REMOTE INTELLIGENT GEOTECHNICAL SEABED SURVEYS – TECHNOLOGY EMERGING FROM THE RIGSS JIP

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Abstract
The Remote Intelligent Geotechnical Seabed Surveys (RIGSS) Joint Industry Project (JIP) is advancing geotechnical site investigation technology. The JIP is developing new types of tools with improved control and instrumentation, and new analysis methods to allow more direct application of data to geotechnical design. The JIP is motivated by three visions: (i) improved use of robotics and intelligent sensors to characterise the seabed, (ii) technologies that are simpler and cheaper to apply early in the project cycle, giving early information, and (iii) a trend towards 'direct design' from *in situ* test results, meaning that measurements can be scaled more directly to geotechnical design applications. Examples of improved site investigation technologies are highlighted. An example of ball penetrometer analysis is described, including dissipation solutions that show the ball can provide more rapid determination of consolidation coefficient than a standard cone penetrometer. A recent class of shallow penetrometer devices is described, which are rotated as well as pushed vertically, allowing a greater range of soil properties to be derived for the geotechnical design of pipelines. Finally, new hardware and interpretations for free fall penetrometers are shown. These advances improve the tools and interpretation methods available for seabed surveys. The sponsors of the JIP are Fugro, Shell, Total and Woodside Energy.

1. Introduction

The Remote Intelligent Geotechnical Seabed Surveys Joint Industry Project (RIGSS JIP) was initiated by the University of Western Australia (UWA) and is reaching the end of a three-year programme of activities. The JIP is developing new and improved techniques for *in situ* geotechnical investigation of the seabed. The focus is on the upper few metres of the seabed. This setting is particularly important for marine pipelines and cables covering extensive areas, where low-cost, remotely operated SI tools and smart testing techniques offer potential to improve efficiency.

The RIGSS JIP has pursued three 'visions', which are illustrated in Figure 1:

1. The RIGSS SI: a remote SI platform with robotic control of intelligent tools gathering parameters targeted towards design.
2. Earlier geotechnical definition in projects: leading to reduced uncertainty and risk, and a reduced need to carry multiple options through design.
3. Direct geotechnical design: a design philosophy using *in situ* test data more directly to determine the response of pipelines, foundations, and other geotechnical systems.

Work to date has been laboratory-based, with some tools deployed in the field for on-deck testing in box cores, and the tools have been designed with marinisation and on-seabed use as a target.

A particular focus is on shallow surveys over extensive areas, such as for pipelines, where low-cost, remotely operated SI tools and smart testing techniques offer potential to improve efficiency and deliver more valuable data.

