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Editorial

Characterization and engineering properties of natural soils used for geotesting

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Abstract: Benchmarking is of significant importance in geological and geotechnical engineering, for testing and verifying innovative soil investigation methods and foundation solutions. This Special Issue aims to present detailed characterization of a wide range of natural soils used for benchmarking in geological and geotechnical engineering that was presented at the ISGTS symposium in Oslo in June 2019. It also seeks to promote an increase in use of the benchmark sites as a research tool, as training and teaching facilities and as ground for development of new soil models, testing of new investigation methods and to further advance the state-of-the-art in the fields of geological and geotechnical engineering.

Keywords: GeoTest Sites; soil characterization; engineering properties; research sites

1. Introduction

Critical infrastructure—such as offshore energy structures, roads, railways and buildings—is increasingly being built on difficult ground conditions such as soft clays, silt and loose sands. Offshore, problematic geo-materials are encountered in almost all modern development, where water depth often exceed 500 m. Onshore, transport corridors must increasingly make use of poor ground conditions that has proven problematic for other developments. In all such cases, the response of the geo-materials is complex and highly variable, and presents major design and construction challenges.

Benchmarking is a key to the reliability of the solutions in geotechnical engineering. Throughout the world, a system of geotechnical experimentation sites with a wide range of geological ground conditions is available for testing and verifying innovative soil investigation methods and calibrating foundation solutions. These benchmark test sites provide easy access to well-characterized and documented field test sites for advancing the state of the art in areas such as in situ testing, instrumentation, prediction of soil behaviour, and foundation prototype testing.

In June 2019, the Norwegian Geotechnical Institute (NGI) and its partners, the Norwegian University of Science and Technology (NTNU), SINTEF, the University Centre in Svalbard (UNIS) and the Norwegian Public Roads Administration (NPRA), arranged the 1st International Symposium on GeoTest Sites (ISGTS) in Oslo, Norway. The aim of the symposium were to i) present detailed characterization of a wide range of natural soils used for benchmarking in geotechnical engineering, and to ii) promote an increase in use of the benchmark sites as a research tool, as training and teaching facilities and as ground for development of new soil models, testing of new investigation methods and to further advance the state-of-the-art.

This special journal issue contains 30 scientific papers compiling information from 21 international geotechnical test sites. All papers follow a similar structure including: i) Site geology and location, distribution, local and global importance; ii) Engineering geology, including source of material, depositional environment, post-depositional processes and stress history; iii) Composition, mineralogy and fabric; iv) State and index properties; v) Engineering properties (strength, stiffness, hydraulic conductivity, etc.); vi) Comments on quality/reliability of data, with reference to methods of sampling, laboratory testing and standard in situ testing methods; and vii) Engineering problems including a summary of typical problems and hazards and with references to case histories. Also included are papers dealing with the use of soil databases and correlations in engineering practice, and papers describing a spectrum of applications for educational and research purposes.

This introductory paper provides a summary of the geotechnical test sites presented during the 1st ISGTS and major points of discussions. It is hoped that this Special Issue will serve as a reference for potential users of the test sites and for others within the geo-professions, including students and geo-engineers, interested in well-documented site-specific data.

2. Site overview

The term reference site, or test site, as used in this paper refers to a site that is well characterized and that can be used to compare measurements or observations made by different techniques or methods. This means that a test site must be well defined in terms of geological history, soil classification parameters and strength, deformation and flow parameters. Other requirements or specification for a test site usually include, but are not necessarily limited to:

- Representative soil conditions for an area or project type.
- Ease of access.
- Availability.
- Size—e.g. large enough for model testing.
- Relevant infrastructure is in place; e.g. access road, water supply and electricity.

Figure 1 presents the approximate worldwide location of the 22 different GeoTest sites included in this Special Issue. The test sites are in 13 different countries all over the world, from North America, South America, Europe, Australia and Asia.

Figure 1. Location overview of geotechnical test sites presented during 1st ISGTS.

