D1.1 FUNDAMENTAL ASPECTS OF VERTICAL AND HORIZONTAL CONSOLIDATION IN A MULTI-LAYERED SOIL SYSTEM

D1.2 Project Quality and Innovation (50%)

D1.2.1 Aims

With the dramatic increase in capital and maintenance dredging along the coast of Australia, there is an urgent need for a sustainable solution to the enduring question: *What should be done with the millions of tonnes of dredged waste?* In the last thirty years, this has emerged as one of the most crucial issues related to dredging. For example, the Great Barrier Reef Marine Park could be pressured to accept more than 100 million tonnes of dredged waste due to plans to expand coal production and port facilities in Central Queensland (Lloyd 2012), which critically threatens the existing marine life. Ultimately, a solution that furthers economic development whilst protecting the environment is desired. Currently, the primary method of waste disposal involves dumping millions of tonnes of dredged material at sea, a 'solution' which neither protects the environment, nor furthers economic development. A land-based management alternative for dredged material known as land reclamation not only satisfies environmental and economic criteria, but helps resolve issues such as population overcrowding and the need for coastal port expansions, by *creating new land*.

Land reclamation is carried out by first erecting permeable containment bunds (or seawalls), into which fill material is placed. Over time, seawater drains from the contained fill until sufficient bearing capacity has been achieved to allow surface loading. Ideally, coarse-grained material such as sands and gravels would be used as placement fill in land reclamation operations due to their attractive drainage characteristics. However, these types of fill are scarce and costly in comparison with the cheap and extremely abundant dredged waste. Unfortunately, this dredged material comprises fine-grained soils such as clays and silts with extremely *poor* drainage characteristics, which drastically increases the length of time required for sufficient drainage to be achieved. This problem is further compounded by the already existing issue commonly encountered when reclaiming land in the direction of the sea – the foundations upon which the dredged material would be placed often comprise soft alluvial and marine clay deposits with extremely low bearing capacity and a propensity for large settlements. It is therefore imperative that both the dredged material *and* underlying clay deposits be stabilised before infrastructure development. This requires a comprehensive understanding of the mechanics behind consolidation of this two-layered soil system so that both the magnitude and duration of pre-construction settlement can be accurately predicted.

Soft marine clays are abundant across the east coast of Australia where most of the infrastructure development is taking place, and it is therefore paramount that current methods of settlement predictions be perfected wherever possible. *The aim of this interdisciplinary project is to develop an analytical framework for predicting settlements in soft soils, such as the two-layered system where dredged mud contained in reclamation paddocks is underlain by thick deposits of soft Holocene clays. The analytical framework developed over the course of this project will account for:*

1. *Anisotropy of the permeability and compressibility characteristics of the soil, along with variations in soil properties with depth caused by the sedimentation process*
2. *Non-uniform distributions of pre-existing excess pore water pressures*
3. *Partial drainage boundaries (where the boundaries are neither free-draining nor impermeable)*
4. *Multiple layers of consolidating soil similar to the two-layered soil system discussed above*

5. *Time-dependent surcharge loading which replicates field loading scenarios without assuming instantaneous loading (which is assumed in traditional consolidation analyses)*
6. *Two- and three-dimensional consolidation that represents field scenarios*
7. *Degree of heave associated with unloading*
8. *Secondary compression with particular emphasis on the overconsolidated state*

The post-construction settlement required in the design of foundations is a combination of the settlement components due to consolidation processes unique to each of the two layers. The presence of vertical drains installed to accelerate the drainage process, and the free-draining nature of the bunds separating the paddocks make the consolidation process three-dimensional. The non-uniform pore pressure distributions, soil variability with depth, and time-dependent loading resulting from dredged mud placement complicate the problem even further.

It is proposed to carry out an extensive laboratory testing program including sedimentation columns, oedometer tests with pore pressure measurements, and model tests replicating the containment paddocks with two-layer soil systems. The laboratory studies will be complemented by numerical modelling carried out using FLAC, an explicit finite difference code, and further mathematical modelling in MATLAB where the governing partial differential consolidation equation will be solved. Possibilities of developing a holistic computer program that will account for any or all these factors will be explored.

