Towards very large scale laboratory simulation of structure-foundation-soil interaction (SFSI) problems

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Abstract – **We are at the maturity convergence point of a set of actuation, control, instrumentation and data analysis technologies that make it feasible to construct laboratory experimental rigs that will allow us to address key controlling uncertainties in SFSI assessment and design, which can only be addressed by testing at, or near to, prototype scale. This paper will explore the process of innovation that must be established in order to integrate these enabling technologies and thereby create novel test facilities that offer new, high value, capabilities.**

I. INTRODUCTION

Both the developed and the developing worlds face a huge infrastructure provision and renewal challenge. In the UK, the government's National Infrastructure Plan [1] identifies an infrastructure renewal pipeline of £466bn, a total that in fact covers only a subset of the total pipeline. In 2013, EY estimated global infrastructure investment needs of $57 trillion [2]. The global infrastructure sector clearly has significant commercial opportunity, where small percentage improvements in costs or value translate into politically significant sums – for example a 1% saving of £4.66bn equates to a significant tax reduction opportunity for a UK government.

However, a common challenge is that the tax payer can often only fund a small proportion of these renewal costs; the remainder must come from the international capital markets, with the user paying for the investment through user charges of some form. This means that infrastructure investment must compete with other investment opportunities that are often perceived as better understood, less risky, and offering a faster return on investment. In contrast, some infrastructure investments can offer secure, very long term returns, over many decades, after the capital investment is paid off, making them attractive to pension funds that have a long term investment vision. Their downside is often the uncertainty of both the actual initial capital costs and of the long term operating, maintenance and decommissioning costs. The very common cost and time overruns of infrastructure provision are a great disincentive for many investors.

Furthermore, rapid technological, societal and environmental changes increase the difficulty of forecasting the long term utility of many kinds of infrastructure (eg transport, energy, telecommunications), which further complicates the investment decision making picture. For example, the UK has set itself a legal requirement to hit stringent carbon targets (80% reduction of 1990 levels) by 2050. This probably means radical transition to a carbon neutral economy, which can only be achieved with the help of radical change in the use and provision of infrastructure, which we have not yet worked out how to achieve.

The infrastructure sector is still slow in taking up this transformational challenge and the opportunities it offers. The mindset of the whole industry needs recasting away from business as usual approaches.This requires a radical reconceptualization of the purpose and nature of infrastructure and its provision. A new, more holistic, infrastructure worldview must be constructed, which in turn will drive reconfiguration of the infrastructure marketplace and its constituent supply networks around a carbon neutral paradigm. This opens up new horizons for imagination and technical innovation at both the systems and artefact levels. It requires a new concomitant research mindset that better couples focused technical research to the bigger societal and economic benefits picture. By doing so, researchers will be better able to justify investment across the scales for both blue sky and near market research initiatives.

This paper explores how these arguments are being built in the UK to secure £276m of infrastructure research investment over the next 5 years. The UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC) is a partnership of, initially, 14 UK universities, which has secured £138m of UK Government capital investment in new infrastructure research facilities (http://www.ukcric.co.uk). Industry has

promised to match fund the government contribution. In addition, government and industry are aiming to build a portfolio of c£200m research projects to use these facilities. One of the proposed new facilities is an innovative £12m Structure-Foundation-Soil Interaction (SFSI) facility, to be built at Bristol University. The paper first outlines some of the key strategic arguments that underpin UKCRIC, including the need for transformation in infrastructure practice, before setting out how these arguments are being applied to the emerging conceptualization and design of the SFSI facility.

II.   EPISTEMIC UNCERTAINTY, LEARNING AND LARGE SCALE EXPERIMENTS

Underpinning all the above challenges is epistemic uncertainty. Costs, risks and our appetite for innovation are all controlled by what we do not know. As a consequence, we over-design to provide large safety margins, thereby increasing cost and often making subsequent adaptation more difficult and costly. The uncertainty associated with innovative solutions is often considered too great, exacerbated by inflexibility in current codes of practice, such that we resort to perceived tried and tested solutions and persist with the business as usual practices that we know need to change. Business as usual will not deliver a carbon neutral economy.

