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# General Report for TC104 Physical Modelling in Geotechnics

## Rapport général du TC104 Modélisation physique en géotechnique

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**ABSTRACT:** The session of the 18th ICSMGE on physical modelling in geotechnics, held by Technical Committee 104, provides an opportunity to reflect on the varied contributions that physical modelling makes to our profession – in both research and practice. The 27 papers contributed within this theme span many different applications of physical modelling. These range from simple small-scale laboratory tests to reveal mechanisms of soil-structure interaction – particularly where simulation by numerical methods is problematic – through to scaled-down versions of field constructions, performed outdoors, to validate the performance of new monitoring technology. These examples show physical modelling in action across the entire spectrum of geotechnics, from the validation of fundamental analysis principles, to the assurance of construction technology. In all cases, physical models – defined here as physical idealisations of all or part of an envisioned geotechnical system – provide a more convenient method of gaining knowledge than observing or simulating the full geotechnical system.

**RÉSUMÉ :** La session de la 18<sup>e</sup> ICSMGE sur la modélisation physique en géotechnique est l'opportunité de faire le point sur les différentes contributions que cette dernière a apporté à notre profession, dans le domaine de la recherche et des applications pratiques. Les 27 articles retenus dans les comptes rendus de la conférence couvrent un champ varié d'applications de la modélisation physique. Ils incluent notamment des expériences de laboratoire menées à échelle réduite pour révéler les mécanismes d'interaction sol-structure (notamment dans des cas où la modélisation numérique peut s'avérer inadaptée), ainsi que des expériences de terrain réalisées sur des versions réduites d'ouvrage réels pour développer et valider de nouvelles techniques d'instrumentation et de suivi. Ces différents exemples démontrent la variété des applications de la modélisation physique, de la validation de principes fondamentaux, à l'évaluation des performances de technologie de construction. Dans tous les cas, la modélisation physique, définie ici comme l'idéalisation d'un système physique réel, permet d'accéder de manière rapide, économique et rigoureuse à une connaissance élargie du problème étudié.

**KEYWORDS:** Physical modelling. Centrifuge modelling. Field monitoring.

### 1 INTRODUCTION

The papers submitted to the TC104-organised session on Physical Modelling in Geotechnics illustrate a range of applications of physical models to support geotechnical research and practice.

Physical modelling can serve a variety of purposes in geotechnical engineering. It can provide (Gaudin et al. 2010):

1. **Insights into soil-structure interaction and geotechnical behaviour** – qualitative and quantitative. Given the complexity of soil constitutive behaviour and the complex deformations and processes in some construction technologies, physical modelling provides a basis to assess fundamental modes of behaviour in controlled conditions.
2. **Performance data to calibrate analytical or numerical models.** Physical models use well-characterized soil and known boundary conditions, providing reliable performance data for a given idealized problem.
3. **Specific performance data for design and operation.** Physical modelling can be used directly to design geotechnical systems or tools. For example, site-specific soil and loading conditions can be replicated in a centrifuge model, to validate a foundation design. Or, the shape of a geotechnical tool – such as a novel form of ground improvement device or a proprietary anchoring system – can be optimised using performance data from physical models.

4. **Soil characterisation data** – through testing of samples using miniature versions of conventional in situ testing tools. Using physical models in this way can be more cost-effective than full scale in situ tests.

Physical modelling, in its various forms, contributes across the entire proceedings of the 18<sup>th</sup> ICSMGE, not only the 27 papers that were allocated to this session. Physical modelling is a technique that cuts across the traditional categories of ground engineering. The majority of the sessions at the ICSMGE are defined by type of geotechnical system – foundations, slopes, ground improvement and so forth. These are the traditional groupings that our profession forms, pooling expertise and specialist knowledge from experiences in design and construction.

The physical modelling community within geotechnical engineering pools a different type of specialist expertise. The TC104 activity focuses on the technology and principles that allow physical modelling facilities to flourish and provide capabilities that can be applied across all geotechnical topics.

