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Piping of Soils Near Dams

Mécanisme des renards sous les digues

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Summary

Under flood conditions, piping often occurs without warning in the soil near dams. The author has tried to establish the reason for the failure of a dam due to piping. He proposes a system for discovering the most dangerous points where piping is likely to occur.

Piping often occurs at dams and flood-control levees during a period of flood, when a sudden rise of water may cause the total failure of a levee, which makes protection extremely difficult. Piping occurred at many points along the Hungarian section of the Danube during the floods of 1954 and 1956. Observers gave the following account of these events:

Protection works on the dam section near the Ásványráró village near the town of Győr had been in full swing when the flood level reached the top of the dam, while the work of heightening the dam was being carried on. The soil on the downstream portion was already inundated up to an average height of 20 cm, but no sign of boiling was visible. The water surface on both sides of dam was entirely calm. Suddenly there appeared on the downstream side of the dam a water column 1 m in diameter and 1.5 m in height, which was quite pure and almost transparent (Fig. 1). At the same time the surface of the Danube was quite smooth. Two seconds later at a distance of 10 m from the crown of dam on the water side there developed a whirl that, approaching the dam, reached the crown in a minute or two. During this time the boiling increased one and a half times on the downstream side of the dam, and somewhat later the escaping water came to a halt suddenly, most likely as a result of collapse.

The crest of the dam and the slopes remained firm. After a short pause, at the same place of boil, there followed an increased upsurge of water with a diameter of from 4 to 5 m. The water had by that time become extremely muddy and was the colour of chocolate. The water issuing from the boil reached a height of 50-60 cm. Simultaneously the dam suddenly collapsed over a width of from 4 to 5 m.

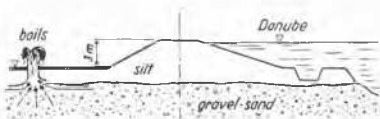


Fig. 1 Piping under the levee of the Danube.
« Renard » sous la digue de protection contre les crues du Danube.

Sommaire

Les « renards » sous les digues de protection contre les crues se produisent souvent de façon inattendue. L'auteur a cherché une relation entre la rupture d'une digue, même sous un gradient hydraulique moyen i inférieur à 0,1, et l'existence d'une onde de plus grand gradient hydraulique. Celle-ci se développe à partir des bulles d'air des pores, qui se mettent en pression avant le soulèvement de la couche de couverture, et prend de l'extension au moment du renard. Une méthode est proposée pour détecter les points les plus dangereux du point de vue de la sécurité contre les renards.

Sweeping over the dam at the site of its collapse, the water caused the failure of a levee over a width of 12 m in only two or three minutes. Width of failure grew from minute to minute.

For this piping, the average value of the hydraulic gradient in the soil is $i = 0.1$ or even less, and is in any case much smaller than $i = 1$, regarded as a critical value.

This failure happened in a soil in which the lower lying, thicker sand-gravel layer is covered by a relatively impermeable silt stratum from 1 to 2 m thick. When the flood rises the sand-gravel layer is saturated by water, and simultaneously air bubbles are enclosed within the pores, which are retained therein by capillary attraction, by the small size of the pores, and by the overlying impervious layer. The captured bubbles can therefore fill up from 20 to 30 per cent of the void space available. As the flood level rises, these bubbles are subjected to pressure and their volume is reduced in inverse proportion to the pressure acting on them.

The increase of pressure is particularly dangerous in a sack-like site of the gravel stratum. The pressure at points relatively remote from the dam is practically the same as the pressure prevailing in the river bed. This applies particularly to the present case, where gravel beds covered by silt of low permeability are present in the meandering course of the river.

Piping will take place along the line of maximum permeability. The sand gravel layer, is not as a rule quite homogeneously permeable enough to guarantee plane flow, as a result of completely symmetrical permeability. In addition to this, the pressure increases from the boil towards the dam. This means in effect that a closed tube can be used for laboratory research into this problem.

