COST Action TU 1202

Impact of Climate Change on Engineered Slopes for Infrastructure

Short Term Scientific Mission

Visit made by
John van Esch and Raymond van der Meij (Deltares)
to the British Geological Survey

16th Sept – 20th Sept, 2013

Visit Contributors:

Deltares: John, van Esch, Raymond van der Meij
British Geological Survey: Tom Dijkstra, Jon Chambers, Holger Kessler, Andrew Barkwith, Jon Mackay, Paul Wilkinson, Peter Hobbs, David Gunn
Newcastle University: Paul Hughes, Rose Hen-Jones, Ross Stirling
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Executive Summary

This report describes the itinerary, scientific exchange and proposed developments associated with a visit made by Deltares to the British Geological Survey in September 2013.

This activity formed a short term scientific mission that was supported by the COST Action TU 1202 Impact of Climate Change on Engineered Slopes for Infrastructure.

Field excursions during the STSM included visits to a natural inland landslide in Yorkshire, a compacted clay earthworks embankment in Northumbria and an aged, end tipped embankment in Nottinghamshire.

The visit also included a workshop from which a plan was devised for further development of an integrated modelling-monitoring methodology. It is anticipated that this will stimulate a phase of collaboration between the BGS and Deltares that will extend over the next 24 months.
1. Remit within the context of COST Action TU 1202

1.1 COST Action TU 1202

The European Co-Operation in Science and Technology (COST) Memorandum of Understanding document COST 4149/12 (dated 4th July 2012) stated the main objectives of Action TU 1202 to include:

i. Review and compare case studies, methods of numerical simulation, monitoring systems and risk analysis systems for climate impacts on engineered slopes,

ii. Explore methods to communicate slope stability risk to stakeholders/asset owners.

Action TU 1202 supports themed workshops and short term scientific missions (STSM) for participating members (staff/organisations) of the Action to spend time with collaborating with other European research groups. Action TU 1202 is broken down into four Working Groups as follows:

WG 1: Demonstration of modelling capabilities - will identify and review available numerical models, which can be used to analyse the stability of engineered slopes subjected to present and future climate scenarios. It will review integration of hydrological and geotechnical processes in numerical models that help to identify potential failure mechanisms. This WG will then generate a research agenda for future development of numerical modelling procedures.

WG 2: Slopes monitoring data knowledge exchange - will facilitate data exchange for model validation between research partners and will review and share knowledge on existing and emerging technologies/methodologies of integrated geotechnical slope monitoring. The effectiveness of different methods and technologies will be explored to improve existing research facilities and develop future experiments.

WG 3: Climate - vegetation - soil interactions - will review current practice in testing and modelling of interactions between climate, vegetation and soil. This will primarily be concerned with induced pore water pressure and permeability changes but will also explore changes in the mechanical properties of soils caused by root growth, desiccation and surface erosion.

WG 4: Hazard/risk - will apply risk based analysis to geotechnical asset failure which is crucial to efficient and effective asset management by stakeholders. WG4 will explore methods to analyse and communicate slope stability risk to stakeholders and infrastructure users.

1.2 Visit Aim

The aim of this visit was to support knowledge exchange between member organisations Deltares, the British Geological Survey and the University of Newcastle to explore the development of integrated modelling and monitoring methods and infrastructure. In this respect, this STSM was a knowledge exchange visit which included the following objectives:

1. Explore the conceptual infrastructure elements (modules) for integrated hydrogeological-geomechanical modelling-monitoring methods that could lead to improved real time (monitored) constraints to model outcomes,

2. Explore the routes and system interfaces (and protocol) for integrating (near) real-time data streams into new numerical modelling schemes to assess climate threats to stability.

3. Explore potential work programmes and case history study sites
1.3 Visit Participants
This STSM involved a trip by researchers from Deltares, Delft, Netherlands to the UK for exchange visits to the British Geological Survey, Nottingham and the University of Newcastle.

1.3.1 Deltares
The visiting party included Dr. John van Esch and Dr. Raymond van der Meij from Deltares.

Deltares is an independent, institute for applied research in the field of water, subsurface and infrastructure. Throughout the world, we work on smart solutions, innovations and applications for people, environment and society. Our main focus is on deltas, coastal regions and river basins. Managing these densely populated and vulnerable areas is complex, which is why we work closely with governments, businesses, other research institutes and universities at home and abroad.

Dr. John van Esch:
- development of real time stability assessment tools for flood defense systems,
- research on the impact of climate change on dikes and embankments,
- modeling of transient groundwater flow and piping under dikes and dams,
- modeling of groundwater flow though dikes and dams for stability assessment,
- research on multi-scale modeling of subsurface flow and transport processes.

Dr. Raymond van der Meij:
- Modeling the stress-strain relationship of peat using an artificial neural network
- Predicting horizontal deformations using an artificial neural network (or fuzzy logic)
- Quickly designing a flood protection embankment that adheres to the Dutch VTV
- Finding the stability of an embankment using a Genetic Algorithm
- Quickly calculating an emergency measure for a flood protection embankment

1.3.2 British Geological Survey (BGS)
The host party at the BGS included Dr. Tom Dijkstra, Dr. Jon Chambers and Dr. David Gunn.

As a public sector organisation BGS is responsible for advising the UK government on all aspects of geoscience as well as providing impartial geological advice to industry, academia and the public. The BGS is part of the Natural Environment Research Council (NERC), which is the UK's main agency for funding and managing research, training, and knowledge exchange in the environmental sciences. The NERC reports to the UK government's Department for Business, Innovation and Skills (BIS). We also undertake an extensive programme of overseas research, surveying and monitoring, including major institutional strengthening programmes in the developing world.

