Advances in the Development and Application of Large Scale Experimental Methods in Earthquake Engineering through the EU FP7 SERIES Project

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SUMMARY:
The EU Framework 7 project, SERIES, is enabling a large number of earthquake engineering researchers from across Europe to collaborate in the investigation of a wide range of leading edge problems. Such collaborations are only possible through an integrating Infrastructures project, such as SERIES, which can draw together many strands of world class research. At the heart of SERIES is the notion of building and sustaining a strong earthquake engineering research and practitioner community in Europe. This paper reflects on the philosophy and process of collaborative research within SERIES as experienced at Bristol, setting this within a cognitive psychology framework, and illustrating how awareness of the ongoing fundamental learning process leads to (i) effective team collaborations, (ii) effectively focused and purposeful projects, and (iii) valuable scientific and community building outcomes.

Keywords: Experiments, Collaboration, Learning, Community-building

1. INTRODUCTION

The EU Framework 7 project, SERIES, is enabling a large number of earthquake engineering researchers from across Europe to collaborate in the investigation of a wide range of leading edge problems, ranging from the development of advanced test concepts, through investigation of fundamental behaviour of structures and geotechnical systems, to the evaluation of specific design features and novel solutions. Such collaborations are only possible through an integrating Infrastructures project, such as SERIES, which can draw together many strands of world class research. At the heart of SERIES is the notion of building and sustaining a strong earthquake engineering research and practitioner community in Europe.

The Earthquake Engineering Research Centre at the University of Bristol is a lead partner of SERIES, offering SERIES users access to the shaking table and associated facilities of the Earthquake and Large Structures Laboratory (EQUALS), which is part of the larger Bristol Laboratories for Advanced Dynamics Engineering (BLADE) facility. Bristol is also playing a major role in the development of new experimental techniques, in particular investigating the potential improvement of soil containers for shaking table testing of geotechnical problems.

There are many general lessons about the modes and impacts of collaborative earthquake engineering research to be drawn from this portfolio of work. Usually, reporting of such work tends to focus on specific technical detail of specific technical projects and the opportunities for learning about and improving the process of collaborative research are overlooked. This paper reflects on the philosophy and process of collaborative research within SERIES as experienced at Bristol, setting this within a cognitive psychology framework, and illustrating how awareness of the ongoing fundamental learning process leads to (i) effective team collaborations, (ii) effectively focused and purposeful projects, and (iii) valuable scientific and community building outcomes. These lessons have a wider relevance to earthquake engineering practice as a whole, since the same fundamental learning processes are active here too.

The paper illustrates these ideas by drawing on examples from the wide range of structural and geotechnical engineering SERIES user projects and facility development projects already done at Bristol. These include some innovative, highly abstracted model studies that have revealed deep understanding of scientific issues, as well as forays into evaluating new technologies, such as actively controlled geotechnical container boundaries using novel actuator concepts. The technical and scientific details of a number of these projects are reported separately in the proceedings of 15WCEE and, therefore, will not be repeated here other than for brief illustration of wider principles.

2. ORGANSIATION OF SERIES TRANSNATIONAL ACCESS PROJECTS AT BRISTOL

SERIES Transnational Access (TA) projects are directed primarily towards European research groups that do not have access to shaking table facilities within their own institutions or countries. Priority is given to groups that have no experience of shaking table testing at all. Emphasis is given to the training of younger researchers. The aim is to spread shaking table experimental experience across the EU research community, with the overall outcome being a more cohesive, collaborative research community that understands and deploys shaking table experimental techniques to best effect.

The Earthquake Engineering Research Centre at the University of Bristol is contracted to support up to eight project teams to use its 3m x 3m, 15t capacity, six degree of freedom shaking table, located in the purpose designed £20m Bristol Laboratories for Advanced Dynamics Engineering (BLADE). Each TA group notionally has up to 20 fully funded access days through SERIES. Funding includes all travel and subsistence costs, specimen costs, small equipment items, and full research assistant and technician support. Each project has a notional overall budget of around 75,000 euros.