Determination of air content in laboratory research

By the Boyle-Mariotte law :

$$Vp = V_0p_0$$

For a tube of uniform cross-section (Fig. 2).

$$l = l_0 \frac{p_0}{p}$$

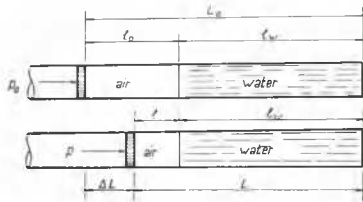


Fig. 2 Compression of water-air mixture.
La compression du mélange air-eau.

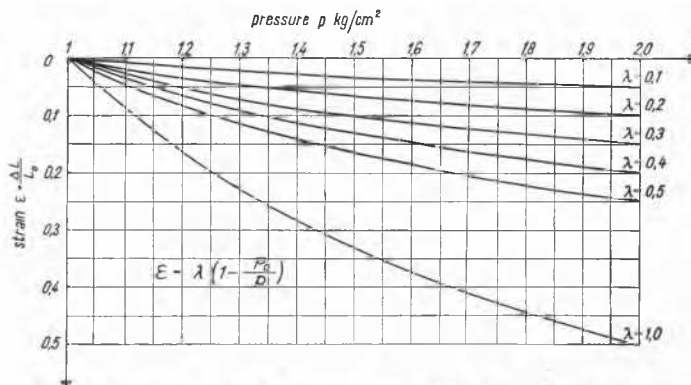


Fig. 3 Diagram for determining percentage of air-bubbles.
Diagramme pour la détermination du pourcentage d'air.

At pressure p the joint length of air and water column :

$$L = l_w + l = l_w + l_0 \frac{p_0}{p}$$

Thus the shortening under influence of pressure increase :
($p - p_0$) :

$$\Delta l = l_w + l_0 - \left(l_w + l_0 \frac{p_0}{p} \right) = l_0 \left(1 - \frac{p_0}{p} \right)$$

The ratio of shortening ϵ in turn :

$$\epsilon = \frac{\Delta l}{L_0} = \frac{l_0}{l_w + l_0} \left(1 - \frac{p_0}{p} \right)$$

Introducing the ratio of $\lambda = \frac{l_0}{l_w + l_0}$ (λ indicates the ratio of air present to the starting pressure of $p = 1$ atmosphere)

$$\epsilon = \lambda \left(1 - \frac{p_0}{p} \right)$$

In Fig. 3 are demonstrated in terms of the various values of ϵ , the ratio of shortening λ of water + air column under the influence of overpressure p . Applying a known pressure to a tube closed at one end and filled with a mixture of soil, water and air, it is possible to measure the reduction of water level and to calculate from this the compression of ϵ , determining the air ratio λ .

Examination of transient phenomena

The author has investigated transient phenomena that appear when the top stratum is perforated. For this purpose, the experiment demonstrated in Fig. 4 may be considered. One end of the tube is filled with a sand-gravel mixture and is closed with a trap-door, the other end is subjected to the pressure of a water column of height H . The model has the following features :

1. An incompressible and immobile network is formed by the grains of the solid part.
2. The air in the voids does not move with the water and its behaviour is governed by the Boyle-Mariotte law.

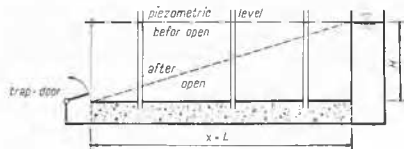


Fig. 4 Experimental arrangement for the examination of piping in two-phase soil.

Montage expérimental pour l'étude du renard dans un sol à deux phases.

3. The water in the voids is governed by the Darcy law.
4. The Darcy law is assumed to be valid in each intermediate phase of non-permanent movement.
5. The solution of air in water is disregarded in relation to the relatively small pressure values.

The author examines the case of a two-phase soil. He assumes, that the flow-resistance r by a given coefficient of permeability k is proportional to the square of actual velocity : v

$$r = Cv^2$$

From the moment of opening the trap-door, two forces act on the water in the tube filled with soil. The water pressure $p = H \gamma$ on the one hand, and a resistance in an opposite direction $r = Cv^2$. The difference between the two pressures accelerates the flow of water through the pores of soil in the tube from its standing position at the moment of opening to

a velocity $v_{\text{perm}} = k \frac{H}{L}$, which corresponds to the permanent flow stage.

