Internal Erosion News, Informal Notes on Imperial College Seepage Workshop and IEWG, Delft, August 31-September 7, 2017

The Imperial College Seepage Workshop marked the commencement of an EPSRC (Engineering and Physical Sciences Research Council) project examining suffusion by modelling and experimental research using 'visible' soil grains[1]. At the Internal Erosion Working Group (IEWG) meeting in Delft, Netherlands, we celebrated the 25th annual meeting of the Group. Deltares, our IEWG hosts, provided a Book of the 38 Abstracts, and a USB stick with the 14 papers.

As presentations and discussions at the two events overlapped, news from the two is given together here. The points mentioned are those of particular interest to me, apologies to authors and presenters not mentioned.

Improved practice resulting from improved understanding of internal erosion

The IEWG had been set up by the ICOLD European 'Club' as the European Working Group on Internal Erosion. The Working Group is an international entity, open to all with an interest in internal erosion, loosely administered by the ICOLD European 'Club', the ICOLD member countries in Europe. The 'Club' recently founded a Working Group on Levees and Flood Defence, recognising that many of the technicalities relevant to water-retaining structures were the same for large dams and 'small' levees or dikes (Koelewijn and Bridle, 2017). The new knowledge in ICOLD Bulletin 164 on internal erosion in existing dams, dikes and levees, to which the IEWG was the major contributor, adds to other knowledge to make it possible to advance from flood risk management towards fully engineered risk-based management of flood defences.

The principal technical difference between dams and levees is that, with the exception of levees along major rivers and in countries particularly vulnerable to flooding, such as the Netherlands, levees are expected to overtop and inundate downstream areas during relatively frequent floods, 1 in 10-year, 25-year, 100-year floods, etc, depending on the standard of protection required, but dams are equipped with overflows to prevent overtopping in all but the most extreme of floods (1 in 10,000-years, for example). Levees should withstand scour on the downstream slopes in extreme floods to limit the probability of rapid failure and potential fatalities to 1 in 10,000-years, say, depending on standards. For the same reasons, levees should be stable during earthquakes or long duration floods which may result in instability from high pore pressures within the embankments with the same low annual probability of 1 in 10,000, say. ICOLD Bulletin 164 on internal erosion makes it possible to estimate the water level that will cause failure by internal erosion, and the annual probability of occurrence of that water level can be assessed from the flood hydrology. The extent of resilience in downstream areas subject to inundation should be proportionate to the inverse of the flood protection standard. Areas subjected to 1 in 10-year inundation should be more resilient than those protected to 1 in 100-year inundation. Ideally, areas subject to frequent inundation should be used for more resilient activities, such as farming, sports fields and similar.

Taking this enumerated risk approach and balancing inundation frequency with appropriate resilience measures leads to fully engineered management of flood risks. Eric Halpin, USACE Special Assistant to Congress for Dam and Levee Safety, has found (Halpin and Escudo-Bueno, 2017) that the risk approach is effective in identifying and finding funding for essential 'high risk' flood defence projects and saving expenditure on 'low risk' projects already adequately protected by existing levees. Thibaut Mallet and colleagues (Mallet and Fry, 2014; Mallet et al, 2015) are putting it into practice on 200 km of levees in the Rhone delta in France, much damaged by concentrated leak erosion, particularly through incompletely sealed badger burrows. Di Pietro (2017) explained how levees had been protected against beaver 'intrusions' using polymer coated steel mesh.

[1] Presentations at: http://www.imperial.ac.uk/geotechnics/research/research-projects/seepage-induced-geotechnical-instability/seepage-workshop/

Regarding concerns about effectively monitoring the long lengths of dikes, Dr Philip Smith made a presentation at Imperial College on the International Levee Handbook (CIRIA et al, 2013). Many levee failures were caused by overtopping, fewer by internal erosion and very few by slope instability. A large number of internal erosion failures and incidents in levees had occurred at ‘local irregularities’ – animal burrows, ploughing in and steepening the toe of levees, locally steep slopes, and at culverts, pipes and other items passing through the levees. In the light of this, monitoring and maintenance should concentrate on identifying such ‘irregularities’ and using practical engineering and the guidance in the Bulletin to correct irregularities, and provide sealed and filtered surrounds to the pipes and other ‘penetrations’ (FEMA, 2006) through embankments, followed by close monitoring to confirm that they remained sealed and filtered.

