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The Future of Geotechnical and Structural Engineering Research

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Summary

A review of publically funded UK structural and geotechnical research showed that it was world class but incremental not transformational. Further, public research investment in this area is less than other sectors despite the significant investment in the construction and infrastructure sectors. This is at a time of a rapid pace of change driven by population growth, resource scarcity and security, developments in technology, society's expectations and aspirations and climate. This led to a major review of the purpose of infrastructure and construction by representatives from academia, industry, research organisations, clients and government. They concluded that the research themes to address are hazards, understanding material behaviour, paradigm shift in design, construction processes, building performance, smart buildings, asset management, intervention, decarbonisation and adaption If transformational research is to take place.

1. Introduction

In 2009, the UK Engineering and Physical Science Research Council published a review (EPSRC, 2009) of academic research into geotechnical and structural engineering (G&SE). This was part of EPSRC's ongoing theme of shaping capability of and building capacity in the UK academic base. The review reached the conclusion that the ranking of UK research in this area was world class and was world-leading in a number of niche areas, especially numerical modelling, fire engineering, vibration engineering, geotechnical engineering and earthquake engineering, but it was incremental not transformational, relatively short term in vision, predominantly industry-led and with little interaction with other disciplines.

The construction industry, the prime recipient of this research and, therefore the sector with the most to gain, is not as engaged in publically funded research as other sectors. This may be due to the fact that all new construction, particularly buildings, are prototypes so industry does not have time and resources to refine the design, unlike other areas of engineering and manufacturing; the inability to create/ maintain some form of competitive advantage in a project led industry where project teams are assembled from many companies; manufacturing is typically technology intensive, construction is service-based and inherently labour intensive; most research on innovation has been focused on large enterprises neglecting the SME sector which dominate construction; and SMEs tend to be more focused on survival and solving immediate project-related problems rather than invest in research. It should also be noted that indicators of research may not be so prevalent in the construction sector as other sectors; for example, the lack of patents will under estimate the innovation activity within the sector. This is unlikely to change because of the fragmented nature of the industry and the reliance on clients to invest in construction; that is, construction industry is often perceived as providing a service. Therefore, privately funded construction is particularly susceptible to economic cycles; publically funded construction is more sensitive to political cycles; and managing national infrastructure assets (e.g. water, rail, and road) is affected by the five year control periods used in the UK. Given the scale of construction projects, particularly infrastructure projects, which can involve significant public funding, the lack of national strategic planning also makes it difficult for the industry to plan and invest. The introduction of the National Infrastructure Plan in the UK has provided an indication of future requirements though it is still susceptible to political will. The most visible aspect of this is the current skills shortage that has resulted from the increasing volume of construction. There are some exceptions. For example, research into high speed railways is underway as the Government has highlighted its intention to develop such networks; that is long term planning facilitates investment in research.

There are a number of barriers to implementing G&SE research when compared to other disciplinary areas which have higher short term impact.

- The output of research in this area has a clear route to transfer knowledge through codes and standards, but the pace of change is slow.
- Public safety is a critical factor because of the scale and life span of projects.
- The industry is risk averse, which makes it difficult to implement research outcomes.
- Research tends to be incremental rather than transformational, which means that it is difficult to demonstrate benefit of research in the short term.

However, the challenges of urbanisation, resource scarcity and security, climate change and population growth are placing greater demands on the urban environment, giving rise to the need to realise the benefits of research. Figure 1 shows that the construction industry uses some 50% of all the world's resources (Minerals Education Coalition, 2015), and it has been suggested that the construction industry can influence 47% of the required reduction in CO2 by 2050 (BIS, 2010) – it therefore impacts greatly on all aspects of society. This implies the industry has the opportunity to make a significant contribution to enhance the resilience and sustainability of society.

The EPSRC review identified four research themes as being dominant:-

- Sustainable construction and infrastructure
- Resilient infrastructure
- Monitoring and field investigation
- Novel materials and their use

Two research networks were formed: Future Infrastructure Forum led by Cambridge University (FIF, 2010) and LimesNET led by the University of Bath (LimesNET, 2010) to develop a vision for the future of research into geotechnical and structural engineering. The Institution of Civil Engineers took this forward involving delegates from universities, contractors and consultants from the industry, client organisations, research organisations and government. This paper is a summary of the recommended areas of research developed from these activities, placing them in context of global challenges, national strategic planning, sustainable economic growth and the vision of the future of civil engineering.