Our ability to resolve the epistemic uncertainty of how actual infrastructure works has been limited until now. We have nearly exhausted the scope of conventional, well controlled, smaller scaled, laboratory experimentation. Approaches to monitor the actual performance of prototype infrastructure are perceived as expensive and are rarely exploited effectively [9]. They are also very limited in what can actually be controlled and monitored. We rely on increasingly sophisticated numerical modelling techniques, but often these lack secure validation against real infrastructure performance data. Alternatively, we persist with highly simplified and over conservative assessment methods that, especially when used to assess the capacity of existing infrastructure, lead to perverse results, perhaps condemning infrastructures that are manifestly performing satisfactorily. As an overall consequence, the infrastructure sector is poor at closing the learning loop between theory and reality. This impedes improvement and innovation and, crucially, our ability to reduce cost, to improve reliability and performance, and to increase the value captured from infrastructure investments.

However, we are now at a maturity convergence point in actuation, control, instrumentation and data analysis technologies that make it feasible to conduct large and prototype scale experiments to resolve key controlling uncertainties in infrastructure assessment and design. By aligning these new capabilities with the ever strengthening infrastructure investment imperative, it is becoming easier to justify the cost of these large scale experiments. Whilst the cost of a particular experimental programme might in itself run into tens of *millions* of dollars, the aggregate economic benefit of that programme might run into tens of *billions* of dollars, inverting the argument from 'can we afford to do the research?' to one of 'can we afford *not* to do the research?'.

This is a major mindset shift for infrastructure researchers who traditionally have survived on relative breadcrumb funding. It is also a major mindset shift for infrastructure practitioners who have been conditioned over generations not to perceive great direct value in research investment. Contrast this with other industry sectors, like the aerospace, automobile and IT sectors, in which research and development are the lifeblood of competition and innovation. However, experimental and measurement technology developments have now reached the point where we can overcome many of the size and uniqueness aspects of infrastructure experiments that to date have been seen as barriers to their ubiquitous incorporation in the infrastructure provision process.

We are on the cusp of transformation of the infrastructure provision process, wherein real-time learning from actual infrastructure performance will become embedded in infrastructure practice and real-time performance management. The momentum towards so-called 'smart cities' and 'smart infrastructure' is probably unstoppable. Low cost, high performance sensors, combined with the advent of the 'intelligent internet' that augments current primitive networking with artificial intelligence and real-time network reconfigurability, will provide a new kind of urban research and learning infrastructure, which in turn should stimulate invention and innovation in future infrastructure provision. However, such practice transformation will not happen automatically. It will require a change in practitioner intent and the development and learning of new theories, methodologies and knowhow in how to exploit these new capabilities to create and capture new value. Reducing epistemic uncertainty of actual infrastructure performance sits at the heart of this learning, and can only be addressed through carefully targeted and designed large and prototype scale test beds of the kind envisaged by UKCRIC.

III.   THE NEED FOR NEW KINDS OF INDUSTRY STANDARDS

The way we frame future practice through standards and codes will have to change radically. Conventional infrastructure standards are framed around safety and adopt a century old model of constraining the engineer to practices that experience has shown are likely to be safe. Whilst life safety will always be paramount, we have learned that current, business as usual, practices generate unanticipated new threats, such as anthropogenic climate change, which our current standards largely ignore and thereby inadvertently exacerbate. If we turn our attention

to the ubiquitous success of the internet, we will see that this success arises from its framing around open architecture standards. These help define purpose, performance, format and interoperability at a generic level, whilst still allowing innovators to imagine, create and protect their intellectual property in new products and services. For example, the USB interface is an open system architecture standard and protocol that effectively defines how propriety IP can be connected together to create and capture new value. It does not specify what is connected through the interface, just how. It is up to the innovators on either side of the interface to define the combined performance of their products and services that will deliver value to the user (eg the value of the flash memory stick plugged into the computer). Mapping these open systems architecture ideas onto infrastructure, we can see that safety and serviceability are kinds of performance requirements that actually emerge from the functional interaction of the infrastructure system components, which include people. We now have many hard and soft systems theories and methodologies that allow us to understand and design these systemic interactions and outcomes [10]. However, the structure of our current standards tends to either preclude their use or make it appear too risky and expensive to develop and validate bespoke approaches. As a consequence, innovation is stifled and business as usual practices persist. Future infrastructure standards need to move towards open systems architecture principles that unlock innovation whilst still delivering safe and valuable performance. Confidence in such an approach will only be established through success stories derived from prototype or large scale exemplars. The UKCRIC test bed facilities are intended to provide such exemplar narratives.

