Lessons learned from Geotechnical Challenges in Celtic Soils and Rocks

by

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Lecture Plan

- Celtic soils and rocks
  - Celtic background – historical and recent
  - Irish Soils and Rocks
  - Geotechnical challenges

- Geotechnical Projects – lessons learned
  - Motorways
  - Housing
  - Dublin Port Tunnel
  - Wind turbines
  - Offshore gas terminal

- Conclusions
Celtic Background
Celtic Ireland – Historical Context

- The Celts came to Ireland in second half of first millennium BC – Iron Age
- They came from central Europe, prior to the Romans, bringing La Tène culture named after a site in Switzerland
- No evidence of large scale invasion
- La Tène objects mostly found in north and west of Ireland
- Culture resulted in Celtic art – Book of Kells and Tara Brooch
- Main significance is they brought a language that became Gaelic
- Hence Ireland is a Celtic country with Celtic culture, soils and rocks

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Celtic Ireland - Recent

- Economic boom in Ireland 1995-2008
  - Boom referred to as “Celtic Tiger”
    - GNP increased by 104% in 1995–2007 – av 8.7% pa
    - Construction output increased by 147% in 1995-2007 – av 12.2% pa
    - Population increased by 24% in this period from 3.61m to 4.40m – 22%. Now 4.8m
- Need for more infrastructure – roads, housing, tunnels, etc.
- Geotechnical challenges to overcome
- Lessons learned
Irish Soils and Rocks
Geology of Ireland

- Range of rock types in Ireland is rather limited
- Over 50% of the Irish Republic is underlain by carboniferous limestone
- Some mountains, e.g. Wicklow Mountains, are igneous intrusions of granite
- Few rocks from the Tertiary Period – no chalk
Limestone Bedrock

- Mostly Karstic
- Except Dublin and south-west of Dublin
- Examples of karstic areas:
  - Cork
  - Galway
- Zones are mineralised
  - Navan - Zinc and lead mine
  - Europe's largest, and the world's 9th largest zinc mine
- Pyrite occurs in some areas
  - e.g. North County Dublin
  - Iron sulphide, FeS₂, Fool’s gold
  - Has caused problems when used as aggregate or fill
Landforms and Soils

- Present landforms and soils in Ireland are largely result of last glaciation
  - Moraines – glacial deposits, lodgement till, outwash till, boulder clay
    - Unsorted or at best poorly stratified
    - Properties depend on parent material
  - Eskers – gravel ridges
  - Drumlins – small hills
- Soft alluvial silts in river valleys and estuaries
- Peat Deposits – often underlain by soft calcareous marl
- Very little pure clay deposits
  - Most clay sized particles are crushed rock
- Former landforms – e.g. buried pre-glacial valleys
  - Beneath Dublin – valleys give sudden changes in rock head level
- These landforms and soils have presented geotechnical challenges
Lodgement Till

- e.g. Dublin Boulder Clay
- Contains sand and gravel lenses
- Presence of stone makes sampling and in-situ testing difficult
- Low plasticity fines can make it very sensitive to changes in moisture content
- w generally 8 – 11%
- Typically $\phi' = 39^\circ$
- Fines: 24% - 46% so classification varies
- Can be stability problems
Lodgement Till Properties

- Boulder Clay has a wide range of particle sizes – so termed “well graded”
- Rarely has boulders
- Sometimes it has a fines content more than 35% and sometimes less
- Sometimes behaves as a “cohesive” material, sometimes as a “cohesionless” material
- Correct description and classification of soil is vital - Incorrect classification has resulted in incorrect prediction of soil behaviour and hence has been basis of claims
Outwash Tills

- Lenses laid down at edges of and beneath ice
- Complex system of lenses as ice expanded and retreated

- Silt, sand and gravel layers
- High permeability
- Typical $k = 10^{-3} - 10^{-5}$ m/s

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Karst drop-out subsidence is potentially the most significant hazard where tills are over karstic limestone.

Principal challenge in road construction is to define the nature of the problem prior to construction.

Geophysical investigation methods useful.

Appropriate solutions need to be chosen. Drainage is important.
Irish Soft Soils Compressibility

- McCabe et al. established new correlation between compressibility index, $C_c$, and index properties of Irish soft soils.
- Found best correlation was between $C_c$ and natural water content.

McCabe et al.  
Proc ICE Geotech Eng  
2014
Marl (calcareous silt) Compressibility

- In a discussion on McCabe et al., Quigley provided a revised more appropriate correlation between $C_c$ and $w$ for marl.
- He said McCabe et al.'s correlation may lead to conservative overestimates of $C_c$ at higher water contents.
- Quigley said care required using correlations for marl high scatter in $C_c$.