2. Background

Geotechnical and Structural Engineering are two themes in EPSRC's portfolio of activity which account for approximately 4% of the total expenditure on Engineering and Physical Science research. It is characterised by individual Responsive Mode grants, though there are some more strategic grants (large multidisciplinary grants; e.g. those led by Powrie, 2010; Mair, 2011; Rogers, 2013; Collins, 2013; and Dawson, 2013). Associated themes include energy, water, transport and environmental engineering which, collectively, define the economic infrastructure of an urban environment (Table 1).

2009 also saw the publication of the UK Council for Science and Technology report on the National Infrastructure for the 21st century (UKCST, 2009) and in 2010 the UK Infrastructure Planning Commission report (IPC, 2010), both of which highlighted the need for a high quality national infrastructure to support economic growth and social well-being.

Much of the existing national economic infrastructure began over one hundred years ago (Table 1) creating a substantial asset. Maintaining this asset has presented a number of challenges in terms of renewing around a patch work of adjacent assets in tight time scales. Meeting these challenges in a commercially economic manner has meant that output of construction on existing assets has focused on keeping the asset running, without considering the longer term strategy. It has also given rise to sub-system specialists who have progressed in their careers without broader systems knowledge. It has been adapted to cope with changes in technology, regulations, environment and demand. Over the last fifty years, there has been a shift from a series of unconnected networks to an interconnected system. The economic infrastructure is primarily owned and operated by the private sector embedded within a regulatory framework.

Importantly, the infrastructure is ageing; resilience is reducing; it is susceptible to the effects of climate change; and there is increasing demand. The cost of replacing ageing infrastructure, the need to decarbonise existing infrastructure by adapting its use and to create new, carbon neutral infrastructure that is adaptable and more resilient have placed the industry in a position that it has never experienced before. This is at a time when the construction industry is embracing the benefits of the digital world.

In 2009, Infrastructure UK, a national body, was created, leading in 2010 to a National Infrastructure Plan (NIP) which set out the challenges facing the UK infrastructure and the government's strategy to deliver the UK's economic infrastructure. The NIP (IUK, 2014) focuses on a £460B pipeline of projects that meet the government's overall strategy (Table 2). Given the scale and life of infrastructure projects, it is inevitable that any investment is based on uncertain projected demands, has to be adaptable to changes in technology and adaptable to changes in the environment, and must be increasingly more resilient as it degrades.

Investment in economic infrastructure is a global challenge (OCED, 2007). For example, OCED suggests that air passenger traffic could double over the next 15 years, air freight triple in 20 years and port handling quadruple by 2030. This in turn suggests that by 2030, US$53T of investment is needed; this is about 2.5% of the global GDP. This would rise to 3.5% of GDP if energy investment is included.

The OCED report also highlights the concept of 'green growth', an objective additional to those of economic and social advantage. The 'greening' of infrastructure is consistent with the UK government's strategy for sustainable construction (BIS, 2008) to provide a better quality of life using long-term solutions that will benefit everyone. The UK construction sector encompasses economic and social infrastructure, accounts for about 8% GDP employing 3 million people and is worth over £100B per year (BIS, 2008). Importantly, it uses about 300 million tonnes of material per year, or about 6 tonnes per person, while construction, operation and maintenance of the infrastructure account for nearly 50% of the UK's emissions. The construction industry makes a significant contribution to the five guiding principles of sustainable development (UKEFR, 2005), particularly that relating to living within environmental limits. In 2013, the areas for improvement included (BIS, 2013):-

- Establishing effective construction programmes (cf. NIP)
- Focused and capable public sector clients
- Whole life value
- Appropriate procurement and construction strategies
- Collaborative working through fully integrated teams
- Evaluating performance and embedding project learning

In 2013, the UK government published its Construction Industry Strategy (BIS, 2013), one of eleven industrial strategies to create a partnership between the industry and government to set out the long-term directions. The aims are to reduce costs (by 33%), reduce time for delivery (by 50%), reduce emissions (by 50%) and improve exports.

