General Report of TC 214
Soft soils

Rapport général du TC 214
Sol mous

Ovando-Shelley E.
Universidad Nacional Autónoma de México
Rangel-Núñez J.L.
Universidad Autónoma Metropolitana

ABSTRACT: The papers in the Soft Soils session cover almost comprehensively the main topics related to soft soil engineering. The 15 papers that were submitted came from countries located in at least four continents, thus demonstrating that soft soils are widely spread and that research into their properties and characteristics is still of paramount importance for an increasing large number of geotechnical engineers worldwide. Theses papers will provide readers an opportunity to learn many aspects of soil engineering from the experiences shared by other colleagues around the world. In almost all of the papers the importance of characterizing soft soils properly is highlighted. It is also evident that thorough soil exploration as well as field and laboratory testing are necessary to achieve this purpose. The papers also show the extensive and extended use of exploration techniques that were rare only a few decades ago. It is also notable that most contributions refer to case histories in which basic soil mechanics concepts have been successfully applied and in which instrumentation was used judiciously to monitor and interpret soil behavior. Also, improved field instrumentation systems have had a positive influence on the development of many projects.

RÉSUMÉ : Les articles de cette session sur les sols mous couvrent presque complètement les principaux sujets liés à la géotechnique des sols mous. Les 15 communications qui ont été présentées proviennent de pays situés dans au moins quatre continents, démontrant ainsi que les sols mous sont largement répandus et que la recherche sur leurs propriétés et caractéristiques est toujours d'une importance capitale pour un grand nombre croissant d'ingénieurs géotechniques dans le monde entier. Ces documents donneront aux lecteurs l'occasion de découvrir de nombreux aspects de l'ingénierie des sols à partir des expériences partagées par d'autres collègues à travers le monde. Dans la plupart des articles est mise en lumière l'importance de la caractérisation des sols mous, et il est donc nécessaire d'avoir une reconnaissance et des essais sur le terrain et en laboratoire d'excellente qualité. Les documents montrent également l'utilisation intensive et prolongée de techniques d'exploration qui étaient rares il y a seulement quelques décennies. Il faut aussi noter que la plupart des contributions se réfèrent à des études de cas dans lesquels les concepts de base de mécanique des sols ont été appliqués avec succès et dans lequel l'instrumentation a été utilisée à bon escient pour contrôler et interpréter le comportement du sol. En outre, l'amélioration des systèmes d'instrumentation sur le terrain ont eu une influence positive sur le développement de nombreux projets.

KEYWORDS: Soft soils, soil improvement, historical cases, characterization of soft soils, analysis, numerical modeling & fracturing.

1 INTRODUCTION.

Urban expansion in many cities around the world as well as the construction of large industrial facilities and associated infrastructure have often made it necessary to build large projects in very soft soils where complex foundation solutions may be are required. Proper characterization of these soils is a crucial first step in applying specific analysis and design methods.

Geotechnical problems related to the presence of soft soils can appear in every other country around the world and in some regions geotechnical engineers face them on a day to day basis. Specialists now make reference to soft, very soft and even ultra-soft soils, depending on their specific properties. This is why characterization of these materials may also require the use of innovative means and even terminology to describe and identify them. Constitutive models for these soils have continued to appear over the last years as well as new conceptual solutions for foundation systems. New constitutive methods and new methods for improving the characteristics of these soils are also available.

The fifteen papers submitted to the Session deal with these topics and cover almost totally the subjects related to soft soil engineering. Three of the papers deal with analytical studies, one of them describes construction procedures, studies related to the determination of mechanical properties are discussed and described in two papers and one paper focused on discussing soil fracturing and fissuring within the context of regional subsidence. The eight remaining papers describe case histories in which characterization, analysis, design and construction related topics are dealt with.

2 METHODS OF ANALYSIS

Espinoza and Li (2013) present a hybrid drained-undrained model to design prefabricated vertical drains to improve the drainage characteristics of soft soil when surcharge loads are applied (Espinoza et al 2011). The model is based on the concept of virtual sand piles, where the soils located closer to prefabricated vertical drains dissipate excess pore pressures generated during construction faster than the soils located farther away. The authors show the influence of the construction rate on the maximum generated excess pore pressure. Their model considers the radial variation of excess pore pressure between drains. In their analyses the authors selected the magnitude of excess pore pressure that would have a negligible effect on the berm stability and then back-calculated the separation between drains necessary to yield this value. Soil columns around each prefabricated vertical drain mobilize their drained shear strength during loading, whereas the soil outside the virtual sand piles develops an undrained shear strength response during loading. This methodology was applied during construction of a high mechanically stabilized earth berm over very soft, low permeability and extremely compressible soil in the Cherry Island Landfill, located in the USA, in Wilmington, Delaware.

