



ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

# Digues submersibles

Aménagements de digues résistant aux débordements

Dr Pedro Manso, SCCER-SoE / EPFL

Berne, 14.03.2018

In cooperation with the CTI



**Energy**

Swiss Competence Centers for Energy Research



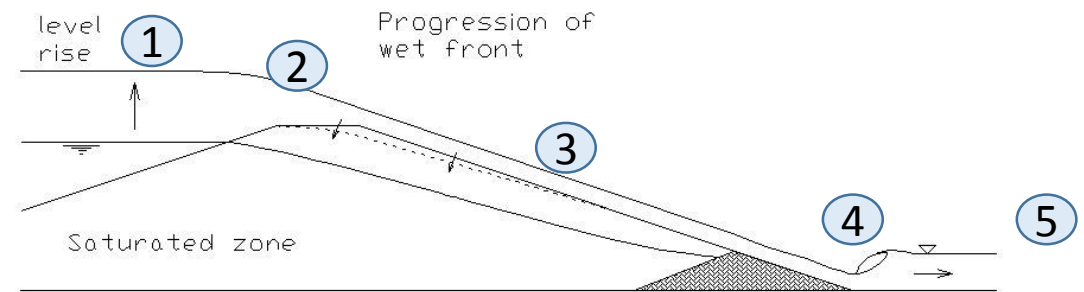
Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

# Processus physiques de la submersion

1. Montée du niveau d'eau dans la retenue (et en amont)
2. Déversement (passage en régime critique)
3. Accélération (eaux noires / eaux blanches) & infiltration
4. Transition vers niveau aval & dissipation d'énergie (ressaut)
5. Transport de matériaux érodés et leur déposition



# Exemple de submersion et rupture

Film

# Statistiques de ruptures de barrages

## Manso (2002), synthèse du Bulletin CIGB 99, 1995

- “in absolute terms, **most failures involve small dams**, which do however make up the greatest proportion of dams in service”;
- “in earth and rock fill dams, the most common cause of failure is **overtopping** (31 % as primary cause and 18 % as secondary cause ), followed by internal erosion in the body of the dam (15% as primary cause and 13% as secondary cause) and in the foundation (12% as primary cause and 5% as secondary cause)”;
- “where the appurtenant works were the seat of the failure, the most common cause was **inadequate spillway capacity** (22 % as primary cause and 39 % as secondary cause)”.

## Et aussi synthèse du Bulletin CIGB 109, 1997

- embankment dams are the most widespread type of dam construction around the world; they account for the majority of the overall world total number of dams;
- around 70 per cent of known failures concern Large Dams less than 30 m - **Table**;
- for the estimated existing 100 000 small dams not classified as large dams, failures have been reported, but hardly any statistics are available and it is not certain that the failure rate is any lower or higher than for Large Dams. The majority of these are embankment dams;
- **overtopping has been the most frequent cause of embankment dam failures, accounting for more than 50 per cent of the cases, frequently due to an under-estimated flood discharge capacity.**

