CHAPTER 3

ANALYSIS AND DISCUSSION OF RESULTS

3.1 INTRODUCTION

The water stored behind dams always seeks to escape and thus gives rise to various seepage problems, which can create serious difficulties and in some cases may even lead to total failure. The problem of seepage through an earth dam is complicated by the fact that the position of upper boundary or the free surface, commonly known as the top flow line, seepage line, or phreatic surface, is not known beforehand. For an earth dam composed of homogeneous material located on a foundation of impervious material the seepage line will cut the downstream face above the base of the dam, unless of course special drainage measures are adopted. If this line is allowed to intersect the outside downstream face much above the toe more or less serious sloughing may take place and ultimate failure may result. Furthermore an inaccurate estimation of the seepage line may result in predicting pore pressures which are different from those occurring in the actual dam section, and this may lead to calculation of factor of safety in the stability analysis which may be at variance with the actual correct values. The accurate determination of the free surface, therefore, is of prime importance for the safe design of earth dams.

The parameters which determine the profile of a homogeneous earth dam section resting on impervious foundation, and consequently govern the location of top flow line as well as length of
downstream seepage face as shown in Fig. 1.1 are:

(i) Slope of upstream face, $\theta_{u/s}$

(ii) Slope of downstream seepage face, $\theta_{d/s}$

(iii) $X_B/H$

Finite element analysis of 96 earth dam sections was carried out to study the effect of the above parameters on the location of top flow line as well as on the length of downstream seepage face. The results are presented in the form of graphs and are described in the following paras. The above mentioned earth dam sections are formed by various possible permutations and combinations of the following values of the above parameters:

$\theta_{u/s} = 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$

$\theta_{d/s} = 60^\circ, 90^\circ, 135^\circ, 180^\circ$

$X_B/H = 0.8, 1.5, 2.0, 3.0$

Thus, vertical clay core in a rockfill dam as well as homogeneous earth dam sections with internal drainage systems, such as chimney, drain, rockfill toe and downstream horizontal drain are all included in the above 96 earth dam sections analysed in this study.

The first essential in any numerical method is to establish its accuracy and degree of reliability so that the results predicted here in may be used with confidence. The location of top flow line as predicted by the finite element method in case of earth dam with parabolic upstream face, show remarkable agreement
with that obtained from Kozney's theoretical solution. Furthermore the length of downstream seepage face in case of earth dam sections with downstream horizontal drain, as obtained by finite element analysis, and expressed in non-dimensional form as a ratio of depth of upstream reservoir, \( L/H \), are compared with the available theoretical results of the exact solution given by Moayeri\(^0\) for the particular case of seepage through homogeneous earth dams with horizontal toe drain. Here also the results obtained by the finite element analysis, exhibit remarkable agreement with the available theoretical results indicating that the result being reported in this thesis, may be used with confidence to study the effect of the above three parameters on the location of top flow line as well as on the length of downstream seepage face, and may also form a reliable basis for evolving a new method as proposed in Chapter 4 for accurate determination of the true location of top flow line as well as the length of downstream seepage face in case of different types of earth dam sections mentioned above.

The effect of the above three parameters \( \theta_U/S \), \( \theta_D/S \) and \( XB/H \) on (i) the gradient of top flow line in general, (ii) inclination of top flow line to the upstream face at the entry point (This should theoretically be 90°, because the upstream face is an equipotential line), (iii) existence or otherwise of the inflection point, (iv) location of top flow line, and (v) the distance starting point of the curve of top flow line from the entry point are described vide paras 3.2, 3.3 and 3.4 wherein an attempt is also made to search for a logical
explanation of the physical behaviour of top flow line in the above respects. The procedure usually in vogue for determination of seepage line is as proposed by Casagrande, and therefore, the top flow line as obtained by Casagrande's method is also compared with that obtained from finite element analysis of earth dam sections. The variation of length of downstream seepage face with slope of upstream face $\theta_{U/S}$, slope of downstream seepage face $\theta_{D/S}$, and $XB/H$ are described in para 3.3, where a comparison is also made with the length of downstream seepage face as obtained by Casagrande's method. A logical explanation is attempted for the behaviour of the above curves as well as for the difference in true value of length of downstream seepage face as obtained by finite element analysis in this study and that obtained by Casagrande's method.

3.2 LOCATION OF TOP FLOW LINE

3.2.1 Effect of Slope of Upstream Face on the Location etc of Top Flow Line.

The top flow line as obtained by the finite element analysis for 6 different slopes of upstream face of the dam, ranging from a very flat upstream face with $\theta_{U/S} = 15^\circ$ to a vertical upstream face with $\theta_{U/S} = 90^\circ$ are plotted vide Figs. 3.1 to 3.12, for 4 different slope of downstream seepage face $\theta_{D/S} = 60^\circ, 90^\circ, 135^\circ, 180^\circ$ and for 4 different values of $XB/H = 0.8, 1.5, 2.0, 3.0$.

The effect of slope of upstream face of the earth dam on
the inclination of top flow line with the upstream face of the
dam in the region close to the entry point, gradient of top
flow line in most of its length, exisistance or otherwise of the
point of inflection, location of top flow line, location of
starting point of the curve of top flow line with respect to
the entry point, are all visually illustrated and clearly brought
out in the above figures. The various ways in which the slope of
upstream face of the dam affects the location as well as the
nature of the curve of top flow line, are described in the
following paras.

3.2.1.1 Gradient of Top Flow Line in the Central Region

The top flow line for the dam sections, with any particular
value of $\frac{XB}{H}$ and slope of downstream seepage face $\Theta_{D/S}$, but
with 6 different slopes of upstream face of the dam $\Theta_{U/S} = 15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, $90^\circ$ are found to be generally parallel to
each other in most of its length except for a small distance from
the entry point on the upstream face, indicating thereby that the
gradient of top flow line in most of its length remains unaffected,
except for a small length in the region close to the entry point,
as the upstream face of the dam is gradually made steeper, start-
ing from a very flat upstream face inclined at $15^\circ$ to the hori-
zontal i.e. $\Theta_{U/S} = 15^\circ$, and increasing its inclination to the
horizontal at regular intervals of $15^\circ$, till the upstream face
becomes vertical i.e. $\Theta_{U/S} = 90^\circ$.

A perusal of the above 6 curves of top flow line for
different values of $\Theta_{U/S}$, also indicate that for smaller values
of XB/H = 0.8, the gradient of all the above 6 curves is quite steep and as the value of XB/H is increased and made equal to 1.5, 2.0 and finally to 3.0, the gradient of all the above 6 curves which are parallel to each other, gradually becomes flatter (Fig. 3.1 to 3.12).

Therefore, it is safely concluded that the gradient of top flow line in most of its length, except for a small length near the upstream face of the earth dam, is governed mainly by the length of seepage path in that earth dam section as manifested by the value of XB/H, and is largely unaffected by the entry conditions on the upstream face. It may be mentioned here that while evolving a new method capable of accurately predicting the true location of top flow line, as described in the next Chapter, it was observed the curves of top flow for all the 6 slopes of upstream face \( \theta_u/s \), are generally parallel to the base parabola for the earth dam section with that value of XB/H, as for the dam sections to which the above 6 curves of top flow line pertain, but with a vertical upstream face (Para 4.3.1).

3.2.1.2 Entry Condition - Top Flow Line not Normal to the Upstream Face.

The upstream face of an earth dam section is an equipotential line and therefore the phreatic line being the top most stream line should theoretically be normal to the upstream face at the entry point irrespective of any other condition on the downstream side of the dam. However the results of finite element analysis of 96 earth dam section, as plotted vide Fig. 3.1
to 3.12 and 3.31 to 3.54, very clearly and visually indicate that this may be true only for a micro-scopic distance from the entry point and therefore may be considered to be not of any practical significance.

The gradient of top flow line in the small length close to the entry point, in all the 96 earth dam sections is found to be such that it is, in general not normal to the upstream face of the dam. The downward inclination of the top flow line in the region adjacent to the entry point is found to be such that while it is less than the downward inclination of normal to the upstream face for the case of dam sections with flatter upstream faces, it is greater than the downward inclination of the normal to the upstream face for dam sections with very steep upstream faces.

The above mentioned deviation of the top flow line from the normal to the upstream face, in the region adjacent to entry point is also affected by the value of XB/H in the dam section. The downward inclination of the top flow line in the region adjacent to entry point is seen to reduce in case of all the 6 slopes of the upstream face, as XB/H is increased from 0.8 to 3.0, the reduction in downward inclination of top flow line being more pronounced in case of flatter upstream face (Fig. 3.1 to 3.12 and 3.31 to 3.54). Consequently in case of earth dam section with horizontal toe drain the inclination of top flow line to the upstream face, in the region close to entry point, which in the case of earth dam section with flatter upstream face \( \theta_{u/s} = 15^\circ \),
116.3° when XB/H = 0.8 (Figs. 3.2 and 3.49) gradually increases to 144.75 as the value of XB/H is increased to 3.0 (Figs. 3.12 and 3.49). Again in case of earth dam section with vertical upstream face, the top flow line in the region close to the entry point should theoretically be horizontal, but this clearly is not the case as indicated by the results of finite element analysis (Figs. 3.1 to 3.12 and 3.49 to 3.54). The inclination of top flow line to the upstream face, in the region close to entry point, for dam section with vertical upstream face i.e. \( \theta_{U/S} = 90^\circ \) is 75° in case of dam section with XB/H = 0.8 (Figs. 3.2 and 3.54) and gradually increases to 82.7 as the value of XB/H is increased to 3.0 (Figs. 3.12 and 3.54).

