Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-1-0

Session report: Pressuremeter and Dilatometer

S. Burlon
Université Paris-Est, ISFTTAR, Marne La Vallée, France

W. Frikha
ENIT, Tunis, Tunisia

P. Monaco
University of L'Aquila, Italy

ABSTRACT: The present report provides an overview of 14 papers dealing with pressuremeter tests (PMTs) and dilatometer tests (DMTs). These papers include many subjects in relation with geotechnical engineering, soil and rock mechanics and engineering geology. Pressuremeter tests and dilatometer tests are used for the assessment of site stratigraphy and ground type (soils and rocks), the derivation of geotechnical design parameters, the calibration of constitutive laws for numerical modelling and the design of geotechnical structures, especially deep foundations with a direct use of measured data. This report presents the application fields of these two materials.

1 INTRODUCTION

The present report shows the various subjects dealt with by the papers accepted for the ISC'5 Conference. Two main parts are presented: the first one dealing with pressuremeter test and the second one treating dilatometer test.

Table 1. Articles received at the ISC'5 Conference (Session Pressuremeter/Dilatometer) for pressuremeter tests.

Papers	References
1	Gaone, F.M., Doherty, J., & Gourvenec, S. (2016) self boring pressuremeter tests at the national field testing facility, Ballina.
2	Kaljahi, Asghari E. (2016) Pressuremeter in the hard soils and rocks of arak aluminum plant site, Iran.
3	Bagbag, A.A., Doherty, J.P., & Lehane, B.M. (2016) Stress-strain response of fine silica sand using a miniature pressuremeter.
4	Ho, C.E. (2016) In situ characteristics of manhattan glacial deposits from pressuremeter tests.
5	Monnet, J., Mahmutovic, D., Boutonnier, L. (2016) Membrane correction for pressuremeter test.
6	Silva, T.Q.. Cândido, E.S., Marques E.A.G., & Minette, E. (2016) Determination of em from pressuremeter insitu tests in gneiss residual soils under tropical conditions.
7	Baud, J.P. (2016) soil and rock classification by pressuremeter data. New developments and applications.
8	Oztoprak, S., Uyar, H.K., & Sargin, S. (2016) Modelling pressuremeter test in sand.
9	Reiffsteck, S.Fanelli & G. Desanneaux (2016) Evolution of deformation parameters during cyclic expansion tests at several experimental test sites.

Regarding the pressuremeter test, 9 papers have been received and the following aspects are considered: materials and *in situ* procedures, test programs and interpretation, soil classifications and correlations, constitutive laws and numerical modelling and foundation design. The list of papers is presented in Table 1.

Regarding the dilatometer test, 5 papers have been received and the following aspects are mostly considered: updates on test interpretation, combination/comparisons with other in situ tests, liquefaction assessment, upgrade of testing equipment. The papers on DMT (initially) included in the Session Pressuremeter/Dilatometer, specifically addressed in this report, are listed in Table 2.

Table 2. Articles received at the ISC'5 Conference (Session Pressuremeter/Dilatometer) for dilatometer tests

Papers	References
1	Cao, L.F., Peaker, S.M. & Ahmad, S. (2016) Use of Flat Dilatometer in Ontario.
2	Ouyang, Z. & Mayne, P.W. (2016) New DMT method for evaluating soil unit weight in soft to firm clays.
3	Rodrigues, C., Amoroso, S., Cruz, N. & Cruz, J. (2016) G-γ Decay curves in granitic residual soils by seismic dilatometer.
4	Rollins, K.M., Remund, T.K. & Amoroso, S. (2016) Evaluation of DMT-Based Liquefaction Triggering Curves Based on Field Case Histories.
5	Shen, H., Haegeman, W. & Peiffer, H. (2016) Interpretation of the instrumented DMT (iDMT): a more accurate estimation of p_0.

1 PRESSUREMETER TESTS

1.1 *History, current status, and updates*

Louis Ménard, undergraduate student at the Ecole Nationale des Ponts et Chaussées, deposited on January 1955, via his alumnus P. Regimbeau, a patent on the pressuremeter. This apparatus resulted from Menard's fruitful thoughts when, as a trainee student, he was handling soil samples at a job site. He then submitted his idea in his graduation project in the form of a theory and a first prototype. The following year, at the University of Illinois in cooperation with Professor Peck, within the four semesters he spent at the Talbot Laboratory, Ménard built a second pressuremeter prototype and started his tests. He understood that he had to develop a new approach too for the design of foundations where by the pressuremeter will play a central role.

With such a new vision of geotechnical engineering, from the late sixties up to his untimely death in 1978, Louis Ménard could become the pioneer in the ground improvement field. With pressuremeter tests he perfectly demonstrated the soil improvement rate in terms of expected settlements before and after treatment.

From this first idea, several developments were made in many countries to develop alternative approaches to pressuremeter Ménard procedure, especially the self-boring procedures. Now, many standards describe the use of pressuremeter tests: ISO 22476-4, EN 22476-4, ASTM D4719, etc.

In parallel, a pressuremeter engineering has emerged considering this tool as useful (Briaud 1992), on the one hand, for the ground investigations with the measurement of deformation and strength parameters and, on the other hand, for the calculation of geotechnical structures with many methods dealing with bearing capacity and settlements of shallow foundations, deep foundations or displacements of retaining walls, etc. (Baguelin et al. 1978, Baker 2005).

