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Overviewing geotechnical issues associated with levees and dams in Europe and USA

Une perspective sur les aspects géotechniques associés aux digues et aux barrages en Europe et aux États-Unis

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ABSTRACT: In ICOLD, a working group has been working on levees since 2015, preparing both a levee situation overview of Europe and USA, and a comparison between dams and levees. In both resulting reports, levee characteristics, geometry, safety and technical standards, design rules, governance, management and knowledge gaps are discussed. Levee and dam engineers can learn from each other. Geotechnical issues are significantly featured. This paper will give an overview of levees in Europe and USA, with special focus on their geotechnical aspects, such as geometry, materials, subsoil, failure modes, design rules and safety standards. Also special attention will be given to site investigation and monitoring. In both levees and dams, understanding of the performance and of associated uncertainties is a challenge. In assessing safety, geotechnical issues like internal erosion and different types of instability are essential, especially in the initiation of failure and the breaching process. Given these common interests, cooperation between TC201 of ISSMGE and a recently established ICOLD Technical Committee on Levees is important and should be encouraged; this cooperation has already been initiated as some members are involved in both committees.

RÉSUMÉ: Au sein de la CIGB, un groupe de travail travaille sur les digues depuis 2015, préparant à la fois une vue d'ensemble de la situation des digues en Europe et aux États-Unis et une comparaison entre les barrages et les digues. Dans les deux rapports qui en résultent, les caractéristiques des digues, la géométrie, les normes techniques et de sécurité, les règles de conception, les lacunes en matière de gouvernance, de gestion et de connaissances sont discutées. Les ingénieurs des digues et des barrages peuvent apprendre les uns des autres. Les questions géotechniques sont très présentes. Cet article donnera un aperçu des digues en Europe et aux États-Unis, avec un accent particulier sur leurs aspects géotechniques, tels que la géométrie, les matériaux, le sous-sol, les modes de défaillance, les règles de conception et les normes de sécurité. Une attention particulière sera également accordée aux investigations et à l'auscultation.
Dans les digues et les barrages, la compréhension des performances et des incertitudes associées est un défi. Lors de l'évaluation de la sécurité, des problèmes géotechniques tels que l'érosion interne et les différents types d'instabilité sont essentiels, en particulier en cas de défaillance et de rupture. Compte tenu de ces intérêts communs, la coopération entre le TC201 de l'ISSMGE et un comité technique sur les digues récemment créé par la CIGB est importante et devrait être encouragée; cette coopération a déjà été initiée car certains membres sont impliqués dans les deux comités.

Keywords: Levees, Dams, Floods, ISSMGE-TC201, ICOLD

1 INTRODUCTION

In the International Commission on Large Dams ICOLD, a working group has been working on levees since 2015, preparing both a levee situation overview of Europe and USA (EUCOLD 2018), and a comparison between dams and levees. In both resulting reports, levee characteristics, geometry, safety and technical standards, design rules, governance, management and knowledge gaps are discussed. These reports from the Working Group on Levees and Flood Defences, (LFD WG, of the European Club of ICOLD, EUCOLD) also include a contribution from the USA, from the Levees Committee of the United States Society on Dams USSD.

The objective of the situation report is to provide an overview of flood protection works and its issues in different countries. The situation of levees in the eleven countries who participated to the report is presented in specific chapters, with a similar format; a synthesis of the national situations is presented in a final chapter. This report is the first report of the EUCOLD Working Group on Levees and Flood Defences. It serves as an overall and approximate overview of levees and protection structures, of the value they protect, of the residual risk including recent flood events, and of maintenance, governance and legislation issues. Further updates are expected in later years under the auspices of the ICOLD Technical Committee on Levees, LE TC, which was established in 2017.

ICOLD 2018 Congress in Vienna had, for the first time, a question devoted to "Small Dams and Levees", resulting in the publication of 20 papers related to small dams, 20 to flood protection levees, 3 to canal or basin embankments and 4 which focus on techniques that apply to small dams and levees. A general report (Tourment 2018) presented a synthesis of these papers and general considerations on these hydraulic structures which are new within ICOLD scope. The information is this paper is widely based on the mentioned documents.