When the ICSMGE was last held in Paris, in 1961, the ISSMFE did not have Technical Committees and there was no session dedicated to physical modelling. However, physical modelling featured heavily in the presented papers. The Proceedings of the Paris conference feature classic physical modelling studies of retaining walls by Rowe and Schofield, as well as model pile tests in the field performed by De Beer, Kerisel and Meyerhof. Many papers show film photographs of

distorted layers of coloured sand, or time-lapse exposures that reveal particle trajectories. Scaling laws are never referred to, aside from commentary by Meyerhof on the effect of stress level on friction angle, and the resulting scale effect between the bearing capacity of small models and field scale shallow foundations.

Over the past 50 years, physical modelling technology has evolved through to two key developments. The development of the centrifuge in the 1970s allowed the realism of physical modelling to be enhanced, through the correct modelling of self-weight stresses. The subsequent development of miniaturised electronics and micro-computers has led to enhanced methods of data acquisition, control, and image analysis. The refinement of these techniques continues to yield dramatic improvements in the utility of physical modelling. More realistic simulations can be conducted, and more detailed observations can be gathered.

Reviews of recent technological developments within physical modelling are described by Mayne et al. (2009) and White (2008).

Meanwhile, continuing cross-disciplinary efforts have led to wider recognition of definitive scaling laws to allow small scale physical models to be related to field scale conditions. TC104 has overseen the cataloguing of scaling law research. The initial publication of a TC2 (as TC104 was previously known) Scaling Law Catalogue (Garnier et al. 2007) has been followed by continuing development of this resource.

Proper application of scaling laws is vital when interpreting physical model tests for purposes (2) and (3) given on the previous page. If physical model test data is to be correctly linked to a field scale prototype, or to a numerical simulation, correct account must be made of the influences of size and timescale effects.

Scaling laws are well-established and straightforward to adhere to for small scale modelling of many geotechnical problems, particularly in fine-grained saturated soils. It is therefore no coincidence that physical modelling is a well-accepted technology in both research and design practice in offshore geotechnics, where soft normally- or lightly over-consolidated soils predominate. Recent state-of-the-art review papers have summarised many such applications (Martin 2001, White 2008, Gaudin et al. 2010).

For purpose (1), listed above, similitude and scaling laws are less significant, since the physical model might be an abstract component of the full system, or precise scaling of particular conditions may not be important. In this categorisation, we are referring to studies that aim to uncover a building block of the geotechnical system behaviour. Perhaps the overall system is not being modelled, or perhaps there is established theory to be tested. In the words of the title of the first Schofield Lecture, the aim might simply be to “*expect the unexpected*” (Bolton 2013).

It is this exploratory nature that makes physical modelling an attractive tool for many researchers and educators in geotechnics. By observing geotechnical systems in action, an intuitive understanding of soil mechanics can be gained, complementing the study of theory. Physical modelling tools for geotechnical education range from the venerable Hele-Shaw cell (Hele-Shaw 1898) to modern miniature – but highly instrumented – geotechnical centrifuges.

The Hele-Shaw cell provides solutions to seepage flow according to Darcy’s Law as a consequence of the Navier-Stokes equations simplifying for narrow planar flow. Henry Darcy studied in Paris – the venue of this 18<sup>th</sup> ICSMGE – at the Ecole Polytechnique and then Ecole des Ponts et Chaussées, before joining the Corps des Ponts et Chaussées. His most famous public work was the water supply system for Dijon. Appendix D of his published account of the Dijon works contains his report on the classic physical model tests in which the linear relationship between head gradient and flow velocity was identified. This work was published in 1856 and two years later Darcy died of pneumonia here in Paris.

Undergraduates studying geotechnics and fluid mechanics have faced Hele-Shaw cells for almost a century. Falling head permeability tests of the form analysed by Darcy in his classic work are standard undergraduate geotechnical laboratory experiments. Some of today’s undergraduates also have access to more sophisticated apparatus. These include miniature experiments that provide detailed measurements and observations of geotechnical constructions – often via bench-top centrifuges. These facilities provide opportunities to apply the analysis tools taught in lectures, completing the learning cycle through practical experience (Wartman 2006, Kolb 1984).