2.2 Materials and in situ procedures

The papers received for the ISC'5 Conference show the diversity of materials and *in situ* procedures: Ménard procedure (Kaljahi, Silva et al.) and self-boring procedure (Gaone et al., Ho et al.). All types of ground (soft soils, soft rocks, etc.) can be investigated with these two procedures and a large range of values can be measured in terms of modulus and limit pressure. The choice between the two procedures depends on the ground type since, in very stiff ground where pre-boring is required only Ménard procedure is appropriate. In soft soils, self-boring pressuremeter is able to provide more reliable measures. Comparisons between the two procedures show the effects of the borehole as underlined by Ho et al. with an example in varved silts and clays. Another interesting development ~~is~~ related to the present limitation of the pressuremeter Ménard tests is due to the difficulty of reaching large expansion volumes and high pressures without any significant risks of bursting of the probe. A new probe has been developed (Jacquard et al. 2013) allowing the volume of the hole to be doubled, even under high pressures: the conventional limit pressure can then be directly measured. Technological innovations increasing the capability and the reliability of pressuremeter probes are described.

The complexity of the project and the quality of the measured data are other aspects to consider. For projects of major importance where the behaviour of the ground has to be characterized in detail and where the prediction of displacements is of a major issue, more complex procedures can be used: self-boring pressuremeter, procedures including unloading and reloading loop, cyclic procedures, etc. It seems important to have a clear and precise ground investigation strategy in order to choose the most appropriate procedure for pressuremeter tests. This strategy must have the ambition to ensure quality ground investigation and cost management.

The present report shows the various subjects dealt with by the papers accepted for the ISC'5 Conference. Two main parts are presented: the first one dealing with pressuremeter test and the second one treating dilatometer test.

Regarding the pressuremeter test, 9 papers have been received and the following aspects are considered: materials and *in situ* procedures, test programs and interpretation, soil classifications and correlations, constitutive laws and numerical modelling and foundation design. The list of papers is presented in Table 1.

1.2 *Test programmes and interpretation*

The test programs and its interpretation ~~is~~ are another important topics for ~~of~~ pressuremeter tests. Monnet et al. propose a new approach to analyze the influence of the membrane rigidity on the measured limit pressures. The aim is to consider the pressuremeter probe in expansion as a shearing test where the measured parameters could be considered as "real" elastic and plastic parameters and compared to those measured in laboratory by means of triaxial tests. This paper raises the problem of the use of the measured parameters by pressuremeter tests and the need to have either direct methods of correlation, for example between the limit pressure and the axial shaft friction, or indirect methods of correlation, for example between the limit pressure and the undrained cohesion and then between the undrained cohesion and the axial shaft friction.

Pressuremeter tests with Ménard procedure are often used to provide the shear modulus *G* and the Ménard modulus E_M while self-boring pressuremeter tests are better used to assess the earth pressure coefficient at rest K_0 and the variation of shear modulus *G* with the strain level (Gaone et al.). In this paper from Gaone et al., the procedure to assess the horizontal pressure based on the lift-off pressure concept is discussed (Figure 1). This type of application can be very interesting for the use of numerical modeling where the influence of the initial earth pressure coefficient at rest can be very significant and really affect the numerical results. The analysis of the pressure-volume curve gives the reduction of the shear modulus with the strain level, which allows as mentioned later in this paper to deal with the calibration of constitutive laws.

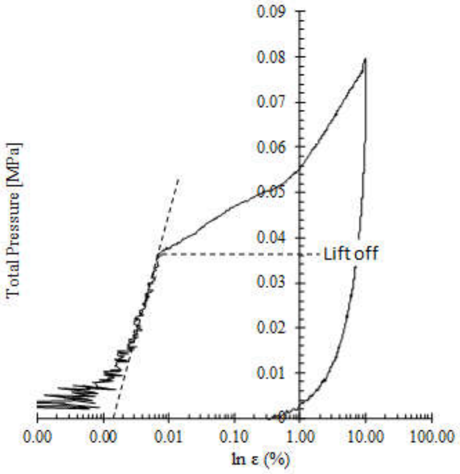

Figure 1. Assessment of the lift-off pressure with self-boring pressuremeter test (Gaone et al.).

Nevertheless, Ménard pressuremeter test equipment allows operators to achieve not only monotonic expansion tests (EN ISO 22476-4 similar to NF P94-110-1 ASTM D4719) but also cyclic tests (NF P94-110-2) (AFNOR, 1999 and 2000). These tests include an unload-reload cycle performed in steps, in the same conditions as the Ménard pressuremeter test described in the EN ISO 22476-4 standard. The conventional expansion test using the drilling conditions recommended by the EN ISO 22476-4 standard and with the proposed loading program, does not give directly available results for deformability prediction of geotechnical structures especially when the modulus in the small strain range is required (Combarieu & Canépa 2001). Therefore, cyclic procedures are developed (Reiffsteck et al.) to assess the accumulation of displacements and strains, the variations of shear stiffness with cyclic loadings and the soil layer sensitivity to liquefaction (Figure 2). The procedure is based on the pressure control and a cyclic loading between two limit pressures is applied.

