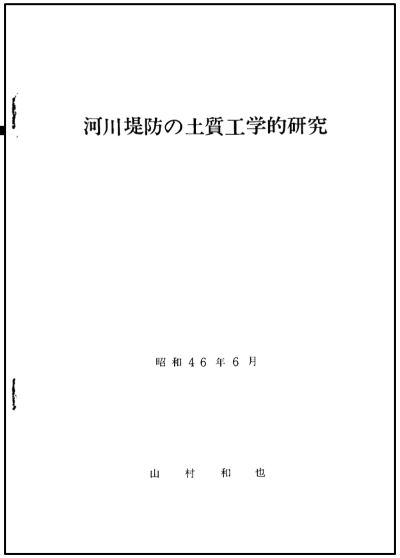
メカニズムに基づくパイピング照査のために必要な研究とは？

～ i_cとG/ Wの先へ ～

京都大学農学研究科
藤澤 和謙

Critical hydraulic gradient



河川堤防の土質工学的研究

昭和４６年６月

山　村　和　也

山村和也 氏の博士論文（1971年）
「河川堤防の土質力学的研究」

$$i_c = (1-n)\left(\frac{\gamma_s}{\gamma_w} - 1\right) \approx 1.0$$

P.99からの抜粋

普通の土では、限界動水勾配は…大体1に等しい。しかし、実際の漏水はこれよりかなり小さい動水こう配で起こっている。たとえばMississippi河の調査によると動水勾こうが0.2～0.6でかなりの漏水が生じ、0.4～0.7になると激しい漏水が生じ、砂の噴き上げは0.5～0.8で起こっている。わが国の矢作川、阿武隈川、長良川の例でも0.2～0.6程度でかなりの漏水が観測されており、理論的に求められる限界動水こう配より小さい値で漏水が激しく起こっていることは事実である。この理由は昔から度々の漏水ですでに表層に弱点が形成されているため、透水層内の水頭のわずかな上昇によって、砂の噴き上げが生じるものと考えられる。漏水の危険箇所では、計画出水時に発生する透水層内の水頭をあらかじめ予測し、少なくとも動水こう配が0.5程度を越えないよう処置をしておくのが安全であろう。

※ 上記の数字は局所動水勾配か？

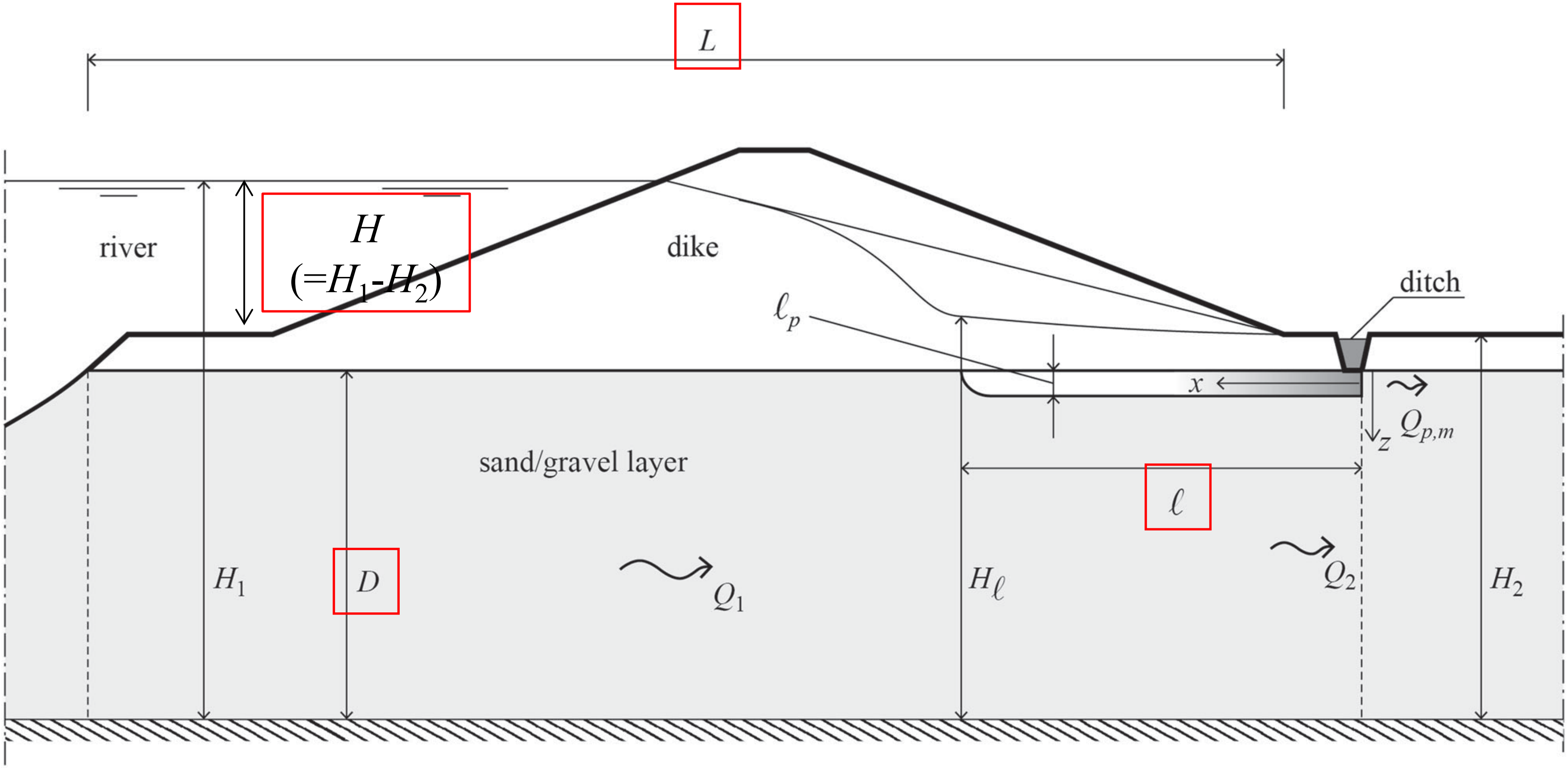
Critical average hydraulic gradient

$$\frac{H}{L}\left(=\frac{H_1-H_2}{L}\right)$$

ブライ式 $L = CH$

レーン式 $L_L = C_L H$

$(L_L = L/3 + L_V)$



G. Hoffmanns and L. Van Rijn: Hydraulic approach for predicting piping in dikes, Journal of Hydraulic Research, 2017.

Critical average hydraulic gradient

Sellmeijer (1988)

$$H/L = \gamma'_p/\gamma_w \tan\hat{\theta}\ \bar{c}\ \left(1 - 0.65\ (\bar{c})^{0.42}\right)$$

$$\bar{c} = \left(d^2/\kappa\ 2d/L\right)^{\frac{1}{3}} / \hat{C}$$

Sellmeijer et al. (2011)

$$\frac{H}{L} = F_r F_s F_g \qquad \text{with} \quad \frac{l}{L} = \frac{1}{2}$$

$$F_r = \frac{\rho^s - \rho^l}{\rho^l}\eta \tan\vartheta\,, \quad F_s = \frac{d_{70}}{\sqrt[3]{\kappa L}}\,, \quad F_g = 0.91\left(\frac{D}{L}\right)^{\varsigma}\,, \quad \varsigma = \frac{0.24}{\left(\frac{D}{L}\right)^{2.8} - 1}.$$

Resistance項　Scaling項　Geometry項

Shields-Darcy model by Hoffmanns (2017)

$$\frac{H}{L} = \frac{\sqrt{g}\left(\Psi_{\ell am,c}\Delta d_{15}\right)^{3/2}}{\nu\sqrt{\alpha_{\mathrm{Re},\ell}}} + \left(1 - \frac{\ell_c}{L}\right)\frac{d_{50}\nu}{\ell_{\mathrm{Re}}KD}$$

$$\text{with} \quad \frac{\ell_c}{L} = \exp\left(-\left(\frac{\alpha_f D}{L}\right)^2 \frac{\sqrt{g}\left(\Psi_{\ell am,c}\Delta d_{15}\right)^{3/2}}{\nu\sqrt{\alpha_{\mathrm{Re},\ell}}}\right)$$

Sellmeijer, J. B. (1988). *On the mechanism of piping under impervious structures* (Doctoral thesis). Delft University of Technology, Delft.

Figure 9-1 shows the computed relations between H/L and l/L. It can be clearly seen that a critical value of H exists. Beyond that, equilibrium cannot be reached. To the left of the critical H the erosion length l is stable. Here a fluctuation in H is compensated for by a small increase in l. But to the right of the critical head a variation in l demands a subsequent decrease of H . If the hydraulic head stays constant a progressive process of erosion is set in motion, resulting in the total collapse of the dike. This behaviour - a stable situation followed by progressive erosion at full swing - exactly coincides with observations in practice.