Meanwhile, to inspire the next generation of geotechnical engineering students, physical models are the most commonly called-upon facility within university departments to enliven events for school students. Physical models show engineering systems in action in a way that is immediately comprehensible.

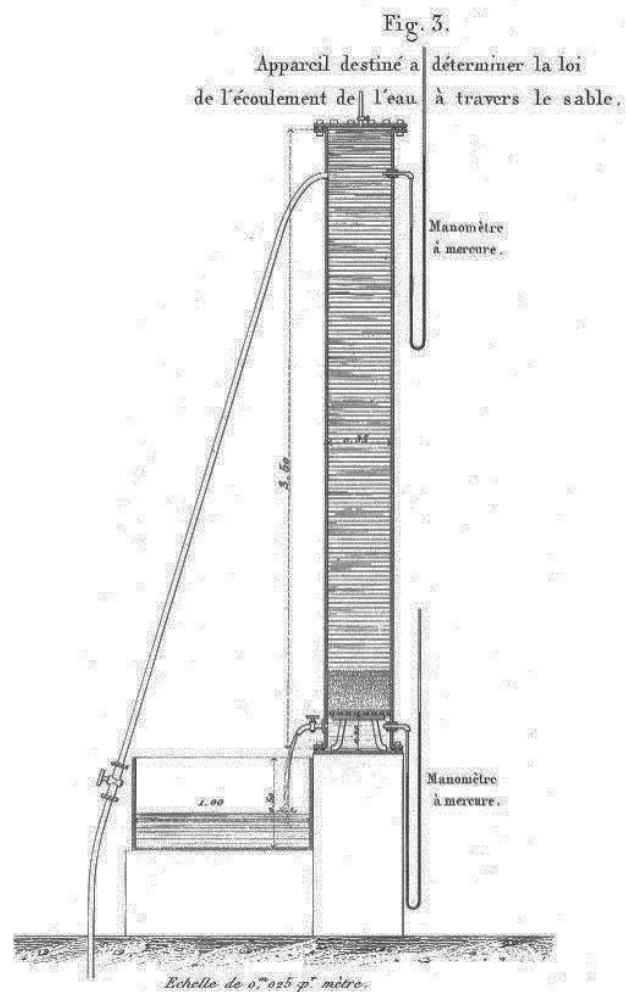


Figure 1. Darcy’s physical model for investigating flow in porous media (Darcy 1856)

The following review summarises and discusses many of the papers contributed to the 18th ICSMGE that fall under the TC104 session. The contributed papers have been divided into the physical modelling categories listed at the start of this report.

## 2 INSIGHTS INTO SOIL-STRUCTURE INTERACTION AND GEOTECHNICAL BEHAVIOUR

### 2.1 Reinforced ground

Several papers have focused on the performance of ground improvement systems utilising reinforced columns – either of cemented material, sand or stone. These systems are difficult to analyse, due to the complexity of the construction process and

the resulting uncertainty in the stress and strength within the vicinity of the column.

Physical modelling is particularly appropriate to investigate ground improvement considering the large resources required to undertake field scale testing and the complexity of numerical modelling: there is complexity associated with modelling of the reinforcement soil interface and of the process of reinforcement installation or construction. In some instances, the research undertaken has led to the development of very sophisticated testing technology, associated with the generation of the reinforcement or mechanism visualisation, which have provided insights that could not have been gained from other investigation techniques.

Ground improvement by the use of reinforced columns can be optimised by minimising the length of columns. They may not need to penetrate entirely through the soft layer.

Physical model tests reported by Tekin and Ergun (2013) compared the settlement of surface foundations on clay, reinforced by sand columns of varying length. The experiments featured a novel miniature extensometer arrangement. This used an antenna to detect magnets buried at multiple elevations within the sand columns. The efficiency was shown to depend on the length of the columns relative to the zone of loaded soil beneath the surface foundation. Columns that were too short settled with the surrounding foundation soil. Columns that extended deeper than the breadth of the surface foundation showed significantly less settlement. The vertical strain field measured by the extensometers supported these observations.