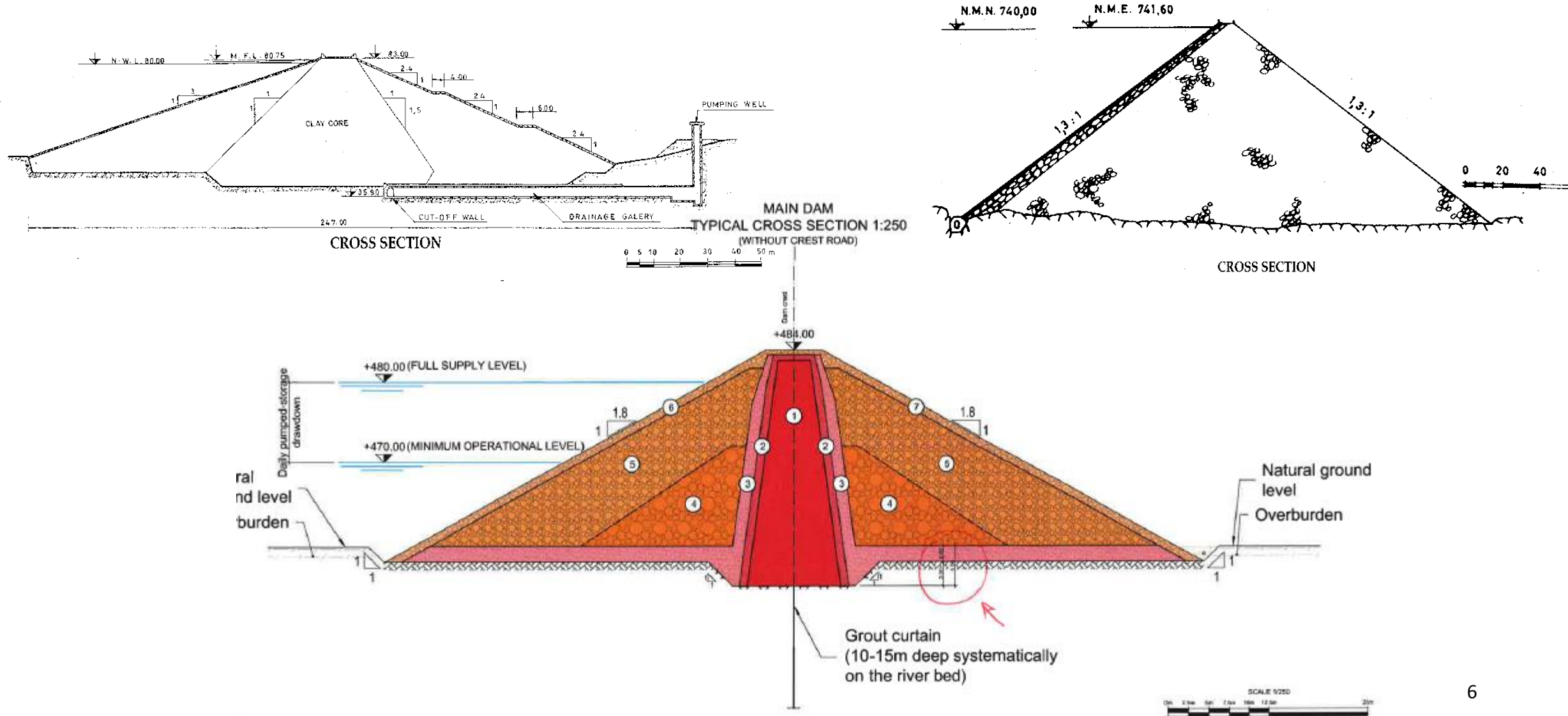
Height	Concrete			Embankment			Other materials			Total
15-20	6	4	3	3	33			1		50
20-25	4	1		1	15	1		1	1	24
25-30	1	1		1	11	1	1			16
30-35	3	2		1	7		1			14
35-40	2			3	5					10
40-45	4				3					7
45-50				1	1	1				3
50-55	1			1	2					4
55-60				1						1
60-65			1	1	2					4
65-70										
70-75										
75-80										
80-85					1					1
85-90										
>90				1	1					2
Total	21	8	4	14	81	3	2	1	2	136