Quigley
Proc ICE Geotech Eng
2016
Trends in Ground Investigation

- Quigley et al. examining trends in GI concluded:
  - Presence of a conservative bias when specialists assess geotechnical hazards
  - Trend for intensity of explorations and GI as a proportion of the project budget to reduce as the site area and project cost increase
  - Considerable improvements and innovation in GI in Ireland in the past 15 years
  - No. and quality of ground engineering specialists has increased significantly
  - Industry has innovated to suit Irish ground conditions

Quigley et al., Proc ICE Forensic Eng., 2016

- Improved use of geophysics
- Greater understanding of sampling disturbance of soft soils
- High quality drilling methods such as Geobar S and sonic coring used in stiff glacial till
Geotechnical Challenges

- Motorways/Roads
  - Problems with soft ground – treat or design against
  - Peat – should it be removed or not?
  - Groundwater – slope stability, drawdown

- Buildings/structures
  - Ground usually provides sufficient bearing resistance for spread foundations and piles
  - Normally settlement is not a problem
  - Some material is unsuitable

- Tunnels/deep excavations
  - Ground movements usually small
  - Vibrations disturbing neighbours
Projects with Geotechnical Challenges and Lessons Learned
Motorways
Motorways and Main Roads in Ireland

1993: Only 2 short stretches of motorway close to Dublin
2010: Hundreds of km of motorway completed radiating from Dublin
Rocks and Peat

- Peaty soils are problematic due to their:
  - High compressibility
  - Creep behaviour,
  - Low bulk density
  - Low undrained shear strength

- National Roads Authority (NRA) required peat be fully removed or road supported on piles or on other support systems

- Generally preferred option was to remove peat removed when up to 3m or 4m deep but greater depths, up to 13m were excavated, but side slope stability became a problem

- Despite NRA requirements, the poor geotechnical properties of peat did impact on several road projects
Piled Embankments

Pile installation for an overbridge embankment
Construction on Peat

- Piled embankments on peaty material are often constructed over very poor ground conditions
- Even foot access can be limited
- Amphibious investigation vehicle bogged down in Flurry Bog, Co. Louth during additional investigation
- Safe working platforms form a critical element of the construction
Working Platforms

• Working platforms need to be strong enough to take the piling rig but weak enough to allow piles to punch through when driving.

• If the embankment is too thick, it could settle significantly and the consequence needs to be taken into account in basal reinforcement and pile design.

• To achieve a relatively thin but strong working platform to support the piling rig being used, it was found that a combination of geotextiles and geogrids with strong interlocking rockfill was successfully to build platforms 0.5m to 0.6m thick.
Piled Embankment at Flurry Bog

- Piled Embankment:
  - 300mm square precast piles with 0.8m caps on a 2.5m grid
  - 2 layers of Polyfelt (PET) ranging from 600 and 800kN/m
  - Supporting an embankment 3.5m high
  - Issues with pile verticality and positional tolerances
  - Post construction road has formed well
Basal Reinforcement Design

- Basal reinforcement design:
  - Consider effect of arching of the soil between the pile caps
  - Stresses required to maintain the arch and to keep the embankment soil not supported by the arch in position
  - Reinforcement also has to resist horizontal movement of the embankment side slopes (lateral sliding)
  - Basal reinforcement perpendicular to the embankment therefore takes higher tension loading than that running parallel.
Basal Reinforcement on Very Compressible Soil

- When designing basal reinforcement for embankments over very compressible peat, the entire embankment loading needs be taken onto the piles with no support from the subsoil.
- The weight of the working platform alone can result in the subsoil settling away from the basal reinforcement.
- The solution adopted was to remove the failed embankment and replace the geotextile reinforcement with a concrete slab and then reinstate the embankment.
- Failure of embankment delayed road opening by one year.

Anaholty bog - Gap below reinforcement
Some Lessons Learned

• Because of the very low strength of peat, designers need to rely on the additional tensile strength of the uppermost vegetative peat layer, the small amount of near-surface consolidation and additional strength due to the working platform load when designing embankments.

• Piling through peat is very different to normal piling. It takes a few blows to penetrate through the working platform before a pile free falls a few meters into the weak peat. The pile tends to slip off vertical and then is too deep to be forced back into the vertical.

• Positional errors can also be a problem.

