

Table of Contents

Foreword	xiii
Jean-Louis BRIAUD	
Introduction	xv
Stéphane BONELLI	
Chapter 1. State of The Art on the Likelihood of Internal Erosion of Dams and Levees by Means of Testing.	1
Robin FELL and Jean-Jacques FRY	
1.1. An overview of the internal erosion process as it affects dams and levees.	1
1.1.1. A description of the overall process.	1
1.1.2. The four mechanisms of initiation and progression of internal erosion	2
1.1.3. Concentrated leak erosion	6
1.1.4. Backward erosion	7
1.1.5. Contact erosion	8
1.1.6. Suffusion	9
1.2. Concentrated leak erosion	11
1.2.1. Situations where concentrated leaks may occur.	11
1.2.2. Estimation of crack width and depth of cracking	23

1.2.3. The mechanics of erosion in concentrated leaks	23
1.2.4. Commentary on the state of the art and the role of laboratory testing in assessing concentrated leak erosion	35
1.3. Backward erosion piping	37
1.3.1. The mechanics of backward erosion piping	37
1.3.2. Soils that are subject to backward erosion piping	40
1.3.3. Methods available for assessing whether backward erosion piping will initiate and progress	43
1.3.4. Some field observations	51
1.3.5. Global backward erosion	52
1.3.6. Commentary on the state of the art and the role of laboratory testing in assessing backward erosion piping and global backward erosion	53
1.4. Suffusion	57
1.4.1. The mechanics of suffusion	57
1.4.2. Methods of identifying soils that are internally unstable and potentially subject to suffusion (geometric criterion)	58
1.4.3. Hydraulic conditions where soils are internally unstable and potentially subject to suffusion	69
1.4.4. Commentary on the state of the art and the role of laboratory testing in assessing suffusion	71
1.5. Contact erosion	74
1.5.1. The mechanics of contact erosion	74
1.5.2. Methods available to assess the likelihood of contact erosion	76
1.5.3. Contact erosion or “scour” at the interface between open joints in rock foundations and the core of dams	82

1.5.4. Commentary on the state of the art and the role of laboratory testing in assessing contact erosion	83
1.6. Bibliography	85
Chapter 2. Contact Erosion	101
Pierre PHILIPPE, Rémi BEGUIN and Yves-Henri FAURE	
2.1. Introduction	101
2.2. General presentation	103
2.2.1. Typical conditions of occurrence	103
2.2.2. Specific nature of CE	107
2.3. At sample scale: quantification of the CE threshold and kinetics	110
2.3.1. Influence of geometry on the occurrence of CE	111
2.3.2. Direct configuration	112
2.3.3. Inverse configuration	129
2.3.4. Summary	133
2.4. At pore scale: local hydrodynamics of CE and statistical modeling	134
2.4.1. Experimental characterization of local hydrodynamics	135
2.4.2. Integration at macroscopic scale	143
2.4.3. Contribution made by the local scale study	158
2.5. At hydraulic structure scale: identification of failure scenarios by CE and scale effects	162
2.5.1. Reasons for a study at this scale	162
2.5.2. Description of the experimental rig and instrumentation	163
2.5.3. Test protocol and the results obtained	167
2.5.4. Proposed interpretation and description of the erosion process	172
2.5.5. Scale effect	176
2.5.6. Summary	179
2.6. Conclusion and outlook	179
2.6.1. Description of CE mechanisms	180

2.6.2. Impact on the safety of hydraulic structures	182
2.7. Bibliography	186
Chapter 3. Backward Erosion Piping	193
Vera VAN BEEK, Adam BEZUIJEN and Hans SELLMEIJER	
3.1. Introduction	193
3.2. Phases leading to failure due to backward erosion	197
3.2.1. Seepage	198
3.2.2. Backward erosion – initiation and progression	199
3.2.3. Widening	204
3.2.4. Failure	205
3.3. Backward erosion in the laboratory – overview and setup	206
3.3.1. Overview of experimental research	207
3.3.2. Setup	208
3.4. Backward erosion piping in the laboratory – erosion mechanism	214
3.4.1. Single grain transport	215
3.4.2. Sand boiling phase	216
3.4.3. Regressive or equilibrium phase	217
3.4.4. Progressive phase	220
3.4.5. Which process will occur when?	221
3.5. Backward erosion in the laboratory – critical gradient	226
3.5.1. Initiation of backward erosion piping	226
3.5.2. Progression of backward erosion piping	234
3.5.3. Progression of pipes for vertical seepage paths	240
3.6. Analysis tools	245
3.6.1. Initiation of the pipe	246
3.6.2. Progression of the pipe	250
3.6.3. Progression for structures	256
3.6.4. Summary	258
3.7. From laboratory to field – challenges for the future	259

