SIMSG ISSMGE

ISSMGE Bulletin

Volume 10, Issue 4
August 2016

International Society for Soil Mechanics and Geotechnical Engineering

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Research highlights

Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS)

The research activities at the National University of Singapore (NUS) Centre for Soft Ground Engineering (CSGE) are grouped into two main areas, namely urban geotechnics and offshore geotechnics, both of which are reflected in the Singapore government's Research Innovation and Enterprise Plan up to 2020 (RIE2020). The focus of urban geotechnics is captured under the "Urban Solutions and Sustainability (USS)" thrust of the RIE2020, which include creating and optimizing liveable space. Within CSGE, this is translated into several research thrusts including underground construction, ground improvement, land reclamation and coastal protection as well as risks and hazards arising from man-made and natural catastrophes.

A particularly important aspect of urban geotechnics in Singapore is large-scale underground development. In many large cities, usable space is a premium resource and underground development is often more a matter of necessity rather than choice. Singapore is an extreme example of this since it is completely surrounded by sea. The need for large-scale underground development is not new. This is captured in the Economics Strategies Committees' Report (2010), which noted that we need to "***…adopt a long term perspective and invest ahead to create new land and space.*"** *While we can expand our land mass through reclamation as we have done for Marina Bay, there will be limits in the long-run. In the next 10 years, the Government should seek to catalyse the development of underground space as a means to intensify land use. We should put in place enablers for underground development such as by developing a subterranean land rights and valuation framework, and by establishing a national geology office. We must also develop an underground masterplan to ensure that underground and aboveground spaces are synergised, and invest in the creation of basement spaces in conjunction with new underground infrastructural projects (e.g. rail), so as to add to our "land bank".*

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This forms the backdrop of a substantial and long-term "space creation" programme which is driving a significant part of the geotechnical research strands in CSGE.

The impetus for the need to create space on geotechnical research at CSGE is reflected in the following strands of research work:

(a) Deep excavation and underground construction: Fook-Hou Lee, Chun-Fai Leung, Yean-Khow Chow, Kwet-Yew Yong and Harry Siew-Ann Tan.
(b) Land reclamation and coastal development: Darren Siau-Chen Chian and Soon-Hoe Chew.
(c) Ground improvement: Fook-Hou Lee, Darren Siau-Chen Chian, Kwet-Yew Yong and Soon-Hoe Chew.
(d) Site investigation and ground characterization: Kok-Kwang Phoon and Taeseo Ku.
(e) Impact of earthquakes and ground vibration on subterranean structures: Siang-Huat Goh and Darren Siau-Chen Chian.

The need for offshore geotechnics, as a part of marine and offshore engineering, is also reflected in one of the RIE2020's Strategic Technology Domains "Advanced Manufacturing and Engineering", under which "marine and offshore" is one of eight key industry pillars. The Singapore Maritime Institute (SMI) currently co-ordinates all marine and offshore research activities in Singapore. Within NUS, research activities in this sector are co-ordinated by the Maritime Institute@NUS (MI@NUS), the Director for which is Professor Yean-Khow Chow. The offshore geotechnical research work at NUS covers the following topics:

(i) Spudcan foundations: Yean-Khow Chow, Chun-Fai Leung and Fook-Hou Lee.
(ii) Plate and dynamically installed anchors: Yean-Khow Chow, Chun-Fai Leung and Fook-Hou Lee.
(iii) Deepwater pipelines: Fook-Hou Lee.

More details on the research works can be found in the write-ups of the respective researchers.

Fook-Hou Lee

Fook-Hou Lee is a professor in the Department of Civil & Environmental Engineering, where he developed the NUS Geotechnical Centrifuge. He is also the co-chairman of the National University of Singapore-Ministry of Defence Centre for Protective Technology (CPT) as well as the director of the Department's Centre for Soft Ground Engineering (CSGE). He is an editorial board member for several international journals and Managing Editor for the Journal of Earthquake and Tsunami. He is also a member of the World Federation of Engineering Organization Committee Engineering and The Environment Task Group on Disaster Risk Management (DRM/WFEO-CEE). He is a Fellow of the Singapore Academy of Engineering, as well as a registered Professional Civil Engineer and Professional Geotechnical Specialist Engineer.

In the area of geotechnics, Fook-Hou's primary research interest lies in soil improvement, especially in relation to urban and underground construction. His earlier works on this area dealt mainly with sand compaction piles and dynamic compaction, which were more relevant to land reclamation. With the shortage of sand for reclamation works in Singapore, and the resulting shift in national attention to underground space creation, his research efforts is currently directed towards cement treatment, principally deep cement mixing (DCM). Although DCM has been in use for several decades, much remains unknown about the mass performance of the treated ground, especially in relation to its use in underground construction. Fook-Hou's research is currently directed towards the development of technology which will allow engineers to design, implement and quality control DCM for underground construction more efficiently and innovatively. His research thrusts in this area lie mainly in the following aspects of DCM:

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1. Constitutive behaviour and modelling. The earlier works on compressive strength and micro-structure of cement-admixed clay has been extended to cover yielding and post-yield behaviour, tensile strength, compression behaviour under very low effective stress, small strain non-linear behaviour as well as the effect of the inclusion of random fibres into cement-soil matrix (Huawen Xiao, Jiahui Ho, Yutao Pan and Kai Yao). A constitutive model for cement-admixed clay based on an extension of the Cam Clay energy equation to include the effect of cementation and loss of cementation has just been published (Huawen Xiao). This is currently being extended to include the effect of fibre-reinforcement in the cement-soil matrix (Yannick Ng). A central idea in this development is that the loss of cementation can be quantified through the energy dissipated within the cement-soil matrix.

2. Spatial variability of the cement-treated ground. An important feature of cement-treated ground is its non-uniformity. Recent centrifuge model and field data study by his researchers (Chen-Hui Lee, Jian Chen, Yong Liu, Yijie Jiang, Linqiao He) indicate that this spatial variability can be explained by quality of mixing (intra-column variability with short scale-of-fluctuation), natural variation in soil state especially in-situ moisture content (inter-column variability with long scale-of-fluctuation) as well as workmanship especially positioning error and off-verticality in the mixing equipment. The non-uniformity in cement content is accentuated by the non-linear relationship between cement and water contents and treated soil strength. As a result, the strength of the treated soil often shows greater spatial variation than the cement content. Recent and on-going research activities also revolve around the effect of these spatial variation on the mass strength of the treated ground (Yong Liu, Yutao Pan, Muhammad Faizal bin Zulkefli, Kai-Qi Tan, Akanksha Tyagi) using random finite element analyses, Fig. 1. The cement-treated soil is often assessed by strength testing of core samples. Recent works have also led to statistical guidelines on the number of core samples which are required to ensure adequate representation of the treated soil mass, as well as methods of evaluating representative properties from these cores.

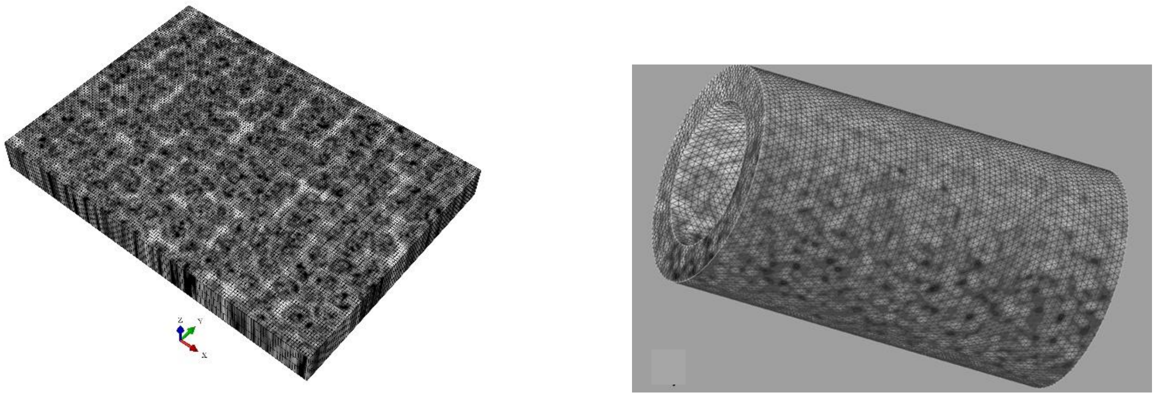

Figure 1. Random finite element analysis of cement-treated soil slab and tunnel

3. Computational tools. Computational tools have also been developed to facilitate the computational demands of random finite element analyses (Yong Liu, Ben Zhao). These include the incorporation of random finite element capabilities, multi-core and multi-computer parallel processing (using MPI) into GeoFEA (GeoSoft Pte. Ltd.). Highly convergent Krylov subspace solution techniques and global and local equilibration processes have also been incorporated into the code to allow progressive failure of highly non-uniform domains to be studied (Ben Zhao).

