Proven strength for piping

La résistance Démontrée pour le phénomène Renard

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ABSTRACT: The phenomenon piping is a catastrophic failure mechanism of water-retaining structures. In order to be able to design the Dutch dikes more economically, the method of Sellmeijer has been developed. At first, this paper represents the evaluation of Sellmeijer's method. Secondly, the paper focuses on a practical case. This practical case indicates the importance of proven strength in a piping calculation.

RÉSUMÉ: Le phénomène Renard est un méchanisme de rupture catastrophique d'ouvrages de controle des eaux. Afin de pouvoir concevoir les digues néerlandaises d'une manière plus économique, la méthode de Sellmeijer a été développée. D'abord cet article représente l'évaluation de la méthode de Sellmeijer, avant de se concentrer sur un cas pratique. Ce cas indique l'importance de la résistance démontrée pour un calcul du phénomène Renard.

1 PIPING

The phenomenon piping is an intriguing failure mechanism of water-retaining structures (e.g. a dam or a dike). During a flood, piping can be detected by the occurrence of sand boils behind a dam or a dike. In the top of the sand layer under the dike, erosion channels develop as a result of seepage induced by high river-levels. For levels smaller than a critical level the situation is stable. However, a small increase in level will enlarge the erosion channels until a new equilibrium is reached or, beyond a critical level progressive erosion occurs. In short time a disaster may develop (Fig. 1 and 2).

The most important methods for the evaluation of piping occurrence are the method of Bligh, Lane and Sellmeijer. The methods of Bligh and Lane are empirical and have been used for nearly a century (Bligh, 1910; Lane, 1935). The method of Sellmeijer is based on a sound physical concept; a microscopic process (channel erosion) has been consistently attached to a macroscopic process (groundwaterflow) (Sellmeijer, 1989). Especially, the method of Bligh is commonly employed in the Netherlands; this method is regarded as too conservative.

The method of Sellmeijer has been developed in order to be able to design the Dutch dikes more economically. In general, Sellmeijer's method does yield significantly better results than the method of Bligh. In some cases however, calculations with Sellmeijer's method are lower then the lowest limit of Bligh's method, in the Netherlands defined by $C_{Bligh}=10$. Under other circumstances however, the opposite is the case; the calculation with Bligh is the more favorable one. This has raised the question, whether it is safe to apply the method of Sellmeijer in all circumstances. This has lead to a revalidation of Sellmeijer's method (van Loon, 2000).

Figure 1: piping failure of an earth dam (Teton dam, USA)

2 EVALUATION OF THE FORMULA OF SELLMEIJER

The method of Sellmeijer consists of an analytical model, that describes the piping mechanism. A practical formula has been derived from this model by means of curve-fitting, Formula (1). First, the theory of the analytical model has been thoroughly reviewed. In the second place the curve-fitting, that has resulted in the formula, has been verified. Finally, tuning of fundamental parameters for practical use has been established by means of the prior conducted large-scale tests in the Delta Phlume (Silvis, 1991).

$$\frac{\Delta H_c}{L} = \alpha \cdot \frac{\gamma_p'}{\gamma_w} \cdot c \cdot \tan\theta \left[0.68 - 0.1 \cdot \ln(c)\right] \qquad (1)$$

$$\text{with } c = \frac{\eta \cdot D_{70}}{\sqrt[3]{\kappa \cdot L}} \quad \text{and} \quad \alpha = \left(\frac{D}{L}\right)^{\left[\frac{0.28}{(D/L)^{2.8}-1}\right]}$$

and:

- ΔH_c = the critical level [m]
- L = the length of the structure [m]
- D = the thickness of the aquifer [m]
- γ_w = the volumic weight of water [kN/m^3]
- γ_p' = the submerged volumic weight of sandgrains [kN/m^3]
- η = White's coefficient [-]
- κ = the intrinsic permeability of the aquifer [m^2]
- D_{70} = grain size distribution curve value [m]
- θ = the bedding angle of sand [°]

This research shows, that both on the basis of the theory as well as on the basis of the practical tests the faith in the Sellmeijer's

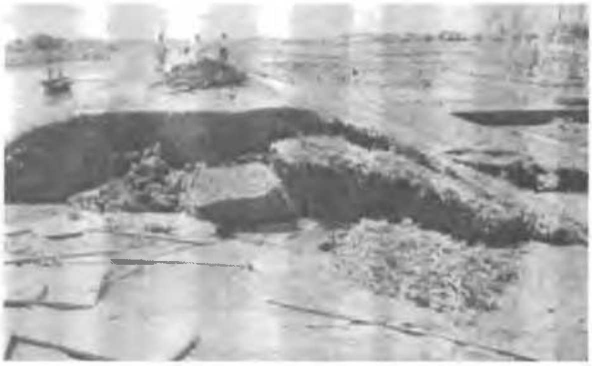

Figure 2. Piping failure of a clay dike (Nagoya, Japan)

method is justified. From the verification of the practical tests it appeared, that the value of two parameters had to be adjusted; the coefficient of White η is adjusted from 0.3 to 0.25 and the bedding angle of sand θ from 41 to 38 degrees.

