EFFECT OF SEEPAGE CUT OFF BELOW EARTHEN DAM UNDER RAPID DRAWDOWN

S. Tung ¹, G. N. Bhandari ², S. P. Mukherjee ³

ABSTRACT

A dam is constructed across a river, as a barrier, to accumulate water in the reservoir to use it for various purposes like irrigation, navigation etc. Seepage through and below an earthen dam plays an important role in determining the stability of dam. The rapid drawdown condition creates a critical limit State which occurs when the water level drops rapidly adjacent along upstream slope relative to the time required for water pressures to dissipate along it. Stability analysis during rapid drawdown is an important consideration in the design of embankment dams. During rapid drawdown, stability of embankment is reduced as the pore water pressures within embankment remain high. Seepage cutoff below an earthen dam is necessary for reducing seepage flow and thereby increasing its stability. The current study was carried out using FLAC 2D and SEEP/W software’s to evaluate the factor of safety with the help of the strength reduction method in case of rapid drawdown. The analysis has been done for an embankment dam with base width of 17m and side slope 2(H):1(V) made of homogeneous soil. For numerical modeling the different sheet pile locations adopted for seepage analysis are B/8, 2B/8 and 3B/8 (B=Base Width of Dam) distances away from the downstream end in different drawdown ratio. Variations of sheet pile length for the numerical analysis are 5m, 10m and 15m. Pore pressure variation, Flownet, Phreatic surface and fluid flow vector have been obtained for the numerical models by FLAC 2D software. Based on the numerical results an attempt has been made to gain an insight into the effect of seepage cut off (sheet pile) on those parameters. It has been observed, that during rapid drawdown, there is a tendency of failure of slope. The factor of safety has been found to increase when sheet pile is considered to be placed below a dam than the same when no sheet pile was considered below the dam because of increase of length of flow path. Increase of length of sheet pile the factor of safety has increased for a fixed location of sheet pile with respect to base width of a dam. It has been found to this study that drawdown ratio has great influence on factor of safety. It has been observed that, factor of safety decreases when drawdown ratio increases. As Sheet pile length increases seepage path increases, which reduce the exit gradient. It is observed that for a fixed length of sheet pile exit gradient increases when sheet pile position is shifted away from downstream end.

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It has been noticed that Pore pressure value within the dam is more if sheet pile is shifted towards the upstream end. It has been observed that when sheet pile length increases flow vector reduces indicating quantity of fluid flow is less. Due to this fact the path traced by the percolating water \( i.e. \) creep length increases and thereby hydraulic gradient is reduced. It also has been observed that the negative signs are due to the fact that fluid flows in the downward direction along the length of sheet pile. At the position of sheet pile there is an abrupt jump of fluid flow vector.

Keywords: Earthen dam, Sheet pile, Rapid drawdown, Flownet, Factor of safety, Pore pressure, FLAC 2D, SEEP/W, Fluid flow vector.
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ABSTRACT: The rapid drawdown condition creates a critical limit State which occurs when the water level drops rapidly adjacent along upstream slope relative to the time required for water pressures to dissipate along it. Stability analysis during rapid drawdown is an important consideration in the design of embankment dams. During rapid drawdown, stability of embankment is reduced as the pore water pressures within embankment remain high. Seepage cutoff below an earthen dam is necessary for reducing seepage flow and thereby increasing its stability. The current study was carried out using FLAC 2D and SEEP/W software’s to evaluate the factor of safety with the help of the strength reduction method in case of rapid drawdown. The analysis has been done for an embankment dam with base width of 17m and side slope 2(H):1(V) made of homogeneous soil in different drawdown ratio. For numerical modeling the different sheet pile locations adopted for seepage analysis are B/8, 2B/8 and 3B/8 distances away from the downstream end. Variations of sheet pile length for the numerical analysis are 5m, 10m and 15m. Pore pressure variation, Flownet, Phreatic surface and fluid flow vector have been obtained for the numerical models by FLAC 2D software. Based on the numerical results an attempt has been made to gain an insight into the effect of seepage cut off (sheet pile) on those parameters. It has been observed, that during rapid drawdown, there is a tendency of failure of slope. Increase of length of sheet pile the factor of safety has increased for a fixed location of sheet pile with respect to base width of a dam.