The relatively inexperienced user community means that a host laboratory, such as BLADE, must be a fully active participant in the design, development, execution, and reporting of each project. Training of the inexperienced users pervades all aspects of this process. Projects have relatively little shaking table occupation time, and so must be efficiently planned and executed, and must be incorporated within a busy laboratory time table. TA users gain valuable experience of both technical design and planning, and of overall project management. They are encouraged to be active participants *and learners* in all aspects of the project planning and execution.

2.1. User selection process

User teams generally comprise of representatives from at least three different research organisations (which may include industry participants provided the work programme is clearly of generic, publishable research). A senior researcher from one of the research organisations acts as user team leader and is responsible for establishing the user team and its overall research objectives, preparing the application for TA resources, and ensuring that results are processed and published. Each user team eventually signs an agreement with the host laboratory.

In order to secure project funding, the user team leader, working in conjunction with the proposed host laboratory, prepares a short application document that sets out the overall scientific purpose and intended outcomes of the proposed project as well as a technical conceptual design of the experiment. This is submitted to the SERIES User Selection Panel (USP), which meets around twice a year, for evaluation against published criteria. The USP process involves reviews from independent technical experts as well as representatives of the seven Transnational Access laboratories within the SERIES consortium.

2.2. Organisation of Transnational Access project at Bristol

Each SERIES host laboratory organises TA projects to their own methodology. At Bristol, once a project has been approved by the USP, the user team embarks on the elaboration of the test programme with the host laboratory. A Bristol support team is allocated, comprising an experienced lead academic, an experienced postdoctoral researcher (PDRA) and a lead technician.

The project elaboration process begins with a kick-off user meeting in Bristol, attended by all the user team members, which typically is an intensive two day work shop led by the Bristol support team. The workshop culminates in signature of the formal collaboration agreement, which includes a fairly detailed provisional test method statement that has been drawn up on the basis of the work shop discussions. This process will be discussed in great detail in section 3.

The Bristol support team and the user team then develop the method statement in detail through electronic discourse. This will typically involve iterations of the detailed design of the specimen and test rig, instrumentation arrangements, data processing schemas, safety and training plans, and full test schedule etc. Once the method statement has been agreed, procurement and fabrication of the test specimen and associated rigs will begin.

Typically, a project is split into two, 2-week test blocks, possibly separated by several months. The reasoning behind this is the recognition that the experimental programme is a learning programme focused on a novel and unique problem about which there is usually much epistemic uncertainty. The purpose of the first test block is often to explore the fundamental (especially taken-for-granted) assumptions on which the research hypothesis is based. No amount of conceptual, theoretical or analytical prior modelling can possibly capture all the influential aspects of an experiment. By definition, these models are abstractions of reality (the reality being the experimental specimen and associated rigs as prototypes in their own right) and the quality and reliability of the abstraction is ultimately due to the experience and understanding of the modeller. If an experimental programme is totally new, then the modeller and designer of the experiment cannot be aware of every influential aspect. Across the authors' long and wide experiences, every new experiment throws up unexpected issues, sometimes major, which prompt a rethink or significant modification to the ultimate experimental programme. The two test block approach permits a first learning cycle through which a more dependable, definitive test programme can be established for the second test block.

Depending on the nature of the actual experiment, a project team workshop might be held between the two test blocks in order to consolidate the team learning and to update and confirm the details of the second test block. A final, post test workshop might also be held to review data processing and findings and to finalise formal reporting and dissemination.

2.3. Typical kinds of user projects

SERIES user projects conducted, or in progress, at Bristol up April 2012 included:

1. Piled foundations in layered dry sand deposits, tested in a 6m long geotechnical shear stack (Fig. 3).

2. Cantilevered retaining walls retaining dry sand deposits, also in the shear stack (Fig. 1).

3. Soil-structure interaction dynamics of a soil mass with piled inclusions (Fig 5).

4. Seismic performance of prefabricated timber framed buildings (Fig. 4).

5. Investigation of the seismic performance of thin rubber sound insulation sheets in the interfaces between masonry walls and supported floors (Fig 2).