IV.   OVERVIEW OF THE UKCRIC FACILITIES

UKCRIC was proposed by a partnership of 14 UK universities in response to a government request for a stimulus in UK infrastructure research. It will start in April 2016 and will be open to participation of all UK universities. Initially, UKCRIC is a capital investment project, creating a portfolio of innovative, shared use, laboratory facilities across the UK. The facilities are grouped into three main 'strands', coordinated through a fourth stand known as the 'Coordination Node'. The three main strands are 'Large Scale Laboratories', 'Urban Observatories', and 'Data and Modelling'. Full details can be found at http://www.ukcric.co.uk. The Large Scale Laboratories include, in addition to the SFSI facility at Bristol, a new Linear Infrastructure Laboratory at Southampton, a buried infrastructure laboratory at Birmingham, an urban water systems laboratory at Newcastle, a human-infrastructure interaction facility at UCL, and advanced materials laboratories at Imperial College, Leeds and Manchester.

The Urban Observatories include 'living laboratory' facilities at Newcastle, Sheffield, Bristol, Manchester, UCl, Cardiff and Strathclyde in which experiments can be conducted in the city itself. For example, the innovative Bristol Is Open (BIO) facility (http://www.bristolisopen.com) is a state of the art, city-scale, programmable and reconfigurable high performance fibre optic and wireless network infrastructure overlain by a City Operating System and powered the University of Bristol's supercomputer. BIO provides a very powerful research infrastructure across the city. It will enable easy installation and control of sensors and actuation systems on infrastructure (eg bridges, water supply networks, transport systems) in order to improve our understanding of how these infrastructures actually work and to develop ways of real-time adaptation of their performance.

The Data and Modelling stand encompasses large scale data sets and high performance modelling capabilities, distributed across the UKCRIC network.

The Coordination Node will include a 'Learning Hub' built around state of the art social learning and collaboration tools. This will be the repository for the collection and dissemination of the collective learning from across the UKCRIC enterprise. Whilst its origin is in academia, UKCRIC is a sector wide partnership, including universities, industry, owners, investors, government, and infrastructure users. It will have global connectivity to cognate research and practice.

V.   THE BRISTOL SFSI FACILITY

Structure-foundation-soil interaction is a poorly understood aspect of infrastructure performance, offering plenty of opportunity to extract better value by reducing epistemic uncertainty and improving industry practice. There is still an artificial separation between structural and geotechnical engineering practice which militates against a holistic approach to SFSI. This is particularly true for dynamic and seismic SFSI, where the whole system response cannot easily be separated into structural and geotechnical parts. There is a need to develop an improved performance based framing of SFSI, but this will need validation against realistic data.

Workshops with industry have confirmed the SFSI challenge for both static and dynamic loads. Several industry scale problems have been identified that would benefit from large or prototype scale testing; the resolution of any one of these problems would more than justify the cost of the new SFSI facility. Typical problems include integral bridges with no deck bearings, strengthening of live railway embankments, pile group effects, dynamics of piles in layered soils, offshore wind turbine foundations, and high speed rail bridge-embankment interactions.

The opportunity to de-risk new SFSI technologies has also been identified. For example, major railway

electrification projects require installation of thousands of piles into a variety of soil conditions. Optimization of the installation process using a flexible test facility that permits comprehensive measurements and thorough understanding of the installation mechanisms could significantly reduce costs.

In all of the above cases, building the associated business case for large scale testing will be an important challenge. The costs of such tests will be high, but the potential benefits will be disproportionately higher. They will require de-risking and careful planning. Large scale tests will not in themselves be sufficient. They should be seen as an addition to the portfolio of tools available to the SFSI engineer, filling a gap between smaller scale 1g and ng laboratory and centrifuge testing and current prototype monitoring capabilities, and complementing soil element testing and numerical analysis. Often the goal of a testing campaign will be to validate a numerical methodology which can then be applied widely and with confidence to solve the engineering problem. Thus, a particular study should be seen as a series of learning cycles that gradually define and elaborate the problem and its solution, starting with the simpler modelling and analysis techniques and gradually adding complexity and cost as they are justified. Successful articulation of the disproportionate benefit to a skeptical funderwill be a normal goal. This is likely to become easier once a number of success stories have been established, as these can be powerful means for changing people's minds [3].One of the core features of the UKCRIC Coordination Node is the concept of 'learning journeys' [4] in which the research campaign is designed as an multiple iterative loop learning journey, drawing on established principles from the education domain.