The industry will be smart, sustainable, underpinning a growing economy. The Strategy has forty three recommendations including five covering research. In 2014, it was estimated that EPSRC-funded research into construction-related topics amounted to £188m (i.e. 0.2% of the annual construction expenditure) with 80% supported, mostly in kind, by industry, although the uptake of the research output and development was limited. This compares to the total expenditure in the UK of 1.72% of GDP on research (ONS, 2012). The challenges are to disseminate the research knowledge more widely, make greater use of existing technology, remove barriers that inhibit innovation and anticipate future research needs. It highlighted research in green construction, smart construction and digital design funded by EPSRC and the Innovate UK as examples of industry-relevant research.

The national infrastructure and construction strategies emphasise the need for the government to have a long term plan for investment to allow businesses to build capacity to deliver. They also provide a commitment that enables research to flourish. The strategic aims of reducing costs, emissions and time for delivery, increasing investment for growth, and tackling the priorities of the digital economy and green growth, all provide a means of aligning the research agenda with the needs of society.

3. The Future of Civil Engineering

Construction is a transformational process. It produces an outcome that transforms peoples' lives; therefore the views of the users, operators and owners are important. Historically, construction has had an output focus, relying on experience, regulation and guidelines to create something that had value.

The evolution of design for construction is similar to that for research. It has been an incremental process starting with an empirical approach based on observation of actual behaviour. Gradually, a more scientific approach developed as testing of materials and elements became possible. This led, at the beginning of the 20th century, to the development of standards and regulations which, over time, have been updated to recognise practice and research findings. Towards the end of the 20th century, numerical modelling became a reality and, more recently, the ability to monitor performance of buildings a possibility. This is now leading to the realisation of the concept of the built environment as a system.

This aligns with the concept of convergence which is a cross-, inter- and multi-disciplinary systems approach informed by social science research and underpinned by the natural and physical sciences (Figure 2). It requires a different approach to research, and this has been both encouraged and manifestly advanced by the UK Research Councils, and EPSRC in particular via its pioneering Sustainable Urban Environments programme. There are now programmes of research that are exploring the far future needs of cities and their citizens, and the research is having impact in spheres such as the UK Government's Foresight Future of Cities project and via the Future Cities and Transport Catapults. Thus, there is a hierarchy of research (Figure 2) addressing the challenges at different scales. A challenge for the research community is to demonstrate the impact of their research outside of the pockets of excellence where this is happening, and specifically in the construction industry rather than the organisations and structures within which the community works. The hierarchy and key themes provide a means to do just that.

In 2007, the American Society of Civil Engineers held a summit to create a vision for civil engineering in 2025 (ASCE, 2007) in which civil engineers will help society achieve a sustainable world and raise the quality of life, a sentiment conveyed by the UK's infrastructure and construction strategies. They suggest that civil engineers, as a body of professionals, will be leaders as builders, stewards of the environment, innovators, managers of risk and leaders in public policy. The drivers for change, that is resources and the environment, are similar for all global and national strategies. It will require highly multi-disciplinary collaboration on projects, research and development, taking advantage of developments in information technology, smart infrastructure and digital simulation. They envisaged that the profession would take a more preventative approach rather than a remedial approach, and conduct 'clinical' trials in the natural and built environment to create information that reduces risk and enhances design, construction and operation. Developments in sensors, biotechnology and nanotechnology will impact on construction materials and processes, thus enhancing the industry and its outcome.

Most of the built environment in the UK has been built over the last two hundred years (Table 1) though in some cases its history can be traced back over 2000 years. It is continually upgraded or replaced because of changes in use, regulations or technology and because of degradation. For example, the UK has over 150k bridges which are essential components of road, rail and waterway networks. Natural degradation and changes in loading conditions means that their capacity relative to the increasing requirements is in decline. This requires considerable ongoing investment. In future, however, changes to the environment will have a greater impact on performance. For example, increased rainfall intensity will lead to more infrastructure failures, particularly road and rail embankments. Most rail embankments were constructed prior to the implementation of codes for construction and, given the equipment available at the time, would not meet current compaction criteria. These are potentially at risk because of the relatively basic level of engineering at the time. Yet modern engineered embankments, which are optimised for performance not redundancy, are also increasingly susceptible because climate change will affect the pore pressure regime.