Dr. Tom Dijkstra: Engineering Geologist:
- Quaternary geology and geomorphology (including geomorphology and geohazards of Chinese loess landscapes)
- Climate change and slope instability (including resilience of the UK infrastructure network)
- Engineering geomorphology (field and laboratory shear strength assessments, slope instability processes/modelling and associated hazard/risk assessments)
- Geophysical investigations (electrical resistivity of clay soils)
- Geotechnical engineering (geophysical assessment of soil properties and suction levels in clays)
- Lime stabilization of swell/shrink clays
- Remote sensing and pedometric techniques for soil erosion/landslide modelling

Dr. Jon Chambers: Geophysicist
• Development and application of electrical imaging methods: electrical resistivity tomography (ERT); self-potential tomography (SPT); induced polarisation tomography (IPT); spectral induced polarisation (SIP)

• Engineering geophysics: investigation and monitoring of engineered structures (e.g. earthworks), and geophysical-geotechnical-hydrogeological property interrelationships

• Geohazards: landslide investigation and monitoring

• Hydrogeophysics: non-invasive 4D imaging of contaminant transport, saline intrusion in coastal aquifers, and unsaturated (vadose) zone processes

• Quaternary deposit characterisation: high resolution 3D imaging of economic mineral deposits

Dr. David Gunn: Engineering Geophysicist

• Geophysical-Geotechnical property relationships

• Transportation geotechnics

• Geohazard monitoring

1.3.3 University of Newcastle (NU)
The host party at the NU included Dr. Paul Hughes of the School of Civil Engineering and Geosciences at the University of Newcastle.

The School of Civil Engineering and Geosciences is the largest and best equipped group of its type in the UK with 160 staff and 670 students. We have six programme groups which specialise in: Water Resource Engineering, Environmental Engineering, Transport Engineering, Geotechnical and Structural Engineering, Geoscience and Geomatics. We carry out world class research focusing on the challenges of science and engineering at the interface between technological, human and natural systems. We command a unique position both to tackle the fundamental science related to intensifying global change and to confront the challenges this presents to our society and its supporting infrastructure.

Dr. Paul Hughes: Lecturer – Civil Engineering / Geosciences

• Developing binders from industrial wastes for use in stabilisation/cementation and ground improvement

• Geotechnical instrumentation to measure ground movement and soil pore water pressure in artificial slopes

• Impacts of climate change on slope stability including improved process modelling
### 2. Visit Itinerary

**Itinerary for visit by:** John van Esch, Raymond van der Meij, Deltares

<table>
<thead>
<tr>
<th>Date</th>
<th>Approx. Time</th>
<th>Activity</th>
</tr>
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<tbody>
<tr>
<td><strong>Monday</strong></td>
<td></td>
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<tr>
<td>16th Sept</td>
<td>09.00</td>
<td>Arrive at the BGS. Meet staff from GTom / GGPP</td>
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<tr>
<td></td>
<td>09.30</td>
<td>Travel to Hollin Hill, Terrington, near Malton, Yorkshire</td>
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<td></td>
<td>11.30</td>
<td>Morning Tea: Either Highwayman A64 or Tea Shop in Welburn (Sandwiches from the shop in Terrington / or pub.)</td>
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<td></td>
<td>11.30 - 12.00</td>
<td>Discuss / describe Hollin Hill site over brunch .... Tom, Jon, DG present material re: Hollin Hill ground model, geology, geomorphology, landslide processes.</td>
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<td></td>
<td>14.00-15.00/15.30</td>
<td>Hollin Hill walkover: See section 3.1</td>
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<td></td>
<td>15.30-18.30</td>
<td>Travel to Premier Inn, Newcastle / overnight Newcastle.</td>
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<td></td>
<td><strong>Evening</strong></td>
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<td><em>Meal in Newcastle:</em></td>
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<tr>
<td><strong>Tuesday</strong></td>
<td>09.30</td>
<td>Drummond Building, University of Newcastle, Newcastle upon Tyne</td>
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<tr>
<td>17th Sept</td>
<td>09.30 - 12.00</td>
<td>Seminar-Discussion: Integrating laboratory and field data (datasets) Chaired by Dr. Paul Hughes - Civil Engineering / Geosciences</td>
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<td>Discussion Topics / Discussion Leaders included:</td>
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<tr>
<td></td>
<td></td>
<td>Paul Hughes: Introduction to the BIONICS site</td>
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<td></td>
<td>Ross Stirling: Study of cracking in lab and field</td>
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<td></td>
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<td>Rose Hen-Jones: Geophysical-geotechnical property relationships</td>
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<td>Raymond van der Meij: Dam / embankment testing facilities</td>
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<td></td>
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<td>John van Esch: Modelling groundwater and dam failure processes</td>
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<td></td>
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<td>David Gunn: iSMART: field - laboratory integration</td>
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<td>12.45</td>
<td>Buffet lunch</td>
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<td></td>
<td>13.15-13.45</td>
<td>Tour of labs: Tensile strength test facility</td>
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<td></td>
<td>13.45</td>
<td>Travel on to BIONICS, Nafferton Farm, Northumberland.</td>
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<td></td>
<td>14.15-15.15</td>
<td>BIONICS walkover: See section 3.2</td>
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<td></td>
<td>15.15</td>
<td>Return to Nottingham</td>
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<td></td>
<td>Approx. 19.15</td>
<td>Back to hotel</td>
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<tr>
<td><strong>Wednesday</strong></td>
<td>09.00</td>
<td>Arrive BGS:</td>
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<tr>
<td>18th Sept</td>
<td>09.00-10.30</td>
<td>Introduction to the East Leake embankment:</td>
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<td></td>
<td></td>
<td>i. 19th century ‘cut-fill’ construction methods at East Leake</td>
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<td>ii. Cutting source and embankment fill materials</td>
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<td>iii. Geotechnical / geophysical data to aid building of a site scale ground model</td>
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<td>10.30 - 10.50</td>
<td>Travel to East Leake</td>
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<td></td>
<td>11.00 - 12.10</td>
<td>Walkover East Leake: See section 3.3</td>
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<tr>
<td></td>
<td>12.45</td>
<td>Return travel - Raymond van der Meij</td>
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<td></td>
<td>13.00 - 14.00</td>
<td>Lunch</td>
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<td></td>
<td>14.30</td>
<td>Tour of BGS labs: Geotechnical laboratories</td>
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<td>Instrumentation labs</td>
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<td></td>
<td>Hydrogeophysical / Geophysical labs</td>
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<td></td>
<td>17.00</td>
<td>Return to hotel - administrative catchup</td>
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<td></td>
<td>18.00 for 18.30</td>
<td>Evening Lecture: Tackling Congestion Beneath Our Streets: - A “BIM” approach for the future?</td>
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<td>Meeting of the East Midlands Group of the Institution of Civil Engineers</td>
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<td>Best Western Premier Yew Lodge Hotel, Packington Hill, Kegworth, DE74 2DF</td>
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<tr>
<td><strong>Thursday</strong></td>
<td>09.30</td>
<td>Arrive BGS</td>
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<tr>
<td>19th Sept</td>
<td>10.00</td>
<td>Workshop: Integrated Monitoring and Modelling of Engineered Slopes See report section 5.0</td>
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<td>16.00</td>
<td>Free time for administration, organisation etc...</td>
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<td></td>
<td>17.00</td>
<td>Return to hotel</td>
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<tr>
<td></td>
<td><strong>19.30</strong></td>
<td><em>Meal in Nottingham:</em></td>
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<tr>
<td><strong>Friday</strong></td>
<td>09.30</td>
<td>Arrive BGS</td>
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<tr>
<td>20th Sept</td>
<td>09.30 - 12.15</td>
<td>Discussion: Future Research Opportunities See report section 6.0</td>
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<td></td>
<td>12.15</td>
<td>Return to East Midlands Airport</td>
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3. Field Site Summaries