The above findings may also be seen from another angle. The slope of upstream face has been varied in this analysis from 15° to 90° to the horizontal. Therefore, the angle between the curves of top flow line in the region adjacent to entry point, for the case of \( \theta_{U/S} = 15^\circ \) and \( \theta_{S} = 90^\circ \) should theoretically be 75°, but the results obtained from finite element analysis indicate that in case of earth dam section with horizontal toe drain it varies from a maximum value of 33.7°, when XB/H = 0.8 (Fig. 3.2) to a minimum value of 12.95°, when XB/H is made equal to 3.0 (Fig. 3.12). It may be mentioned here that as explained in para 3.2.3 different horizontal and vertical scales have been used here. The above angles were measured from large sized drawings plotted to same horizontal and vertical scale.

The above conclusions can be explained as under. It has been shown earlier that the gradient of top flow line in most of
its length, specially in the central region is governed by the length of seepage path as manifested by the value of $XB/H$ and is largely unaffected by the entry conditions. Furthermore, a close examination of the curves showing the location of top flow line for 6 different values of $\theta_{U/S}$, clearly brings out the fact that the inclination of the top flow line in the reach just adjacent to the entry point is significantly affected by the slope of the top flow line in the central portion which is largely governed by the length of seepage path as manifested by the value of $XB/H$. In the case of flatter upstream slope $\theta_{U/S} = 15^\circ, 30^\circ$, when the normal to the upstream face has a greater downward inclination than the slope of top flow line in the central region, the slope of top flow line near the entry point adjusts itself in such a manner that it is somewhere in between the two slopes i.e. that of normal to the upstream face and that of top flow line in the central portion. Thus even for the same slope of upstream face in case of flatter upstream face, say $\theta_{U/S} = 15^\circ$, the downward inclination of top flow line at the entry point is less than that of normal to upstream face in case of $XB/H = 0.8$, and is further reduced in case of $XB/H = 3.0$ (Figs. 3.1 to 3.12, 3.31, 3.37, 3.43 and 3.49).

Similarly, for steeper upstream faces i.e. $\theta_{U/S} = 90^\circ, 75^\circ$, the normal to the upstream face is either horizontal (in case of vertical upstream face), or is inclined downwards at $15^\circ$ to the horizontal (in case of $\theta_{U/S} = 75^\circ$), however the top flow line in the central region has a much greater downward inclination
as governed by the seepage flow consideration, and this causes of the top flow line to dip downwards. For the dam sections with steeper upstream face, but with same slope of upstream face, this deviation from the normal to upstream face, in the gradient of top flow line close to entry point, is more in case of dam section with \( XD/H = 0.8 \), because in that case the gradient of top flow line in the central region is very steep, whereas the above deviation is less in case of dam sections with \( XB/H = 3.0 \), because in that case the gradient of top flow line in the central region is comparatively much flatter (Fig. 3.1 to 3.12 and 3.35, 3.36, 3.41, 3.42, 3.47, 3.48, 3.53, 3.54).

Now, in between the two extreme cases, one of a flatter upstream face, \( \theta_{US} = 15^\circ \), and the other of a very steep upstream face \( \theta_{US} = 90^\circ \), there should be a upstream slope, in which case the normal to the upstream face, has the same gradient as that of the central portion of the top flow line, and in such a dam section the top flow line will be exactly normal to the upstream face at the entry point. Obviously such as upstream slope, for which the top flow line is normal to the upstream face at the entry point, will depend on the gradient of top flow line in the central region, which in turn is governed by the value of \( XB/H \). Thus for a dam section with smaller value of \( XB/H = 0.8 \), such a slope of upstream face, for which the top flow line is normal to the upstream face at the entry point, is seen from Fig. 4.2 to be a value close to but slightly less than \( 60^\circ \), whereas for the dam section with a large value of \( XB/H = 3.0 \), the slope of upstream face, for which the top flow line is normal to the upstream
face at the entry point, is seen from Fig. 4.12 to be a value somewhere between 75° and 90°.

3.2.1.3 Existance or otherwise of the Inflection Point

The effect of the slope of upstream face of an earth dam on the existence or otherwise of the point of inflection is visually illustrated and is very clearly brought out in Figs. 4.1 to 4.12, where curves of top flow line for 6 different slopes of upstream faces are plotted for comparison, for earth dam sections with different values of $\theta_D/S$ and $XB/H$. In case of an earth dam section with a very flat upstream face $\theta_U/S = 15^\circ$, the point of inflection is very well defined, but as the upstream face is made steeper the inflection point is seen to vanish. This phenomenon is explained as under.

In case of an earth dam with a very flat upstream face $\theta_U/S = 15^\circ$, the seepage water enters the dam section with a much greater downward inclination and so the gradient of the top flow line at the entry point, (which otherwise also should theoretically be normal to the upstream face which is an equipotential line) is quite large. After a certain small distance from the entry point, when the top flow line has dipped to a somewhat lower elevation, it downward inclination is reduced substantially, because here the gradient of top flow line, now in the central region a small distance away from the upstream face of the dam, is mainly governed by the length of seepage path in the earth dam section as manifested by the value of $XB/H$ and is largely unaffected by the entry and exit conditions.
A comparatively large downward inclination of the top flow line in the small length adjacent to the entry point, and then the substantially reduced gradient of the top flow line immediately thereafter in the central region, coupled with the fact that after this point the gradient of top flow line gradually increases for points on the downstream side, manifests itself in the development of the point of inflection in the curve of top flow line, in case of an earth dam sections with a very flat upstream face. As the upstream face of the dam is made steeper, the downward inclination of the top flow line in the region adjacent to the entry point reduces gradually, whereas the gradient of top flow line in the central region remains largely unaffected by the change in the entry condition. The above facts explain the reduction in the magnitude of infection as the upstream face is made steeper till it is completely eliminated and inflection point vanishes, in case of an earth dam section with horizontal toe drain, and an upstream face with a value of $\theta_{U/S}$ which is very close to but is slightly less than 60°, in case of earth dam section with $XB/H = 0.8$ (Fig. 3.2), as well as in the case of earth dam section with a value of $\theta_{U/S}$ some where between 75° and 90° in case $XB/H$ equals 3.0 (Fig. 3.12). For the above slopes of the upstream face of the dam, the downward inclination of the top flow line, in the region adjacent to the entry point reduces significantly and to such an extent that it now equals the slope of the top flow line in the central portion, which being mainly governed by the length of seepage path only, remains largely unaffected by any change in entry condition, and this results in elimination of contraflexure and disappearance of
inflection point in the above earth dam sections.

When the upstream face of an earth dam is made still steeper, the downward inclination of top flow line in the region adjacent to the entry point is reduced further to such an extent that this downward slope now becomes less than the slope of top flow line in the central region which as described earlier remains largely unaffected by the entry condition. Thus in earth dam sections with very steep upstream face i.e. \( \theta y/\delta \) greater than 60° in case of dam section with \( XB/H = 0.8 \) and \( \theta y/\delta \) close to 90° in case of dam section with \( XB/H = 3.0 \), the downward inclination of top flow line which is comparatively small in the beginning, that is in the region adjacent to the entry point, gradually increases for points on the downstream side, resulting in an upward convex shape of the phreatic line in this region.

Mayoris\(^{20}\) has obtained an exact solution to the problem of seepage through homogeneous and isotropic earth dams with horizontal toe drain, and has given the value of slope of upstream face at which the inflection point disappears in case of dam section with different values of \( XB/H \). His theoretical results indicate that in an earth dam section with \( XB/H = 0.8 \), the inflection point disappears in case the slope of the upstream face is made equal to 58.5°. This theoretical result agrees with the findings of the finite element analysis as reported earlier in this para, and this gives a further indication of the accuracy and reliability of the results being reported in this thesis.
3.2.1.4 Location of Top Flow Line

The effect of slope of upstream face, on the location of top flow line in earth dam sections, is visually illustrated and is clearly brought out from the plots of top flow line for 6 different slopes of upstream face, as shown in Figs. 3.1 to 3.12, in case of dam sections with different $\theta_{U/S}$ and $XB/H$.

As the slope of upstream face of the dam is made steeper, the location of top flow line is seen to shift upwards in the central portion and in the downstream direction in the region close to exit point. This upward shift in the location of top flow, consequent to the upstream face of the dam being made steeper, is seen to depend on the length of seepage path as manifested by the value of $XB/H$ in that earth dam section. Thus, this shift in the location of top flow line, as the slope of upstream face is increased from $\theta_{U/S} = 15^0$ to $\theta_{U/S} = 90^0$, is seen to be quite large in case of earth dam section with $XB/H = 0.8$ (Figs. 3.1 and 3.2), but decreases gradually as the value of $XB/H$ is increased and has a minimum value of less than half, in case of dam section with $XB/H = 3.0$ as compared to that of the shift in the dam section with $XB/H = 0.8$ (Figs. 3.3 to 3.12).

Furthermore, this shift in the location of top flow line due to upstream face being made steeper, is small in case of earth dam sections with flatter upstream face, but increases progressively as the upstream face is made steeper, as manifested by the progressively increasing gap between the 6 curves of top flow line for different values of $\theta_{U/S}$ which is varied from $\theta_{U/S} = 15^0$. 
to $\theta_{U/S} = 90^\circ$ by increasing its value at a constant interval of $15^\circ$. The above phenomenon is explained as under.