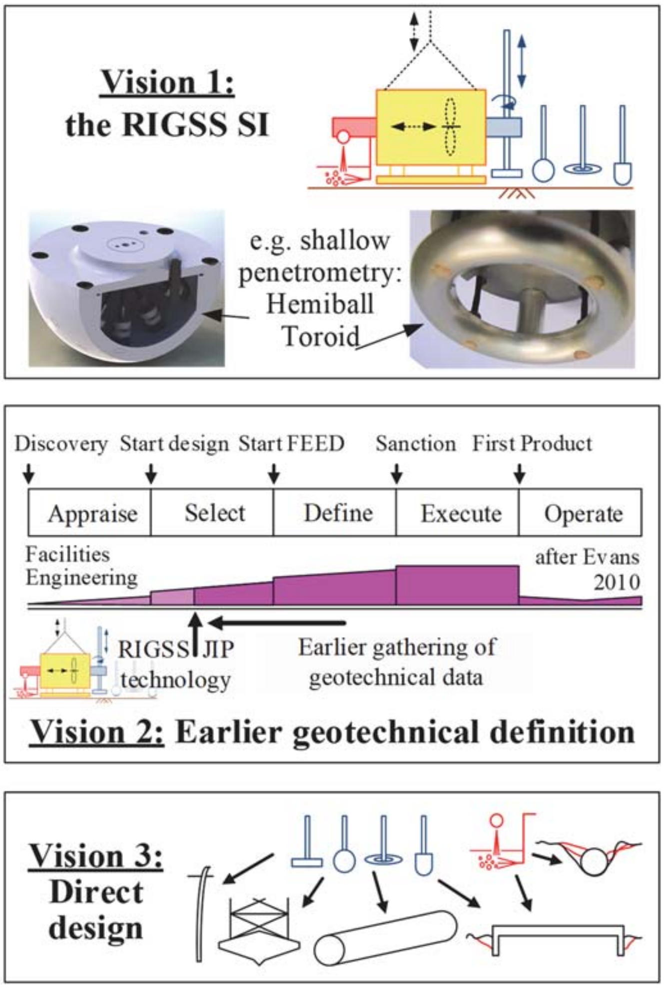


Figure 1: RIGSS JIP motivations

The conventional elements of a geotechnical site investigation, leading to geotechnical design, are shown in Figure 2. This figure also illustrates the two general ways in which the RIGSS JIP tools can improve the process. Remote tools – such as free fall penetrometers – gather large quantities of data rapidly. The results generally need conversion or scaling to conventional *in situ* test parameters, to feed into the design process. Intelligent tools – such as the shallow penetrometers – give data that can be more directly fed into geotechnical design, reducing the timescale and uncertainty associated with the design outcome. For example, by direct measurement of pipeline friction, via pipe-like shallow penetrometers. Or, by scaling T-bar or ball penetration resistance directly to spudcan penetration resistance (e.g. Erbrich, 2005).

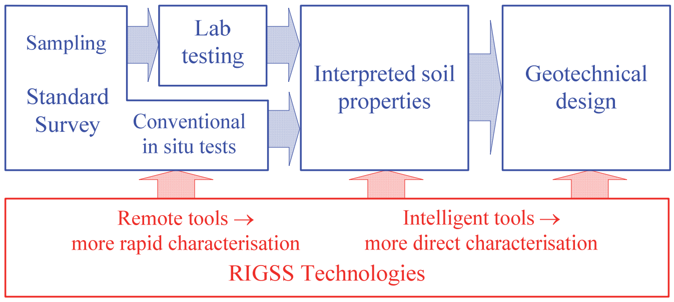


Figure 2: RIGSS technologies relative to conventional SI

2. Tools advanced by the RIGSS JIP

The main tools advanced during the RIGSS JIP are outlined in *Table 1*, along with the key advantage that each offers relative to conventional practice and the most relevant design applications.

3. Piezoball Penetrometer

The piezoball penetrometer provides a profile of intact strength and it can be used for both dissipation tests (to determine coefficient of consolidation, c_h) and cyclic tests (to determine remoulded strength).

New solutions to interpret the pore pressure dissipation response to determine the consolidation coefficient have been derived numerically (Mahmoodzadeh et al. 2015) and validated via field measurements (Colreavy et al. 2016). Testing has shown that the mid-face pore pressure transducer position yields rapid dissipation.

The pore pressure dissipation around a piezoball is more rapid than around a cone when expressed in terms of dimensionless time, $c_h t/D^2$ (where D is the device diameter). This is due to the three-dimensional shape of the tool and the top-to-bottom direction of flow.

Table 1: Tools advanced by the RIGSS JIP

Tool	Key advantages over conventional tools	Most relevant applications
Free fall penetrometers	Rapid deployment and retrieval	Pipelines, trenching/ploughing/burial assessment, shallow foundations, suction caissons
Piezoball penetrometer	Cyclic and dissipation capability gives intact and remoulded strengths, plus coefficient of consolidation	Shallow foundations, suction caissons, piles, pipelines
Toroid penetrometer Hemiball penetrometer	Vertical and torsional actuation gives interface strengths (undrained and drained) as well as soil strength and consolidation properties	Pipelines Shallow foundations
Parkable piezoprobe Multi-PPT lance	Provide near-surface measurement of consolidation coefficient and do not require actuation after deployment, allowing simultaneous operations (SIMOPS)	Pipelines Shallow foundations
In situ erosion flume	Measures erosion properties (e.g. for scour) at seabed, without sample disturbance	Scour prediction and mitigation, self-burial assessment: for pipelines, shallow foundations, piles

Figure 3 compares dissipation times for a range of in situ tools, including standard ones and those developed within RIGSS. The chart is based on a compendium of theoretical and numerical solutions for pore pressure dissipation around the various different devices. The vertical lines show published values of c_v or c_h for a range of locations worldwide.

The t_{50} dissipation times for the 80 mm and 60 mm diameter piezoball penetrometers are 2% and 42% quicker than a standard CPT. The most rapid method of determining c_h is the 1 cm^2 cone-tipped piezoprobe (Peuchen and Klein, 2011) – a specialised tool for measuring this property – which is ten times faster than a standard CPT.