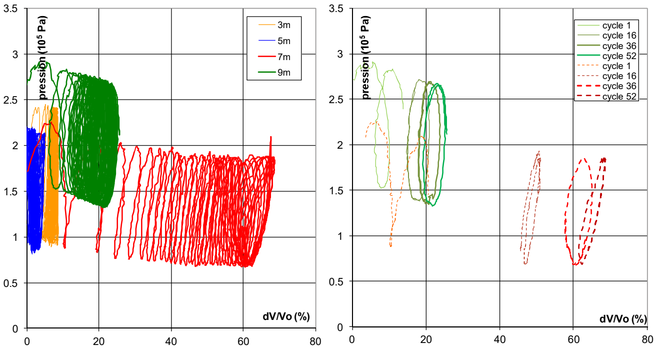

Figure 2. PMT cyclic expansion tests at the Gosier site (Reiffsteck et al.)

Quality control for soil improvement such as stone columns addresses the problem of the inclusion continuity into the ground and their mechanical properties and thus relies on in-situ testing. Interpretation of pressuremeter tests can provide very interesting information related to this topic.

1.3 *Ground classifications and correlation*

Results from pressuremeter tests allow to classify the ground types since the nature of the ground can be defined by the analysis of the bored ground sampling and assess its mechanical properties in terms of deformation and resistance. Many proposed papers confirm this approach and explain how the use of pressuremeter tests can be gainful for the understanding of a site (Gaone et al. 2016, Kaljahi 2016, Ho et al. 2016, Silva et al. 2016). For example, undrained cohesions are usually derived from limit pressures (Figure 3).

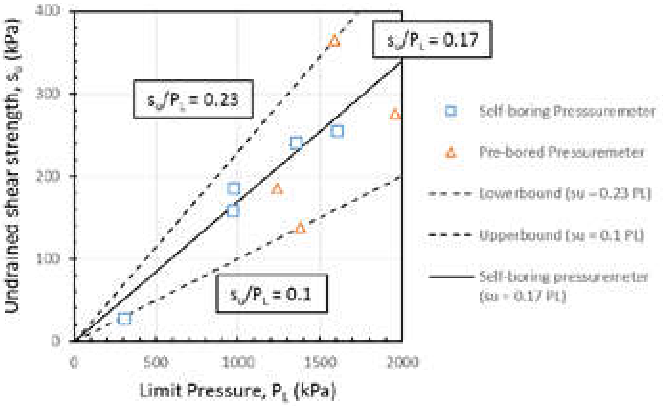

Figure 3. Correlation between undrained cohesion and limit pressure (Ho)

Comparisons with shear vane tests and cone penetration tests show good agreements. In complex grounds, for example, in gneiss residual soils (Brazil), pressuremeter tests provide very interesting information related to the variation of the stiffness with the depth. Data from pressuremeter both Ménard modulus and limit pressure can be used to appreciate the ground heterongeneity by analyzing their scatter. Several comparisons with plasticity index, N_{SPT} or uniaxial compression strength show that the heterogenity is more or less the same. Variations according to the horizontal plane and the depth can be highlighted in a homogenous ground layer with pressuremeter tests showing variations of stiffness and strength resistance.

Soil profiling chart based on SPT and CPT results have a great success among practitioners. One resistance parameter is figured versus another one dimensional or normalized (by the first one) and zones of specific behavior are delimitated by curves. As these parameters do not vary linearly between each other, logarithmic scales are often used to linearize non linear trends. Recently the same development was initiated for pressuremeter tests results.

Baud gives in his paper an update of previous development of their soil behavior chart called Pressiorama (figure 4). This tool defines soil classes or mechanical properties, in a plane constructed with the normalized limit pressure versus the ratio of the Ménard modulus to the limit pressure. The new version presented skip from limit pressure to rheological factor α invented by Louis Ménard. In order to complete the Pressiorama diagram with an α values axis, the authors used a calibration mostly based on PMT performed in various soil types from soft clay to rock.

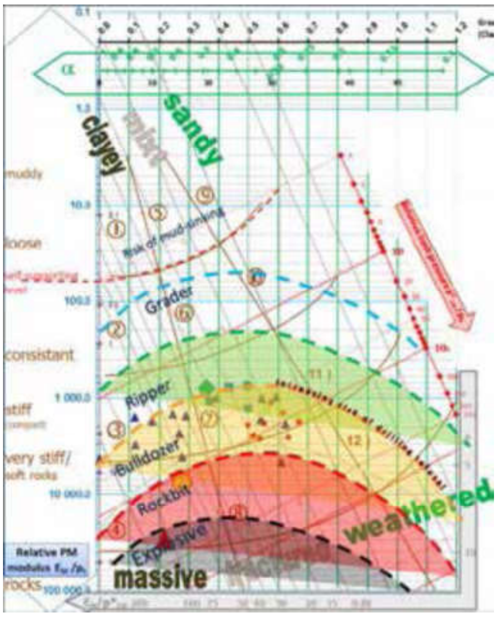

Figure 4. Pressiorama (Baud)