## Le rôle des barrages de moins de 30-40 m ( $\approx$ Classes 1, 2 et 3 en Suisse)

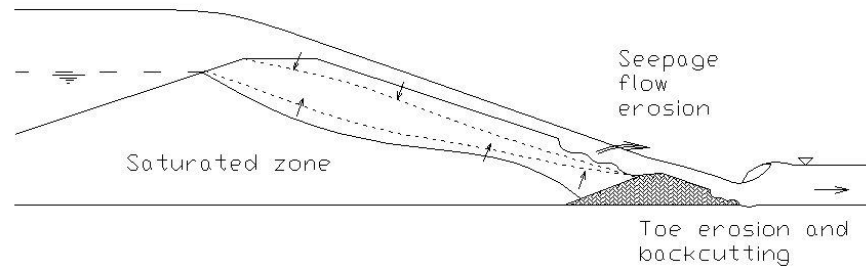
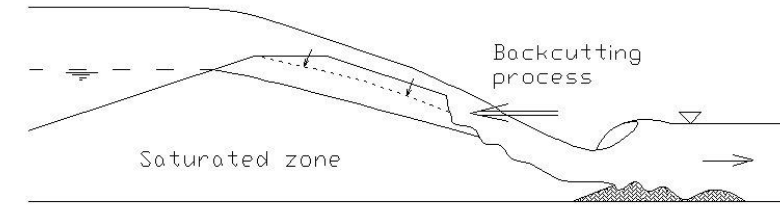
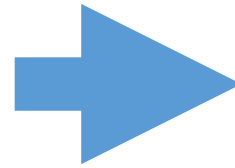
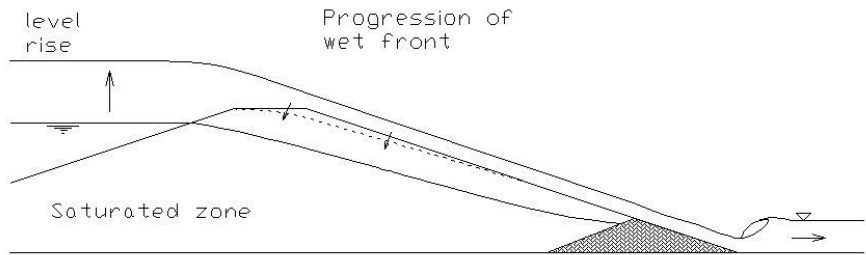
### Bulletin 109, ICOLD (1997)

- Rupture de barrages  $< 30$  m a été la cause des 10x plus de victimes que les barrages plus hauts (où il y a moins de digues)
- Dans ce groupe il y a env. 35'000 Grands Barrages, 90% en remblai avec des déversoirs non-contrôlés;
- Il y a environ 1000 barrages de 10-30 m de hauteur avec une retenue  $\geq 0.1$  hm<sup>3</sup> en construction autour du monde chaque année, desquels seulement 200 à 300 peuvent être nommés Grands Barrages. Leur coût moyen  $\leq 1$  million USD.
- **EVC peut faire 50% CAPEX.**

# Nombre élevée de typologies de digues



# Peut-on permettre le déversement par-dessus d'un barrage en remblais?



1. Erosion du pied de la digue par ressaut libre
2. Remontée du processus érosif
3. Montée de la zone saturée
4. Instabilité des talus érodés
5. Glissement de surfaces instables
6. Formation d'une brèche
7. Elargissement progressif/par à coups de la brèche



## Protection avec blocs en béton qui dissipent l'énergie de l'écoulement !

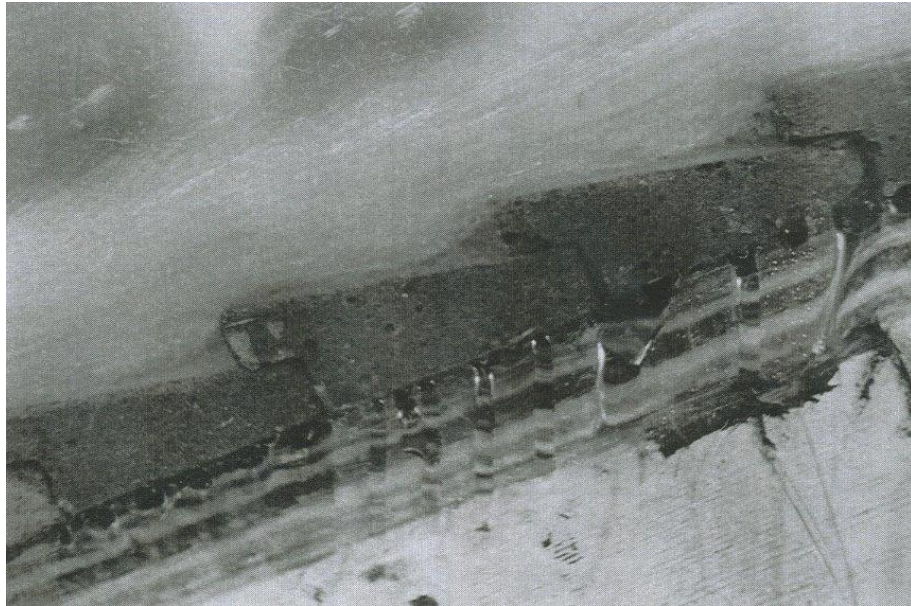


Photo Bulletin CIRIA (1998)



Ouvrage à Leithen, Linz (Autriche)