Given the common interests, cooperation between TC201 of ISSMGE and ICOLD Technical Committee on Levees is important and should be further encouraged. This cooperation has already been initiated as some members are involved in both committees.

2 CONSEQUENCES OF FLOODS IN EUROPE AND USA

Worldwide, 37% of the global population live in flood-prone areas (Dilley 2005) and at least

600 million people were displaced the last three decades (Dartmouth 2018). In Europe only, it is estimated that total costs of flooding in 2050 under current protection is more than 3500 billion Euro (CESR 2011). In the period 1950-2005, over 45 major flood events were reported which either involved over 70 casualties or over 0,005% of the European GDP in damage (Starflood 2018).

In addition levees, also called dikes, dykes or flood embankments, and other flood protection structures including urban flood walls, upstream regulating and flood protection dams have a key role in reducing this risk.

Their vast number and in many cases unknown state may imply a significant safety and flooding risk.

Table 1 Some examples of recent catastrophic floods involving levees (Tourment 2018)

Country	Event	Consequences
Belgium, England, Netherlands	1953 Storm Surge	> 2500 casualties
Czechia, Germany, Poland	1997 Oder and Morava floods	114 fatalities; 3.8 billion euro damage
Central Europe	2002 Danube, Elbe, Vltava floods	21 casualties; > 12 billion euro damages
USA	2005 Hurricane Katrina	1836 casualties; 125 billion dollar damages
UK	Summer 2007 floods	13 fatalities; 3 billion £ damages
France	2010 Xynthia storm	59 casualties; 1-3 billion euro damages
Germany	2013 Elbe, Saale, Danube floods	7 casualties; > 4 billion euro damage

Recent floods have continued to demonstrate that this is not just an academic risk, but a risk that even today regularly results in major damage and even risk to life across Europe. In recent years (period of 1989-2008), floods caused about 150 casualties per year across Europe, as well as 40% of all natural disaster damage (EUCOLD 2015). In table 1 an overview of recent catastrophic floods involving levees and geotechnical levee failures is listed.

3 LEVEE INFRASTRUCTURE

Besides demonstrating the relevance of levees, the objective of the LFD WG and the LE TC is also to give a first indication of levee-related issues, so as to facilitate future comparisons with similar issues related to dams, especially embankment dams and small dams. The main outcomes are the recognition of the high importance of flood defences in the countries who participated in the study and the lack of a central levee inventory in the majority of these countries. Levees indeed seem to be a relevant issue in many countries, or at least for many regions across European Countries. England, France, Germany, Italy, Netherlands, Poland, Spain and others each have several thousand kilometres of levee, and many more still have a significant number of levees, see table 2.

The majority of levees and protection structures are found along rivers but, especially in Western Europe, a significant fraction of levees and structures has been built along the coasts, lakes and estuaries. Urban levees and floodwalls, as well as associated hydraulic structures, i.e. gates and barriers, represent a smaller but still important fraction, because they protect many people as well as valuable assets and properties.

Typical levee heights are within the range of a few metres, but occasionally can exceed over 10 metres in height and therefore, coming close to the dimensions of small dams.

Table 2 Estimates of levees (EUCOLD 2018)

Country	Levees	Protected stakes
Belgium	700 km (large ones only)	1 million people
Czechia	4000 km	unreported
England	8000 km	2.4 million properties
Finland	80 registered levees	unreported
France	9000 km	2 million people, 20000 km2
Germany	10000 km	12 million people, 2 billion €
Hungary	4200 km	unreported
Italy	Po river: 650 km; Eastern Alps district: 6300 km; more on nation scale	unreported
Netherlands	3500 km of primary flood defences	12 million people; 450 billion € yearly production; 1 trillion € value
Poland	7400 km	unreported
Slovenia	> 100 km	750.000 people
Spain	Several thousand km	2-3 million people
USA	> 160000 km	Tens of million of people

4 GEOTECHNICAL ISSUES RELATED TO LEVEES

Several countries have experienced levee failures in the last 50 years. Most commonly observed failure causes are erosion by overtopping or overflowing, internal erosion, problems with conduits crossing through levees, problems with structure transitions (Tourment 2012a and 2012b). Other causes are slope sliding during floods, including sliding during uplift pressures (Van 2005) and even flooding due to a levee influenced by drought (Bezuijen, 2005). Stability problems due to rapid draw down are accounted for in standards, but not often observed in practise. Levees and other flood defences can also be damaged without consequences in terms of flooding since river levels are mostly low.