The theme of sand columns partially penetrating through clay continues in the paper by Sadek and Lattouf (2013). They performed drained triaxial tests on models of sand columns with varying volume ratio, relative to the full clay sample. The sand columns did not extend to the base of the clay. Careful exhumation of the samples after testing allowed the failure mechanism to be identified. The samples were treated as a single soil element in the interpretation. By fitting a Mohr-Coulomb failure envelope to the ultimate loads, the 'smeared' strength of the composite element was determined. These physical models essentially simulate a building block of a larger network of ground improvement columns.

The previous two studies focused on the in-service behaviour of a reinforcing column placed within a pre-bored hole in clay. Gautray et al (2012) focus more closely on the stone column construction process, through centrifuge modelling. Their aim was to examine the changes in column geometry and the pore pressures in the surrounding soil, as the compaction process evolves. Their tests include the full process of lance insertion – expanding a cased hole in the clay – followed by a cyclic retraction process whilst granular material is filled into the hole. Their data show the loading of the surrounding soil as the lance is inserted. The changes in pore pressure are significant. They are precipitated both by the initial insertion of the lance, and also by the lateral expansion of the granular column by the vertically-oscillating lance, during extraction.

After completion of the model construction process, the granular columns were loaded by a model foundation. The exchange from a column installation tool to a model foundation was made possible using the independent tool table of the ETH Zurich drum centrifuge. The model foundation was pushed into the ground, over the stone column, and the bearing capacity of the reinforced ground was identified. In this case, analytical solutions based on previous studies were able to bracket the identified capacity.

Two further systems for studying column-reinforced ground are reported. Houda et al. (2013) describe a modular experimental apparatus that has been developed to allow parametric studies, including cyclic loading events, to be imposed on improved ground – using combinations of columns and geosynthetics.

Takano et al (2013) describe a highly sophisticated system which allows grout columns to be constructed within a X-ray

CT scanner, providing data of the changes in density surrounding each grout bulb, as the column is constructed in increments. The sample container is also instrumented to calculate any changes in earth pressure coefficient. Subsequent centrifuge model tests, using a shaking table, demonstrate that the increased earth pressure coefficient leads to a reduction in the tendency to liquefy.

An alternative ground improvement system – the use of a cellular geosynthetic – is explored by Xu and Wang (2013). They describe investigations into the bearing capacity of footings on saturated granular soil, with and without geocell reinforcement. This ground improvement technology is relatively new development, and is most suited to reclaimed or filled ground. The geocell is laid on the ground then covered by fill. The tests showed that the geocell reinforcement serves to provide tensile capacity within the composite material. This changes the bearing capacity by altering the failure mechanism. The settlement around a surface footing becomes more bowl-shaped, rather than involving a punching shear mechanism. The punching shear is prevented by the tensile action of the geocell, which also serves to prevent tension cracks from opening adjacent to the footing.

These studies into ground improvement reflect the increasing need for urban developments and transport corridors to utilise poor ground, requiring mitigation measures to limit settlements.

## 2.2 *Shallow and deep foundations*

Several papers report experimental studies into the behaviour mechanisms of shallow and deep foundations. These focus on interaction effects – between pile base resistance and tunnels (Williamson et al. 2013), between pile base resistance and water jetting (Shepley and Bolton 2013) and between foundation and soil stiffness (Arnold and Laue 2013).

While loading of shallow and deep foundations can be undertaken relatively easily at full scale, physical modelling offers the possibility to investigate complex installation and interaction processes as illustrated in the examples below. The development of miniaturised electronics and sophisticated computer controlled motion systems, has enabled a continuously increasing realism of the modelling, providing invaluable insights into problems related to soil-structure interaction.

The complex experimental arrangement presented by Williamson et al. (2013) allows three model piles to be independently loaded, whilst a model tunnel is 'constructed' (through the simulation of volume loss) in the ground beneath. The effects of tunnel construction on overlying piled foundations is of increasing relevance as new urban railways – such as London's Crossrail project – burrow beneath existing buildings.

