**Institution:** Imperial College London

**Unit of Assessment:** 14-Civil and Construction Engineering

**Title of case study:** 4: Mitigation of geotechnical risk through the development of advanced numerical tools – ICFEP

## 1. Summary of the impact

The development of the bespoke finite element software ICFEP (Imperial College Finite Element Program) is the main research outcome of the numerical group in the Geotechnics Section at Imperial College (IC). The research conducted in the Section since 1993 has led to a substantial growth of ICFEP's modelling capabilities in both complexity and robustness, following closely the advancements in understanding of real soil behaviour achieved through laboratory and field investigations of soils. Between 2008 and 2013 the application of these modelling capabilities to practical engineering problems, which are generally unavailable with a similar degree of sophistication in commercial software, amounts to over 80 projects of which a third are worth multi-billion pounds in global value. The impact of ICFEP's application has been to reduce the geotechnical risk and the cost of design and construction, and to give confidence in the environmental stability of design solutions, by providing accurate predictions of soil response associated with individual projects.

## 2. Underpinning research

ICFEP's capabilities in terms of numerical analysis cover a broad range of geotechnical applications. The research described in this section focuses only on developments that have been utilised directly in the projects that describe the impact in Section 4.

*Progressive failure* is characteristic of soils with brittle behaviour, where soil strength reduces gradually with deformation level, leading to ultimate collapse. Since traditional methods of analysis are unable to predict the impact of progressive failure, the development of advanced numerical tools for the simulation of this complex phenomenon has been a central topic in the research carried out between 1993 and 1997 by Potts (academic staff member since 1979). The implementation of coupled consolidation facilities in ICFEP, as well as that of strain-softening constitutive models and porosity/stress level-dependent soil permeability models, enabled the quantification, for the first time, of the geotechnical risk associated with mechanisms of progressive failure in cut slopes and embankment dams. This pioneering research led to the prize-winning publications [1] and [2], the latter becoming the key reference for the development of design strategies for such structures. More recently, in order to extend this procedure to the simulation of progressive failure of large underwater slopes, Potts developed advanced boundary conditions and specific numerical strategies, [3], to combine this type of analysis with ICFEP's large deformation capabilities.

Assessment of *serviceability limit states* ( SLS) of geotechnical structures has been one of the constant drivers for numerical developments in ICFEP, as the demand for increased accuracy of predicted ground movements due to construction has grown rapidly over the years. This was particularly important for urban environments such as London, where design requires assessments of damage induced to existing structures and services by e.g. tunnelling or deep excavations. To address this type of problem, both new constitutive relationships aimed at reproducing soil behaviour under a wide range of strains, and novel numerical strategies for simulating structural elements, were implemented into ICFEP. With respect to the former, the initial isotropic nonlinear elastic soil models were systematically applied and developed further through the PhD research of Addenbrooke (1992-1996), Franzius (2001-2004) and Grammatikopoulou (2000-2004), the latter developing the most advanced framework [4]. Concurrently, the 3D modelling capabilities of ICFEP were enhanced with the development of novel structural shell elements and their constitutive models through the PhD research of Schroeder (1998-2002). The academic staff involved with these PhDs include Potts and Zdravkovic (academic staff member since 1999). The findings of this research enabled the quantification of the effects that nonlinearity, anisotropy and plasticity below gross yield have on the predictions of ground movements, in particular around tunnels and deep excavations. Moreover, the advanced modelling of structural components (such as tunnel linings and retaining walls), accounting for anisotropy of their axial and bending stiffness, clearly showed that an isotropic idealisation, which is standard in design practice, leads to unsafe predictions of ground movements. Most of this research originated from the group's involvement with the Jubilee

Line Extension project in London between 1993 and 1996, and was instrumental in subsequent studies, [5], performed for the Crossrail project in London from 2003 to 2010.