3.7.1. Scale effects	259
3.7.2. Heterogeneity	262
3.7.3. Uncertainties	263
3.8. Conclusion	264
3.9. Bibliography	264
Chapter 4. Concentrated Leak Erosion	271
<i>Stéphane BONELLI, Robin FELL and Nadia BENAHMED</i>	
4.1. Introduction	271
4.2. Theoretical background	275
4.2.1. Assumptions	275
4.2.2. The model for pipe flow with erosion	276
4.2.3. The singular head loss factor	278
4.2.4. The momentum loss factor	279
4.2.5. Characteristic values	280
4.2.6. Closed-form solution in the case of a constant pressure drop	281
4.2.7. Closed-form solution in the case of a constant flow rate	282
4.3. The HET: testing procedure	283
4.3.1. The HET apparatus	283
4.3.2. Preparation of the specimen	285
4.3.3. Determination of the final hole diameter . .	288
4.4. The HET: method of interpretation	289
4.4.1. Determination of the pipe radius and the wall shear stress	289
4.4.2. Determination of the friction coefficient . .	291
4.4.3. Determination of the head loss coefficient ..	292
4.4.4. Determination of the parameters of erosion	294
4.4.5. Examples of results	294
4.4.6. Slaking at upstream or downstream faces of sample of HET	296
4.5. Mechanically based relations for time to failure and peak flow	299
4.5.1. A simplified approach	299
4.5.2. Onset of erosion in the pipe	301

4.5.3. Visual detection of the leak	302
4.5.4. Enlargement of the pipe	303
4.6. Dam and levee break modeling.	307
4.6.1. Order of magnitude on case studies	307
4.6.2. A model for dam- and levee-break due to concentrated leak erosion	311
4.6.3. Application to the failure of a homogeneous moraine dam by piping	313
4.6.4. Model analysis.	317
4.7. Modeling concentrated leak erosion statistically	319
4.7.1. The probabilistic approach	319
4.7.2. The probability density function of the stress ratio.	321
4.7.3. Probabilistic description of erosion.	323
4.7.4. Order of magnitude of the relative intensity of the shear stress fluctuations.	325
4.7.5. Order of magnitude of the coefficient of variation of the soil critical stress.	326
4.7.6. A stochastic erosion law for cohesive soils.	327
4.8. Comments	329
4.8.1. Comment on the friction coefficient	329
4.8.2. Comment on the linearity of the erosion law.	333
4.9. Bibliography.	335

**Chapter 5. Relationship between the Erosion
Properties of Soils and Other Parameters** 343
Robin FELL, Gregory HANSON, Gontran HERRIER,
Didier MAROT and Tony WAHL

5.1. Introduction	343
5.2. Definitions of soil erosion properties and the relationships between them	344
5.3. Effects of test methods on soil erosion properties.	346
5.3.1. Effect of testing methods on erosion rate .	346

5.3.2. Effect of testing methods on critical shear stress (τ_c)	350
5.3.3. Correlation between critical shear stress and erosion rate index	353
5.4. Relationship to field performance	355
5.4.1. JET tests done in the laboratory and in the field	355
5.4.2. Assessment of rates of erosion from JET and large-scale laboratory tests	355
5.5. Effects of the type of soil	358
5.5.1. General trends	358
5.5.2. Relationship to soil classification	359
5.5.3. Effects of soil structure	360
5.6. Effects of compaction parameters	360
5.6.1. Relationship to compaction parameters	360
5.6.2. Relationship to degree of saturation after compaction	364
5.7. Effects of dispersivity and slaking	366
5.7.1. Effects of dispersivity on erosion rate and critical shear stress	366
5.7.2. Effects of slaking on erosion rate and critical shear stress	369
5.8. Modifications of soil erosion properties	371
5.8.1. Modification by lime	371
5.8.2. Modification by cement	376
5.9. Bibliography	376
List of Authors	383
Index	387