During these centrifuge experiments, the soil movements are watched intently by an array of cameras, allowing displacement fields to be generated through particle image velocimetry (PIV). These results allow the full soil deformation mechanism to be visualised – rather than gathering only boundary movements measured by instruments located at the edges of the model. The displacement field extending from the tunnel construction to disrupt the existing piles can then be observed.

Pile construction can also be disruptive to existing infrastructure, particularly if dynamic or percussive installation methods are used. An alternative is to install piles through a jacking method, and the limited capacity of hydraulic pile jacking machines can be countered by the use of water jetting to reduce the penetration resistance. Shepley and Bolton (2013) describe centrifuge experiments which investigated the effects of water jetting.

The interaction between water jetting and the penetration resistance in sands is complex. Jetting serves to locally raise the pore water pressure at the pile tip, whilst also potentially causing migration of fines. Both of these effects will ease

penetration, but the former is temporary whilst the latter may have an irreversible effect on the properties of the surrounding soil.

The model tests showed the variation in pile penetration resistance into saturated sand with jetting flow rate. The response is highly non-linear. There is only a modest reduction in resistance at low flow rates, until a significant fall in penetration resistance occurs. Full liquefaction appeared present during penetration at the highest flow rate, with negligible resistance encountered. Scaling of this behaviour is naturally very challenging, particularly if the response is due to both particulate (internal erosion) and continuum (effective stress reduction) effects.

Arnold and Laue (2013) describe an experimental study into the load distribution beneath surface foundations, and the influence of the relative stiffness between the foundation and the soil. Centrifuge model tests were performed with a vertical point load applied at the central point of the foundation. Two model foundations were used, with and without edge stiffening to represent building walls. The stiffer foundation shows a more even distribution of foundation-soil pressure. The same response is evident in field measurements using pressure cells built into building foundations.

### 2.3 *Flow-induced migration through porous media*

Truong et al (2013) describe a set of experiments using an apparatus which is somewhat similar to Darcy's (Figure 1). They have studied clogging effects during one-dimensional flow using a 2.5m long cylinder, 0.18 m in diameter. Unlike Darcy, they used electrical transducers to record flow rates and pressure, mercury manometers being general outlawed in modern laboratories. The experimental results show the inadequacy of assuming Darcian flow if the pore fluid introduces fine particles that may accumulate and block pores. The paper presents an example of steady flow through the tube, with a Darcian distribution of pore pressure. On injection of a bentonite slurry, the pore rapidly clog downstream of the injection point, causing a sudden rise in the upstream pore pressure.

These results are highly relevant to seepage through dams or embankments, where careful control of drainage is important to assure stability. The experiments illustrate that flow regimes and pore pressure distributions can be quickly altered if fine particles are transported within the pore fluid. The intrinsic permeability within Darcy's Law may be a material property, but fines migration can rapidly change the composition of a material, and therefore its properties.

Sarma and Sarma (2013) discuss the flow of cementitious material into the zone surrounding a bored pile. They report a detailed laboratory investigation which mimicked the bored pile construction process to evaluate the parameters controlling the thickness of the soil zone at a pile wall that is strengthened by the inflow of cementing products during construction. The distance of impregnation was identified by a novel staining method, in which the carbonated cementation products are highlighted. The subsequent measurements of impregnation depth are extremely detailed, and have been elegantly interpreted into a link between voids ratio and particle size.

### 2.4 *Reactive effects on soil behaviour*

Cardoso and Nogueira Santos (2013) describe a careful physical model of electrokinetically-enhanced consolidation behaviour. Their study is motivated by the potential use of electrokinetics to improve the efficiency of soft ground improvement, in combination with drains. They initially consider one-dimensional consolidation of kaolin clay, using a modified cell that allows a voltage to be applied across the sample. Improvements in the rate of consolidation are identified, with  $c_v$  increasing by a factor of 6, typically.