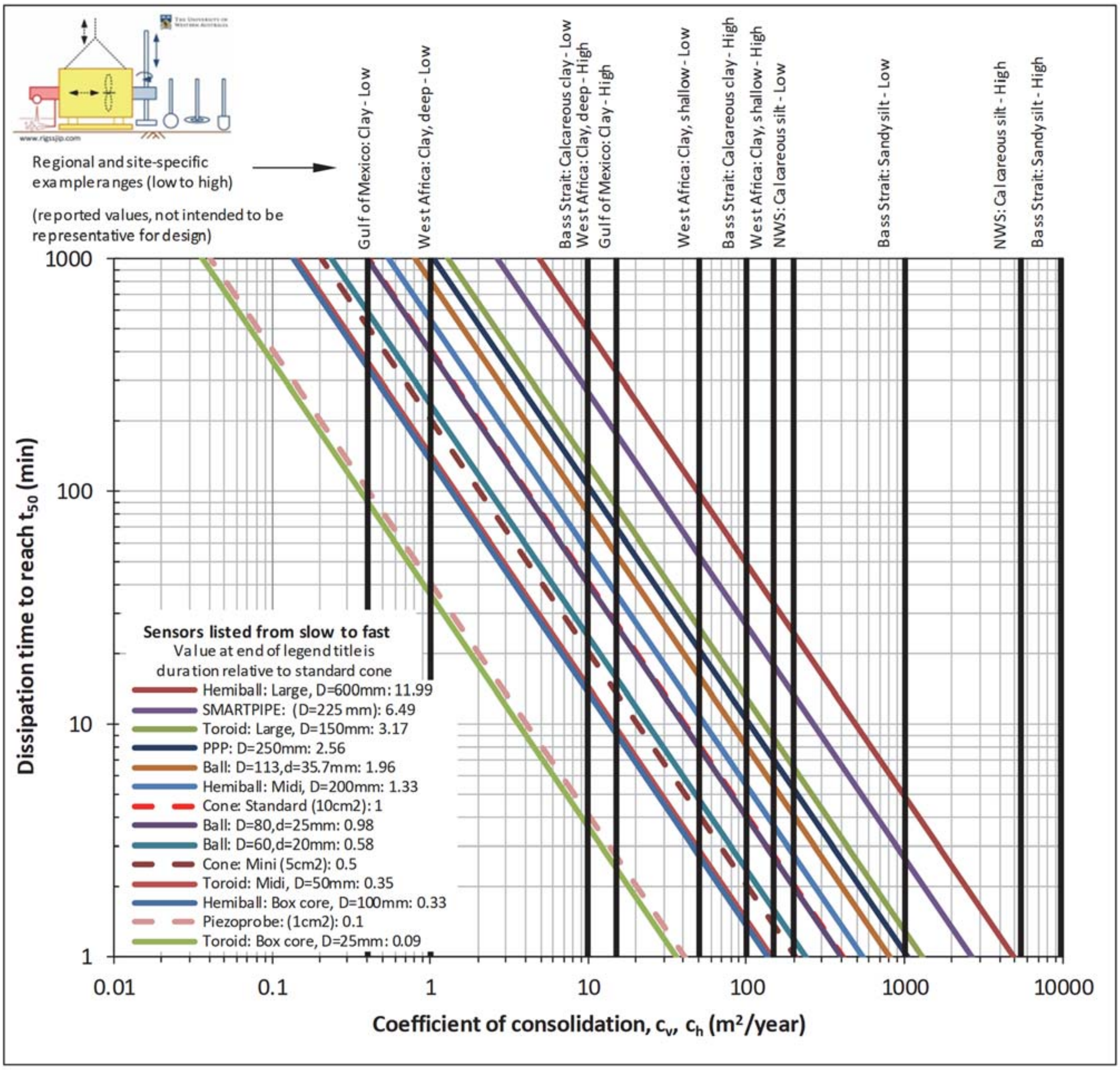


Figure 3: Comparison of timescale required by different tools for determination of consolidation coefficient

4. Shallow penetrometers: toroid and hemiball

The toroidal and hemispherical ('hemiball') penetrometers were first described by Yan et al. (2011). These devices resemble a pipeline and are actuated by a robotic motion control system. The aim is to subject the seabed to a stress path and loading history that replicates the real conditions around a pipeline, therefore deriving measurements that can be easily scaled to the design scenario.

A test involves penetration to a depth of less than a diameter followed by one or more stages of rotation under maintained vertical load. The soil-interface resistance is measured by the torque on the device. Dissipation stages allow the consolidation coefficient to be determined. The rotation stages are designed to deduce both drained and undrained interface strengths.