• It is essential that the first layer of fill incorporating the basal reinforcement is good interlocking rockfill. The remainder of the embankment should also be constructed from granular material which has better arching ability and less tendency to creep in the long term.
Housing
Buildings near Dublin with Cracks

Houses in Drynam, North Co. Dublin

Ballymun Youth Facility, North Dublin
Damage in Buildings

Cracks in exterior rising wall

Cracks in interior rising wall

Bowing of stud wall
Cracks inside Buildings

Crack in ground floor slab

Cracks in blocks in interior partition wall
Pyritic Fill

Fill and damaged concrete

Fill material with pyrite (Fool’s gold)
Mechanism due to Pyritic Heave

- Oxidation of pyritic fill caused it to expand and exert vertical and horizontal pressures that caused floors and structural walls to crack and partition walls to bow

- Framboidal pyrite particularly reactive
Investigation of Pyrite Problems

- Pyrite first found beneath the ground floor slab of a house in 2006
- Subsequently about 750 homes in 74 estates in North County Dublin were identified as being at risk from 'pyrite heave'
- Pyrite Panel Commissioned by the Minister of the Environment, Community and Local Government to investigate pyrite problem – its causes and resolution – and reported in 2012
- Report highlights that when expansion occurs in pyritic hardcore that is well compacted and confined between rising walls and a ground floor concrete slab, e.g. in a dwelling, it may result in:
  - The cracking of floors, internal partitions and external walls
  - Outward movement of external walls, and/or
  - The heaving of ground floors and
  - Bulging of internal partition finishes.
Some Lessons Learned

- Reasons for pyrite problem:
  - Move in recent years away from suspended ground floors to ground bearing floor slabs
  - In past fill beneath ground floor slabs was typically strong rock fluvial gravels or gravels from tills. It is difficult to compact these to meet modern compaction standards, so crushed angular rock now used
  - With huge demand for homes in early 2000s and demand for fill, some quarries provided material that was of poor quality – weak with fines
  - Also modern housing construction methods are more likely to manifest distress which might have been obscured or accommodated in the past
- Quarries must supply and contractors must only use suitable fill beneath ground floor slabs
- Pyrite problem resulted in one of the longest running and most expensive legal cases in the history of the Irish State
- New Standard prepared on use pyritic rock in buildings
NSAI Standards on Pyrite: I.S.398:2013

Two parts of a new standard prepared to determine whether or not a building is or may be affected by reactive pyrite and specifies a methodology for the remediation

Part 1: *Testing and categorisation protocol*

- Details accurate and reliable protocols to determine whether or not a building is or may be affected by reactive pyrite in the sub-floor hardcore material which is a key component in the prioritisation of remediation works.

- Building shall be categorised based on the results of the Building Condition Assessment and classification of the hardcore
  - Acid-soluble sulfate (AS): Fail if \( > 0.2\% \text{ SO}_4 \)
  - Water-soluble sulfate (WS): Fail if \( > 1500 \text{ mg/l } \text{SO}_4 \)

The reason why only the SO\(_4\) and not FeS\(_2\) is measured is because the test is determine if oxidation has occurred and SO\(_4\) formed, not if it could occur

Part 2: *Methodology for remediation works*

- Specifies a methodology for the remediation by the complete removal of sub-floor hardcore affected by reactive pyrite
Dublin Port Tunnel
Dublin Port Tunnel

- First road tunnel in Ireland
- Third longest urban tunnel in Europe after tunnels in Madrid and Stockholm
- Purpose to link Dublin Port with motorway to Belfast (M1) remove HGVs from Dublin city
- Largest construction project in Ireland
  - 2.6km bored 10.8m internal diameter twin tunnel
  - 1.9km cut & cover tunnel
  - Value €480 million
- Duration 43 Months
  - Start 5 June 2001
  - Completion January 2005
Geotechnical Challenges of DPT

- 2.6 km of bored tunnel beneath residential area
- Tunnelling in Boulder Clay and rock – mixed ground conditions
- Boulder clay with sand lenses
- Fault zones in rock
- Face stability problems
- Water inflow problems

Exit to M1 to Belfast and link to other Motorways
Marino Residential Area
Dublin Port

Boulder Clay
Limestone Rock
Design Considerations

- Origin plan in 1994 was for tunnel to be constructed using NATM
- In 1994 a major NATM tunnel collapse occurred at Heathrow
- Residents of Marino above route of tunnel feared possible collapse of tunnel
- Residents also concerned about:
  - Settlements
  - Vibrations
  - Noise
- At tender stage contractor actually chose TBM on commercial grounds

- Measures taken to allay residents’ concerns:
  - Depth of tunnel increased to 30m
  - Buildings monitored for cracks, settlements and vibrations
  - Regular meetings with residents
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Residents’ fears win Dublin NATM safety probe

The Irish Health & Safety Authority is ready to call in experts involved with the Heathrow Express tunnel collapse investigation to assist with its work on the Dublin Port Tunnel project.