3.1 Hollin Hill

**Location:** Approx. BNG: 468097E, 468826N

Hollin Hill is located at Mowthorpe, Terrington near Malton, North Yorkshire within an area designated by the Ryedale District Council as the Howardian Hills Area of Outstanding Natural Beauty (famous for Castle Howard – famous for Brideshead Revisited). This is the site of a complex landslide on the south facing escarpment of Hollin Hill, which has an overall slope of approximately 12°.

**Geology:** LIAS

Hollin Hill is part of a low-lying range of hills running NW – SE mainly comprising rocks of the Lower and Middle Jurassic that formed on the SSW margin of the Cleveland Basin approximately 200 to 170 million year BP. Hollin Hill is a smooth, flat-topped hill capped by calcareous sandstone and ferruginous limestone of the Dogger Formation (DF), Middle Jurassic age. The DF could host a potential aquifer above the Whitby Mudstone Formation (WM). It gives rise to free-draining sandy soil rich in gravel- to cobblesize rock fragments and is a principal component of head deposits on the escarpment. It occupies hollows in the angular unconformity with the underlying WM, and ranges considerably in thickness across the region to attain a local maximum of 8 m (to the north of the site). The WM is characterised by grey to dark grey mudstone and siltstone with scattered bands of calcareous and sideritic concretions. The formation is approximately 25 m thick, with a sharp upper boundary marked by the erosive base of the DF. The WM is distinctly weathered near to the ground surface, giving rise to a red-brown, poorly drained clay soil. The boundary between the underlying Staithes Sandstone Formation (SS) and the WM is represented by an upward transition from sandstone/siltstone to shaley mudstone and there can also be scattered sideritic nodules present where the Cleveland Ironstone Formation (CI) persists. The SS is up to 20 m thick and is associated with well-drained loam soil in the middle part of the escarpment. The upper boundary of the formation is taken at the junction with mudstone or ironstone of the overlying CI. The SS lies conformably upon the Redcar Mudstone Formation, which comprises grey, silty, calcareous and sideritic mudstone with thin shelly limestones. The bedrock is relatively flat lying with a gentle dip to the north of approximately 5°. In common with the surrounding area, the bedrock succession at Hollin Hill is overlain by a thin veneer of head. This deposit is characterised by gravelly, sandy, silty clay with occasional organic inclusions, representing locally derived material, reworked by a combination of near-surface processes including hillwash, slope failure and soil creep. The thickness of head deposits is highly variable, ranging from 0.2 m to 1.3 m, generally increasing towards the base of the escarpment.

**Natural Landslide:**

Landsliding appears to have occurred as a series of multiple, shallow retrogressive failures, that produce a series of wedge-shaped terraces around 1 – 1.5 m thick over an oval shaped area approximately 10 m (downslope axis) by 20 m. The backscar had been formed from past and current phases of failure and runs along a contour within 10 m of the boundary between the DF and WM. The hill slope flattens to a sub-horizontal plane beneath the toe of the current failure zone, and again, this sub-horizontal plane extended laterally along hillside at a roughly constant contour. This flat sub-horizontal ground represents the base of the most recent failures on the upper slope of the WM. Beneath it, an accumulation zone of hummocky ground has been formed from material depleted from the current and most recent failures, where the hummocks have a similar aerial extent to the mass of material within the terraces of the current failure. These combined features of an along-contour backscar and zone of hummocky ground occur again (although in subdued form) approximately 30 m downslope, closer to the boundary between the SS and the WM. Reworked material within this lower zone of hummocky ground provides the source material for the upper parts of translatory lobes. This lower zone is believed to have been formed by an earlier phase of failure lower down on the scarp slope of the WM. Within this earlier phase, the sub-horizontal plane is approximately 10 – 20 m above the boundary between the WM and the underlying SS, with the accumulated material forming a
plateau above the upper dip slope of the SS. This material feeds into slowly moving lobes of slumped material that flow over and down the scarp slope of the SS. Lobe advancement has occurred as multiple, prograding phases, where younger materials override older material, believed to have been controlled by cyclic changes in moisture content, pore pressure and associated material property changes. This pattern of rotational features and active lobes extend approximately 150 m down the slope from the top of the hill, and also extend laterally into Mowthorpe Wood to the west.