As discussed in earlier paras the gradient of top flow line is mainly governed by the length of seepage path in an earth dam section as manifested by the value of $X_B/H$ and is largely unaffected by entry conditions. However the location of the top flow line in the central and the downstream region is clearly affected by the slope of upstream face of the dam. This fact is quite obvious. In case of earth dam sections with flatter upstream face, in which the downward inclination of the top flow line in the region close to the entry point, is more than its downward inclination in the central region, the top flow line dips considerably downwards before attaining the slope of the top flow line in the central region. This explains the fact, as observed from the above figures, of the location of top flow line in case of a very flat upstream face $\theta_{U/S} = 15^\circ$, being at the lowest elevation amongst all the 6 curves of top flow line. Now as the upstream face is made steeper this downward inclination of top flow line in the region close to entry point is reduced and consequently the amount by which the top flow line dips downwards, before attaining the slope of top flow line in the central region, is also reduced. This results in an upward shift in the location of top flow line as the upstream face is made steeper. Furthermore in case of earth dam sections with very steep upstream face in which the downward inclination of top flow line in the region close to the entry point is less than the downward inclination of the top flow line
in the central region, the top flow line travels a certain small distance at a comparatively higher elevation before attaining the larger downward inclination of the top flow line in the central region, and this has the effect, so to say, of lifting up of the curve of top flow line and explains the upward shift in location of top flow line in case of dam section with steeper upstream face.

Now as described vide para 3.2.1.2 the top flow line in the region close to the entry point, except for a microscopic distance, is in general not normal to the upstream face of the dam and that its gradient in this region is greatly affected by the gradient of top flow line in the central region. Thus even though the slope of the upstream face $\theta_{US}$ is increased at a constant interval of $15^\circ$, the reduction in the downward inclination of the top flow line in the region close to entry point is not uniform, being small in case of earth dam section with flatter upstream face and gradually increasing as the upstream face is made steeper. This greater reduction in the downward inclination of top flow line in the region close to entry point, in case of steeper upstream face, results in increasing the upward shift in the location of the top flow line as the upstream face of the dam is gradually made steeper, and this explains the progressively increasing gap between the curves of top flow line, as the upstream face of the earth dam is gradually made steeper, by increasing the value of $Q_{US}$ at a constant interval of $15^\circ$, from $\theta_{US} = 15^\circ$ to $\theta_{US} = 90^\circ$. 
3.2.1.5 Starting point of curve of Top Flow Line

Although as described later vide para 3.2.4 the true location of top flow line as obtained by the finite element analysis of 96 earth dam sections, differ widely from Cosagrande's base parabola in case of a very large number of earth dam section, the curves of top flow line in all cases resemble to a very large extent the shape of a parabola. In the course of attempts being made for evolving a new method for correctly predicting the true location of top flow line, as described in Chapter 4, it was discovered that in case of earth dam sections with a particular value of XB/H, all the curves of top flow line, irrespective of the slope of upstream face, as well as that of downstream seepage face, are in general parallel to the base parabola for earth dam section with the above value of XB/H, but with a vertical upstream face.

The forgoing discussion leads to the unescapable conclusion that the contention by Cassagrande that the curve of top flow line passes through a point on the water surface at a distance in front of the dam equal to 0.3 times the horizontal wetted face length, is just not true. This fact is crystal clear, because in an earth dam section with horizontal toe drain, with particular value of XB/H, if the curve of top flow line would have even approximated a parabola whose focus is at the beginning of the toe drain and which passes through a point on the water surface at a distance in front of the entry point equal to 0.3 times the wetted horizontal face length, the curves of top flow line for 6 different slopes of upstream face would not have been parallel to each other, because
the location of the above mentioned point on the water surface, differ very widely in earth dam sections with different slopes of upstream face.

In fact in case of earth dam sections with a particular value of $XB/H$, the top flow line for different slopes of upstream face of the dam, appear to follow a curve obtained by horizontal shifting of the base parabola in an earth dam section with the above value of $XB/H$ but with a vertical upstream face.

The distances from the entry point on the upstream face, of the point at the elevation of water surface through which the curve of top flow line (ignoring the small length in the region close to entry point), appears to pass, in case of earth dam sections with horizontal toe drain and having upstream reservoir depth $H = 100$ m, are given in Table 3.1, for different values of $\Theta_{U/S}$ and $XB/H$. The corresponding distance i.e. $0.3 \times H \cot \Theta_{U/S}$ as suggested by Casagrand is also given for comparison. These values, were obtained from plots of top flow line on large size graph sheets with equal horizontal and vertical scale.
TABLE - 3.1

Horizontal Distance from the entry point, of the points at the elevation of water Surface through which the Curve of top flow line in an earth dam section having reservoir depth equal to 100 m and with horizontal toe drain, appears to pass.

<table>
<thead>
<tr>
<th>$\theta_{u/s}$</th>
<th>$0.3 , H , \cos , \theta_{u/s}$ (after A.Casagrande)</th>
<th>$X_B/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>-111.96</td>
<td>-8.80</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>-51.96</td>
<td>-5.40</td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>-30.00</td>
<td>-2.00</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>-17.3205</td>
<td>+0.4</td>
</tr>
<tr>
<td>$75^\circ$</td>
<td>-8.04</td>
<td>+3.60</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>+0</td>
<td>+8.20</td>
</tr>
</tbody>
</table>

(+) indicates location down stream of entry point.

(-) indicates location upstream of entry point.
The finite element results tabulated above clearly indicate that the distance of starting point of the curve of top flow line at the elevation of water surface (neglecting the small length close to entry point), from the entry point i.e. from the point of intersection of water surface with upstream face of the dam is much below the value of 0.3 H Cot $\Theta_{U/S}$ as suggested by Cassagrande. Furthermore the above starting point of curve of top flow line is not always located on the upstream side of the entry point. In fact in case of earth dam sections with very steep upstream face, the above starting point of the curve of top flow line is seen to be located on the downstream side of the entry point.

3.2.2 Effect of Slope of Downstream Seepage Face on the Location of Top Flow Line.

The top flow line as obtained in case of earth dam sections for 4 different slopes of the downstream seepage face, $\Theta_{D/S} = 60^\circ$ representing vertical core in a rockfill dam, $\Theta_{D/S} = 90^\circ$ representing chimney drain, $\Theta_{D/S} = 135^\circ$ representing rockfill toe, and $\Theta_{D/S} = 180^\circ$ representing horizontal toe drain, in a homogeneous earth dam section, are plotted vide Figs. 3.13 to 3.30, for 6 different slopes of upstream face $\Theta_{U/S} = 15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, $90^\circ$ and for 4 different values of $XB/H = 0.8$, $1.5$, $2.0$, $3.0$.

The effect of slope of downstream seepage face of an earth dam, howsoever minimal or indirect, on the downward inclination of the top flow line in the region close to the entry point, the gradient of top flow line in most of its length, existence or
otherwise of the point of inflection, location of top flow line, location of starting point of the curve of top flow line with respect to entry point, are visually illustrated in the above figures. A close examination of the above Figs. 3.13 to 3.30 indicates that the curves of top flow line for all the 4 different values of $\Theta_{D/S}$, are very close to each other, and even coincide with each other in many cases. This leads to the unescapable conclusion that as compared to the other two parameters the exit condition as manifested by the slope of downstream seepage face $\Theta_{D/S}$ has very little effect on the location etc of the top flow line. These are briefly described below in the following paras.

3.2.2.1 Gradient of Top Flow Line in the Central and Downstream Region.

The exit condition as manifested by the slope of downstream seepage face $\Theta_{D/S}$ affects the gradient of top flow line, only in the region close to the exit point as indicated by the curves of top flow line plotted vide Figs. 3.13 to 3.30. The extent of this increase in the gradient of top flow line, consequent to the downstream seepage face being tilted in the upstream direction also appears to be related to a certain extent to the length of seepage path in that earth dam section as manifested by the value of $XB/H$. These observations are briefly explained as under.

Starting from horizontal toe drain $\Theta_{D/S} = 180^\circ$, as the downstream seepage face is made vertical as in the case of chimney drain, and is finally made to incline in the upstream direction as in the case of vertical core, the gradient of top
flow line in the region close to the exit point is seen to increase by a certain amount depending upon the value of $XB/H$ in that earth dam section. This increase in the downward inclination of the top flow line in the region close to exit point, on account of the downstream seepage face being either made vertical as in the case of chimney drain in an earth dam section or made to incline in the upstream direction as in the case of vertical core, appears to be a direct consequence of shortening of the length of seepage path, because in both the above cases the downstream seepage face intercepts the top flow line at a much higher elevation, resulting in considerable reduction in the length of seepage path as well as in the consequent increase in the gradient of top flow line in the region close to exit point.

Furthermore, this increase in the gradient consequent to inclination of $\theta_{D/S}$ being varied from $180^\circ$ to $90^\circ$ and finally to $60^\circ$, is more prominent in case of dam section with $XB/H = 0.8$, so much so that a considerably larger length of top flow line on the downstream side is affected by this increased gradient. The reason for the above fact is quite obvious. In case of earth dam sections with the value of $XB/H = 0.8$, the reduction in the length of seepage path consequent to the downstream seepage face being made to incline in the upstream direction, is a much greater fraction of the total length of seepage path, and therefore the effect of slope of downstream seepage face $\theta_{D/S}$ on the gradient of top flow line is clearly visible on a much greater length of
top flow line as indicated by the plots of top flow line (Figs. 3.13 to 3.15). However, on the contrary, in case of an earth dam section with a large value of XB/H = 3.0, the length of seepage path is quite large and therefore the reduction in the length of seepage path consequent to the downstream seepage face being made to incline in the upstream direction as in the case of vertical core, is comparatively a much smaller fraction of the total length of seepage path, and therefore the effect of slope of downstream seepage face on the gradient of top flow line is comparatively less pronounced and is limited to a relatively smaller portion of the total length of top flow line (Figs. 3.25 to 3.30).

The curves of top flow line in case of earth dam section with rockfill toe $\Theta_D/S = 135^\circ$, and for the case of horizontal toe drain $\Theta_D/S = 180^\circ$, are so close to each other that they seem to coincide in most of the length. This also can be explained on the basis of above discussion, because in an earth dam section with a particular value of $\Theta_U/S$ and XB/H, there is practically no significant reduction in the length of seepage path as the value of $\Theta_D/S$ is changed from $180^\circ$ to $135^\circ$, and consequently there is only negligible effect on the gradient of top flow line in this case.