INTRODUCTION
Stability analysis during rapid drawdown is an important consideration in earthen dam. Seepage through and below earth dam plays an important role in determining the stability of dam. The basis for rational seepage analysis was developed about one hundred and fifty years ago by Darcy (1856), whose experiments led to the conclusion (Darcy’s law) that determines velocity with which water flows under a hydraulic gradient through porous medium. Seepage analysis is necessary for obtaining the quantity of seepage losses and the distribution of pore water pressure in the medium through which seepage occurs. During the low tides, as the water levels fall from their initial position, the condition is termed as ‘Drawdown’ – a state in which the rate of receding water level and the permeability of the associated earthen dam is vital, as due to rapid drawdown in low permeability soils, pore pressure induced may cause slope failure as well as piping failure. Rapid draw-down consists of a relatively high water table which has remained against an earth levee for a period of time such that pseudo steady-state conditions are created in the levee. In such scenarios, the pore-water pressures present in the Embankment dam during drawdown do not have enough time to dissipate. In that situation heightened pore-water pressures on the up-stream side of an embankment can trigger either deep or shallow failures.

The foundation below the dam is affected by the differential head formed between upstream and downstream. The seeping flow generates erosive forces which tend to pull soil particles with the flow. The seepage may lead to occurrence of
piping phenomenon which results in collapse of the dam. To prevent such hazards it is necessary to lengthen the seepage path. One of the methods of such lengthening is to introduce sheet piles as cutoff below the dam. The partial differential equation which governs the seepage through a heterogeneous, anisotropic, saturated unsaturated soil can be derived based on the principle of conservation of mass for a representative volume under consideration. During a transient process if the total stresses remain constant, the differential equation governing three dimensional transient case through a porous medium when the controlling parameters change with respect to has been can be written as,

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial h}{\partial z} \right) = m_r \frac{\partial h}{\partial t} \quad (1)
\]

where \( h \) = total available head under which unsteady seepage occurs; \( x, y \) = two mutually perpendicular directions i.e. horizontal and vertical direction respectively; \( k_x, k_y \) = permeability in horizontal and vertical directions respectively; \( m_r \) = storage co-efficient.

Bishop (1955) has done the analysis for slope stability by method of slices. Bishop’s method can be used for total stress as well as effective stress analysis. Wenjun Dong and Schwanz (2005) presented the results of Finite Element Soil-Pile-Interaction for analysis of floodwall in soft clay. By using appropriate soil parameters, interaction effects were modeled in the finite element model. Xu et al (2005) investigated experimentally factor of safety against stability in soft ground in Huai-He rivers levee. It was found that mechanism of instability during sudden drawdown of floodwater, preceded with a local failure of slope instability in embankment slope, whose slip surface passes through the toe of slope. Rapid rise of water also cause wetting of unsaturated region in the structure result in slope failures. The key problem lies in determination of the position of phreatic surface in transient simulations, when water table level dramatically changes during extreme floods (Chen, Zhang, 2006). Schmertmann (2006) observed that permeability and shear strength of each soil varies with the degree of saturation. Thus saturated and nearly saturated conditions may cause reduction of stability of slopes, dam and earth dikes.

Huang et al (2009) investigated the influence of transient seepage on stability of dam considering water level draws down rapidly. It was evaluated using finite element method that lowest factor of safety induced on the upstream side of dam immediately after drawdown and the factor of safety of upstream slope increases rapidly with time. David et al (2010) investigated the effect of water dynamics on earth dam based in transient simulation seepage condition using two-dimensional numerical model based on Richards’ equation for water flow in porous medium. Freduland (2011) analyzed the effects of the pore water pressures and the stability of the earth dam under rapid drawdown condition focusing on the changing of pore-water pressures in the levee in an uncoupled fashion. It was found that in an earth dam the impact of rapid draw-down can vary significantly based on the hydraulic conductivity of the individual layers. Hansen et al (2012) analyzed transient pore water pressure fluctuations of Doroodzan dam using 3-D finite element model. It was found that Phreatic line at the upstream face of the dam closely followed the reservoir level rapid drawdown, whereas at the interior sections of the dam phreatic line did not drop as fast.