Plate 1: Left to right: Andrew Barkwith (BGS), John van Esch (Deltares), Tom Dijkstra (BGS), Raymond van der Meij (Deltares) and Jon Mackay (BGS) above the backscarp of shallow rotational failures at Hollin Hill.

**Monitoring Brief:** Two permanent electrical resistivity monitoring arrays have been installed at Hollin Hill. The first covers a large area with a relatively large sample spacing, capturing the processes including the upper slope shallow rotational failure, the mid-slope translation and the lower slope earth flows. The second covers a small area with a smaller sample spacing capturing the earth flow processes in more detail. We aim to use a series of time lapse electrical resistivity images inverted from measurements on these arrays to study the near surface groundwater processes controlling the landsliding and also to map the movement and dynamic distribution of materials during the process. Figure 1 below is an example of a 3D volumetric resistivity image showing the distribution of slipped Whitby Mudstone (low resistivity - blue colours) flowing over the underlying Staithes Sandstone (higher resistivity - green colours).

![Image of monitoring team above backscarp](image1.jpg)

![3D resistivity image](image2.jpg)

**Figure 1.** Example of a 3D resistivity image produced from measurements (right) on the 5 line, 148 m by 48 m area resistivity array at Hollin Hill (left).
3.2 BIONICS

**Location:** Approx. BNG: 406415E, 565800N

The BIONICS research embankment is located at Nafferton Farm, Northumberland. It was constructed using varying amounts of compaction in 2005 from sandy, silty clay.

**Engineered Embankment:** Constructed in Durham Till (index geotechnical properties in following section).

The embankment axis is orientated in an east - west direction. It is 90 m long, 6 m high, has a 29 m base width and a 5 m wide crest with 1 in 2 slopes on the flanks. The embankment was constructed in 2005 in four main 18m-long sections, with the two inner-most sections constructed according to Highways Agency specifications using 0.3 m lifts and 18 passes of a 7.3 tonne self-propelled smooth drum vibrating roller. These have been termed the ‘well compacted panels’ and simulate new-build highway embankments (Panels B and C in figure 2a). The two outer-most sections were built to represent poorly constructed/heterogeneous rail embankments, using four lifts, each nominally of 1.3 m height with minimum tracking by site plant; termed ‘poorly compacted’ (Panels A and D in figure 2a).

![Figure 2. BIONICS: embankment structure and layout of resistivity line in poorly compacted section.](image)

To prevent any hydraulic connectivity between each section vertical impermeable membranes were installed during construction between the panels. Immediately after construction the embankment slopes were seeded with grassland seeds typical of the North East of England and other plant species allowed to colonise the embankment naturally. The earthworks fill comprise a sandy, silty clay, which was a locally sourced glacial till (Durham Till) with matrix supported clasts (of greater than coarse gravel size) removed. Atterberg limit tests indicated moisture contents at the Plastic Limit (PL) of 24% w/w (approx. 53% v/v) and Liquid Limit (LL) of 45% w/w (approx. 85% v/v), which classifies the fill material as intermediate plasticity. The dry density of material dried from around the PL is approximately 1.6 Mg/m³. The crest was capped with a 0.5 m thick layer of basalt ballast.
Plate 2: Left to right: Ross Sterling (Newcastle University), Paul Hughes (Newcastle University), Tom Dijkstra (BGS), Rosalind Hen-Jones (Newcastle University), John van Esch (Deltares) and Raymond van der Meij (Deltares) at the SW toe of the BIONICS embankment.

A 3D resistivity monitoring array has been installed at the western end of the BIONICS embankment, see photo below. This will provide a series of time lapse 3D resistivity images (at a weekly interval), over the ensuing period into 2016. These images will be inverted and transformed into equivalent moisture content distributions using geophysical – geotechnical property relationships developed from laboratory testing of the Durham Till under different levels of compaction and water saturation.

Plate 3: 3D electrical resistivity array on the south facing slope at the western end of the BIONICS embankment. (Foreground of Plate 2 is at the lower left corner of Plate 3).

3.3 East Leake

Location: Approx. BNG: 454015E, 325100N

This is a section of Victorian embankment on the former Great Central Railway line located to the south of East Leake, Nottinghamshire.

Geology: Mercia Mudstone Group

Research at East Leake includes ground investigations over a 140 m section along the whole embankment on the former Great Central Railway (GCR) that extends 800 m. The embankment was
built up over the Branscombe Formation of the Mercia Mudstone Group in 1897 using local materials excavated from cuttings to the SW and NE. The material was tipped and then compacted by subsequent movement of shunting locomotives and tipping wagons across the tipped material. The tipping method has been deduced to have been end tipped (e.g. based on historical photographs taken by S.W. Newton of end tipping wagons and operations in the vicinity of the site at the time of construction). The embankment has been subject to several phases of site investigation spanning from Sept 2005, which has included drilling, collection of core samples, invasive probing and non-invasive geophysical surveying; borehole locations and the resistivity lines are shown figure 3.

Figure 3. East Leake: Layout of resistivity surveying and monitoring lines on a section of embankment.