D1.2.2 Background

<u>Land reclamation</u>

Port cities and other coastal areas are central hubs for economic growth and prosperity. The continuous influx of people to these coastal regions perpetuates a consistent need for land expansion. Often natural geographic and environmental limitations prevent inland expansion which inevitably leads to the sole remaining option of expansion in the direction of the sea. Ports require deep waterfronts for shipping berths with adjacent land for port facilities, a land-sea combination that rarely occurs naturally. As a result, capital dredging is often employed to create navigable sea channels alongside existing port infrastructure. Maintenance dredging is then required to ensure previously dredged channels, berths or construction works are maintained at their designated dimensions. If the material dredged from these operations could be subsequently used as reclamation fill, the issues of waste disposal and space demand can be simultaneously resolved. However, with this solution comes a new problem; dredged fill at high water content has little to no bearing capacity and requires extensive stabilisation prior to the construction of industrial facilities and urban development. Here, future settlements of both the deposited material and underlying soft clay are mitigated using ground improvement techniques such as surcharge preloading or prefabricated drain installation. By examining the different stages of land reclamation, factors which significantly influence the settlement behaviour of the two-layer system can be identified. In this case, land reclamation operations currently underway at the Port of Brisbane can be used as an example. A standard geographical profile at the Port of Brisbane comprises two consolidating layers; freshly sedimented dredged mud underlain by a thick layer of Holocene clay. A thin ‘capping’ layer of sand is often found above the dredged mud, whilst the Holocene clay is underlain by Pleistocene, a stiff over-consolidated clay interspersed with sand and gravel (Berthier et al. 2009).

Prior to ground improvement, the dredged material is pumped into containment paddocks in slurry form with solids concentration of 2-5% by weight. Currently, the reclaimed land at the Port of Brisbane contains reclamation paddocks at various stages of ground improvement. Older paddocks located closer to the mainland comprise a surface layer of sand (with or without vertical drains) which is surcharging the underlying dredged mud and Holocene clay. Newer paddocks are encountered as the port expansion progresses further out to sea, which contain recently pumped dredged mud where excess seawater is being allowed to drain through surrounding rock walls. The boundary conditions and mechanisms affecting consolidation of the dredged material and underlying marine clay will vary according to the type of ground improvement technique used. These factors must be identified and incorporated into the analytical model.

Sedimentation/consolidation process

Immediately after the dredged mud is pumped into a containment paddock, the suspended soil particles gradually settle, thereby forming a soil layer at the base of the paddock which subsequently undergoes consolidation under its own weight. The extremely high water content of the deposited slurry facilitates grain size sorting as the particles settle. As a result, the permeability of the segregated soil profile can be expected to increase with depth, thereby requiring consideration of *variable soil properties*. Furthermore, the dimensions of the rectangular containment paddocks into which the slurry is pumped are finite. The permeable paddock walls allow horizontal drainage to occur which equates to a *three-dimensional consolidation* problem. As the containment bunds sustain continuous traffic, the permeability of the rock walls actually deteriorates over time. Therefore, three scenarios must be considered; initially freely draining containment walls, intermediate *partially draining* walls, and finally, impermeable walls, where drainage is allowed in the vertical directly only. In addition to variable soil properties and three-dimensional drainage, a *non-uniform initial excess pore water pressure distribution* at the beginning of the consolidation process can also be expected. This is due to the nature of soil deposition, where excess pore water pressures increase in direct proportion with soil depth.

Ground improvement

Once a considerable portion of seawater has drained from the paddock, the dredged mud has developed sufficient bearing capacity to withstand an application of surcharge, usually in the form of sand fill. Surcharge preloading is one of the most successful and commonly used techniques for improving the shear strength of soft soil, where application of a surcharge and its subsequent removal reduces the post-construction settlement. However, in order to control the development of excess pore pressure, the surcharge embankment is usually applied in stages, with rest periods between each loading stage. Thus, the analytical model must be capable of incorporating *time-dependent loading*. Once the surcharged soil has reached the desired settlement, the sand fill is removed in preparation for infrastructure. This *unloading* can cause the underlying soil (both dredged material and Holocone clay) to expand or *heave*, a reverse-consolidation process that can critically affect subsequent construction operations.