Müller and Larsson (2013) investigate and discuss the differences between six of the available analytical models to evaluate the average degree of consolidation U describing the characteristics of the disturbed zone around prefabricated vertical drains (eq 1), and evaluate the influence on the results of the variables incorporated in these models.

$$U = 1 - e^{\frac{-8xT_h}{F}} \tag{1}$$

where $T_h = c_h \times t/d^2$ is the time factor for horizontal consolidation, $c_h = k_h \times M_v/\gamma_w$ is the undisturbed horizontal coefficient of consolidation in the clay, *t* is the consolidation time, *d* is the diameter of the assumed unit cell dewatered by a single drain and the expression *F* is dependent on the model.

The influence of each variable x_i (i.e. *F*, T_h and κ) on can be assessed through the parameter α:

$$\alpha_i = \frac{\partial U/\partial x_i}{\sqrt{\sum_{i=1}^{n}(\partial U/\partial x_i)^2}} \tag{2}$$

The authors concluded that "although more realistically models may capture the nature of the smear zone, the impacts on the assessment of U of the more complex models are insignificant under the assumptions made in this paper. Hansbo´s simplified model "is still useful for practical engineering purposes due to its simplicity". They also state that "it is more important to put an effort into reducing the uncertainty in c_h the trying to investigate *s* and *m* in ordinary engineering projects".

Juárez-Badillo (2013) applies his general time-settlement equation (eq 3), provided by his principle of natural proportionality on the evaluation of settlements in soft soils for the Kansai International Airport.

$$S = \frac{S_T}{1+\left(\frac{t}{t^*}\right)^{-\delta}} \tag{3}$$

where $t^*=t$ at $S=1/2S_T$, and S_T and *d* are parameters which may be obtained from experimental data. Using experimental data from Kansai International Airport and calibrating his equation, his estimates of total settlements in the long term tend to be similar to the observed data.

3 CONSTRUCTIVE PROCESS

Lui *et al.* (2013) study the application of X-section cast-in-situ concrete piles as a method for improving soft soils. They describe a construction method with a special pile-driving machine. The quality of piles driven with this machine was verified excavating the surrounding soil. They also used static and low-strain integrity testing methods making reference in all the process to the amount of concrete poured during concreting. A large scale model test program was carried out on X concrete piles and circular ones, to obtain the load transfer behavior of both pile types under three different loading modes: compression, uplift, and lateral loads. The authors also report the results of a field test.

Lui and his co-workers reached concluded that X piles have a larger contact area at the pile-soil interface and a larger inertia factor or lateral stiffness (*EI*) than circular piles for the same volume of concrete used.

4 DETERMINATION OF MECHANICAL PROPERTIES OF SOFT SOILS

Two papers were presented regarding about this issue:

Equihua-Anguiano and Orozco-Calderón (2013) estimated the undrained shear strength of marine soft soils based on the vertical penetration of a horizontal cylinder of 3.35 to 9m long and 1 to 2m in diameter, using steel and PVC tubes. An experimental program was carried out to validate the results of this device using a large rigid tank where a reconstituted marine soft soil was placed. The undrained shear strength was estimated from the analysis of the penetration of the cylinder and from miniature vane shear tests. The results show that the two methods yield similar values of the undrained shear strength.

Bobei and Locks (2013) present the results and interpretations of data collected during the procurement phase of a motorway upgrade in New Zealand. The strength and consolidation characteristics are investigated for a soil identified as a sensitive soft soil, Late Pleistocene–Holocene marine sediment. The estimate of undrained shear strength based on empirical methods is found to have limitations to predict the undrained shear strength of the sensitive soil. The authors propose that one-dimensional compression response of the virgin sensitive may be estimated using a relationship between the liquidity index and the vertical effective stress. The predictive capability of this relationship is demonstrated by numerical simulations of settlement monitored during the construction and post-construction phase of the original SH16 motorway embankment. The soil sensitivity represents an indicator of soil micro-structural bonding or development of inter-particle forces between particles or their aggregates. The disturbance to the soil structural bonding during loading could have some serious consequences such as: (a) strength reduction; and (b) changes in the overall soil behaviour due to an increase in soil compressibility properties.