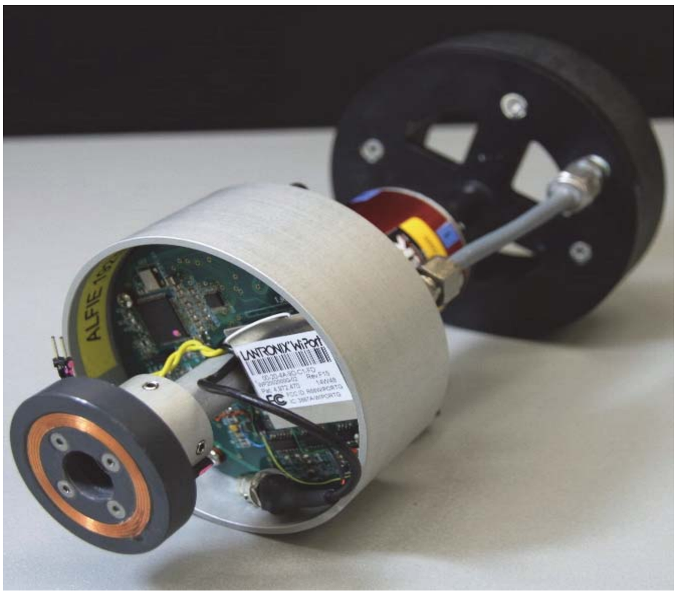
The shallow penetrometers can be conceived at two scales. A 'full scale' device has comparable dimensions to a pipeline, and is deployed at the seabed from a frame (similar to the Fugro SMARTPIPE system, Hill & Jacob, 2008). A box core scale device is deployed on deck for testing in a box core (similar to the Fugro DECKSCOUT system, Borel et al. 2010). Versions of these penetrometers scaled for use in box cores have been built by the RIGSS JIP, and used successfully on the deck of an offshore survey vessel, testing on the surface of box cores samples.

The actuation system for box core shallow penetrometer testing is shown in Figure 4a and the box core toroid penetrometer is shown in Figure 4b. The actuator has a motion control system that operates in load-controlled and displacement-controlled modes. This allows the dissipation stages to be performed under constant vertical load, with the penetrometer automatically advancing as the consolidation settlement accumulates. The penetrometer is equipped with four pore pressure transducers around the invert and has an onboard data acquisition unit to minimize cabling and signal noise. The motion control and data acquisition systems have evolved from UWA's geotechnical centrifuge systems (Gaudin et al. 2009, De Catania et al. 2010).

The box core shallow penetrometers have been trialled on reconstituted kaolin and carbonate silt samples at UWA. The system has also been taken offshore, for field trials on a survey by the RIGSS JIP partners, and operated successfully. Field use is more challenging than laboratory use since real box core samples are not as uniform or flat-surfaced as lab samples, so careful interpretation of the penetrometer embedment is required. Also, the back deck of a survey vessel is a more challenging environment, for example due to vessel motions and changes in ambient temperature, as well as schedule pressures associated with an ongoing campaign. However, a successful field trial has shown that these issues do not prevent the data being gathered. To date, the testing equipment has required operation by a researcher familiar with the equipment and software controls. As the technology evolves, a simpler and therefore more commercially practical system will be evolved. The system would then be available on a basis similar to the existing Fugro DECKSCOUT and other in-box-core penetrometer systems.

The results from a typical pair of hemiball and toroid tests conducted in the UWA laboratory using kaolin clay samples are shown in Figure 5 to Figure 8. The vertical penetration stage is interpreted via bearing capacity theory to determine the soil strength. The measured resistance is shown in Figure 5a. The response is then interpreted using solutions for the variation in bearing factor, N_c, with depth and normalized soil strength gradient, that are expressed analytically and derived from numerical simulations (Stanier & White, 2015).