2.1. Norway

NGI has in its 60 years of history made use of several test sites. A list of the most referenced ones is given in Table 1. Most of the sites have been on soft clays, with varying sensitivity and plasticity. The sand site at Holmen in Drammen and the silt site at Halsen close to Trondheim have also been much used. The sites have been used for developing new and improved equipment and methods for soil characterization in terms of in situ testing, sampling and laboratory testing. The test sites have also been very useful for trying out or verifying new foundation solutions by large scale testing. Unfortunately, most of these sites have been lost over time due to urbanization or because they were used to their maximum capacity.

Table 1. Overview of historical reference test sites in Norway.

Site	Soil type	Operator	Reference (s)
Onsøy	Lightly OC marine clay	NGI	[1]
Drammen	Lightly OC marine clay	NGI	[2]
Holmen	Loose to medium dense sand	NGI	[3]
Lierstranda	Lightly OC marine clay	NGI	[4]
Emmerstad	Quick clay	NGI	[5]
Haga	Overconsolidated clay	NGI	[6]
Lysaker	Lightly OC marine clay	NGI	[7]
Longyearbyen	Permafrost	NGI	[8]
Halsen	Silt	NTNU	[9]
Tiller	Quick clay	NTNU	[10]
Glava	OC clay	NTNU	[11]

In recent years the NTNU developed a small research field on a very sensitive clay deposit close to its campus at Dragvoll [12]. The site is mostly used as a training and teaching facility, but has also been used for large-scale testing to e.g. evaluate the use of potassium chloride for in situ stabilization of very sensitive clay deposits [13]. The paper by Helle et al. [14] gives a good overview of the data available at this site, and focuses on the mineralogical and geochemical properties of this clay.

Another recent research site was developed by the Norwegian Public Roads Administration, the NGI and Multiconsult in conjunction with the redevelopment of the E6 motorway in the Klett area, some 13 km south of Trondheim city centre in Norway. The site comprises non-sensitive clay to about 6 m to 8 m and quick clay with significant silt lenses below this down to at least 30 m. Several full-scale experiments have been performed at the site including i) Pile capacity tests; ii) Lime-cement column tests and; iii) Full-scale embankment test. Results from these tests allowed considerable savings to be made for the highway construction project and provide very useful data for the calibration of soil constitutive models. A complete overview of site conditions and large-scale testing is given in the paper by Long et al. [15].

Between 2016 and 2019 the Norwegian Geotechnical Institute (NGI) and its partners, the Norwegian University of Science and Technology (NTNU), SINTEF Building and Infrastructure, the University Centre in Svalbard (UNIS), and the Norwegian Public Roads Administration (NPRA) have established five GeoTest Sites (NGTS) in Norway. This project, funded by The Research Council of Norway (RCN), is unique because of the size of the research infrastructure, the wide range of soils covered and the availability of the test sites to all users for at least the next 20 years. Until today the NGTS project has focused on completing a full geotechnical characterization of the five sites, and on establishing the necessary infrastructure at the sites to make them amenable for specimen testing and model testing up to prototype scale. The installations include, for example, permanent piezometers, thermistor strings and pressure cells, electricity and water supply to the sites, climate stations and shelters. Figure 2 shows the geographical location of these five Norwegian test sites. Two of the sites are in southeastern Norway; the soft clay site in Onsøy [16] and the silt site in Halden [17]. The quick clay site at Tiller-Flotten [18] and medium dense sand site at Øysand [19] are both situated in mid-Norway, close to Trondheim. The two permafrost sites are located near

Longyearbyen, Svalbard [20]. These sites are included within the NGTS infrastructure to investigate topics including foundation methodology, site investigation techniques, embankment behavior, and artificial cooling systems in saline marine clays and intermediate permafrost soils. These sites were selected as they are representative of the soil conditions in Svalbard and other Arctic locations. Each of the five NGTS sites are thoroughly described in papers found in this Special Issue [16–20].

The NGTS infrastructure is a geotechnically well-documented arena for the entire geotechnical community for basic and applied research and education on soil testing, soil behavior and calibration of foundation design methods. The availability of the sites, the high-quality data and the established facilities has already led to its use for e.g. large-scale testing and for verification of investigation techniques [21–23].