4. Key Issues

The EPSRC-supported Future Infrastructure Forum held five two-day workshops involving representatives from academia, industry, and client, including government. The forum started with a review of research currently taking place. As expected, it included materials, instrumentation, design, processes, modelling and civil engineering as a system. Given the context in which the challenge was set, it suggests that the research activity was addressing many of the emerging issues, but not necessarily in a structured or collaborative manner. The link between research projects and the issues was not clear in all cases, and the research outcomes were not necessarily impacting on the industry. The focus of the research community, which has become increasingly scientific, was not necessarily aligned with that of industry, which is more commercial.

It was recognised that establishing a strong research base in geotechnical and structural engineering is important to provide underpinning knowledge for industry, as well as maintaining an academic base necessary to deliver the next generation of engineers.

The key drivers identified in the workshops were climate change, urbanisation, ageing infrastructure and resource scarcity with cross cutting drivers of low carbon engineering, adaptable infrastructure, and sustainability and energy/water footprints (Figure 3).

A number of messages emerged from the workshops:-

- 'Home is more than a shelter – it is a workplace, an energy store, a communications centre and it cares for you'
- 'A sustainable city state will produce its own energy and food, and communicate with other city states'
- 'Infrastructure has a value and an infinite life'
- 'The construction industry is an industry that can adopt manufacturing processes'

By 2050, the construction industry, through research and practice, will have according to the participants: -

- An understanding of
    - behaviour of materials through life;
    - critical aspects of structures;
    - resilience and its implications;
    - risk and its implications;
    - and the performance of existing infrastructure, how it degrades and its remaining value.
- Tools to
    - undertake holistic diagnostic analysis;
    - and design for performance.
- An ability to
    - manage demand;

- minimise both the need for intervention and the impact of any interventions;
- realise the true capacity of the ground;
- create zero carbon buildings;
- and utilise the ground and buildings as a source and store of energy.

5. Themes

The output from the workshops can be summarised in ten themes, but these themes should not be considered in isolation as indicated in Figure 3. Table 3 lists the activities under each of the research themes.

5.1 Hazards

Increased urbanisation, development in marginal land and land under threat particularly along coasts and waterways, and increasing vulnerability of society because of its reliance on fully functioning infrastructure are leading to a greater focus on design for resilience. This requires a multi-scale approach integrating all those involved in designing, building, operating and using the built environment. It requires a systems approach at all levels because of the interdependency of the networks within the built environment, whether it is national major infrastructure such as the transport networks, local infrastructures or community-scale domestic buildings.

Hazard assessment and risk, seismic design, flood management, and response, recovery and rebuild are routinely undertaken. They can focus on preventing economic and social loss, minimising such losses, minimising the time to fully recover or increasing the resilience of the environment to make communities less vulnerable to catastrophic events. There is a need to share good practice and learn from experience, because the impacts of these increasingly frequent events are leading to greater damage and loss, and this is likely to continue as the world's population increases and becomes more concentrated through urbanisation.

5.2 Understanding Material Behaviour

Material behaviour is a key science that underpins all engineering projects. The process of testing materials to study their physical and natural characteristics and modelling those characteristics in design are understood. Thus, there is an established process when new materials are introduced to determine their characteristics and establish their performance. However, the performance of materials *in situ* has not received as much attention. Material behaviour *in situ* is affected by the environment, the loading regime and the constraints imposed by the assembly, and these are different from those conditions experienced in the laboratory.

Materials degrade with time for a variety of reasons, yet this degradation and how it impacts on their performance is not fully understood. This is especially important when considering building elements where materials are acting in conjunction with other materials, something that is not necessarily considered in design. For example, the degradation of underground utilities and the ground within which they sit is the subject of a major research project (Rogers, 2013) to improve the management of this fundamental asset.

New materials, for example biomimetic (mimicking nature) materials, smart (responding to the environment) materials, composites and autogenous (self-healing) materials, are being introduced. The process of integration into the industry is understood, yet the risk-adverse nature of industry and the lack of understanding of material performance *in situ* may prevent the value of these materials being fully realised.