At the time of writing, the UKCRIC SFSI facility concept is under development. A co-production approach is being taken, with practitioners and end users being active participants in the concept evolution and design. A key principle that this co-production process has established is that the system solution must be modular, adaptable and extensible. The varied nature of the research problems means that a fixed design will have limited utility. Each research problem is unique and is poorly understood (otherwise it would not require researching) and so the experimental design will be a major engineering challenge in its own right.

Figure 1 shows one possible conceptual configuration, which illustrates the main component technologies. This particular rig design is targeted at piled foundations subject to earthquake motions. The aim is to test large scale pile specimens embedded in realistic soils with confining pressures more representative of prototype conditions than can be achieved in smaller scale 1g experiments [5]. While ng centrifuge testing can overcome the soil scaling issues, it is impossible to model the nonlinear failure behavior of concrete piles in such

tests. Thus, the proposed SFSI rig will fill a gap in experimental capability. Like any experiment, it will not cover all issues fully, but when used in conjunction with centrifuge testing and prototype monitoring as part of an integrated campaign, it can supply an important part of the overall spectrum of knowledge and understanding.

An important gap in knowledge relates to the kinematic interaction of the pile or pile group with the surrounding soil, especially when the latter is layered with different stiffnesses, and how this interplays with the overall system dynamics. Knowledge of the bending moment distribution in the pile and how this is influenced by the embedment, soil-pile interface conditions, end bearing etc is essential for design purposes. Whilst numerical analysis is possible, there are few data available to validate such analyses, especially up to the point of plastic hinge development in the pile. The conceptual rig would enable an experimental assessment of a large scale pile system subject to reasonable emulation of field conditions up to large strain deformations. In essence, the specimen would be treated as a prototype in its own right.

The rig consists of a large flexible box mounted on a shaking table. A pile is inserted in the soil. Interface forces and displacements of a superstructure will be emulated by dynamic substructuring, where a numerical model of the superstructure is embedded in the real-time control loops of the actuators that supply the interface tractions [6].

The flexure of the sides of the box will be actively controlled by hydraulic actuators to emulate the dynamic response of an insitu soil column and induce realistic soil strains through the soil body. These will be dominated by vertically propagating horizontal shear waves. However, wave reflections from the flexible boundaries will be problematic and could pollute the idealized soil column response. A crucial rig development challenge will be to improve both the active and passive control of these wave reflections. A further complication is the strain incompatibility at the vertical boundaries. Whilst these can be designed to emulate the shear stiffness of the adjacent soil, their normal stiffness and dilatant behaviors will be a distinct contrast to that of the contained soil. This is known to generate active/passive wedges at the boundaries of laminar boxes used in conventional shaking table and centrifuge testing, which pollute the soil stress and strain conditions; the normal way of overcoming this limitation is to use a box with a length to height aspect ratio of at least 4:1 so that the middle third of the specimen experiences reasonably uniform conditions [5]. Such an aspect ratio would make the new SFSI unfeasible, so new, multi-axis, actively and passively controlled boundaries will have to be developed. These will use dynamic substructuring (hybrid testing) techniques [6]. In essence, the new boundaries will have to generate a smoother strain transition from the soil to the mechanical boundary. One possibility is to use a new

generation of piezoelectrically deformable advanced composite materials [7] which might be configured to give the correct strain tensor.

The advent of low cost MEMS sensor technologies makes comprehensive instrumentation of such a rig feasible provided that the data acquisition challenge can be met. For example, the authors' recent research on physical shaking table modelling of the graphite cores of nuclear Advanced Gas-cooled Reactors (AGR) has developed a module miniature data acquisition system capable of handling up to 20,000 sensors [8]. The small 32 channel data acquisition modules, each populated with signal conditioning, analogue filtering, simultaneous sample hold analogue to digital converters and onboard storage, can be distributed around the test rig and connected via small industrial standard serial cables. Processing of the terabytes of data that can be obtained from such experiments is non-trivial and needs careful engineering design in its own right. The learning journey methodology aids the purposeful design of the data model in order to target the epistemic uncertainties that need to be resolved.