The installation of prefabricated vertical drains (PVDs) is another widely-used ground improvement technique. The duration of consolidation is essentially dictated by the square of the distance the water must travel to exit the soil. A PVD simply shortens the drainage paths through which water may discharge and, depending upon the number and spacing of PVDs, consolidation within the Holocene layer can be primarily governed by horizontal drainage. When considering analytical and numerical models, this arrangement can be reduced to a *two-dimensional* plane-strain model allowing both horizontal and vertical drainage (Indraratna and Redana 1997). Analysis of the settlement behaviour of either layer (dredged material or Holocene clay) irrespective of contiguous soil is complex. Understandably, analysis of the problem as a whole (i.e. *multi-layered system*) is greatly complicated by the interaction between layers.

Consolidation theory

The Theory of Consolidation developed by Dr. Karl von Terzaghi (1925) could be argued as the most significant theoretical contribution that has been made to soil mechanics since its inception in the 1930s (Taylor and Merchant 1940). In its most basic form, the solution to Terzaghi's consolidation equation quantifies the decay of excess pore water pressure during consolidation, assuming the following conditions hold true; drainage occurs in the vertical direction only, soil properties are uniform throughout the soil layer, drainage boundaries are absolute (i.e. either drained or undrained), and most importantly, the existence of a linear relationship between stress and strain. Due to the complex nature and behaviour of soils, results obtained using this solution often fall short of the high standard of accuracy required for engineering estimates.

Since the advent of Terzaghi's one-dimensional consolidation theory, substantive research has been conducted to develop a solution to the complex phenomenon of consolidation in both analytical and numerical arenas. Rendulic (1957) extended Terzaghi's one-dimensional consolidation theory to include the horizontal flow of pore water, but did not adequately account for the three-dimensional nature of strains in the soil. This 'Terzaghi-Rendulic' theory is known as the 'diffusion' theory of consolidation, which operates by uncoupling the equilibrium of total stresses and the continuity of the soil mass. Subsequently developed analytical solutions to the consolidation problem stem from one of two somewhat diverging theories; the diffusion theory noted above and the Biot (1941a, 1941b) theory. Biot's theory of consolidation can be regarded as a true theory of consolidation which satisfies not only Darcy's law for water flow through the soil, but also the requirements of displacement compatibility (Davis and Poulos 1972). However, in many cases, the diffusion theory gives results in close agreement with those given by the Biot theory regardless of the value of Poisson's ratio allocated to the soil skeleton, so that the use of the diffusion theory is quite justified for practical engineering purposes (Murray 1978). The analytical framework developed in this project will be primarily based on the diffusion theory, although there is potential for extension to Biot's theory also.

D1.2.3 Methodology and Research Components

The proposed project will address each component of the 'research trifecta' – an analytical model will be developed and implemented in the program MATLAB, and then validated using experimental results. Once validated, the analytical program will then be used to assess the efficacy of the software package FLAC, along with the numerical program used at the Port of Brisbane, CAOS (Consolidation Analysis of Soils).

<u>Analytical modelling:</u> A generalised form of the diffusion theory will be integrated into the computer program MATLAB, where a solution can be generated based on designated input consolidation parameters. The solution to the general consolidation equation can be achieved using a unique collocation approach coupled with strategic truncation of collocation points. This type of strategy has already been successfully used to develop a solution for one-dimensional consolidation with variable initial excess pore water pressure distributions by truncating collocation points within the immediate vicinity of discontinuities (Lovisa et al. 2010). The results gathered during laboratory testing will be used to validate the analytical framework developed during this stage.

<u>Laboratory testing:</u> A series of extensive laboratory tests involving dredged mud from the Port of Brisbane and artificially made clay composites (e.g. Kaolinite/silt mix) is proposed for this study. The following summary outlines the different apparatus configurations required to assess the nuances of consolidation behaviour:

- A series of *rectangular* oedometer apparatus', with provision to partially drain along the walls, will be constructed to simulate the *three-dimensional consolidation* that occurs in containment paddocks and observe the effect varying paddock dimensions has on the time rate of settlement.