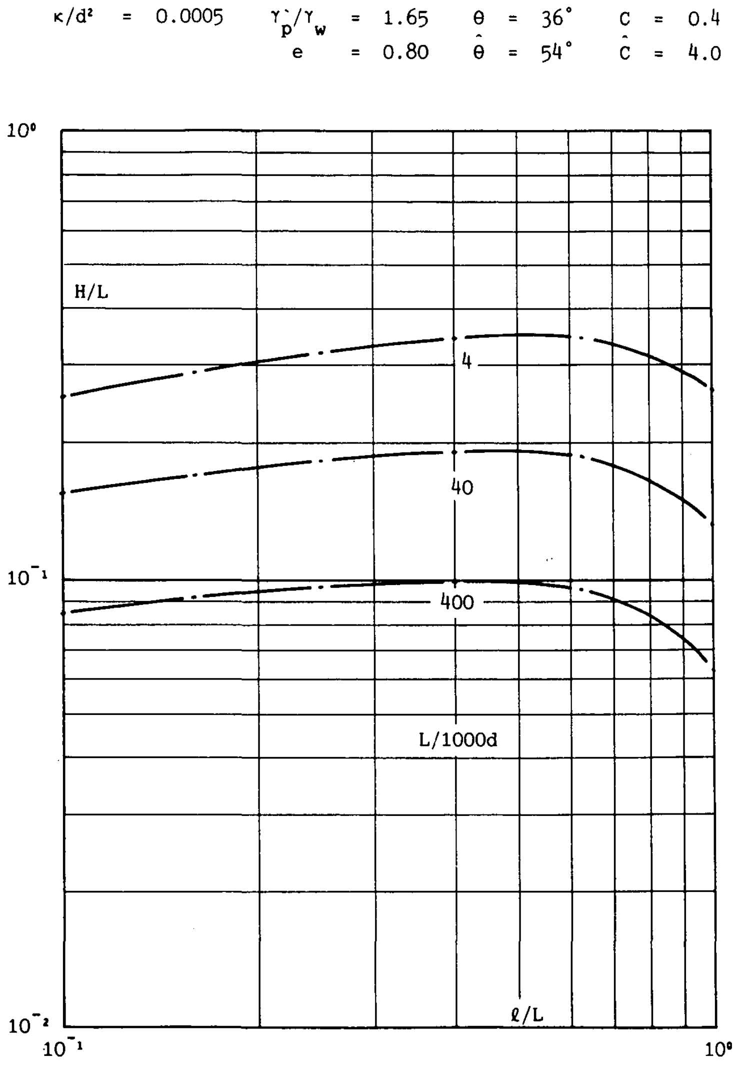


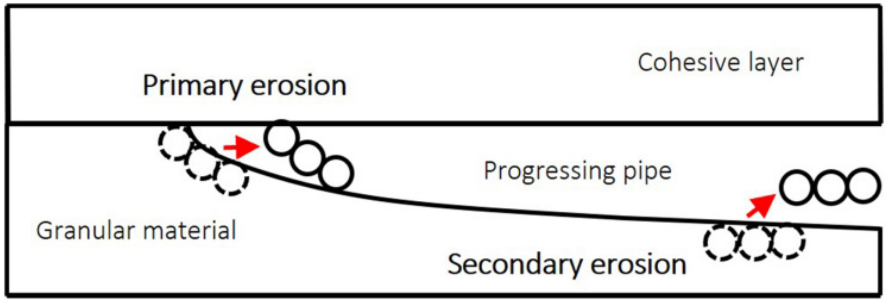
Fig. 9.1 : Relation between H/L and ℓ/L

Sellmeijer, J. B. (1988). *On the mechanism of piping under impervious structures* (Doctoral thesis). Delft University of Technology, Delft.

This equation supplies a range of values for H/L as function of l/L from which the maximum possible one must be calculated in order to obtain the critical head. One may observe in figure 9-1 that the desired maximum value is fairly well represented by the head for l=H/2. Therefore the critical head will be defined as that for l=H/2.

≪何をしたのか？≫
パイピング（侵食距離 l）が初期に存在するとして，限界水位Hを求めた。

1. パイピング（侵食距離 l）が存在する場合の水の流れを解く。
2. 土粒子が動き出すときの水位Hを求める。
3. 侵食距離lとHの関係から，Hの最大値とその時のlを求める。

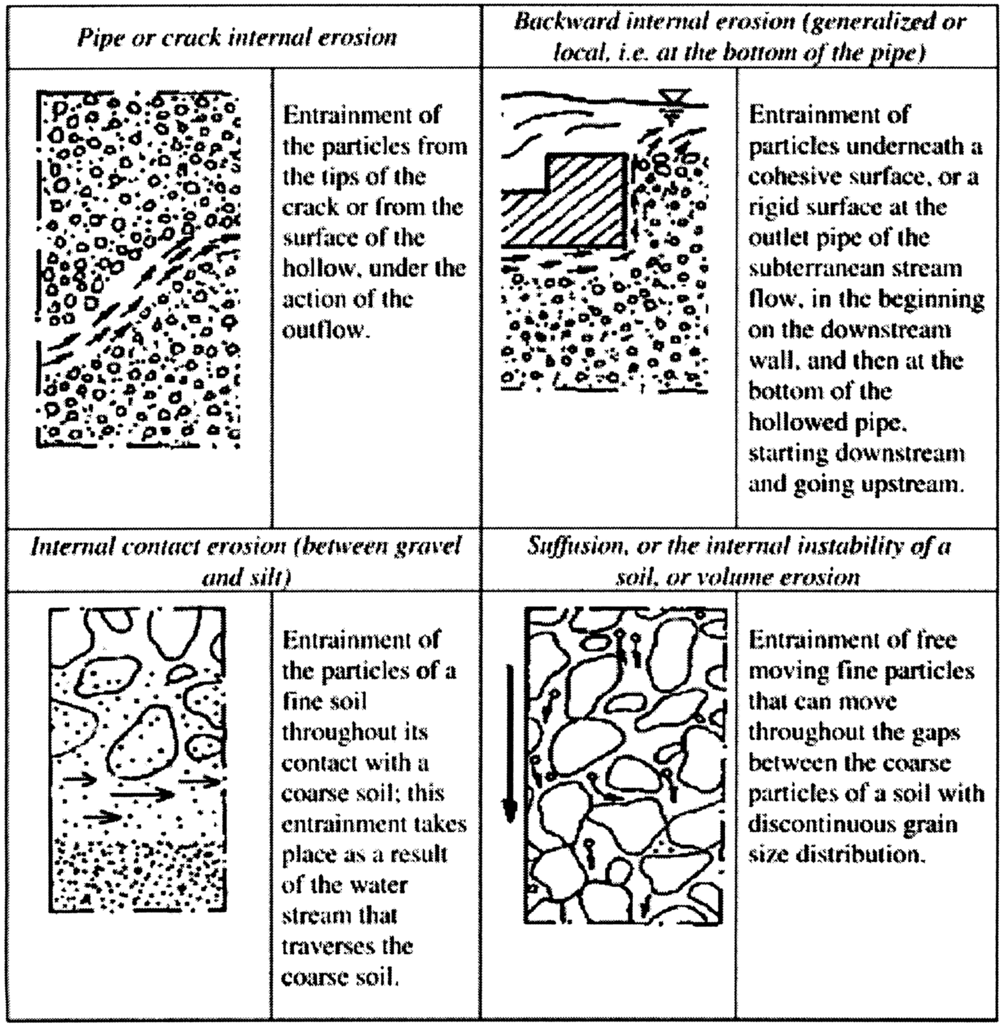


S. Ramezanifouladi and J. Cote. An improved small-scale test setup for assessing backward erosion piping, Canadian Geotechnical Journal, 2024.

Types of internal erosion

- Pipe or crack internal erosion
- Contact erosion
- Backward erosion
- Suffusion

内部侵食（土の内部での侵食現象，浸透流に起因する侵食現象）が4つに分類される。後退侵食は内部侵食の1つとなっている。



Pipe or crack internal erosion	*Backward internal erosion (generalized or local, i.e. at the bottom of the pipe)*
Entrainment of the particles from the tips of the crack or from the surface of the hollow, under the action of the outflow.	Entrainment of particles underneath a cohesive surface, or a rigid surface at the outlet pipe of the subterranean stream flow, in the beginning on the downstream wall, and then at the bottom of the hollowed pipe, starting downstream and going upstream.
Internal contact erosion (between gravel and silt)	*Suffusion, or the internal instability of a soil, or volume erosion*
Entrainment of the particles of a fine soil throughout its contact with a coarse soil; this entrainment takes place as a result of the water stream that traverses the coarse soil.	Entrainment of free moving fine particles that can move throughout the gaps between the coarse particles of a soil with discontinuous grain size distribution.