A senior HSA official said that the expertise available to the HSE in its NATM investigations would be sought for Dublin “should the need arise”.

“The HSA is paying full attention to all of the recommendations made by the HSE after the Heathrow collapse. It would be unacceptable if the same problems occurred here as happened at Heathrow,” he said.

Residents of Marino, directly opposite the track alignment, have been kept informed of the situation and have been kept informed of the situation and the potential for a collapse.

The HSE’s report criticised NATM practice in UK construction at the time of Heathrow’s failure. It approved NATM conditional on its recommendations being fulfilled. The Heathrow investigation is continuing and

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- Width of measured surface settlements as a result of ground movement due to tunnelling is 90m on either side of tunnel axis
- Measured surface settlement curve is wider than calculated Gaussian surface settlement curve
Ground Model for DPT

Ground includes:

- Limestone bedrock overlain by glacial boulder clay
- Drumlins (glacial hillocks) and eskers
- Buried valleys infilled with sand and gravel
- Former braided rivers, bogs and lakes
Tunnel Route, Geological Features and Damage

Features shown:

- Tunnel alignment
- Rivulets
- Buried valley
- Drumlins
- No. of Damaged properties
  - Serviceability (3)
  - Aesthetic (32)
- In figure 3 dark rectangular properties suffered serviceability damage. All were over a rivulet.
Surface Settlements, Features and Damage

- Surface settlements directly above tunnel mostly less than 5mm
- Some up to 10mm
- Only a few small areas more than 20mm (red areas)
- Settlements due to a number of overlapping mechanisms:
  - Volume loss due to deformation and local failure at tunnel face
  - Dewatering and loss of fines
  - Vibro densification of soil
  - Slow tunnelling
Lessons Learned

- Much geotechnical investigation, specialised soil and element testing and modelling of ground was carried before and during the Dublin Port Tunnel out so that much has been learned about properties of Dublin Boulder Clay and the underlying limestone rock.

- Many papers published on findings from Dublin Port Tunnel Projects, for example in ICE Proceedings Geotechnical Engineering.

- Designers and contractors need to take account of residents concerns from the earliest stages of a projects.
Wind Turbines
Derrybrien Windfarm

- Construction of 71 850 kW turbine foundations on a mountain, including excavation, disposal, blinding and reinforced concrete to bases and crushed stone backfill on top of base
- Design and maintenance of approx 20 km of site access roads for all construction traffic
Derrybrien Landslide

- Derrybrien landslide occurred in October 2003 on side of hill called Cashlaundrumlahan, Co Galway
- Landslide triggered by construction wind turbine foundations
- Disrupted construction. Opened quietly in 2006
- Dislodged 450,000 m$^3$ after dry period

- Up to 100,000 fish killed including virtually all fish in 10-mile stretch of the river down to Lough Cutra

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Pollatomais Landslides

- In July 2004 landslides occurred on slopes above Pollatomais as a result of very heavy rainfall following a dry period
- Some houses impacted
Lessons Learned

- Peat is susceptible to sliding, particularly after intense rain following a dry period
- A small excavation and loading on peat at Derrybrien caused a huge landslide with massive consequences
- Geological Survey of Ireland initiated research into landslides in Ireland
- Research also carried out into properties of peat
- Has resulted in greater knowledge of peat and its behaviour
- Residents committees and other groups were very active seeking compensation following landslides
- Construction of windfarms on peat on mountains subsequently carried out with much greater caution, particularly with regard to disturbance of natural peat bogs
Offshore Gas
Corrib Gas Field

- Corrib gas field 83km off Mayo coast, 3000m below seabed with 355m water depth
- Discovered in 1996 by Enterprise Oil
- Enterprise Oil was acquired by Shell in 2002
- With 1 trillion ft$^3$ it is Ireland’s largest gas field Kinsale (1.4 trillion ft$^3$)
- The Corrib development has four distinct parts:
  1. Offshore wells and subsea facilities
  2. Offshore pipeline from the wells to the landfall at Glengad
  3. Onshore pipeline between landfall
  4. Bellanaboy Bridge Gas terminal
Route of pipeline

- Area of great natural beauty
- Sensitive peat bog landscape
- Area of importance in Irish legend
- Important marine habitat
- E.U. Special Area of Conservation (SAC)
- EU Special Protected Area (Birds Directive).
Resistance to Project