3.2.2.2 Inclination of Top Flow Line to the Upstream Face.

As described in para 3.2.2.1 the effect of slope of downstream seepage face $\Theta_D/S$, on the top flow line in an earth dam section is comparatively much less pronounced, than that of the
other two parameters, and that too is generally limited to the length of top flow line in the downstream portion of the dam, except in the case of vertical core ($\Theta_D/S = 60^\circ$) with a smaller value of $XB/H$, in which case practically the whole length of top flow line appears to be affected and is somewhat lowered as the downstream seepage face is made to incline in the upstream direction (Figs. 3.13 to 3.15). The reason for the above observation is obvious. In case of earth dam section with a small value of $XB/H = 0.8$, as the downstream seepage face is made to incline in the upstream direction in case of vertical core, the length of seepage path is drastically reduced and so the whole length of top flow line is affected and its elevation is somewhat lowered.

Thus the slope of downstream seepage face do not have any affected on the inclination of top flow line with the upstream face, except in case of vertical core ($\Theta_D/S = 60^\circ$) with a small value of $XB/H = 0.8$, in which case also there is only a minimal increase in the downward inclination of the top flow line in the region close to entry point.

3.2.2.3 Existance or otherwise of Inflection Point

Since, as described in earlier paras 3.2.2.1 and 3.2.2.2, the effect of slope of downstream seepage face $\Theta_D/S$ is limited only to the downstream portion of the top flow line, it has no effect on the existance or otherwise of the inflection point (Figs. 3.13 to 3.30).
3.2.2.4 Location of Top Flow Line.

As discussed in para 3.2.2.1, starting from the case of earth dam with horizontal toe drain, as the downstream seepage face is made vertical \( \theta_{D/S} = 90^\circ \) as in case of chimney drain and is then finally inclined in the upstream direction \( \theta_{D/S} = 60^\circ \) as in the case of vertical core, the length of seepage path is reduced, and this consequently results, in general lowering the elevation of top flow line in the downstream region. Obviously, this lowering in the elevation of top flow line is more pronounced and a comparatively larger proportion of the length of top flow line is affected by this phenomenon of lowering in the elevation of top flow line, as a consequence of the downstream seepage face being made to incline in the upstream direction, in case of earth dam section with a smaller value of \( XB/H = 0.8 \), because in such an earth dam section the reduction in the length of seepage path due to the value of \( \theta_{D/S} \) being varied from \( 180^\circ \) to \( 90^\circ \) and finally to \( 60^\circ \), is a very significant fraction of the total length of seepage path in that earth dam section (Fig. 4.13 to 4.15). On the contrary in case of earth dam section with a very large value of \( XB/H = 3.0 \), any reduction in the length of seepage path consequent to the downstream seepage path being made to incline in the upstream direction, is a considerably much smaller fraction of the total length of seepage, as compared to the earlier case, and hence its effect on the location of top flow line is now not only minimal but is
confined only to a very small length close to exit point.

3.2.2.5 Starting Point of Curve of Top Flow Line.

Since as described earlier vide paras 3.2.2.1 and 3.2.2.2, the top flow line in the region close to the entry point is not affected by the slope of downstream seepage face. The starting point of the curve of top flow line at the elevation of reservoir water surface, which is obtained by extending the curve of top flow line from the point of inflection or in cases where point of inflection do not exist from the point on the top flow line where the effect of entry condition vanishes, therefore, is also not affected by the slope of downstream seepage face.

3.2.3 Effect of $XB/H$ on the location etc of Top Flow Line.

The curves of top flow line as obtained by the finite element analysis of 96 earth dam sections are plotted for 4 different values of $XB/H = 0.8, 1.5, 2.0, 3.0$ vide Figs. 3.31 to 3.54, for 6 different slopes of upstream face $\theta_{u/s} = 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$ and for 4 different slopes of downstream seepage face $\theta_{D/S} = 60^\circ, 90^\circ, 135^\circ, 180^\circ$. In order to accommodate the curves of top flow line for dam sections with all the four values of $XB/H = 0.8, 1.5, 2.0, 3.0$, on the same page to facilitate comparison, these curves of top flow line are plotted with different scales in vertical and horizontal directions. Thus the vertical scale is slightly more than twice of that in
the horizontal direction.

The value of X/B/H in an earth dam section is a direct manifestation of the length of seepage path in that dam section, and therefore it almost completely governs the average gradient of the top flow line in the central region, and consequently has a very major influence on the downward inclination of top flow line in the region close to entry point, existence or otherwise of the point of inflection, location of top flow line, and the location of starting point of the curve of top flow line with respect to the entry point. The effect of the value of X/B/H on the top flow line in respect of all the above points is visually illustrated and clearly brought out in the above figures.

The curves of top flow line in case of all the above 96 earth dam sections, as obtained by the method suggested by Casagrande are also plotted in the above figures, to facilitate comparison with the true location of top flow line as predicted by the finite element analysis of earth dam sections. The necessary calculations were carried out and plots obtained on VAX-11/780 DEC Computer Dot Matrix Printer and hence the three components which form the basis for obtaining the curve of top flow line in the Casagrande's method, i.e. (i) normal to upstream face at entry point, (ii) base parabola for that dam section, and (iii) location of exit point on the downstream seepage face, are plotted
separately in the above figures. The entrance and exit conditions are adjusted by sketching two smooth arcs by hand, one tangent to the base parabola in the upstream region and normal to upstream face at entry point, and the other tangent to base parabola in the downstream region and intersecting the downstream seepage face at exit point, either tangentially in cases where $\theta_{D/S} \leq 90^\circ$ or vertically where $\theta_{D/S} > 90^\circ$.

The various ways in which the value of $XB/H$ in an earth dam section affects the location etc of the top flow line are described in the following paras.

3.2.3.1 Gradient of Top Flow Line in the Central Region.

The plots of top flow line in earth dam section with 4 different values of $XB/H = 0.8, 1.5, 2.0, 3.0$ as shown in Figs. 3.31 to 3.54. Separately for different values of $\theta_{U/S}$ and $\theta_{D/S}$, are a clear and visual illustration of the very major influence of the length of seepage path as manifested by the value of $XB/H$ in an earth dam section, on the gradient of top flow in most of its length in the central region. In case of earth dam sections with horizontal toe drain, and with a vertical upstream face $\theta_{U/S} = 90^\circ$, the average gradient of top flow line in the central portion in case of earth dam section with $XB/H = 0.8$ is nearly 3.298 times to that of the average gradient of top flow line in the central portion in case of earth dam section with the value of $XB/H = 3.0$. In case of earth dam section with very flat upstream face $\theta_{U/S} = 15^\circ$, 
the upstream triangular portion of the earth dam is also added to the flow region, and this has the effect of increasing the length of seepage path and consequently increasing the gradient of top flow line. This effect is minimal in case of earth dam section with \( XB/H = 3.0 \), but is comparatively more prominent in case of earth dam section with \( XB/H = 0.8 \). Thus in the above example of earth dam with horizontal toe drain, with a very flat upstream face \( \theta_{u/s} = 15^\circ \), the average gradient of top flow line in the central region in case of earth dam section with \( XB/H = 0.8 \) is now 3.465 times the average gradient of top flow line in the central region of earth dam with \( XB/H = 3.0 \).

It has been shown earlier vide para 3.2.1.1 that the slope of upstream face has practically no influence on the gradient of top flow line in the central region, and curves of top flow line in an earth dam section with a particular value of \( XB/H \) and \( \theta_{u/s} \) remain parallel to each other as the upstream face is gradually made steeper. Further more, as described in para 3.2.2.1, slope of the downstream seepage face also is found to have practically no influence on the gradient of top flow line in the central region, except in case of vertical core section with a very small value of \( XB/H = 0.8 \), where also the effect is only minimal and is a direct consequence of reduction in the length of seepage path as the downstream seepage face is made to incline in the upstream direction. In the light of above observations it can safely be concluded the value of \( XB/H \) in an earth dam section is the main factor which governs
and has a very major influence on the average gradient of top flow line in most of its length. As the value of \(XB/H\) in an earth dam section is gradually increased from 0.8 to 3.0 the gradient of the top flow lines in the central region changes from a very steep gradient to a comparatively much flatter gradient (Figs 3.31 to 3.54).

3.2.3.2 Inclination of Top Flow Line to the Upstream Face.

The upstream face of an earth dam section is an equipotential line and therefore the phreatic line being the top most stream line should theoretically be normal to the upstream face at the entry point irrespective of any other condition in the downstream portion of the dam. However the results of finite element analysis of 96 earth dam sections, as plotted vide Figs 3.31 to 3.54, very clearly and boldly, visually illustrate that this may be true only for a microscopic distance from the entry point.

In each of the above figures, curves of top flow line for earth dam section for all the 4 values of \(XB/H = 0.8, 1.5, 2.0, 3.0\), but with a particular value of \(\theta_{u/s}\) and \(\theta_{D/S}\) are plotted. It is seen that although the slope of upstream face \(\theta_{u/s}\) is same for all the 4 earth dam sections plotted in each graph, the downward inslination of top flow line in the small region close to the entry point on the upstream face, in all the 4 earth dam sections differ very widely from each other,
as well as from the normal (shown dotted) to the upstream face at the entry point. The above observations are explained as under.

In case of earth dam sections with a very flat upstream face, the gradient of the top flow line in the central portion, is less in case of all 4 values of \( X_B/H = 0.8, 1.5, 2.0, 3.0 \), than the very steep downward inclination of normal to the upstream face at the entry point (shown dotted). Consequently, the top flow line after following the normal to the upstream face for a microscopic distance (not visible in the plots of top flow line), tries to attain the much flatter slope of central portion of top flow line, in a very short distance and this explains marked reduction in the downward inclination of the top flow line in the region close to entry point, as the value of \( X_B/H \) is gradually increased from 0.8 to 3.0.