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4. Failure of tunnels and headings with cement-treated soil surrounds. Physical model studies are also being conducted into the failure of tunnels and headings with cement-treated soil surrounds (Muhammad Faizal bin Zulkefli, Kai-Qi Tan, Akanksha Tyagi), Fig. 2. Although these models do not reflect the spatial variability of actual improved soil domains, they nonetheless give an indication into the failure behaviour of cement-treated soil masses and provide data for validation of numerical results. The failure mode study shows that collapse can occur either by shear or tensile fracture, depending upon the mode of loading, thickness:diameter ratio and the strength of the treated soil zone relative to that of the surrounding soft soil.

Fig. 2. Centrifuge modelling of tunnels with improved soil surround and heading

5. Construction technologies. The feasibility of pumping and mixing fibres deep into the ground is also studied as part of the research activities (Chong-Hun Yeo, Hui-Juen Teo and Chujun Zhang). The results to date suggest that it is feasible to pump fibres into the ground, although there may be a degradation in the mixing quality. In addition, a joint has also been developed which will enable deep mixing to be conducted around corners and potentially allow regions obstructed by overlying obstacles and infrastructures to be treated, Fig. 3. A full prototype is being developed (Liang-Hong Tay, Qingsheng Chen).

Fig. 3. Field test on an equipment for deep mixing around corners and obstacles

Kok-Kwang Phoon

Kok-Kwang Phoon, PhD, PEng, FSEng, FIES, FASCE is Distinguished Professor and Vice Provost (Academic Personnel) at the National University of Singapore. He is a Professional Engineer in Singapore, an ASEAN Chartered Professional Engineer, and past President of the Geotechnical Society of Singapore. He was elected Fellow of the Academy of Engineering Singapore (FSEng) in 2012.

Dr. Phoon received his BEng (First Class Honours) and MEng from the National University of Singapore and his PhD from Cornell University where his research on reliability-based design has influenced recent codes and specifications, including the 4th edition of ISO2394:2015, *General Principles on Reliability for Structures*. Dr. Phoon's main research focus is on risk and reliability in geotechnical engineering. He is the lead editor of 3 books: *Reliability-Based Design in Geotechnical Engineering* (Spon Press, 2008), *Risk and Reliability in Geotechnical Engineering* (CRC Press, 2015), and *Reliability of Geotechnical Structures in ISO2394* (CRC Press/Balkema, 2016).

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Dr. Phoon has been active in coordinating and promoting geotechnical risk analysis and reliability-based design codes. He is current Chair of TC304 - Engineering Practice of Risk Assessment and Management, International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE). He was past Chair of the Geo-Institute Technical Committee on Risk Assessment and Management.

Dr. Phoon's recent research efforts have been directed towards injecting greater realism into geotechnical reliability-based design (RBD), particularly in the characterization of multivariate soil databases and in the development of information-sensitive yet practical RBD that links data explicitly to design. The "value of information" can thus be quantified. It is easier for engineers to present site investigation as an investment rather than a cost to clients when project needs are complemented by a quantitative notion of "value of information". This is arguably the most significant value that RBD brings to current practice. Two main activities in this direction are highlighted below.

1. Characterization of geotechnical variability. Site investigation and the interpretation of site data are necessary aspects of sound geotechnical practice. Any design methodology, be it RBD or otherwise, should place site investigation as the cornerstone of the methodology. Site investigation is also the key feature that distinguishes geotechnical from structural design practice. Phoon and Kulhawy (1999) presented an extensive compilation of univariate soil data, covering data produced by many common laboratory and field tests. Soil databases covering more than one parameter have also been compiled recently as summarized in the table below. These databases are exceedingly useful. They can be used by the engineer as prior information to update more limited site specific data, which is the norm in practice. They can be used by the code writer for reliability calibration of resistance/partial factors. Fundamentally, a design methodology that is sensitive to the quantity and quality of geotechnical information would redress the balance that is presently tilted towards keeping site investigation efforts to a minimum. The contributions of the collaborators, particularly Dr Jianye Ching from the National Taiwan University, are acknowledged in the cited publications.

Multivariate soil databases

Database	Reference	Soil parameters	# data points	# sites/ studies	Range of properties		
					OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012)	LI, s_u, s_u^{re}, σ'_p, σ'_v	345	37	1~4		Sensitive to quick clays
CLAY/6/535	Ching et al. (2014)	s_u/σ'_v, OCR, $(q_t-\sigma_v)/\sigma'_v$, $(q_t-u_2)/\sigma'_v$, $(u_2-u_0)/\sigma'_v$, B_q	535	40	1~6	Low to very high plasticity	Insensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013)	s_u under 7 different test modes	6310	164	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	Ching and Phoon (2014)	LL, PI, LI, σ'_v/P_a, σ'_p/P_a, s_u/σ'_v, S_t, $(q_t-\sigma_v)/\sigma'_v$, $(q_t-u_2)/\sigma'_v$, B_q	7490	251	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/4/BN	Ching et al. (2010)	OCR, s_u, N_{60}, $(q_t-\sigma_v)/\sigma'_v$	-	-	1~50	-	-
F-CLAY/7/216	D'Ignazio et al. (2016)	s_u, σ'_p, σ'_v, LL, PL, w_n, S_t	216	24	1~8	Low to very high plasticity	Insensitive to quick clays
SAND/4/BN	Ching et al. (2012)	D_r, ϕ', $(N_1)_{60}$, q_{t1}	-	-	-	-	-

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Soil parameters:
LL: liquid limit; PL: plastic limit; PI: plasticity index; LI: liquidity index; w_n: natural water content; s_u: undrained shear strength; s_u^{re}: remolded s_u; σ'_p: preconsolidation stress; σ'_v: vertical effective stress; σ_v: vertical total stress; OCR: overconsolidation ratio; q_t: corrected cone tip resistance; u_2: pore pressure behind the cone; u_0: static pore pressure; B_q: CPTU pore pressure parameter; P_a: one atmosphere pressure; S_t: sensitivity; N_{60}: SPT N (corrected for energy ratio); D_r: relative density; ϕ': effective friction angle; $(N_1)_{60}$: SPT N (corrected for energy ratio & normalized by overburden stress); q_{t1}: normalized q_t (normalized by overburden stress).

References:

Ching, J., Phoon, K. K. and Chen, Y. C. (2010). Reducing shear strength uncertainties in clays by multivariate correlations. Canadian Geotechnical Journal, 47(1), 16-33.

Ching, J. and Phoon, K. K. (2012). Modeling parameters of structured clays as a multivariate normal distribution. Canadian Geotechnical Journal, 49(5), 522-545.

Ching, J., Chen, J. R., Yeh, J. Y. and Phoon, K. K. (2012). Updating uncertainties in friction angles of clean sands. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 138(2), 217-229.

Ching, J. and Phoon, K. K. (2013). Multivariate distribution for undrained shear strengths under various test procedures. Canadian Geotechnical Journal, 50(9), 907-923.

Ching, J. and Phoon, K. K. (2014). Transformations and correlations among some clay parameters – the global database. Canadian Geotechnical Journal, 51(6), 663-685.

Ching, J., Phoon, K. K., and Chen, C. H. (2014). Modeling CPTU parameters of clays as a multivariate normal distribution. Canadian Geotechnical Journal, 51(1), 77-91.

D'Ignazio, M., Phoon, K. K., Tan, S. A. & Länsivaara, T. T. (2016). Correlations for undrained shear strength of Finnish soft clays, Canadian Geotechnical Journal, in press.

2. General Principles on Reliability for Structures (ISO2394:2015). From a geotechnical perspective, the key departure of the current ISO2394:2015 from previous versions is the introduction of a new informative Annex D on "Reliability of Geotechnical Structures". The need to achieve consistency between geotechnical and structural reliability-based design is explicitly recognized for the first time in ISO2394 with the inclusion of Annex D. Hence, the publication of Annex D of ISO2394:2015 on "Reliability of Geotechnical Structures" marks a major milestone in the advancement of geotechnical RBD. Annex D is the first guideline that attempts to identify features in geotechnical reliability that are distinctive from structural reliability. In particular, existing simplified RBD formats such as the Load and Resistance Factor Design (LRFD) do not allow room for the geotechnical engineer to exercise judgment in response to local site conditions and to incorporate local experience. Site-specific issues are however critical to geotechnical practice.