- A tall oedometer will be used to assess the effect of *multi-layer consolidation*. Two-layer tests are currently underway.

Within each consolidation test, at least eight surcharge pressures will be applied (in load increment ratios of unity) to monitor the variation in consolidation properties with applied load. Furthermore, a sequence of unloading tests will also be conducted to assess the *time rate of swelling* (or heave) that occurs upon removal of surcharge. Although standard instantaneous loading will be carried out in all consolidation tests, *time-dependent loading* of both a constant and erratic nature will also be used in select experimental configurations. In all instances, consolidation will be allowed to occur until an appreciable level of creep has been achieved so that the rate of *secondary compression* can be assessed in each instance.

<u>Numerical modelling:</u> It is proposed to numerically model the consolidation behaviour of each of the scenarios tested in the experimentation phase. The primary goal of this modelling phase is to develop a coupled numerical model to study the rate of settlement and pore pressure decay that occurs within soft clays (such as dredged mud and Holocene clay) when subjected to the consolidation arrangements outlined in the Background. The explicit finite difference software, FLAC, will be used as the primary numerical program for this study. Possibilities of using other software such as Plaxis will be explored. Interest has been expressed by Senior Principal Jay Ameratunga of Coffey Geotechnics with regards to a comparison between results obtained using the aforementioned analytical program and those obtained from the numerical software CAOS (Consolidation Analysis of Soils), developed by Professor Harry Poulos for Coffey Geotechnics.

D1.2.4 Significance

The benefits of a comprehensive analytical program for predicting the magnitude and rate of soft soil settlement are not restricted to land reclamation scenarios only. In fact, any ground stabilisation situation requires state-of-the art predictions of future settlement. The stability of problematic soils prior to construction is of particular economic significance in Australia, specifically along the east coast in Northern Queensland (Cairns to Townsville) and the New South Wales coast zone (from Newcastle to the Queensland border), where saturated soft clays up to 30 m in thickness can be encountered. In order to determine the appropriate method of ground improvement, detailed consolidation simulations need to be conducted.

Notable advances have been made to consolidation theory from an analytical standpoint (with particular emphasis on project aims) by McNamee and Gibson (1960), Sills (1975), Olson (1977), Schiffman (1980), Mahmoud and Deresiewicz (1980), Cargill (1984), Lehner (1984), Xie et al. (1999), Tewatia and Sridharan (2012). However, in each of these studies the analytical solution has accounted for only one to two of the eight criteria listed in the project aims. Few attempts have been made to incorporate a broader range of consolidation factors, and as a result, settlement predictions are confined to specific consolidation scenarios. By implementing a *general analytical model* within the program MATLAB, it is possible to tailor the output solution to satisfy a variety of initial and boundary consolidation conditions. This model can be used to investigate the sensitivity of variables such as non-uniform initial excess pore pressures, time-dependent loading, soil properties that vary with depth etc. A wide variety of laboratory experiments will be conducted, each focused on a different variable, in order to confirm analytical results. Once the analytical model has been validated, it can be used to investigate the efficacy of notable numerical programs such as FLAC and Plaxis. Ultimately, the results gathered during this project will *significantly advance knowledge in the realm of consolidation*, which will be of particular importance in land reclamation and ground improvement operations. This advancement of knowledge will have far-reaching implications in terms of both small-scale and large-scale consolidation operations –laboratory testing techniques will be critically refined and the accuracy of field settlement predictions will be fundamentally improved.