Now, in case of earth dam sections with very steep upstream face \( \theta_{u/s} = 90^\circ, 75^\circ \) the normal to the upstream face at the entry point is either horizontal or has a very flat downward inclination, and in contrast the top flow line in the central portion in case of all the four values of \( X_B/H \), has a comparatively steeper gradient. Consequently the top flow line after following the normal to the upstream face for a microscopic distance (not visible in the plots of top flow line), tries to attain in a very short distance the comparatively steeper gradient of the top flow line in the central region, which in
turn is governed only by the value of $XB/H$ in that dam section. Thus in case of earth dam sections with steep upstream face, also, the downward inclination of top flow line in the region close to entry point decreases, although the slope of upstream face $\theta_{u/s}$ remains unchanged, just like that as in the central portion as the value of $XB/H$ is gradually increased from $0.8$ to $3.0$.

As described earlier the gradient of top flow line in the central region is governed only by the value of $XB/H$. Also the gradient of top flow line in the region close to the entry point is somewhere in between that of the normal to the upstream face and that of the central portion of top flow line. This explains the fact that as the upstream face in an earth dam section is made steeper the downward inclination of top flow line in the region close to entry point is reduced but by a significantly smaller amount as compared to the increase in the steepness in the slope of the upstream face. Thus in case of earth dam section with downstream horizontal toe drain, as the upstream face is gradually made steeper and the value of $\theta_{u/s}$ is increased by $75^\circ$, from a very flat upstream face $\theta_{u/s} = 15^\circ$ to a vertical upstream face $\theta_{u/s} = 90^\circ$, the variation in the downward inclination of top flow line in the small region close to entry point, theoretically should also be equal to $75^\circ$, but the results of finite element analysis of earth dam sections indicate that this variation is only $33.7^\circ$ in case of earth dam section with $XB/H = 0.8$ and further.
reduces to $12.95^\circ$ in case the value of $XB/H$ is increased to 3.0 (Figs 3.49 to 3.54).

3.2.3.3 Existance or Otherwise of Inflection point.

The phenomenon causing the development of inflection in the curve of top flow line in the region close to entry point has also been described earlier vide para 3.2.1.3.

Except for a very small length that too in case of earth dam section with flatter upstream face, the top flow line resembles the shape of a parabola and follows a curve which is convex upwards. Therefore, for the existance of inflection point the gradient of top flow line in the small region close to the entry point, should be steeper than the average gradient of top flow line in the central portion, so that as this curve of top flow line in the region close to upstream face gradually attains the flatter slope of top flow line in the central region as it travels on the downstream side, it attains a concave upward shape and consequently results in the development of inflection point.

Therefore, obviously the inflection point will vanish in case of earth dams with steeper upstream face in which the gradient of top flow line in the region close to the entry point is equal to or flatter than the slope of top flow line in the central region, which in turn is governed only by the value of $XB/H$ in that earth dam section, and decreases
significantly as XB/H is increased from 0.8 to 3.0. The above observations explain the fact that in case of earth dam sections with smaller value of XB/H = 0.8, the inflection point vanishes in case of earth dam section with a value of $\theta_{u/s}$ which is slightly less than 60°, whereas in case of earth dam section with a greater value of XB/H = 3.0, the inflexion point vanishes in case of dam section with a more steeper upstream face with the value of $\theta_{u/s}$ somewhere between 60° and 75° (Figs. 3.49 to 3.54).

3.2.3.4 Location of Top Flow Line.

The effect of the value of XB/H on the location of top flow line is so large and prominent, as visually illustrated by the plots of top flow line for four different values of XB/H, that any attempt to describe it in words seems superfluous (Figs. 3.31 to 3.54). This behaviour of top flow line as the value of XB/H is increased from 0.8 to 3.0 is obvious and quite expected. As described vide para 3.2.3.1, as the value of XB/H is increased from 0.8 to 3.0 in case of an earth dam section with vertical upstream face for example, the average gradient of top flow line in the central region is reduced to less than one third of the former value. This explains the large upward shifting of top flow line in the central region as the value of XB/H is increased from 0.8 to 3.0 in an earth dam section.
3.2.3.5 Starting point of Curve of Top Flow Line.

The distance of starting point of curve of top flow line at the elevation of reservoir water surface from the entry point, in case of earth dam section with reservoir depth 100m and with horizontal toe drain are given in Table 3.1 (para 3.2.1.5), for all the 6 values of $\theta_u/s$ and all the 4 values of $XB/H$. The discussion in this regard of para 3.2.1.5 is not being repeated here. However it may be pointed out that as the value of $XB/H$ is increased from 0.8 to 3.0, the location of the starting point of the curve of top flow line shifts slightly towards the upstream (Table 3.1). This is a direct consequence of the large amount of reduction in the average gradient and upward shifting of top flow line as $XB/H$ is increased from 0.8 to 3.0.

3.2.4 Top Flow Line as obtained by Casagrande's Method - Comparison with the True Location as predicted by finite element analysis.

The procedure usually in vogue for determination of seepage line is proposed by Casagrande, who by graphical sketching showed that the computed seepage line approximates quite closely the "base parabola" established by Kozany for the free surface in an earth dam on an impervious base with a parabolic upstream face and a downstream horizontal under-drain, with departures therefrom due to the local condition of
ingress and egress. Casagrande, on the basis of graphical studies by means of flownet, in case of earth dams of trapezoidal cross sections, gave the location of starting point of the parabola, on the water surface at a distance in front of dam equal to 0.3 times the horizontal wetted face length ie 0.3 H Cot θ_u/s. The assumed parabolic shape results from the Dupuit approximation that the hydraulic gradient is constant for any vertical section and equal to the slope of phreatic line. Casagrande also suggested a correction to be applied at the lower end of the base parabola.

Casagrande's method, probably because of its simplicity has been widely used in engineering practice. Therefore, it is considered prudent to compare the location of top flow line calculated by this method with the true location of the top flow line as obtained by the finite element analysis of earth dam sections. Thus the curves of top flow line as obtained by the finite element analysis of 96 earth dam sections as well as those obtained by the method suggested by Casagrande, are plotted vide Figs. 3.31 to 3.54, to facilitate comparison, for 4 different values of XB/H = 0.8, 1.5, 2.0, 3.0, for 6 different values of θ_u/s = 15°, 30°, 45°, 60°, 75°, 90°, and for 4 different values of θ_D/s = 60°, 90°, 135°, 180°. The required calculations were carried out and plots were obtained on VAX-11/780 DEC Computer Dot Matrix Printer and hence the three components which form the basis for obtaining the curve of top line in the Casagrande's method, ie.,
(i) normal to upstream face at entry point, (ii) base parabola for that dam section, and (iii) location of exit point on the downstream seepage face, are plotted separately in the above figures. The entrance and exit conditions are adjusted by sketching two smooth arcs by hand, one tangent to the base parabola in the upstream region and normal to upstream face at entry point, and the other tangent to base parabola in the downstream region and intersecting the downstream seepage face at exit point, either tangentially in cases where \( \theta_{D/S} \leq 90^\circ \) or vertically in cases where \( \theta_{D/S} > 90^\circ \).

In order to accommodate the curves of top flow line for dam sections with all the four values of \( XB/H = 0.8, 1.5, 2.3, 3.0 \), on the same page to facilitate comparison, these curves of top flow line are plotted with different scales in vertical and horizontal directions. Thus the vertical scale is slightly more than twice of that in the horizontal direction.

In case of earth dam sections with flatter upstream face say with \( \theta_{u/s} = 15^\circ, 30^\circ \), the top flow line as calculated by Casagrande's method is seen to be much below the true location of top flow line as obtained by the finite element analysis of that earth dam section, irrespective of the slope of downstream seepage face. This difference in the location of the top flow line as obtained by the above two methods is quite large in case of earth dam section with smaller value of \( XB/H = 0.8 \), but reduces gradually in magnitude as the value
of \( XB/H \) is increased to 1.5, 2.0 and finally to 3.0. Since the effect of exit conditions is absent in case horizontal toe drain comprising the downstream seepage face, such earth dam sections will now be considered first of all. As the upstream face is made steeper in case of earth dam section with horizontal toe drain, the gap between the curves of top flow obtained by the above two methods gradually decreases till it reaches a minimum value in case of earth dam section with \( \theta_{w/s} = 60^\circ \), so much so that the two curves seem to coincide in most of its length in the downstream region in case of earth dam section with value of \( XB/H \geq 1.5 \). When the upstream face is made still steeper with \( \theta_{w/s} = 75^\circ \) or \( 90^\circ \), this gap between the curves of the top flow line as obtained by the two methods is now seen to increase slightly. However it may be mentioned that the top flow line as calculated by the Casagrande's method is in all cases seen to be below the true location of top flow line as obtained by the finite element analysis of earth dam sections. Thus even in case of slope of upstream face \( \theta_{w/s} = 60^\circ \), when the top flow line obtained by the two methods seem to coincide in the downstream portion in case of earth dam section with \( XB/H \geq 1.5 \), the top flow line calculated by Casagrande's method is seen to be somewhat below the true value of top flow line in the upstream portion (Fig. 3.52).

Almost similar behaviour is observed in case of earth dam sections with downstream rockfill toe i.e
\( \theta_{D/S} = 135^\circ \), because here in this case the length of seepage path is only marginally less than that in the case of downstream horizontal drain and consequently the location top flow line as obtained by the finite element analysis nearly coincides for both cases of \( \theta_{D/S} = 180^\circ \) and \( 135^\circ \) and the Casagrande’s base parabola is not governed by the slope of downstream seepage face and any departure due to the local condition of egress is only minimal in this case (Fig. 3.43 to 3.48).