Jurgen Dornstädter, one of the three attendees at the first IEWG meeting in 1992, who made many contributions to ICOLD Bulletin 164, presented Dornstädter et al (2017), explaining how temperature measurements by probes within embankments monitor seepage flow, and can be used to determine pore velocity, to detect increasing permeability, for example, which may result from loss of fines by suffusion or contact erosion. More details are given in Volume 2 of ICOLD Bulletin 164.

Internal erosion on the interface between soil mechanics and hydraulics

At the Imperial College Workshop, Rod Bridle presented ICOLD Bulletin 164 on internal erosion in existing dams, levees and dikes and their foundations (ICOLD, 2015, 2016). The Bulletin is in two volumes and reports on the present state of knowledge about internal erosion in all water-retaining earth embankments – be they dams, dikes or levees, high or low, long or short. Much is new knowledge, in particular on the mechanics of internal erosion. The four internal erosion mechanisms: contact erosion, concentrated leak erosion, suffusion and backward erosion, are initiated when the hydraulic forces imposed by water flowing or seeping through the soils in earth embankments exceed the ability of those soils to resist them. The hydraulic loads (usually expressed as water level) causing internal erosion can be estimated using the information and empirical methods in the Bulletin.

Internal erosion has many similarities to sediment transport on the seabed and on the beds of rivers. Dr Remi Beguin’s contact erosion curves (Figure 5.2 in Volume 1 of ICOLD Bulletin 164) show that if the Darcy velocity in the coarse soils exceeds about 0.01 m/s, contact erosion of the fine soils may occur and detailed examination is required. The similarity of the curves on Figure 1 to the Shields curve (Shields, 1936), shown in Figure 2 (from Professor Dey’s keynote at ICSE8 in Oxford last year, Dey and Ali, 2016) which governs sediment transport, suggests that internal erosion by contact erosion is governed by a similar law. Intuitively, it seems that concentrated leak erosion and suffusion may be similar, backward erosion less obviously so (but see later).

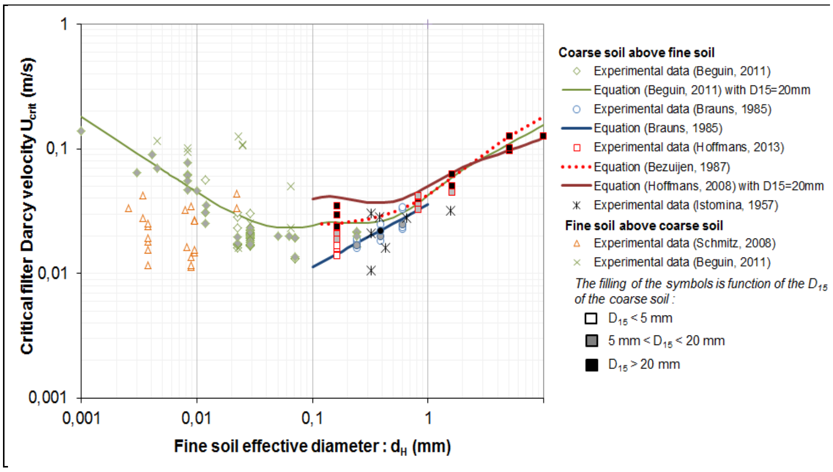

Figure 1. Darcy velocity in coarse soils to cause contact erosion of fine soils at the interface (Figure 5.2 in ICOLD, 2015, courtesy of Dr Remi Beguin (Beguin, 2011)

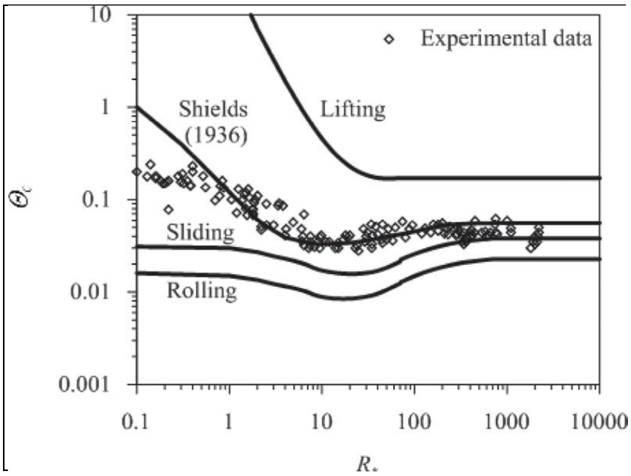

Figure 2. Threshold Shields function Θ*c* versus shear Reynolds number *R** in rolling, sliding and lifting modes (from Figure 6, Dey and Ali, 2016)