The ISO2394 revision secretariat consisting of Michael Havbro Faber (Convenor), Kazuyoshi Nishijima (Secretary), and Johan Retief is credited for the initiative to draft Annex D. The ISO2394:2015 Annex D drafting group consisting of Jianye Ching, Mahongo Dithinde, Kok-Kwang Phoon (Chair), Johan Retief, Timo Schweckendiek, Yu Wang, and Limin Zhang. The interested reader may refer to the following key publications:

Phoon, K. K. & Retief, J. V. (Eds.) (2016). Reliability of Geotechnical Structures in ISO2394, CRC Press/Balkema.

Phoon, K. K., Retief, J. V., Ching, J., Dithinde, M., Schweckendiek, T., Wang, Y. & Zhang, L. M. (2016). Some Observations on ISO2394:2015 Annex D (Reliability of Geotechnical Structures), Structural Safety, 62, 24-33.

Research highlights

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Chun-Fai Leung and Yean-Khow chow

Performance of foundations due to soil movement

Dr C F Leung is a professor in the Department of Civil and Environmental Engineering, NUS. His research interests include soil-structure interaction, offshore geotechnics, and centrifuge modeling. Prof Leung currently serves on the editorial board of Geotechnique, OAME Journal, ISOPE Journal and other journals. He is a technical committee member of the ISO mobile jackup rig foundation panel and Singapore's national civil and geotechnical works standards. Prof Leung has served as Chairman of ISSMGE Geotechnical Physical Modeling and currently sits on the ISSMGE Offshore Geotechnics Technical Committee.

Professor Y K Chow is with the Department of Civil & Environmental Engineering, National University of Singapore (NUS). His research interests include offshore geotechnics, computational geomechanics, and soil-structure interaction. Professor Chow is the Executive Director, Maritime Institute @ NUS, Executive Director, Centre for Offshore Research & Engineering (CORE) and Director, Keppel-NUS Corporate Laboratory. He is on the Editorial Board of Computers and Geotechnics, International Journal of Geomechanics, Geomechanics and Geoengineering, and Geomechanics & Engineering. He is a Professional Engineer (Civil) and a Specialist Professional Engineer (Geotechnical Engineering) in Singapore.

Similar to many urban areas in the world, slope and deep excavations as well as tunneling are often carried out close to existing buildings. The large soil movements due to the above construction activities may induce severe stresses on the adjacent foundations supporting buildings and infrastructure nearby. Research studies have been carried out at NUS to investigate the above problems using centrifuge and numerical modeling.

The thick deposits of soft clay in many parts of Singapore are still consolidating and the large soil settlement would cause downdrag of the piles. As a pile would carry at least the structural dead loads of the structure, the centrifuge model study reveals that the magnitude of downdrag on the pile under such scenario would reduce as the pile has to settle under the loading. Tests on instrumented pile groups illustrate that the corner piles would experience the largest dragload while the center piles experience the least dragload, as shown in Figure 1. The deployment of pile group is beneficial against downdrag as that the average dragload per pile would decrease with increasing number of piles in a group. The mechanism of the load transfer of the pile-pile cap-soil interaction is further delved using numerical back analyses on the test results. It is found that the presence of rigid pile cap would moderate the load distribution of pile and as a result additional bending moments are induced on the pile cap and the pile tops due to interaction. The magnitude of reduction for a free head pile group and a capped head pile group is found to be of similar magnitude but with different pile load distribution.

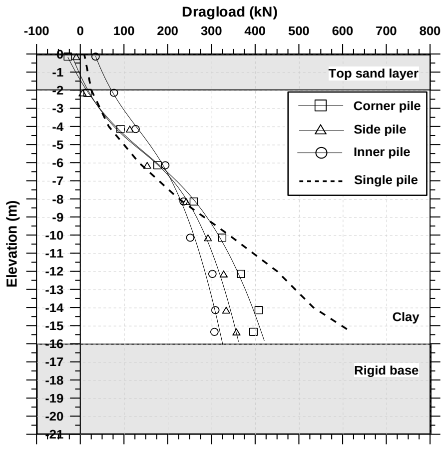

Figure 1 Distribution of loads among piles in a 16-pile group

Research highlights

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Deep excavations are often carried out for the construction of deep basements for high-rise buildings in many parts of the world. Centrifuge model studies on the behavior of pile group subjected to excavation induced soil movement in sand and clay reveal that existing theories using the active pile approach would over-predict the pile bending moments and deflections. Under large free field lateral soil movements, the sand would flow pass the pile while the clay would induce less stress on the pile due to development of tension cracks. Coupled with numerical back analyses, the limiting pressures acting on a pile in sand and clay respectively have been developed and the pile performance can hence be more accurately predicted. The deployment of pile groups is again beneficial as the impact of lateral soil movement is reduced due to shielding of front piles over the rear piles. The findings from the research have been successfully applied to back analyze a case history of damage of bored piles due to slope excavation induced soil movements. Using the theoretical model developed from this research, the degree of structural damage of the bored piles at different stages has be identified, as illustrated in Figure 2.

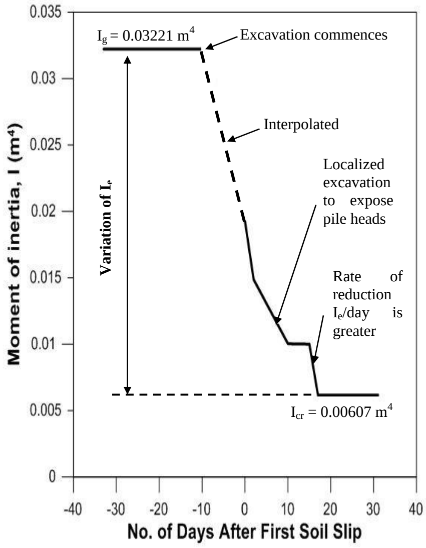

Figure 2. Damage of bored piles during different stages of soil movements (Ong et al., 2015)

Centrifuge and numerical model studies are ongoing to investigate the behavior of deep and shallow foundations adjacent to and beneath tunnel excavation. Compared to green field soil movements due to tunnelling, the foundation distortion is not as severe due to foundation rigidity. The distortion of buildings supported on foundations with various degrees of rigidity is being examined. The research findings reveal that regardless of centroid of the building load in relation to its foundation, the foundation response can be unified using the building plan dimension parameters. It is planned that the findings from the centrifuge and numerical studies will be evaluated against actual case studies of building and foundation due to tunneling in Singapore.

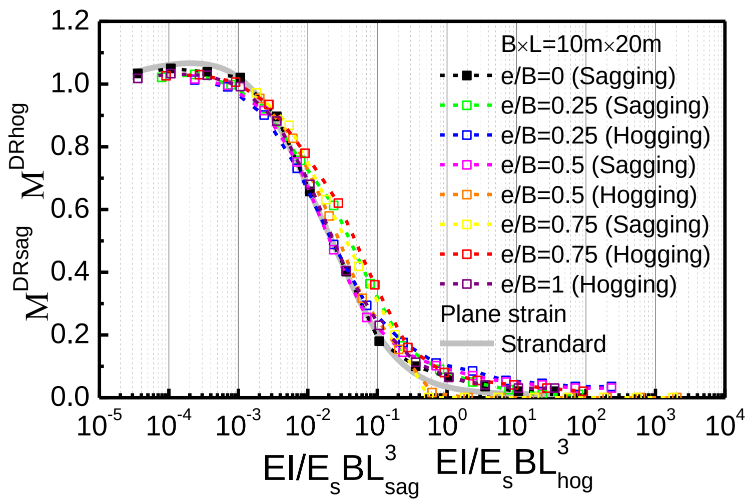

Figure 3. Unified foundation responses for building with different eccentricities

Research highlights

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Kwet-Yew Yong

Professor Kwet-Yew Yong is Professor of Civil Engineering and Vice President (Campus Infrastructure) at the National University of Singapore which oversees the planning and sustainable development of campus infrastructure including the completed S$1 billion University Town, one of the largest construction program undertaken in NUS. He has held senior positions including Head of Civil Engineering, Founding Director of Centre for Soft Ground Engineering, Chairman of NUS-MINDEF Centre for Protective Technology and Co-Chairman of NUS-MINDEF Infrastructure Committee.