Now, as the downstream seepage face is made vertical \( \theta_{D/S} = 90^\circ \) as in case of chimney drain and then is made to incline in the upstream direction \( \theta_{D/S} = 60^\circ \) as in case of vertical core in a rockfill dam, the length of seepage path is reduced slightly and this consequently results in slight lowering of the elevation of true location of top flow line as obtained by the finite element analysis, in the downstream portion, the effect being comparatively more prominent in case of earth dam section with smaller value of \( \frac{XB}{H} = 0.8 \) (Para 3.2.2.4). However on the other hand, although the base parabola is not governed by the slope of downstream seepage face, but the departure therefrom due to local condition of egress is quite significant, due to the large correction which is applied to the intercept between the focus and point of intersection of base parabola with downstream seepage face, as suggested by Casagrande, to obtain the location of exit point. Thus in cases where \( \theta_{D/S} \leq 90^\circ \), the top flow line as obtained
by Casagrande is significantly lowered in the small length close to exit point. This effect is clearly visible in the plots of top flow line as obtained by the above two methods in case earth dam sections with $\theta_{D/S} \leq 90^\circ$. Thus unlike the case of earth dam section with downstream horizontal drain where the gap between the curves of top flow line as calculated by Casagrande's method and that obtained by the finite element analysis, as shown in Figs 3.49 to 3.54 is minimum at the exit point and gradually increases for points in the upstream region, the gap between the curves of top flow line as obtained by the above two methods in case of vertical core section or in case of earth dam section with chimney drain i.e $\theta_{D/S} \leq 90^\circ$ is minimum at a point a small distance upstream of the exit point and is seen to increase in the region both upstream and downstream of that point, in case of earth dam section with flatter upstream face i.e with $\theta_{U/S} \leq 30^\circ$ (Figs. 3.31, 3.32, 3.37, 3.38). As the upstream face is made steeper (i.e $\theta_{U/S} > 45^\circ$), in case of vertical core section ($\theta_{D/S} = 60^\circ$) or in an earth dam section with chimney drain ($\theta_{D/S} = 90^\circ$), the top flow line as calculated by Casagrande's method although still slightly below the true location of top flow line as obtained by the finite element analysis in the upstream region, is now seen to be above the true location of top flow line in the central region and just before the exit point is again seen to be below the true location of top flow line (Figs. 3.33 to 3.36 & 3.39 to 3.42).
3.3 LENGTH OF DOWNSTREAM SEEPAGE FACE.

The parameters which govern the location of top flow line in an earth dam section and hence determine the location of exit point where the top flow line intersects the downstream seepage face, and thus govern the length of downstream seepage face are

(i) Length of seepage path in the earth dam section as manifested by the value of \( XB/H \).

(ii) Slope of downstream seepage face, \( \theta_{D/S} \)

(iii) Slope of upstream face of the dam, \( \theta_{U/S} \)

The variation of the length of downstream seepage face, both as obtained by the finite element analysis of 96 earth dam sections, as well as that calculated by Casagrande's method, and expressed in non dimensional form as \( L/H \), are plotted separately against each of the above 3 parameters (Fig. 3.55 to 3.82). A logical explanation is also given for the variation of \( L/H \), as obtained by the above two methods, with each of the above three parameters.

3.3.1 Effect of XB/H on the Length of Downstream Seepage Face, \( L/H \)

The variation of \( L/H \) with \( XB/H \) is plotted vide Figs. 3.55 to 3.64. In order to study the effect of the slope of downstream seepage face \( \theta_{D/S} \), as well as that of the slope
of upstream face of the earth dam $\theta_{u/s}$, on the variation of $L/H$ with $XB/H$, two different sets of plots are presented. In the first set, the curves showing the variation of $L/H$ with $XB/H$, in case of earth dam sections with all the 4 values of $\theta_{D/S}=60^\circ$, $90^\circ$, $135^\circ$, $180^\circ$, but for only one particular value of $\theta_{u/s}$ are plotted vide Figs. 3.55 to 3.60. In the second set, the curves of $L/H$ Versus $XB/H$ in case of earth dam section with all the 6 values of $\theta_{u/s}=15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, $90^\circ$ but with only one particular value of $\theta_{D/S}$ are plotted vide Figs. 3.61 to 3.64.

The plots indicate that the value of $L/H$ as obtained by both the methods is maximum in case of earth dam section with $XB/H = 0.8$ and is seen to decrease rapidly as $XB/H$ is gradually increased to 3.0. This behaviour is due to the fact that the top flow line in an earthdam section obtained by either of the above two methods, in general approximates a parabola and obviously with the value of $H$ as fixed, as the horizontal distance of focus from the starting point of parabolic curve on the water surface is increased, the gradient of the parabolic curve is reduced drastically and consequently the intercept between the focus and the point of intersection of the parabolic curve with the downstream seepage face is also reduced significantly.

Considering the first set of plots presented vide Figs. 3.55 to 3.60, it is seen that for any value of $XB/H$ the value
of $L/H$ is maximum in case of vertical core section $\theta_{D/S} = 60^\circ$ and reduces rapidly for $\theta_{D/S} = 90^\circ$ (Chimney drain), and finally attains the minimum value for $\theta_{D/S} = 135^\circ$ & $180^\circ$ i.e for rockfill toe and downstream horizontal drain when the two curves of $L/H$ Vs $XB/H$ seem to coincide. This behaviour arises from the property of the parabola. The intercept between the focus and the point where any straight line passing through the focus intersects the parabola is minimum, when the above straight line is horizontal and increases rapidly as the above straight line is made vertical and is finally inclined in the upstream direction.

Further more the variation of $L/H$ with $X_{SA}/H$ is quite large in case of vertical core section $\theta_{D/S} = 60^\circ$ and is seen to reduce significantly as $\theta_{D/S}$ is increased to $90^\circ$ and then finally to $135^\circ$ & $180^\circ$. The above phenomenon is also a consequence of the fact that the top flow line in both cases, either obtained by the finite element analysis or as calculated by the Casagrande's method, approximates a parabolic curve. To explain the effect of slope of downstream seepage face $0_{D/S}$ on the variation of $L/H$ with $XB/H$, consider a parabolic curve aligned in the same direction as the plots of top flow line presented vide Figs. 3.1 to 3.54 and 4.1 to 4.4. It is common knowledge that the gradient of the parabolic curve at a point vertically above the focus is unity, irrespective of the horizontal distance of the starting point of parabola on the water surface from the focus. Moreover the effect of this
distance of starting point of parabola from the focus, on the location of the parabolic curve is comparatively small on the portion of the parabolic curve downstream of the focus, and this explains the fact that the variation of $L/H$ with $XB/H$ is significantly small in case of earth dam sections with rockfill toe $\theta_{D/S} = 135^\circ$, or with downstream horizontal drain $\theta_{D/S} = 180^\circ$. On the contrary, the gradient of the parabolic curve in the portion upstream of focus, is greatly affected by this horizontal distance of the focus from the starting point of the parabola on the water surface. When this horizontal distance of the focus from the starting point of parabola is small, the gradient of the parabolic curve in the portion upstream of the focus is very steep, and if a straight line is drawn through the focus and is inclined in the upstream direction, the intercept between the focus and the point where this straight line intersects the parabolic curve, is quite large. However, when the distance of the focus from the starting point of the parabola is increased, the gradient of the parabolic curve in the portion upstream of focus, reduces drastically, resulting in considerable lowering in the elevation of the parabolic curve in the portion close to and upstream of the focus, and consequently if a straight line is drawn through the focus and is inclined in the upstream direction, the intercept between the focus and the point where this straight line intersects the parabolic curve is now comparatively much smaller. This explains the
fact that the variation of $L/H$ with $XB/H$ is quite large in case of earth dam section with $\theta_{D/S} \leq 90^\circ$ ie in case of vertical core or chimney drain. In the Casagrande's method the starting point of base parabola on the water surface is at a distance $0.3 H \cot \theta_{u/s}$ upstream of entry point and in case of earth dam section with flatter upstream face, this distance is a significant portion of the total length of seepage path, and to that extent the effect of $XB/H$ on the location of base parabola and consequently on the length of downstream seepage face is reduced, and this explains the considerably smaller variation of $L/H$, as calculated by Casagrande's method, with $XB/H$ in case of earth dam sections with smaller values of $\theta_{u/s}$ ie with flatter upstream face.

Now coming to the second set of curves plotted vide Figs. 4.61 to 4.64, it is seen that the variation of $L/H$ with $XB/H$ is more in case of earth dam sections with steeper upstream face. This phenomenon as regards the curves $L/H$ Versus $XB/H$, obtained from Casagrande's method has been explained above. The explanation regarding the behaviour of curves $L/H$ versus $XB/H$ as obtained from the results of finite element analysis of earth dam sections, is given below. As described vide para 3.2.1.4, and shown vide Figs. 3.1 to 3.12, when the upstream face is made steeper, the top flow line shifts upwards in the central portion and in the downstream direction in the region close to exit point. This shift in the location of top flow line consequent to the
slope of upstream face being increased from $\theta_{u/s} = 15^\circ$ to $\theta_{u/s} = 90^\circ$, has a maximum value of more than twice, in case of earth dam section with $XB/H = 0.8$, as compared to that of the shift in the location of top flow line in the case of dam section with $XB/H = 3.0$, and this explains the greater variation of $L/H$ with $XB/H$ in case of earth dam sections with steeper upstream face.

