Pore Pressure in Earth Dams

Etude de la pression des pores dans des barrages en terre à filtre incliné vers l'amont et son application

by Dr. V. J. PATEL, B. E. (Civil) Hons., Dr. Engg. (Civil), Munich,
and
B. L. MAHESHWARI, B. Sc., B. E., M. S. (Ill), Indian Institute of Technology, Kanpur, India

Summary

The authors give the results of experiments carried out by the electric analogy method to measure the pore-pressure in earth dams with upstream slanting filter for different drawdown conditions. The height, position and slope of such filters were varied and equipotential lines were traced by experiments. Based on the experimental values, flow-nets were drawn for different conditions of filter. The authors refer to the effect of an upstream rock-toe in earth dams with upstream sloping filter.

The provision of an upstream slanting filter in a dam creates a free water table in the filter, whereas the upstream slope is a free water table during rapid drawdown condition ; so the difference of pore pressure between a point on the upstream slope and the other in the filter is zero. Thus the provision of such a filter facilitates the design of earth dams with steep slopes leading to greater economy. The authors show the effect of a filter on the critical slip circle and on the stability of earth dams.

The authors also deal with the economic design of earth dams with an upstream slanting filter connected to the down stream part by a horizontal filter at the base of the dam.

Sommaire

La communication donne pour des conditions variées de vidange, les résultats d'expériences, par analogie électrique, pour la détermination de la pression des pores dans des barrages en terre à filtre incliné vers l'amont. On a fait varier la hauteur, le pourtour et l'inclinaison du filtre, et les équipotentielles ont été tracées d'après les résultats expérimentaux. Sur la base de ces résultats, on a tracé les réseaux d'écoulement pour les diverses conditions. La communication traite également de l'influence d'un talon amont en enrochements conjuguée avec le filtre incliné.

Il se crée une « nappe libre » dans le filtre, alors qu'en cas de vidange rapide, le talus amont est également une « nappe libre ». La différence entre les pressions des pores de deux puits situés à la même cote, l'un sur le talus amont, l'autre sur le filtre, est nulle. En prévoyant un filtre incliné on peut donc raidir le talus amont et faire des économies. La communication montre l'influence du filtre sur le cercle critique de glissement et sur la stabilité des digues en terre.

Dans sa dernière partie, la communication traite de l'économie des projets à filtres amont inclinés, liés à l'aval par un filtre horizontal à la base du barrage. Elle contient également deux nomogrammes qui permettent le calcul des digues en terre pour différentes hauteurs et caractéristiques du sol.

1. INTRODUCTION

From the earth dam with a horizontal filter at its base a recent development is a similar type of dam with a vertical filter in the centre. With the provision of such a filter, the phreatic line becomes steeper and runs towards the filter with the result that the major portion of the downstream slope behind such a filter will remain dry. The downstream slope can therefore be designed at a much steeper angle than the usual type. Because of the filter, a free water-table is established in the centre of the dam. A part of the slip circle for the stability analysis of the up stream slope passing through the vertical filter will have no pore-pressure in that particular slice which has a filter at the plane of failure, as the upstream slope represents free water-table during rapid drawdown. This again increases the stability of the upstream slope so that this slope can be steeper. If an up stream slanting filter is provided in such a way that a major part of the critical slip circle of a dry slope passes through the filter, the pore-pressure decreases considerable and the factor of safety increases. This again opens up the possibility of designing steeper slopes (2). It seems that no experimental work has been done on this aspect. An effort has been made by the authors to present the results of experimental work on the effect of an upstream slanting filter on pore-pressure in earth dams.

2. Experimental set-up

First of all, the phreatic line was found on a hydraulic model of an earth dam with a vertical filter at half the height of water-level (H). This line was slightly lower than the line drawn with the help of Kozney's parabolic formula, considering only the horizontal filter at the base and neglecting the vertical filter. Thus the vertical and upstream slanting filter brings down the phreatic line drawn with the help of Kozney's formula. Further work on this is in progress and it should not be difficult to develope an equation.