# Différents systèmes selon Manso (2002)

System	Slope	Velocity	Discharge	Overflow depth at crest	Energy dissipation	Built Examples	Features	References
	(V/H)	(m/s)	(m³/s/m)	(m)				
Grass		3.7	<2				Data from short duration events over cohesive fills	ICOLD (1997)
Reinforced Rip Rap	1/2.5; 1/20	<1.8 m/s	0.6; 1.85			Ust-Khantaysky	Prone to vandalism	MIKHAILOV et al. (1985)
	1/5		3.7				Grain size: 15-60 cm	FRIZELL et al. (1996)
Geotextile	1/2; ¼	6.7	2.25				With and without cover; failure due to poor anchorage or poor stretching of the material	FRIZELL et al. (1996)
Gabions	¼ 1/3	<8	<3		Between 40% and 90%		Laboratorial results	PEYRAT et al. (1991) FRIZELL et al. (1996)
Reinforced concrete			12	3.7		Lebna dam (Tunisia)	Conventional spillway	SCHOBER (1991); ALBERT et al. (1992) ICOLD (1993)
Reinforced soil (Terre armée)				1.0	Vertical Fall ~100%	Dnestrovskaya dam (ex-URSS) Vallon de Bîmes (France)	Dam height = 9 m	MIKHAILOV et al. (1985) ALBERT et al. (1992) ICOLD (1993)
			12			Taylor Draw Dam (USA)	Dam height = 22.5 m	ALBERT et al. (1992) ICOLD (1993)
Soil cement				1.2	Low		Laboratory results USBR; protection against erosion is a function of the thickness ; deterioration problems	POWLEDGE et al. (1989) FRIZELL et al. (1996)
RCC lining			<10					LEMPÉRIÈRE (1993)
			<10	4.3 m during 4-5 days	Between 40% and 90%	Brownwood Country Club Dam (USA)	Dam height = 5.79 m	POWLEDGE et al. (1989)
			<0.5		<90%			ALBERT and GAUTIER (1992)
			8-10		~70%	M'Bali	Dam height = 23,5	ALBERT and GAUTIER (1992)
Concrete blocs and slabs			<50	3-4		Cabora-Bassa Cofferdams (Mozambique)	During operation. Upstream cofferdam was protected with blocs of 400 kg. Downstream cofferdam had concrete slabs of 7 x 7 x 2.5 m, without water-tightness system to prevent up-lift pressures	ICOLD (1984)
Reinforced concrete blocks cast in situ			12			Toktogul (ex-URSS)	Drop of 20 m, observed discharge	MIKHAILOV et al. (1985) LAFITTE (1985)
Cable tied concrete blocks		7.9				Jackhouse Dam (UK)	135-160 kg/m², under layer of geotextiles, anchored, cohesive subsoil, observed discharge without failure	POWLEDGE et al. (1989)
		8.6					With grass cover; anchored; products like ARTIOFLEX, PETRAFLEX, TRI-LOCK with intensive use for river protection	FRIZELL et al. (1996)
Pre-cast wedge concrete blocks	1/ 6.5; 1/ 4.5; 1/ 6.5	17-23; -; -	60; 13; 5		-	Dnieper; Dneister cofferdam; Moscow water supply scheme (ex-URSS)	Designed upon ratio block thickness /unit discharge; 3rd example was under 2 m²/s during one month without damage (dam height=12 m)	PRAVDIVETS and SLISSKY (1981) PRAVDIVETS (1987)
			1.5-2	1			Adequate for earth fill dams with low permeability, K>10 <sup>-5</sup> m/s	BAKER et al. (2000)
	½	<13	<2.88		f=0.11 in uniform flow		Better than equivalent smooth surface; cost decrease of about 60% when compared with conventional structures	FRIZELL et al. (1996)
Geomenbrane	0.17 (~1/6)	6-8					Observed results; sensible to mechanical damage and deterioration	TIMNLIN Jr. et al. (1988)