These phases of SI have shown the embankment to be highly heterogeneous. Across the site, modern ballast generally occurs from the surface to around 0.5 m. Immediately underlying the modern ballast in the SE half is the original engineered ballast comprising angular granodiorite gravel over granodiorite cobbles. Glaciofluvial sand and gravel occurs beneath the modern ballast over the NE half. The sand is generally uncemented but occasionally the sand was bound within layers around 100 mm thick by fine, white, powdery non-carbonate cement believed to be gypsum leached from other fill materials. Siltstone appears to have been used as an original final dressing to the earthworks fill prior to the laying of the original ballast, but has degraded in situ in the embankment. It occurs across much of the section apart from the furthest 30 m in NE end where it is believed to pinch out into the glaciofluvial sand and gravel. All of these materials overlie degraded Late Triassic mudstones that make up the bulk of the earthworks fill either comprising dark grey-black Westbury Mudstone and Clay or red-brown Branscombe Mudstone and Clay.

Monitoring Brief: At East Leake, installations included an array of 64-electrodes spaced at 1.5 m that ran parallel to the west rail (‘along-axis’ black dashed line in figure 3). Also, several 32-electrode line arrays were installed across the embankment, each spanning from the toe of the west flank to the toe of the east flank with a 1 m spacing (‘cross-axis’ blue and red dashed lines in figure 3). These lines were installed during July 2006, when a series of resistivity measurements were first made using an AGI SuperSting R8 system. From that time for a period extending into early 2008, repeat measurements were made on the along-axis line and the cross-axis line at the 60 m station at approximately 6 weekly intervals using the same equipment. Measurements were made using the dipole-dipole configuration with current and potential dipole widths (a) of 1 – 4 times the electrode spacing and unit dipole separations (n) of 1 to 8.

During Sept 2010, a permanent resistivity monitoring array was installed within a 22 m section of the embankment, comprising twelve cross-axis lines spaced at 2 m intervals. This 3D zone was approximately centred on the existing cross-axis line at the 60 m station (red dashed line in figure 3). The additional lines also comprised 32 electrodes spaced at 1 m intervals, running from the toe of the
eastern flank to the toe of the western flank. An ALERT system was also installed at the site at this time, with which measurement schedules were variably programmed to capture (with high temporal resolution) weather event triggered water movement within the embankment. In this way, response to heavy rainfall events could be studied. The system was powered by a combination of solar panel and a methanol fuel cell charging banks of 12 V batteries. Remote monitoring over this 3D array was undertaken over the period from September 2010 to February 2012. A network of proprietary temperature sensors was also distributed in the embankment to depths of 3.7 m, which are used to study the seasonal temperature change patterns throughout the embankment.

Record-breaking rainfall during the 2007 winter-summer transition was captured by a schedule of 6-weekly resistivity image monitoring on the ‘cross-axis’ line at the 60 m station, figure 4a. This extreme rainfall event led to the gradual infiltration and near full saturation of the east flank of the embankment (left side). In fact, the infiltration zone extends into the underlying Branscombe Formation, implicating bedrock processes as part of the drainage problem.

![Figure 4](image.png)

**Figure 4.** Imaging moisture movement and moisture conditions within embankment.

Algorithms are available for temperature correction and transformation of the resistivity difference images into moisture content ranges for the Westbury Formation fill materials at the East Leake site. The resistivity-moisture content transformation is based upon fitting a modified Archie equation and based on this transformation, figure 4b provides an imaged estimate of the saturation distribution throughout the embankment after a heavy rain event on 30th March, 2010.
4. Meeting at Newcastle

The meeting hosted by Newcastle University on Tuesday 17th Sept was intended to explore overlap between Newcastle University, the BGS and Deltares, especially in relation to the integration of field and laboratory activities. The meeting format included a series of show and tell presentations followed by a discussion of potential applications. Key points from the presentations are bulleted below. The discussion enabled the distillation of the STM Outcomes and Follow Up Activities that are outlined in section 6 of this report.

Meeting Delegates:

**Newcastle University**: Paul Hughes (Chair); Ross Sterling; Rosalind Hen-Jones

**Deltares**: John van Esch; Raymond van der Meij

**BGS**: Jon Chambers; Tom Dijkstra; David Gunn

Presentations:

**Ross Stirling**: Study of cracking processes; including the description of field mapping of cracks and development of a laboratory technique for measuring the soils tensile strength and potential control on cracking process.

**Rose Hen Jones**: Laboratory measurement and analysis inter-properly relationships of moisture content, pore suction and strength (UCS and shear) properties of soil. [Aims include the application of these relationships to field monitored data via resistivity-moisture content transformations.]

**Raymond van der Meij**: Ijkdijk (Live Dike) Network: [www.ijkdijk.nl](http://www.ijkdijk.nl): Stichting IJkdijk is the innovative dike monitoring organisation for inspection and testing based on sensor systems. This development programme results in nationally and internationally marketable dike monitoring systems (smart levees).

**John van Esch**: FEWS-DAM is a modelling platform that can provide real-time simulations of ground water flow and provide pore pressure fields for input into slope stability analysis of engineered earthworks.

**David Gunn**: Laboratory methods for developing electrical resistivity – moisture content relationships for transforming field resistivity measurements to moisture content images.

Immediate Actions Arising (from this meeting):

1. D Gunn explore SEM facilities at the BGS to support iSMART project.
2. T Dijkstra advise R Hen-Jones / P Hughes on pore suction measurements using bentonite pellets.
3. All to develop library of point sensing technology for field monitoring.
5. Workshop: Integrated Monitoring and Modelling of Engineered Slopes

Workshop Delegates:

**Deltares**: John van Esch

**BGS**: Tom Dijkstra; Andrew Barkwith; Jonathan Mackay; Holger Kessler; Paul Wilkinson; Peter Hobbs; David Gunn

5.1 Overview

![Conceptual overview of the COST-Workshop showing activity linkages](image)

Figure 5. Conceptual overview of the COST-Workshop showing activity linkages

The workshop provided a knowledge exchange opportunity for the group to explore the ‘TOOLS’ available and ‘INFRASTRUCTURE’ required to further develop an integrated monitoring and modelling strategy and related activities between Deltares and the BGS. Figure 5 above provides a conceptual overview of the ‘TOOLS’ and the linkages required to form the ‘INFRASTRUCTURE’ for an integrated modelling-monitoring strategy.