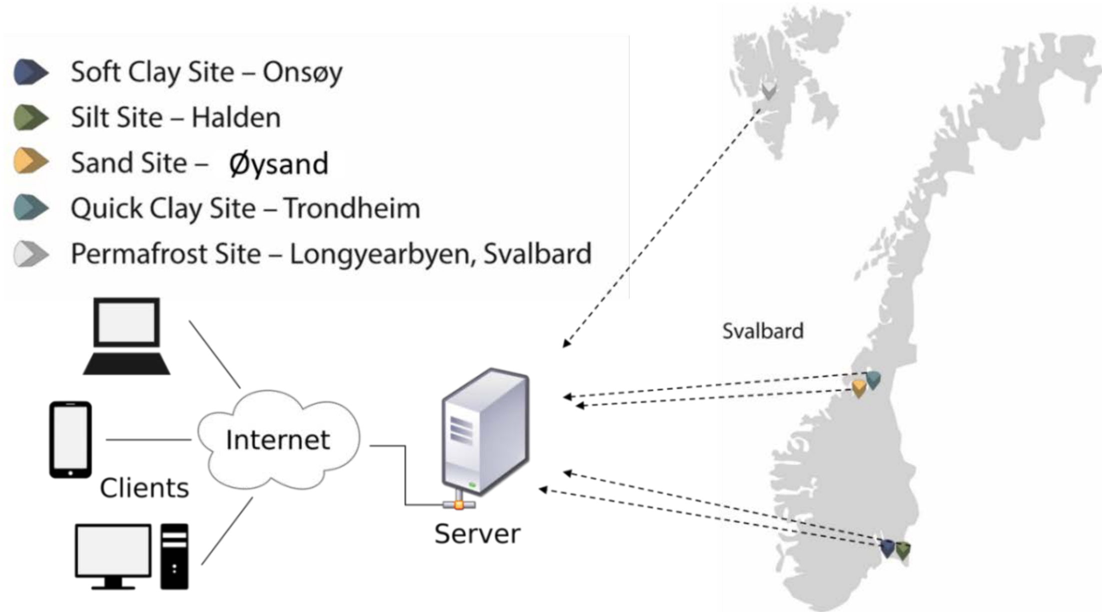

Figure 2. Location of the NGTS geotechnical research site in Norway.

2.2. Canada

Some of the major cities in eastern Canada like Ottawa, Montreal and Quebec are partly built on the soft and sensitive Champlain sea clays. In 1954, in an effort to improve the understanding on the behavior and engineering properties of these clays, the National Research Council of Canada (NRCC) established the Canadian Geotechnical Research Site No. 1 at South Gloucester, Ontario, about 24 km south of the capital city of Ottawa. Early geotechnical interests focused on problems related to excessive settlements and poor shallow foundation performance of existing dormitory buildings at the site circa 1954 [24]. Thereafter, an impressive and extensive geotechnical study was conducted by Bozozuk [25] that involved careful borehole sampling and laboratory testing, limited field test methods, and the construction of a full-scale instrumented earthen embankment at the Gloucester site. Since then, many supplementary studies involving e.g. in-situ penetrometer and probe tests, laboratory testing, geophysics, and pile foundations have been completed. A thorough overview of the geotechnical test site at Gloucester is provided in this Special Issue by Mayne et al. [26].

Another well-known geotechnical test site in the Champlain sea clay includes the St-Alban test site, near Quebec City, which was the locus of one of Canada's largest known landslides back in 1894 [27]. The geotechnical site at St-Alban has been used over the years to study e.g. the behavior of sensitive clay during pile driving [28,29] and embankment loading, and for calibration of soil models in geotechnical engineering [30]. Large scale excavation tests have also been performed in similar Champlain Sea clay deposits at e.g. St-Hilaire [31] and Rivière Vachon [32].

Recently, the Quebec ministry of transportation (MTQ) in collaboration with Laval University have carried out intense field work and laboratory investigation in the small community of St-Jude, 50 km North of Montreal, to determine the characteristics and properties of the sensitive clay involved in a deadly landslide in 2010 [33]. The paper by Locat et al. [34] presented in this Special Issue presents field observations, in situ testing, sampling using thin-wall tubes and Laval sampler, as well as laboratory tests that enabled to obtain information on the stratigraphy of the deposit and the geotechnical, mineralogical, micro-fabric and physico-chemical properties of the soils at St-Jude.