Experiments were acrried out by using an electrical analogy method with the upper boundary condition determined by Kozney's formula, which in this particular case gives higher values of pore-pressure. The results therefore err on the side of safety. The experimental set-up comprises a tray having an upstream slope with a number of copper strips. These strips were connected to 100 per cent voltage on the potentiometer corresponding to a full reservoir and to varying potential for rapid drawdown. Similarly, the filter consisted of number of strips connected to different potentials as it represents free water-table inside all conditions. It is needless to describe the electrical analogy method as it is very simple and well known.

The following assumptions are made :

1. The foundation of the dam is impervious. If not, the

flow lines will run towards the base making equipotential lines flatter and more parallel to the base, which results in the decrease of pore-pressure and increase in the factor of safety.

2. The material in the same zone is homogeneous.

3. Darcy's Law is applicable.

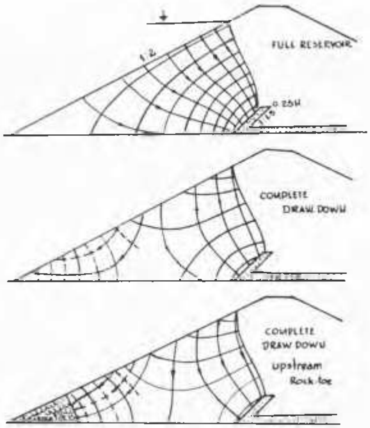

Fig. 1 Flow-nets.
Réseaux d'écoulement.

The typical flow-nets for the full reservoir, complete rapid draw down and the effect of the upstream rock-toe has been given in Fig. 1.

3. Calculations

It has already been stated that if an upstream sloping filter is provided along the critical slip circle of a dry slope in such a way that the major lower part of the slip circle passes through this filter, the factor of safety of the slip circle increases; also the factor of safety of the slip circles downstream of this critical slip circle is higher. Thus the new critical slip circle will move towards the upstream of this circle and filter[3]. The slope was examined with five different slip circles all lying upstream of the filter with three different sets of φ and c values namely 25° and 3·33 ton/m², 20° and 4·98 ton/m² and 15° and 7·02 ton/m² respectively. It was found that a single slip circle gives minimum factor of safety. This enables us to derive an expression and chart of stability for different slopes and spacing of filter, height of water level (H), and differnt soil characteritics. In order to simplify calculations, material in the slice above the slip circle is assumed to be completely saturated, which gives a lower value of the factor of safety than is the case in practice.

The equation for stability[4] for the given slip circle is :

$$F = \frac{(\sigma - u)\tan\varphi}{\tau} + \frac{c \cdot l}{\tau} = \left(\frac{\sigma}{\tau} - \frac{u}{F_\tau \cdot \gamma_{sat}}\right)\tan\varphi + \frac{c \cdot l}{F_\tau \cdot \gamma_{sat}} \quad \ldots\ (1.1.)$$

$$= \left[a - \left(\frac{u}{F_\tau}\right)\frac{1}{\gamma_{sat}}\right]\tan\varphi + \frac{cA}{H\gamma_{sat}} \quad (1.2.)$$

$$= \left[2{\cdot}49 - \left(\frac{u}{F_\tau}\right)\cdot\frac{1}{\gamma_{sat}}\right]\tan\varphi + 7{\cdot}5\,\frac{c}{H\gamma_{sat}} \quad \ldots\ (1.3.)$$

(values of a and A are from the experiments)
where F_τ is the area of τ-curve for the slip circle.

