because the reduction in total flow made by

Position of 2·5% leakage area	Increase in flow under the floor: %	Increase in total flow (including through the banks):%	Increase in uplift force: %	Increase in centre exit gradient: %	Increase in edge exit gradient: %
Watertight sheet pile wall	0·0	0·0	0·0	0·0	0·0
Centre upper	7·02	0·64	3·58	1·82	0·91
Centre lower	4·67	0·29	0·90	0·74	0·36
Edge upper	3·87	0·18	0·91	0·41	0·45
Edge lower	3·33	0·09	0·21	0·17	0·18

Table 1. Effect of locations of leakage on flows, uplift force and exit gradients. Case (a) of single cut-off located at the centre of the structure

Area of leakage as % of total area	Flow efficiency E_Q for under floor flow: %	Total flow efficiency E_Q (including flow through the banks): %	Increase in uplift force: %	Increase in centre exit gradient: %	Increase in edge exit gradient: %
Watertight sheet pile wall	17·6	3·2	0·0	0·0	0·0
2·5	11·8	2·6	3·6	1·8	0·9
5	10·3	2·3	4·9	2·5	1·3
10	8·2	1·9	6·2	3·5	1·8
100 (no wall)	0·0	0·0	12·1	7·3	4·1

Table 2. Flow efficiency, uplift force and exit gradients for varying areas of leakage. Case (a) of single cut-off located at the centre of the structure

placing a watertight sheet pile wall at the middle of the floor can be found from

$$0.032 = \frac{(Q_0 - Q)}{Q_0}$$

giving $Q = 0{\cdot}968Q_0$, indicating a decrease of 3·2%. The reason for this limited reduction in seepage is due to the existence of the impermeable floor and abutments. It should be noted that when only the flow below the structure is calculated, the leak effect is greater, with the flow efficiency decreasing from 17·6 to 8·2% at a 10% leakage area.

The total increase of the uplift force when there was no cut-off compared to the case of watertight sheet pile wall was about 12%. The effect of leaks on the uplift force was more pronounced than its effect on the total seepage flow below the structure and through the banks. A leakage area of 10% increased the uplift force by about 6% – that is, half the value of increase produced from the case of no sheet pile wall. It

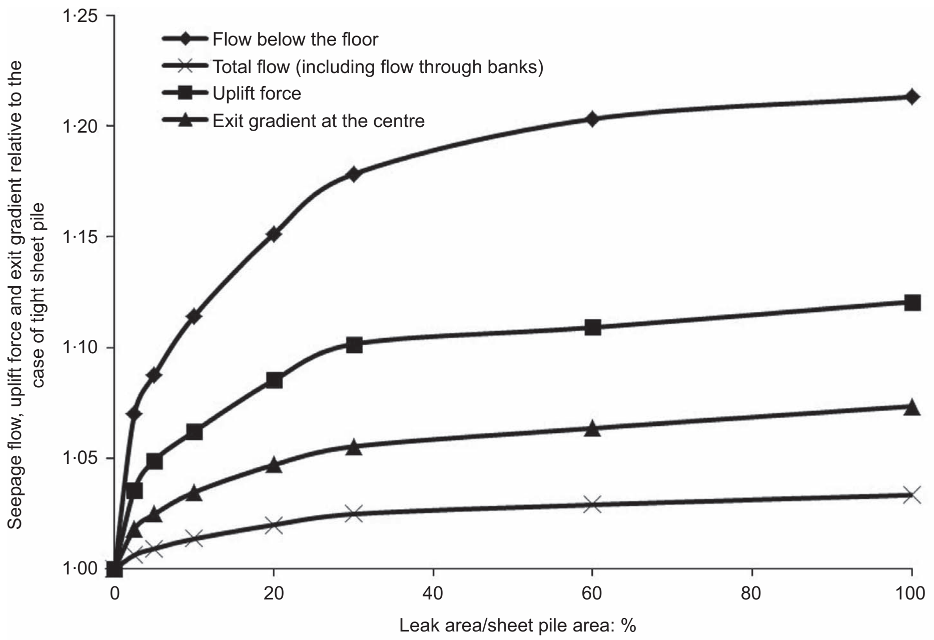

Figure 2. Change of flow, downstream uplift force and exit hydraulic gradient with leakage area. The *y*-axis is normalised to the case of tight sheet pile wall