2.3. USA

National Geotechnical Experimentation Sites (NGES) were established across the United States in the 1990s to create a network of well-characterized and documented sites where innovative research on soil behaviour and foundation engineering could be conducted. The (NGES) was established by a joint partnership between the NSF (National Science Foundation) and the Federal Highway Administration (FHWA) in the United States. The history, scope, testing program and results of the NGES are described in details in Benoît and Lutenegger [35]. Two Level I sites (most thoroughly investigated) and four Level II (somewhat less thoroughly investigated) sites were established as shown in Table 2. The work performed at the established sites included a relatively large body of site characterization data and several industry-backed, full-scale testing projects.

Table 2. Level I and II sites established in the U.S. through the NGES project.

Site	Soil type	Soil conditions	Reference (s)
Treasure Island, CA	Level I	Sand fill over soft clay	[36,37]
Texas A&M, TX	Level I	Both a stiff clay and a sand site	[38]
Northwestern University, IL	Level II	Soft to medium glacial clay	[39]
University of Houston, TX	Level II	Very stiff clay	[40]
University of Massachusetts Amherst	Level II	Soft lacustrine varved clay	[41]
Spring Villa, Alabama	Level II	Very stiff clay, residual soil	[42–44]

As part of the NGES effort, a National Geotechnical Experimentation Site was established at Auburn University (AUNGES) in the 1990s to study the behaviour of Appalachian Piedmont residual soils in the Eastern United States. The site is situated east of the Auburn University campus in an unincorporated part of Lee County, Alabama often referred to as Spring Villa [42,43]. The site consists of two sub sites, one that is a thick profile of residual soil and the other is an outcrop of fractured weathered quartzite. Extensive site investigation has been conducted at the site by many agencies and researchers using a wide array of in-situ soil tests. Foundations, excavations, and retaining structures have been constructed and load tested at the AUNGES. A summary of the work carried out at the site since its inception in addition to recent activities is presented in the companion paper by Anderson et al. [44].

Over the years a few other geotechnical research sites have been developed in the U.S. In the late 1990’s the University of Massachusetts (UMass) developed a site on a sensitive marine clay in Newbury, Massachusetts (MA), 60 km north of Boston. The clay is locally known as Boston Blue Clay (BBC). The site was initially developed by UMass Lowell for a research program on behaviour of deep pile foundations. In this volume, the paper by DeGroot et al. [45] presents data from advanced tests as well as other soil classification, index, and engineering properties based on in situ measurements and laboratory test results on the BBC. A synopsis of constructed facilities built on and in BBC within the greater Boston area is also presented in [45].

Geotechnical engineering usually focuses on shallow soil conditions (i.e. <30 m) and so do most reference test sites. Recently the University of South Carolina, with support from the South Carolina Department of Transportation (SCDOT) and the United States Federal Highway Administration, developed and characterized two sites in the state of South Carolina. The first site is in the town of Aynor in Horry County, while the other is in the town of Andrews in Williamsburg County. Both sites are located in the Lower Coastal Plain; a region that is within one of the highest seismic hazard areas in the Southeastern United States. In this Special Issue, Sasanakul et al. [46] presents a unique set of field and laboratory testing results down to a depth of 160 m below ground level.

2.4. Finland

In Finland, a major geotechnical issue involves the stability and deformation of railway embankments built on soft clays. Recently, the Tampere University of Technology (TUT) and the Finnish Transport Agency (FTA) have been carrying out a number of research projects aiming to improve the commonly used stability calculation methods and the quality of ground investigation data [47]. A reference site was developed at Perniö in Western Finland. Here the soil conditions consist mainly of very soft saturated sensitive clay, with apparent overconsolidation due to aging effects. A complete geotechnical characterization of the Perniö clay is given in this Special Issue in the paper by Di Buo et al. [47]. Over the years, the Perniö site has been the locus of several research studies on Finnish clays. As an example, a full-scale railway embankment failure test was conducted in 2009 to collect extensive monitoring data and test the reliability of the stability calculation methods [48].

2.5. Poland

The Adam Mickiewicz University (AMU) in Poznan, Polen, recently developed a geotechnical test site on the University campus of Morasko for research purposes and to solve difficulties in geotechnical design in western Poland. A full overview of data available at the AMU soft clay site and is presented in the companion paper by Radaszewski and Wierzbicki [49].