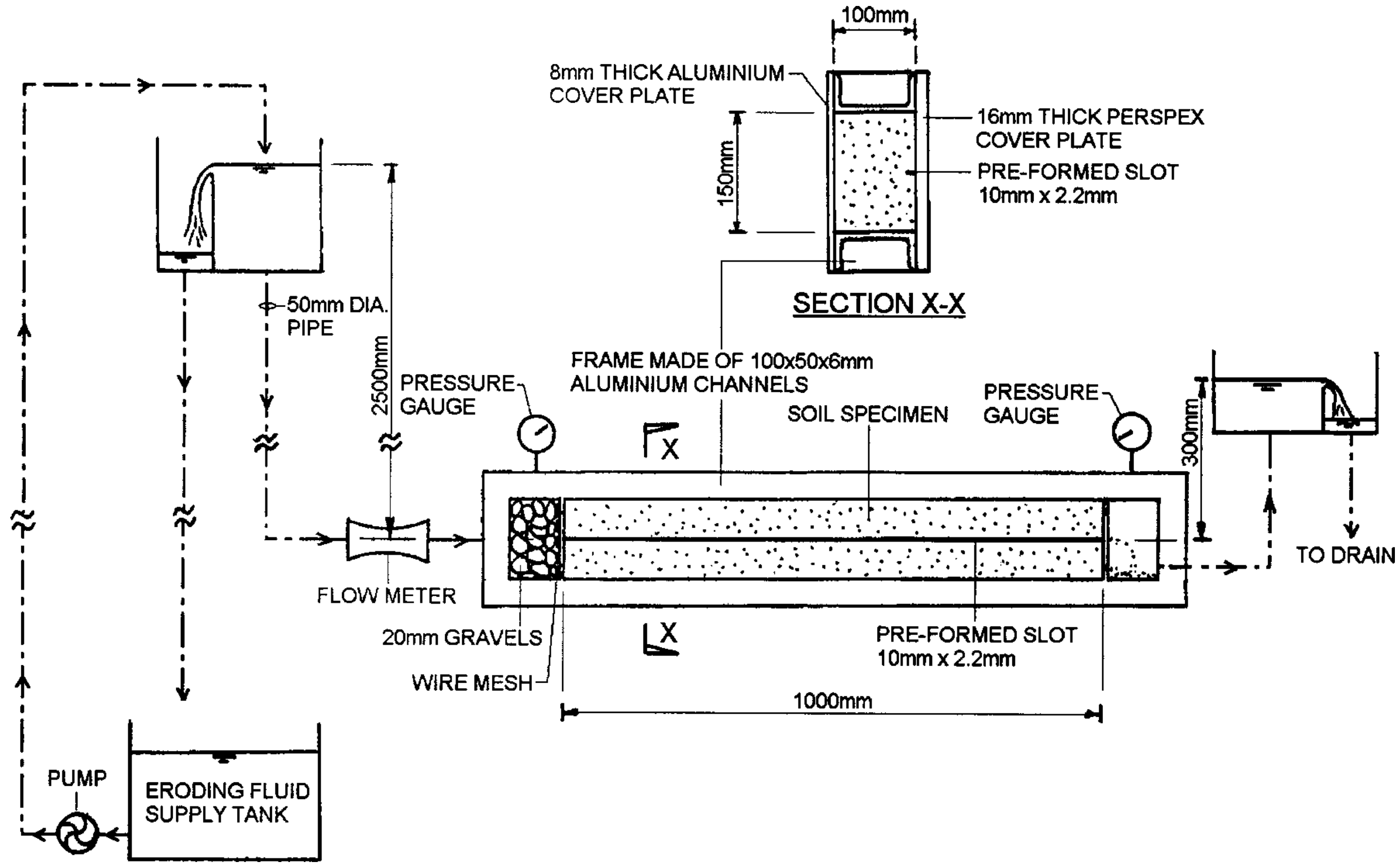
S. Bonelli: *Erosion of Geomaterials*, Wiley, 2012

Prediction level

予測レベル

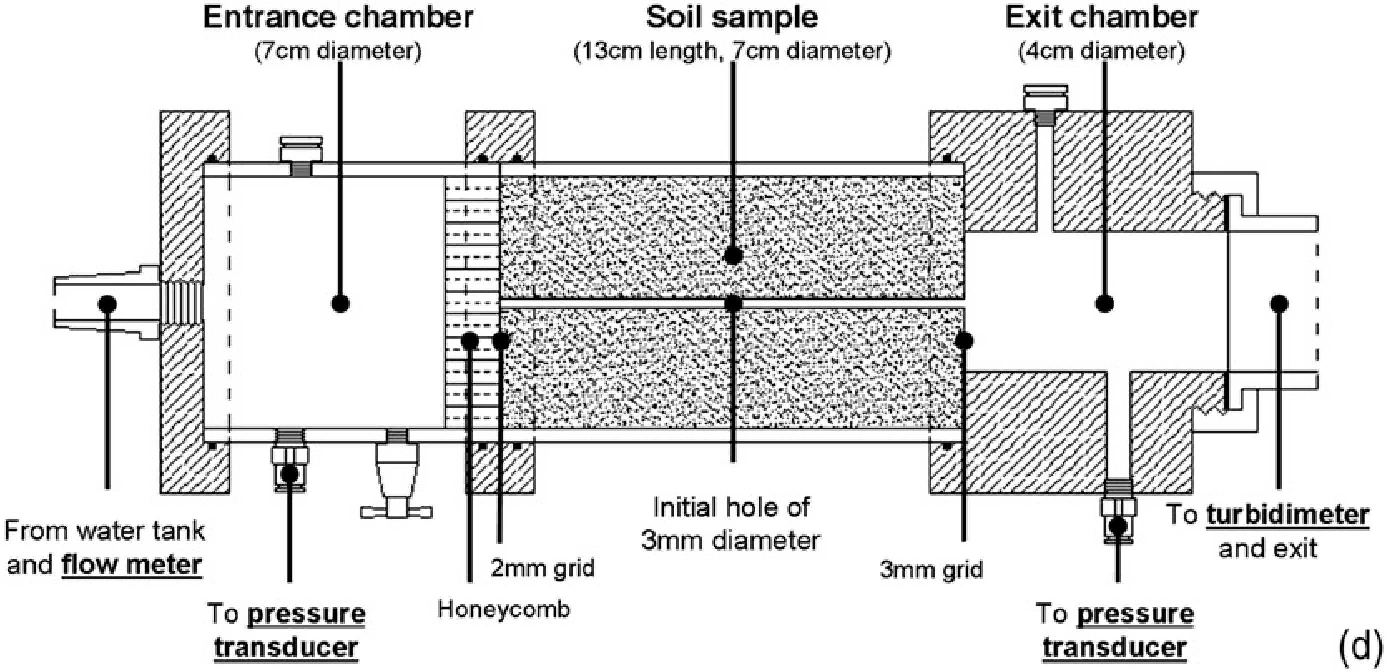
内部侵食の種類	安定・不安定	侵食量 侵食スピード	進展予測
Pipe or crack internal erosion	○	○	○
Contact erosion	○	×	×
Suffusion	○	△	×
Backward erosion	○	△	×

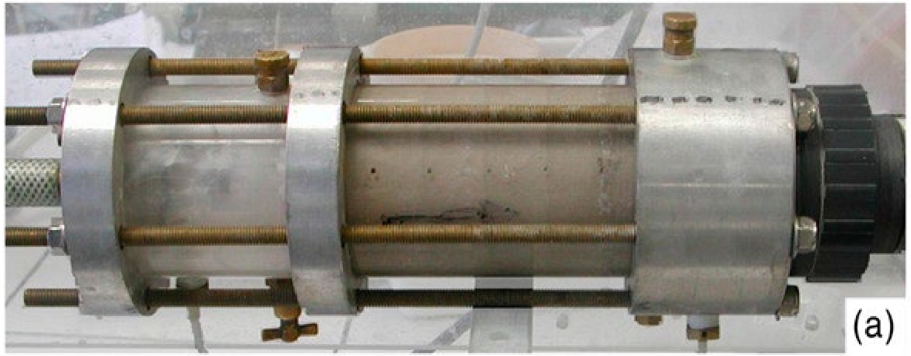
Pipe or crack internal erosion

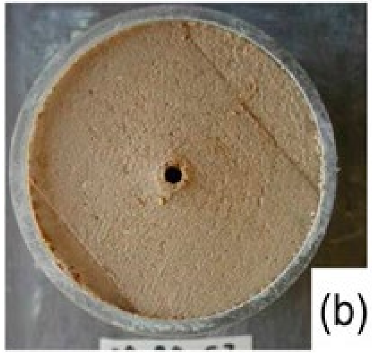


C.F Wan and R. Fell: Investigation of Rate of Erosion of Soils in Embankment Dams, J. Geotech. Geoenv. Eng., 2003.