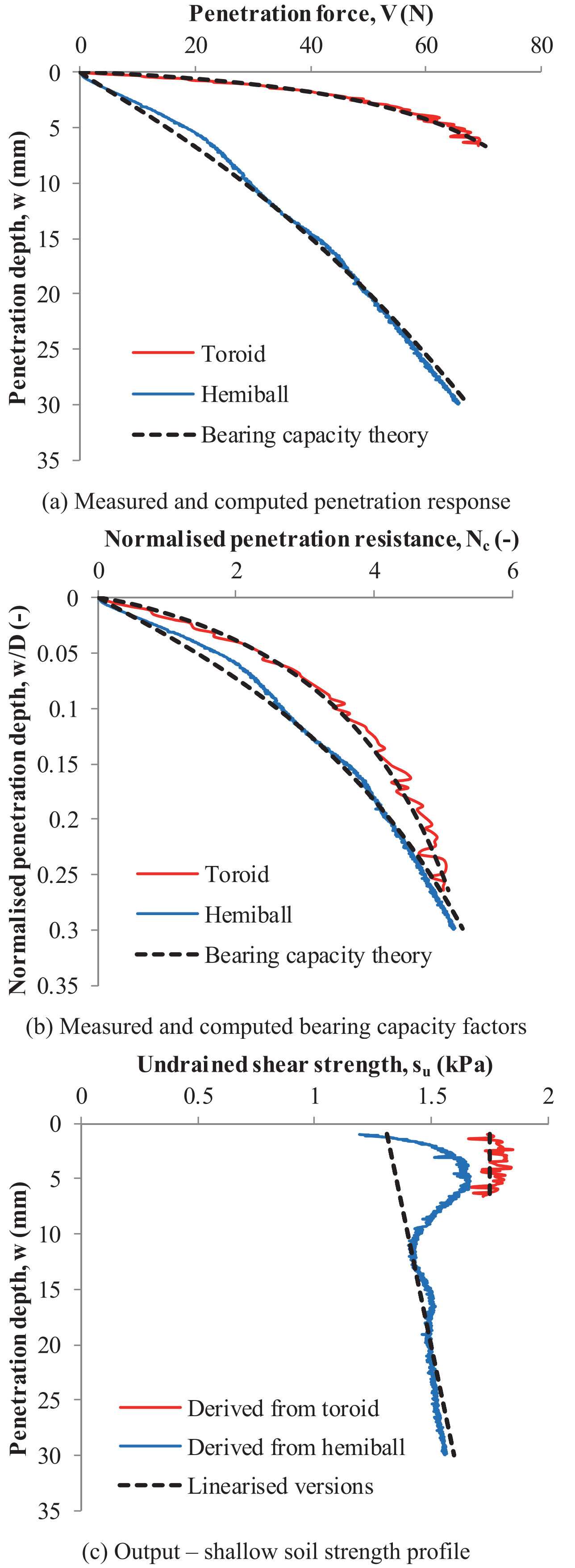
(a) Robotic actuator with toroidal penetrometer



(b) Box core-scale toroidal penetrometer, with onboard DAQ

Figure 4: Box core-scale shallow penetrometer equipment

Figure 5b shows the profile of bearing factor, N_c, with depth from the experimental data assuming the linear soil strength profile shown as dotted in Figure 5c. Conversely, Figure 5c shows the derived strength profiles assuming the theoretical profiles of N_c shown dotted in Figure 5b.



(a) Measured and computed penetration response

(b) Measured and computed bearing capacity factors

(c) Output – shallow soil strength profile

Figure 5: Shallow penetrometer vertical penetration response

The profiles from the two penetrometers are in close agreement with each other, and with the theoretical strength based on the stress history of the soil sample, which was prepared by consolidation under a surcharge.

After penetration to the target depth, a dissipation stage under constant vertical load is performed. The resulting dissipation curves are shown in Figure 6. Numerical solutions have been developed to interpret this stage to derive the coefficient of consolidation. The t_{50} durations for the toroid and hemiball tests were around 10 minutes, in these tests on a kaolin clay with a consolidation coefficient of ~ 10 m^2/year.

The aim of the rotation stage is to measure the undrained and drained interface strengths, for soils where both conditions are of practical relevance. In addition, the transition between these two values is recorded, either during continuous rotation, or through multiple episodes of undrained rotation interspersed with consolidation. These measurements provide the parameters required for assessments of axial pipe-soil friction, as well as the sliding resistance of shallow foundations.

Results from a continuous rotation stage are shown in Figure 7. The rotation response is fitted by three parameters which are the inputs to industry-standard models for axial pipe-soil friction (White et al. 2017). The initial resistance indicates the interface undrained strength. For these tests, this corresponds to the normally-consolidated interface undrained strength, controlled by the strength ratio, $(s_{u\text{-}int}/\sigma'_n)_{nc}$. The final resistance indicates the drained interface friction ratio, tan δ (where δ is the interface friction angle). The timescale of the transition indicates the consolidation coefficient.

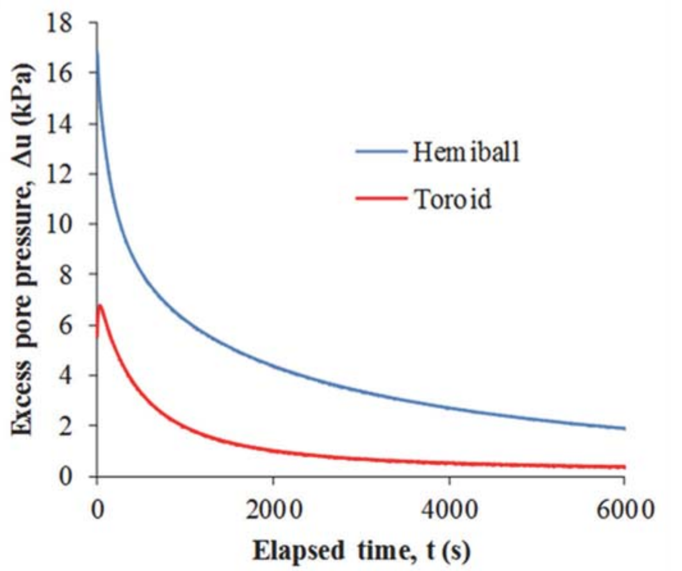
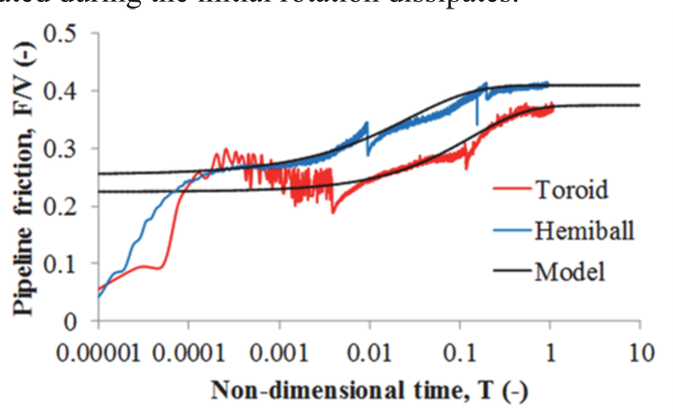