The measure of soil sensitivity (S_t) adopted in this study is based on the ratio between peak undisturbed strength (s_u) and the remould strength (s_r) when the soil reaches its residual state. The results of shear vane tests were interpreted to determine the strength sensitivity manifested by virgin AH soil as shown in Figure 1b.

(3)

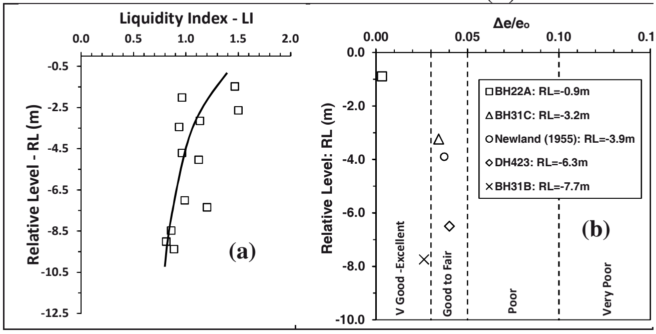

Figure 1. (a) Variation of liquidity index with depth; (b) Sample quality assessment based on (Lunne *et al.* 1997) classification system.

The main findings of the paper are summarized below:

- The undrained shear strength of virgin sensitive soils increase linearly with depth.
- The compressibility of virgin AH soil in one-dimensional testing displays non-linear characteristics when stresses exceed the pre-consolidation pressure.
- The assessment of undrained shear strength of virgin AH soil is not readily predicted by methods such as SHANSEP.
- The one-dimensional response of virgin AH soil is found to uniquely relate *LI* and σ'$_v$. The predictive capability of a proposed relationship is

demonstrated by numerical simulations of settlement monitored during the construction and post-construction phase of SH16 motorway embankment.

5 CASE HISTORIES

Eight papers on case histories were presented: Tashiro *et al.* (2013), Kim *et al.* (2013), Tan *et al.* (2013), Popovic and Stanic (2013), Massad *et al.* (2013), Ooi *et al.* (2013), Asiri and Masakasu (2013) and De Silva and Fong (2013). All of them dealing with aspects of embankments or earth structures over soft soils where soil improvement was applied.

Tashiro *et al.* (2013) study the case of a large field test performed on a trial embankment (150 by 27m) resting over a peaty soft soil deposit 50m thick. Upon the application large surcharges, the embankment settled 11m on average, after four years. Nearby structures were affected on account of lateral displacements and relative emersions of 2 and 1m, respectively. The authors analyzed several strategies for reducing settlement in the trial embankment and its surroundings by means of either sand drains or card board drains (wick drains). Field observations and comprehensive soil testing was carried out to characterize the soft soil.

The effects of countermeasures to prevent excessive deformations and settlements such as ground improvement with sand drains, replacement of the existing embankment with lightweight materials, and reduction of the loading rate, were also investigated using numerical analysis. These analyses were performed using the soil-water coupled finite deformation analysis program GEOASIA, in which the SYS Cam-clay model was mounted as the constitutive equation for the soil skeleton. The results showed that improvement of the mass permeability and the slow or lightweight banking are effective means of improving the stability during loading and reducing the residual settlement after entry into service. The results analyzed in this paper were applied to the actual construction design of a culvert and the lightweight embankment surrounding it.

Kim *et al*. (1013) present a case history about the expansion of the second branch of the Namhae Expressway in Korea which overlies a 53m thick soft soil deposit. The original design plans were reviewed, problems were discussed and solutions for the problems were proposed. With the improved plan, it was not necessary to dispose of soil and asphalt concrete removed from the existing road. The constructability of the project would be improved because the sequence of activities would be simplified and issues related to the difficulty of installing PBD (Plastic Board Drains) by drilling on the slope of the existing road could be avoided. The improved plan reduces the construction cost. Installation of PBD beneath the existing road would involve additional costs for drilling or removing gravel and crushed stone underneath the existing road. In addition, there would be a cost for disposal of the waste asphalt concrete. If PBD is used to improve the soil under the existing road, it is expected that coupled settlement will occur near adjacent structures due to the soil settlement. The improved plan does not involve improvement of the soft soil and consequently protects the stability of structures located near the existing road.