Prof Yong's research is a microcosm of the infrastructure development in Singapore. In the early 1980s during the tall buildings boom, his research was on performance of pile foundation. Some of the findings were later incorporated into the Singapore Code for Pile Design. In the late 1980s, his research with several colleagues on land reclamation led to an award winning layered clay-sand scheme of reclamation using marine clay as an alternative to sand-only fill for reclamation. In the 1990s, several innovative methods of ground improvement including dynamic replacement and mixing, and inverted jet-grouted arch were developed to control movements associated with deep excavations and flood alleviation projects in urbanized Singapore and used widely in several reclamation and infrastructure projects in Indonesia and Malaysia. In the 2000s, with the rapid development of underground transportation, the focus was in the effects of tunneling on nearby buildings. The research group developed capabilities in 3D analyses of underground construction using GeoFEA and Plaxis programs that were used to predict performance of tunnelling through challenging ground and site conditions including mixed face tunnelling in a number of MRT projects. In the 2010s, the optimal use of land and underground space ranks high on the national agenda. Prof Yong is Co-Chair and Scientific lead in the Ministry of National Development (MND)/National Research Foundation (NRF) National Innovation Challenge on Land & Livability that looks into space creation and optimization in land scarce Singapore. He has published more than 200 technical publications, delivered over 30 keynote/guest lectures at international conferences.

Prof Yong is past Chairman of the Association of Geotechnical Societies in Southeast Asia and Past President of Southeast Asia Geotechnical Society. He also chairs/chaired several boards and national committees in land transport and construction including the International Board of Advisers to Land Transport Authority, Advisory Committee on Occupational Safety & Health for the Construction Industry (MOM), the Accredited Checkers Selection Panel (BCA) and MINDEF Supervisory Board for Land & Estates. He is a member of a high-level Development Projects Advisory Panel that vets and review large and complex public projects for the Ministry of Finance. He also serves on the Board/Exco of Land Transport Authority and chaired LTA's Independent Investigation Panel on Nicoll Highway Collapse in 2004 and was a member of the Expert Panel on Enhancing Flood Protection in Singapore, Ministry of Environment Water Resources (MEWR) in 2011/12. He received commendations from the Ministry of Manpower in 2000 and Ministry of Education in 2006, and 3 National Day Awards - Public Administration Medal (Silver) in 2000, Public Service Medal in 2004 and the Public Service Star in 2008 – for significant contributions to the university, construction safety and land transport respectively.

Research highlights

Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS) (Con't)

Harry Siew-Ann Tan

Harry Tan graduated in Civil Engineering from Auckland University in 1977, and did his MEng in Geotechnical Engineering in NUS in 1980, and MSc and PhD degrees in Geotechnical Engineering in UC Berkeley, California in 1981 and 1985, respectively. He has been on the faculty of NUS since 1980.

He has published over 200 technical papers covering topics such as Deep Excavations, Pile Foundations, Geosynthetics, Ground Improvement of Soft Clays, and Land Reclamation. He serves on the editorial board of "Geotextiles and Geomembranes", of the International Society of Geosynthetics, and the Journal of "Geotechnical Engineering" of the South East Asian Geotechnical Society since 1997. He has served as a committee member of several technical committees, including the US Transportation Research Board committee A2K06 on subsurface drainage in highway pavements, TC-09 Technical Committee on Earth Reinforcement for the International Society of Soil Mechanics and Geotechnical Engineering, SPRING Singapore technical assessor on geotechnical testing and site investigation, Singapore SPRING committee on earthworks and geotechnical engineering. Prof Tan had served as Chairman of TR26 the new Technical Reference for Deep Excavation Works from 2005 to 2010. This code is the latest and current code for deep excavation in soft clays in Singapore.

He serves on the International Scientific Network committee for the Plaxis BV (Nederlands) code development, training and applications since 2002. He was actively involved as course leader and instructor in teaching Computational Geotechnics with Plaxis Asia for industry in the Asia-Pacific region since 2000. He has taught the use of Plaxis in Singapore, Malaysia, Korea, India, Australia and the Netherlands over the last 20 years.

He is a registered professional engineer in Singapore since 1992, and specialist geotechnical engineer since 2006, and has been involved in several major consulting jobs in Singapore and Malaysia. He was the leader of the State "Expert Witness Team" comprising of four international experts in the COI (Committee of Inquiry) for the Nicoll Highway LTA C824 cut/cover tunnel collapse incident of 20th April 2004. He also served as the State Expert Witness for the Church Street pile foundation failure case.

He was actively involved in many deep excavation and other geotechnical projects in both public sector and private sector cases: including many LTA projects in Circle Line, MCE, DTL1 and DTL2 stations and tunnels. He was an invited speaker at ER2010 (Earth Retention Conference at Seattle USA) for the session on case histories to address the subject of pitfalls in numerical analysis of retention systems for deep excavation.

Research highlights

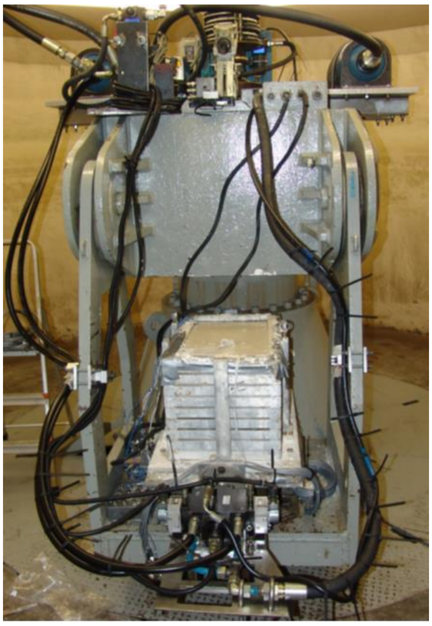
Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS) (Con't)

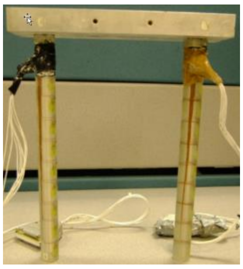
Siang Huat Goh

Siang Huat Goh is an Associate Professor in Geotechnical Engineering and the Deputy Director of the Centre for Protective Technology. He has a strong interest in soil dynamics, and has carried out research on characterizing and modeling the response of sands and clays under dynamic loadings, such as those caused by earthquakes and buried explosions. He has also looked into various problems involving dynamic soil-structure interaction. His work covers both experimental testing (centrifuge modeling and full-scale field trials) and advanced numerical simulations of wave propagation in dry and saturated soils.

Siang Huat was the principal investigator of a project that examined the potential for blast-induced liquefaction in reclaimed sand deposits. Centrifuge tests were performed which successfully captured both the initial high-pressure blast pulse propagating through the saturated soil and the subsequent build-up and dissipation of the residual pore pressure associated with the liquefaction process. Also arising from this project was the development of an overlapping mesh method for performing fully-coupled dynamic finite element analyses in saturated porous media, which can be readily implemented on commercial software platforms such as ABAQUS. Currently, he is involved in a follow-up project to study the effects of impact and shock loading on buried pipelines.

The effect of soft ground amplification on single piles and pile groups due to far-field seismic ground motion excitation is another area of study for Siang Huat. Both centrifuge experiments and 3-D finite element analyses have been performed, the results of which were used to derive simplified correlations for estimating the pile bending moments and the raft accelerations. As part of this study, a PC network cluster was also set up to perform highly parallelized 3D FE computations of large scale dynamic soil-structure interaction problems involving several millions degrees of freedom.





2-Pile

Partially completed centrifuge blast test model during sensor placements

12-Pile

Partially completed model with instrumented pipe

Centrifuge Model Setup with Laminar Box Containing Soft Clay and Embedded Pile Group System

Research highlights

Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS) (Con't)

Soon-Hoe Chew

Dr. Soon-Hoe Chew, a Professional Engineer, graduated with a PhD from the University of California at Berkeley, USA, after completing a Research Project on Geosynthetics Reinforced Soil Walls. He is currently an Assistant Professor with the Department of Civil and Environmental Engineering, National University of Singapore. His past administrative roles include Assistant Dean of the Faculty of Engineering, and the Deputy Director of the Centre for Protective Technology (CPT), a research and development centre jointly formed by the Ministry of Defence, Singapore, and NUS. He was elected to be a council member of the Institution of Engineers, Singapore, IES 2006-2011, as was re-elected for 2011-2015 and 2016-2018. He is also currently the President of Southeast Asia chapter of International Geosynthetics Society (IGS), and a Council member of Singapore Chapter of American Society of Civil Engineers (ASCE).