In addition, the parameter D_{70}, related to the sand type, should be changed into D_{60} for practical reasons. Calculations with the formula of Bligh and Lane however, may result in unsafe designs of water-retaining structures. Hence it is recommended to use the formula of Sellmeijer in order to make piping predictions valuable and safe. Sellmeijer's formula can however yield economically more favorable designs, but also less favorable designs. In any case, the risk of inundation is reduced properly.

Subsequently, it appeared that the formula of Sellmeijer can be simplified into Formula (2). This makes the method easier to apply. The error induced by the suggested simplification appears always smaller than 10%.

$$\frac{\Delta H_c}{L} = \left(\frac{D}{L}\right)^{\left[\frac{0.28}{(D/L)^{2.8}-1}\right]} \cdot \frac{\gamma_p'}{\gamma_w} \cdot c \cdot \tan\theta \cdot \left[0.68 - 0.1 \cdot \ln(c)\right] \qquad (2)$$

$$\text{with} \quad c = \frac{\eta \cdot D_{60}}{\sqrt[3]{\kappa \cdot D}} \quad \text{for} \quad 0.01 < \frac{D}{L} \le 1$$

$$\text{and} \quad c = \frac{\eta \cdot D_{60}}{\sqrt[3]{\kappa \cdot L}} \quad \text{for} \quad \frac{D}{L} > 1$$

3 PROVEN STRENGHT

In this research project, a practical case has been studied; the 'Waalbandijk' in Opijnen, the Netherlands. This is a case where many sandboils have been found, especially during the high level floods in 1995. At the location of this dike, the subsoil aquifer consists roughly of 3 layers. The problem in this case is, that one of these layers is a coarse sand layer with relatively high permeability.

Since in the analytical formula of Sellmeijer inhomogeneous soil is not taken into account, an apparent average permeability has to be determined for the entire aquifer. This can be done in various ways. The aquifer may be considered as a serial or as a parallel system. The reality is however a combination of both systems, because the water doesn't flow exclusively in a horizontal or vertical way.

For this case all three methods have been applied (parallel, serial and combination), in order to show the differences.

A numerical approach has been performed with the computer code MSEEP in order to asses reality (the combined system) as close as possible. The result shows that the apparent permeability of the aquifer should be taken as 10 m/d (Table 1). This value

Table 1: The critical level for different permeabilities

approach	*average permeability [m/d]*	*ΔH_c [m]*
Parallel system	33.7	3.59
Serial system	14.5	4.64
Combination	10.0	5.19
	Proven strength: drop in 1995	4.6 to 4.7

is lower than found for both 'engineering values', the parallel and the serial system. The anisotropy of the layers is accounted for; the vertical permeability of the top sand layer is considerably lower because it contains horizontal thin clay deposits.

During the high-level floods of the river Waal in 1995, a number of sandboils have developed along the dike in Opijnen, at a distance of about 100 meters behind the dike. The development of these sandboils indicates, that the piping process has started, but there was no question of progressive failure yet. In 1995, the dike in Opijnen stood without problems a level of 4.6 to 4.7 meters. This fact proves, that a permeability on the basis of common engineering approach, i.e. a parallel or a serial system, does not properly describe the reality. Table 1 shows that the correspondingly calculated critical level *(ΔH_c)* for a parallel system is lower than the level the dike has successfully withstood in 1995.

Even a calculation with a serial system does not come up to the proven strength. The calculation with the numerical program MSEEP however, shows that the dike should be able to retain a level more than 5 meters.

4 CONCLUSION AND RECOMMENDATION

The conclusion of the evaluation of the formula of Sellmeijer is, that both on the basis of the theory as well as on the basis of the practical tests in the Delta Flume the faith in the Sellmeijer's method is justified. Subsequently the calculations with regard to the 'Waalbandijk' in Opijnen show, that this dike has been close to failure in 1995; only a margin of 0.4 m was left. It is striking that the proven strength of the Waalbandijk shows, that the common engineering approach for piping predictions simply yields unsafe results. The elaborated practical case shows clearly, that the calculation with the method of Sellmeijer and a correct parameterization of the actual inhomogeneous subsoil corresponds well with observations in practice.

In Sellmeijer's formula it is not possible to include different geometries. To account for that a complete numerical approach is required. For a numerical computation a FEM steady groundwater flow code may be used. This code must be extended with a new boundary condition, which represents the pipe flow and limit equilibrium of the sand particles. It can be accomplished by the introduction of a new line element. This is an important future development to incorporate piping in FEM flow programs.

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