# Système de blocs superposés en béton



Laboratory

Q      0.325 m<sup>2</sup>/s

W      ddddd kg

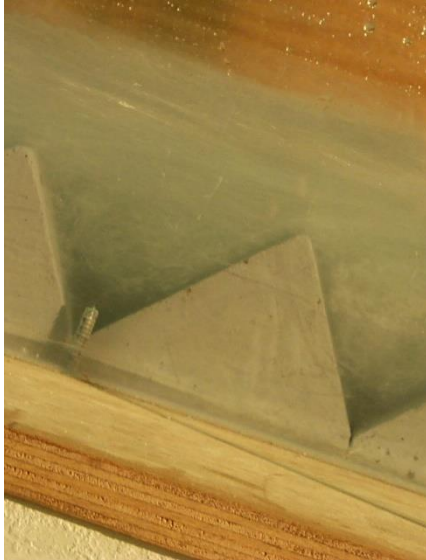
h<sub>o</sub>      ≤ 0.25 m

Pinheiro A., Relvas A., ASCE J. Hydraul. Eng., 2008, 134(8): 1042-1051.

DOI: 10.1061/(ASCE)0733-9429(2008)134:8(1042)

EPFL-LCH, Dr P. Manso, Bern, 14.03.2018

## Protection par blocs en béton. Tests à l'EPFL [Manso, 2002]



Type 1



Type 2



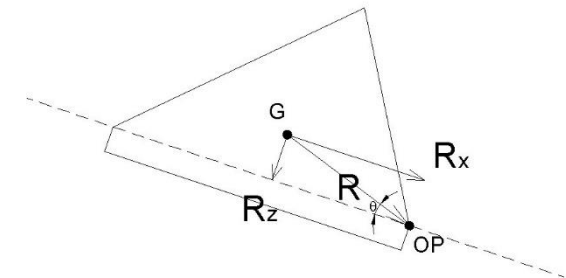
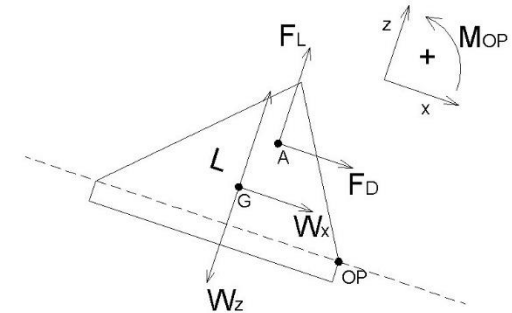
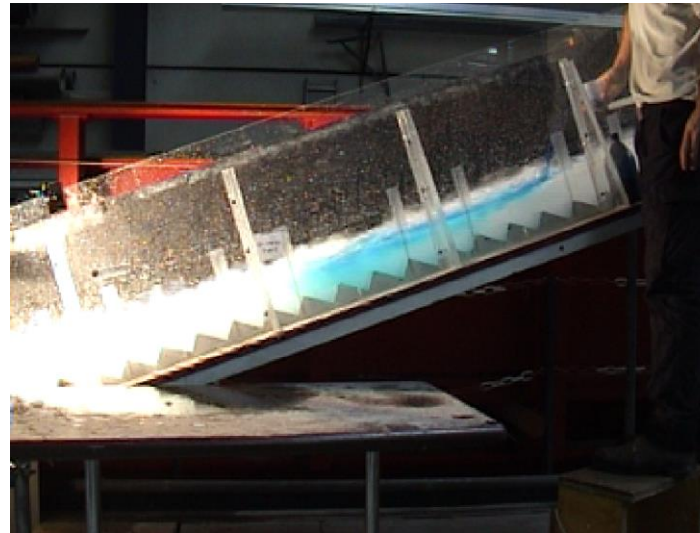
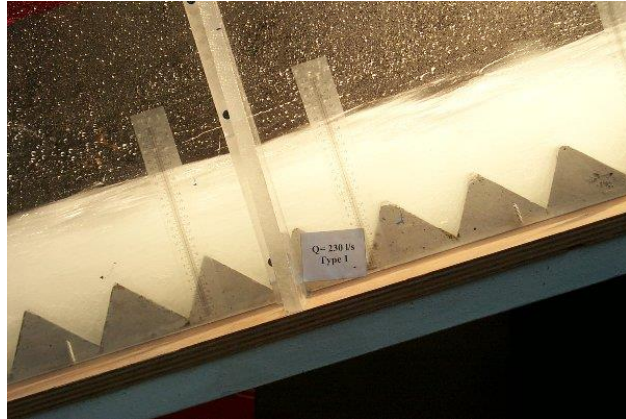
Type 2+ES