Since 1999 a significant effort has been applied to the development and implementation of *advanced dynamic analysis* capabilities in ICFEP, which enabled the investigation of earthquake engineering and general dynamic soil problems. This research was led by Zdravkovic and Potts, through the PhDs of Hardy (1999-2003), Kontoe (2002-2006, academic staff member since 2006) and Taborda (2006-2010, academic staff member since 2012). Apart from the formulation and implementation of a coupled consolidation dynamics framework into ICFEP, three novel developments during this research have been particularly successful: efficient and accurate time integration schemes, a sub-structuring approach in terms of the domain reduction method, [6], and advanced constitutive models that can account for soil response under cyclic loading, including the prediction of the occurrence of liquefaction.

**3. References to the research** *References that best indicate quality of underpinning research


[1] Dounias G.T., Potts D.M. and Vaughan P.R. (1996) ‘Analysis of progressive failure and cracking in old British dams’; *Geotechnique* **46**(4) pp 621-640, doi:10.1680/geot.1996.46.4.621

*[2] Potts D.M., Kovacevic N. and Vaughan P.R. (1997) ‘Delayed collapse of cut slopes in stiff clay’ *Geotechnique* **47**(5) pp 953-982, doi:10.1680/geot.1997.47.5.953

[3] Kovacevic N., Jardine R.J., Potts D.M., Clukey C.E., Brand J.R. and Spikula D.R. (2012), A numerical simulation of underwater slope failures generated by salt diapirism combined with active sedimentation; *Geotechnique* **62**(9) pp 777-786, doi:10.1680/geot.12.OG.004

[4] Grammatikopoulou A., Zdravkovic L. and Potts D.M. (2006) ;General formulation of two kinematic hardening constitutive models with a smooth elasto-plastic transition’ *ASCE Int. Jnl. of Geomechanics* **6**(5) pp 291-302; doi:10.1061/(ASCE)1532-3641(2006)6:5(291)

*[5] Zdravkovic L., Potts D.M. and St. John H.D. (2005) ‘Modelling of a 3D excavation in finite element analysis’ *Geotechnique* **55**(7) pp 497-513; doi:10.1680/geot.2005.55.7.497

*[6] Kontoe S., Zdravkovic L. and Potts D.M. (2008) ‘The domain reduction method for dynamic coupled consolidation problems in geotechnical engineering’ *Int. Jnl. for Numerical and Analytical Methods in Geomechanics* **32**(6) pp 659-680; doi:10.1002/nag.641


Paper 1 was awarded the ICE Telford Premium prize and paper 2 was awarded the ICE Telford Medal.

## 4. Details of the impact

### 4.1 General

ICFEP’s impact on Geotechnical Engineering practice is delivered through direct consulting activities of the staff in the Geotechnics Section and through its strategic partnership with the Geotechnical Consulting Group (GCG) from London, who have adopted ICFEP as their key numerical tool and employ specialists dedicated solely to performing numerical analysis using ICFEP. Indeed, the latter has maximised the reach and practical relevance of the geotechnical numerical research carried out at IC, amounting to approximately 80 projects in the UK and abroad undertaken during the assessment period 2008-2013. This has impacted on a broad range of beneficiaries such as London Underground, Thames Water, BP America, Crossrail, Health and Safety Executive, British Airport Authority, Shell, Rome Metro and Darwin Port, by providing solutions that led to design cost savings, reduced environmental impact of construction, and/or enhanced safety of construction [A]. In most of these projects ICFEP was employed due to the inadequacy of commercial software and/or the IC’s ability to develop specific numerical algorithms that were necessary for some of the projects. Four of the most significant projects from the past 5 years are described below as examples of impact.