Increasing water levels, but also soil subsidence, for example due to drainage, oxidation or mining, will also increase flood hazards and risks.

Damage after a flood to flood defences has to be seperated from damage due to the flood event. The flood water is often trapped behind levees, this is more than the existing drainage systems can cope with. Stagnant flood water can cause piping and slope failure. This was the case in the Elbe flood in 2013 (EUCOLD 2018).

Many countries have to deal with animal burrowing. Burrows increase the hydraulic gradient in the levee which decreases the geotechnical slope stability, increases leakage which can initiate or increase internal erosion problems (Taccari 2016).

Large vegetation on Levees is generally not accepted by the water authorites, but often asked for by public from landscape and recreational point of view. Existing vegetation like trees and bushes cause potential problems for internal erosion and slope stability. Bushes also increase the animal activity because they provide shelter. During extreme wind events trees can fall and erosion holes might occur. Due to shadow, trees and smaller bushes prevent a good grass cover as revetment. Erosion of the soil under trees and bushes are therefore more severe than in the case of a good grass revetment. More extreme weather paterns, expected due to climate change, can aggravate these issues.

In general, guidance and standards are available, but the models and approaches are uncertain, which results in overconservative design or designs which will underperform. Breaches are caused by failure scenarios that involve more than one mechanism, as depicted in Figure 1.

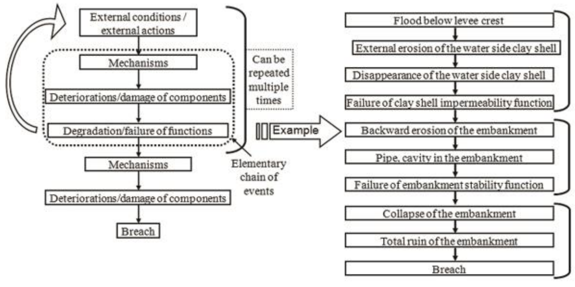

Figure 1 Scenario or chain of events leading to a structural levee failure and breach (ILH 2013)

Table 3 presents a first overview of critical geotechnical knowledge and data gaps related to levees and dams.

Table 3 List of knowledge gaps (EUCOLD 2018)

Knowledge gaps
Assessing structural properties and strength characteristics of levees/
Dealing with uncertainties
Levee Information Management
Levee Risk Assessment
Resilience of levees
Impact of wetting/drying cycles
Levee behaviour during flood
Interaction of failure mechanisms
Performance of transitions
Detections of and dealing with anomalies
Realizing added value of levee monitoring (from smart levees to smart use of levees)
Breach initiation/growth retarding measures
Overtopping resistance/resilience
Performance/erodibility testing of riprap, grass, woody vegetation, road presence etc
Vegetation cover management guidance
Effect of vegetated foreshores
Overtopping/overflowing hydraulic loading conditions
Burrowing animal activity
Emergency measures

Three types of knowledge and data gaps could be considered, ie. lacking fundamental insight and understanding, unsuccessful transfer of existing body of knowledge and missing hands-on praticitioners guidance.

In many countries overtopping was often the main failure mode; as levees were increased in height over time, other failure modes have become proportionately more important. As mentioned, breaching is often a combination of different failure modes. Design rules were initially based on empirical rules such as Bligh or Lane for internal erosion (backwards erosion). Over the years, more process based models have been developed. In example, for backwards erosion the Sellmeijer model was developed, which describes the process and transport capacitity of sand in a pipe underneath a confining layer, which is in general a clay layer. The Sellmeijer model describes the initiation process of the total failure scenario of a levee due to backwards erosion.