Pipe or crack internal erosion

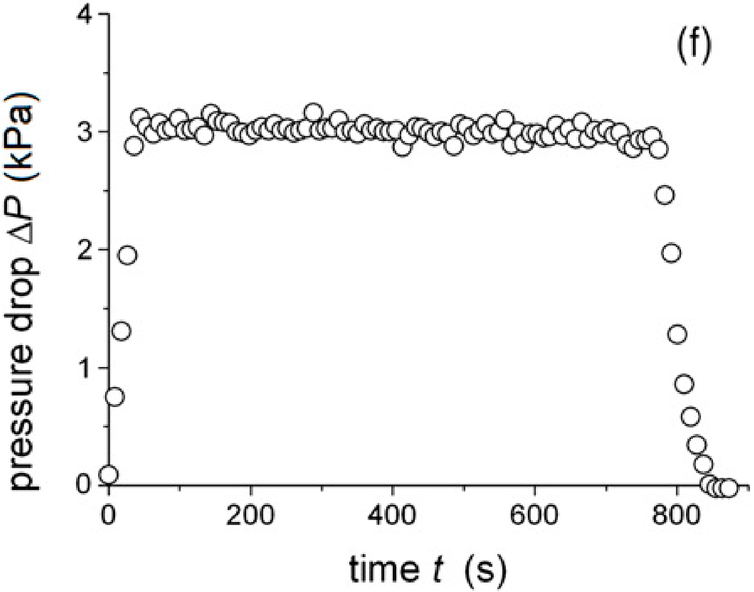


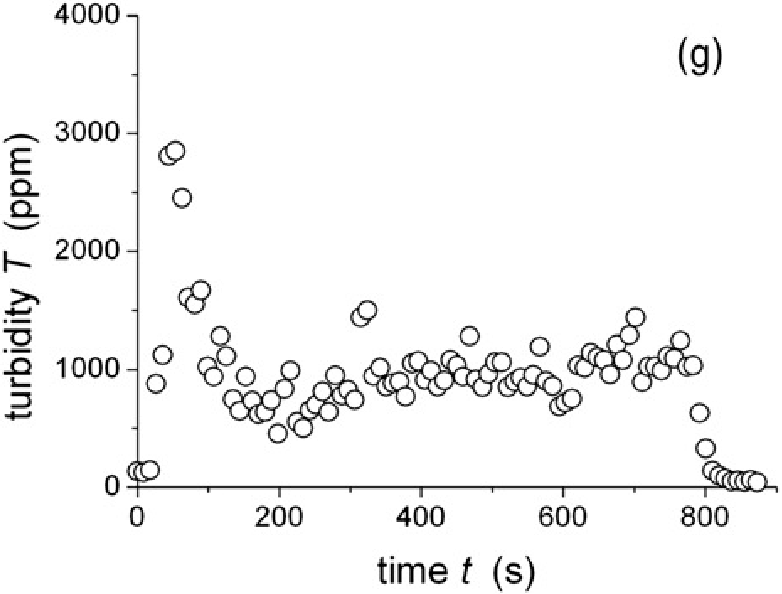


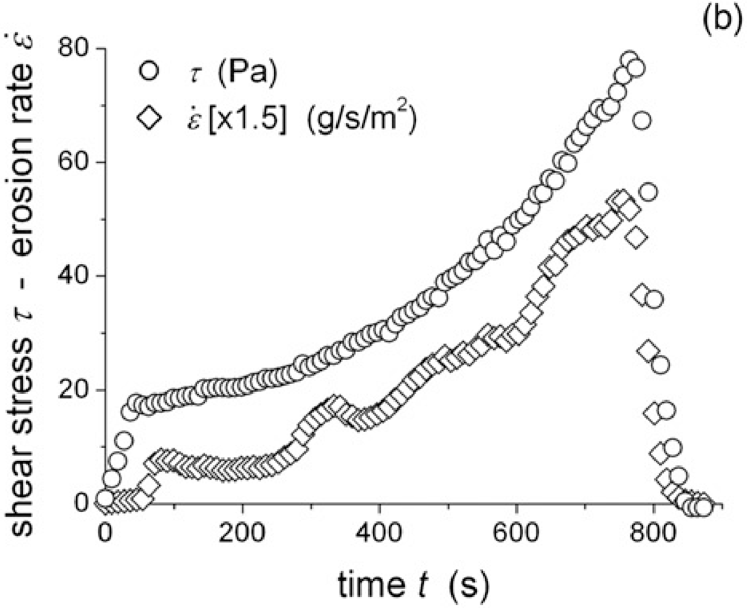


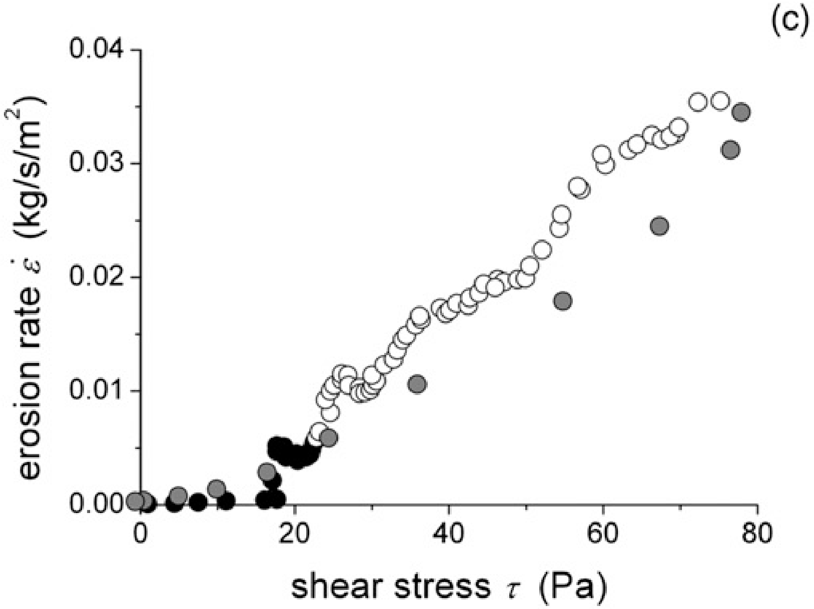
I. Haghighi et al.: Improvement of Hole Erosion Test and Results on Reference Soils, J. Geotech. Geoenv. Eng., 2013.

Pipe or crack internal erosion





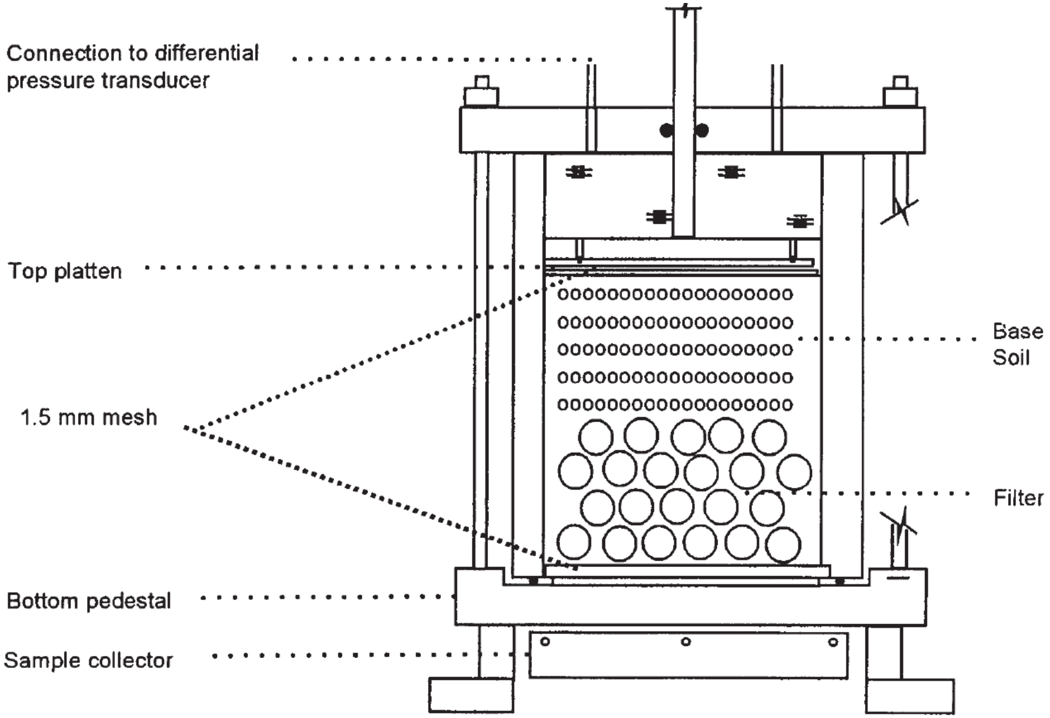




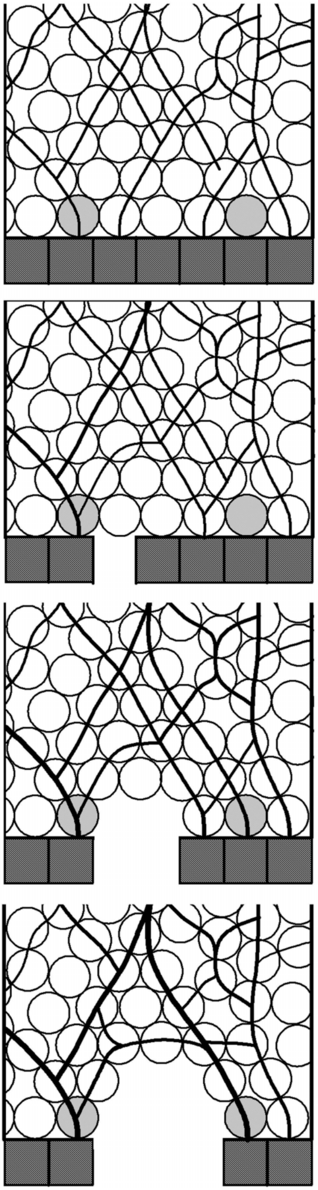
Contact erosion

フィルター則

$$D_{15} / d_{85} < 4 \text{ or } 5$$



フィルター則の見直し

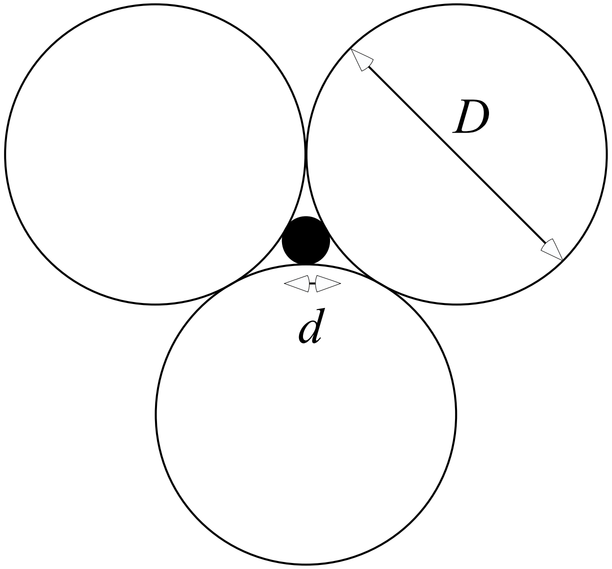


S.S. Tomlinson and Y.P. Vaid: Seepage forces and confining pressure effects on piping erosion, Can. Geotech. J., 2000.