### 4.2 Mardi Gras

In the Gulf of Mexico, BP America is carrying out hydrocarbon exploration in geologically young and active regions, where kilometres of escarpments, approximately 700m high, have been created by locally uplifting and translating salt diapirs and simultaneous large scale sediment deposition in water depths over 1km. Large underwater slope failures of these escarpments present a significant geotechnical hazard to exploration equipment, with a potentially catastrophic environmental impact. Between 2008 and 2011 an IC/GCG team carried out studies using ICFEP for BP America’s Mardi Gras project – a billion dollar highest capacity deepwater pipeline system ever built – confirming that periods of slope instability were likely to have occurred in the past and should be expected in the future, but that these processes developed over hundreds, rather than thousands of years as previously thought. The analysis of such a complex geological setting, which followed the progressive failure modelling approach developed in [2], required the use of ICFEP's large displacement and coupled consolidation facilities, as well as the specific development of novel methods for simulating the underwater deposition of geomaterials [3]. The outcome of the performed analyses had a direct impact on risk assessments, by identifying reasonable estimates for the current annual probability of slope failure, which enabled BP America "to more effectively determine how to properly locate pipelines and facilities and mitigate risk along this escarpment" [B].

### 4.3 Abberton Reservoir

Following the forecast of a substantial growth in future demand for public water supply in the east of England, Northumbrian Water opted to raise the water level in Abberton Reservoir, the largest freshwater body in Essex, by 3.2m (resulting in an increase in reservoir capacity of 58%). Given the complex history of the reservoir, which involved the failure of the original dam in 1937 and its reconstruction in 1938, as well as its status of an environmental haven, designated as a Special Protection Area (SPA), IC/GCG were commissioned in 2009 by the main designer MWH (Montgomery-Watson-Harza) to carry out a numerical study of the planned raising of Abberton's main dam. ICFEP's unique combination of advanced constitutive relationships [4], coupled consolidation capabilities and progressive failure facilities [2], enabled the successful simulation of the complete dam history, including the prediction of the failure of the original dam and the post-reconstruction behaviour of the existing dam. This gave credibility to the results obtained from the subsequent modelling of the dam rising, which demonstrated satisfactory embankment stability during all phases of work. The analyses were pivotal in developing the design solution for the steeper downstream slope, impacting directly on the design cost by reducing the use of land and the amount of fill material for dam raising, thus also having a significantly positive environmental impact, with different aspects of savings amounting to an estimated several tens of millions of pounds. The convincing analyses results contributed to the efficient approval of the planning permission by presenting the solution which persuaded the stakeholders that the SPA will not be degraded. The raising of the dam has now been successfully completed and MWH note the fact that "this is the first time that an SPA has been altered in Europe and to do so without recourse to Public Inquiry is a notable success" [C].

### 4.4 Crossrail

Crossrail is the biggest tunnelling project in London in recent history, both in monetary value and the length of tunnel construction. The main challenge of the project is to ensure the stability, applying accurate assessment of ground movements, of existing undergrounding lines, utilities, services and building foundations in Central London, due to the construction of new 21 km long twin bore tunnels. An additional challenge is that new tunnels run at about 40 m depth, requiring access via deep station boxes, a type of structure for which there is little prior experience in London. Following the outcome of key research carried out at IC, [5], the Crossail project team commissioned IC/GCG between 2008 and 2011 to perform a 3D FE study to establish assessment procedures for ground movements induced by box excavations. In addition to ICFEP's capabilities in reproducing the nonlinearity of soil behaviour at small strains, advanced constitutive models for shell elements were used to model the retaining walls of the box excavations. By providing more accurate estimates of ground movements, this study reduced the geotechnical risk associated with estimation of building damage caused by the deployment of the Crossrail project, compared to standard assessment methods. It is estimated that the developed assessment procedure led to about 350 critical buildings along the Crossrail route (a quarter of the total number) being eliminated from further detailed assessment and costly structural survey [D].