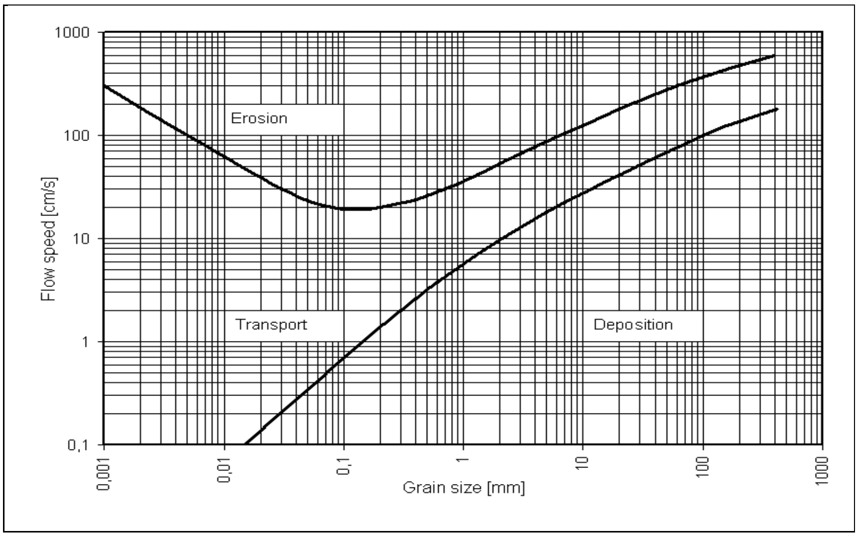

Figure 3. The Hjulström (1939) version of the Shields diagram

Figure 3, the Hjulström (1939) version of the same law shows the velocity required to move grains of various sizes. The erosion line shows the velocity that will lift particles from the river bed which, once lifted, will be transported downstream until the velocity drops below the transport-deposition line. Coarse grains are moved by high velocities, grains around 0.1-0.2 mm are most susceptible to erosion and are eroded at the lowest flow velocity, and finer grained soils resist lift because of pore suction, inter-granular forces and cohesion. The fine grained soils, once lifted, are easily transported and are not re-deposited until the velocity is very low.

This process parallels the four phases to failure by internal erosion: initiation, continuation or arrest by filtration; progression and breach. A significant point is that the hydraulic load needed to initiate erosion is greater than the load required to continue to move the eroded grains, and this may explain the rapid progress that often occurs in internal erosion to failure. Teton Dam, for example, failed in a few hours during first filling in 1976. The highest hydraulic loads in existing dams and levees usually occur during floods when it is not possible to reduce them by lowering the water level.

Existing dams and levees have shown that they have the 'seepage strength' to resist erosion at the highest water level to which they have been subjected, but because of the potentially rapid progress to failure once erosion has initiated, monitoring cannot reliably give early warning of impending failure by internal erosion. Investigations and analyses should be made to estimate the critical water level by using the new knowledge in the Bulletin.

The conclusions of the presentation were:

- The four internal erosion processes are caused by the hydraulic forces imposed by seepage or flow through soils
- The challenge is to estimate the hydraulic forces causing internal erosion in vulnerable soils
- ICOLD Bulletin 164 collects current knowledge, and provides guidance for engineers
- There is more to research and learn about internal erosion (e.g. Bridle (2016), research suggestions, ICSE8, Oxford)

Suffusion (or internal instability)

Several researchers were addressing the challenge of estimating the hydraulic forces causing suffusion, often progressing from earlier work devoted to the means of identifying susceptible soils. One of the drivers for this was that Eurocode 7 on earthworks, in what seems to be an imposition of regulation in advance of knowledge and experience, requires that hydraulic failure by internal erosion be addressed as follows:

- Filter criteria shall be used to limit the danger of material transport by internal erosion
- If the filter criteria are not satisfied, the hydraulic gradient should be well below the critical gradient at which soil particles begin to move

Professor Jonathan Fannin (University of British Columbia, Canada) gave a progress report on permeameter testing on potentially suffusive soils, including results showing how successively higher hydraulic gradients were required to initiate suffusion as confining pressure increased (e.g. as imposed at increasing depths in a dam) (Li and Fannin, 2011). He described tests with a rigid wall permeameter to examine suffusion leading to suffosion, volume change resulting from movements of particles in the coarse matrix (Slangen and Fannin, 2017; Garner and Fannin, 2010). He was developing a research programme (Fannin and Hartford, 2017) that would progress from present empirical approaches, as presented in the ICOLD Bulletin and for example by Ronnqvist et al (2014), to a continuum mechanics based theoretical modelling framework supporting model informed experimental investigations.