Figure 6: Shallow penetrometer dissipation test with load-hold

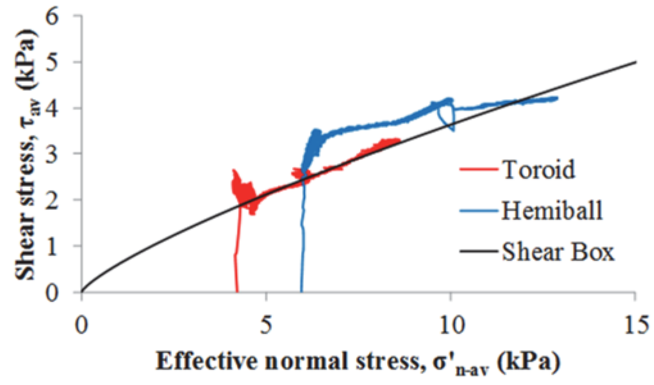
The rotation stage is performed in three steps, with reductions in rotation speed between each step. This allows the initial undrained resistance to be fully mobilised in a short period of time (before being affected by consolidation), but the extra rotation prior to reaching the fully drained resistance is minimal, which prevents excessive settlement of the tool.

Figure 7a shows the torque converted to equivalent friction on a pipeline at the same normalised embedment, by dividing by the effective radius of the device. The black lines show the fitted profiles based on the industry-standard axial friction model. The difference between the results for each device is due to the difference in embedment and therefore the friction wedging factor (White & Randolph, 2007).

The hemiball and toroidal penetrometers are equipped with pore pressure transducers, which record the excess pore pressure during the rotation stages. These measurements can be used to convert the recorded vertical load and torque responses into an effective stress profile in normal stress – shear stress space, as shown in Figure 7b. These results are in close agreement with a non-linear failure envelope derived from drained interface shear box testing using the same soil and interface material. During the rotation stages, the effective stress path moves to the right as the shearing-induced excess pore pressure generated during the initial rotation dissipates.



(a) Transition of interface resistance due to drainage

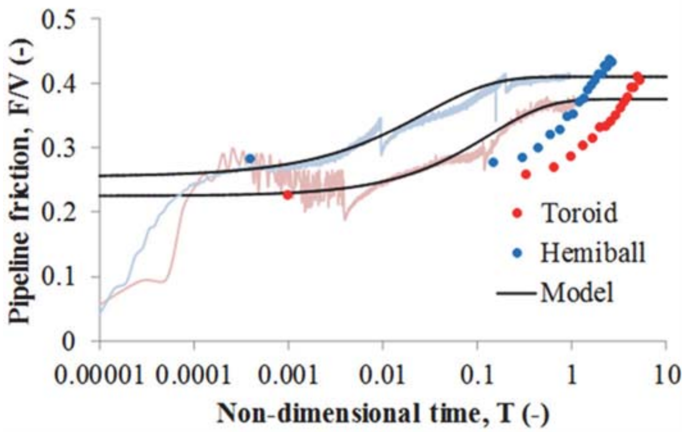


(b) Derived effective stress path

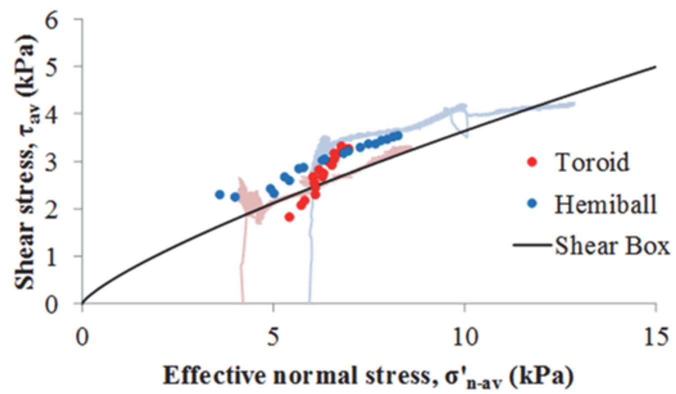
Figure 7: Shallow penetrometer test: continuous rotation stage