On the basis of the outcome of these studies the present investigation has been done to carry out stability and seepage analysis of an earth dam under rapid drawdown condition with and without sheet pile. This has been done to examine the influence of length and position of sheet pile cut-off on exit gradient, overall factor of safety, pore pressure within the dam, in rapid drawdown condition.

**MODEL FOR STUDY**

The model dam studied is presented with its dimension and the relevant soil parameters are also indicated in Figure. 1.
In the 2D model, 2D was used to model earthen dam geometry without sheet pile and with sheet pile. The models are presented in Figure 3 and Figure 4, respectively. The flow net is also drawn by solving the Laplace equation using SEEP/W. In such case, a triangular mesh was considered within the domain (as shown in Figure 2). The elliptic equations were used for modeling flows through porous media.

Table 1 Details of sheet pile

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of cross section per meter</td>
<td>0.03 m²</td>
</tr>
<tr>
<td>Moment of inertia per meter</td>
<td>0.00225 m⁷</td>
</tr>
<tr>
<td>$E_{steel}$</td>
<td>2E+11 N/m²</td>
</tr>
</tbody>
</table>

Bulk modulus ($K$) and shear modulus ($G$) were used in FLAC-2D as stiffness parameters. Drained bulk and shear modulus for the various soil layers were calculated using the following relationships:

Bulk modulus $K$ is given by,

$$ K = \frac{E'}{3(1-2\nu')} $$

(2)

Shear modulus $G$ is given by,

$$ G = \frac{E'}{2(1+\nu')} $$

(3)

where, $\nu'$ = Poisson ratio under effective stress conditions; $E'$ = Modulus of elasticity of the soil under effective stress conditions. The interface properties include normal stiffness ($K_n$), shear stiffness ($K_s$) and shear strength parameters of the interface. The interface stiffness was calculated as follows:

$$ K_n, K_s = 10. \ Max \left[ \frac{(K+4G)}{\Delta Z \ min} \right] $$

(4)

where, $K_n$ = Normal stiffness of the interface; $K_s$ = Shear stiffness of the interface and $\Delta Z$ min= Minimum width of the neighboring zone.

Table 2 Properties of interface elements

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal and shear</td>
<td>2.019E+8 Mpa</td>
</tr>
<tr>
<td>stiffness</td>
<td></td>
</tr>
<tr>
<td>Adhesion</td>
<td>13.0 kN/m²</td>
</tr>
<tr>
<td>Friction</td>
<td>3.3°</td>
</tr>
</tbody>
</table>

PARAMETRIC STUDIES

Table 3 shows the different studies under different hydraulic head conditions and with different sheet
pile locations. In the table, $B$ is the width of the base of the dam.

![Image](image_url)

**Table 3 Different cases for parametric study**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Sheet pile length (m)</th>
<th>Sheet pile position from downstream end</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>B/8</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>B/8</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>B/8</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>B/8</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>2B/8</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>2B/8</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>2B/8</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>2B/8</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>3B/8</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>3B/8</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>3B/8</td>
</tr>
<tr>
<td>13</td>
<td>20</td>
<td>3B/8</td>
</tr>
</tbody>
</table>

Note: $B$= width of the base of the dam

**RESULTS**

The seepage analysis in the present study has been carried out considering different cases; such as sheet pile length, sheet pile position and upstream draw down, using the SEEP/W and various parametric studies of the earthen dam with or without sheet pile using FLAC 2D. Figure 3, Figure 4 and Figure 5 show the flow net diagram obtained from SEEP/W with sheet pile, for drawdown rate 0.66 m/hour for drawdown ratio (L/H)= 0, 0.3, 0.85 respectively. Figure 6,7 and 8 show the flow net diagram, pore pressure variation contour and phreatic surface and fluid flow vector with and without sheet pile as obtained from FLAC 2D. Similarly, Figure 9 show stability analysis of embankment using sheet pile for drawdown rate 0.66 m/hour for drawdown ratio (L/H)= 1 as obtained from SEEP/W.

