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An overview of research activities and achievement in Geotechnics from the Scottish Universities Geotechnics Network (SUGN)

Une vue d'ensemble des activités de recherche et la réalisation de Géotechnique de la Géotechnique Réseau écossais universités (SUGN)

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ABSTRACT Design of geotechnical systems is often challenging as it requires the understanding of complex soil behaviour and its influence on field-scale performance of geo-structures. To advance the scientific knowledge and the technological development in geotechnical engineering, a Scottish academic community, named Scottish Universities Geotechnics Network (SUGN), was established in 2001, composing of eight higher education institutions. The network gathers geotechnics researchers, including experimentalists as well as centrifuge, constitutive, and numerical modellers, to generate multiple synergies for building larger collaboration and wider research dissemination in and beyond Scotland. The paper will highlight the research excellence and leading work undertaken in SUGN emphasising some of the contribution to the geotechnical research community and some of the significant research outcomes.

RÉSUMÉ Conception de systèmes géotechniques est souvent difficile car elle nécessite la compréhension du comportement des sols complexes et son influence sur la performance échelle du champ de géo-structures. Pour faire avancer la connaissance scientifique et le développement technologique en ingénierie géotechnique, une communauté universitaire écossais, nommé écossais universités Géotechnique réseau (SUGN), a été créé en 2001, la composition des huit établissements d'enseignement supérieur. Le réseau réunit géotechnique chercheurs, y compris les expérimentateurs ainsi que centrifugeuse, constitutif, et les modélisateurs numériques, de générer des synergies multiples pour la construction de plus grande collaboration et une plus large diffusion de la recherche en Ecosse et au-delà. Le document mettra l'accent sur l'excellence de la recherche et de diriger le travail entrepris dans SUGN soulignant certains de la contribution à la communauté de recherche en géotechnique et certains des résultats importants de la recherche.

1 INTRODUCTION

The Scottish Universities Geotechnics Network (SUGN), was established in 2001. The major vision of the network is to create synergies in geotechnical research, aiming to build larger collaboration and wider research dissemination in and beyond Scotland. SUGN currently has 27 members from Universities of Aberdeen (UoA), Dundee (UoD), Durham (DU), Edinburgh (UoE), Glasgow (UoG), Heriot-Watt (HWU),

Napier (NU) and Strathclyde (UoS). The members have diversified with cross-disciplinary research portfolios, which converge to the common goal of tackling sophisticated engineering problems. The paper highlights the research excellence and leading work currently undertaken in SUGN.

2 FUNDAMENTAL SOIL BEHAVIOUR

2.1 Novel development of experimental techniques

SUGN members have a strong interest in characterising the fundamental soil behaviour through experimental techniques. Special attention is paid to unsaturated soil, especially from the groups in UoG and UoS. Improved understanding can aid the design of foundations; climatic effects on embankments; and behaviour of clay barriers for underground disposal of nuclear waste. The UoG group has a wide range of specialised laboratory facilities for testing hydro-mechanical soil behaviour, including multiple sets of suction-controlled triaxial apparatus. Currently, a number of member universities (UoD, UoG, UoS and HWU) have a common interest to study thermo-hydro-mechanical behaviour of soils (Haghighi et al. 2012). An example is a joint project recently established between UoD and UoG, co-funded by *Energy Technology Partnership* and *Transport Scotland*. The project investigates the potential use of energy piles as a heat exchanger to promote the development of soil suction that would help enhance the stability of soil slopes.

There is also an increasing focus to study the microstructure of unsaturated soils when subjected to mechanical and hydraulic loadings. Members from HWU and UoS use an Environmental Scanning Electron Microscope and Mercury Intrusion Porosimetry (El Mountassir et al. 2014) for microstructure analysis. This approach has broad applicability in explaining macro-scale behaviour. For example, observed evolution of soil microstructure could be used as a tool to specify appropriate compaction conditions for earthworks where fill material is susceptible to volumetric collapse (El Mountassir et al. 2014). The School at DU houses X-ray computed tomography (XRCT) scanning facilities for visualising soil microstructural evolution (Fig. 1). This facility has proved revealing in improving understanding of soil-based construction materials and finding a link between intrinsic macro-properties and microstructural features.