6. Seismic structure-foundation-structure interaction in dense urban areas.

7. Seismic behaviour of flat-bottomed grain silos.

Projects 4 and 5 involved specimens at, or close to, prototype scale, and were related to generic evaluation of new construction approaches proposed by industry partners working in collaboration with their academic partners. The remainder were scale models, focusing on fundamental understanding of response phenomena. Projects 3 and 6 were highly abstracted physical models of soil-structure interaction problems having the aim of exploring and validating simplified elastic theoretical and numerical modelling of the problems. Projects 1, 2 and 7 involved testing to large strains with the aim of understanding non-linear mechanisms up to failure.

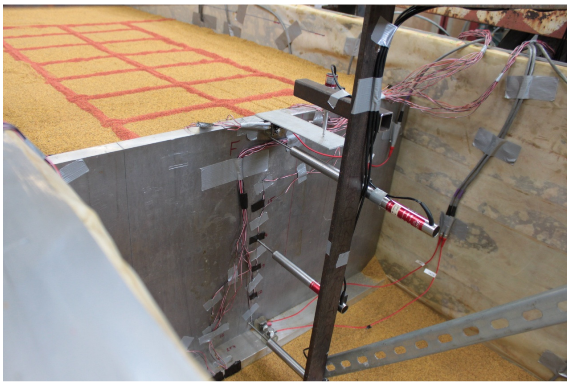

Figure 1. Retaining wall, project no 2

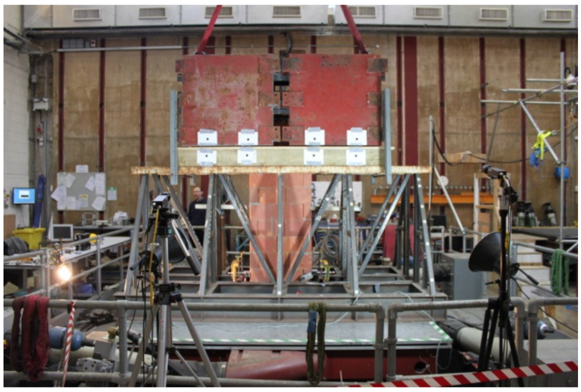

Figure 2. Masonry wall, project no 5

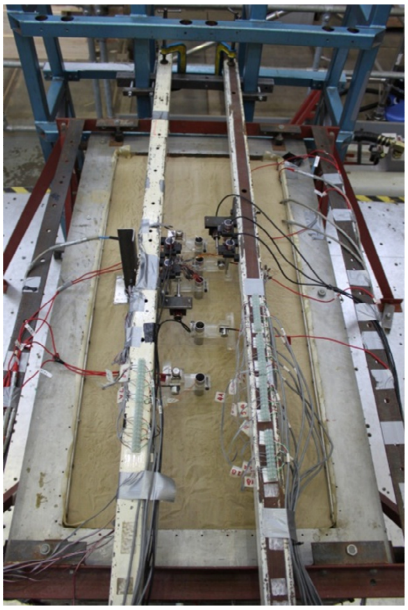

Figure 3. Piles in layered soils, project no 1

Figure 4. Timber building, project no 4

2.4. Overview of the BLADE shaking table facility

The Earthquake and Large Structures Laboratory (EQUALS) is part of the Bristol Laboratories for Advanced Dynamics Engineering (BLADE) in the Faculty of Engineering at the University of Bristol. It houses a 15t capacity, 6 DoF earthquake shaking table surrounded by a strong floor and adjacent strong walls up to 15m high. The shaking table is accompanied by a set of 40 servo-hydraulic actuators that can be configured to operate in conjunction with the shaking table, strong floor and reaction walls, providing a highly adaptable dynamic test facility that can be used for a variety of earthquake and dynamic load tests.

The shaking table consists of a stiff 3mx3m cast aluminium platform weighing 3.8 tonnes (Fig. 5). The platform surface is an arrangement of 5 aluminium plates with a regular grid of M12 bolt holes for attaching to the platform body and for mounting of specimens. The platform can accelerate horizontally up to 3.7g with no payload and 1.6g with a 10t payload. Corresponding vertical accelerations are 5.6g and 1.2g respectively. Peak velocities are 1 m/s in all translational axes, with peak displacements of ±0.15 m. Hydraulic power for the shaking table is provided by a set of six shared, variable volume hydraulic pumps, providing up to 900 lt/min at a working pressure of 205 bar. The maximum flow capacity can be increased to around 1200 lt/min for up to 16 seconds at times of peak demand with the addition of extra hydraulic accumulators.