D1.2.5 Innovation

In order to develop and validate the proposed analytical program, an innovative approach is required in terms of both mathematical solution techniques and gathering of experimental results. The innovative aspects of this project can be summarised according to the following categories:

1. Analytical model development – Traditionally, analytic solutions to the classical consolidation equation are found using one of two techniques, namely; particular solutions using similarity transformations, or series solutions obtained using separation of variables. In the first case, these solutions are severely restricted and only applicable to a small number of practical engineering problems, as the partial differential equation and boundary conditions must both be transformable. However, these solutions do assist in understanding the features of the solution and for calibrating finite element and finite difference (i.e. numerical) codes. *In order to develop solutions for a broader range of consolidation scenarios, an alternative solution technique must be developed, and herein lies the most innovative aspect of the project.* Series solutions are applicable to a much wider range of problems, provided the partial differential equation and boundary conditions are separable. Although more robust in their application, past studies have avoided using series solutions as they come with their own set of limitations, in particular Gibbs phenomena and slow convergence rates. Gibbs phenomena leads to oscillatory behaviour and numerically inaccurate solutions, while slow convergence rates usually result in computationally expensive solutions that may also have questionable levels of accuracy. These issues will manifest unless the boundary conditions are modelled using a periodic series expansion, which severely limits their applicability, and explains why series solutions are continually overlooked. *We have developed techniques that minimize or remove entirely these issues* (Lovisa et al. 2010). Using a collocation approach along with strategically spaced collocation points, accurate and efficient solutions can be obtained for problems with markedly non-periodic boundary conditions, including problems where the boundary conditions are discontinuous.
2. Experimental results for validation – Traditional laboratory consolidation tests are designed to satisfy the conditions of Terzaghi's basic one-dimensional consolidation theory. Thus, innovative modifications are required to incorporate the variables listed in project aims. The laboratory tests proposed herein, such as the rectangular oedometer with three-dimensional drainage, are the *first of their kind*, and will be a valuable tool in the validation exercise. Consolidation tests in a tall oedometer with more than one clay layer will greatly improve our understanding of the consolidation behaviour of two-layered systems such as those seen at the Port of Brisbane.

D1.3 Research Environment (10%)

D1.3.1 Supportive and collaborative research environment

An interactive network of active collaborations has already been established within the proposed area of study, as evidenced by the publications listed in C2. Funding for this project would not only strengthen these ties but will enable new collaborations. Our existing academic standing will be enhanced through participation in notable geotechnical conferences, at both national and international levels to disseminate our findings.

Internally, much of the progress already made within the project-related area is owed to the success of cross-disciplinary collaboration. As a postgraduate student, I was supervised by A/Prof Read and A/Prof Sivakugan, from the Mathematics and Civil Engineering disciplines, respectively. A/Prof Read's unparalleled expertise in mathematical modelling of seepage problems coupled with A/Prof Sivakugan's extensive knowledge of real-world consolidation problems ensured that my work was both conceptually and practically relevant. Over the course of my degree, we have become a well-oiled machine, continually publishing our findings on theoretical consolidation with relevance to real-world problems. This existing intellectual infrastructure combined with project funding would further our proposed study of consolidation mechanisms and improve state-of-the-art predictions of settlement in ground stabilisation operations. Externally, I will continue to collaborate with academics such as A/Prof Arul Arulrajah (Swinburne University of Technology), Professor Myint Win Bo (DST Consulting) and A/Prof Sanjay Shukla (Edith Cowan University). A/Prof Arulrajah and Professor Bo are both leaders in the field of dredging and land reclamation and are Chief Investigators of the ARC Linkage project (LP0989164) involving dredged material stabilisation at the Port of Brisbane. Part of my postgraduate research that was relevant to this ARC Linkage project was published in a conference paper, with co-authors Jay Ameratunga (Senior Principle, Coffey Geotechnics), A/Prof Arulrajah, Professor Bo and Peter Boyle (Manager of Reclamation and Land Development, Port of Brisbane).

D1.3.2 Capacity and opportunity to develop an independent record of innovative, high quality research

The proposed project has substantial fundamental research components in its early stages, followed by applied research that addresses a pressing practical problem. Examination of the eight criteria listed in 1.2.1 provides a wide range of areas that can be explored in this project, thereby increasing publication opportunities. The high-quality research generated by this healthy balance between numerical, analytical and experimental research components will be of great interest to academics and practicing engineers alike.