J.R. Valdes and J.C. Santamarina: Clogging: bridge formation and vibration-based destabilization, Can. Geotech. J., 2008.

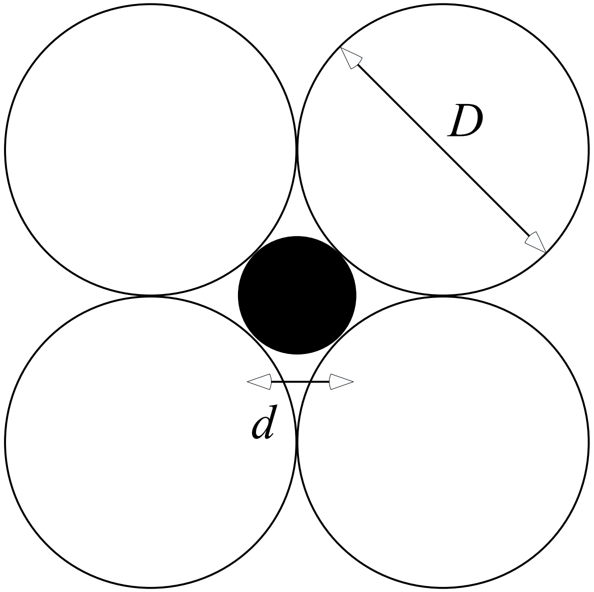
4や5の意味は…例えば

$$D_{15} / d_{85} < 5 \Rightarrow \frac{D_{15}}{5} < d_{85}$$



$$d_c = \left(\frac{2\sqrt{3}}{3} - 1 \right) D$$

$$d_c = \frac{D}{6.46}$$

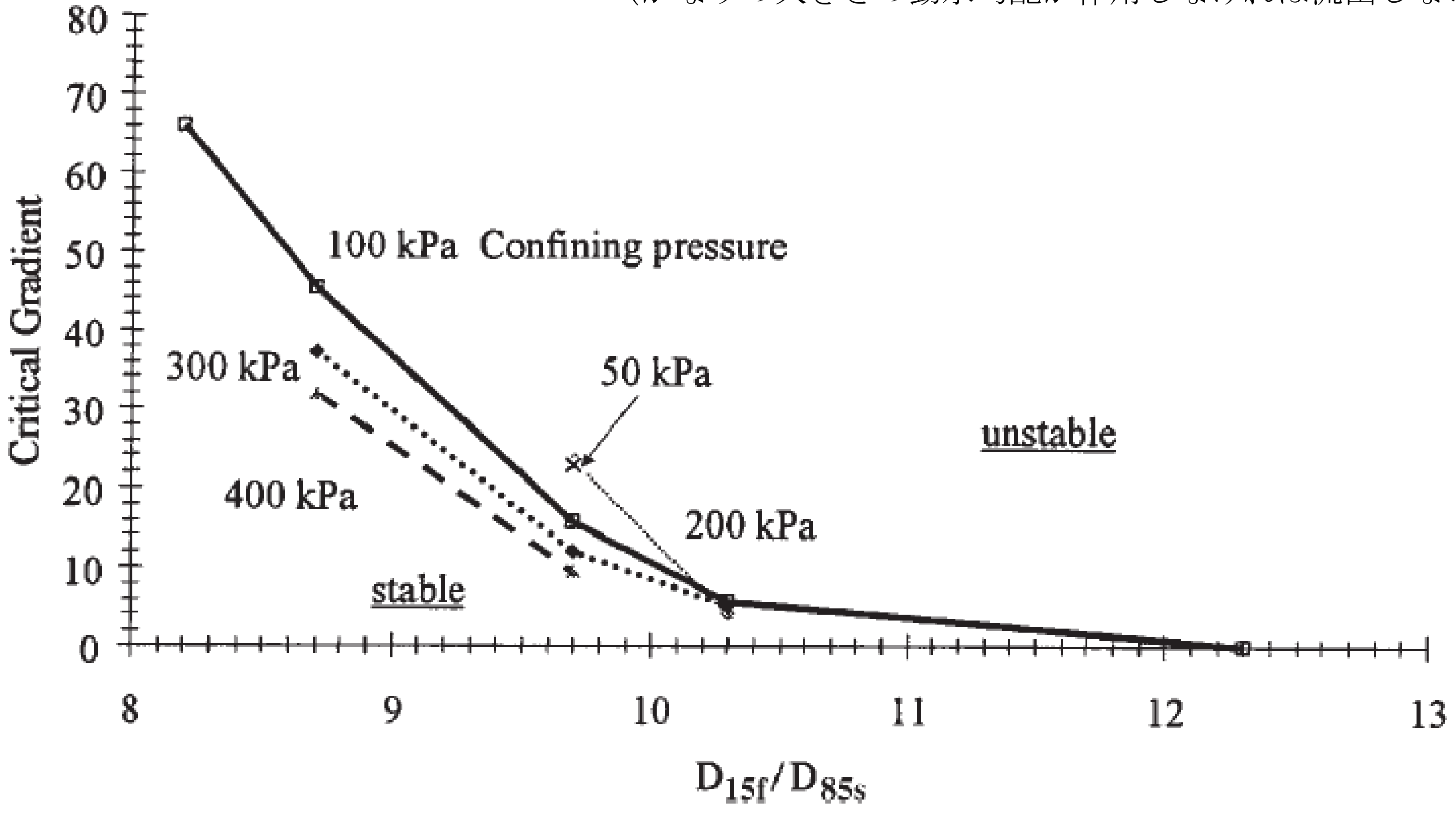


$$d_c = \left(\sqrt{2} - 1 \right) D$$

$$d_c = \frac{D}{2.41}$$

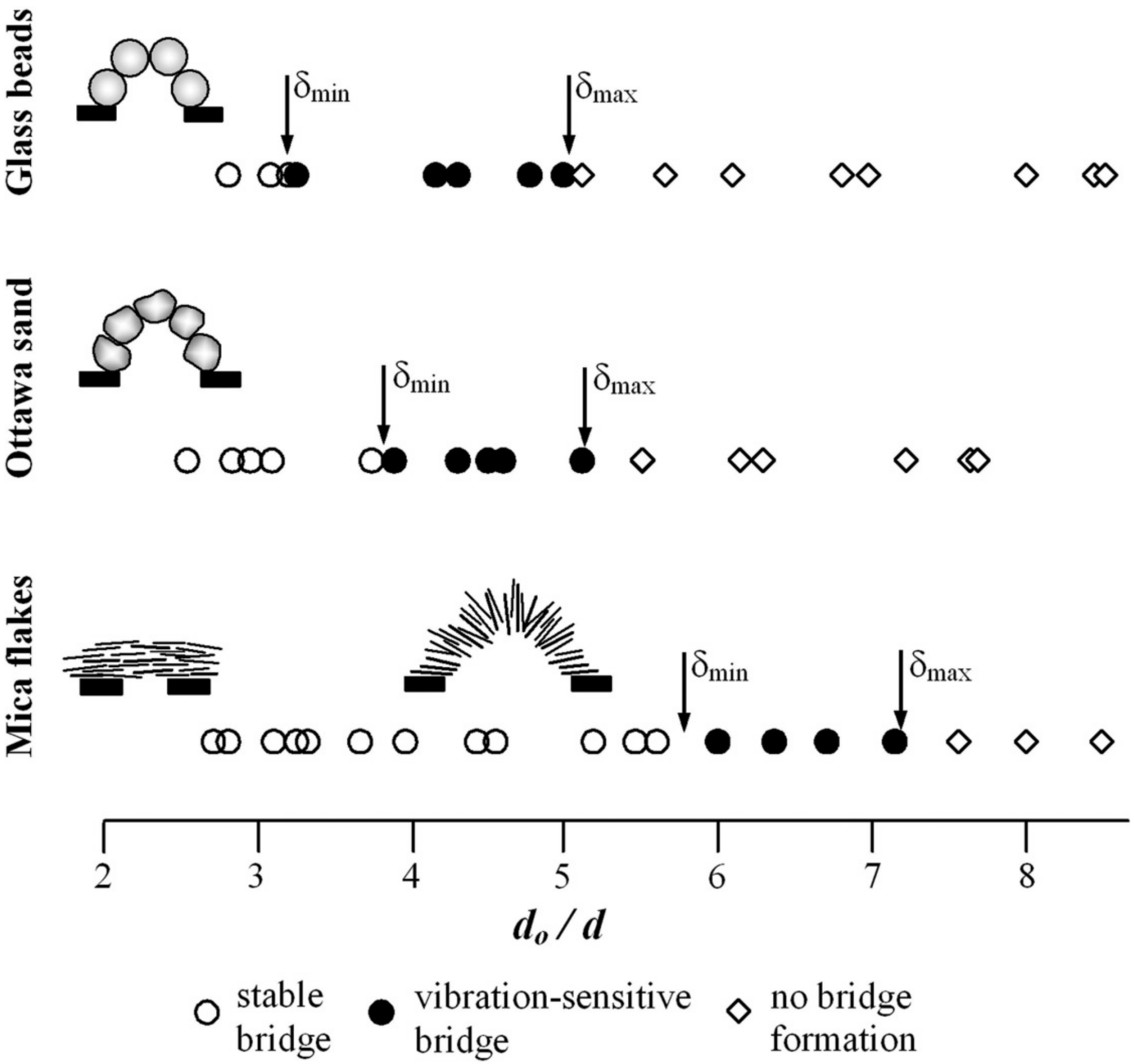
１つの小さな粒子が通過できるかどうか

実際には粒子径の比が10～11程度までは安定している
（かなりの大きさの動水勾配が作用しなければ流出しない）



