A REVIEW OF MEDIUM- TO LARGE-SCALE LABORATORY TESTING FACILITIES FOR SOIL-PILE INTERACTION

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ABSTRACT

A recently started European Union (EU) project, GEOLAB brings together 11 unique facilities for studying soil-structure interaction (SSI). The ultimate aim is to integrate key European national research infrastructures into an excellent one-stop-shop for performing groundbreaking research and innovation with respect to SSI in order to address the challenges faced by the critical infrastructures (CI) of Europe. Among these installations is the Geotechnical Test Pit of the Technical University of Darmstadt (TUDa), Germany. With a plan dimension of 19.5 m x 5 m, the facility allows for medium- to large-scale pile model testing, thereby closing the gap between small-scale testing, on one hand, and very rare and expensive in-situ testing, on the other hand. In this paper, the TUDa test pit is presented and a review of other globally existing pile testing facilities of similar scale is given, with focus on parameters as model preparation, pile installation, and instrumentation, among others. The aim is to present the state-of-the art in medium- to large-scale physical modelling of soil-pile interaction, and identify the gaps for further development, particularly where they are relevant for enhancing CI resilience. Potential scope for future collaborations is also highlighted.

Keywords: critical infrastructure, soil-structure interaction, physical modelling, GEOLAB

INTRODUCTION

Like all critical infrastructures (CI) worldwide, the CI of Europe are facing tremendous pressure from the impacts of global changes such as climate change, unprecedented population growth with its concomitant increase in demand for services, and evolving societal goals, e.g. reduction of greenhouse gas emissions, increase in the share of renewable energies, transition to "smart mobility", less congestion, higher safety, less environmental impact and lower operational costs (GEOLAB 2021). Within this context, the GEOLAB Consortium was formed and recently officially started as a project funded under the European Union's Horizon 2020 Research and Innovation Programme. GEOLAB brings together key geotechnical research infrastructures in Europe with the aim to integrate them into an excellent one-stop-shop for performing groundbreaking research to enhance the resilience of CI in the region.

Realizing that crucial to building such resilience is ensuring the integrity of these structures itself, and that such integrity depends to a great extent on the interaction of the structure with the subsurface soil, research in GEOLAB focuses on soil-structure interaction (SSI). How this interaction is influenced by expected changes in environmental (e.g., climate change), loading (e.g., increased traffic) and other related conditions is an important aspect that will be looked into under the project. Clearly, the issues involved are very complex such that their appraisal would require interdisciplinary cross-cutting approaches using advanced suite of physical research infrastructure to allow investigation from different perspectives, in diverse scopes and at varying scales.

In this connection, GEOLAB offers free access to a set of 11 complementary and synergistic experimental facilities from leading European institutions for coordinated research and innovation actions (Fig. 1). These include three large geotechnical centrifuges of varying focus applications: that of the Université Gustave Eiffel (Uni Eiffel) for unsaturated soil behavior, Deltares for very soft soil, and University of Cambridge for behavior during construction phases. Meanwhile, the smaller centrifuges of the Technical University of Delft (TU Delft) and Eidgenössische Technische Hochschule Zürich (ETHZ) allow more economically viable testing and therefore larger series of experiments than possible in the large centrifuges. In addition to these centrifuges are facilities for more specific applications such as the geotechnical test pit of the Technical University of Darmstadt (TUDa) with its main application on pile foundation testing, static liquefaction tank of TU Delft, railway track simulator of Centro de Estudios y Experimentación de Obras Públicas (CEDEX) and traffic load simulator of the University of Maribor. Finally, GEOLAB also offers a set of 5 well-documented field test sites owned by the Norwegian Geotechnical Institute (NGI). With such a broad suite of installations, therefore, it is possible to design a comprehensive experimental program as for instance scale modelling in a large centrifuge followed by complementary field trial tests (GEOLAB, 2021).

As mentioned above, one of the GEOLAB facilities, the TUDa geotechnical test pit, has its main application on pile testing. With a total areal dimension of 19.5 m x 5 m, the facility offers the rare possibility of medium- to large-scale pile model testing or even full-scale (e.g. micropile) testing. Thus, it is able to close the gap between small-scale testing, on one hand, and expensive in-situ testing, on the other hand. The facility also overcomes some of the limitations of centrifuge testing such as scalability of the soil/soil grain and, thereby, the difficulty in observing some phenomena like soil-water interaction.