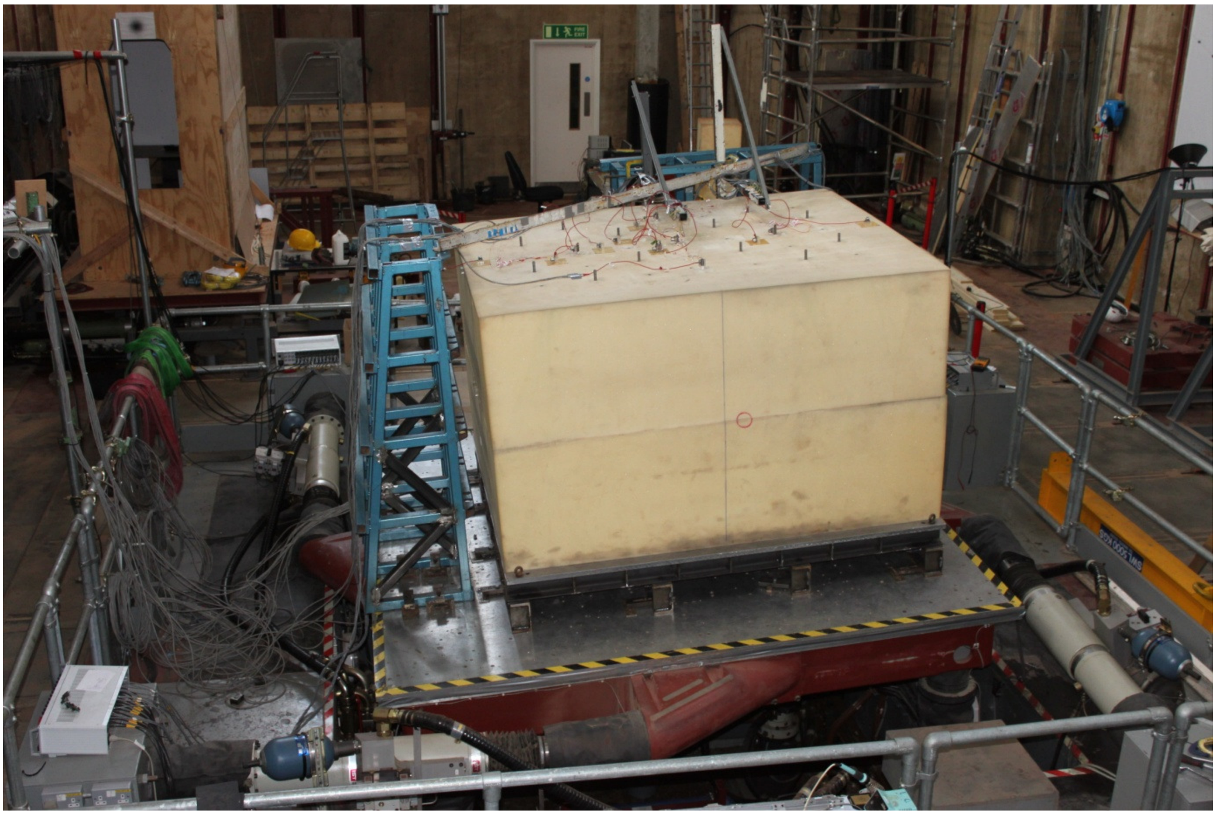

Figure 5. Bristol shaking table with specimen for project no 3

Extensive instrumentation is available, including 256 data acquisition channels. The EQUALS facility is supported by a multi-disciplinary group of academics specialising in advanced dynamics and materials from across the Civil, Aerospace, Mechanical Engineering, and Non-linear Dynamics fields, providing to users day-to-day support, specimen fabrication and manufacturing, as well as shaking table operation, electronics and instrumentation support. The Faculty has an extensive manufacturing workshop equipped with numerically controlled machines, etc.