S.S. Tomlinson and Y.P. Vaid: Seepage forces and confining pressure effects on piping erosion, Can. Geotech. J., 2000.

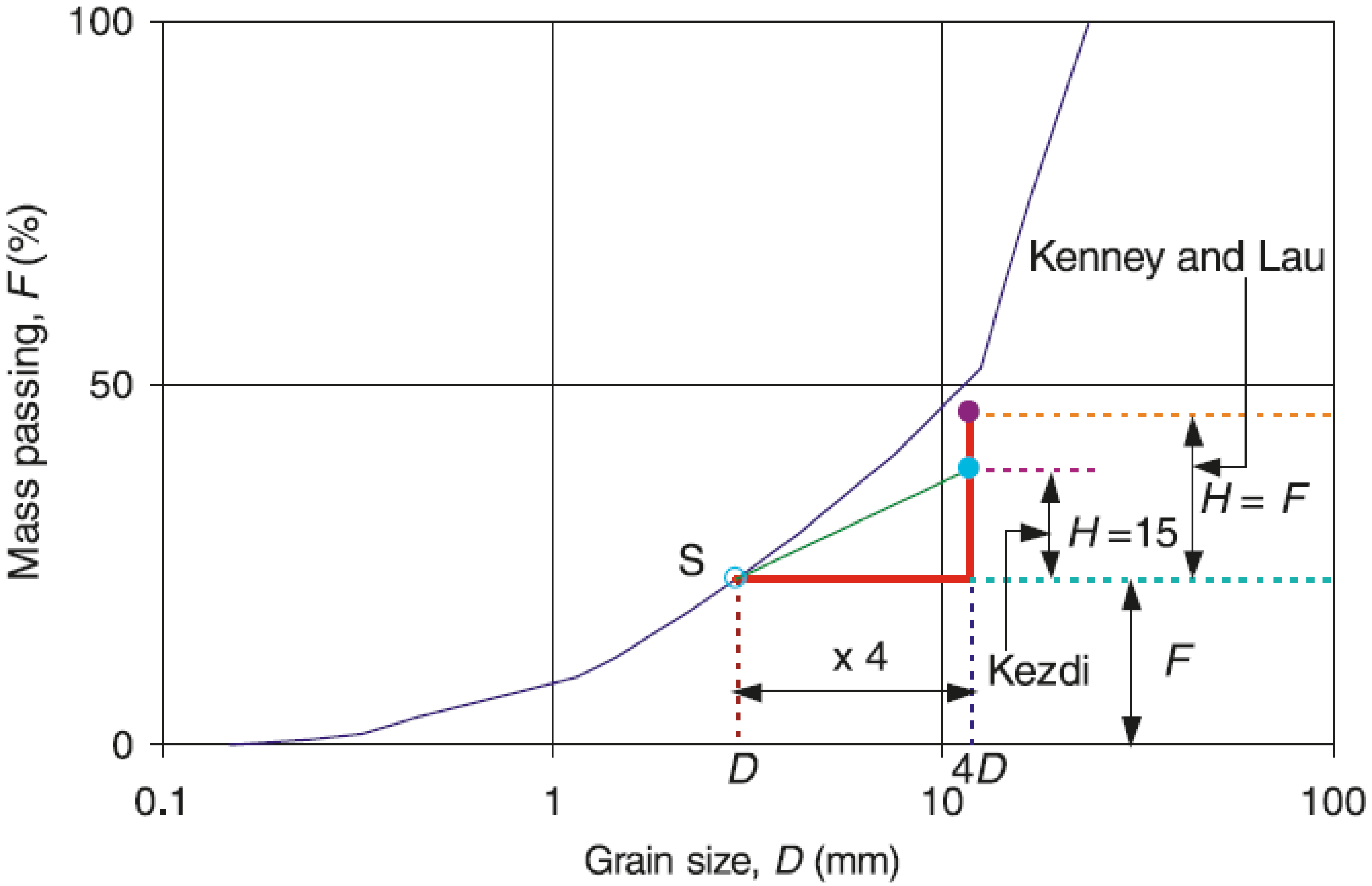
アーチの形成（粒径と穴の比は3〜４程度までは安定する）



J.R. Valdes and J.C. Santamarina: Clogging: bridge formation and vibration-based destabilization, Can. Geotech. J., 2008.

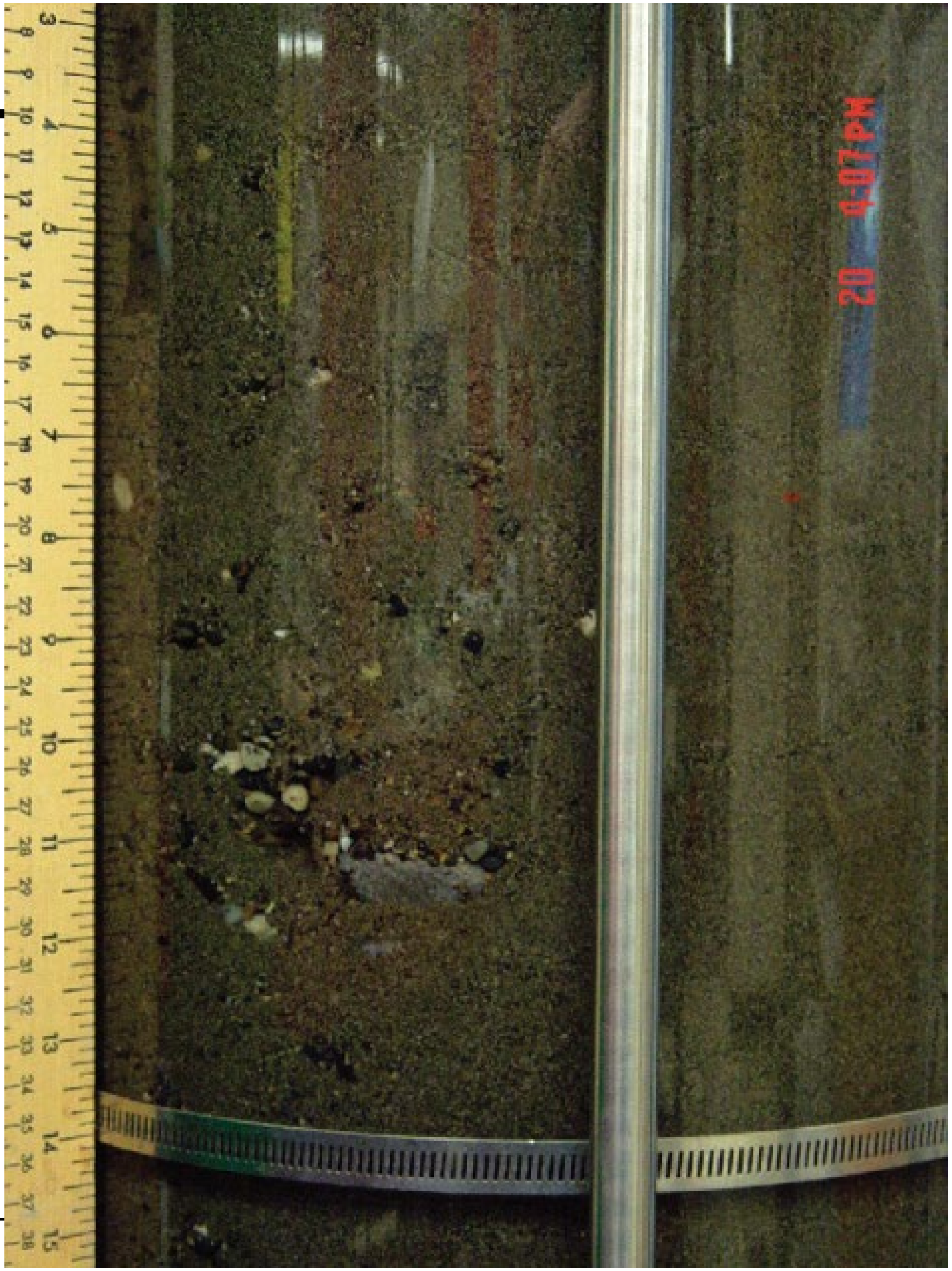
Suffusion

Criteria: Internal instability



M. Li and R.J. Fannin: Comparison of two criteria for internal stability of granular soil, Can. Geotech. J., 2008.

Suffosion



Suffusion
(じわじわ抜ける、体積変化なし)