Dr Catherine O'Sullivan (Imperial College. UK) gave an overview of the joint Imperial College-Sheffield University EPSRC project that would combine modelling with visualisation of suffusion. Dr Elisabeth Bowman (Sheffield University, UK) presented her permeameter which uses glass particles of selected refractive properties that make it possible to 'see' into the sample and watch particle movements as water flows through the pores in suffusive samples (e.g. Hunter and Bowman, 2015). Dr Tom Shire (Glasgow University, formerly Imperial College) described Discrete Element Modelling at micro-scale of suffusive soils (Shire et al, 2014) and how the hydraulic forces including the drag force might be included. Tom was considering coupling DEM with Computational Fluid Dynamics (CFD). This presents considerable challenges in computational capacity which other members of the team were tackling in different ways: pore scale characterisation of granular materials (Dr Adnan Sufian); pore scale modelling of fluid flow in dense grain packings with the Immersed Boundary Method (Chris Smith); and codes and computer power to link CFD and DEM for large scale simulations (Dr Ed Smith).

Dr Hans Ronnqvist (Ronnqvist, 2017) had examined the potential for suffusion or 'internal instability', the Kenney and Lau, (1985, 1986) term for the erosion of fines through the pore spaces in the coarse matrix in gap-graded soils, in silt-sand-gravel soils, finer than the filter materials examined by Kenney and Lau and the moraine core materials he had examined previously (Ronnqvist, 2015). He found that the stability number H/F, below which suffusion could be expected, for these soils was about 0.45, lower than that for the coarser soils (1.0) found in moraines. Silva et al (2017) had also investigated suffusion in moraine cores.

Dr Eric Vincens presented Seblany et al (2017) which merges criteria on Constriction Size Distribution and the definition of local pores to examine the effectiveness of filters. Dr Paul Winkler showed spectacular images of particle packings illustrating the bimodal structure of widely graded soils (Winkler and Salehi-Sadaghiani, 2017).

Professor Akihiro Takahashi (Tokyo Institute of Technology, Japan) tested samples by centrifuge and assessed changes in mechanical (not hydraulic) shear strength (Takahashi et al, 2017). Professor Didier Marot (University of Nantes, France) (Marot et al, 2017) made presentations at IC and Delft. He had carried out large scale triaxial tests to examine suffusion erodibility, the energy expended in suffusion and the effect of erosion on the mechanical behaviour of coarse soils. He had also developed a small portable apparatus to identify suffusive soils in the field; we saw the prototype at Delft. In the large triaxial, the shear strength of suffused samples was found to be less than that of complete samples. Similar results were also found by Li et al (2017). Some other Marot et al (2017) results, such as a rise in hydraulic gradient after initiation of suffusion, surges in hydraulic conductivity during the test and the incomplete removal of suffusive fines from the sample, thought to be the result of filtering action within the sample, seem not to comply with expectations from Shields or Hjulström.

Concentrated leak erosion

Dr Philippe Sentenac (Strathclyde University) is examining the possibility of using geophysics to identify fine fissuring and desiccation, which if better understood may help to avert failures caused by concentrated leak erosion such as Situ Gintung (Bridle, 2016).

Dr Remi Beguin (Beguin et al, 2017) had carried out tests at increasing time intervals to determine I_e, the erosion index, a proxy for the ‘critical shear stress’ (the name given to hydraulic shear strength of soils when resisting concentrated leak erosion) of silty soils proposed as fill in re-constructed levees. The index increased with age, and after one year the ‘very rapid’ erosion rating had become ‘moderately rapid’. The erosion index and the critical shear stress, explained in Chapter 3 of Volume 1 of the Bulletin, are recognised not to be inherent properties of soils, but change over time as drying causes increases in pore suction for example. The unknown is how the soil would respond when wetted rapidly during a flood after years of being ‘dry’ above water level. This is an issue suggested for further research in Bridle (2016).