![Fig. 3 Earth Earthen dam flow net with sheet pile of length 15m at B/8 distance from downstream end for drawdown rate= 0.66 m /hour and L/H= 0 (obtained from SEEP/W)](image_url)

![Fig. 4 Earthen dam flow net with sheet pile of length 15m at B/8 distance from downstream end for drawdown rate= 0.66 m /hour and L/H= 0.3 (obtained from SEEP/W)](image_url)
Fig. 5 Earthen dam flow net with sheet pile of length 15m at B/8 distance from downstream end for drawdown rate= 0.85 m/hour and L/H= 0 (obtained from SEEP/W)

Fig. 6 Earth Earthen dam flow net with sheet pile of length 15m at B/8 distance from downstream end for drawdown rate= 0.66 m/hour and L/H= 0 (obtained from FLAC)

Fig. 7 Pore pressure variation of earthen dam without sheet pile

Fig. 8 Pore pressure variation of earthen dam with sheet pile

Fig. 9 Stability of earthen dam using 15m long
sheet pile at B/8 position from drawdown end at drawdown rate 0.66 m/hour for drawdown ratio (L/H)= 1 (obtained from SEEP/W)

DISCUSSION
Based on the numerical results presented above an attempt has been made to gain an insight into the effect of seepage cut off (sheet pile) on exit gradient, factor of safety against piping and pore pressure developed within the body of the dam.

Effect of sheet pile length and location on exit gradient
An attempt has been made to observe the effect of location and length of sheet pile, used, as seepage cutoff on exit gradient. For this purpose a plot of exit gradient vs. sheet pile length has been performed for different sheet pile position indicated in Figure 10. It is observed from Figure 10 that for any fixed position of sheet pile, exit gradient reduces with sheet pile length for any particular position of sheet pile in drawdown condition, when drawdown rate 0.66 m/hour and drawdown ratio (L/H)= 1. As Sheet pile length increases seepage path increases, which reduce the exit gradient. It is observed that for a fixed length of sheet pile exit gradient increases when sheet pile position is shifted away from downstream end.

Factor of safety
Overall factor of safety of the dam has been obtained from FLAC 2D and SEEP/W. Factor of safety of the dam has been obtained by numerical analysis. The FLAC Shear strength method determines a factor of safety based on a defined maximum unbalanced force for a failure surface utilizing the stress/strain characteristics for the soil. (Reference: Itasca 2005). The factor of safety takes into account both piping and overall stability of the dam. In Figure 11 overall factor of safety has been plotted against different sheet pile positions for different sheet pile lengths. It is observed from the figure that for a fixed length of sheet pile overall factor of safety remains almost constant when sheet pile position moves away from downstream end. For a particular position of sheet pile, when length of the sheet pile increases, overall factor of safety increases with sheet pile length.

Fig. 10 Exit gradient vs. sheet pile length for different sheet pile positions

Fig. 11 Factor of safety vs. different sheet pile positions for different sheet pile length at B/8 position from drawdown end at drawdown rate 0.66 m/hour for drawdown ratio (L/H)= 1

Effect of Drawdown in Factor of Safety for fixed sheet pile position
An attempt has been made to observe the effect of drawdown on factor of safety using cutoff presented in figure 12. Figure 12 represents factor of safety in steady state condition and drawdown condition of drawdown rate 0.66 m/hour and drawdown ratio (L/H) = 1 for earthen dam in B/8
position from downstream end using of sheet pile. It is attributed to the fact that that in rapid drawdown condition when water level changes factor of safety drastically changes due to variation of pore water pressure.