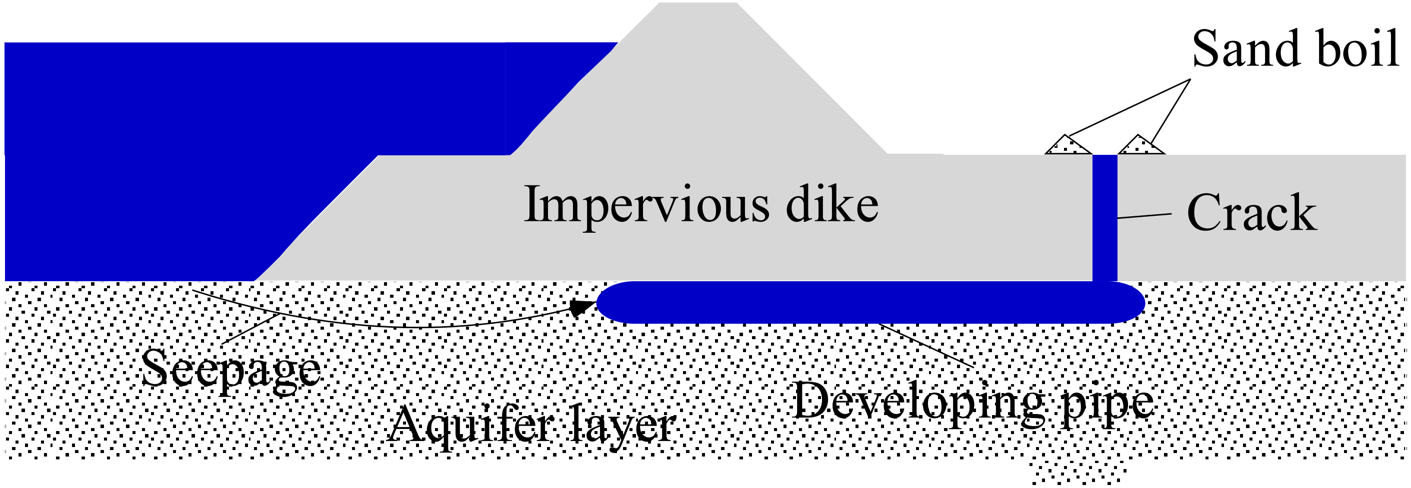
↓

Suffosion
(変形、内部動水勾配の急激な変化)

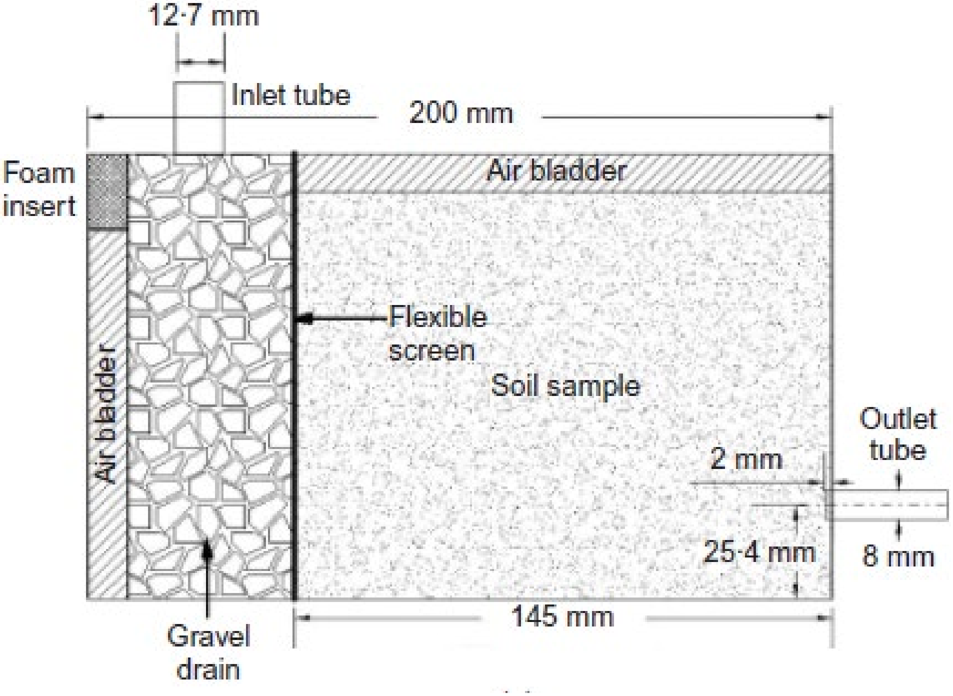
↓

Piping
(浸透流の集中)

Backward erosion

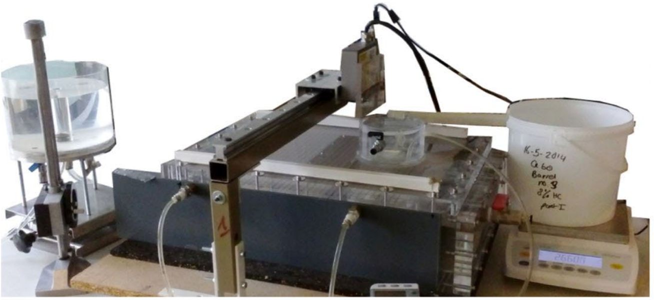


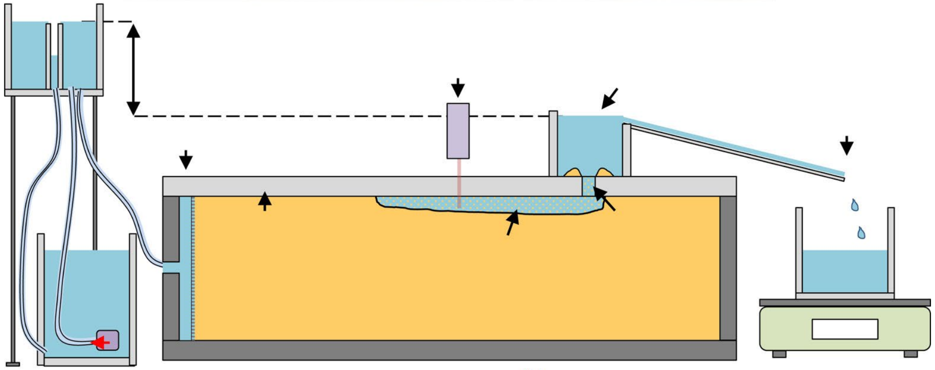
- σ1～3応力を制御し，パイピングの様子を観察
- 流量、動水勾配、流速等条件を変化
- 流入水圧、流出水圧、流出水濁度の計測

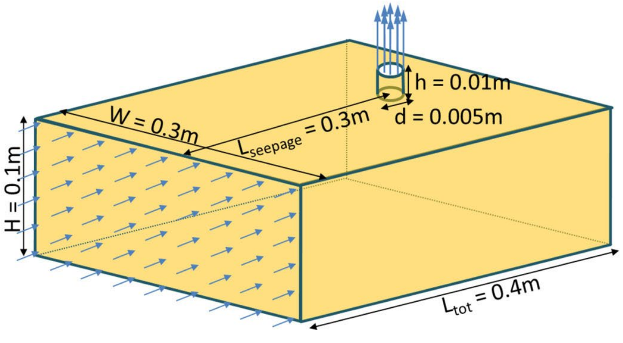


K.S. Richards and K.R. Reddy: Experimental investigation of initiation of backward erosion piping in soils, Geotechnique, 2012.