Backward erosion (and piping)

The Netherlands is thought of as being particularly vulnerable to backward erosion and piping, and although there are many sand boils, there have not been any recorded failures since 1926. The country is in the delta of the Rhine, and all the delta outlet rivers (Waal, etc) appear to be on recent sandy deposits above the older Pleistocene deposits. The recent sands are coated by fine soil and clay ‘confining layers’ and are consequently potentially vulnerable to 3D backward erosion in which large aquifers fuel the backward erosion process once it initiates at a break through the confining layer, where sand boils often form. Dr Hans Niemeyer presented the results of a major study of piping throughout the Netherlands. There are a number of ‘active’ sand boils (sometimes called ‘sand volcanoes’), which had not progressed to cause failure by piping. There were historic instances of failures above sand deposits attributed to overtopping and surface erosion, but it was likely that the crests of these embankments had settled because of backward erosion piping through the underlying sand.

On the field visit we saw points in the major levees which had been breached by overtopping in the past. The rush of water over the crest removed the entire levee and formed a deep scour pit downstream. These are now ‘scour ponds’ and easily identified because the replacement levee passes around them in obvious loops to rejoin the line of the unaffected lengths of levees. It seems that the breaches occurred because the crest was locally low, because of settlement, possibly caused by backward erosion and piping through the underlying sand.

We visited test sites on low ‘field’ levees where 2D backward erosion had been induced. The empirical methods in Chapter 4 of Volume 1 of the Bulletin apply in 2D situations, which occur where there is a ditch through the confining layer or no confining layer at the downstream toe of the embankment, thereby providing a continuous ‘free’ outlet along the length of the levee. This restricts the width of the aquifer providing water to initiate erosion by uplift at the toe, to drive the tip of the erosion pipe ‘backwards’ towards the waterway, and to transport eroded particles downstream to the be released at the toe of the embankment. 3D backward erosion occurs at lower hydraulic gradients than 2D backward erosion because the 3D aquifer is larger, consequently the risk from 3D erosion is higher.

Vulnerability to 3D backward erosion seems to require an understanding of the hydrogeology in order to assess groundwater pressures that will arise when floods occur. Geophysics may provide information on points in the confining layer at which uplift will occur. This was explored by Mooney et al (2017). During floods, sand boils occur and re-activate downstream of levees along the River Po in Italy (Aielli et al, 2017). No breaches have occurred but the sand boils cause much concern and in some cases (Giliberti et al, 2017) diaphragm walls were constructed, which was later shown not to have been necessary (Bezuijen, 2017). Garcia Martinez et al (2017) describe numerical simulation of groundwater flow causing sand boils to re-activate. Cavagni et al (2017) pass on experience in 3D modelling to predict piping in soils below levees. Rotunno et al (2017) have developed a finite element method to investigate piping in levees. Froiio et al (2017) developed a discrete numerical model of the tip region in backward erosion piping.

Professor Adam Bezuijen (Bezuijen, 2017) uses a small variation of the classic USACE (1956, 2000) ‘blanket theory’ hydrogeological analysis to examine the situation along the River Po, which will apply in other semi-confined aquifer situations. The analysis in effect examines the potential for high groundwater pressures under the confining layer that would cause uplift and initiate a sand boil, and examines the potential of the aquifer to drive an erosion pipe ‘backwards’ under the levee and into the river to cause a failure. It switches from the 2D to the actual 3D situation by including sand boils at 50 m intervals, as is approximately the case along this part of the River Po. The analysis makes use of recent research determining the depth of backward erosion pipes, which is only a few grains (Vandenboer et al, 2017). It makes the point that although Shields (1936) would not be expected to apply in such a confined situation, the gradient along the erosion pipe carrying eroded particles away from the tip is similar to the Shields value. In the Po situation, this gradient is insufficient to extend the pipe into the river, consequently backward erosion piping and failure cannot occur. The paper considers passive and pumped relief wells as mitigation measures, in this case required only to limit the formation of the innocuous sand boils to convenient locations. In the Po situation, where there is ‘a relatively long impermeable foreshore and a long leakage length, there is a significant difference between the river water level necessary to start sand boils and the level that will lead to breaching of the dike. In this example, it appears that failure due to overtopping is more likely than failure due to piping although the large visible sand boils suggest otherwise’.

The applicability of Shields to backward erosion and piping was examined by Robbins and van Beek (2017) who found that Shields applied in the backward erosion pipes formed in the uniform sand (d_{10} 0.227 mm, d_{60} 0.322 mm) in their apparatus. The flow was at the upper end of the laminar flow regime, at a Reynolds number a little less than 10, the lower limit of the transition to turbulent flow.