3. LEARNING MODEL FOR EXPERIMENTAL DESIGN AND EXECUTION

Research programme design and execution at Bristol is set within a cyclic learning model known as Accelerated Learning (Smith, 1998). This model (Fig. 6) is widely used in school education in the UK, and has its basis in emerging understanding of cognitive neuroscience and educational psychology. The authors' experience is that the model maps well onto the engineering process and is a very useful way of framing engineering learning and practice.

From a neuroscience perspective, the model recognises the iterative nature of the formation of secure neural networks in the brain. Learning is deemed to have been achieved when a neural network is secure and can be recalled automatically without effort. Neural networks are formed by the connection of the axons (i.e. outgoing nerves) of individual neurons (brain cells) to the dendrites (incoming nerve connections) of other neurons. Each time a neuron, or neural network, fires, biochemical processes coat the axons and the dentritic connections with materials that both speed up the electrical impulses travelling through the axons and bind the connections more securely. The more often a network is fired, the stronger and securer it becomes. Thus, learning is perceived to be a process of first establishing neural connections and then repeatedly exercising them until they become so secure that they are automatically invoked in response to appropriate external stimuli. The above, is of course, a highly simplified description of a complicated and complex phenomenon, but is sufficient for the purpose of this paper.

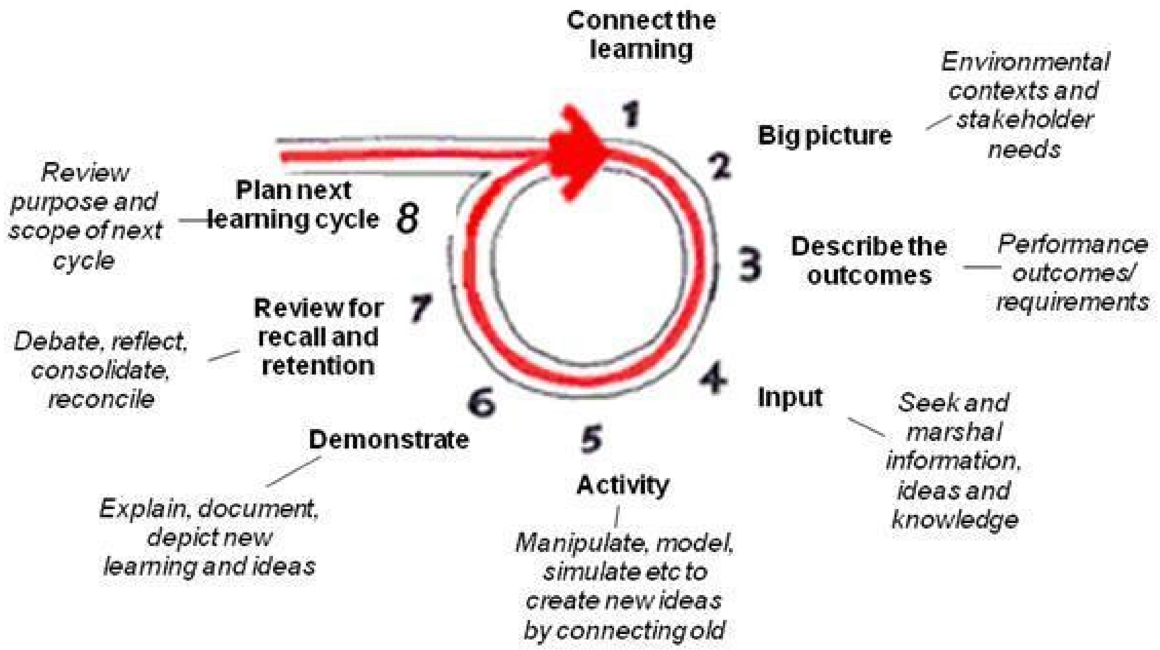

Figure 6. The Accelerated Learning cycle mapped onto the engineering learning process (adapted from Smith (1998))