3.3.2 Effect of Slope of Downstream Seepage Face $\theta_{D/S}$ on the Length of Downstream Seepage Face $L/H$.

The variation of $L/H$ $\theta_{D/S}$ is plotted vide Figs. 3.65 to 3.74. The results are presented as two sets of plots. In the first set the curves of $L/H$ Versus $\theta_{D/S}$ pertaining to earth dam sections with all the 4 values of $XB/H = 0.8, 1.5, 2.0, 3.0$ but for only one particular value of $\theta_{u/s}$ are plotted vide Figs 3.65 to 3.70. In the second set, the curves of $L/H$ versus $XB/H$ in case of earth dam sections with all the 6 values of $\theta_{u/s} = 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$ but for only one particular value of $XB/H$ are plotted vide Figs. 3.71 to 3.74.

The plots indicate that the value of $L/H$ as obtained by both the methods is maximum in case of vertical core section $\theta_{D/S} = 60^\circ$ and decreases rapidly as the downstream seepage face is made vertical in case of chimney drain $\theta_{D/S} = 90^\circ$ and attains a minimum value in case of downstream rockfill toe.
and horizontal drain $\theta_{D/S} = 135^\circ$ & $180^\circ$. Furthermore it is seen that the value of $L/H$ is almost same in case of earth dam section with $\theta_{D/S} = 135^\circ$ and $\theta_{D/S} = 180^\circ$. As described earlier this behaviour arises out of the fact that the top flow line in general approximates a parabolic curve, with starting point of the parabolic curve at the water surface, and with focus at the toe in case of vertical core section or at the upstream end of internal drainage system. In case of a parabola, if a straight line is drawn through the focus, the intercept between the focus and the parabola, is minimum for $\theta_{D/S} = 180^\circ$, and increases only marginally when $\theta_{D/S} = 135^\circ$, and thereafter increases rapidly as $\theta_{D/S}$ is made equal to $90^\circ$ and finally made equal to $60^\circ$. In case of Casagrande's method the value of length of Seepage face is obtained by applying a correction depending on the value of $\theta_{D/S}$ to the above intercept, while the top flow line as obtained by the finite element analysis is seen to dip downwards in the region close to the exit point and that is the reason for $L/H$ having almost the same value in case of earth dam section with $\theta_{D/S} = 135^\circ$ & $180^\circ$. It is also noted from the plots that the variation of $L/H$ with $\theta_{D/S}$ is quite large in case of earth dam section with $XB/H = 0.8$ and this variation of $L/H$ with $\theta_{D/S}$ reduces considerably as the value of $XB/H$ is increased to $3.0$. This behaviour is quite obvious because when $XB/H = 0.8$, the gradient of top flow line upstream of the toe of the vertical core is very steep and consequently the length of seepage face
in case $\theta_{D/S} < 90^\circ$, is quite large. However when $XB/H$ is increased to 3.0 the gradient of top flow line upstream of the toe of vertical core is drastically reduced, resulting in a considerably smaller length of seepage face in case of $\theta_{D/S} = 60^\circ$. On the contrary the effect of $XB/H$ is comparatively less marked on the location of top flow line downstream of focus of the parabolic curve ie downstream of upstream end of the internal drainage system. This explains a large variation of $L/H$ with $\theta_{D/S}$ in case of earth dam section with smaller value of $XB/H = 0.8$, and a considerably smaller variation of $L/H$ with $\theta_{D/S}$ when the value of $XB/H$ is increased to 3.0.

The second set of plots presented vide Fig. 3.71/illustrates the effect of $\theta_{u/s}$ on the variation of $L/H$ with $\theta_{D/S}$. It is indicated that although the variation of $L/H$ with $\theta_{D/S}$ is not markedly affected by the slope of upstream face of the earth dam, $\theta_{u/s}$, the value of $L/H$ at any particular value of $\theta_{D/S}$ increases as the upstream face of the dam is made steeper. As described earlier vide paras 3.2.1.1. and 3.2.3.1, the gradient of top flow line is governed largely by the length of seepage path as manifested by the value of $XB/H$ in that earth dam section. In case of flatter upstream face the water enters the upstream face with a greater downward inclination and this has the effect of lowering the location of top flow line and hence the top flow line intersects the downstream seepage face at a lower elevation, resulting in a smaller value of length of seepage face. In case of a very
steep upstream face, water enters the dam section at a very flat gradient and this has the effect of so to say of lifting up the top flow line which now intersects the downstream seepage face at a higher elevation, resulting in a greater value of the length of downstream seepage face.

Obviously this effect of entry conditions is more marked in case of earth dam section with a smaller length of seepage path as manifested by $XB/H = 0.8$ (Fig. 3.71) and is markedly reduced when the length of seepage path is increased by making the value of $XB/H = 3$ (Fig. 3.74).

3.3.3. Effect of Slope of Upstream Face $\theta_{u/s}$ on the Length of Downstream Seepage Face.

Here also the variation of $L/H$ with $\theta_{u/s}$ is presented in two sets of plots. In the first set the curves of $L/H$ versus $\theta_{u/s}$ for all the 4 values of $\theta_{D/S} = 60^\circ$, $90^\circ$, $135^\circ$, $180^\circ$ but for a particular value of $XB/H$ are plotted vide Figs. 3.75 to 3.78. In the second set of plots, the curves of $L/H$ versus $\theta_{u/s}$, for all the 4 values of $XB/H = 0.8, 1.5, 2.0, 3.0$ but for a particular value of $\theta_{D/S}$ are presented vide Figs 3.79 to 3.82.

The plots indicate that the length of downstream seepage as expressed in nondimensional form by $L/H$ and obtained by either of the above two methods increases as the upstream face of the earth dam is made gradually steeper by increasing the value of $\theta_{u/s}$ from $15^\circ$ to $90^\circ$ at an interval of $15^\circ$. The
variation of $L/H$ with $\theta_{w/s}$ is quite large in case of vertical core section $\theta_{D/S} = 60^\circ$ with a smaller value of $XB/H = 0.8$, but reduces rapidly to a very small value when $\theta_{D/S}$ is made equal to $135^\circ$ or $180^\circ$ in case of earth dam with rockfill toe or downstream horizontal drain, or when the value of $XB/H$ is increased to $3.0$.

A comparison of the curves of $L/H$ versus $\theta_{w/s}$ as obtained by the above two methods indicate that the behaviour of the curves $L/H$ versus $\theta_{w/s}$ as obtained by the finite element analysis of 96 earth dam section is exactly the opposite to that of the curves of $L/H$ versus $\theta_{w/s}$ as obtained by the Casagrandes method. Thus the curves of $L/H$ versus $\theta_{w/s}$ as obtained by the finite element analysis, are comparatively flatter for smaller value of $\theta_{w/s}$ and gradually becomes steeper as the value to $\theta_{w/s}$ is increased to $90^\circ$. On the contrary the behaviour of the curves of $L/H$ Versus $\theta_{w/s}$ as obtained by Casagrandes method is exactly the opposite of the above. Here the curves of $L/H$ Versus $\theta_{w/s}$ are comparatively steeper in case of smaller values of $\theta_{w/s}$ and become flatter as the value of $\theta_{w/s}$ is increased to $90^\circ$. The above behaviour of the curves of $L/H$ versus $\theta_{w/s}$ explains the greater difference in the value of $L/H$ as obtained by the two methods, both for a very small value of $\theta_{w/s} = 15^\circ$, as well as for a large value of $\theta_{w/s} = 90^\circ$, while for an intermediate values of $\theta_{w/s} = 45^\circ$ or $60^\circ$ this difference in the value of $L/H$ as calculated by the two methods is seen to be minimum. In other words, since the
length of downstream seepage face as obtained by the finite element analysis tally exactly with Kozney's theoretical solution for dam section with parabolic upstream face and with the results of exact solution of earth dam section with horizontal toe drain presented by Moayeri, it can be safely concluded that in an earth dam section the length of downstream seepage face as obtained by the Casagrandes method is in greater error both in case of earth dam section with very flat as well as in case of very steep upstream face and is comparatively closer to its true value in case of earth dam section with moderate slope of upstream face.

The above behaviour of the curve of L/H Versus \( \theta_{w/s} \) is explained as under. In Casagrandes method, the starting point of the base parabola is on the water surface at a distance 0.3H Cot \( \theta_{w/s} \) upstream of the entry point. In case of very flat upstream face this distance is quite large and this results in considerable lowering of the elevation of the curve of base parabola in the downstream region. As the upstream face is gradually made steeper, this distance 0.3H Cot \( \theta_{w/s} \) decreases at a rate which rapidly reduces as \( \theta_{w/s} \) is increased to 90° and consequently the elevation of the curve of base parabola also increases at a decreasing rate as the upstream face is made steeper, and obviously this behaviour is also reflected in the value of the intercept of any straight line between the focus and the base parabola. This explains the steeper slope of L/H Versus \( \theta_{w/s} \) curves as
obtained by Casagrande's method, in case of smaller values of $\theta_{w/s}$ and a flatter slope of $L/H$ versus $\theta_{w/s}$ curve as the value of $\theta_{w/s}$ is gradually increased to 90°.

Now coming to the curves of $L/H$ Versus $\theta_{w/s}$, as obtained by the finite element analysis of earth dam section, as discussed vide para 3.2.1.1 & 3.2.1.4 the top flow lines for the earth dam sections with any particular value of $X_{B/H}$ and $\theta_{D/S}$, but with all the 6 different slopes of upstream face $\theta_{w/s} = 15°, 30°, 45°, 60°, 75°, 90°$ are generally parallel to each other. As the slope of upstream face of the dam is made steeper, the location of top flow line shifts upwards in the central portion and in the downstream direction in the region close to exit point. Furthermore, this shift in the location of top flow line, consequent to upstream face being made steeper, is small in case of earth dam sections with flatter upstream face, but increases progressively as the upstream face is made steeper, as manifested by the progressively increasing gap between the curves of top flow line for different values of $\theta_{w/s}$ which is increased from $\theta_{w/s} = 15°$ to $\theta_{w/s} = 90°$ at a regular interval of 15 (Figs 3.1 to 3.12). Consequently if a straight line is drawn, through the toe in case of vertical core section or through the upstream end of internal drainage system in other dam sections, the intercept of this straight line between the above point and the point where it will intersect the top flow line obtained for gradually increasing value to $\theta_{w/s}$ will increase at a pro-
gressively faster rate as the upstream face of earth dam is gradually made steeper. This explains the comparatively flatter slope of the curve of $L/H$ Versus $\theta_{u/s}$ as obtained by the finite element analysis of earth dam sections, in case of smaller values of $\theta_{u/s}$ and a steeper slope of the curve of $L/H$ Versus $\theta_{u/s}$, as the value of $\theta_{u/s}$ is gradually increased to $90^\circ$.