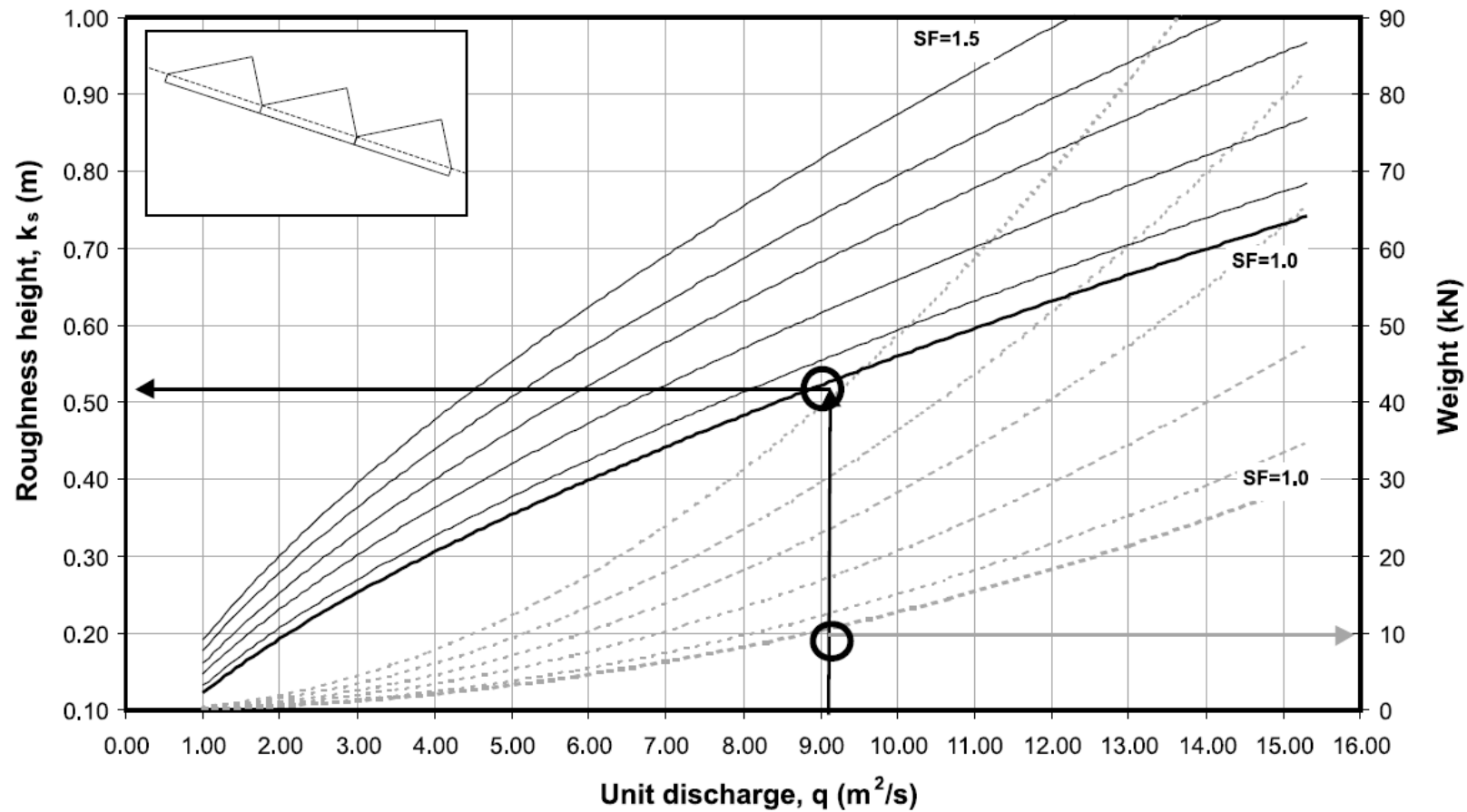
Type 3



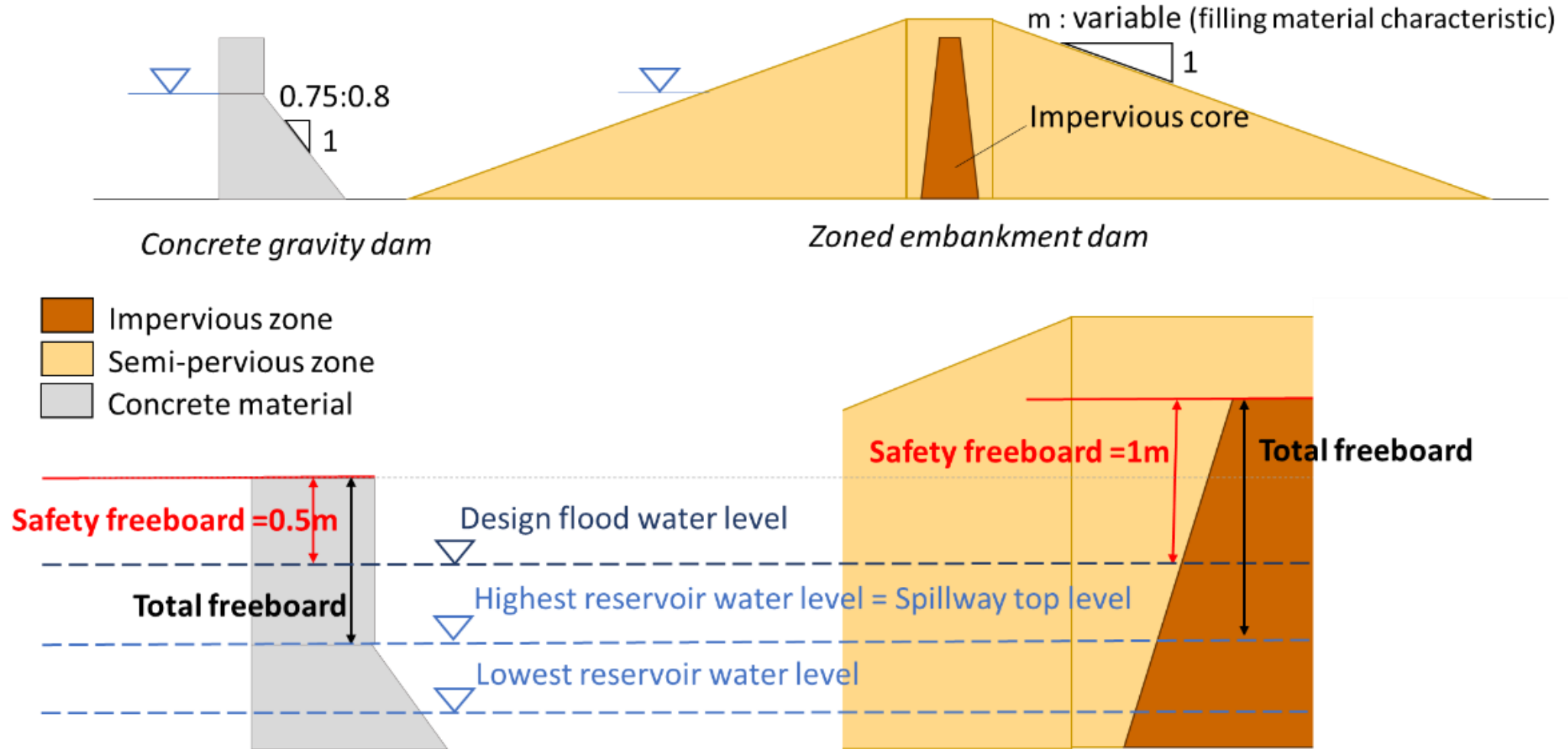
# Tests à l'EPFL. Modèle de stabilité.



# Abaques de dimensionnement



# L'importance de la revanche de sécurité (et de la cote de danger)



# En conclusion

- Submersion est la principale cause de rupture de barrages en remblai
- Plusieurs systèmes de recouvrement sont à disposition. Pas de solution universel.
- Il est important de connaître les limites technologiques de chaque système (régime d'écoulement,  $q$ ,  $h_0$ ,  $V_{max}$ ).
- Attention aux détails (filtres, transitions, crête, pied de talus, drainage).

[pedro.manso@epfl.ch](mailto:pedro.manso@epfl.ch)  
+41.76.4265394