From an educational psychology point of view, just because a neural network becomes secure and automatic does not mean that the learning and concept it represents is meaningful or truthful. However, once a neural network is established, it is quite difficult to delete or displace if it is in error. Rigorous, and occasionally forceful, challenge is generally needed to modify erroneous or poorly performing neural networks and the meanings they carry. In aid of such rigour, the Accelerated Learning cycle recognises that humans have three main learning senses (visual, auditory and kinaesthetic – VAK) and seeks to mobilise each of these. (An individual generally has a natural bias towards one of these senses, but nevertheless uses them all at different times and can develop their facility with each.) By invoking all the learning senses, Accelerated Learning seeks to enable the learner to explore the concept in question from many perspectives, each of which reveals something particular while also confirming aspects that appear in other perspectives. If aspects conflict, they become a prompt for challenge and further investigation. The more aspects are confirmed from multiple perspectives, the more dependable they are perceived to be and the securer they become (but they are still not necessarily correct!).

From a team learning point of view, the desired outcome is that everyone in the team holds a similar, (shared) mental model of the team's purpose, goals, values, mode of working, and individual roles and contributions etc.

Figure 6 shows the authors' mapping of the Accelerated Learning cycle onto the engineering process. The cycle starts (Step 1) with an explicit recognition that the current cycle of learning must be connected to the previous learning (i.e. the current cycle is not a disconnected, abstract activity).

A key feature of Accelerated Learning is the initial 'Big Picture' contextualisation of the learning, overall and for each learning cycle (Step 2). Contextualisation is, perhaps, second nature to engineers, but it is nonetheless one of the founding principles of effective education and learning and should be made explicit. It applies both to formal learning in the classroom and to the more informal learning in the work place and teams.

In engineering and research, contextualisation helps establish the most important next step, that of clarity of purpose, from which can then be determined more formal engineering performance requirements (Step 3). When designing an experimental programme, the authors' approach is first to explore the intended outcomes at the end of the research, captured in the basic question: 'What will we be able to do at the end of the project that we can't do now?' Keeping the answer to this question in mind at all times, and regularly revisiting it (especially between test blocks), helps to build and secure common purpose and focus within the team. It becomes a constant reference point for decision making at all levels of detail. For example, when deciding on what to measure in an experiment, it provides a purposeful end point of the mapping of the choice of measurement, through a hierarchy of manipulations, to achieve the ultimate purpose of characterising a particular feature of the overall problem. A very valuable question that should be asked often is: 'What is the purpose of doing X …..?' Doing so gradually teases out, makes explicit, and offers challenge to, many taken-for-granted assumptions that often are actually interpreted very differently by even experienced members of the team. Such repeated questioning and collective answering builds the vital common alignment of understanding and thinking within the team. It also fosters a culture where questioning and rational challenge are welcomed, especially from younger, less experienced, members of the team – for, of course, this is the basis of their learning.

Step 4 of the cycle relates to collecting information and knowledge that effectively 'colours in' the big picture context. At the experiment design stage, it would include a search for similar work done elsewhere, collation and expression of the team's current knowledge, etc. Within the experimental execution, it might relate to data that have been collected.

Step 5 describes what is actually to be done to achieve the outcomes and performance requirements established in Steps 2 and 3. This could be the details of the experimental execution or the data processing activity.

Step 6 is the demonstration of the new learning. This might be visualisation and interpretation of data, production of a report etc. Knowing *how* the learning is to be demonstrated within the team and beyond needs to be decided upon during the earliest planning stages. It is a vital step in the process of mapping specific measurements through to the desired outcomes of the experimental programme.

During the design of the programme, selection of the method and form of demonstration is necessarily predicated on many taken-for-granted or tacit assumptions. It should be expected that some of these will fail once the experiment is realised. At this point, Step 7 deploys the essential stage of *sceptical* reflection and consolidation. A pragmatic approach to demonstrating the quality and veracity of data and findings is to start with the assumption that they are wrong and then forensically attempt to prove this. Just because experimental results appear to match theory (or vice versa) does not necessarily mean that they do so for valid reasons. Sceptical evaluation from a range of perspectives helps build confidence in the dependability of the data and research outcomes. Once such confidence has been established, it is appropriate to decide what should be done in the next learning or experimental cycle, which then cycles through the same steps, starting with a re-evaluation of the context and purpose of that cycle, set against the overall desired outcomes.