TOOLS: broadly defined as including i. data, ii. platforms and iii. methods

INFRASTRUCTURE: defined as i. activity and ii. IT required to support downstream knowledge exchanges.

The meeting format included a series of show and tell presentations followed by a discussion of potential applications.

5.2 Morning Session: Presentations

**Annex 1.1: Holger Kessler**: Geological Mapping and Modelling at BGS

i. Ground model concept to quantitative model/properties for process modelling

ii. Outputs model surfaces as triangular mesh; formats voxels / tetrahedral

iii. Platforms: GSI-3D, GOCAD, GEOVISIONARY

iv. ParaView provide link-interface to other platforms
Annex 1.2: Andrew Barkwith: The dynamic cellular automata landscape evolution modelling platform CDP
i. Hydrological, sediment flux mass movement modelling
ii. Mesoscale – application to catchment study / 50 m resolution
iii. Investigate debris flows
iv. Platform: CDP

Annex 1.3: Jonathan Mackay: Natural slope stability modelling at Hollin Hill
i. Challenges dealing with site scale heterogeneity
ii. Hydrogeology relates to water movement/exchange into ground in unsaturated and saturated zones
iii. Capturing different processes and modes of failure / movement and associated coupling
iv. Platforms: STARWARS – water flux model; PROBSTAB – Slope Stability Model

Annex 1.4: Paul Wilkinson: Geoelectrical landslide tracking
i. Differential resistivity images: proxy for water content changes
ii. Electrode movement cause artefacts on inverted apparent resistivity images
iii. Corrections sensitive to changes in along line electrode position but working on cross line corrections as well
iv. Couple subsurface water movement (moisture content) with surface movement [CAUSE-EFFECT coupling]
v. Platform: RES2DINV; RES3DINV ??

Annex 1.5: Tom Dijkstra: Forecasting Infrastructure Resilience for Climate Change
i. Regional scale frameworks for methodologies via integration of groundwater and landslide domains
ii. Topology for model input includes: bedrock, superficial, topography, geomorphology
iii. Patterns in antecedent rainfall includes identification of different durations / intensities as triggers for different events-styles. Relation between failure and duration wrt quantity of water and transport to zones of failure
iv. Transport network model indicates ‘capacity reduction’ due to weather events (sequences) in time and wrt to location within network
v. FUTURENET: Network model framework approach that can incorporate modules defining different physical hazard processes, e.g. landslide, shrink-swell, running sand..
vi. Modular process model platforms such as: SV Slopes (2D); TRIGRS (3D), and others (FLacIR, SINMAP, SUSHI.....)

Annex 1.6: John van Esch: Integrated Modeling and Monitoring for Dikes and Embankments
i. Numerical groundwater flow model simulator: apply to dikes
ii. Set-up model structure / attribute with parameters
iii. Compare model outputs with field monitored data (e.g. water pressure)
iv. Feed parameters into slope stability and geomechanical models
v. Case history: IJSSEL dike
vi. Platform: FEWS-DAM

Annex 1.7: David Gunn: Moisture movement monitoring at East Leake
i. Field resistivity influenced by engineering geology-mineralogy, geotechnical properties density-porosity and moisture content
ii. Differential resistivity assumes moisture changes and other factors constant
iii. Laboratory derived resistivity-moisture content relations applied to field data
iv. Aged infrastructure highly heterogeneous: visualise moisture movement with differential resistivity images.
v. Provides volumetric visualisation and context for understanding measurements made on single point sensors.
vi. Geophysical proxy for geotechnical property distribution: potential to inform ground models-property distribution and process modelling.

Annex 1.8: Peter Hobbs: Remote and terrestrial LIDAR at Hollin Hill
i. Terrestrial and remotely sensed LIDAR campaigns.
ii. Terrestrial and remote datasets match well and can be combined.
iii. Aid identification of geomorphological features and land sliding analysis at Hollin Hill.
iv. Platforms: SURFER, POLYWORKS; QT-MODELLER; EYESIGHT STUDIO

5.3 Afternoon Session: Discussion
Key points from the presentations, bulleted above stimulated a discussion which enabled the distillation of the STM Outcomes and Follow Up Activities to be developed. These are outlined in section 6 of this report. The discussion explored the development of an ‘Integrated Monitoring and Modelling’ platform with improved coupling between monitored and modelled datasets for application to asset condition and risk forecasting. While not exhaustive, in considering the development of this new platform the discussion included the infrastructure required to integrate processes and property changes related to:

1. Near-surface movement of moisture:
   1.1 Mechanisms of moisture movement: Rates, Budgets:
   1.2 Migration/Pathways: Continuum vs Discontinuum (fractures, conduits)

2. Temporal-spatial evolution:
   2.1 Discontinuum: Cracks, conduit networks (lateral and with depth, and cycling),
   2.2 Continuum: Geotechnical property changes, thresholds

3. Upscaling:
   3.1 Parameters / sensors, 1D, temporal change
   3.2 Imaging: 2D, 3D and 4D domain characterisation
6. STSM Outcomes and Follow Up Actions

The visit by Dr. John van Esch and Dr. Raymond van de Meij highlighted much complimentarity between activities and approaches within Deltares and the BGS. Particularly, the workshop demonstrated that several ‘tools’ are already available and can contribute towards new ‘integrated modelling-monitoring approaches’.