1.4 *Constitutive laws and numerical modeling*

The analysis of the pressure-volume curve can be very interesting for the calibration of constitutive laws. A numerical procedure is developed in laboratory with a miniature pressuremeter to calibrate a complex constitutive law called Hardening Soil Small model using Plaxis finite element code (Plaxis 2015, Bagbag). The model provides a very good simulation of the measured pressuremeter response at small and medium cavity strains. It is also noticed that the parameters determined from triaxial tests provide a reliable simulation of the pressuremeter tests. Another paper proposed by Oztoprak et al. deals with the same issue. Small strain considerations are coupled with the strain-hardening/softening Mohr-Coulomb (SHS-MC) criterion to better capture the soil behaviour in the small strain range. The SHS-MC model allows the representation of nonlinear material softening and hardening behaviour based on prescribed variations of the MC criterion properties as functions of the plastic shear strain which are not an output in the MC model. Oztoprak et al. show that a pressuremeter test can successfully be modelled through the proposed hyperbolic model. To model the small strain behavior and therefore to obtain the corresponding shear modulus and index properties of the tested soils, loops are of crucial importance. The size and the inclination of loops are completely related to the degradation behavior of shear modulus.

This topic is very interesting for pressuremeter engineering since it allows to clearly assess parameters that are usually measured in laboratory: for example, *E* and ν for elastic parameters and *c*, φ and ψ for plastic parameters. Nevertheless, the pressure-volume curve can provide additional elements to take into account non-linear elasticity with for example the reduction of the shear modulus with strain level, plastic volumetric strains with contraction or dilation, hardening mechanisms, etc. It avoids the discussion about the difference between Ménard modulus and Young modulus.

The main barrier remains the measure of pore pressures that would allow to perform analysis according to the effective stresses framework. It can be interesting to note that very few works try to account for creep effects based on pressuremeter tests whereas the maintained load procedure should allow to study this topic. Creep pressure is rarely considered whereas this parameter could be viewed as the ground reaction compatible with very low strains. For example, this idea leads to limit *p-y* curves to creep pressure in order to limit the pile displacements submitted to transversal loads. The creep pressure can be considered as the lower bound of the limit pressure when the ground is submitted to many cyclic loadings.

1.5 *Geotechnical design*

The use of pressuremeter tests for the geotechnical design has not been addressed by the papers of this conference. Nevertheless, pressuremeter test provides both a failure parameter, the limit pressure, and a deformation parameter, the Ménard modulus, which enables to tackle with the same *in situ* test the problems of bearing capacity of foundations (using the limit pressure p_{LM}), as well as the problems of displacements of foundations (using the pressuremeter modulus E_M). In France, design codes for shallow and deep foundations are based on the use of pressuremeter parameters. Recent developments and new experiments have been performed and show that improvements are possible.

The calculation model based on pressuremeter data for the assessment of pile bearing capacity has been recently improved to take into account new pile techniques and be compatible with Eurocode 7 approach (Burlon et al. 2014). Based on 174 full-scale static pile load tests (IFSTTAR pile database), this work includes a comparison between measured values of pile bearing capacity and calculated values by an improved calculation model 'PMT2012' (figure 5).

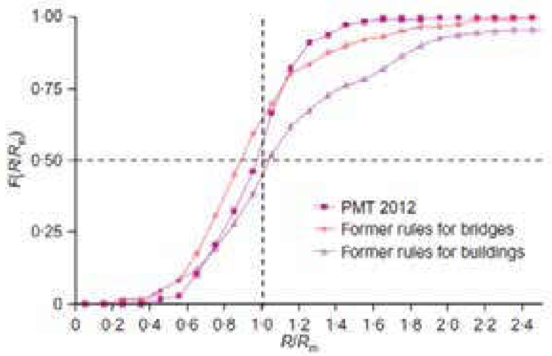

Figure 5. Scatter of different calculation models for pile bearing capacity based on pressuremeter data – Comparison of distribution functions (R-calculated values ; R_m-measured values) (from Burlon et al. 2014)

Pressuremeter data can be used to propose t-z curves (Frank et al. 1981) or p-y curves both for static and cyclic applications (Burlon et al. 2013). Regarding *t-z* curves, from IFSTTAR pile database, new calculation models have been proposed (Abchir et al.). For cyclic applications, the use of the cyclic pressuremeter test can provide relevant data for the calibration of *t-z* and *p-y* curves.

2 DILATOMETER TESTS

2.1 *Current status, background and updates*

The flat dilatometer test (DMT), introduced by Marchetti (1980), is increasingly used in the last years, also stimulated by the diffusion of its efficient "All-in-One" seismic version (SDMT). The DMT is standardized by ASTM (D6635-15). ISO/TC 182/SC1 is currently converting the DMT Technical Specification into a Standard (ISO/DIS 22476-11:2015(E)). The state-of-the-art of DMT/SDMT was recently overviewed in the 3rd International Conference on the Flat Dilatometer DMT'15 (Rome, Italy, June 2015). A basic reference document (Marchetti et al. 2001), including detailed information on DMT equipment, test procedure, interpretation and applications, was released in 2001 by the ISSMGE Technical Committee TC16 (now TC102) – In-Situ Testing. In his DMT'15 keynote, Marchetti (2015) presented some updates to the 2001 TC16 Report, as well as new developments and clarifications on specific aspects on use and interpretation of the DMT. Key papers on DMT/SDMT, including the DMT'15 Proceedings, can be downloaded from the recently restyled website *www.marchetti-dmt.it*.