2.6. Brazil

The Sarapuí II test site consists of a very soft organic clay and is situated on the left bank of the Sarapuí River, some 7 km from Rio de Janeiro city. The test site was established some fifteen years ago after deactivating the Sarapuí I test site (1.5 km from Sarapuí II, on the same bank), which was set up in the mid-1970s, after a significant number of studies were carried out. The initial studies on the Sarapuí II test site were related to pile behavior in soft clays [50,51]. Joint research projects between the Petrobras-Cenpes and the Alberto Luiz Coimbra Post-graduate and Engineering Research Institute of the Federal University of Rio de Janeiro (Coppe/UFRJ), have been undertaken on the test site since 2008. Those projects include the development of the torpedo-piezocone [52] and execution of load tests on model torpedo piles (e.g., [53]). Some of the geological-geotechnical characteristics of the deposit were presented elsewhere [54] and are thoroughly summarized in this Special Issue by Danziger et al. [55].

2.7. Italy

The Treporti Test Site (TTS) was set up in the early 2000s, through a major joint research project aimed at better understanding the stress-strain-time response of the heterogeneous, predominantly silty sediments underlying the historic city of Venice and the surrounding lagoon [56]. The research site has been developed by the Italian Universities of Bologna, Padova and L'Aquila, with the financial support of the Italian Ministry of Education. Over the years a complete database of field measurements has become available for interpretation in terms of compressibility characteristics of Venetian soils. Taking this well-documented site as a base, the paper by Tonni and Gottard [56] explores the capability of cone penetration as an effective tool to estimate the compressibility characteristics of silts, silt mixtures and sand mixtures and discusses the effectiveness of the available interpretation approaches, most of them developed for "standard" sands or clays, in predicting reliable values of the compression moduli when applied to such intermediate sediments. According to the experience gained within the Treporti Test Site project, the paper by Tonni and Gottard [56] draws attention to some key issues on the interpretation of piezocone test results in silts and other sedimentary soils having very scattered grain size distributions and therefore potentially affected by partial drainage effects during the test.

2.8. Netherlands

Nearly half the population of Netherlands live on fibrous peat deposits. Such material is highly susceptible to creep deformation and shows complex mechanical behaviour as well as biodegradation facets. Recently, Deltares in collaboration with the Delft University of Technology and Utrecht University established a test field to assess the geotechnical behaviour of peat [57,58]. The test site is located near Uitdam, approximately 30 km north of Amsterdam. An extensive program comprising a set of in situ testing and laboratory investigation has been performed at the site. Also, a total of six full-scale field trials were performed to establish the operational strength of the peat. The paper by Zwanenburg and Erkens [58] summarizes results obtained at the Uitdam site and provide a direction for future research targeting the development of constitutive models to predict the stress-strain behavior of peats correctly.

2.9. New Zealand

High-quality samples of granular soils are difficult and expensive to obtain in geotechnical practice. Hence, the void ratio and relative density of granular soils is typically estimated using empirical relationships to in situ measurements from penetration testing. For clean sands there is significant variability in these estimates, and for mixed-grain soils the applicability and performance of the empirical relationships is quite uncertain. In this Special Issue , the paper by Stolte and Cox [59] examines the feasibility of evaluating in-situ soil void ratio based on the theory of linear poroelasticity and the propagation velocity of compression and shear waves (i.e., v_p and v_s, respectively) through fluid-saturated porous materials. Their study is based on high-resolution v_p and v_s measurements from direct-push crosshole testing at ten, predominantly clean-sand case history sites in Christchurch, New Zealand.

2.10. Denmark

The seafloor over large portions of the North-West European continental shelf consists of chalk and limestone, a material that is known to degrade when subjected to e.g., cyclic loading. There is generally little information published on the geotechnical properties of such material and thus conservative foundation designs are usually adopted to mitigate again risks in such materials. Onshore Denmark, reviews of the geotechnical experience with Danian limestone have been presented in a few studies e.g. [60–65]. In this Special Issue, Katic et al. [66] provide interesting experience and geotechnical properties for the Bryozoan limestone from Stevns Klint in Denmark. Their results are compared to a wide variety of in situ and laboratory tests from similar rock formations around Denmark.