Arising from the visit, several follow-up activities were identified. These included:

1. Actions arising from the meeting (Tues 17th Sept) at Newcastle University.
2. Integrated modelling-monitoring methodology demonstration study based on the BIONICS embankment.
3. Further exchange visits to explore flood defence infrastructure in the Netherlands.

6.1 Actions Arising from Meeting at Newcastle University: Review

1. D Gunn explore SEM facilities at the BGS to support iSMART project.
2. T Dijkstra advise R Hen-Jones / P Hughes on pore suction measurements using bentonite pellets.
3. All to develop library of point sensing technology for field monitoring.

6.2 Integrated Modelling-Monitoring Demonstration Study: BIONICS

A key aim of the COST-Workshop (19th Sept) was to develop initial integrated modelling-monitoring concept (Figure 5) into a plan for follow-up collaboration supported by the BGS, Deltares and also Newcastle University. Where, this follow-up action would focus on the development of an integrated modelling-monitoring methodology using the platforms available to the group (Figure 6), where the approach used and outputs would be showcased using the BIONICS embankment as a case study.

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Figure 6. Concept and work flow linkages for integrated modelling – monitoring case study.
The demonstration study is envisaged to require the following collaborative involvement / activities:

1. Construct the initial BIONICS embankment physical property model: including structure and parameterisation with initial estimates of geotechnical, geophysical and hydrogeological properties.
   NU: Provide information relating to structure and properties.
   BGS: Explore constructing model in GSD-3D / GOCAD.

2. Explore-develop protocol (procedures/platforms) for transferring physical property model between organisations (NU, BGS & Deltares).

   NU – Nafferton Farm data. BGS BIONICS embankment data.

4. Collate geotechnical property data monitored on the Decagon sensor network (MPS-1 sensors=pore suction; 5TM sensors=moisture content, temperature) for the BIONICS, Panel D.
   BGS – NU. (D Gunn consult with R Hen-Jones)

5. Develop procedures for:
   i. Importing embankment physical property model into FEWS-DAM groundwater model simulator.
   ii. Streaming weather data time series into FEWS-DAM groundwater model simulator.
   iii. Explore further code development needed to output moisture content, pore suction …?
   Deltares

6. Run FEWS-DAM groundwater model simulator and compare outputs with monitored data. Analysis of output parameter / outcome sensitivity to physical property parameters may be required.
   Deltares

7. Circulation / consultation discussions in relation to the results. Exploration / recommendations on improvements in procedure or wrt to limitations in tools. Develop follow-on action plans including organisation of follow-up workshops to discuss future developments, which could include:
   - inversion of apparent resistivity distribution based on translation of moisture content / density / porosity distributions
   - forward model streaming with weather event forecasts (e.g. extreme event modelling)
   NU. BGS, Deltares

It is envisaged that the demonstration study will provide the following deliverables:

- shared project space in DROPBOX for data storage / exchange
- Integrated modelling – monitoring methodology,
- BIONICS case study demonstrating the methodology,
- Draft paper incorporating methodology (i.e. above activities), datasets and results [initially aimed at conference proceedings such as mentioned as part of outcome of COST TU 1202]
- follow-on COST STSM, such as return visit to explore applications in the Netherlands
6.2 Further Exchange Visits

The BGS-Deltares would be interested in exploring the potential application of electrical resistivity tomography to provide holistic 3D and 4D time lapse images of dike infrastructure in the Netherlands. A further COST STSM-visit to the Netherlands would support a series of reconnaissance measurements in order to scope the potential for ERT to provide information to support understanding of:

i. the internal structure of dike embankments;

ii. visualisation of flow processes in dike embankments

6.3 Potential Impact of this Initiative

Were this team successful in developing this integrated modelling-monitoring approach we would anticipate immediate use of the methodology on the EPSRC funded iSMART project in relation to future forecasts of the conditions and properties of engineered slopes. This initiative is also very well aligned to the NERC Innovation B funded Proactive Infrastructure Management and Evaluation (PRIME) project, which aims to develop a low cost platform for remotely imaging electrical resistivity tomographic images of engineered earthworks. The iSMART and the PRIME projects provide immediate UK asset owner engagement with Network Rail, London Underground, Canal and River Trust and Scottish Canals. We would also explore the potential for this methodology in relation to the management of transportation earthworks and hydraulic retaining structures such as dams, canal embankment and dikes across Europe.
Annex 1: Workshop: Integrated Monitoring and Modelling of Engineered Slopes

Start: 10.00 - Introductions / Coffee

Morning Session: Show-Tell –Discuss (e.g. 10-15 min presentation / 5 – 10 min discussion)

10.15 Introduction / Set Scene: D. Gunn

Modelling:

i. Ground Modelling Framework: Concept of Integrating all Data  Holger Kessler
ii. Integrated Environmental Modelling Platform  Andrew Barkwith
iii. Natural slope stability modelling at Hollin Hill  John MacKay

- Interlude (around 11 – 11.20 ish)

Monitoring and Infrastructure

iv. Tracking Slope Movements using Geoelectrical Measurements  Paul Wilkinson
v. Landscape veneer landslides  Tom Dijkstra
vi. Integrated Modeling and Monitoring for Dikes and Embankments  John van Esch
vii. Moisture movement monitoring at East Leake  D. Gunn

12.30 Summing Up: Review key points from presentations  D. Gunn lead

12.30/12.45 ish Lunch - Interactive 3D Demonstrations

Afternoon Session: Discussion-Infrastructure for Integrated Modelling-Modelling

13.30/14.00 Introduction / Set Scene: D. Gunn

i. Overall concepts behind modelling:

a. Ground model: Reviewing available data and developing a conceptual model of the ground
b. Process model: Modelling a process (temporal, spatial change)

ii. Modelling/Monitoring Platforms - Packages

a. Platforms used and related applications.
b. Datasets required, i.e. to build a Ground Model OR to verify a Process Model

iii. Modelling / Monitoring Outputs

a. Temporal data: Resolution
b. Spatial data: Scale / Resolution
- Interlude

iv. Integrated Modelling / Monitoring

a. Frameworks / Platforms  (e.g. Ground Model - GSI-3D + Resistivity Images)
b. Physical Property Distributions - informing Ground Model Attribution
c. Monitored Data to constrain Model Outcomes  (Real Time?! - Is this possible?)

v. Applications  i. UK Perspective  ii. NL Perspective  iii. EU Big Issues

15.30/16.00 Summing Up: Review key points from discussion  D. Gunn lead
Annex 1.1: H Kessler: Key Slides

What makes a geological model?