Major distinctive contributions that the DMT can provide in a *routine* site investigation are: (1) information on stress history, which has a dominant influence on soil behaviour; (2) being a load-displacement test, DMT results are more closely related to soil stiffness than other in situ penetration tests (e.g. CPT). As to the SDMT, the add-on module has added to the parameters measurable by DMT the shear wave velocity V_S, hence information on small strain stiffness.

In most cases the DMT is utilized in site investigations to obtain information and soil parameters (stratigraphy/soil type, undrained shear strength, constrained modulus, etc.) to be used with common geotechnical engineering design methods. Most frequent DMT applications include: prediction of settlements of shallow foundations, compaction control, liquefaction assessment, design of laterally loaded piles, detecting slip surfaces in OC clay. Recently, researchers have also focused on: correlations and comparisons with other in situ (or laboratory) tests, theoretical and numerical modelling of the test, applications in difficult geomaterials (e.g. tailings, residual soils), new developments and improvement of testing equipment (seismic/other instrumentation, nearshore/seafloor test setup), seismic site characterization (SDMT). The papers on DMT submitted to this conference are mostly focused on: updates on interpretation of soil parameters; combination/comparisons with other in-situ tests (mostly CPT); liquefaction assessment; technological innovation of testing equipment (instrumented DMT, upgrade of seismic probe). The main findings revealed by the papers on DMT included in the Session Pressuremeter/Dilatometer are briefly discussed in the following. Comments to these papers are tentatively outlined in a more general framework of current trends and ongoing developments of DMT research and practice.

2.2 *Sensitivity of DMT to stress history*

Research carried out over the years has pointed out the centrality of the horizontal stress index K_D, a key parameter obtained from DMT and one of the few in situ parameters able to provide information on stress history (especially in sand). Knowledge of stress history is fundamental for obtaining realistic predictions, e.g. of settlements and liquefaction behaviour. Numerous researchers have observed that K_D from DMT is considerably more sensitive to stress history than the cone penetration resistance q_c from CPT, either in monitoring compaction in the field and in calibration chamber (see Marchetti 2015 for details and references). K_D reflects cumulatively various stress history effects, such as aging, in situ horizontal earth pressure (K_0), structure and cementation.

2.3 *In-situ multi-parameter/multi-test approach*

Most in situ tests are only able to measure "mixed" soil responses that depend at the same time on strength, stiffness, stress history, etc. Hence "pure" soil properties are determined by solving an inverse problem, based on multiple independent in situ responses. Mayne et al. (2009) emphasized the use of direct-push in situ tests providing multi-measurements, in particular "hybrid" tests that combine the advantages of full-displacement penetrometer probes with downhole geophysics (such as seismic piezocone SCPTU and SDMT), as a more efficient approach to geotechnical site characterization. While in simple problems one in situ technique could be sufficient, in general an adequate number of responses from different in situ tests should be available to define a soil model. Moving towards an in-situ multi-parameter/multi-test approach appears a logical trend. In this respect, the availability of the DMT stress history parameter K_D is important not only "per se", but also in combination with parameters obtained from other in situ tests less sensitive to stress history (e.g. CPT).

An example of in-situ multi-parameter/multi-test approach is the estimation of the overconsolidation ratio *OCR* in sand based on both DMT and CPT. The 2001 TC16 DMT Report (Marchetti et al. 2001) indicated semi-quantitative guidelines of the ratio between the constrained modulus M_{DMT} estimated from DMT and the CPT cone resistance q_c in NC and OC sands. The potential use of the ratio M_{DMT}/q_c as a broad indicator of *OCR* in sands descended from field observations before/after compaction of sandfills, where M_{DMT}/q_c was found to increase with compaction (a way of imposing stress history) due to the fact that compaction increases both M_{DMT} and q_c, but M_{DMT} at a faster rate. Monaco et al. (2014) also combined DMT and CPTU to derive a general correlation for estimating *OCR* in sand from the ratio M_{DMT}/q_t. This correlation was constructed using the results of an experimental study at the research site of Treporti, Venice (Italy), where a full-scale trial embankment was built and then removed four years later, permitting to calculate *OCR* at each depth (by its simple definition), and paired values of M_{DMT} and q_t in sand layers were available.

Other examples of multi-parameter/multi-test approach, based on the combined use of DMT and CPT, are the methods for estimating K_0 in sand (see Marchetti 2015) and the method for estimating liquefaction resistance proposed by Marchetti (2016).

Several papers presented in different Sessions of this conference show comparisons of DMT and CPT results. This interest indicates the trend of increasing diffusion of a combined multi-parameter/ multi-test approach in site investigation practice.

2.4 *Updates on DMT interpretation*

2.4.1 *In situ G-γ decay curves from SDMT*

Predicting settlements of shallow foundations is often considered the No. 1 DMT application. A large number of comparisons collected over the years has indicated, in general, reasonable agreement between measured and DMT-predicted settlements (Monaco et al. 2006). The accumulated experience indicates that the constrained modulus M_{DMT} (Marchetti 1980) can be assumed as an adequate "operative" or "working strain" modulus for most practical purposes.