Subsequent tests use a larger Rowe cell, incorporating vertical drains that encourage radial and well as vertical flow. The electrical field is then applied between a central drain and the outer circumference of the sample. In this case the beneficial effect of the radial flow overshadows the benefit from the electrokinetic effect. The conclusion is that electrokinetics can enhance engineered consolidation of soft ground, but only in certain circumstances.

A similar study using a physical model of an element of cemented barrier cut-off wall is reported by Verástegui-Flores et al. (2013). Laboratory apparatus was modified to provide long term measurements of the permeability and small strain stiffness of cement-stabilised bentonite clay. This is a widely used material for barrier wall construction, but can suffer from deterioration through chemical attack. Two novel pieces of apparatus were developed to provide simple methods of measuring the shear wave velocity and, in the second apparatus, the permeability. The combined data of permeability and small strain stiffness over >250 days shows the effect of sulphate attack on the properties of the cement-stabilised soil. As the cement hydrates, the pores become blocked by cementation, which also raised the shear wave velocity. However, when sulphate is added, these processes are halted, based on the measurements. These new types of test allow the performance of specific stabilised soil mixes to be determined via simple laboratory tests that are more representative than conventional methods.

## 3 PERFORMANCE DATA TO CALIBRATE MODELS

### 3.1 *Seismic soil-structure interaction*

Several papers contributed to this 18<sup>th</sup> ICSMGE focus on the seismic response of slopes, and the estimation of pore pressure build-up and lateral spreading. The use of highly instrumented centrifuge models provides detailed evidence of the internal accelerations and pore pressures within the slope. The models are usually plane strain, with a transparent window allowing the soil movement to be observed.

Due to the inability to undertake seismic field experiments, physical modelling has been used extensively to investigate seismic soil-structure interaction, using both 1g shaking tables and on-board shakers in geotechnical centrifuges. The ability to recreate accurate dynamic loading conditions and to measure pore pressure generation and soil displacements have proven to be essential to provide data to calibrate models.

Haeri et al. (2013) report a centrifuge model test of a slope reinforced by a  $3 \times 3$  pile group, with a surficial non-liquefiable layer. During shaking, the soil liquefies and slides downslope, applying passive loading to the pile. The maximum loads occur at the start of the event, after the motion begins but before the soil is fully liquefied. As the degree of liquefaction increases the passive load reduces, although the load from the unliquefied layer persists.

Back-analysis of the lateral pressures and the resulting internal bending moment in the piles shows that the Japanese Roads Authority (JRA) design code provides good predictions of the maximum pile loading. However, the detailed distribution of load within a pile group is not considered in this code. The experimental data shows that significant shielding effects are present. The most heavily loaded pile was actually the downslope pile: the high load came not from the passive pressure from the upslope soil, but from the loss of active support on the downstream pile, as the downslope soil failed and slid away.

Higo et al (2013) report a study of embankment stability under seismic loading, using similar experimental techniques in a geotechnical centrifuge. They used a compacted clayey silty sand with the same composition as a material used to reinforce river levees in the Kansai region. Their study is focused on the

stability of a slope that is under steady state seepage conditions, with water emerging from close to the toe with the upper part of the slope being unsaturated.

A numerical back-analysis with a kinematic hardening plasticity constitutive model is performed, replicating many features of the physical model observations. In particular, both the physical and numerical models highlight how earthquake-induced excess pore pressures can lead to a rise in the water table and a loss of suction and strength in an unsaturated slope.

Moving to steeper slopes, Aklik and Wu (2013) describe a study of geotextile-reinforced walls, standing at angles of up to 85°. Model tests were performed using a geotechnical centrifuge to induce collapse of the slopes using the ‘gravity turn-on’ method. These simple tests explored the failure mechanisms within the slope and the embedded geotextile layers. A simple camera system was used to record frequent images as the slopes ‘grew in height’. The failure mechanisms were quantified through particle image velocimetry analysis. The failures were shown to occur above the toe of the slopes, and controlled by the spacing of the geotextile layers. This study illustrates how complex geotechnical systems can be investigated using simple rapid experiments in a compact geotechnical centrifuge, with image analysis providing detailed quantification of the soil failure mechanisms.