His main research interests include geosynthetics, slope engineering, land reclamation, soil improvement, deep excavation in soft soils, numerical modeling in geotechnical engineering, geo-environmental engineering and geological engineering. Dr Chew published extensively on soft clay and ground improvement related topics. He was awarded "Defence Technology Prize" from Chief Defence Scientist, Ministry of Defence, Singapore in 2006. He was also the recipient of the "Minister Innovative Awards" from Ministry of Transportation, 2011, on his "innovative use of geotube filled with cement mixed soft clay". He was also awarded with "Friends of Waters" by PUB, the water agency in 2013. His latest award is "2015 Minister's Awards (Team)" by the Ministry of National Development on the project supporting the HDB team of engineers on "Reuse of soft clay for infilling works at Pulau Tekong", awarded on National Day Celebration 2015.

Dr Soon-Hoe Chew's main research interest in the last 10 years is on geosynthetics, geo-environment study and soil improvement. With the shortage of sand for reclamation works in Singapore, and the innovative use of excavated soil as the infilling materials for reclamation purposes, his research efforts are currently directed towards geotextile containment for offshore disposal and reclamation, cement-polymer-soil treatment for this soft fill, use of electric PVD, vacuum consolidation and Special Well Point technique for in-situ treatment during dumping of these soft fill.

The following give a quick summary of some of his latest research thrusts:

1. Geotextile Tube for dewatering application. Geotextile tube gains popularity in the sludge dewatering industry since last decade because of its cost effectiveness in encapsulating a large amount of solid particles while discharging the relatively clean supernatant water. The main mechanism is the effective filter cake formation at the geotextile skin. Several laboratory-scale dewatering tests have been developed (by PhD students Mr Eng Zi Xun and others) to evaluate the dewatering performance of the geotextile tube with respect to the type of selected flocculent or coagulant, soft soil fill characteristic, and geotextile type. Test method takes into account the nature of flow dynamic in the filling action which highly affects the filter cake formation. An analytical method was developed for this. A series of large-scale dewatering test was successfully performed, and the results obtained verified the proposed analytical method.

Research highlights

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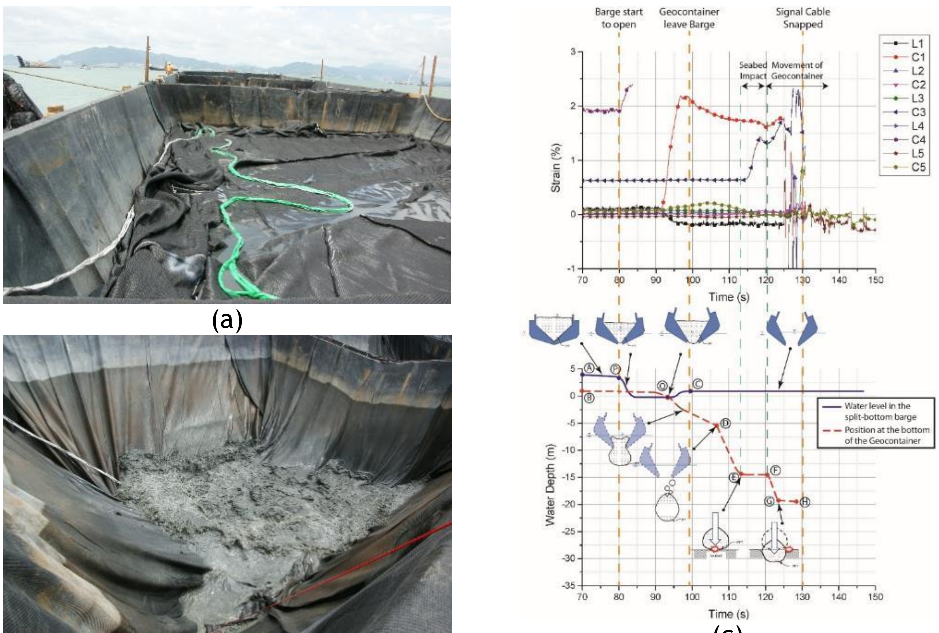
(a) (b)

Figure 1.Dewatering performance test: (a) Modified Geotube Dewatering Test (M-GDT); (b) Large-scale Outdoor Dewatering Test

2. Geotextile Tube for reclamation application. Geotextile tube can be used as a containment system to encapsulate the dredged materials for offshore disposal or reclamation purposes. It was filled in a split-bottom barge. In view of the harsh condition at the filling and dumping stages in offshore environment, the strength requirement of the geotextile to withstand the high tensile forces is critical. With this, a 3-D large scale testing apparatus was developed to test the seam strength of the inlet port. A number of field studies for instrumented geotextile tubes used as the offshore dumping unit were successfully conducted in Singapore and Hong Kong (assisted by PhD student Tan Czhia Yheaw and others). These research works involved the installation of specially designed sensors and was monitored during the filling and dumping stage of geotextile tube. The monitoring results are very helpful in evaluating the safety margin of the operation with geotextile tube as an offshore dumping unit.



(a) (b) (c)

Figure 2. A field study of a geotextile tube used as offshore dumping unit in Hong Kong

Research highlights

Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS) (Con't)

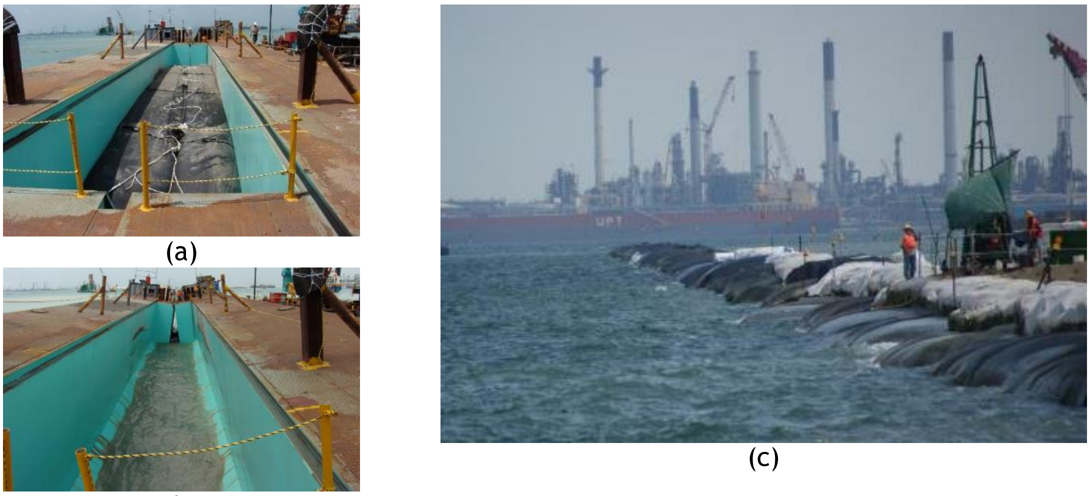


Figure 3. The field study of geotextile tube used to construct the undersea containment bund in Singapore: (a) Filling of geotextile tube in split-bottom barge; (b) Dropping of geotextile tube into seabed; (c) Completion of the undersea containment bund with geotextile tubes

3. Ground improvement techniques and its integration study for reclamation with soft clay fill. As part of a holistic approach for increasing the land reclamation fill volume during the dumping stage, the use of vacuum consolidation with vertical and horizontal drains, and special well point concept are studied. These ground improvement techniques are integrated with each other, and coupled with the bearing capping top layer. One of the key features of this rapidly created top layer is high bearing capacity with low permeability. This high bearing capacity allows for early site access to perform various ground improvement works. The effective method of mixing and optimum mix ratio for cement-polymer-soil admixtures are developed. PVDs with vacuum consolidation is studied, together with the use of the low permeability top layer to eliminate the use of membrane for vacuum consolidation. In addition, the conventional PVDs with vacuum consolidation, the use of Special Well Point concept for consolidation is also being delved into. A number of full-scale pilot trials would be carried out at existing land reclamation sites to evaluate the feasibility of using all the above ground improvement techniques and the integration between them on a large scale basis.