VI. CONCLUSIONS

The infrastructure sector is faced with major challenges to reduce the cost and improve the value of infrastructure provision. Reducing epistemic uncertainty is the key to these challenges. This can only be done through investigating the actual behavior of prototype infrastructure and large scale experiments. The enabling technologies are now available from which to create such research campaigns. Whilst expensive, such tests can provide disproportionate benefits. Researchers need to become more adept at identifying and articulating the cost-benefit arguments to clients and funders. By doing so, they will help to shift the industry mindset from 'can we afford to invest in these tests?' to 'can we afford *not* to invest in these tests?'.

VII. ACKNOWLEDGEMENTS

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Dynamic substructuring
Real time numerical emulations of building and free field soil responses.
Actuators apply real time boundary tractions and displacements

Distributed experiments
Real time Interaction with remote laboratory, and data to distributed repository, via UKNEES

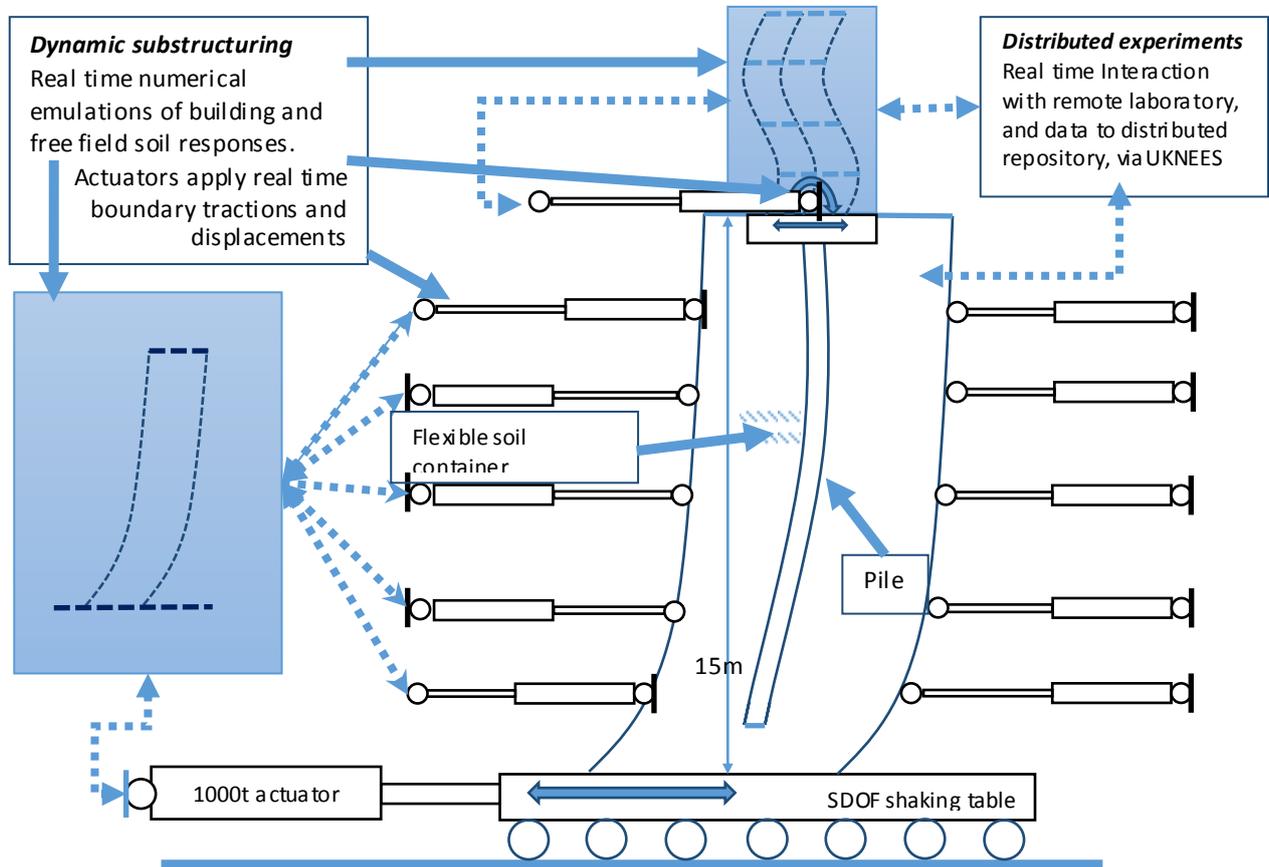Flexible soil container

Pile

15m

1000t actuator

SDOF shaking table

Fig. 1. Conceptual layout of UKCRIC SFSI rig