The value of $L/H$ as obtained by the Casagrandes method in case of earth dam section with downstream horizontal drain, is closest to its true value as obtained by the finite element analysis, when the slope of upstream face $\theta_{u/s}$ is equal to $60^\circ$ (Fig. 3.75). The value of $L/H$ as obtained by Cassagrande's method in case of vertical core or in case of earth dam section with chimney drain, is closest to its true value when the slope of upstream face $\theta_{u/s}$ is equal to $45^\circ$ (Fig. 3.75).
FIG 3.1 EFFECT OF SLOPE OF UPSTREAM FACE $\theta-U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_B/H=0.6$
FIG 3.2 EFFECT OF SLOPE OF UPSTREAM FACE $\theta-U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_B/H=0.8$
FIG 3.4 EFFECT OF SLOPE OF UPSTREAM FACE $\theta-U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $XB/H=1.5$. 
FIG 3.5  EFFECT OF SLOPE OF UPSTREAM FACE $\theta$-$U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_B/H=2.0$
FIG 3.6 EFFECT OF SLOPE OF UPSTREAM FACE $\theta$-U/S ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_6/H = 2.0$. 

- $\theta$-U/S = 90°
- $\theta$-U/S = 75°
- $\theta$-U/S = 60°
- $\theta$-U/S = 45°
- $\theta$-D/S = 90°
FIG 3.7 EFFECT OF SLOPE OF UPSTREAM FACE θ-U/S ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=2.0
FIG 2.8 EFFECT OF SLOPE OF UPSTREAM FACE $\theta-U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $XE/H=2.0$
FIG 3.9 EFFECT OF SLOPE OF UPSTREAM FACE $\theta$-U/S ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_B/H=3.0$
FIG 3.10 EFFECT OF SLOPE OF UPSTREAM FACE $\theta-U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $XB/H=3.0$
FIG 3.11 EFFECT OF SLOPE OF UPSTREAM FACE $\theta$-U/S ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $XE/H=3.0$
FIG 5.12 EFFECT OF SLOPE OF UPSTREAM FACE $\theta$-$U/S$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $X_E/H=3$. 

$\theta$-$U/S$ = $5^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $75^\circ$, $60^\circ$
Figure 3.13: Effect of slope of D/S seepage face on the location of top flow line in an earth dam section with X5/H = 0.8.
Figure 3.14 Effect of slope of D/S seepage face on the location of top flow line in an earth dam section with Xb/H = 0.3
FIG 3.15 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH X5/H=0.8
FIG 3.16 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=1.5
FIG 3.17 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=1.5
FIG 3.19 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH Xb/H=3.0
FIG 3.20 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH X5/H=2.0
Fig 3.21 Effect of slope of D/S seepage face on the location of top flow line in an earth dam section with X5/H = 2.0
FIG 3.22 EFFECT OF SLOPE OF D/S SEEPALE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XH/H=2.0.
FIG 3.23 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=2.0
FIG 3.24 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=2.0
FIG 3.25 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XE/H=3.0
FIG 3.26 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH X5/H=3.0
FIG 3.27 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH X6/H=3.0
FIG 3.26 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=3.0
Fig 3.29 Effect of Slope of D/S Seepage Face on the Location of Top Flow Line in an Earth Dam Section with X6/H=3.0
FIG 3.30 EFFECT OF SLOPE OF D/S SEEPAGE FACE ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH XB/H=3.0
FIG 3.32 EFFECT OF $X_B/H$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $\Theta - D/S = 80$
FIG 3.33 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH O-D/S=60
Figure 3.35: Effect of Xb/H on the location of top flow line in an earth dam section with θ-D/s=60.
Fig 3.36 Effect of \( \frac{X_B}{H} \) on the location of top flow line in an earth dam section with \( \theta - D/S = 60 \)
Fig 3.37 Effect of XB/H on the location of top flow line in an earth dam section with θ-D/S=30
FIG 3.40 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH θ-D/S=90
Figure 3.41: Effect of $XB/H$ on the location of top flow line in an earth dam section with $\theta - U/S = 75^\circ$.
Fig 5.42 Effect of Xb/H on the location of top flow line in an earth dam section with \( \theta - D/s = 90^\circ \)
Fig 3.45 Effect of $X_B/H$ on the location of top flow line in an earth dam section with $\theta$-D/S=135
FIG 3.46 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH θ-D/S=135
Fig 3.42 Effect of $X_B/H$ on the location of top flow line in an earth dam section with $\theta - D/S = 135$
FIG 3.49 EFFECT OF $X_B/H$ ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH $\theta-D/S=15^\circ$
FIG 3.50 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH Θ-D/Σ=180
FIG 3.51 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH 0-D/S=180°
**FIG 3.52 EFFECT OF XB/H ON THE LOCATION OF TOP FLOW LINE IN AN EARTH DAM SECTION WITH θ-D/S=180**
Figure 3.54: Effect of $X_B/H$ on the location of top flow line in an earth dam section with $\theta - D/S = 90^\circ$. 

Legend:
- FEM
- Casagrande

KEY:
- $X_B/H = 2.0$
- $X_B/H = 1.5$
- $X_B/H = 0.3$
- $X_B/H = 3.0$
FIG. 3.55 - VARIATION OF $L/H$ WITH $X_B/H$ FOR DIFFERENT $\theta - D/S$
FIG. 3.56 - VARIATION OF L/H WITH XB/H FOR DIFFERENT θ-D/S
FIG. 3.57 - VARIATION OF L/H WITH XB/H FOR DIFFERENT θ-D/S
FIG. 3.58 - VARIATION OF L/H WITH XB/H FOR DIFFERENT θ-D/S
Fig. 3.59 - Variation of L/H with XS/H for different θ-D/S.
FIG. 3.64 - VARIATION OF L/H WITH B/H FOR DIFFERENT Ø-D/S
FIG. 3.61 - VARIATION OF L/H WITH XB/H FOR DIFFERENT $\theta$-U/S
FIG. 3.62 - VARIATION OF L/H WITH XB/H FOR DIFFERENT θ-U/S
FIG. 3.63 - VARIATION OF L/H WITH XB/H FOR DIFFERENT θ-U/S
FIG. 3.64 - VARIATION OF L/H WITH XB/H FOR DIFFERENT $\theta$-U/S
FIG. 3.65 - VARIATION OF L/H WITH θ-D/S
FOR DIFFERENT XB/H

θ-D/S (degrees)

LEGEND
F E M
CASAGrande

θ-U/S = 15°

θ-D/S < 90°: VERTICAL CORE
90°: CHIMNEY DRAIN
>90°: ROCKFILL TOE
=180° HORIZONTAL DRAIN
FIG. 3.66- VARIATION OF L/H WITH θ-D/S FOR DIFFERENT XB/H
FIG. 3.67- VARIATION OF L/H WITH θ-D/S FOR DIFFERENT XB/H
Fig. 3.68 - Variation of L/H with $\theta$-D/S for different $XB/H$. 

Legend:
- F.E.M.
- CASAGRANDE

- $\theta$-D/$S \leq 90^\circ$: Vertical core
- $90^\circ$: Chimney drain
- $>90^\circ$: Rockfill toe
- $=180^\circ$: Horizontal drain
FIG. 3.63- VARIATION OF L/H WITH θ-D/S FOR DIFFERENT XB/H
FIG. 3.70 - VARIATION OF L/H WITH THETA-D/S FOR DIFFERENT XB/H
FIG. 3.71- VARIATION OF L/H WITH θ-D/S FOR DIFFERENT θ-U/S

LEGEND
F E M
CASAGRANDE

θ-U/S = 90°
θ-U/S = 75°
θ-U/S = 60°
θ-U/S = 45°
θ-U/S = 30°
θ-U/S = 15°
Fig. 3.74 - Variation of L/H with θ-D/S for different θ-U/S
FIG. 3.75- VARIATION OF L/H WITH θ-U/S FOR DIFFERENT θ-D/S
FIG. 3.76 - VARIATION OF L/H WITH G-U/S FOR DIFFERENT S-D/S
FIG. 3.77 - VARIATION OF L/H WITH θ-U/S FOR DIFFERENT θ-D/S
$\theta_D/S < 90^\circ$ VERTICAL CORE
+90$^\circ$ CHIMNEY DRAIN
>90$^\circ$ ROCKFILL TOE
<180$^\circ$ HORIZONTAL DRAIN

FIG. 3.78 - VARIATION OF L/H WITH $\theta_U/S$
FOR DIFFERENT $\theta_D/S$
FIG. 3-3 - VARIATION OF L/H WITH θ-D/S FOR DIFFERENT X/B/H
FIG. 3.80- VARIATION OF L/H WITH θ-U/S FOR DIFFERENT XB/H
FIG. 3.81 - VARIATION OF L/H WITH $\theta$-U/S FOR DIFFERENT XB/H
FIG. 3.82 - VARIATION OF L/H WITH θ-U/S FOR DIFFERENT XB/H