Area of leak as percentage of total area	Flow efficiency E_Q for under-floor flow: %	Total flow efficiency E_Q (including flow through the banks): %	Increase in uplift force: %	Increase in centre exit gradient: %	Increase in edge exit gradient: %
Watertight sheet pile wall	3·3	2·7	0·0	0·0	0·0
2·5	2·8	2·4	−1·2	293·2	−0·8
5	2·5	2·2	−1·9	263·4	−1·3
10	1·9	1·8	−3·1	251·1	−2·1
100 (no wall)	0	0	−8·6	262·5	2·5

Note: minus donates a reduction in the variable

Table 3. Flow efficiency, uplift force, and exit gradients for varying areas of leakage. Case (b) of single cut-off located at the downstream end of the structure

means that a 10% leakage reduced the sheet pile efficiency with respect to the uplift force by 50%. This confirms the need for a significant factor of safety against uplift in design.

The increase in the uplift force and in the total flow around and below the structure is generally lower than the values obtained by Ahmed *et al.* (2007). This is because Ahmed *et al.* (2007) have not considered the flow through the banks of the canal; they considered only the flow below the structure.

The central exit hydraulic gradient when no cut-off was installed was 7·3% greater than when a watertight cut-off was present. A 10% leakage increased the hydraulic exit gradient by 3·5% compared to the case of watertight sheet pile. This again is about 50% of the increase in exit hydraulic gradient caused by the case of no sheet pile, which means that a 10% leakage dropped the efficiency of the sheet pile with respect to exit hydraulic gradient by about 50%. In general, the reduction in the exit hydraulic gradient resulted from the installation of watertight sheet pile, is not large. This is attributed to the existence of the concrete floor.

Karadi *et al.* (1980) found that, for relative penetration depth of 0·75, the exit gradient may attain a value of 4 or 5 times that for equivalent impervious sheet pile. This again is greater than the increase in the exit gradient observed in this study, which also has a sheet pile with penetration depth of 0·75 of the aquifer thickness. The reason for this disagreement is due to the assumption made by Karadi *et al* (1980) that the leak is uniformly distributed on the whole sheet pile and not at a local

Area of leak as percentage of total area	Flow efficiency E_Q for under-floor flow: %	Total flow efficiency E_Q (including flow through the banks): %	Increase in uplift force %	Increase in centre exit gradient: %	Increase in edge exit gradient: %
Watertight sheet pile walls	18·1	3·0	0·0	0·0	0·0
2·5	12·2	2·4	3·2	1·1	0·9
5	10·8	2·2	4·4	1·5	1·2
10	8·7	1·8	5·6	2·1	1·7
100 (no walls)	0	0	11·1	4·5	3·9

Table 4. Flow efficiency, uplift force, and exit gradients for varying areas of leakage. Case (c) of two cut-offs, with leakage occurring in the central cut-off

Area of leak as percentage of total area	Flow efficiency E_Q for under-floor flow: %	Total flow efficiency E_Q (including flow through the banks): %	Increase in uplift force: %	Increase in centre exit gradient: %	Increase in edge exit gradient: %
Watertight sheet pile walls	3·9	2·4	0·0	0·0	0·0
2·5	0·5	2·1	−1·3	285·1	−0·7
5	0·2	2·0	−2·0	256·3	−1·2
10	−0·3	1·6	−3·4	244·0	−2·0
100 (no walls)	0	0	−9·5	253·1	2·3

Note: minus donates a reduction in the variable

Table 5. Flow efficiency, uplift force, and exit gradients for varying areas of leakage. Case (d) of two cut-offs, with leakage occurring in the end cut-off

point. In addition, Karadi *et al* (1980) only conducted a two-dimensional analysis; hence the seepage through the canal banks is not accounted for.