2.11. Australia

A national geotechnical soft soil field testing facility was established near Ballina, Australia, for the purpose of reducing cost and risk of infrastructure construction on low-strength, poor-quality ground onshore and offshore soft soils [67,68]. The facility is being operated by the Australian Research Councils Centre of Excellence for Geotechnical Science and Engineering (CGSE) which is a collaboration between the universities of Newcastle, Wollongong and Western Australia as well as industry partners Advanced Geomechanics, Coffey Geotechnics and Douglas Partners.

The need for a national soft soil field testing facility was first identified by the Ballina Bypass Alliance (BBA). The alliance, comprising of NSW Roads and Maritime Services of (RMS), Leighton Contractors, Aecom, Coffey Geotechnics and SMEC, constructed the Ballina Bypass motorway over deep deposits of soft estuarine clay. During construction settlements up to 6.5 m were recorded. In contrast, target post construction settlements over 40 years ranged from 50 mm to 200 mm. Significant challenges were encountered in accurately characterizing the properties of the soft clay.

In this Special Issue, Pineda et al. [69] provide an overview of the work done at the Ballina National Field Testing Facility (NFTF) over the last five years. The main results obtained from *in situ* and laboratory characterization studies are combined with the results of a microstructural study carried out to assess the effects of tube sampling on soil fabric [70]. In addition, the main outcomes of an international prediction symposium held in Newcastle in 2016, focusing on predicting the behavior of a trial embankment [71] and large-scale shallow foundation load tests on soft clays [72], are presented and discussed. The paper by Pineda et al. [69] provides important lessons learnt from the work carried out and the legacy provided by the Field Testing Facility to the local roads authorities, local and international practitioners and academics.

Another well-documented test site in Australia is the Burswood site situated on the Burswood peninsula, inside a meander of the Swan River a few kilometers upstream from the city center of Perth, Western Australia. The site has been the focus of two extensive geotechnical studies conducted by the University of Western Australia (UWA) Geomechanics Group and Centre for Offshore Foundation Systems (COFS), together with local and international collaborators and industry partners. A wide range of insitu tests were carried out at the Burswood site, including full-flow penetrometer tests (T-bar, ball and plate). In addition, thin-wall tube samples and high-quality Sherbrooke block samples were collected for laboratory testing. The stress-strain-strength, consolidation and compressibility characteristics of Burswood clay were investigated, and the performance of various penetrometers in characterising the soft Burswood clay was assessed in a paper by Low et al. [73].

2.12. Ireland

Recent interest in renewable energy developments in upland peat areas has led to an increase awareness regarding the stability of peat slopes in Ireland. The results from several sites in Ireland, Scotland and the Netherlands were published by Boylan and Long [74] to gives guidance for the assessment of peat strength for stability assessments.

Ireland has also been the locus of important studies on the behaviour of silts with benchmark test sites at e.g. Skibbereen, Letterkenny and Athlone [75–77].

In this Special Issue, Igoe and Gavin [78] describe the site characterization of a dense sand test site developed in an active quarry located near the village of Blessington, Ireland. The site has been used to investigate the field response of several foundation systems including jacked closed and open-ended piles, driven concrete and steel open-ended piles, shallow footings, bored axially loaded piles and laterally loaded steel piles. The soil at the location is an over-consolidated, glacially deposited, dense to very dense fine sand with a CPT q_c resistance, that increases from ≈10 MPa near the ground surface to 15–20 MPa over a depth of 10 m.

2.13. Portugal

In Portugal, widespread loose alluvial sandy deposits can be found mainly in the center and south regions, where seismicity is high to very high, particularly in the South and Atlantic margins [79]. Within the scope of a research project on liquefaction (LIQ2PROEARTH), an extensive geological, geotechnical, and geophysical database was recently established, including specific site investigation campaigns in four testing locations, in the municipalities of Benavente and Vila Franca de Xira, near Lisbon. In this Special Issue, the paper by Viana da Fonseca et al. [80] addresses the geotechnical characterization of this very large geotechnical test site and describes the advanced sampling processes for liquefaction assessment. In particular, the paper focuses on the performance of SPT, CPTu, SDMT and geophysical tests, as well as on the collection of high-quality soil samples using advanced sampling techniques.