5.3 Paradigm Shift in Design

Design is supported by guidelines and experience, restricted by codes and enhanced by analysis. It is continually evolving but the pace of technological change, the environment and society's expectations means that the current codified approach to design may be increasing the risk to the built environment as the pace of change accelerates. The built environment is continually being maintained, updated and adapted. This will accelerate to minimise environmental impact.

The number and impact of catastrophic events are increasing. For example, increase in rainfall intensity, failure to adhere to planning guidance and rising sea levels are engendering increasing economic loss. In 2007, worldwide, there were 200 major floods affecting 180m people and causing $40B of damage (Pitt, 2008). The UK was ranked first in the world for economic loss due to flooding as the summer rains in 2008 in the UK flooded 55,000 properties leading to £3B of insurance claims.

Swiss Re (Swiss Re, 2013) identified 616 urban environments, home to 1.7B people (25% of the global population), which generate $34,000B GDP (40% of the global GDP). They have characterised catastrophic events in these environments as *major*, such as earthquakes, which require response, recovery and rebuild phases to re-establish the norm; *medium*, which can be dealt with by design and operation; and *local*, which can be dealt with through design and the support of the community.

Codified design is current practice, but scenario modelling, risk-based design and design for flexibility (adaptive design) are emerging because current codes may no longer be relevant. Examples of the limitation of current codes are those used prior to 2010 in New Zealand. Following the Christchurch earthquake, buildings are being reassessed, and strengthened if necessary, using more stringent criteria. Dealing with *local* and *medium* catastrophes is introducing the concept of designing for resilience.

5.4 Construction Processes

Quality control and workmanship are key risks to any construction. Factors can be applied in design to compensate for these risks, but increasingly complex structures will require improvements in assembly to overcome human error. Offsite manufacturing, 3D printing and robots have developed to an extent where application in the construction industry is feasible. This is primarily driven by commercial investment, skills shortages, reduced transport costs and concerns over health and safety. However, it does offer an opportunity to undertake research into the expected enhancement in the improvements to the structures. Optimisation becomes feasible. For example, producing beams shaped to optimise material use leading to material reduction is now feasible provided the building performance is fully understood.

Construction is a manufacturing process in which most projects are prototypes, even though they are assembled from elements that have been optimised both in design and manufacture because of their repeatability. Offsite manufacture has the potential to improve quality, reduce times for construction and improve safety because it is possible to implement optimised, manufacturing processes. These processes, together with lean construction, could be applied to on site construction.

5.5 Building Performance

A building is a system, therefore to truly capitalise on its components it should be considered as a whole – the structure, the fabric, the utilities as well as the function. This is currently subdivided such that components of a building are often considered in isolation. For example, the foundation provides a stable base upon which to build a structure, yet the foundation and structure interact. The distribution of loads within a structure, the response of the structure to movement of the foundations and the impact of the load on the foundations are not fully understood. Therefore, greater use of instrumentation to monitor actual performance, leading to a database which can be interrogated for future projects, should lead to improvements in design. This will be facilitated by Building Information Modelling (BIM) though an understanding of the risks associated with this has yet to be resolved. Instrumentation and data capture are now a commercial reality such that project instrumentation could become standard though, unless there is some direct benefit to the industry, it may prove impossible unless made mandatory through the specification or law. Thus, instrumentation *per se* will become a commercial tool, allowing research to focus on the interpretation of the data leading to improved modelling and enhanced design. Evidence of this is emerging from the EPSRC/TSB IKC grant held by Cambridge (Mair, 2013) and programme grants held by Birmingham (Rogers, 2013).

5.6 Smart Buildings

The impact of the digital world in the built environment is increasingly being recognised as an opportunity to fully realise the capacity and capability of the environment, to improve its operation, to minimise interventions, to focus interventions and to improve future design. The cost and design of sensors is such that it is now possible to install them during construction, thus providing greater insight into how the built environment performs at all levels and how it impacts on human behaviour and life. Further, the built environment can be seen as a 'living' organism that adapts to its environment, and makes greater use of the intrinsic properties of the materials and elements that create the environment to be more resilient and multi functional. Further, through observation and intervention, the concept of 'infinite' life performance can be realised to cope with degradation, adaption and reuse.