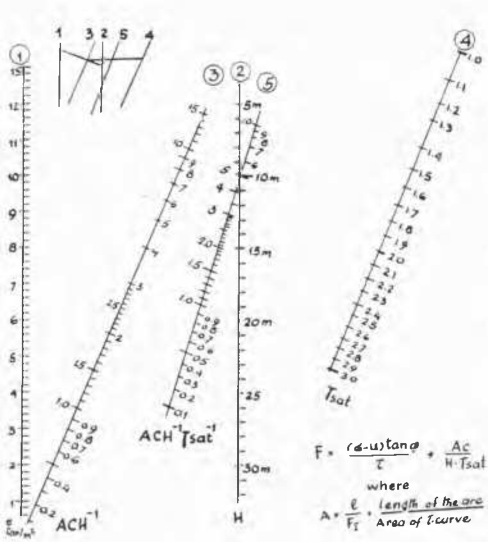

Fig. 2.1 Nomograph to find the value of $A.C.H^{-1} \cdot \gamma^{-1}_{sat}$.
Nomogramme donnant la valeur de $A.C.H.^{-1} \cdot \gamma^{-1}_{sat}$.

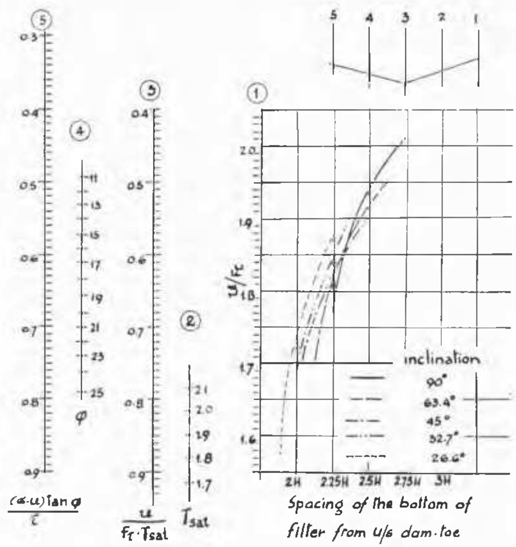

Fig. 2.2 Nomograph to find the value of $(\sigma - u)\tan\varphi/\tau$.
Nomogramme donnant $(\sigma - u)$ tg φ.

Thus, knowing the value of u/F_τ from Fig. 2·2, the factor of safety for a given height of the earth dam with different values of c, φ and γ_{sat} can be obtained or conversely the best position and slope of the filter can be found if H ,c and γ_{sat} are known.

Thus the equation enables us to draw two nomographs for the values of $c{\cdot}A{\cdot}H^{-1}{\cdot}\gamma_{sat}$ and $(\sigma - u)$ tan φ/τ as given in Fig. 2·1 and 2·2 respectively. The right hand part of the Fig 2·2 has also a graph of u/F_τ against spacing of the filter from the upstream toe for different slopes of the filter, which enables to find out the value of u/F_τ.

4. Discussion of results

For simplification and comparision, stability was calculated for the water level (H) of 20 m and soil characteristics $\varphi = 25°$, $c = 3{\cdot}33$ tons/m^2 and $\gamma_{sat} = 2{\cdot}1$. From Fig. 3 it can be seen that for the same slope of the filter, the factor of safety decreases as the filter is moved downstream. By moving the filter from upstream to downstream by 10 m, the factor of safety for *A*. *B*, *C*, *D* and *E* decreases by 0·055, 0·045, 0·038, 0·084 and 0·086 respectively. This shows that there is

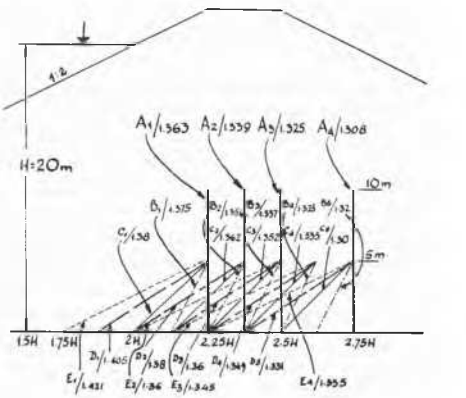

Fig. 3 Factor of safety of earth dams with various spacing and slope of filters for $\varphi = 25°$, $c = 3{\cdot}33$ ton/m^2, $\gamma_{sat} = 2{\cdot}1$ and $H = 20$ m.