Van Beek and Hoffmans (2017) also consider the matter in relation to the Sellmeijer rules (as in the Bulletin) and the Shields Darcy model developed by Hoffmans (to be published). The Sellmeijer model uses White (1940) rather than Shields to address erosive forces. Sellmeijer is limited to 2D flow situations. The authors note the limitations and conclude that ‘future developments should aim for an improved piping model, which include aspects of both models, such as the Shields approach for prediction of the head loss in the pipe, the pipe flow through shallow and wide pipes and the numerical calculation of groundwater flow towards the pipe, combined with new insights on a local, scale-independent criterion for progression at the pipe tip. In addition better subsurface characterization and collection of field observations are essential for model validation and safety assessment’.

While there are reservations about the 2D Sellmeijer rules, the water level required to initiate 2D backward erosion to failure is greater than that for 3D failure through a confining layer. Therefore, if a free outlet is available, or a ditch can be safely excavated through the confining layer at the toe of the embankment, the probability of failure is lower than for the 3D situation. Consequently practice can follow 'theory' – or the Sellmeijer rules as presented in the Bulletin - to improve safety in particularly vulnerable locations.

Numerical models were being used to examine proposals for inserting a coarse sand barrier to halt the progress of backward erosion pipes under embankments (Rosenbrand et al, 2017). When we visited the vast and well equipped Deltares soils and hydraulics laboratories we saw the physical model of the proposal assembled in the small backward erosion testing 'box' which Dr Vera van Beek had designed and used for her fundamental research on backward erosion (e.g. van Beek, 2015; van Beek et al, 2015). We also saw the large rotating box, which makes it possible to completely fill the box, and then rotate it, leaving no gaps below what becomes the top plate.

A case of upward backward erosion, see Section 2.2.2 in Volume 1 and Section 2.3.2 in Volume 2 of ICOLD Bulletin 164, was reported by Fannin and Roos (2017). Coursier dam in Canada had been damaged by sinkholes over some years, to the extent that the owners decided to empty the reservoir and breach the dam. This revealed that the sinkholes were formed by upward backward erosion pipes through the inclined fine soil core initiating at 'free' outlets in the coarse gravel foundation material which was in local contact with the base of the core. The grading of the foundation material was finer than a 'continuing erosion filter' and should not therefore have provided the 'free outlet' at the base of the erosion pipe. The no-, some-, excessive- and continuing-erosion boundaries (see Section 7.3.4 in Volume 1 of the Bulletin) were developed for the situation at the base soil-filter boundary in dams and may not apply in upward backward erosion situations. The particles eroded by the tenacious tip of an upward backward erosion pipe seemed, from case histories at Shikwamkwa and Lar (in Volume 2 of the Bulletin), to follow a course through the fine materials between the coarser particles and would probably contain only the finer fractions of a typical base soil, which would pass through a very coarse 'filter'. The breached dam provided many opportunities to see evidence of internal erosion, to take samples and see the variability of dam fills and foundations, and Professor Fannin invited IEWG to consider meeting at the dam in 2019. It is about 30 km south-east of Revelstoke in the valley of the Columbia River in south-eastern British Columbia.

The future of the Internal Erosion Working Group

Dr Stephane Bonelli, Chairman, thanked Deltares, our hosts, particularly Drs Vera van Beek and Andre Koelewijn, for organising the IEWG meeting, attended and found stimulating and enjoyable by a record number of 75 delegates, from researchers to practitioners.

The IEWG was in good health, was affiliated to ICOLD and to the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) through Technical Committee 213, Chairman Professor Richard Whitehouse (HR Wallingford, UK) which organised the International Conferences on Scour and Erosion (ICSE). We were also firmly linked to colleagues in levees, dikes and flood defence through the new ICOLD Working Group, the ICOLD Bulletin on Internal Erosion in Dams, Dikes and Levees, and through national committees and groups. Professor Bonelli would update the IEWG website, kindly hosted by Irstea (France), to keep all those interested in internal erosion informed of events, publications and other news.

The next IEWG meeting was ICSE9 to be held in Taipei, Taiwan, November 5-8, 2018. More details from: http://www.icse2018.com/. Coursier Dam, near Revelstoke in Canada was being considered for the 2019 meeting. There may be opportunities to visit sites and laboratories, and to meet and hold discussions on particular specialist topics, etc, at other times. The Imperial College Workshop was an example, Milan is considering something similar, and other invitations were always welcome.

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Rodney Bridle
rodney.bridle@damsafety.co.uk
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