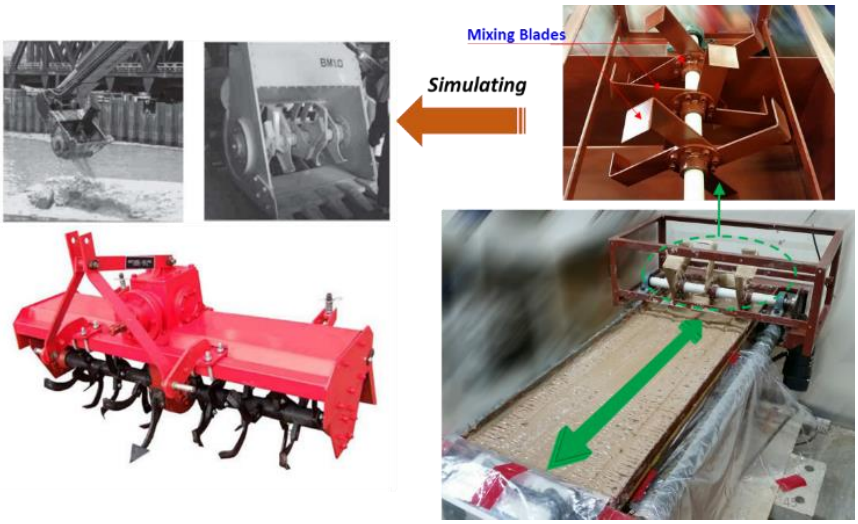


Figure 4. A "Shallow Mixing Machine" developed for cement-polymer-soil in NUS Geotechnical Laboratory

Research highlights

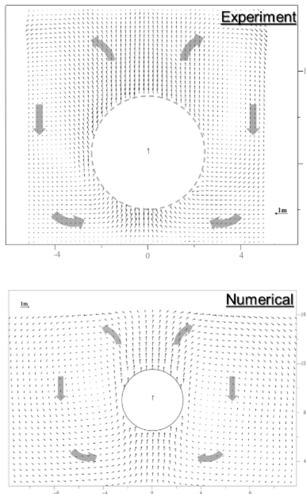
Centre for Soft Ground Engineering (CSGE), National University of Singapore (NUS) (Con't)

Siau Chen CHIAN (Darren)

Dr. Darren Chian is an Assistant Professor in the Department of Civil and Environmental Engineering at the National University of Singapore (NUS) and the Operations Manager of the MINDEF-NUS Centre for Protective Technology. He is also the vice-president of the Geotechnical Society of Singapore (GeoSS), and a nominated member for several ISSMGE technical committees, namely, TC104 Physical Modelling in Geotechnics, TC203 Earthquake Geotechnical Engineering, and TC217 Land Reclamation. Dr. Chian obtained his Ph.D. and B.Eng. with Gold Medal from Cambridge University and Nanyang Technological University (NTU) respectively.

Building collapse, 2009 Padang Earthquake, Indonesia (EEFIT, 2009)

In the area of earthquake geotechnical engineering, Dr. Chian was the geotechnical-specialist in post-earthquake missions to the Mw7.6 Padang Earthquake in 2009 and the Mw9.0 Tohoku Earthquake in 2011 with the UK Earthquake Engineering Field Investigation Team (EEFIT), under the auspices of the Institution of Structural Engineers (IStructE), London. His research has succeeded in capturing the phenomenon of uplift damage of underground structures in details that has not been observed before with the use of a high-speed camera. The novelty is the analysis with Particle Image Velocimetry (PIV) technique, particularly in liquefied soil, supported with miniature sensors to measure the conditions of the soil surrounding the tunnel. His research confirms that the transient softening of the soil due to seismic shaking permits the lighter tunnel to displace upward, however the pressure induced by the uplifting tunnel also regains the overlying soil's strength which inhibited continual uplift. Hence, uplift ceases as soon as the earthquake shaking ends. This important research finding has corrected and shed new light on the long-standing hypothesis that the uplift phenomenon is merely an Archimedes principle of buoyancy which persists past the earthquake duration. Presently, his research is extended to manholes which are more susceptible to uplift than pipelines and has greater impact to urban society as evident in the recent 2011 & 2012 Christchurch Earthquakes, 2011 Tohoku Earthquake, and 2010 Chile Earthquake. Several remediation techniques have been devised following an extensive suite of centrifuge modelling tests. In addition, studies on non-uniform cyclic testing of liquefiable soils is also on-going with attempt to represent the irregularity of earthquake loading in the field better. Although larger shear strain amplitude tends to generate high excess pore pressures as commonly observed in uniform cyclic tests, they produce lower excess pore pressures in non-uniform cyclic tests due to greater tendency of dilation.



Experimental (PIV) and numerical (FLAC) analysis of uplift of circular underground structures (Chian, Tokimatsu & Madabhushi, 2014), ASCE JGGE

In the area of land reclamation, Dr. Chian has carried out an extensive suite of laboratory tests of cement treated clays as a means of converting unwanted soils from underground construction and sea dredging to useful reclamation fill materials. Three significant milestones have been achieved: 1) an improved predictive strength development model was developed which considers the effect of soil-water-cement mix proportions and curing duration. The model was demonstrated to be superior to existing classic prediction models used in the industry, and applicable to several clays and cement types with good fit to experimental data indicated by correlation coefficients exceeding 0.95, 2) the introduction of the free-water:cement ratio, $(w/w_L)/c$, in order to account for the variation in microfabric characteristics

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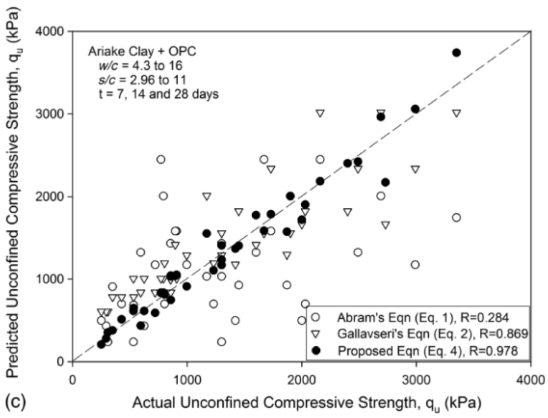
and pore spaces induced by sand, which was proven to be more appropriate in assessing strength development of cement-treated soils than conventional water:cement ratio (*w/c*), 3) the introduction of the several correlations between early- and later-age strength and the use of portable bender element devices to identify potential defective mixes for quality control in construction as early as within 3 days for timely remedial actions.



Strength prediction of cement treated Ariake clay with OPC at different water:cement, soil:cement ratios and curing ages (Chian, Nguyen & Phoon, 2015), ASCE JGGE

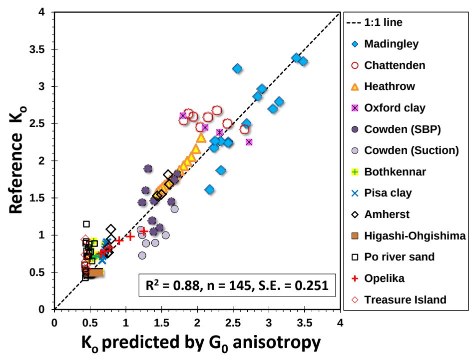
Dr. Chian's expertise in the area of earthquake engineering and land reclamation has led to the invitation to speak in several international and regional conferences and meetings. He also advises the Disaster Assistance and Rescue Team (DART) of the Singapore Civil Defence Force on building and geotechnical safety during overseas earthquake search and rescue missions. Dr. Chian is the awardee of Asia's Top 10 Innovators under 35 years by MIT Technology Review in 2015, 1st Prize in the National Technical Paper Competition in 2013, and Best Young Researcher Award at the 8th International Conference on Urban Earthquake Engineering in 2011.

Taeseo Ku

Dr. Taeseo Ku is an Assistant Professor in the Department of Civil and Environmental Engineering at the National University of Singapore. Dr Ku joined the NUS in 2013 after some research experiences (graduate assistant, post-doc and senior researcher) in the United States and Korea. He obtained his Ph.D. from Georgia Institute of Technology (GT in-situ testing group in GeoSystems Division), M.S. in GeoEngineering from University of California-Berkeley, and B.S. from Yonsei University, Korea. He is currently a nominated member for TC 101 (Laboratory Stress Strength Testing of Geomaterials) and TC 102 (Ground Property Characterization from In-Situ Tests), ISSMGE.

Dr Ku's research interests are on the related areas of in-situ geotechnics and geophysical site investigations. He has attempted to develop consistent, rational, and practical unified geotechnical interpretation frameworks for evaluating soil parameters based on both in-situ, geophysical, and laboratory tests. For instance, a focused area centers on the measurement, evaluation, and application of elastic waves (e.g., shear wave velocity (V_S) and the related small-strain stiffness (G_0) in soils), with particular interests related to geotechnical site characterization. In terms of the advanced seismic wave-based geo-characterization, some recent applications and/or current research projects are introduced.

1. <u>Geostatic Stress State Evaluation by Paired Directional Shear Waves</u>. His recent research concerned the evaluation of geostatic stress state and stress history by use of directional shear wave velocities. He developed statistical algorithms for assessing stress history and geostatic stress conditions (e.g., lateral earth pressure) based on paired complementary sets of directional shear wave modes from a special elite worldwide database that was compiled for this purpose. The observed degree of in-situ VS or G_0 anisotropy can provide the ideal opportunity.