The authors use the Accelerated Learning cycle as a flexible, informal, framework for guiding the development and execution of a research programme. It is especially useful for helping inexperienced experimentalists to form their own framing of the experimental process and its purpose. It is a useful checklist of activities and questioning points that does not necessarily need to be proceduralised in formal detail (although in some cases, eg nuclear safety, this might be deemed necessary).

4. EXAMPLE APPLICATION

Project 3 (Fig 5) is a good example of how informal application of the Accelerated Learning process led to a novel experimental solution to the need for providing physically derived data for validating a novel theoretical perspective on the dynamics of a soil mass reinforced with a network of piles.

In the theory (Boutin et al, 2010), the dynamic response of a soil-pile-group system is modelled using homogenisation theory, which considers the system as a periodically reinforced system. The transverse mode of an infinite lateral extension of a reinforced matrix is governed by the following equation, where G is approximated by the soil modulus, EI is the inertia of the piles, and S is the period area of the periodic reinforcement pattern and $<\rho>$ the mean density:

$$G|S|\frac{d^2U}{dx^2} - E_p I_p \frac{d^4U}{dx^4} + <\rho> S\omega^2 U = 0$$

The modes and eigen frequencies can be deduced from the boundary conditions (e.g. clamped, free).

The challenge was to design a repeatable and reusable experiment that could yield data for a well-defined physical specimen. During the work shop process, various options were reviewed, including use of a geotechnical shear stack. However, through careful analysis of the purpose and desired outcomes of the experiment, it became clear that an idealised, essentially elastic, specimen would give the kind of dependable data needed for the validation of the theory. It was not necessary, for example, to seek to produce a scale model of a larger prototype (given the size of a prototype scenario, such scaling would only be possible in a high g centrifuge, but this would suffer from major uncertainties about the boundary conditions and homogeneity of material properties etc.) The chosen solution was that illustrated in Fig. 5.

The physical model was constructed from analogue materials that matched the basic assumptions of the theoretical modelling, namely, a soft linear-elastic matrix made of polyurethane foam (E_m = 54kPa) and steel bars as vertical reinforcement piles with perfect adherence at their interface. The foam block was 2.13 by 1.75 by 1.25m tall. The steel bars were mild steel tube with 12.7mm outside diameter and 3.25mm wall thickness. 35 reinforcements (1.3m of lengths) were used on a seven by five grid at 250mm centres. The foam block was rigidly bonded onto a stiff aluminium base plate, which in turn was bolted to the shaking table. The vertical sides and top surface of the block were unconstrained. The steel piles were simply instrumented with strain gauges, whilst accelerometers were placed on the upper surface. This simple instrumentation arrangement yielded the strain profiles, which had been determined as the key means of comparison with the theoretical model, whilst the accelerometers enabled the measurement of the gross modal properties, which were determined adequately to characterise the overall system dynamics. Excellent comparison was achieved between the theoretical and experimental models, which, although heavily idealised, met the requirements for this degree of validation from which further, more detailed and complex developments and evaluations might be justified. Thus, these experiments were part of a wider context of further advancement of the theoretical modelling context.

The conclusions of the project (which will be detailed in forthcoming publications elsewhere) were that a large soil/pile stiffness contrast leads to full coupling in the transverse direction of the bending behaviour from the piles and the shear behaviour from the soil. The analytically derived performance predictions captured important characteristics of the experimentally observed response. The shear/bending analytical modelling approaches should provide a simple manner to design and describe soil/piles system submitted dynamically to lateral ground motions.

5. CONCLUSIONS

The FP7 SERIES project is a good example of how funding of transnational access to large facilities across Europe can lead to strong and diverse research communities that are able to disseminate and combine expertise to make valuable scientific and capacity building contributions. Apart from the specific technical advances of particular projects, there is much to be gained from reflection on the learning and team building processes of this activity. Fostering and enhancement of these processes can only help raised the quality and effectiveness of such collaborative activity.

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