- From the start the project was dogged with controversy
- There were heated exchanges with objectors during Planning hearings
- Many objections related to environmental impacts
- Objections included:
  - Large lorries on small roads to remove peat and create terminal site
  - Wanted terminal site located at sea – Shell to Sea campaign
  - Danger to environment
  - High pressure pipeline across bog and possible leakage and explosion
- Shell was initially unresponsive to objectors
- Initially a PR disaster
Campaign Against Project

- Residents picketed the site and tried to stop work on terminal site and for high pressure pipeline across their land at Rossbeg
- A committal order was sought by Shell
- Rossport 5jailed in 2005 for contempt of court after refusing to obey the injunction forbidding them to interfere with work by Shell for pipeline on their land
- Spent 94 days in gaol
- They appealed to the High Court

- Stance of the Rossport Five was vindicated
- Shell had to pay €1 million costs, including those of the Rossport landowners.
- As a result of national and international pressure Shell decided to put land pipe in tunnel
Scruwaddacon Bay Tunnel

- Shell decided to tunnel pipeline under Scruwaddacon Bay linking sea pipeline with Bellanaboy Terminal Plant
- 4.9km tunnel is 300m longer than the Dublin Port Tunnel
- The longest tunnel ever built in Ireland
- Constructed from Jan 2013 to Jun 2014
- Once completed and tested it was backfilled with concrete
Lessons Learned

- Main lesson learned was need for good public relations, particularly in the case of major infrastructure projects.
- It is very hard to improve relations was one gets off to a bad start.
- Shell initially did not inform public of their plans.
- After objections raised, they then devoted tremendous effort into PR, including funding local clubs and providing local sponsorships in addition to much local employment. This has transformed area.
- Apart from project taking 19 years, from 1996 to 2015, the opposition resulted in a cost overrun of €2.4 billion.
- Concerned about peat stability contributed to research into behaviour of peat initially stimulated by the earlier peat slides.
Conclusions

- 1993-2008 – boom period for Irish economy – Celtic tiger
- Need for infrastructure
- Boom in construction
- More stringent planning requirements and EU Directives
- Legal disputes a feature of all examples described
- Need for improved PR in case of major infrastructure projects
- More geotechnical investigation and geotechnical engineers
- Many reports, papers and books published on Celtic soils and rocks
- Much greater understanding and experience of how to deal with geotechnical challenges in Celtic soils and rocks
Thank you

Any Questions?
Call for scientific session proposals for INQUA 2019 Dublin is open, and will be open until 31st March 2018

Contact: Prof Pete Coxon: pcoxon@tcd.ie
Pyrite Remediation Scheme

The Pyrite Resolution Board operates the pyrite remediation scheme

- The aim of the Pyrite Remediation Scheme (the Scheme) is to procure the remediation of certain dwellings with damage caused by pyritic heave of hardcore under floor slabs.
- The Housing Agency will be responsible for the testing of dwellings and the implementation of the remediation process.
- They will also be the contracting authority for the Scheme and will engage all necessary construction professionals, advisors and contractors to carry out the remediation of dwellings which are included in the Scheme.

Costs covered by Remediation Scheme

- Sampling, testing and damage verification;
- Preparation of specification of remediation works in accordance with I.S. 398-2;
- Management of the tender process and implementation of remediation works;
- Remediation of dwelling as per specification and schedule to required standard;
- Monitoring and inspection of works, snagging and final certification.
Eligibility Conditions for Remediation

Conditions to be satisfied for a dwelling to be eligible for remediation

- Dwellings must be located within Dún Laoghaire-Rathdown, Fingal, Kildare, Meath, Offaly or South Dublin County Councils; or Dublin City Council
- Dwellings must have been constructed and completed between 1st January 1997 and 12th December 2013;
- Dwellings must have been assessed, tested and certified as having a damage condition rating of 2 and it must be verified that damage is attributable to pyrite heave;
- Applicant must be owner or joint owner of dwelling. An application can only be made in respect of 1 dwelling and dwelling must have been purchased before 12th December 2013;
- Applicant must be able to show, to satisfaction of PRB, that he/she does not have available to him or her any practicable option, other than under the Scheme or the use of his or her own resources, to remediate or secure the remediation of the dwelling.
- There may be rare exceptional circumstances concerning damage to or from an adjoining dwelling that can be considered by the Board.
- An extension, used for habitable purposes, is considered to be a dwelling for the purposes of the Pyrite Resolution Act 2013.