Tan *et al*. (2013) studied another trial embankment constructed over a 15m thick deposit of very soft clay whose relevant mechanical properties are shown in Figure 2. Pre-fabricated vertical drains (PVD) were installed in the soft soil deposit following a triangular pattern (1.2 m separation). The trial embankment was 50m long and 14.2m wide, a 50cm thick sand layer was placed at the bottom of the embankment as well as a geotextile sheet.

The embankment was instrumented with inclinometers, displacements markers, extensometers, vibrating wire piezocones, settlement gauges, stand pipes. Experimental observations were used to back analyze the embankment using the Plaxis computer software, using the "soft soil model" for the clays and the "hardening soil model" for sandy strata. Their analyses included indirectly the presence of PVDs. To achieve this, the authors used an equivalent vertical permeability for the soft clay stratum. The back analysis yielded a value of this equivalent permeability which turned out to be almost six times larger than the original permeability of the soft soils.

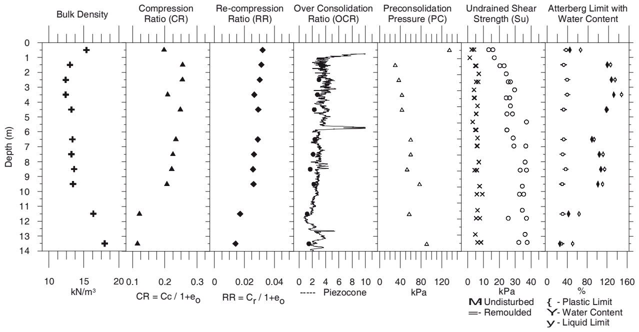

Figure 2. Mechanical properties of the trial embankment (Tan *et al*. 2013).

Popovic and Stanic (2013) analyze soil-structure interaction and effectiveness of soil improvement through back-analyses based on measurements conducted during the early stages of the construction of a new container terminal in the port of Ploce in Croatia. The soil profile is formed by a surface layer of silty sand and low plasticity silt of 8m of thickness followed by a low to high plasticity clay that reaches 33m of depth. After that, a low plasticity poorly graded silty sand is founded. Subsoil treatment consisted in dense and sparse stone columns (triangular grid 2x2m and square grid 2.8x2.8m, respectively).

Back analyses were performed based data on soil settlement and pile displacement measured with instruments installed to monitor the progress of construction. The objective of back analyses was to establish "actual" soil parameters and the condition of internal forces and displacements in the structure. The authors were able to verify the efficiency of planned works aided by the geotechnical measurements described in the paper.

Finally, the results of numerical models were used as a means for controlling the construction processes. The authors point out that it is necessary to perform back analyses during and after the construction of complex projects in difficult geotechnical environments on the basis of measurements and through the collaboration of structural and geotechnical engineers.

The paper by Massad *et al.* (2013) is based on data from a work in Santos Harbor, in São Paulo State, Brazil, in which three experimental fills were built and monitored, one of them partially with geodrains. The monitoring of earth fills built on soft clays has been done frequently through the Brazilian coastline. As the most common measurement is the settlement along time, the interpretation of the results is usually done by Asaoka's Method, generally involving extrapolations that have given rise to doubts (for instance, about the secondary consolidation effect) and to a double interpretation, and even to controversies, especially when it comes to evaluating the effectiveness of vertical geodrains to accelerate settlements.

The uppermost soil stratum is the SFL clay, a sedimentary material (fluvial-lagoon-bay) of the Pleistocene that has become lightly overconsolidated due to erosion, sea level oscillations and dune action. The authors describe and comment on the results of extensive soil exploration as well as field and laboratory testing with which a detailed and thorough characterization of the SFL clay was possible, for the sites at the three trial embankments.