In this paper, the TUDa test pit is described, followed by a review of other globally existing pile testing facilities of nearing size. The elements and capabilities of these facilities are presented, focusing on parameters such as soil model preparation, pile installation, loading system and instrumentation, among others. The aim is to present the state-of-the art in medium- to large-scale physical modelling of soil-pile interaction, and identify potential areas for advancement, particularly where they are relevant for enhancing CI resilience. Potential scope for future collaborations is also underlined.

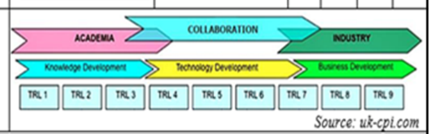
Research Infrastructure	Features	Application Energy	 Water	 Urban	 Transport	Research Infrastructure	Features	Application Energy	 Water	 Urban	 Transport
	TU Delft Static Liquefaction Tank 5 x 2 x 2 m TRL 3 – TRL4	X	X		X		TU Delft Beam Geo-Centrifuge Beam 1.3 m TRL 3 – TRL4	X	X	X	X
	Deltares Geo-model Container 4 x 2.5 x 1.2 m TRL 3 – TRL4	X	X	X	X		ETHZ Drum Centrifuge Diameter 2.2 m TRL 3 – TRL5	X	X	X	X
	UMaribor Traffic Load Simulator 0.7 x 0.7 x 1.2 m TRL 3 – TRL4			X	X		Deltares Geo-Centrifuge Beam 5.5 m TRL4 – TRL6	X	X	X	X
	CEDEX Track Box 21 x 5 x 4 m TRL5 – TRL6			X	X		Uni Eiffel Geo-centrifuge Beam 5.5 m TRL4 – TRL6	X	X	X	X
	TUDa Geotechnical Test Pit 19.4 x 5 x 3/6 m TRL5 – TRL6	X		X	X		Cambridge Centrifuge Beam 10 m TRL4 – TRL6	X	X	X	X
	NGI GeoTest Sites 5 field sites TR6 – TRL7	X	X	X	X						

Fig.1 The GEOLAB facilities and their application on the focus CI sectors (GEOLAB, 2021)

THE TUDa GEOTECHNICAL TEST PIT (GTP)

The GTP is located in the 23 m x 23 m x 7 m (L x W x H) experimental hall of the Institute of Geotechnics. It consists of a stiff concrete box caisson, the lateral and bottom boundaries of which are rigid. The GTP has a total length and width of 19.5 m and 5 m, respectively, and has two parts: a 6 m deep pit with areal dimension of 5 m x 4.35 m and a shallower 3 m deep pit of 14.5 m x 5 m areal dimension. Due to its size, this shallow part of the pit is ideal for pile group testing. Smaller-scale tests is, however, also possible by creating smaller bays using mobile steel walls. Currently, only dry testing is possible, but where wet testing is desired, a 4.3 m x 3 m (diameter x height) steel cylinder with water connections at the bottom is available.

The facility is equipped with actuators that can transmit static and dynamic force uniaxially or multi-axially to the pile. Two vertical and one angle-adjustable loading frames are available, which can be positioned at various places across the pit to accommodate different test and loading conditions. Table 1 gives further details on the technical specifications of the GTP, while Figure 2 shows an overview of the facility

The facility uses sand, the Darmstadter Sand, as standard test material, but use of other soil types is in principle also possible. Sourced from the Main River, Darmstadter Sand is a poorly-graded, medium-grained clean silica sand. For the installation of this sand, the main method adopted is dry pluviation. Figure 3 shows the pluviation system consisting of a sand hopper with a volume capacity of ca. 1 m^3 and 4 rigid tubes. It is attached to the crane that is then electronically-controlled to traverse the pit back and forth. Maximum capacity of the crane is 5 tons. Sand flow is controlled through the slots at the nozzles of the hopper, which together with the height of fall determine the density of the soil model. For wet testing in the cylindrical pit, layer-wise pouring and compaction with a vibrating machine is used. This latter installation method may also be used where dry testing takes place in a small section of the rectangular pit. For pile installation, an impact or vibratory hammer may be used depending on pile size, or the pile can also be wished-in place.

