Leakage in embankment dams - Functional analysis and strengthening by adding a downstream berm

Leckagen in Schüttdämmen - Funktionsanalyse und Bauwerksertüchtigung durch Einsatz einer luftseitigen Berme

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Abstract

The new Swedish dam safety guidelines require high consequence dams to withstand the “maximum possible leakage” that can be expected during their lifetime. For existing dams there is commonly a need to improve the resistance for seepage. One possibility for improvement of existing dams is to construct a toe-berm of coarse material along the d/s toe of the dam.

Zusammenfassung

Die neuen Schwedischen Sicherheitsvorschriften für Talsperren fordern, dass Stauanlagen mit großem Gefährdungspotenzial die “größte denkbare Durchsickerung“ ertragen sollen, die während ihrer Lebenszeit vorkommen könnte. In Schweden werden zur Zeit mehrere Staudämme verstärkt, um diese Bemessungsdurchsickerung durch den Untergrund oder den Dammkörper sicher abzufangen. Dieser Beitrag behandelt das gegenwärtige Verfahren der Bemessungsdurchsickerung für vorhandene Staudämme und die notwendigen Vorkehrungen für stabilisierende und erosionsverhindernde luftseitige Auffüllungen.

1 Introduction

Swedish experiences of leakage, internal erosion and sinkholes based on a survey which has been conducted on large embankment dams, shows that most of the observed sinkholes and leakage cases reported in the survey are assumed to have been caused by internal erosion within the impervious core [1]. In order to compensate for deficiencies in existing dams with moraine (glacial till) core and broadly graded d/s filters the Swedish dam safety guidelines require that high consequence dams should withstand the “maximum possible leakage” that can be expected during their lifetime.

The maximum possible leakage is considered to be unique for each dam, and methods to assess this maximum leakage, as well as measures to increase the resistance for leakage, are considered to be of utmost importance. This paper describes the procedure in the Swedish guidelines for determining the design leakage for existing embankment dams with moraine cores, and outlines the considerations for design of stabilising toe berms. During the last couple of years a large number of dams in Sweden have been upgraded with a stabilising berm, zoned as a reverse filter, along the d/s slope. The berms are considered as preventive measures improving the ability of the dam to safely pass large leakage.

For dams, which have experienced deficiencies in the core, it also has to be considered to improve the sealing element of the dam, and thus reduces the potential for occurrence of large leakage (**Figure 1**), [2]. There are several potential means to improve the water tightness, for example remediation by adding a slurry trench, sheet pile walls, jet grouting etc. In some cases retrofitting of filters and drains have been used. Further discussion on such measures directed towards improvement of the sealing element and filters have been outside the scope of this paper.

2 Function analysis

The susceptibility for internal erosion caused by the filter gradation in Swedish dams has been evaluated and a correlation exists [3]. Initiating root causes of leakage and resulting failure mechanisms caused by through flow are illustrated in Figure 1, together with possibilities to intervene in the different phases of a leakage scenario. Governing factors for initiation, continuation and progression of a leakage scenario, and methods for estimating the potential for failure of embankment dams by internal erosion and piping are described by Fell et al (2004) [4].