5.7 Asset Management

The built environment has a value which is continuously being updated through maintenance and adaption. The built environment can last several generations and is fundamentally important for the health, wealth and well-being of society. Therefore, in addition to its capital value, it also has cultural and economic value. In order to realise the true value of the built environment it is necessary to appreciate current capacity and capability, and establish the remaining life at that capacity and capability. Extending the capacity and capability is feasible through maintenance and adaption. Changes in regulations, use, technology and the environment require a reassessment of capacity and capability if the value of the existing built environment is going to be fully realised.

Building performance is inextricably linked to asset management which aims to extend the life of the asset, intervene before failure occurs and realise the full value of the asset. Therefore, performance monitoring extends to predicting lifetime performance and capacity remaining at the end of life for re-use.

5.8 Intervention

Interventions, either planned (e.g. change of use) or unplanned (e.g. minor catastrophes leading to reduced capacity), inevitably affect the structural performance and the value of the structure. Unplanned interventions occur when materials or elements fail to function. Treating the structure as a system enables preventative measures to be in place through an early warning system. Planned interventions can be optimised to achieve change and add value while minimising cost, carbon and impact.

This clinical approach to manage the asset, enhance the asset and repair the asset should lead to a reduction in costs and carbon. Further, a reduction in the number of interventions leads to improved benefit from the existing structure and a reduction of risk in altering the structure's performance unnecessarily.

5.9 Decarbonisation

In order to meet the 2050 carbon targets (an 80% reduction from 1990 levels), much of the built environment has to be adapted. Hence, adaption not only applies to change of use and dealing with environmental changes, but also decarbonisation. In order to decarbonise existing buildings, it will be necessary to change the buildings' operating environment. This requires modification to the building structure and the environment in which the building functions. For example, increasing insulation can lead to thermal stresses across building elements; adding solar collectors on roofs adds structural load. Therefore, studies into retrofit (upgrading) as well as refurbishment (renovation) are required. Changes to infrastructure to reduce energy use will require changes to the operating systems, but may also require a change to the underlying structure. Therefore, decarbonising the existing environment will focus on energy reduction, increased use and retrofit. Reducing the carbon emissions of new construction will focus on materials, optimisation, form, energy and water demand in construction and operation. Carbon emissions, energy and water requirements will become design criteria.

Buildings and infrastructure can generate and store energy in a variety of ways. They are solar collectors, heat exchangers and moving objects. For example, a road surface is a solar collector which can store energy in the underlying subgrade. Therefore utilising existing and new structures as energy generators and stores reduces the imported energy requirement.

5.10 Adaption

Changes in technology, regulations, user requirements and degradation set against the design life of the built environment have led to a continuing need to adapt the built environment. The UK transport infrastructure, for example, has gone through a number of phases from tracks to waterways to railways to modern highways driven by user requirements and technology. These networks having been adapted to cope with change. Therefore, realising the value of the existing built environment, decarbonisation and climate change requires the existing environment to be adapted and new build to be adaptable.

6. Conclusions

The ESPRC review of geotechnical and structural engineering occurred at the same time as the political recognition of the value of economic infrastructure. The commercial realisation of instrumentation, data capture and interpretation and modelling are occurring at the same time as the impact of the grand challenges of climate change, resource security and scarcity, a growing population combined with a changing demographic, and growing urbanisation are impacting on the built environment.

This is the background to a partnership created with the support of EPSRC to identify the research that geotechnical and structural engineering academic community needs to address. A series of workshops involving delegates from consultants, contractors, clients, research organisations and universities led to ten themes:- hazards, understanding material behaviour, paradigm shift in design, construction processes, building performance, smart buildings, asset management, intervention, decarbonisation and adaption.

One parallel outcome of these discussions was the announcement in March 2015 by the UK government of a £138m investment in the UK Collaboratorium for Research in Infrastructure and Cities to provide leadership and support for the development and growth of a coordinated and coherent, world class, UK-based national infrastructure research community, which engages academia, industry and citizens in a joint venture that drives innovation and value creation. This demonstrates the increasing importance of the need for research in infrastructure and construction.

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