**Geological Modelling (or “3D mapping”)**

Map and DTM + Boreholes → Cross-sections

- Exploded model, synthetic sections, etc.
- Geological Block model
- Fence diagram


**3D grid export – future work**
Annex 1.2: A Barkwith: Key Slides

CDP (CAESAR-DESC-Platform)

- Coupled mesoscale environmental modelling platform developed by BGS
- Assessing environmental sensitivity to climate change
- Based on landscape evolution and hydrological principles
- Several interacting environmental ‘modules’ that can be switched on/off

Platform

- Multi-core approach based on CAESAR-Lisflood model
- Sediment transport at a range of scales, using Einstein-Brown or Wilcox-Crowe methods.
- Modified with a bespoke distributed surface-subsurface hydrological model, which provides the parameters needed to investigate landscape processes and their responses using a quantitative approach
- Integrated debris flow model, SCIDDICA, with a hydrological trigger for flow initialisation

Platform Processes

Debris Flow

- SCIDDICA family of debris flow models used to simulate a variety of flow types
- Current version (S3) uses a wetness index and pore pressure from CDP, combined with a stability index, to trigger flow events
- Implementing a complex, more process-based trigger, where unsaturated zone water properties are simulated in greater detail
- Initially UK focussed, but with an expectation to expand into other regions with several bespoke debris-flow algorithms

SCIDDICA - D’Ambrosio et al., 2003
Annex 1.3: J MacKay: Key Slides

Numerical modelling: Linking slope hydrology and stability

**STARWARS**

- Vadose Zone
  - 1D flow (vertical only)
  - Simplification of Richard’s equation (gravity flow only)
  - Explicit solution

- Saturated zone
  - 2D Darcy flow (lateral only)
  - Explicit solution

**PROBSTAB**

- Slope stability
  - Limiting equilibrium approach
  - Infinite slope model (1D)
  - Stochastic

Numerical modelling: Challenges and limitations

- Parameterisation
  - Scale/Resolution
  - Model stability

- Model complexity
  - Fixed shearing plane?
  - Infinite slope model?
  - Staithes/Whitby interactions?
  - Role of Dogger formation?

- Current understanding
  - Sensitivity analysis

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van Beek (2002)
Modelling movement artefacts

Effects on dipole-dipole data

Inverting for movement

$$f = \sum |\Delta r_j|^2 + \alpha \sum |\delta_j| + \beta \sum \theta(\delta_j) \delta_j$$

$\Delta r_j$ constraint on the data discrepancy vector (difference of predicted and observed apparent resistivity ratios).

$L$, damping constraint on the model vector (electrode movements).

Negativity constraint on the model vector (favours downhill movement).

Minimise $f$ using a Quasi-Newton method to find $\delta$.

Corrected ratio image
Annex 1.5: T Dijkstra: Key Slides

Research areas

Three aspects:
• landslides domains
• groundwater domains
• threshold determination

FUTURENET 1D model

FUTURENET visualisation

Further/planned developments

Needs?
More funding/attention to develop modelling capability
• An important component of NC delivery
• A focus of RC funding bids

Long term vision required
• Served by pragmatic, short term deliverables

Continue with the step-wise approach
• Engineered slopes - 1D continued, 2D/3D/4D under development
  • From site to section to network
• Domains - multiple 1D analyses and 2D/1D models
  • Model DEMs - 3D analyses with hourly weather
  • Catchments - model ones analysed in 3D/4D
  • Nationwide landscape veneer stability model

Case studies to highlight capabilities - data quality and coverage
• monitoring, lab data, properties database

FUTURENET 1D model

FUTURENET visualisation

Further/planned developments

• Landscape veneer at top of ‘zone of human interaction’
• Needs focus on both natural and engineered materials
• Aiming to provide ‘better geological solutions’

With list
• Better coupling of hydro-geology and soil mechanics
• Better characterisation of flow, moisture content and effective stress, soil water re/discharge
• Better analysis of vegetation effects
• Apply to real sites, more complex topographies

Options
• Integration with DESC and others
• Internal collaborations - many, and more possible!
• External collaborations, e.g. STARWARS/PCRaster/FEWS
• More models: SUSHI, FLAIR, SINMAP, GEOTOP, ensembles
Annex 1.6: J van Esch: Key Slides

- Groundwater Flow (saturated and unsaturated)
- Soil Deformation (elasto-plastic)
- Erosion (White + Poiseuille)
- Stability (Spencer and Bishop)
- Data Assimilation
Annex 1.7: D Gunn: Key Slides

Upscaling Issues: (Temporal-Spatial Integration): Point Sensor → 3D / 4D Image
- 4 x 2 m lifts – Durham Till
- Ballast pocket – moisture sump
- 5TE / MPS sensors – yellow dots

Create a time series from any voxel or volume from numerical image.

East Leak Embankment, Great Central Railway, Nottinghamshire.
Annex 1.8: P Hobbs: Key Slides