According to Newton's law :

$$ma = p - r$$

and

$$ma = p - C_1 v^2$$

where acceleration a is the first derivative of velocity v and m is the mass of the moving water in a tube of unit cross-section.

Therefore

$$\frac{dv}{dt} + \frac{C_1}{m} v^2 = \frac{p}{m} \quad \frac{C_1}{m} = C_1 \quad \text{and} \quad \frac{p}{m} = C_2$$

hence

$$\frac{dv}{dt} = C_2 - C_1 v^2$$

$$dt = \frac{dv}{C_2 - C_1 v^2}$$

$$t = \frac{1}{C_1} \int \frac{dv}{A^2 - v^2}$$

where

$$A = \sqrt{\frac{C_2}{C_1}}$$

$$t = \frac{1}{A} \frac{1}{C_1} \text{ area } \operatorname{tgh} \frac{v}{A} + K$$

if

$$t = 0, \quad v = 0 \quad \text{so} \quad K = 0$$

$$t = \frac{1}{AC_1} \text{ area } \operatorname{tgh} \frac{v}{A}$$

and

$$v = A \operatorname{tgh} AC_1 t$$

$$AC_1 = C_1 \sqrt{\frac{C_2}{C_1}} = \sqrt{C_2 C_1}$$

thus :

$$v = \sqrt{\frac{C_2}{C_1}} \operatorname{tgh} AC_1 t = \sqrt{\frac{C_2}{C_1}} \operatorname{tgh} \sqrt{C_2 C_1} t$$

If t is large enough, so $AC_1 t = 1$

and

$$v = v_{\text{perm}} = \sqrt{\frac{C_2}{C_1}} = k \frac{H}{L} \quad \frac{C_2}{C_1} = \frac{p}{C} = v_{\text{perm}}^2$$

thus :

$$C = \frac{p}{v_{\text{perm}}^2}$$

and the flow resistance r :

$$r = C v^2$$

$$r = p \frac{v^2}{v_{\text{perm}}^2}$$

Consequently speed increases from the moment of opening until a constant speed is attained, in accordance with the relationship already described.

In the case of three-phase soil (Fig. 5), the above described phenomenon can be followed thus.

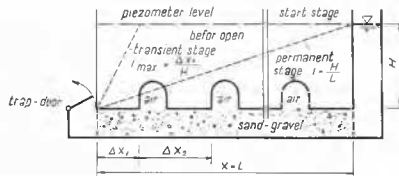


Fig. 5 Experimental arrangement for the examination of piping in three-phase soil.

Montage expérimental pour l'étude du renard dans un sol à trois phases.

Assume that the air volume of bubbles is concentrated at a distance Δx from each other along a tube, at opening the speed starts on the first section Δx_1 under the influence of pressure prevailing in the air-space V_1 . In air-space V_1 pressure should be decreasing by Δp_0 in order that flow may start on the next section Δx_2 . Although the value Δp is small, it is not zero owing to capillary effects.

In this way, $i_0 = \frac{\Delta p_0}{\Delta x_1}$ as an hydraulic gradient is required for starting Δx_1 . This phenomenon is of wave type.

Both theory and practice have proved that no soil will issue from boils unless the hydraulic gradient has reached a value of $i = 1$, and therefore the author has to assume either a hollow space-tube with free way for water, or a progressive expansion of bubbles under pressure in voids resulting in a wave of $i_{\text{max}} > 1$ proceeding through the soil, in the most permeable zone under the top stratum.

In consequence of wave i_{max} in procession, piping sets in progressively in a relatively short time. The air in the voids is compressed with the result that it expands suddenly after the manner of an explosion and thereby causes piping.

Detecting the points of minimum safety

The most permeable lines indicate the points of minimum safety from the point of view of the formation of boil, more so when the water of a river saturating the soil cannot flow freely. The author continued his investigations with pore-water measuring instruments which he placed in permeable strata in lines, at equal distances from the dam.

The values of pore water-pressure izochrons, recorded at identical times and plotted on a site map, determined the points where the pore water-pressure increased in relation to the environment. A study of the izochrons enabled the position of dangerous points to be established.