The results presented in Figure 2 confirm that when leakage exists in a sheet pile wall derived at the middle of the floor, the flow under the floor is the most influenced by this leakage. Note that the vertical axis represents the flow, the uplift force and the exit hydraulic gradient normalised to their values obtained for the case of watertight sheet pile. A 10% leakage caused the flow below the structure to increase by about 11%. This is equivalent to the 8·2% flow efficiency shown above. The total flow below the structure and through the banks is the least influenced by the existence of leakage. The total flow increased by only 0·6% as a consequence of a leakage area of 2·5% of the cut-off wall area.

Figure 2 shows that at small leakage areas, any slight increase of this area caused a large increase in the seepage losses under the floor, in the downstream uplift force, and in the exit hydraulic gradient at the centre of the canal. When the leak area exceeded 30%, the rate by which the seepage losses, uplift force, and hydraulic exit gradient increase was small. This means that when the leak area is 30% or higher of the sheet pile area, the sheet pile will be rendered ineffective.

5.2 Single sheet pile wall at downstream end

The installation of a watertight sheet pile wall at the end of the floor was found to have increased the total flow efficiency to 0·027, or a reduction in the total seepage flow of 2·7%, and to actually increase the uplift force on the structure. The reason for the increase in uplift force is that the drop in potential head is concentrated at the cut-off location rather than being distributed along the length of the floor. When leakage in the sheet pile wall was represented, the flow below the structure showed a lower drop in flow efficiency than that found for a cut-off in the middle of the structure.

The hydraulic exit gradient at the canal edges was slightly decreased. This is because the flow through the hole represented in the sheet pile has slightly reduced the flow through the banks of the canal leading to slight decrease in the exit gradient at the edges of the canal.

The exit hydraulic gradient at the centre of the channel markedly increased because of the leakage in the sheet pile. A leakage area of 2·5% increased this exit hydraulic gradient to almost three times that resulting from an impervious cut-off and was even greater than when the cut-off was not present. At a leakage area of 5%, the gradient was similar to that when there was no cut-off. While the flow decreased with decreasing leakage area, its concentration in a small region resulted in high local gradients.

5.3 Two sheet piles with leakage in the middle wall

The results presented in Table 4 show similar trends to those in Table 2. While the absolute values of uplift force were found to be about 10% larger than those calculated for a single cut-off in the middle of the structure, they follow the same trends. The major difference was found to be in the exit hydraulic gradients at the centre of the channel. Their magnitudes were significantly decreased because of the increased flow path length produced by the presence of the second cut-off wall. Consequently, when leakage occurred in the middle wall, its effect was of lesser magnitude. The absolute exit gradient was 0·12 for case (a), and 0·034 for case (c). These absolute values are calculated when watertight sheet piles are installed.

5.4 Two sheet piles with leakage in the end wall

The results presented in Table 5 show similar trends to those in Table 3. The effect of leakage through the end cut-off wall causes a small reduction in the uplift force. This is because the existence of the end cut-off wall makes the drop in potential head to be concentrated at the cut-off location rather than being distributed along the length of the floor. The existence of the leakage slightly reduces this potential head concentration at the end cut-off wall. As a result, the downstream uplift force slightly decreases.

As with a single cut-off wall at the end of the floor, the leakage in the end wall for the two wall configuration causes a marked increase in the central exit hydraulic gradient. Again, a leakage area of 2·5% increased the exit hydraulic gradient to almost three times that resulting from an impervious cut-off.

5.5 Practical relevance of the study

In the design of hydraulic structures in rivers and canals, especially where the foundation is reasonably permeable, sheet pile cut-off walls can be used to limit seepage flows and minimise hydraulic gradients. Such cut-off walls are assumed to be watertight but are often subject to leakage. The standard forms of a composite section are

(*a*) a straight horizontal floor of negligible thickness with a sheet pile wall at the end
(*b*) a depressed floor of finite thickness but no cut-off wall
(*c*) a straight horizontal floor of negligible thickness with an intermediate sheet pile wall.

Khosla *et al.* (1954) developed pressure charts for intermediate and end pile walls from which pressures at key points can be predicted. However, these do not consider the consequences of wall leakage. The current study enables designers of structures, which incorporate single or dual sheet pile cut-offs, to evaluate the effect of leakage on the seepage rates, the consequent hydraulic gradients and the uplift forces on a structure in a canal or river. Hence the design can include a factor of safety against such leakage. A further research is needed to accurately estimate this factor of safety.