<u>Fundamental research</u> – A significant ground-breaking *mathematical* contribution is anticipated due to the innovative use of series solutions to accommodate special boundary conditions, and strategies used to avoid traditional shortcomings associated with these applications. This will create new knowledge through the advancement of current theories and the generalised solution obtained during this study will be of considerable relevance to *theoretical soil mechanics*. Prestigious journals such as *Geotechnique*, *Canadian Geotechnical Journal*, *ASTM Geotechnical Testing Journal* would be targeted for publications of this fundamental research.

<u>Applied research</u> – In land reclamation and ground stabilisation operations, a program capable of generating accurate predictions of settlement without relying upon numerical techniques would be considered invaluable. Furthermore, the method of delivery (i.e. user-interface program instead of design charts) would be particularly attractive to a practicing engineer. *Canadian Geotechnical Journal*, *Geotechnical Testing Journal* and *ICE Geotechnical Engineering* would be targeted for this work. Some of the findings will also be disseminated through *Australian Geomechanics Journal* which has a wide readership among practicing professionals.

As evidenced by the number of publications in C2 that disseminated from the incorporation of only one project variable into the analytical model, the successful completion of this project is expected to yield a significant number of publications in high-quality journals. Timely dissemination of results will also be maintained by presenting my work at notable geotechnical conferences such as the *International Conference of the International Association for Computer Methods and Advances in Geomechanics* (IACMAG). I envisage this project to unfold similarly to my Ph.D. research, particularly with reference to our publication strategy. We will gather results directly related to project goals in preparation for submission to a first-class journal. As past experience has shown, interesting tangents unfold along the way which may merit publication in a good-quality journal, sometimes in the form of technical notes. Close collaboration with industry (e.g. Coffey Geotechnics, Port of Brisbane) will be maintained throughout the project in sourcing the dredged mud, sampling, data etc. including some site visits. Validation with real-world data will give practical meaning to the analytical and numerical work proposed herein, and make the work attractive to scholarly journals.

D1.3.2 Access to necessary facilities

Upon consideration of the existing interdisciplinary research environment at the host university and the collaborating institutions and industry professionals involved in this project, the research team is optimally positioned for the successful realisation of this project. The School of Engineering and Physical Sciences at JCU is currently equipped with an excellent geotechnical laboratory which is staffed by extremely capable technicians. Preliminary discussions are already underway regarding the manufacture of small-scale consolidation apparatus' that can replicate some of the conditions outlined in the Background. All facilities required for characterisation of soil properties are available at JCU, both through the geotechnical lab and the Advanced Analytical Centre. The AAC is a central analytical facility that provides a wide range of services, in particular x-ray diffraction data analysis for determination of particle size distribution and composition.

D1.4 Feasibility and Benefit (10%)

As demonstrated in Section C, a highly functioning cross-disciplinary network involving academics and industry professionals has already been established, with experience in all areas related to this project. Currently, the basic framework for the analytical model is already in place and has been successfully used to simulate settlement behaviour of a soil layer subjected to an initially non-uniform distribution of excess pore water pressure (the driving force behind consolidation). This framework was developed and simulations conducted over the course of 18 months during my PhD research. With the basic framework in place, subsequent extensions to this model can be achieved in a much shorter timeframe. Furthermore, it is possible to simultaneously run experimental studies and numerical simulations whilst refining the analytical model, which significantly shortens the overall project timeframe. Field settlement data is readily available from Coffey Geotechnics and it is simply a matter of collating this data for comparison with results obtained using the analytical model, an exercise that can also be done in concurrence with the analytical programming.

The proposed project is applicable to a multi-billion dollar global industry and involves a candidate with a proven record of quality publications and academic qualifications of the highest calibre. The successful completion of this project will further our understanding of the fundamental processes of consolidation by examining various scenarios involving different boundary conditions, thereby *creating new knowledge* in this area. Due to the prevalence of soft soils in coastal regions of Australia and the growing industry of land reclamation, accurate estimates of consolidation settlement are required both prior to and during ground improvement operations. These estimations of time to consolidation completion are not expressed in terms of months, but are expressed in terms of decades and centuries. Thus, any improvement upon existing levels of accuracy would translate to huge savings of both time and project costs. Consequently, this project falls within National Research Priority "*Frontier technologies and transforming Australian industries: Breakthrough Science.*"

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