Additional results are shown to illustrate an alternative rotation stage that involves episodes of rapid (undrained) rotation, interspersed with dissipations. This sequence mimics a pipeline subjected to cycles of thermal expansion and contraction in operation. The steady resistance rises with each rotation, and is shown by the markers on Figure 8a (overlain on the data from Figure 8a) and Figure 9. The effective stresses match the continuous rotation case (Figure 8b). The episodic response is expressed in Figure 9 via a drainage index, ψ, rising from zero to unity from the initial undrained to the final drained resistance. In this case, ψ = 0.5 is reached after 6 cycles.

These examples show that shallow penetrometers are uniquely able to determine the key near-surface soil parameters required to estimate pipeline friction.



(a) Transition of interface resistance due to drainage



(b) Derived effective stress path

Figure 8: Shallow penetrometer test: episodic rotation stage

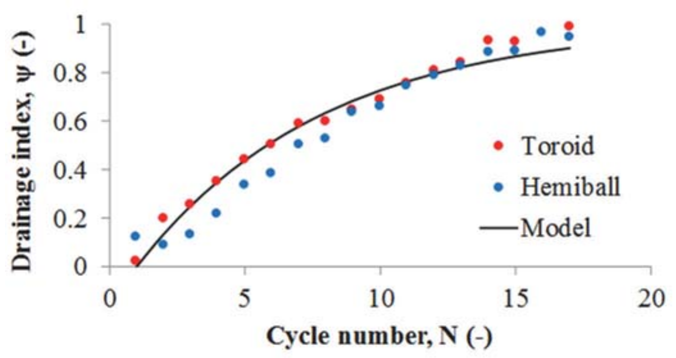


Figure 9: Transition of undrained resistance to drained limit

5. Free fall penetrometers (FFPs)

The RIGSS JIP has also pursued new designs and new interpretations of free fall penetrometers. The RIGSS free fall penetrometers use the miniature inertial measurement unit (IMU) shown in Figure 10a. The unit is equipped with three axis MEMs accelerometers and gyros, from which the full three-dimensional motion of the system can be derived (Blake et al. 2016). Trials using the IMU within a free-falling sphere (Morton et al. 2016) have been performed in the East China Sea (Figure 10b). These were successful despite a strong current making deployment challenging, but drag force on the recovery line did hamper interpretation.

(a) Inertial measurement unit

(b) Field testing of a free falling sphere in the East China Sea

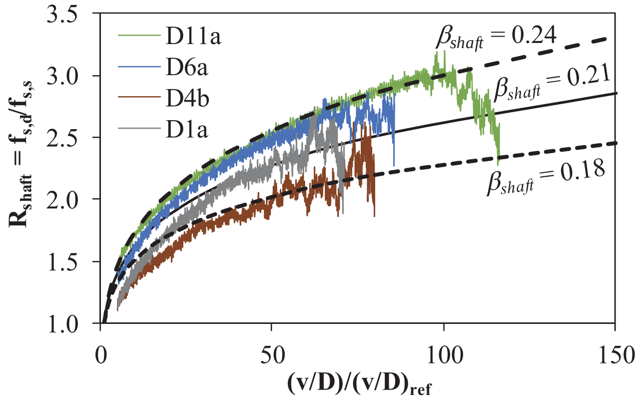
Figure 10: Free fall penetrometer equipment

Improvements to the interpretation methods for free falling penetrometers have been developed. These have focused on rigorous quantification of the drag and buoyancy forces acting on the penetrometers in both the water (prior to impact) and in the soil, which must be discounted to derive soil strength accurately.