2.14. Other sites

The Bothkennar National test site was purchased in 1989 by the then Science and Engineering Research Council (SERC) to provide facilities for research into the properties of low OCR, high plasticity clays in the United Kingdom. The soft clay site at Bothkennar consists of a remarkably uniform deposit compared to other similar deposits in the UK. A very comprehensive soil characterization programme was carried out in period 1988–1992 by several universities and research organizations. The results of the characterization were published in 1992 in Géotechnique (Vol. 42, Issue 2) as a symposium in print with a total of 380 pages. After 1992 Bothkennar has been used as a national test site for both industry and academia.

Over the years, several experimental and field studies have been undertaken in the UK on deposits of the stiff London Clay to investigate the potential effects of e.g. sampling disturbance, anisotropy, loading rate, time and stress history, and for large scale experiments. Tests sites were established with significant efforts at Sizewell in Suffolk [81], at Heathrow Terminal 5 [82], at Lodge Hill Camp, Chattenden, Kent [83,84]. A reference site consisting of a boulder clay has also been thoroughly tested and used for many R&D programmes at Cowden, Humberside [85]. Furthermore, an important program of large diameter pile testing was carried out in the UK at a silt site in Pentre and at a stiff clay site at Tilbrook Grange in the 1980's. The work on these two sites is summarized in a conference proceeding held in London in 1993 [86].

In Cuxhaven, Germany, a test site owned by Plambeck Erdund Tiefbau GmbH was developed in an aged, dense, over-consolidated sand. The site is used as a sand pit and the over-consolidation comes from pit excavation that removed 16 to 20 m of overburden over several years. The Cuxhaven test field has also been used for research studies related to monopile installations and thus, several monopiles of 4.3 m diameter and 21 m buried length placed with 26 m distance in between. An overview of the site and data available for Cuxhaven is presented in [87].

In 2002 and 2006 the National University of Singapore organized two international symposiums entitled "*Characterisation and engineering properties of natural soils*". The main goal of these symposium was to compile the existing body of knowledge on natural soils. Results were published in a series of four volumes [88,89]. A great number of benchmark test sites were presented during these symposiums including alluvial clays, marine clays, estuarine clays, lacustrine clays, stiff clays, organic clays, peat, loess, silt, sand, volcanic soils, residual and other tropical soils, weak rocks.

Reference sites have been of great importance for testing and verifying soil investigation methods and foundation solutions in geotechnical engineering. Therefore, a great number of geotechnical test sites exists all over the world and many papers describing these sites are available in the literature.

3. Data availability and use of data

The *in situ* behaviour of natural soils is complex and influenced by geological origin, formation and evolution processes affecting both the nature of soils and their mechanical properties. To achieve a proper understanding of soils, it is often necessary to draw upon experience. Knowledge of ground conditions depends on the extent and quality of the geotechnical investigation and these always follow a given budget. Furthermore, soil exhibits complex behavior, making the choice of reliable geotechnical design parameters all the more challenging and crucial for the final result.

Data from the benchmark test sites presented in this Special Issue provide a great opportunity to test and establish correlations for geotechnical design parameters worldwide. The high-quality data can be used as guidelines for reliable estimation of soil parameters in industry project e.g. Paniagua et al. [90] and D'Ignazio et al. [91]. The increasing availability of geodata also provides new interests and opportunities for the apportioning, development and maintenance of offshore and coastal facilities as shown in the companion papers by DeGroot et al. [92] and Peuchen et al. [93].