A distinctive feature of the SDMT is its ability to provide routinely, besides the *working strain* modulus M_{DMT}, also the *small strain* shear modulus G_0 (obtained as $G_0 = \rho V_S^2$, where ρ is the soil density).

The potential of obtaining stiffness decay curves in situ is of considerable interest, since such curves are difficult and expensive to achieve in the laboratory. A procedure to derive in situ curves depicting elemental soil stiffness variations with strain level from SDMT was outlined by Marchetti et al. (2008). Such decay curves could be constructed by fitting "reference typical-shape" laboratory G/G_0-γ curves through two points, both provided by SDMT: (1) the *small strain* shear modulus G_0 from V_S; (2) a *working strain* shear modulus G_{DMT} derived from M_{DMT} (using linear elasticity formulae, as a first approximation). To locate the second point on the curve it is necessary to know, at least approximately, the elemental shear strain γ_{DMT} corresponding to G_{DMT} along the G/G_0-γ curve. Typical ranges of γ_{DMT} in different soil types (0.015-0.30% in sand, 0.23-1.75% in silt and clay) were inferred by Amoroso et al. (2014) based on comparisons of SDMT data with reference stiffness decay curves from laboratory tests or back-calculated from full-scale tests. Amoroso et al. (2014) also proposed a hyperbolic stress-strain formulation for estimating G/G_0-γ decay curves from SDMT, which require to input the ratio G_{DMT}/G_0 obtained from SDMT at a given site and a "typical" shear strain γ_{DMT} estimated for the given soil type.

Rodrigues et al. present an interesting application of the Amoroso et al. (2014) procedure for estimating G/G_0-γ decay curve from SDMT in granitic residual soils in the area of Guarda (Portugal). The behaviour of these structured soils, often classified as "problematic", is strongly influenced by bonding and fabric. The investigated soils are characterized by very high values of K_D and M_{DMT}, which suggest significant cementation. Rodrigues et al. applied the Amoroso et al. (2014) procedure by comparing SDMT data with stiffness decay curves obtained by triaxial tests (CID) with internal instrumentation executed on samples retrieved at the same depth and subjected to the same confinement stress. The comparisons (Figure 6) indicate that in these residual soils γ_{DMT} falls in the range 0.0025-0.003%, i.e. one order of magnitude lower than γ_{DMT} proposed by Amoroso et al. (2014) for sedimentary soils of similar grain size (0.015-0.30%). This finding clearly reflects the influence of cementation/fabric on the mechanical behaviour of these soils and points out the necessity of specific calibration of methods developed for "textbook" soils.

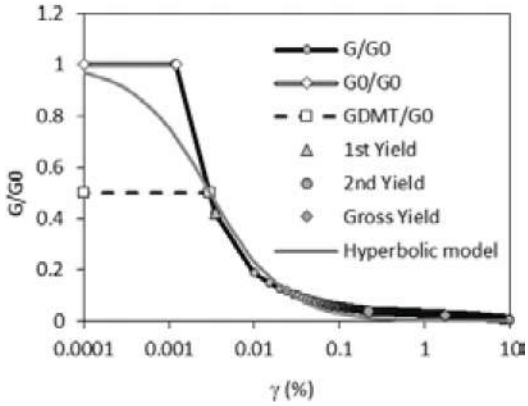

Figure 6. Laboratory G/G_0-γ curve, superimposed G_{DMT}/G_0 data points and hyperbolic G/G_0-γ curve (Amoroso et al. 2014) in granitic residual soils at Guarda, Portugal (Rodrigues et al.)

2.4.2 *OCR*, c_u *and* γ *in clays*

Cao et al. present the results of DMTs conducted in silty clay and silty clay till at two sites in Ontario, Canada. They used semi-theoretical formulas developed from cavity expansion theory in the Modified Cam Clay (MCC) model to estimate *OCR* and c_u from the DMT measurements p_0 and p_1 (also requiring additional information, e.g. the friction angle ϕ'). The profiles of *OCR* and c_u obtained by these formulas were compared with those interpreted from DMT using the original Marchetti (1980) correlations and with corresponding results from field vane, triaxial and oedometer tests. Cao et al. found in general good agreement between *OCR* and c_u obtained by their semi-theoretical formulas and determined by other reference tests (Figure 7), while the Marchetti (1980) correlations provided higher *OCR* and c_u estimates at both sites. It is noted that at the first site various indicators (very low in situ void ratio, very high p_0) suggest significant stress history of the till deposit, denoted as very stiff to hard, while based on oedometer test the deposit is defined NC to slightly OC. At the second site (Figure 7) very low values of the DMT material index I_D suggest that the silty clay deposit is a so-called "niche silt" (Marchetti 2015), where the difference $(p_1 - p_0)$ is "too low" and so are the derived parameters.

As pointed out by Marchetti (2015), the original Marchetti (1980) *OCR*-K_D correlation in clay (origin of many derived correlations, including c_u-K_D by SHANSEP) was later confirmed by experimental and theoretical research work. The Marchetti (1980) *OCR* and c_u correlations can be considered roughly as "median" correlations for "average" soils, able to provide reasonable estimates in many "textbook" clays. It is not surprising that the till deposits investigated by Cao et al. present some deviation compared with the generality of "textbook" clays.