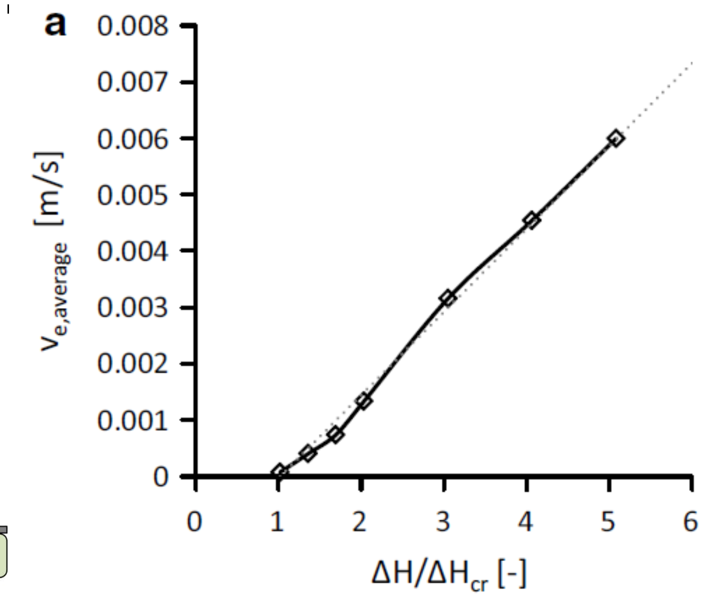
Backward erosionの進展速度の計測

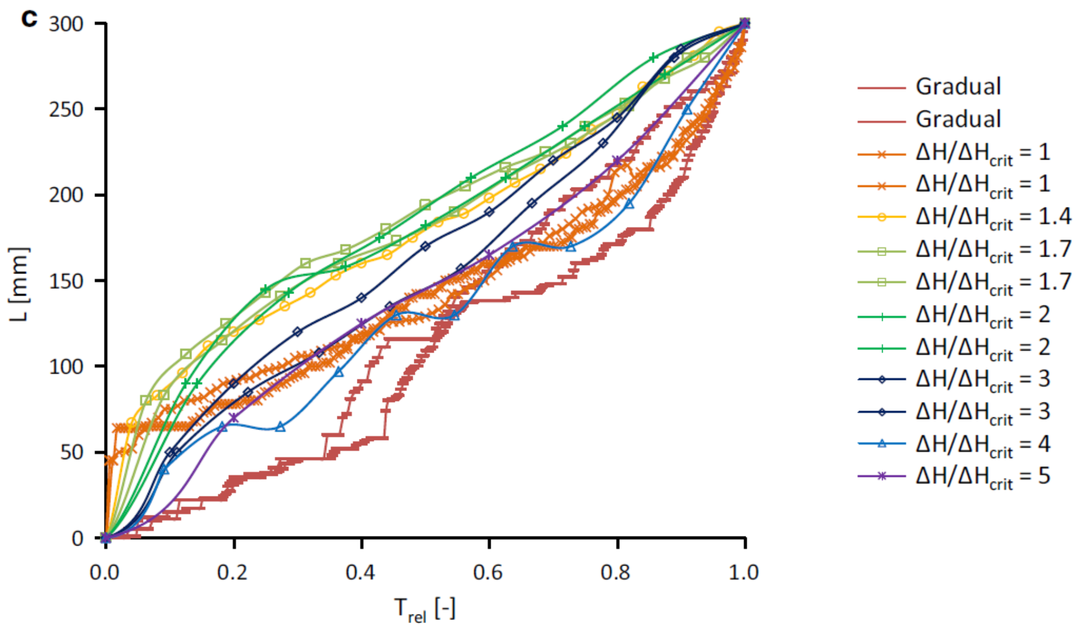






$$v_{e,avg} = L_{seepage}/T = 0.0015\,\frac{m}{s}\cdot\frac{\Delta H - \Delta H_{cr}}{\Delta H_{cr}}$$

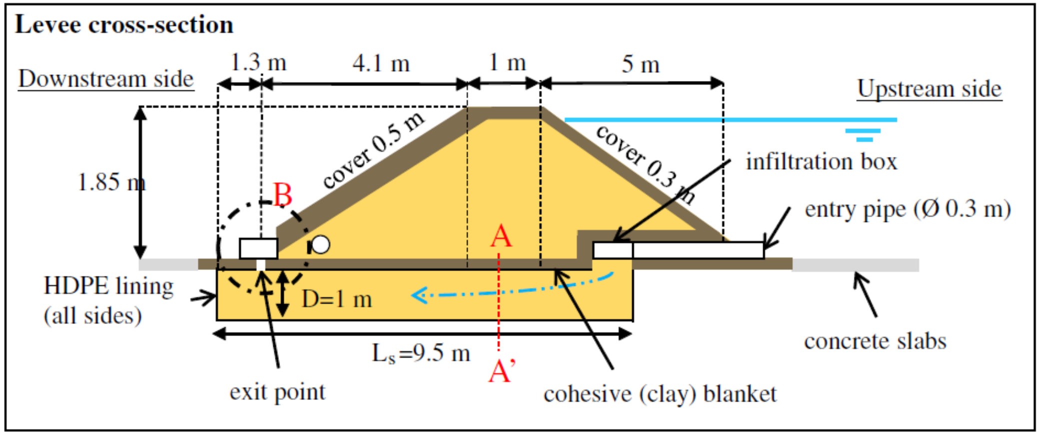


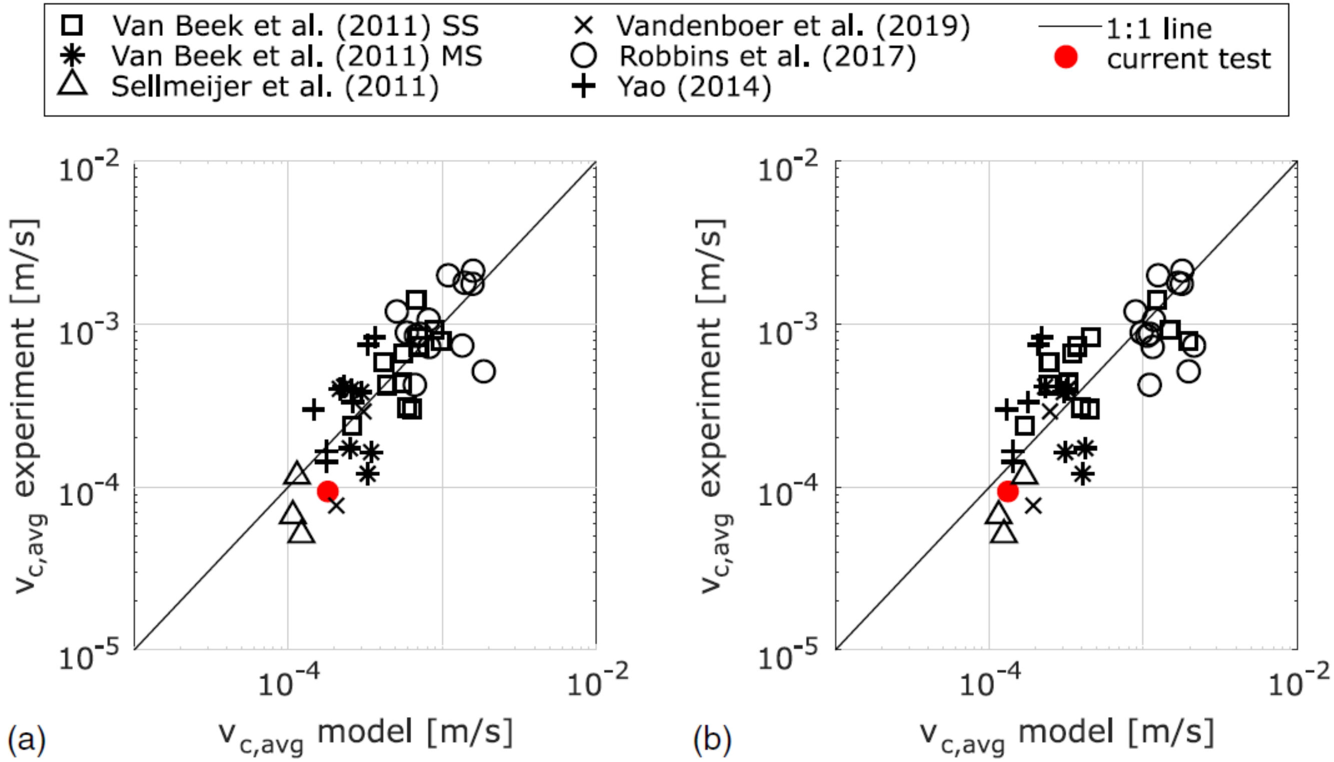


K. Vandenboer, F. Celette, A. Bezuijen (2019): The effect of sudden critical and supercritical hydraulic loads on backward erosion piping: small-scale experiments, *Acta Geotechica*, 14:783–794.

Backward erosionの進展速度の計測

J.C. Pol, W. Kanning and S.N. Jonkman (2021): Temporal Development of Backward Erosion Piping in a Large-Scale Experiment, *J. Geotech. Geoenviron. Eng.*,147(2), 04020168.





$$v_{c,avg} = 4 \cdot 10^{-3} \left(\frac{H}{L}\right)^{1.4} \left(\frac{k}{3.4 \cdot 10^{-4}}\right)^{0.57}$$

$$v_{c,avg} = \frac{3.2kH}{nL}$$

We should try …

- パイピングによる空洞が存在すると仮定して，限界水位などを求める展開を図らなければならない。

→限界水位Hを侵食距離lの関数として求めることで，パイピングの経路に応じた安定性を把握できる。

- パイピングの進展速度を初期値・境界値問題の解として得る方法を持たなければならない。そのためには，Backward erosionの侵食速度の把握が鍵となる。

→パイピングの開始〜進展を時間方向に予測できる。