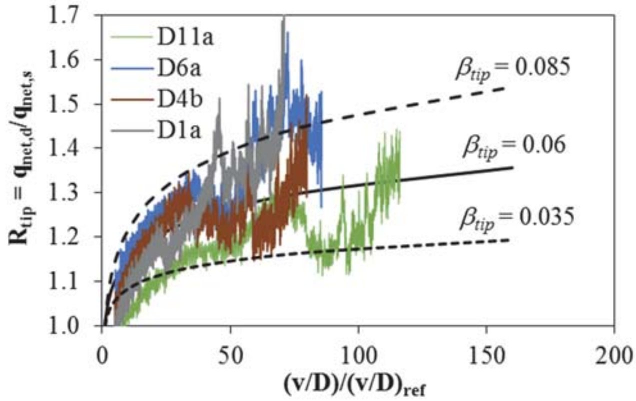
In addition, tests using a miniature instrumented free falling cone penetrometer in the centrifuge have shed light on the difference in rate effect on the shaft and tip resistance. The tip ($q_{net(d)}$) and shaft ($f_{s(d)}$) resistance during dynamic (free fall) penetration of the cone have been compared with the static resistances on the same device ($q_{net(s)}$, $f_{s(s)}$) pushed in statically at a reference velocity, v_{ref}. The rate effects are quantified by the parameters, β_{tip} and β_{shaft}:

$$R_{shaft} = \frac{f_{s,d}}{f_{s,s}} = \left(\frac{v/D}{(v/D)_{ref}}\right)^{\beta_{shaft}}, R_{tip} = \frac{q_{net,d}}{q_{net,s}} = \left(\frac{v/D}{(v/D)_{ref}}\right)^{\beta_{tip}} \quad (1)$$

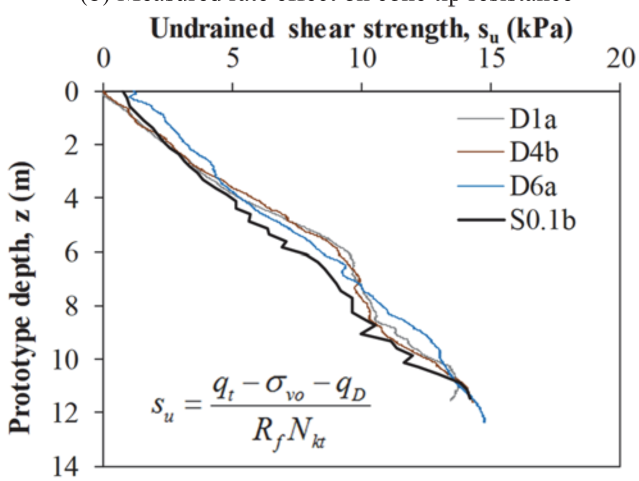
where v/D represents the strain rate, and allows scaling between objects of different diameter, D. A higher rate effect is observed on the sleeve friction (Figure 11a) compared to the cone tip resistance (Figure 11b), with the latter being comparable to the effect seen in laboratory element tests. This unexplained phenomenon highlights the value of using a load cell for tip resistance to determine soil strength rather than attempting to interpret strength from the deceleration of a slender FFP. Consistent profiles of s_u from static and free fall cone penetrometer tests in the beam centrifuge are shown in Figure 11c (Chow et al. 2017).



(a) Measured rate effect on cone shaft resistance



(b) Measured rate effect on cone tip resistance



(c) Comparison of s_u profiles from static and free fall CPTs

Figure 11: Free fall centrifuge CPT results (Chow et al. 2017)

6. Summary and Conclusions

The RIGSS JIP has advanced the development of a series of tools for geotechnical seabed surveys, with two aims in mind: the use of remote technology to derive a greater volume of data more rapidly, and the development of intelligent tools to derive better data, more directly suited for application in geotechnical design. For each type of tool, the JIP has refined the design and instrumentation, devised a test protocol that maximises the quantity and quality of data gathered, and developed the test interpretation to best derive geotechnical parameters from the measurements.

This paper shows some results from the JIP activities. The comprehensive capabilities of the piezoball penetrometer have been highlighted. A set of results from box core-scale toroid and hemiball shallow penetrometers display their ability to determine pipeline design parameters. Improved free fall penetrometer interpretations are shown, based on centrifuge tests.

The JIP deliverables include recommended practices for planning, executing and interpreting tests using the new tools. To help transfer these technologies into practice, the JIP partners are provided with engineering drawings of the tools and bespoke software that implements the derived interpretation methods. Field trials using some of the tools are already underway.

This JIP represents a step towards utilisation of the capabilities offered by remote and autonomous technologies in offshore site investigation. A future can be envisaged in which shallow geotechnical investigations are performed by AUVs, equipped with intelligent micromachines carrying tools that probe the seabed in a manner designed to mimic construction and operation, giving measurements that are directly applicable in design.

7. Acknowledgements

The RIGSS JIP sponsors are Fugro, Shell, Total and Woodside Energy. In addition, David White and Mark Randolph have been supported by the Shell Chair in Offshore Engineering and the Fugro Chair in Geotechnics, respectively. This work forms part of the activities of the Centre for Offshore Foundation Systems at UWA, currently supported as a node of the ARC Centre of Excellence in Geotechnical Science and Engineering.

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