In the first experimental site an earth fill was placed in area reclaimed from the sea. Application of loads was carried out in three stages and that made it possible to apply Asaoka's Method, as shown graphically in the paper. A second experimental fill (Pilot Embankment 2) was built with a maximum height of 5.2m. The values of the end of primary settlement (ρ_f) and $c_v/H^2{}_d$ were determined from instrumental data for the two loading stages. The authors interpreted measurement to find equivalent c_v values, after roughly 5 months when at least 95% of the primary settlement was reached. In the third experimental fill, with a maximum hight of 6.7, they also inferred c_v values from instrumental observations. A third experimental fill (Pilot Embankment 3), built also in Area 3, with a maximum height of 6.7m, behaved in a similar way, with $c_v/H^2{}_d$ averaging $1.8.10^{-2}$/day; the *EOP* settlement was ~80 cm and 95% of this value was reached after ~6 month.

Due to the relatively high *OCR* values of the SFL Clays, the c_v were also high, of the order or 10^{-2}cm^2/s. As a consequence, there was no need to use geodrains in the Embraport site.

This conclusion was supported by instrumental observations in three experimental earth fills without geodrains and, more important, by the monitoring of settlements in the area where temporary surcharges were used. These results show that controversies that after arise about the use of geodrains can be overcome with proper characterization of soils present in the field and from thorough and careful interpretation of instrumental observations from properly instrumented trial fills.

The paper by Ooi *et al.* (2013) discusses the development of geogrid applications in soft ground in Malaysia starting in 1984 when a road pavement field trial was first carried out. Other experiences followed in the following years and in this paper they report another project in which geogrids with geocells were used. They compare the performance of three cases in which geogrids were used, a fabrication yard, a heavy duty working platform and a container yard working platform. They compare and assess the pavements used in them and the magnitude of settlement they underwent under construction and later operations. All the three platforms were built over soft clays 4.5 to 10m thick and applied stresses due to heavy equipment was as high as 500kPa and axial loads of heavy vehicles reached 105tonnes. Granular fill of varying thicknesses were used in all three working platforms. The authors state that mechanically stabilized soils using biaxial and triaxial geogrids with granular fill with or without geocell mattress performed satisfactorily in terms of platform settlement performances to support the heavily loaded platforms.

The case history presented by Asiri and Masakasu (2013) deals with the design and performance of a highway embankment constructed in Sri Lanka over very soft soils and alluvial clays. The project required that settlements be limited to less that 15cm after three years and those residual differential settlements be less than 0.3%. Soils were improved by means of wick drains, heavy tamping, pre loading with surcharges and vacuum consolidation. The soil improvement method was adjusted depending local geotechnical conditions. The major steps in ground improvement method and illustrated in Fig 3 are: a) placing surcharge loads with or without drains for soft clays of shallow thickness; b) removal of peaty soil, replacing it rock fragments; c) applying heavy tamping or, alternatively, vacuum consolidation for deeper strata. Heavy tamping was only effective down to 3.5 to 4.0m

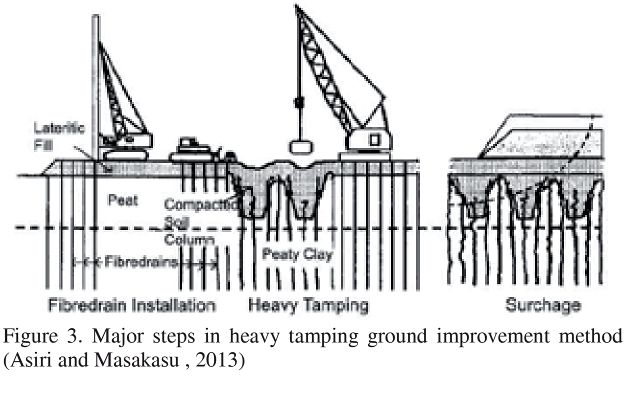

Figure 3. Major steps in heavy tamping ground improvement method (Asiri and Masakasu , 2013)

Vacuum consolidation was applied using band drains with a spacing of 1m. Primary consolidation settlements were compensated and secondary consolidation deformation minimized by applying a vacuum pressure of 70kPa. There were places where it was not possible to apply vacuum and in those cases, soil improvement was carried out by applying surcharge.

The continuous assessment of the improvement of soft ground was carried with field instruments: settlement plates, pyrometers, a vacuum pressure monitoring unit and a water discharge meter. The decision to remove the surcharge was made on the basis of the monitoring data obtained during the surcharge period. The aim was to eliminate 100% of the primary consolidations settlement and enough secondary settlement.