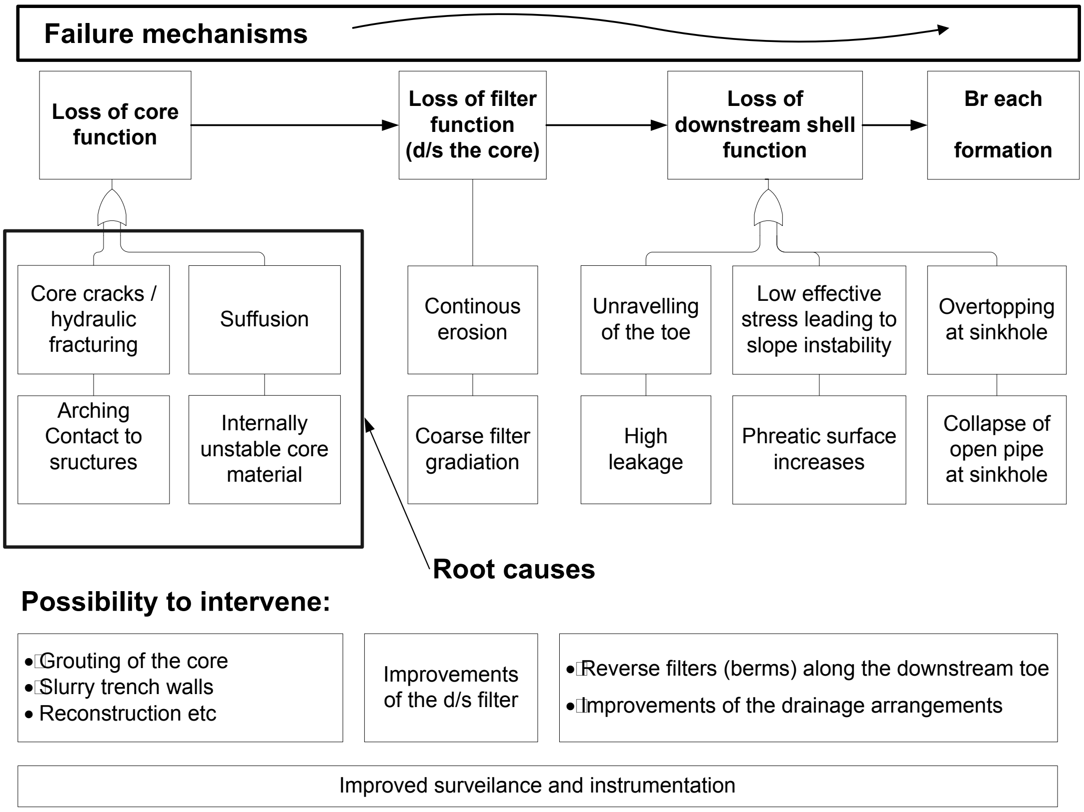

Figure 1: Failure mechanisms caused by through-flow and possibilities to intervene in different phases. Modified from [2].

The Swedish guidelines prescribe that high consequence dams should be designed to have sufficient drainage capacity and erosion resistance to withstand potential failure modes related to leakage, and possible associated internal erosion, as illustrated in **Figure 2,** [5]. The main failure mode is leakage followed by slope unravelling or scouring at the d/s toe (pathway no. 1). The risk for failure induced by leakage has usually been assessed assuming that the discharge flow, toe-stone size and slope angles are the governing factors.

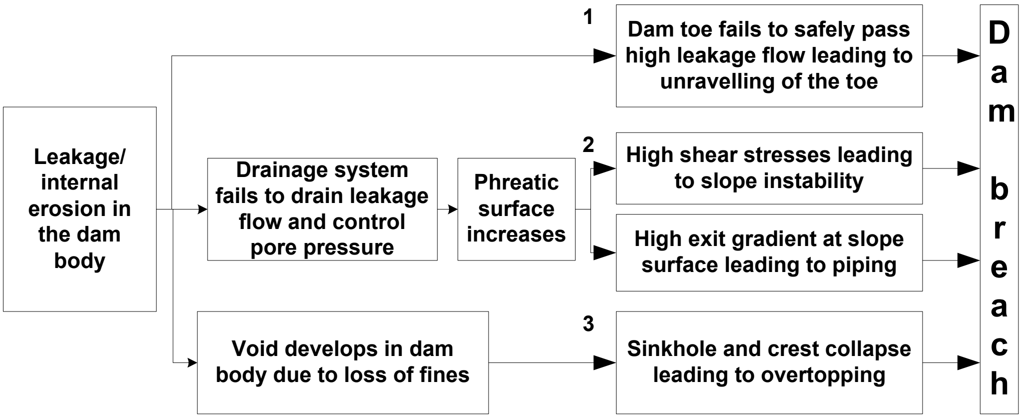

Figure 2: Failure scenarios initiated by leakage/internal erosion in the dam body, [5].

Mass sliding is another potential failure mode, where the friction angle, the slope angle and the pore pressure distribution are the governing factors. If the drainage system fails to drain the leakage and control the pore pressure, the phreatic surface will increase in the d/s shell (pathway no. 2). Leakage may spring from the d/s slope causing local stability problems (or piping) close to the point of leakage. With time further slides may progress backwards and cause overall instability and overtopping following settlement of the crest. One possible means to prevent such stability problems in existing dams is to construct a stabilising toe-berm of coarse material along the d/s toe of the dam. The gradation of the fill material of the toe-berm should be coarse enough to permit safe passage of maximum possible leakage and prevent scouring at the down stream toe.

A third possibility is that of wash-out of fines resulting in cavities in the dam body. The collapse of such a cavity may lead to sinkholes causing the crest to collapse and overtopping (pathway no. 3). This failure mode should be considered particularly for dams with a small free board and/or a narrow crest. A possible measure to decrease the vulnerability to this failure scenario is to extent a stabilising toe-berm to cover the d/s slope of the dam all the way up to the crest of the dam. Thereby the crest will be wider and overtopping of the crest is prevented in the event of a major sinkhole in the area of the core.

3 Design leakage

3.1 Earth-fill dams

For earth-fill dams the design leakage can be assessed in a very conservative manner by the assumption that the shoulder material determines the leakage rate. Thus the fines in the core material are assumed to have been lost by internal erosion and transported through possible filters and through the materials in the shoulders. The calculation is done without regard of the permeability of the core material. The permeability of the filter zone may also be disregarded, if the filter is narrow or if it may be eroded into the shoulder material in the event of severe leakage. In the most conservative case both the core and the filters are assumed to be damaged by internal erosion to such a degree that the dam is assumed to be homogeneous and with the same permeability as the material in the shoulders.