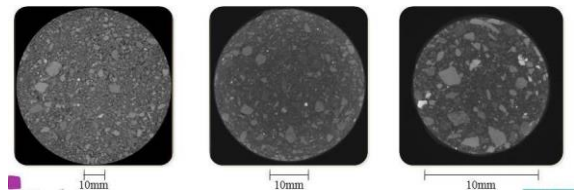

Figure 1. XRCT scans of cylindrical rammed earth samples of different diameters (100, 38 and 12 mm) showing microstructure at different scales (Smith and Augarde 2014)

Mechanical behaviour of degradable soils is studied by the members from NU. They have developed an innovative hydro-bio-mechanical model for capturing its behaviour. Volumetric change and shearing resistance in granular mixtures at a range of particle sizes have been investigated in small-scale mixtures. Particle loss leads to an increase in void ratio with associated changes in behaviour - from dilative in the intact state to more contractive following particle loss (Fig. 2; McDougall et al. 2013). Associated grading changes have been interpreted using concepts of grading entropy, by which means frequency distributions can be depicted as data points thereby providing a useful means of tracking grading changes. This work has recently found added relevance in the analysis of landfill, reclaimed and treated soils that retain a proportion of organic content.

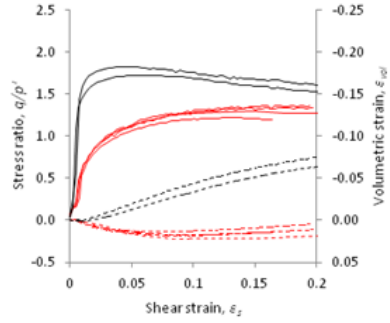

Figure 2. Stress-ratio and volumetric strain (dashed) responses for sand-salt and post-dissolution tests, 1.0 mm salt, 15% by weight

Testing the evolution of fabric anisotropy during straining and the effect of this on mechanical behaviour is one of the major focuses of the members from UoG. This can be of considerable practical importance for construction of embankments on soft clays or problems of sand liquefaction. The research has led to the development of constitutive models incorporating anisotropy evolution for both soft clays and sands (Gao et al. 2014).

2.2 Constitutive and numerical modelling

The UoG team has made important contributions in the development of improved constitutive models for unsaturated soils, perhaps most significantly a coupled mechanical and water retention model (Wheeler et. al. 2003). This model is based upon improved understanding of the physical processes occurring at the inter-particle and inter-aggregate level, with the result that it is able to better predict both mechanical and retention behaviour, and their complex coupling, for the full range of possible stress paths. Lloret-Cabot et al. (2014) showed that the model predicts well the variations of both void ratio and degree of saturation of a soil that involved large magnitudes of compression during successive stages of drying, isotropic loading and wetting.

Other SUGN members have also developed several novel computational techniques. The group in DU implemented various efficient and accurate methods for nonlinear continuum modelling and fracture, including finite element (FE) and meshless techniques. The team has also worked on Material Point Method (MPM), an exciting mix of meshless and FE methods which can capture very large deformation events as often found in geomechanics. This new method is currently being applied in a collaborative project with UoD on offshore soil ploughing. Another contribution made by the DU team is the development of an improved approach to study the cone penetration test and evaluate the effect of strain softening on the penetrating resistance (Osman and Randolph 2014). In this approach, the strain components are treated as field variables. The global solution is obtained using the streamline upwind Petrov–Galerkin method, together with an Eulerian-based FE formulation.

An advanced technique, Discrete Element Method (DEM), is used by the group in NU to study the failure of granular materials under three-dimensional stress conditions, while considering the influence of the intermediate stress ratio (Barreto and O'Sullivan 2012). DEM has aided the quantification of fabric and void anisotropy to identify the particle scale interactions. DEM is being used to explore the significance of real particle characteristics and particle-size distribution on the simulation of cemented soils, such as shales. This method has also been used to study the behaviour of dissolving soils and responses of piles under dynamic loads.

3 FIELD MONITORING TECHNIQUES

The research teams in DU and UoS have a common interest in developing local sensors for the purpose of long-term monitoring of suction (e.g. high capacity tensiometers) and water content in the laboratory and field. In addition, members from UoS focus on the implementation of non-invasive methods that enable enhanced understanding of the subsurface. A microseismicity technique has been developed for detecting the location and orientation of rock fracture planes at depth. The validity of Electrical Resistivity Tomography (ERT; Fig. 3) for accurate detection of desiccation cracks in flood embankments was demonstrated in a series of miniature and field-scale studies (Jones et al. 2014).

Figure 3. ERT monitoring along the crest of a flood embankment

4 ENGINEERING APPLICATIONS

In addition to fundamental research, SUGN members have also had a diversified research portfolio to evaluate the engineering performance, and hence improve the design, of various types of critical geotechnical infrastructure. Within the network, a number of successful collaborative projects have been established.