Table 1 TUDa GTP technical specifications

Parameter	Value
Test Pit Dimension	19.5m x 5.0m (L x W)
Deep Pit	5.0m x 4.35m x 6.0 m (L x W x H)
Shallow Pit	14.5m x 5.0m x 3m (L x W x H)
Steel Cylinder	4.3m x 3m (D x H)
Test Type	
Pit	Dry Testing
Steel Cylinder	Wet Testing
Test Material	Medium Sand (Darmstadter Sand)
Model Preparation	Dry Pluviation; Moist Tamping-Layer Wise Compaction with a Vibrating Machine
Pile Type	Steel, Concrete, Timber
Typical Single Pile Size	
Diameter	100 ≤ D ≤ 500 mm
Length	1000 ≤ L ≤ 4000 mm
Pile Groups	Feasible
Pile Installation	Drop Hammer; Vibrohammer; Wished-in-Place
Sensor and Instrumentation	Load Cells, Displacement Transducers, Pressure Transducers, Strain gauges, accelerometer, tensiometer, CPT, SPT, Terrestrial 3D Laser Scanner, soil moisture sensor, thermographic camera
Vertical Load	
Static	Up to 2000 kN
Cyclic	Up to 100 kN @ 2 Hz
Horizontal Load	
Static	Up to 1000 kN
Cyclic	Up to 100 kN @ 2 Hz

Fig.2 The TUDa Geotechnical Test Pit


Fig.3 Pluviation system

While the TUDA GTP has its main application in pile testing, other tests can also be performed in the pit, including, among others, testing of new installation techniques, prototype foundation or ground improvement methods. In the past, the behaviour and interaction with soil of other geo-structures such as shallow foundations and buried structures like pipes have also been investigated in the facility (Breth et al., 1976; Rau, 1987).

OTHER MEDIUM- TO LARGE-SCALE GEOTECHNICAL TEST PITS

The result of our survey of other geotechnical test pits for medium- to large-scale physical modelling of soil-pile interaction is presented in the succeeding discussion. Note that for possible comparison with the TUDa pit, only those installations with areal dimension equal to or bigger than about 4 m x 4 m and a minimum depth of 3 m were included. Information was sourced mainly from the homepage of the facility owners, reports and publications, and email query. For possible leads, the ELGIP (European Large Geotechnical Institutes Platform; https://elgip.org/) and GEOLAB networks were tapped, as well as contacts from leading institutions from various countries. It was assumed that, since these leading institutions are usually active in collaboration work with the academe, government, industry and other sectors, they would know if such test pits are available in their respective countries, or at least who to contact for information. Thus, in addition to the availability of online information and published documents, the survey results were also limited by the availability of contact persons and the validity of the said assumption. Among those countries where information was found and/or which returned the query include Germany, Netherlands, UK, France, Norway, Sweden, Italy, Switzerland, Greece, Spain, Romania, Lithuania, Portugal, Austria, Slovenia (and neighboring countries, which the contact person also surveyed), USA, Australia, Columbia and Hong Kong.

As can be seen from Table 2, test pits of the considered scale, as far as known, exist only in a very limited number in only a couple of countries, with concentration in Germany. This sparsity is not surprising considering the large space and capital requirements for building such a facility. Of those in existence, only that of Leibniz University of Hannover is larger in dimension than the test pit of TUDa, the former being the world's largest testing facility of its kind. With strong support from the government, as well as from the wind energy industry, to whose needs the test environment is specifically tailored, this new and modern foundation test pit of the Leibniz University features first-class and high-capacity equipment.

Aside from the test pit of Leibniz University, other facilities such as that of Deltares, TU Berlin, and BTU Cottbus have also been used for testing monopile foundations for offshore wind turbines (Coronel, 2020; Isik, 2020; Tasan, 2011). Like the pit of TUDa, most of the pits are also used for other purposes in addition to pile testing. For instance, an investigation into the load-bearing capacity of pegs as anchoring elements for horizontal loads was conducted in the pit of TU Kaiserslautern (Berker, 2003). The facility of RWTH Aachen was used to study the influence of ground reaction force on punching shear of isolated foundations (Ulke, 2008). Another study in this pit was on sheet pile walls not as a foundation element but on their thermal activation for the development of the large regenerative energy potential of open waters (Koppmann et al. 2019). Meanwhile, testing of sheet pile walls as a vertical load bearing element for bridge abutment was conducted in the pit of UNC Charlotte (Rice et al, 2014; Sylvain et al., 2014). The facility of UNC Charlotte is the smallest in the lot; however, it offers advanced testing capabilities and state-of the-art support services. Of almost the same dimension is the pit of Norwegian University of Science and Technology (NTNU). The NTNU pit has also flexible applications and the test environment can be adopted to the needs of the projects (Eiksund, *pers.comm.*). As to the pit of Vilnius Gediminas Technical University, the 6 x 6 x 7 m dimension indicated in Table 2 is based on that reported by Martinkus et al. (2013). It is, however, possible that the facility is bigger, with the option to create smaller sections, since other sizes have been reported in the literature (assuming they refer to the same pit), e.g., 5 x 7.8 x 4.5 m (Martinkus et al., 2021), 5 x 7 x 4.5 m (Norkus and Martinkus, 2019).