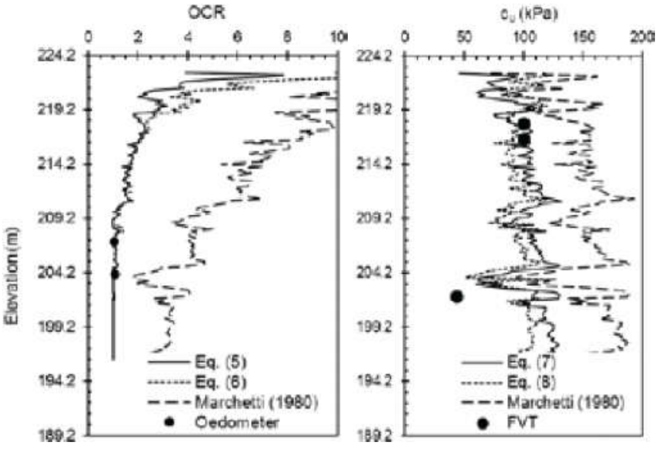

Figure 7. Comparison of *OCR* and c_u obtained from DMT and from other tests at Bradford West Gwillimbury, Ontario, Canada (Cao et al.)

Ouyang & Mayne present a new method for estimating the total soil unit weight γ_t from DMT in soft to firm clays. The study is based on a re-interpretation of DMT results from 31 NC to lightly OC (*OCR* ≈ 1-2) clay deposits in different countries, mostly homogeneous and having a shallow groundwater table (≈ 1-3 m depth). The database comprises laboratory data from undisturbed samples, including γ_t determinations. In these clays, as commonly observed in NC clays, the DMT contact pressure p_0 increases almost linearly with depth z. Using a regression analysis, Ouyang & Mayne defined a new slope parameter $m_{p0} = \Delta p_0/\Delta z$.

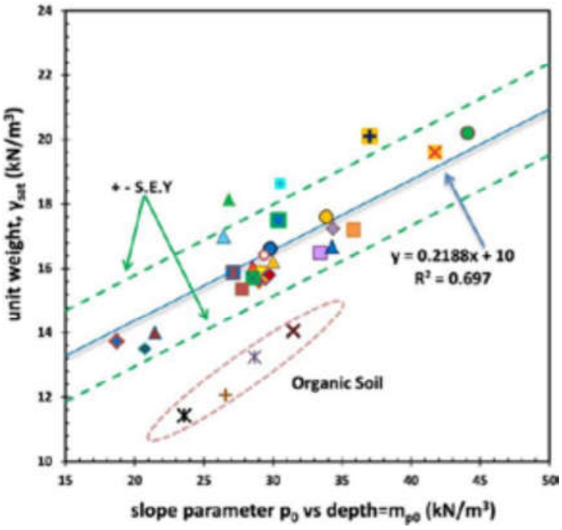

Figure 8. Total unit weight versus slope parameter m_{p0} (Ouyang & Mayne)

The comparison with laboratory γ_t values (Figure 8) indicated a correlation between γ_t and m_{p0} in most inorganic clays, while a few organic clays showed different trends. Based on this finding, Ouyang & Mayne proposed an approximate expression for deriving γ_t from m_{p0}. Compared statistically with the earlier Marchetti & Crapps (1981) chart, the new correlation was found to give a better estimate of γ_t in the tested clays. However Ouyang & Mayne note that the proposed m_{p0} approach is not applicable to stiff and hard clays, nor to silts and sands, thus it appears to be specific only for soft to firm inorganic clays.

2.5 *Liquefaction assessment based on DMT-K_D*

The use of the DMT for liquefaction assessment has received increasing attention in the last years and is a central topic in recent DMT research. Simplified methods for estimating the cyclic resistance ratio (*CRR*) based on the horizontal stress index K_D have recently been proposed by Monaco et al. (2005), Tsai et al. (2009), Robertson (2012). The *CRR*-K_D correlation has potentially the advantage of incorporating the high sensitivity of K_D to stress history, besides to other factors that increase liquefaction resistance (relative density, in situ horizontal earth pressure, aging, cementation). Recently Marchetti (2016) proposed a method to estimate *CRR* based on the combined use of CPT-DMT results, in the form $CRR = f(Q_{cn}, K_D)$, where Q_{cn} (or q_{c1N}) is the normalized cone resistance. The interest in combining the information obtainable from both tests is in that the commonly used CPT-based liquefaction curves are based on a vast field performance experience, but stress history, which has a primary influence on *CRR*, is modestly reflected by Q_{cn}, while K_D is a sensitive indicator of stress history. This is a remarkable example of multi-parameter/multi-test approach. It is expectable that an estimate based at the same time on two measured parameters could be more accurate than an estimate based on just one parameter. Another useful multi-parameter approach facility when using the SDMT is the possibility to obtain two independent estimates of *CRR*, one from K_D and another from V_S using existing *CRR*-V_S correlations.