4.1 Offshore engineering

4.1.1 Cable ploughing and installation processes

The members, DU and UoD, have recently awarded a joint research project looking at the use of MPM to model seabed ploughing for infrastructure installation. Soil ploughing, an activity carried out by man for thousands of years for agriculture, is now used at a much larger scale on the seabed to connect offshore energy generation devices to the supply network (Lauder et al 2013). However, there is a lack of un-

derstanding of the mechanical and hydraulic processes associated with soil ploughing. In this project, MPM will be applied to simulate seabed ploughing to provide better estimates of key parameters such as tow force and ploughing speed in a given seabed deposit along with insights into plough stability. Given the likely ploughing activity in the next 20-50 years in UK waters, this new predictive approach could result in major savings for the industry.

Another active collaborative project being carried out by the members of UoD and UoA is the study of the critical specific gravity (SG) for cables and umbilicals during various backfilling and installation processes. Seabed conditions, wave action and tidal effects, coupled with ship movement/anchoring and fishing activity may cause a threat to submarine product (i.e., cables/umbilicals). One solution to reduce the risk is to bury products below the seabed through ploughing and backfill. For a cost-effective design, reducing the SG of products has obvious cost savings, but the drawback is that buoyancy effects may result in product movement or de-burial. The project aim is to develop a greater understanding of the controls on the product behaviour during burial. The outcome will be to develop guidance on the most appropriate burial techniques. This will be further extended to look at min. burial depths and the effects of co-burial using the 1-g soil bed tank available at UoD.

4.1.2 Ground anchor systems and trawling

Dynamic behaviour of ground anchorage systems is studied by UoA, through numerical modelling along with complementary laboratory tests of anchorages installed in rock and soil (Palop et al. 2013). The interface between the bearing plate of an anchor and the concrete surface has been shown to be the main element in determining the pre-stress load of the anchorage. Testing of the interface between the grout and the steel bar has also been undertaken using experimental tests and contact mechanics. The findings have been used to develop a non-destructive testing method GRANIT which is currently used commercially.

Another interesting topic that the member from UoA is investigating is the impact of trawling on the benthos ecosystem (seabed). Towed demersal fishing gear is used globally by the fishing industry to catch species that live on or close to the seabed. To understand these processes and to be able to assess their wider implications on the benthic ecosystem, it is essential to understand the physical interaction of the individual gear components with the seabed. The impact of a cylindrical clump weight and an otter trawl door on a cohesive soil was developed by Ivanovic et al. (2011), who validated their approach by comparing the results from experimental sea trials with model predictions. Both studies use the FE Abaqus software package where Arbitrary Lagrangian-Eulerian mixed formulation was used. This study has been extended to investigate how the dimensions, the weight, the cross sectional geometry and the soil material properties affect the drag force and the penetration into the seabed of cylindrical clumps. The study of ground gear elements using Combined Eulerian and Lagrangian methods has been undertaken and the results between the laboratory and numerical studies are very encouraging to be potentially used in further studies (Esmaeili and Ivanovic 2014).

4.1.3 Foundation engineering

The teams of UoD and UoA have a joint project investigating enhanced gravity foundations on rock for marine energy generators. This project focuses on an alternative design of the foundation as a gravity base where resistance is provided by its self-weight and the interface friction between seabed and the foundation. Very little work has been done to assess the interface friction between steel foundations and rock. The project aims to develop a greater understanding of the material controls on the foundation interface behaviour. The outcome will be to develop a database of rock/foundation interface properties and improved design procedures that will lead to less conservative design and improved financial viability of marine energy generators (See paper by Ziogos et al in the proceedings).

Members from NU, focus on another type of foundation. They study the dynamic behaviour of pile-supported structures under different types of cyclic loading such as earthquakes, wind and wave loading. It is recognised that the foundation behaviour depends on complex soil-structure interaction and nonlinear soil response. In addition, in the presence of saturated loose to medium dense sandy soils, excess pore pressure generated by loading cycles may induce significant soil softening which, in extreme cases, may lead to liquefaction phenomena.

Current research in NU is investigating the effects of wave-induced liquefaction on the behaviour of offshore wind turbines supported on different types of foundations (monopile, suction caisson, jacket foundations), by means of a combination of small-scale physical modelling and full-scale numerical modelling (Lombardi et al. 2013).