Table 2 Medium- to Large-Scale Geotechnical Test Pits Worldwide

Facility Owner	Size (L x W x D) [m]	Soil Model Type	Soil Model Installation	Pile Installation	Loading system	Instrumentation	Other remarks
A. Germany							
1. Leibniz University of Hannover *https://www.tth.uni-hannover.de/de/ausstattung/grundbauversuchsgrube/*	14 x 9 x 10	Medium Sand Inclusion of clay interlayers possible	Layer-wise pouring and compaction; layer thickness of 30 cm and 25 cm before and after compaction	Various, e.g., impact pile driving hammer, vibratory hammer; designed up to an impact energy of 20 kJ per impact	Max.cap +1500/-1000 kN Static and dynamic, uniaxial and multi-axial Loading frequency up to 5 Hz	Load cell, Displacement Transducer, Strain gauge, CPT	Vertical span 8m high along pit length extends load possibilities Equipped with four wells for obtaining homogeneous soil water content
2. Technical University of Munich* *https://www.bgu.tum.de/gb/forschung/poster-von-forschungsarbeiten-und-projekten/poster-von-forschungsarbeiten-und-projekten/007-2006-grossmassstaebliche-pfahlprobebelastungen-in-der-versuchsgrube/*	Total (L x W): 8 x 5 Parts: Shallow pit 4 x 5 x 4 Deep pit 4 x 5 x 8	Munich Tertiary Sand (slightly gravelly silty fine to medium sand)	Layer-wise pouring and compaction; maximum thickness of 20 cm	Boring using a double rotary drilling machine	Servo-hydraulic system; no information on max. cap. but from previous experiments: Static +/- 300 kN Dynamic +150 kN / -120 kN Load cycles from 20 minutes up to 0.5 minute Load frame capacity up to 2000 kN	Load cell, Inductive displacement transducer, Strain gauge	Drill rig can be used; working platform can be built on the pit CPT measurement possible
3. Technical University of Berlin *https://www.grundbau.tu-berlin.de/fileadmin/fg99/Labore/Laborpraesentationen/TU_Berlin_Lab_presentation_engl.pdf*	7 x 5 x 3.7 With steel walls for subdivision /creating smaller sections; divisible into a maximum of 6 segments	Berliner Sand	Flushing procedure Layer-wise pouring and compaction	Push-in using hydraulic press	Four hydraulic cylinders with nom. cap. +/- 16 / 63 / 250 / 1000 kN Static and dynamic, uniaxial or multi-axial Operating frequency: 0-2 Hz	Force and displacement transducer integral to the load piston, Displacement transducer, Strain gauge, Porewater pressure transducer	Movable load frame Water-filling system for moist and saturated testing Planned extension: Rotable cylinder

							for multi-directional loading
4. Brandenburg Technical University Cottbus-Senftenberg *https://www.b-tu.de/fg-geotechnik/forschung/profil/erdbauversuchsgrube#c79116*	7 x 4 x 4	Sand, but other soil in principle is also possible	Dry pluviation	Wished-in-place	Max. cap. 30 kN; displacement range +/- 220 mm Static and dynamic, uniaxial	Load cell, Displacement Transducer, Strain gauge. CPT	Wet testing possible
5. RWTH Aachen University *https://www.gut.rwth-aachen.de/cms/Geotechnik/Forschung/Dienstleistungen/~lhjmk/Technikumsversuche/lidx/1/*	6 x 4 x 2.5 Depth can be increased to 3.5m using high density fiber (HDF) board panels	Sand, but in principle other types of soil possible	Dry pluviation Layer-wise pouring and compaction	Wished-in-place	Four hydraulic cylinders, max. cap. 600 kN Static, uniaxial	Load cell, Tension force transducer, Earth pressure transducer, Displacement transducer, Strain gauge	Moist/saturated testing possible Crane runway above the pit; crane max. cap. of 2 tons Pit can be modified per test requirements
6. Technical University of Kaiserslautern* *https://www.bauing.uni-kl.de/bodenmechanik/dienstleistungen/*	4.5 x 4.5 x 5	Friedelsheimer Sand (medium sand with 30% fine sand)	Layer-wise pouring and compaction with surface vibrator	Cast-in situ concrete piles	Assumed max. cap. based on previous experiments (Shen, 2006): ~1000 kN	Load cell, Displacement transducer, Strain gauge	
B. Other countries							
7. Deltares (Netherlands) *https://www.deltares.nl/en/facilities/water-soil-flume/*	Soil-Water-Flume: 50 x 5.5 x 2.5; can be divided into compartments of variable sizes	Gravel, sand, silt, clay	Layer-wise pouring and compaction using vibrating needles; layer thickness of 0.5 m	Ram driving with IHC Fundex CP25D pile driver; ram mass 1650 kg	Max. pulling force 30 kN	Displacement transducer, Flow meter, Pressure gauge, Porewater pressure sensor, Temposonic, Cameras, CPT, In-situ falling head test equipment	Travelling carriage over the flume with: - multipurpose installation platform - vibrating needles for compaction of sandy soils - travelling speed adjustable from 0.02 to 2.5 m/s - two adjustable mixture-pumps, 70 l/s and 250 l/s