(figure from Ku and Mayne 2015)

Research highlights

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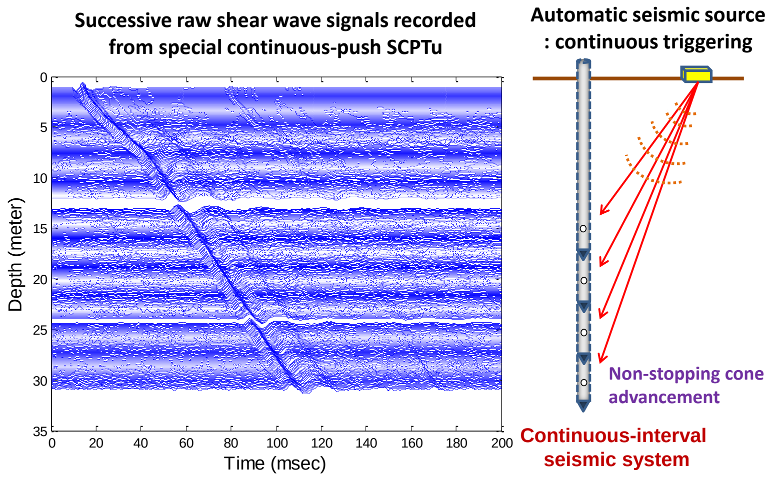
2. Continuous-interval VS Profiling by Auto-Source and Seismic Piezocone Tests. Dr Ku's another contribution involves the development of reliable and automated evaluation techniques for continuous shear wave velocity measurements taken during seismic cone penetrometer testing. A new exploratory procedure for collecting continuous VS measurements via cone penetration testing using a special autoseis source is presented whereby wavelets can be generated and recorded every 1 to 10 s. The continuous-interval seismic piezocone test offers a fast, productive, and reliable means to expedite the collection of downhole VS profiles, as well as additional readings on cone tip resistance, sleeve friction, and penetration porewater pressures with depth.



(figure from Ku et al. 2013)

3. Non-invasive Geophysical Study for Bedrock Evaluation. This is an ongoing project supported by The Singapore Land Transport Authority. The goal of this research is to examine and establish technically and economically preferable non-invasive seismic wave-based methods (e.g., surface wave, reflection/refraction) for underground bedrock detection, with consideration of degree of rock weathering which is commonly observed in tropical regions like Singapore. This study is expected to provide critical scientific/ experimental observations on characteristics of surface wave propagation in Singapore's geologic context with various rock mass conditions.

4. V_S-based Global Correlation Study for Evaluating Soil Properties: He has also focused on comprehensive geocharacterizations with both analytical geotechnical solutions and empirical approaches based on advanced data analysis techniques. For instance, some recent researches include shear wave velocity based estimation of soil unit weight and undrained shear strength via a special database compiled from well-documented geotechnical test sites. Stress-dependent and anisotropic characteristics of V_S are considered.

Offshore Geotechnics

(Inputs by Yean-Khow Chow, Chun-Fai Leung and Fook-Hou Lee)

Singapore shipyards fabricate about two-third of mobile jack-up rigs worldwide. At NUS, extensive centrifuge and numerical model studies had been carried out to investigate the behavior of jack-up spudcan foundation in relation to foundation punch through and extraction difficulties, interaction between spudcan and adjacent pile, and interaction between spudcan and existing footprints due to previous spudcan installation. Three Joint Industrial research projects (JIP) on the above topics have been completed.

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For spudcan jack-up punch through hazard in sand over clay, the studies identify that conventional bearing capacity theories do not predict the punch through hazard correctly as a sand plug beneath the spudcan base is being formed during preloading. The centrifuge study summarized in Figure 1 reveals that the prediction of punch through distance is also critical, which is now referred to in the ISO 19905-1 2012 code. For spudcan extraction, it is established that the suction between the spudcan base and the clay develops with time and a large extraction force is required if the jack-rig remains longer at a site. The findings of the above research studies are now provided in the InSafe Guidelines on safe spudcan operation jointly conducted by NUS, Oxford University and University of Western Australia.

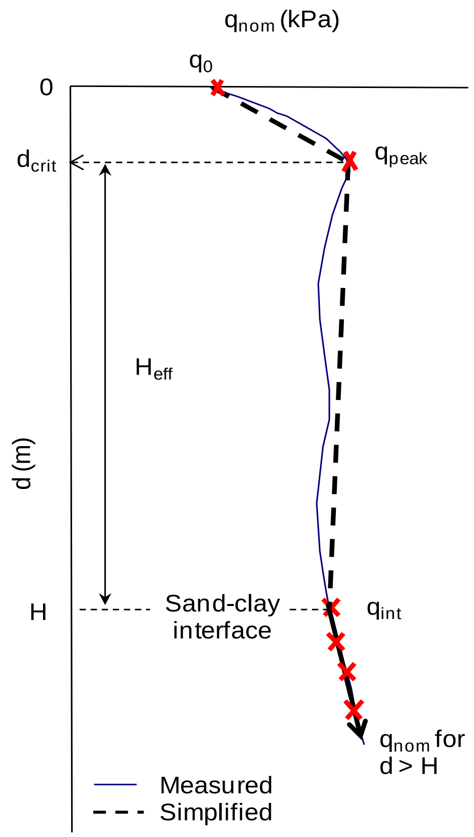

Figure 1. Identification of important parameters for spudcan punch through hazard in sand over clay (Teh et al. 2010 from *Géotechnique*)

For the study on the interaction between spudcan installation and the adjacent piled foundation supporting the permanent jacket platform, SNAME specifies that spudcan-pile interaction needs to be evaluated in detail if the clearance between the spudcan and pile is smaller than one spudcan diameter. Arising from the NUS research, design charts on induced pile moments between spudcan and pile in close proximity was presented at an earlier OTC conference in Houston. A JIP funded by 8 offshore engineering organizations on remediation measures of spudcan reinstallation in footprints has just been completed. The spudcan-footprint interaction characteristics and mechanism are now much better understood. If used strategically and systematically, stomping of footprints is established to be an effective method in alleviating the severe interaction without the danger of spudcan sliding into the footprint during reinstallation. Another aspect of spudcan study is the effect of lattice leg on soil flow, cavity formation and ultimately, on settlement and bearing capacity. The results of the study, which are currently in press, indicate that the main effect of the lattice leg is to deepen the cavity immediately after installation, Figure 2. The shape of the cavity is also different from that without lattice leg and is characterized by a

Research highlights

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section of steep-sided cavity wall that is co-planar with the lattice leg. This accentuates the likelihood of soil collapse into the cavity during operation, thereby increasing the possibility of large settlement. This can also potentially influence punch-through occurrence and measures to alleviate punch-through have been proposed.

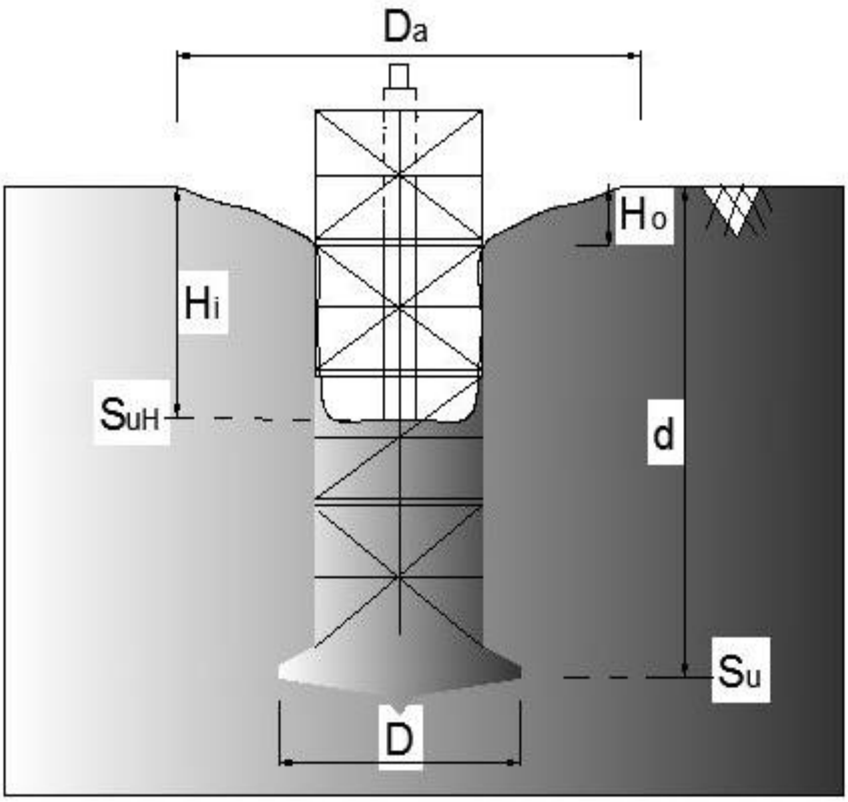

Figure 2. Typical cavity shape with lattice leg

Oil and gas explorations now advance into deep waters. Anchoring is a common foundation mean of securing floating platforms in open seas. Numerical and centrifuge model studies are carried out to examine the anchor performance in normally consolidated clay and in non-homogeneous clay. The DNV guidelines specify that the shear strength of the clay at the initial anchor elevation may be considered as the reference strength for design. The study at NUS shown in Figure 3 clearly establishes that the failure mechanism for anchor uplift in normally consolidated clay and clay with increasing strength profile are marked different. The dimensionless soil overburdening factors incorporating the soil strength profile are found to be appropriate in predicting the anchor uplift resistance in non-homogeneous clay. The study on long term capacity of plate anchors under sustained loadings is currently in progress. Study is also on-going on dynamically installed anchors. This study encompasses the effects of soil states, fin shapes and pullout orientation. An important finding is that the fin shape has a very significant effect on the lateral capacity of the anchors.