De Silva and Fong (2013) describe and discuss the case of the Cotai Landfill, the main receiving facility in Macau for building construction waste. As the dumping site is underlain with a thick layer of very soft to soft marine clay deposits, the uncontrolled end-tipped material has generated mud waves and they were encroaching the piles supporting the Macau International Airport taxiway nearby. In order to prevent future potential damage to the taxiway, the Macau Government commissioned the design of a containment bund adjacent to the taxiway to retain the waste and to prevent further generation of mud waves that would affect the taxiway.

This paper presents the design approach of the containment bund including the results of a limit equilibrium stability analysis and the numerical analyses carried out that demonstrated that the solution is appropriate as the bund will contain the landfill with minimal impact on the taxiway bridge piles. The analyses also demonstrated that the impacts during construction are also negligible. The sustainable design comprised the installation of vibrocompacted stone columns installed in over 20m thick, very soft to firm, moderately sensitive marine clay and alluvial clay, as the foundation to the waste retention bund, thereby avoiding the dredging and off-site disposal of a significant volume of dredged sediments. This paper presents the design approach and construction of the stone columns and the behaviour of the completed seawall.

The authors show instrumental observations to monitor during the taxiway and seawall during construction. Survey results indicated that the installation of the stone columns and construction of the bund had minimal impact on the taxiways foundation piles. The seawall was been completed in November 2011.

6 SOIL FRACTURING

Auvinet and Mendez (2013) present updated information concerning land subsidence and associated soil fracturing in Mexico City. Subsidence was estimated from the evolution of the elevations of 2064 benchmarks and other references located in former Texcoco Lake. Geodesic and topographic surveys carried out in the middle of the XIXth century proved to constitute an excellent initial reference for subsequent measurements of land subsidence. Extensive use was made of new geocomputing tools to process these data. Results of surveys of soil fracturing associated to subsidence are also presented and discussed

The demographic development in Mexico City has created an accelerated demand of services, mostly of potable water. One of the cheapest ways to meet this demand has been the exploitation of the local aquifer by pumping water from deep wells. This has produced a water pressure drawdown in the subsoil that in turn is causing general subsidence of the former lacustrine area and soil fracturing. This problem has been around for almost a century but is now reaching new worrying dimensions. Although regional land subsidence is an old phenomenon, it has not been possible to control it. In fact, it is expected to continue in the future for many more years since, due to the high cost of other alternatives, water pumping from the local aquifer cannot be suspended. Studies and analyses are thus necessary to rethink criteria and strategies to mitigate future effects

The authors describe the efforts of their research group to monitor the subsidence phenomenon of the lacustrine zone of Mexico City, as well as of others aspects of the problem, like soil fracturing. A Geographic Information System was developed to this end, using as a support a similar system developed previously by the authors. Up to now, 868 fracturing sites have been documented. About 45 sites where cracks had been reported were discarded when, during the field visits, it became evident that no fracturing could be detected and that defects in the soil surface could be attributed to other factors (mainly scour).

Figure 4. A dramatic example of soil fracturing in a site near Mexico City

Engineers and practitioners as well as local and federal authorities will surely profit for the crack and fissure maps produced by the authors, not only for assessing the feasibility of specific projects but also in the planning of urban development schemes or land usage regulations.

7 CONCLUSIONS

The papers in the session cover almost comprehensively the main topics related to soft soil engineering. The 15 papers that were submitted came from countries located in at least four continents, thus demonstrating that soft soils are widely spread and that research into their properties and characteristics is still of paramount importance for an increasing large number of geotechnical engineers worldwide. Sharing experiences with problems associated to soft soils is also very important. The papers submitted to the session will provide readers an opportunity to learn many aspects of soil engineering from the experiences shared by other colleagues around the world.

In almost all of the papers the importance of characterizing soft soils properly is highlighted. It is also evident that thorough soil exploration as well as field and laboratory testing are necessary to achieve this purpose. The papers also show the extensive and extended use of exploration techniques that were rare only a few decades ago.

It is also notable that most contributions refer to case histories in which basic soil mechanics concepts have been successfully applied and in which instrumentation was used judiciously to monitor and interpret soil behavior. Also, improved field instrumentation systems have had a positive influence on the development of many projects. In this respect, the submitted papers, especially those presented in the case histories, show different manners in which the observational method can be applied successfully, under a wide range of geotechnical conditions and within the context of a variety of problems.

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