4.2 Earthquake geotechnics

Within SUGN, UoD is the only member university that possesses a geotechnical centrifuge facility (3.5 m radius, 150 g-ton capacity) mounted with the state-of-the-art earthquake simulator. This facility is unique in Scotland and is only one of three in Europe. Compared with 1-g physical model tests, centrifuge tests at elevated gravitational acceleration levels correctly model the stress levels of a much larger prototype. By using this facility, the group has made significant and important contributions in earthquake engineering. One example is a recent study of the engineering performance of rocking-isolation inelastic reinforced concrete (RC) bridge piers (Loli et al. 2014). In this study, a novel scale model RC (1:50 scale; Knappett et al. 2011) that simulates reasonably well the elastic response and the failure of prototype RC members is utilised to model a bridge pier (Fig. 4). A variety of seismic ground motions are considered as excitations. They result in consistent demonstrably beneficial performance of the rocking-isolated pier. Foundation uplifting has a self-centering potential, whereas soil yielding is shown to provide an effective energy dissipation mechanism, exhibiting significant resistance to cumulative damage. Thanks to such mechanisms, the rocking pier survived, with no signs of structural distress, a deleterious sequence of seismic motions that caused collapse of a conventionally designed pier.

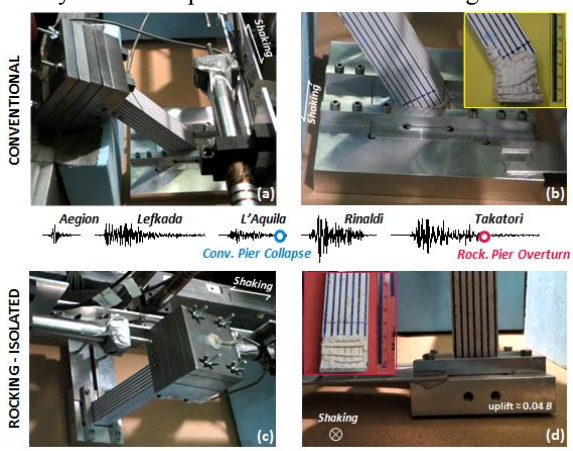

Figure 4. Photos of bridge models (a) the conventional pier having failed after shaking and (b) closer view of its column base and foundation; (c) the rocking pier after shaking plus two additional strong motions and (d) its foundation (Loli et al. 2014).

Members from UoD currently have a wide spectrum of research utilising this facility. This includes the seismic performance of other soil–structure systems such as piled foundations, retaining systems, and underground structures and also development of novel foundations and offshore anchoring solutions.

4.3 Railway engineering

Members from HWU are dedicated to research in railway engineering. Railway track settlement has considerable cost and time implications to the rail industry through maintenance operations, track reconstruction and line speed restrictions. Settlement occurs in both the soil and substructure, and it is important that it is monitored before differential track settlements give rise to faults (Woodward et al. 2014). Therefore, to model the railway track settlement process, HWU has developed the unique Geo-pavement and Railways Accelerated Fatigue Testing facility (GRAFT; Fig. 5) that enables accelerated, full-scale testing of existing and new railway products under realistic railway conditions. It is the largest of its kind in the UK and has a hydraulic capacity of 200 tonnes. Thus it enables the performance of new settlement solutions and new track-forms to be quantified and compared with confidence. In parallel, the team at HWU has been working on modelling to fully understand the train-induced vibration at different conditions of interest (El Kacimi et al. 2013).

Figure 5. GRAFT facility at HWU

5 CROSS-DISCIPLINARY TOPICS

Various types of cross-disciplinary research are developed within SUGN. This includes the teams of UoS and DU, who focus on contaminant fate in unsaturated soil and remediation. The UoS team has a particular interest in studying the potential use of microbial processes to alter the behaviour of porous media and fractured rock. The team has investigated microbially induced calcite precipitation for sealing rock fractures. This represents a means of controlling the gel time of low viscosity grout for injection into fractured rock (MacLachlan et al. 2013), which is a new avenue of research in geotechnical engineering.

Members from UoD have a strong interest in developing the use of plant roots as a green stabilisation technique for enhancing the sustainability and resilience of earthwork infrastructure against environmental loadings including rainfall and earthquake. They are currently quantifying the mechanical root reinforcement (both in failure strength and pre-failure deformation), and strength enhancement due to transpiration-induced suction (Ng et al. 2014).

6 FINAL REMARKS

This paper presents a wide range of interesting and challenging research topics within SUGN. This covers the characterisation and modelling of soil behaviour and multiple engineering applications. Mutual synergies created by SUGN have made significant contributions to the geotechnical research community and industry, providing useful insights into better understanding of complex soil behaviour and improved design of geotechnical systems. However, there are still many scientific questions yet to be answered. Some of them are cross-disciplinary, which would potentially break out of old subject straitjackets, forming new research links that may themselves lead to other unusual future research themes.