							Special ‘clay-factory’ Glass wall for visualisation
8. Vilnius Gediminas Technical University (Lithuania)*	6 x 6 x 7	Sand (dry, uniformly graded, medium-coarse grained)	Layer-wise poring and compaction with single direction plate compactor	Push-in using hydraulic press	Two hydraulic cylinders, cap.1200 kN	Load cell, CPT, Dynamic plate load	
9. University of Bristol (UK) *https://www.bristol.ac.uk/engineering/ research/ukcricbristol/sofsi/*	6 x 5 x 4				Two 1000 kN pseudo-static actuators (1000mm stroke) and one 1000 kN dynamic actuator (500mm stroke)		Not yet in operation; still in construction stage
10. Norwegian University of Science and Technology (Norway) *https://www.ntnu.edu/research/lab*	4 x 4 x 3	Sand (uniformly graded, medium grained)	Dry pluviation	Usually wished-in-place, but can also be driven or pushed in place	Hydraulic actuators, typical load capacity 20-200 kN; static and cyclic Multidirectional screw-ball actuators, typical load capacity 2 kN; static and cyclic Impact loading	Load cell, Strain gauge, Earth pressure sensor, Accelerometer	Pit designed for dry sand, but wet sand possible Loading system can be tailor-made for each project Application of surcharge pressure on the sand surface possible using a vacuum system
11. University of North Carolina in Charlotte (USA)* *https://epic.uncc.edu/laboratories/epic-highbay-laboratory/projectspublications*	3.7 x 3.7 x 3	Sand	Layer-wise pouring and compaction using vibratory plate and hand tampers: loose thickness of 10 mm	Impact pile driving hammer, vibratory hammer	Maximum capacity ~ 1459 kN (328 kips) Static and dynamic, vertical	Load cell, Displacement transducer, Strain gauge, accelerometer Dilatometer, SPT, CPT, MASW, Cross-hole seismic testing	Wet testing possible

**Based on previous experiments*

It is worth noting that the facility of Deltares, being a flume, has more comprehensive applications, many of which are not possible in any of the other pits. These includes plume dispersion, beaching deposition of slurries and tailings, sand/mud mixture flows and segregating behavior, and Physics of Non-Newtonian flows among others, i.e., pile testing is just one of the many possibilities in this type of facility. This, however, implies that in principle and where suitable equipment and features are available (e.g., loading frame and actuators, partitioning walls), all the other hydrodynamic (basin and flume) and related facilities existing worldwide can be used for medium- to large-scale modelling of soil-pile interaction. This makes it possible to investigate topics that usually cannot be investigated in conventional test pits, e.g. scour in piles. Some of these facilities, with their owner and dimension (L x W x D), are listed below (Deltares, 2021; ICAIR, 2021; University of Birmingham, 2020; WETO, 2019):

- Delta Flume (Deltares, Netherlands) – 300 m x 5 m x 9.5 m
- Large Wave Flume (Oregon State, USA) - 104 m x 3.7 m x 4.5 m
- Directional Wave Basin (Oregon State, USA – 48.8 m x 26.5 x 2.2
- Hydraulics Wave Basin (University of Iowa, USA) – 40 m x 20 m x 3 m
- David Taylor Model Basin -Carderock (US Navy, USA) – 846 m x 15.5 m x 6.7 m
- Alfond Wind/Wave Ocean Engineering Laboratory (University of Maine, USA) - 30 m x 9 m x 4.5 m
- Offshore Technology Research Center Wave (Texas A&M, USA) – 45.7 m x 30.5 m x 5.8 m, with adjustable depth pit (9.1 m x 4.6 m x 16.8 m),
- National Buried Infrastructure Facility (University of Birmingham, UK) - 25 m x 10 m x 5 m
- National Distributed Water Infrastructure Facility (University of Sheffield, UK) – 45 m x 6 m x 5 m