3.2 Rock fill dams

For rock fill dams the flow can be turbulent, and the design leakage must also be assessed from case to case. For high dams a total design leakage of 5 m^3/s, or a flow per meter of 0.5 m^3/s, is expected to give a considerable increase of the time available for self-healing if a large quantity of leakage would occur due to internal erosion. However, for many Swedish rock fill dams a smaller design leakage can be justified since the shoulders usually consist of fairly fine-grained rock-fill originating from required excavations of tunnels and underground power stations. In such cases, the above indicated very conservative assumption that the shoulder material governs the flow could still be used. In many cases this results in practical sizes for the material in a berm along the toe.

The Swedish guidelines have adopted Eq. (1) for the permeability for turbulent flow [6].

$$k_t = \frac{1.7 \cdot d_{10} \cdot g \cdot n^3}{\beta_{\circ} \cdot (1-n)} \qquad (1)$$

where:

k_t = turbulent permeability, cm^2/s^2

$\beta_{\circ}$ = grain form coefficient, (3,6 for crushed rock)

d_{10} = grain size for the 10 % passing material, ($1.7 \cdot d_{10}$ = dominant grain size)

n = porosity (assessed to 0.3)

g = gravity acceleration (assumed to 9.81 m/s^2)

The turbulent permeability is used to calculate the velocity (v) by Eq. (2). The velocity, and thus the design leakage (q), through the assumed homogeneous dam is assessed from the gradient (i) from a flow net, which is assumed to be similar to that for laminar flow conditions. A_{mean} is the mean through flow area for the leakage, where the mean height can commonly be assumed to be 2/3 H, where H is the height of the dam.

$$v^2 = k_t \cdot i \qquad q = v \cdot A_{mean} \qquad (2)$$

When the flow velocity has been calculated Reynolds number should be determined in order to verify the flow conditions. When Reynolds number is greater than 600 the flow condition can be assumed to be fully turbulent. When Reynolds number is smaller than 1 or 2 the flow is assumed to be fully laminar. It is always conservative to assume turbulent flow. For values of Reynolds number that is in the lower range say below 100 an interpolation can be justified.

4 Design of the downstream stabilising berm

Toe berms will improve the drainage capacity and stability of an existing dam, and thus to some extent compensate for potential deficiencies in existing dams in the core and filter that may result from older design standards. However, it is important to stress that the potential for initiation of a leakage scenario is not reduced (Figure 1). The berm along the dam toe is designed according to the following principles:

- Stones with sufficient size to withstand design outflow are placed along the toe of the d/s slope at the contact to the foundation

- The d/s slope should have a sufficiently gentle slope, or be stabilised with coarse berm material, so that sliding will not occur if design leakage results in high pore pressures in the shoulder material.

The material gradation of the material in the berm is selected to have the required erosion resistance. The relationship between a stable stone size D in a granular fill material is recommended to follow the relationship according to Eq. (3), [6]. The relationship includes a load factor of minimum 1.5. This gives a margin to failure or collapse in the rock-fill (damages are accepted but no failures) and a margin to the uncertainty in the estimation of the unit flow.

$$D_{50\,\mathrm{dim}} = 0.60 \cdot S_0^{\,0.43} \cdot q^{0.78} \tag{3}$$

where

$D_{50\,dim}$ = rock size in metres (load factor 1.5)

S_0 = down stream slope of rock fill (1V:S_0H)

q = unit discharge in m^3/s, m

The size according to Eq. (3) is conservative when used also for higher elevations of the berm. For a d/s slope inclination 1V:1.5H and horizontal foundation it is as an example required to use a D50 of 300 mm for a design flow of 0.5 m^3/s,m.

5 Example

A recent example of the design of a toe berm is given in **Figure 3**.

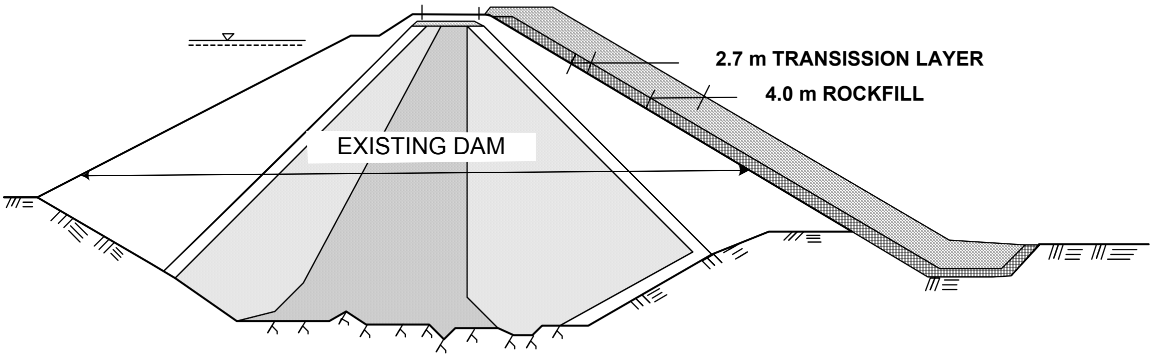

Figure 3: Example where the toe-berm has been extended up to the crest

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