6. Conclusions

When a sheet pile cut-off wall which is installed below a hydraulic structure within a channel leaks, it can affect the stability of the structure. The current study suggests that when a single cut-off wall is driven at the middle of the floor of the structure, the leakage does not have significant influence on the performance of the cut-off. The total flow bypassing the structure, increased by only 0·6% as a consequence of a leakage area of 2·5% of the cut-off wall area. Water seeping only below the floor of the structure increased by about 7% because of 2·5% leakage.

For the above case of single cut-off wall driven at the middle of the floor of the structure, a leakage area of 10% increased the downstream uplift force on the floor by some 6%. This shows that the possibility of leakage should be taken into consideration at the design stage. However, there was no significant change in the value of the exit hydraulic gradients as a consequence of the leakage. Thus piping within the soil, causing undercutting of the structure, is unlikely.

When flow through the canal banks was considered, it was found that the flow efficiency was much less than the efficiency of flow seeping only below the structure. This result confirms the need to consider flow through banks as, if it is not included, seepage flows tend to be overestimated.

A single cut-off wall located at the downstream end of the floor will increase the uplift force. The leakage in such wall slightly reduced the uplift force on the floor. More importantly, if leakage occurs, it will greatly increase the exit hydraulic gradient, therefore dramatically affecting the stability against piping. A leakage area of 2·5% was found to increase the exit hydraulic gradient at the channel centreline to almost three times that experienced at a watertight cut-off wall. Although for an end sheet pile wall, leakage causes a reduction of the uplift force, the increased risk of piping is of concern.

When two cut-off walls are installed at the middle and end of a structure, the uplift force on the structure is increased. Leakage in the first wall will have little effect on the overall performance of structure. However, leakage in the downstream cut-off wall will cause a slight reduction in the uplift force and a large increase in the exit hydraulic gradient at the centre of the channel producing a significant risk to the stability against piping at this wall.

REFERENCES

Ahmed AA (2008) Saturated–unsaturated flow through leaky dams. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* **134(10)**: 1564–1568.

Ahmed AA (2009) Stochastic analysis of free surface flow through earth dams. *Computers and Geotechnics* **36(7)**: 1186–1190.

Ahmed AA (2011) Design of hydraulic structures considering different sheetpile configurations and flow through canal banks. *Computers and Geotechnics* **38(4)**: 559–565.

Ahmed AA and Bazaraa AS (2009) Three-dimensional analysis of seepage below and around hydraulic structures. *ASCE Journal of Hydrolgic Engineering* **14(3)**: 243–247.

Ahmed AA, Soliman AM and Bazaraa AS (2007) 3-D steady analysis of leaky hydraulic structures: 1. Leaky sheetpiles. *Journal of Engineering and Applied Science* **54(2)**: 141–157.

Desai CS and Baseghi B (1988) Theory and verification of residual flow procedure for three dimensional free surface seepage. *Advances in Water Resources* **11(4)**: 192–203.

Karadi GM, Miguel E and Krizelc RJ (1980) Analysis of leaky sheet pile by summary representation. *International Journal for Numerical and Analytical Methods in Geomechanics* **4(3)**: 199–213.

Khosla AN, Bose NK and Taylor EM (1954) *Design of Weirs on Permeable Foundation*. Central Board of Irrigation and Power, New Delhi, India, publication no. 12.

Krizek RJ, and Karadi GM (1969) Effectiveness of leaky sheetpile. *Highway Research Record* **282**: 57–62.

Leliavsky S (1965) *Design of Dams for Percolation and Erosion*. Chapman and Hall, London, UK.

Panthulu TV, Krishnaiah C and Shirke JM (2001) Detection of Seepage paths in earth dams using self potential and electrical resistivity methods. *Engineering Geology* **59(3–4)**: 281–295.

Swamee PK, Mishra GC and Salem AS (1997) Effectivity of multiple sheet piles in weir design. *ASCE Journal of Irrigation and Drainage Engineering* **123(3)**: 218–221.

van Genuchten M Th (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44(5)**: 892–898.

WHAT DO YOU THINK?

To discuss this paper, please email up to 500 words to the editor at editor@britishdams.org. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.