REFERENCES

Barreto, D. & O'Sullivan, C. 2012. The influence of inter-particle friction and the intermediate stress ratio on soil response under generalised stress conditions. *Granular Matter* **14**(4), 505-521.

El Kacimi, A. Woodward, P.K., Laghrouche, O. & Medero, G.M. 2013. Time domain 3D finite element modelling of train-induced vibration at high speed, *Computers and Structures*, **118**, 66–73.

El Mountassir, G. Sanchez, M. & Romero, E. 2014. An experimental study on the compaction and collapsible behaviour of a flood defence embankment fill, *Engineering Geology* **179**, 132-145.

Esmaeili, M. & Ivanović, A. 2014. Numerical Modeling of Fishing Ground Gear Component on the Seabed, *Ocean Engineering* **91**, 316–328.

Gao, Z.W. Zhao, J.D. Li, X.S. & Dafalias, Y.F. 2014. A critical state sand plasticity model accounting for fabric evolution, *International Journal for Numerical and Analytical Methods in Geomechanics* **38**(4), 370-390.

Haghighi, A. Medero, G.M., Marinho, F.A.M. Mercier, B. & Woodward, P.K. 2012. Temperature effects on suction measurement using the filter paper technique *Geotechnical Testing Journal*, **35**(1). doi: 10.1520/GTJ103575

Ivanović, A. Neilson, R.D. & O'Neill, F.G. 2011. Modelling the physical impact of trawl components on the seabed, *Ocean Engineering* **38**(7), 925-933.

Jones, G. Sentenac, P. & Zielinski, M. 2014. Desiccation cracking detection using 2-D and 3-D electrical resistivity tomography: validation on a flood embankment *Journal of Applied Geophysics,* **106**, 196-211.

Knappett, J.A. Reid, C. Kinmond, S. & O'Reilly, K. 2011. Small-scale modelling of reinforced concrete structural elements for use in a geotechnical centrifuge. *J. of Struct. Eng.*, **137**(11), 1263–1271.

Lauder, K., Brown, M.J., Bransby, M.F. & Boyes, S. 2013. The influence of incorporating a forecutter on the performance of offshore pipeline ploughs *Applied Ocean Research J.* 39: 121–130.

Lloret-Cabot, M. Wheeler, S.J. & Sanchez, M. 2014. Unification of plastic compression in a coupled mechanical and water retention model for unsaturated soils, *Canadian Geotechnical J.* (In press).

Loli, M. Knappett, J.A. Brown, M.J. Anastasopoulos, I. & Gazetas, G. 2014. Centrifuge modeling of rocking–isolated inelastic RC bridge piers, *Earthquake Engineering and Structural Dynamics* DOI: 10.1002/eqe.2451.

Lombardi, D. Bhattacharya, S. Muir Wood, D. 2013. Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil, *Soil Dynamics and Earthquake Engineering*. 49, 165–180.

MacLachlan, E.C. El Mountassir, G. & Lunn, R. 2013. Use of bacterial ureolysis for improved gelation of silica sol in rock grouting, *Géotechnique Letters* **3**(4), 180–184

McDougall, J.R. Kelly, D. & Barreto, D. 2013. Particle loss and volume change on dissolution: Experimental results and analysis of particle size and amount effects, *Acta Geotechnica* **8**(1), 1-9.

Ng, C.W.W. Leung, A.K. & Woon, K.X. 2014. Effect of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. *Canadian Geotechnical Journal*, **51**(3): 311–321.

Osman, A.S. & Randolph, M.F. 2014. On the calculation of cumulative strain around full-flow penetrometers in steady-state conditions, *International Journal for Numerical and Analytical Methods in Geomechanics* (In press). DOI: 10.1002/nag.2312.

Palop, D.K. Ivanović, A. & Brennan, A.J. 2013. Centrifuge Modeling of the Nondestructive Testing of Soil Anchorages, *Journal of Geotechnical and Geoenvironmental Engineering* **139**, 880-891.

Smith, J.C. & Augarde, C.E. 2014. XRCT scanning of unsaturated soil: microstructure at different scales? In *Geomechanics from Micro to Macro*, Soga et al. (Eds), 1137-1142.

Wheeler, S.J. Sharma, R.S. & Buisson, M.S.R. 2003. Coupling of hydraulic hysteresis and stress-strain behaviour in unsaturated soils, *Géotechnique* **53**, 41-54.

Woodward, P.K. Kennedy, J. Laghrouche, O. Connolly, D. & Medero, G.M. 2014. Study of railway track stiffness modification by polyurethane reinforcement of the ballast, *Transportation Geotechnics* (In press). DOI: 10.1016/j.trgeo.2014.06.005).