Dashti et al (2013) present a series of centrifuge model tests results exploring the performance of buried water reservoir structures, made from concrete. The test arrangement includes a novel transparent laminar shaking container which allows the internal deformation to be visualised. In addition, the end walls of the container have pressure pad sensors, to record the distribution of pressure during shaking.

The tests are performed with and without a buried structure, providing calibration data for 2D and 3D numerical models. Time histories from historic earthquakes are used as the input shaking motion, after filtering out frequency components that are irrelevant or would damage the centrifuge. The data from these tests is currently being used by the Los Angeles Department of Water and Power, to assess the seismic performance of existing and planned subsurface reservoirs.

### 3.2 *Ground improvement*

Two studies describe experimental work to determine benchmarking data for the performance of ground improvement techniques for enhanced seismic performance.

Bahadori et al. (2013) report a series of shaking table tests used to evaluate the performance of tyre chips as soil reinforcement to improve liquefaction resistance. The stiffness and damping properties of tyre-chip – sand mixtures are assessed through intensively instrumented physical model tests. A level ground surface was modelled, and the results from an array of accelerometers were used to derive stress-strain loops at different elevations within the soil. These loops allow the stiffness and damping ratio to be determined.

An alternative novel material to improve the seismic performance of structures is expanded polystyrene – known as geofoam. In the example application studied by Dave et al. (2013), a layer of geofoam is used at the rear of a retaining wall. Tests were performed on a ~1m<sup>3</sup> sample using the shaking table at IIT Bombay. A surcharge was applied at the top of the retained soil to mimic field scale stress conditions. Varying magnitude of shaking were applied, whilst the pressures and acceleration within the backfill and at the wall facia were recorded. This soft layer of geofoam served to reduce the ground accelerations felt at the wall, and lowers the lateral pressures generated within the backfill.

The final contribution on the topic of ground improvement, to calibrate new analysis methods, is a paper describing a new foundation system for embankments on soft soil. Detert et al. (2013) describe a hybrid structure comprising two parallel sheet pile walls connected by a tension membrane. The embankment

is constructed in top of the membrane, and undergoes reduced settlement due to the support from the membrane.

This system acts to reduce embankment settlements through a combined action. The sheet pile walls prevent spreading, whilst the membrane generates tensile forces when distorted, supporting the embankment and relieving the soft layer of load.

To validate this foundation system, parallel streams of research using complementary physical and numerical modelling have been undertaken. Physical modelling is particularly important since large deformations and a complex composite system are involved. However, once the mechanisms of behaviour are clarified, suitably calibrated numerical modelling is planned to allow the system to be optimised.

### 3.3 *Vibration screening barriers*

The final paper in this category is concerned with geotechnical barriers to insulate sensitive areas from vibrations created by railway traffic. Masoumi and Vanhonacker (2013) describe an experimental programme studying the transmission of vibrations through a bed of sand, ~10 m<sup>3</sup> in volume. Careful attention was given to bed uniformity and scaling laws, with the vibration frequency being scaled up to reflect the reduced scale of the experiment.

The impedance of the soil bed was first established by impact testing, to determine stiffness and damping parameters for subsequent numerical analysis. Vibration transmission tests were then performed using a line of accelerometers at the soil surface, and a surface foundation with a vibrating live load. Tests were performed with and without concrete isolation walls, which were shown to reduce the transmission of vibrations. The results were compared with complementary numerical results.

## 4 PERFORMANCE DATA FOR DESIGN AND OPERATION

### 4.1 *Pipeline protection from anchor dragging*

Offshore pipeline-soil interaction is a relatively new field of investigations, which has greatly benefited from the development of physical modelling techniques. The advantage in terms of resources and timescale compared to field testing is obvious. More importantly, the recent development of sophisticated motion control has enabled modelling of the full life cycle of a pipeline, from the 3D dynamic motion at the touch down zone during laying, to the on-bottom stability under storm loading and large ‘post-failure’ lateral sweeps under thermal buckling. The large database developed from physical modelling tests over the last five years has been used to develop analytical models now currently used in design (Gaudin & White 2009, White & Cathie 2011).