Coefficient de sécurité d'un barrage en terre avec distance et inclinaison variable du filtre, pour $\varphi = 25°$, $C = 3{\cdot}33$ t/m^2, $\gamma_{sat} = 2{\cdot}1$ et $H = 20$ m.

a very small variation in the factor of safety for a filter slope 1 : 1. The theoretical slip circle for the slope taking into account the pore-pressure from the experiment (Fig. 2.2.) and c and φ equal to 3·33 ton/m^2 and 25° respectively has a slope of 0·944 i.e. a filter with a slope of less than 1 : 1 and more than 1 : 0·5 or between 45° and 63·4° is better. If a graph of the change of factor of safety against the slope of the filter is drawn, a slope of 50° gives the best results for these values. Similarly a critical slope of the filter for different height of dam and soil properties can be found with the help of Fig. 2.1. and 2.2. From Fig. 4, it is clear that the effect of rotating the filter about its crest and making it more slanting upstream gives a greater factor of safety. The curve of the factor of safety against the angle of the filter becomes flatter and parallel as the top of the filter is moved downstream. This is due to the fact that the critical slip circle for the dry slope for these values passes at a distance of 47·5 m (2·375 H) so that the change in the factor of safety effected by rotating the filter with a height of 0·25 H at 47·5 m is a maximum. If the filter is moved upstream or downstream of the critical slip circle of the dry slope, the curve of the factor of safety against the angle of the angle of the filter becomes flatter. This agrees with the theoretical proposition that the best position of the upstream slanting filter is on the critical slip circle of the dry slope for the given values of c and φ[3].

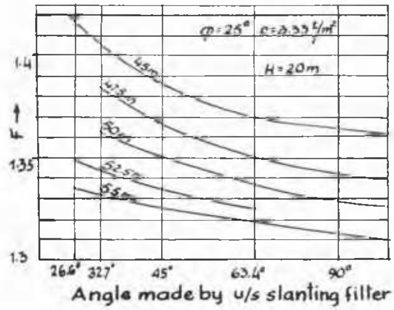

Fig. 4 Effect of the slope of filter on the factor of safety of the dam.

Influence de l'inclinaison du filtre sur le coefficient de sécurité du barrage.

5. Application in earth dam designing

5.1. The factors affecting the theoretical factor of safety of the upstream slope are c, φ, γ, γ_{sat}, height of the dam and the height of the water level. Knowing these values, pore-pressure for the most dangerous case and permissible factor of safety which is generally not less than 1·3 and not more than 1·5, the best position of the filter for the upstream slope of 1 : 2 can be obtained from Fig. 2.1. and 2.2. Let us design a dam of 30 m height with water level (H) at 28 m, $\varphi = 18°$, $c = 7$ ton/m^2 and $\gamma_{sat} = 2$. First find out the value of $A{\cdot}c{\cdot}H^{-1}{\cdot}\gamma^{-1}{}_{sat}$ with the use of Fig. 2.1. which gives a value 0·9. If the factor of safety desired is say 1·5, then the desired value of $(\sigma - u)$ tan φ/τ is 0·6. Find out the value of u/F_τ for $(\sigma - u)$ tan φ/τ, φ and γ_{sat} of 0·6, 18° and 2·00 respectively which gives the value of 1·75. Draw a line parallel to the x-axis from $u/F_\tau = 1{\cdot}75$ to cut the various curves. Then the following slopes can be adopted :

Slopes in degrees	90°	63·4°	45°	33·6°	26·4°
Distances of the bottom of the filter	63·8 m	62·2 m	60·8 m	60·0 m	57·5 m
Distance of the top of the filter	63·8 m	65·6 m	67·8 m	70·5 m	71·5 m

5.2. *Thickness and Height of the sloping Filter* [3] :

Generally the vertical permeability is more than the horizontal one. If only onepermeability is known, then the horizontal filter at the base should be designed with this value and the same thickness may be assumed for a sloping filter which should not be less than 2·0 m for ease of construction [3]. Also the filter material should agree to the filter law [6].