### 4.5 Panama Canal

The Panama Canal is a key water route for global trade and security between the Pacific and Atlantic oceans and a primary source of income to Panama, contributing to 30% of its GDP. Its width governs the maximum size of container ships and warships passing through and studies at the beginning of this century showed that the Canal was operating close to its maximum capacity, thus generating the need for its expansion. In 2009 IC/GCG was commissioned to assess Royal Haskoning's solution for widening and deepening of the Panama Canal including the construction of a third set of locks. Due to the high seismicity in the area, the main concern of the design was the potential for a rocking mode of deformation of the high lock walls and the risk of up-lift and pounding of the central lock foundations in the event of a strong earthquake. ICFEP's advanced capabilities in terms of coupled consolidation analyses under dynamic solicitations, [6], and cyclic nonlinear constitutive modelling, as opposed to industry practice of simple pseudo-static or equivalent linear modelling, demonstrated that such a mode of deformation would not occur under the design earthquakes. These results impacted directly the design, with significant savings made on construction material and construction time. [E]

### 4.6 Examples of other lasting impact

*Stabilisation of the Leaning Tower of Pisa*: ICFEP was key software in the development of stabilisation solutions for the tower and prevention of its collapse (1992 – 2000); the remarkable agreement between measured and predicted (by ICFEP) tower's response to implementation of temporary stabilisation (counterweight) in 1993/94 and subsequent permanent stabilisation (soil extraction) in 1999/2000, enabled the understanding of the basic mechanism of the ground-tower interaction, which was otherwise impossible to assess [F]; it provided confidence to the long-term stability of the adopted permanent solution, leading to the eventual re-opening of the tower to public access in Dec. 2001; continuous monitoring of the tower to date shows no signs of further lean, hence enabling its open access and providing lasting confidence in ICFEP's predictions. A number of outreach lectures, TV and radio broadcasts have presented the Pisa research (e.g., article in The Daily Telegraph Newspaper on the 28 Jul 2010 http://bit.ly/dy9Y8Z [J] and a BBC One 'One Show' feature on 6 May 2011 [K]).

*Two text books* on finite element analysis in geotechnical engineering, [G, H]; presenting both the finite element theory and its practical application on real geotechnical problems, as developed and applied in ICFEP, these books have been not only an essential academic text, but also a source of guidance for appropriate use of numerical methods by industry; they continue to be re-printed to date and have just been issued as eBooks by the publisher Thomas Telford; due to a specific demand, the books were translated into Chinese and published by the China Science Press in 2010.

*ICE Manual of Geotechnical Engineering* [I]; Chapter 6 of this manual is dedicated to computational geotechnical analysis, providing guidance on the correct use of numerical analysis, based on experiences gained through application of ICFEP in solving real geotechnical problems.

### 5. Sources to corroborate the impact


[A] Technical Director, GCG to corroborate ICFEP's impact on Geotechnical Engineering practice

[B] Geotechnical Advisor, BP to corroborate ICFEP impact on BP America's Mardi Gras project

[C] Technical Director for Dams, MWH UK Ltd to corroborate ICFEP impact on Abberton Reservoir

[D] Head of Geotechnics, Crossrail to corroborate ICFEP impact on Crossrail project

[E] Senior Partner, Geotechnical Consulting Group-Royal Haskoning Team to corroborate impact of ICFEP on assessment of Royal Haskoning's solution for Panama Canal

[F] Potts D.M. and Burland J.B. Development and application of a numerical model for simulating the stabilisation of the Leaning Tower of Pisa; in Developments in Theoretical Geomechanics, Smith & Carter (eds) © 2000 Balkema, Rotterdam, ISBN 90 5809 158 9

[G] Potts D.M. and Zdravkovic L. (1999), Finite Element Analysis in Geotechnical Engineering: Theory; Thomas Telford, London, doi:10.1680/feaiget.27534

[H] Potts D.M. and Zdravkovic L. (2001), Finite Element Analysis in Geotechnical Engineering: Application, Thomas Telford, London, doi:10.1680/feaigea.27831

[I] Potts D.M. and Zdravkovic L. (2012), Computer analysis principles in geotechnical engineering; ICE Manual of Geotechnical Engineering; Chapter 6: 35-57, doi:10.1680/moge.57074

[J] http://www.telegraph.co.uk/culture/art/architecture/7907298/Solving-the-800-year-mystery-of-Pisas-Leaning-Tower.html. Archived https://www.imperial.ac.uk/ref/webarchive/48f

[K] http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_11-5-2011-11-25-32 Archived https://www.imperial.ac.uk/ref/webarchive/28f