Pipelines that cross shipping lanes or lie in regions of intensive fishing often require protection from anchor dragging. If a ship anchor or fishing trawlgear snags a pipeline both may be damaged. Pipelines can be protected by burial, often with rockdump backfill.

To assess the required depth of burial, and the performance of the protection scheme, the interaction between a passing anchor and the backfill must be assessed. Physical modelling is commonly used for this purpose, since the large deformations and chain-anchor-backfill interactions must be properly accounted for.

A model testing arrangement that can be used to determine performance data for direct use in design is described by Bezuijen et al. (2013). An elongated centrifuge strongbox is used to allow significant lengths of anchor dragging to be simulated. A faithful reproduction of a ship anchor, manufactured by 3D printing, is attached to a miniature chain, and dragged over a model seabed. A pipeline is buried in a trench that has been back-filled with coarser material.

The paper compares results from tests performed at 1g and at 80g in the Delft centrifuge. The results can be compared using

well-established scaling laws, although a limitation is the assumption that the sandy soil behaves as a purely frictional material, with a constant angle of friction. The results show that such an approach does not provide similitude between the two tests. The 1g tests indicate higher scaled resistance, but reduced anchor penetration into the seabed – which is unconservative. This discrepancy could be due to the higher operative friction angle in the sand and gravel at 1g. Correct scaling is shown to be important when gathering design data for anchor-pipeline interaction.

#### 4.2 Open-pit mine stability

The stability of open-pit mines is investigated through physical modelling by Pipatsonga et al. (2013). This study was prompted by stability concerns at the Meo Moh mine in Thailand. A series of model tests was performed to investigate the mechanism by which arching across a steep cut slope provides additional stability, compared to the simple planar case.

The investigation comprised physical model tests performed at 1g and in a centrifuge using the gravity turn-on method, to identify different failure mechanisms. Slopes with supports of different geometry were constructed. Failure mechanisms included sliding and buckling of the undercut slope. The critical conditions for failure depended on the strength and stiffness of the buttressing supports.

These observations were used to calibrate simple design expressions for the conditions for failure. The results were immediately applied to the Meo Moh mine in Thailand, using site-specific characterisations data to provide input soil properties. The improved design of the open pit supports resulted in reduced requirements for excavation, transportation and dumping.

#### 4.3 Performance of dike monitoring systems

Physical modelling on an extremely large scale is reported by Keolewijn et al. (2013). They describe a set of field experiments which were focused both on understanding the geotechnical performance of the structures, and also on the performance of the monitoring systems. A set of 3.5 m high dikes were constructed at a soft ground test site in the north east of the Netherlands. The study trialled different proprietary systems for monitoring dike performance and providing data that can be used to guide flood protection activities. Real time monitoring of dike performance is important for safety and maintenance programming in the Netherlands. New technology for remote sensing and data transmission allow dike networks to be monitored continuously from a central control location.

Various forms of instrumentation, including piezometers, inclinometers, fibre optic strain gauges, synthetic aperture radar and thermal cameras were used to monitor the behaviour of the three test dikes during controlled impounding on one side. The dikes were constructed in different ways, to encourage different failure mechanisms, including basal piping, internal erosion and overtopping.

The monitoring systems used the data streams in different ways to assess the dike status and predict the onset of instability. In some cases, the data was linked in real time to finite element simulations. These physical model tests have proven successful in demonstrating the potential of these dike monitoring systems, some of which are now in use in other countries worldwide.

#### 5 CLOSING COMMENTS

The papers submitted to the TC104 session, and the physical modelling papers to the wider ICSMGE program provide contributions across the whole realm of geotechnical engineering. This report describes highlights, and provides a

broader commentary on the role that physical modelling plays in advancing research and practice in geotechnics.

#### 6 ACKNOWLEDGEMENTS

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