Taking the factor of safety of 2 and using Darcy's Law :

$$q = 2qt = kF_h\frac{H}{l}F \qquad (2)$$

$$\text{and} \quad F = \frac{H_r + t}{2} \quad \text{and} \quad H = t - H_r$$

so equation 2 changes to :

$$t = 2(q_t/kF_h)^{1/2} \text{ (neglecting } H_r \text{ which is small)} \quad \ldots\ldots (2.1.)$$

Thus if q_t and kF_h are known, it is easy to find out the thickness of the horizontal filter. It is not possible to give the value of q_t here, but this can be found out by drawing flownets for a full reservoir with the help of a trial and error method[6]. The phreatic line should be drawn with the help of Kozney's parabolic formula, taking only the horizontal filter at the base into consideration. Similarly, if vertical permeability is known, the slanting filter can be designed. After drawing the phreatic line, mark the position of the slanting filter to cut the phreatic line to give the required height of the slanting filter.

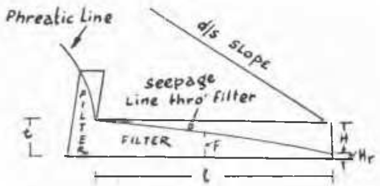

Fig. 5

Let: q_t = quantity of seepage through impervious zone.
q = quantity of water flowingg through filter.
t = thickness of the filter.
k_{Fh} = co-eff. of permeability of horizontal filter.

5.3. The downstream slope below the filter can be constructed of any type of material readily available on site, as this slope remains dry. Stability calculations should be made assuming it to be dry. This makes the project economical as any material available on site can be used downstream of the filter.

6. Conclusion

By assuming the foundation to be impervious, determining the phreatic line by Kozney's formula, designing of a filter with the factor of safety of 2, the calculations of the factor of safety is much lower than the actual value and so can be safely adopted. It is questionable, whether the sudden drawdown will bring an extreme change of stress in highly impervious soils. It has been already stated that the filter is provided upstream of the cirtical slip circle of the dry slope and so a new critical slip circle moves upstream. Thus the slip circle that crosses the filter will have a higher factor of safety. The doubt raised is only in the zone upstream of this filter, but all the assumptions are that the foundation is impervious, the phreatic line by Kozney's formula and a factor of safety of 1·5 do account for this and so there is no reason to think that the factor of safety is not adequate.

For the general use, the authors feel that a dam up to 27·5 m high needs no upstream semipervious zone 2, 3, but a 3 to 5 m wide zone of semipervious or pervious material over this section for a dam height of more than 27·5 m will definitely increase the factor of safety and can be recommended. Also by providing an upstream rocktoe up to 0·13 to 0·15 of the height of the dam will make many more flow lines to run towards the rock-toe which otherwise could have run towards the upstream slope (Fig. 1) exerting a disturbing or breaking effect on the upstream slope[2,3]. Thus, either a rock-toe or upstream semipervious zone is recommended for a dam with a height of more than 27·5 m. By this provision, there is no disturbing effect on the upstream slope by flow lines in the draw down case and so the slope protection has to be designed against wave action only [2,3].

7. Acknowledgement

We are extremely thankful to Principal V. Laxminarayanan who not only gave us the necessary facility to carry on research work but also inspired us during our work by taking personal interest. We thank many of our collegues who helped us in bringing out this work.

8. References

[1] L. V. Davis Handbook of Applied Hydraulics.

[2] V. J. Patel. Pore-pressure in earth dams during draw-down. *Die Wasserwirtschaft*, Nov. 1958 and *Irrigation and Power*, Oct. 1959.

[3] — (1960). Designing of earth dams with upstream slanting filter. Asian Regional Conference on Soil Mechanics and Foundation Engineering, Feb.

[4] — (1959-1960). Concept of stability against sliding in dams, *B.E.C.M.A.G.*, Vol. XI.

[5] Reinius, E. The stability of the upstream slope of earth dams, *Swedish State Committee for building Research*, Stockholm.

[6] Taylor, D. W. Fundamentals of Soil Mechanics.