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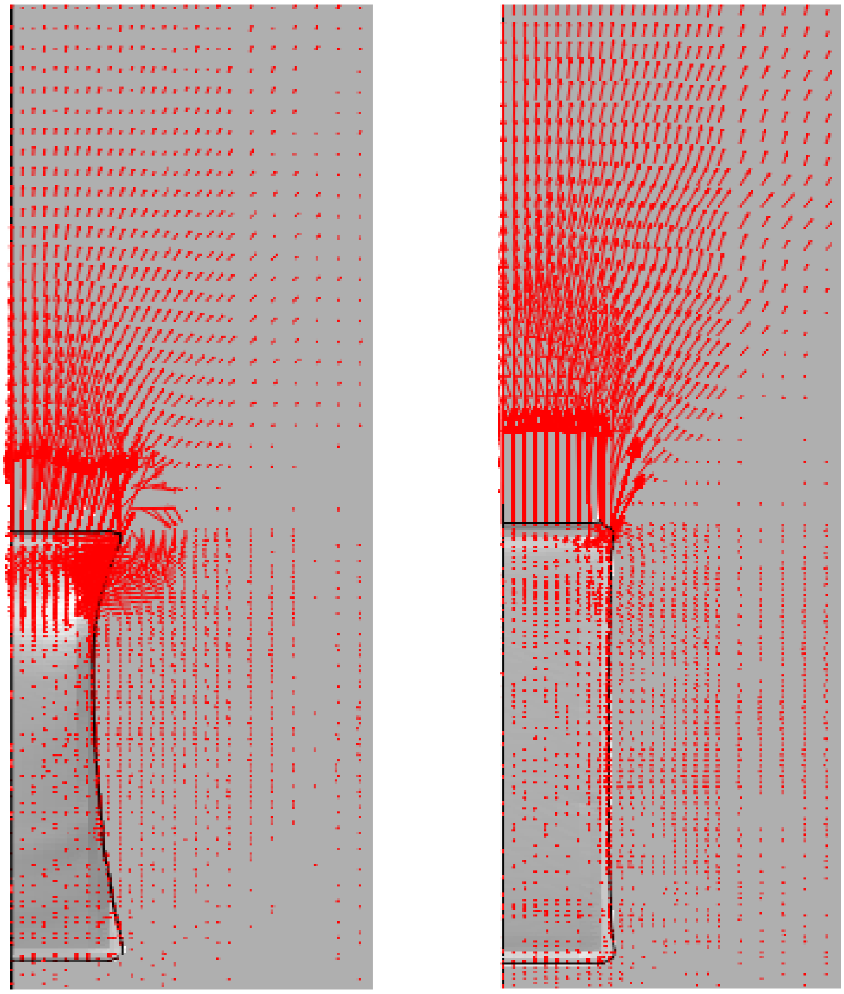

Figure 3. Differences in failure mechanisms for uplift resistance of plate anchors in (a) normally consolidated clay and (b) non-homogeneous clay (Tho et al. 2013 *Canadian Geotechnical Journal*)

Another deep water offshore geotechnics problem involves pipeline-soil interaction. Pipelines within the touch down zone of the seabed would be subjected to repeated vertical motion. The results of centrifuge tests reveal that the soil would be almost fully remolded after about 8 cycles of vertical pipeline motion. Figure 4 shows the differences in the load-displacement responses in normally consolidated clay and in overconsolidated clay having an overconsolidation ratio of 3. Back analyses of the test data reveal that the remolded shear strength obtained from ring shear tests can be used to predict the soil resistance in the long term. Ongoing research is being carried out to examine the behavior of pipelines having free span length without soil support. Centrifuge and numerical studies are being carried out to examine the behavior of the pipeline resting on the soil shoulder in the vicinity of free span. In addition, centrifuge model and numerical studies are also on-going to examine pipeline-soil interaction in “pipe-walking”, and how this may vary with displacement and time.

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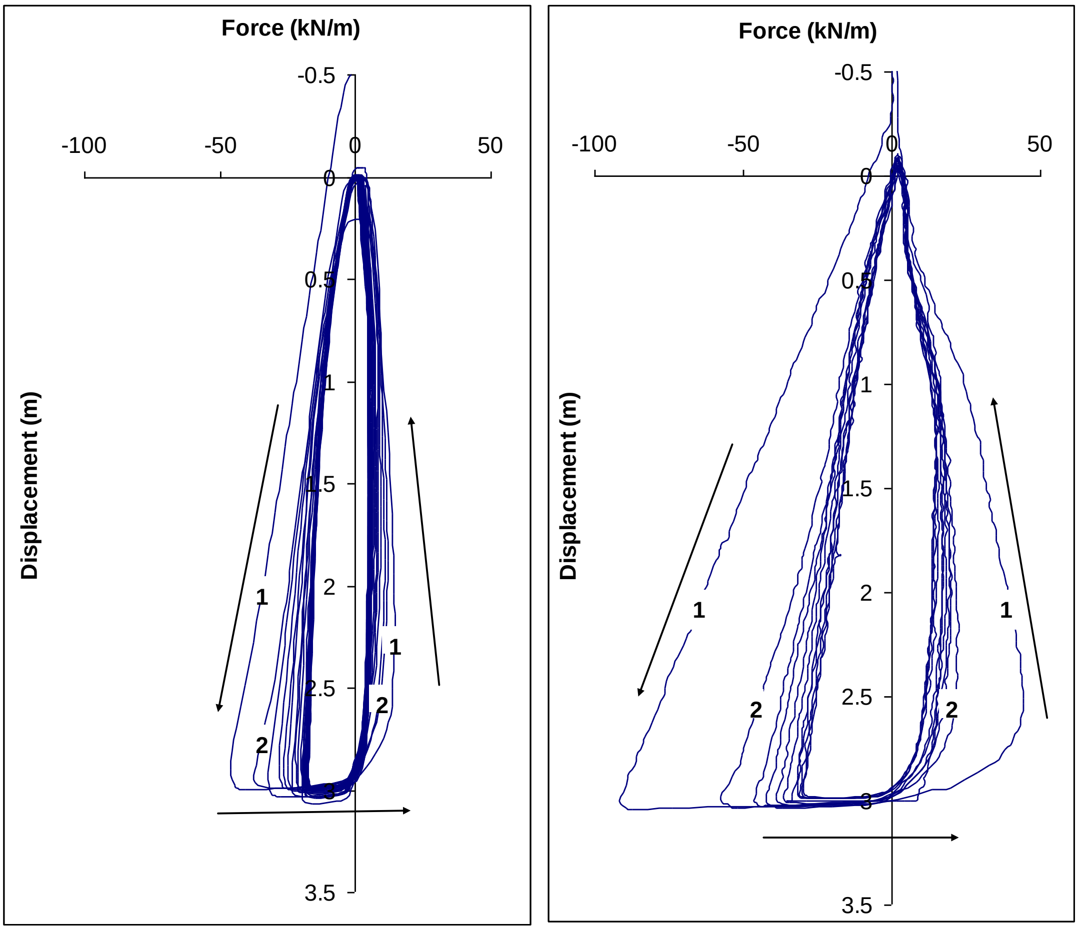

Figure 4. Load-displacement responses for repeated vertical motion of pipeline in (a) normally consolidated clay and (b) overconsolidated clay with OCR = 3 (Hu et al. 2011, Ocean Engineering)

Fook-Hou Lee
Director, Centre for Soft Ground Engineering (CSGE), NUS