Finally, in the newly inaugurated test facilities of Pontificia Universidad Javeriana, Bogota, a 10 m x 4 m x 6 m test pit is available. It was conceptualized as a multi-purpose geotechnical pit, but is currently configured and used mainly for testing pavement structure (Prada Sarmiento, *pers. comm.*).

Going to the elements and capabilities of the facilities, one important thing to note is that some information in Table 1 was based only on what was used/applied in previous experiments. Thus, for instance, while sand is indicated for soil model building in the pit of TU Munich as reported in Gruber (1985) and Schwarz (2002, 2006), it is possible that other types of materials can also be used in the facility. This notwithstanding, it can be seen from the table that all facilities mainly use sand as test material, although other types of soil are in principle also possible in most of the pits. Layer-wise pouring and compaction is the soil installation of choice, probably due to ease of handling, and moreover because this method does not require specialized equipment such as a pluviation system. For the TUDa test pit, however, whose areal dimension is relatively large, but not large enough as to permit easy maneuvering of a small soil compactor vehicle, pluviation remains a practical choice and the more efficient way to achieve a uniform soil model. However, layer-wise pouring and compaction using a vibrator plate and hand tamper similar to that of UNC Charlotte is also an option, particularly in smaller bays. For pile installation, a variety of methods is used such as hydraulic press-in, impact hammering, vibro-hammering, wished-in-place and even boring or cast-in-situ. One important factor in the decision as to which method to use is the effect of the resulting noise/vibration in neighboring buildings/structures, as for instance considered by Tasan (2011) in choosing hydraulic press-in for the TU Berlin test pit.

Loading system capacity covers a wide range from the lowest 16 kN of one of the four actuators of TU Berlin to the 2000 kN of TUDa (but only for static vertical load). All facilities have a fairly standard set of measuring instruments, although the Deltares and UNC Charlotte offer a wider range of measuring possibilities. This is expected for Deltares due to the wide application of its facilities as mentioned earlier.

CONCLUSION AND OUTLOOK

In general, excluding the flume facility of Deltares, which cannot be considered a geotechnical/foundation test pit in the usual sense of the term, the features of and methodologies used in all the facilities are fairly standard and uniform, reflecting the current state-of-the-art in medium- to large-scale physical modelling of soil-pile interaction. From this, a couple of areas for advancements can be identified to enhance present capabilities to address the challenges faced by CI. One such is the possibility to test clays. At present, most tests in the pits are done in sand mainly due the difficulty of handling clays. However, expected changes in the environmental conditions with the advent of climate change, as well as the effect of aging, will have their greatest impacts on clays (e.g., freeze/thaw, shrink/swell, thermal expansion, creep). Since the interaction between the atmosphere and geosphere mainly takes place in the near surface, where unsaturated condition exists, the capability to test under this condition will have increasing importance in the coming years. Related to this is the capability to control the temperature environment during physical modelling, since the properties and behavior of unsaturated soils are very much temperature-dependent.

In GEOLAB, one realization is that while each partner operates state-of-the art facilities, work in these installations has been largely independent and unintegrated, significantly limiting the scope of outcome. However, the increasing complexity of the problems the CI are facing compels us to come together to align our efforts. Such a collaborative framework has to be expanded, and in this regard large-scale research facilities like those presented in this paper can play vital catalytic role. In particular, the scarcity of field data on one hand, and the need to elucidate how foundation interacts with the surrounding soil and environment on the other hand, make near full-scale to full-scale testing a key component of our research strategy, vital in the testing and validation of new/existing numerical models and design procedures. At this scale, however, testing becomes very expensive and time consuming such that a collaborative research would be the most efficient and cost-effective way to obtain cutting-edge results. Based on the results of the present review, one potential topic for collaborative research that can immediately be identified is pile installation effect since a wide range of equipment/methodologies have been applied across facilities. Currently inadequately understood, advancement in knowledge of this topic will have far-reaching effect in enhancing CI resilience in particular, and in our understanding of SSI in general. In the end, international collaboration on this and other topics can play a critical role in harnessing the individual and collective power of our facilities, where each can capitalize on the strength of the other facilities.

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