In comparison with dams, levees are often long linear structures, old or very old (many centuries), raised many times during their history, having failed and being repaired multiple times. The control and treatment of their foundation is not as complete as with dams, partly because levees sediment foundations are often higher than the levees themselves, and also because the creation of an impervious screen between the river bed and the alluvial plain would have adverse consequences. Because of all these reasons, levees, including their foundations, often are heterogenous in all of their dimensions, as section 3.3.3 of the ILH (ILH 2013) points out, see figure 2. This causes specific problems regarding their assessment, and need for specific investigation methods, associating both classical geotechnical methods with specific geophysic investigations.

Since levees are long structures and often only sparse data for design was available of the subsoil and the potential and phreatic lines. Recently data is increasing due to increased monitoring through local instrumentation; continues monitoring by fibre optics and remote sensing such as lidar-tools and satellites (Tourment 2018). Whilst currently mainly in pilots, in the near future this data will become available via local or global open databases to be used in stadard levee assessment and design. This information will lead to reduced uncertainties and increase the calculated safety.

In urban areas the upgrading of existing levees is done with hard structures. Questions regarding the interaction between soil and construction and especially stiffness differences between soil and construction materials as well as strain compatibility issues have to be answered. Furthermore 3D-effects at the transition to the earthen levee, the 3D effect in the structure or in gaps of the structure have to be included. Also new improvement techniques are developing or available in other earth structures, but the safety assessment guidance for these solutions, as for instance soil nailing in levees, or soil mixing techniques, has to be soundly derived.

The cost of material to rebuild a levee is often high. To reduce costs the available soil can be improved by adding lime or cement during construction or by improving the soil under the flood defence (e.g. through mixed in place techniques). The role of compaction of the soil during construction is often overlooked. In the past this has often not been done due to lack of means and it should be done during construction. (Tourment 2018).

Multifunctional use of levees is increasing. E.g. Roads, houses, underground pipelines, are on and in the levees. Breaches have occured at the location of these objects or its transitions (ILPD, 2018). Transitions and rules for design, inspection and maintenance of these object are extremely important but often neglected.

Finally, we have to learn from our mistakes and share these with others. In some countries levee failure databases exist but in most they do not. The SAFElevee project has started an International Levee Performance Database to share this information (ILPD 2018).

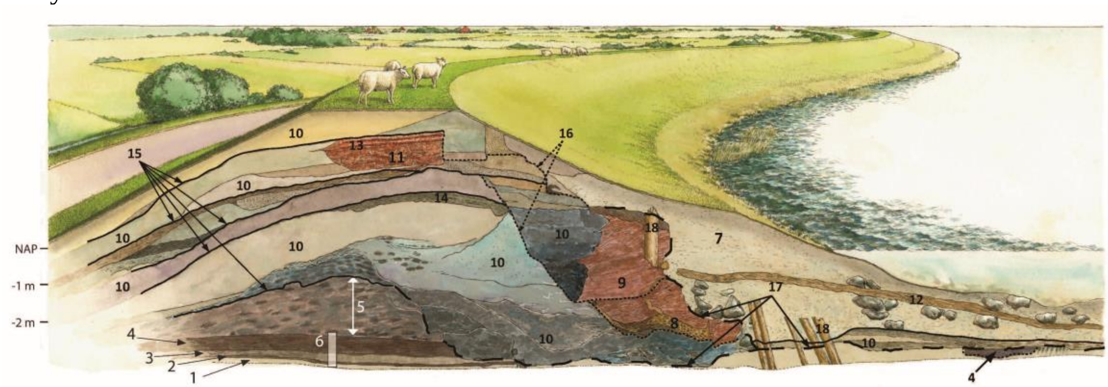

Figure 2 Cross section of a sea levee near Enkhuizen, which became a lake levee in 1932 (ILH, 2013)

5 GOVERNANCE, MANAGEMENT AND REGULATION FOR LEVEES

Governance, legislation and responsibilities strongly differ by country. There seems to be no central levee database in most countries. Some, but certainly not all, countries have central levee registers, often in combination with dam registers.