Fig. 12 comparison of Factor of safety vs. different sheet pile position from drawdown end at drawdown rate 0.66 m/hour for drawdown ratio (L/H) = 1 and steady state condition

Effect of Drawdown ratio on Factor of Safety for fixed sheet pile length

An attempt has been made to observe the effect of drawdown ratio on earthen dam in different sheet pile position for fixed sheet pile length of 5m. Figure 13 represents that effect of drawdown ratio on factor of safety of earthen dam for fixed sheet pile length with variation of sheet pile position. It observe form figure 13 that when sheet pile position moves away from downstream end factor of safety drastically decreases. It also observed from the figure that when drawdown ratio increases factor of safety decreases. When drawdown ratio varies in between 0.4 to 0.85 factor of safety abruptly decrease. This is attributed to the fact that for fixed sheet pile length and different position of sheet pile from downstream end for lower drawdown ratio (L/H < 0.8), the increased weight of the slope has a proportionately greater destabilizing effect than the increased frictional strength and the factor of safety decreases drastically.

Fig. 13 Factor of safety vs. different sheet pile positions for 5m length sheet pile from drawdown end at drawdown rate 0.66 m/hour for different drawdown ratio

Effect of Drawdown ratio on Factor of Safety for fixed sheet pile position

An attempt has been made to observe the effect of drawdown ratio on earthen dam in fixed sheet pile position for variation of sheet pile length. Figure 14 represents that effect of drawdown ratio on factor of safety of earthen dam for fixed sheet pile position with variation of sheet pile length. It observe form figure 14 that when sheet pile length increases factor of safety drastically increases. It also observed from the figure that when drawdown ratio increases factor of safety decreases. When drawdown ratio varies in between 0.4 to 0.85 factor of safety abruptly decreased.
Fluid flow vector

Fluid flow vector is defined as discharge per unit area i.e. in the unit of velocity. Figure 16 and presents the graph of fluid flow vectors at a depth of 2m below the base of the dam for different positions of a typical 3B/8 from downstream end and for different sheet pile length respectively. It is observed from Figure 16 that maximum flow vector occurs at sheet pile position. For each case the flow vector is increased at the sheet pile position indicating vertical flow along sheet pile. Irrespective of length and position, negative flow vector occurs at the upstream side of sheet pile. The negative signs are due to the fact that fluid flows in the downward direction along the length of sheet pile. At the position of sheet pile there is an abrupt jump of fluid flow vector. At the upstream side of sheet pile, fluid flow vector decreases along the length and at the downstream side of sheet pile it increases with length. It is observed that for the same position of sheet pile in case of different sheet pile length fluid flow vector is maximum for 5 meter length than those for 10m, 15m, 20m length. As sheet pile length increases flow vector reduces indicating quantity of fluid flow is less when sheet pile length is more. Due to this fact the path traced by the percolating water i.e. creep length increases and thereby hydraulic gradient is reduced.
CONCLUSIONS

The following conclusions may be drawn from the present study:
1. Exit gradient reduces with sheet pile length for any particular position of sheet pile when sheet pile position is shifted in rapid drawdown.
2. For a fixed length of sheet pile exit gradient increases when sheet pile position is shifted away from downstream end in rapid drawdown.
3. Sheet pile length increases the seepage path, reducing the exit gradient and hence reduces the chance of piping failure also in rapid drawdown.
4. For a fixed length of sheet pile factor of safety against piping decreases when sheet pile position is shifted away from downstream end.
5. During drawdown, factor of safety drastically decreases when drawdown ratio increases.
6. Pore pressure value within the dam is more if sheet pile is shifted towards the upstream end.
7. Flow vector reduces with increase of sheet pile length.

NOTATION

The followings symbols are used in this paper:

\[
\begin{align*}
B & = \text{Base width of earth dam} \\
C & = \text{Cohesion of soil} \\
E & = \text{Modulus of Elasticity} \\
E' & = \text{Stiffness of Soil} \\
\Phi & = \text{Angle of internal friction} \\
G & = \text{Shear Modulus} \\
K & = \text{Bulk Modulus} \\
K_n & = \text{Normal stiffness of the interface} \\
K_s & = \text{Shear stiffness of the interface} \\
\nu' & = \text{Poisson ratio} \\
\eta & = \text{Porosity} \\
\Delta Z_{\text{min}} & = \text{Minimum width of the neighboring zone}
\end{align*}
\]

REFERENCES

Engineering and Design RETAINING AND FLOOD WALLS.