The characterization of natural soils primarily focuses on sampling, testing and the development of models that can account for the complex effective stress-strain-time responses to external loads. Topics such as microstructure, evaluation of sample quality, anisotropy and evaluation of geotechnical properties from remote sensing techniques are under active research. However, natural variability is less well studied because it is often difficult to quantify in standard engineering projects. Natural variability occurs at all scales and is mainly linked to the depositional history of the deposit and to post-depositional processes such as e.g. weathering. Spatial variability studies have been done for clay deposits e.g. [94–96], but there are few studies available for sands. To bridge this gap and to compare the spatial variability of sand and clay, the paper by Liu et al. [97] presents a statistical study based CPTU data at the Øysand benchmark site near Trondheim [19]. In Liu et al. [97] several autocorrelations functions were considered, but the single exponential function was found to be the one offering the best autocorrelation. The spatial variability in the vertical and horizontal directions was analyzed statistically, using three different approaches, i.e. auto-correlation fitting, maximum likelihood estimation and simplified Vanmarcke method. The results indicate short autocorrelation distances of 3.5 m or less in the horizontal direction, suggesting a very variable sand at the Øysand site. To study spatial variability, one needs large datasets such as the ones available at the benchmark test sites.

Presenting geotechnical data in a well-organized, systematic and easy to access manner is a challenge in our domain given the quantity and variety of data, but also due to the spatial distribution of the data across a site. Recently, the University of Western Australia (UWA) developed a web based application called "Datamap" to address the major challenges of capturing, classifying, organizing and making available geotechnical research data [98]. Datamap was developed to allow researchers to create and share ''Projects", and therefore provides a general platform for sharing geotechnical data. At this stage, data from the Australian National Field-Testing Facility (NFTF) in Balina and all work carried out at the NGTS infrastructure in Norway is being made available through Datamap application. Information from these sites includes results from field and laboratory tests, published articles and reports.

Access to the dataset can be accomplished in two steps. First, users register with the system at http://www.geocalcs.com/datamap by creating a user name and password. Once logged in, the user navigates to the "Join Project" tab by first clicking the "My Projects" link in the upper right-hand corner of the map viewing screen. They then, must enter the details in Table 3 and click on the "Join Project" button. Users can then navigate back to the Map view by clicking a link in the upper right corner.

Furthermore, researchers or site owners that wish to make their data available through the Datamap application are welcome to do so. The more researchers that can access the same dataset, the more likely it is that this dataset will be transformed into new and useful knowledge.

Table 3. Access codes and project names to access data from the Australian and Norwegian geotechnical research sites in the Datamap application.

Site	Soil type	Operator	Project name	Project code	Reference(s)
Onsøy	Lightly OC marine clay	NGI	NGTS-Clay	NGTS2016	[16]
Halden	Silt, clayey silt	NGI	NGTS-silt	NGTS2016	[17]
Øysand	Gravelly sand to silty sand	NGI	NGTS-Sand	NGTS2016	[19]
Tiller-Flotten	Very sensitive clay	NGI/NTNU	NGTS-Quick_clay	NGTS2016	[18]
Longyearbyen	Permafrost	NGI/UNIS	NGTS-Permafrost	NGTS2016	[20]
Ballina	Soft clay	UWA	NFTF	Ballina	[98]

4. Concluding remarks

The 1st International Symposium on GeoTest Sites (ISGTS) was held in Oslo, Norway, in June 2019. The major goal of this symposium was to compile the existing body of knowledge on natural soils used for benchmarking in geological and geotechnical engineering. The resulting Special Issue contains 25 research papers covering the engineering properties of marine clays, sensitive clays, silts, sands, peat, permafrost, residual soils and soft rock such as limestone, and 5 papers pertaining to the engineering implications and the use of high-quality data for reliable estimation of soil parameters.

This ISGTS symposium was initiated as a part of the Norwegian GeoTest Site (NGTS) project. The NGTS infrastructure consists of five benchmark test sites developed as field laboratories for testing and verification of innovative soil investigation methods. The NGTS is intended for the entire geotechnical profession, for both basic and applied geotechnical research and for education purposes. The immediate availability of high-quality data and facilities is already leading to the use of the benchmark sites in Norway. The test sites serve as reference sites for the industry, public authorities, research organizations and academia. The NGTS sites will be operative for a minimum period of 20 years.

Research investment into well-characterize geotechnical test sites is necessary to provide more cost-effective and sustainable solutions within the building and construction, transportation and energy sectors and to mitigate the effects of climate change. It is hope the benchmarked data and results from the ISGTS symposium will be used by several generations of scientists and engineers to develop soil material models, new investigation methods, new foundation solutions and advance the state-of-the-art in geotechnical engineering.

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Conflict of interest

All authors declare no conflict of interest.

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