Levees are rarely explicitly addressed in the deliverables required by the EU Floods

Directive as these deliverables often focus on a general policy level for flood risk management. However, in some countries, the Floods Directive was an incentive for revised safety standards and/or reinforcement works on levees and flood defences.

In several countries, dams and levees fall under the same legislation (or legislative framework) and thus under the same or similar regulations. This clearly demonstrates the need to verify whether and to what extent general guidelines and best practices for dams are applicable to levees, and vice versa.

Standard of protection often is, or used to be, in the order of 1/100 per year, but especially in high-risk areas, the degree of protection tends to be raised because of risk and/or cost-benefit considerations, and standards in the order of 1/1000 and even up to 1/100000 per year are becoming common. It is noted that different countries have different definitions or approaches to define standards of protection or safety standards. Some countries consider only the protection level as defined by the absence of flooding, while others incorporate a safety level as an extremely low probability of failure and/or a risk level (Tourment 2017). A better understanding of the differences in approaches will lead to improved harmonization in management of the residual flood risk in areas porotected by levees. Levee-related governance (who is responsible for what) is quite complex in many countries, with significant differences among countries, or amongst states within federal countries. Also many stakeholders are involved in flood risk management, even when levee system management relies on a designated organization.

Most countries largely rely on national guidelines, often inspired by international best-practices. The International Levee Handbook (ILH 2013) and ICOLD Bulletins are rarely used directly, the latter mainly because at the moment they were produced for dams. The applicability to levees instead of dams still has to be demonstrated.

Table 4 Levee regulations and governance in a few countries (EUCOLD 2018)

Country	Legislation and regulation framework	Governance
Belgium	Levee act from 1979	Clearly organized. Most levees managed by governmental agencies.
Czechia	Same as dams	Managed by River Board State agencies
England	Floods and levees, 1991 and 2010; Levee safety same framework as dams	Clearly organized but fragmented
Finland	Levee safety same as dams	Fragmented
France	Similar to dams	Flood protection is clearly attributed to the EPCI
Germany	Specific to State: national standards (DIN) and guidelines (DWA, BWK)	Depends of the State
Italy	New Technical Norms for Constructions (2008, 2018).	Organized by Basin authority, Regions, Autonomous Province but fragmented
Netherlands	Levees and dams regulated through the Water Act of 2009	Primary flood defences managed by local Water Boards; key national flood defences managed by the National Water Authority
Spain	No specific regulatory framework for levees; Requirements vary per region	Fragmented; Organized at River Basin scale
USA	National levee safety act of 2007 amended in 2014 authorizes a national levee safety program	Fragmented; National levee safety program amended in 2014 (not yet fully implemented) calls for state levee safety programs

Levee inspections and safety assessments are in general scheduled less frequently and/or less systematically than inspections for large dams. Inspection of levees are, in general, more in line with the ICOLD experiences for small dams.

Finally, it is interesting to note that levee maintenance is done at a relatively low financial cost. On the other hand, (re)construction of levees is often relatively expensive, in the order of 1-2 million Euro per kilometer and up to 20 million Euro per kilometer in complex/urban areas. Therefore a trend towards more intensive levee inspection, maintenance and assessment is expected.

6 CONCLUSIONS

The outcomes of this work by the LFD WG once again highlight the necessity of levees for the effective management of flood risk, and infrastructural growth.

The majority of levees and flood protection structures are found along rivers, but also a significant amount of levees and structures have been built along the coasts, lakes and estuaries.

For the whole of Europe, both annual flood damage and Flood Risk Management (FRM) investments run into the billions of Euros (per year), while the protected value is over three trillion Euro

Levees often have a long and complicated construction history, many of them have been heightened step by step after major flood events.

Basic geotechnical mechanisms involved in the failure of dams and levees are similar, but the different way these two types of structures are loaded result in different analysis for both existing structures and for design. Comparison of dams and levees approaches will be undertaken in the next years by the new Technical Committee on levees of ICOLD. This will most certainly benefit both specialisms.

Levee management governance and legislation strongly differ by country. There is no central levee database and, from many countries, only estimated data and incomplete information were available.

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