The major obstacle to the diffusion of DMT-based liquefaction triggering methods today is their limited experimental validation based on field performance data from real earthquakes, in contrast to methods based on CPT, SPT or V_S. The paper presented in this conference by Rollins et al. is a valuable attempt to fill this gap. The Authors note that, despite the availability of liquefaction triggering curves based on CPT and SPT, a DMT-based liquefaction triggering curve is highly desirable because it is more sensitive to factors, such as aging, stress history and horizontal earth pressure, which are particularly important when evaluating increased liquefaction resistance produced by ground improvement techniques that increase both the density and lateral pressure. Rollins et al. assessed comparatively the accuracy of three available K_D-based methods (Monaco et al. 2005, Tsai et al. 2009, Robertson 2012) built on DMT data collected at sites where liquefaction did or did not occur in various earthquakes (California, Taiwan, New Zealand, Italy). They found that the DMT-based field performance data provide reasonable discrimination between liquefaction and no liquefaction for $K_D < 4$ (Figure 9). Both the Tsai et al. (2009) and Robertson (2012) curves provide reasonable triggering boundaries within this range, while the Monaco et al. (2005) curve is somewhat unconservative. In the region where $K_D > 4$ and the cyclic stress ratio $CSR > 0.20$, there is currently insufficient data to constrain the triggering boundary curve and additional testing is necessary. It is noted that, as today, fines content corrections are not accounted for by existing DMT liquefaction triggering curves, valid only for clean sand. Rollins et al. included also silty sand and sandy silt data points, regardless of fines content, in their DMT data collection. However they observe that the implementation of the DMT case history database could support the introduction of a more consistent liquefaction curve that could also consider the fines content influence using the material index I_D.

The construction of an adequate field performance database for the validation of DMT-based liquefaction triggering curves, including information on fines content and/or cementation, is a strong address for future research. The inclusion of data points from sites affected by severe lateral spreading, which may influence to a significant extent the post-liquefaction K_D, requires caution and further investigation.

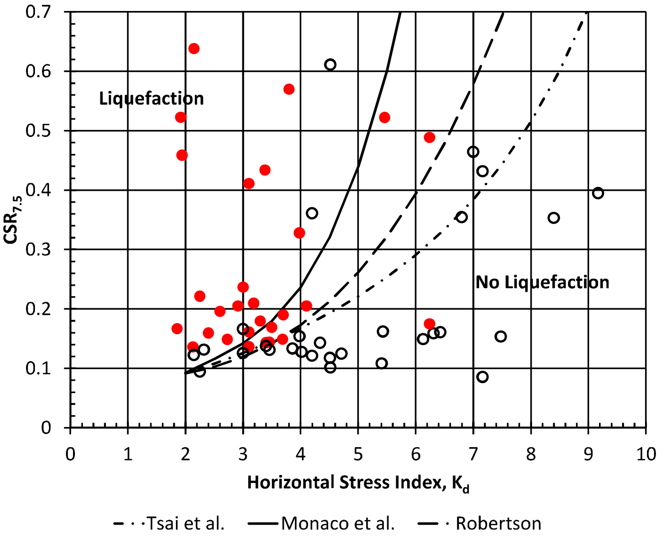

Figure 9. Comparison of DMT-based liquefaction triggering curves with field performance data points using the Boulanger & Idriss (2016) approach for *CSR* (Rollins et al.)

2.6 *Modified instrumented DMT*

A number of modified instrumented DMT (iDMT) have been prototyped in the years by various researchers. Some of these modified probes incorporate a pressure sensor and a displacement sensor, able to produce a full pressure-displacement curve instead of the standard DMT pressure readings at two fixed displacements.

Shen et al. present a novel method for determining the "lift-off" pressure p_0 from interpretation of the full pressure-displacement curve provided by iDMTs. The difference with the standard DMT interpretation is in that the original formulation for p_0 (Marchetti 1980) derives from the assumption of a linear pressure-displacement relation; actually p_0 (corrected pressure at zero displacement) is not measured directly, but is back-extrapolated from the pressure readings at 0.05 mm and 1.10 mm displacements. Shen et al. observe that the standard method can provide accurate and repeatable p_0 as long as the pressure-displacement relation is nearly linear, while a biased estimation of p_0 is obtained in case of high non-linearity, which could only be evidenced if a full pressure-displacement curve is available. The analytical procedure proposed by Shen et al. involves the identification of a yield point and then the back-extrapolation of p_0 at zero displacement from a regression model fitting the post-yield curve. The yield point is identified by use of a graphical method, implemented in Matlab, resembling the Casagrande method for estimating the preconsolidation pressure in the oedometer test. Shen et al. present examples of application of their p_0 interpretation method to available iDMT pressure-displacement curves obtained by various researchers both in the field and in calibration chamber, in different soil types (Figure 10). Comparisons with p_0 estimated by the standard Marchetti (1980) formulation show a variable trend, depending on the non-linearity of the pressure-displacement curve. In most cases the p_0 estimated by Shen et al. from iDMT were larger than the standard DMT p_0, with a percentage increase from 6% in sand to a large 43% in soft varved clay. A decrease (24%) was observed for calibration chamber data on Toyoura sand.

The reliable determination of p_0 is a central issue in DMT interpretation, since p_0 is a necessary input for all three intermediate DMT parameters (I_D, K_D, E_D) which are used to derive common soil parameters. In particular, the p_0-derived stress history parameter K_D has a dominant role. At present, the new interpretation technique for p_0 proposed by Shen et al. appears to need further validation. It should also be considered that existing correlations for determining a variety of soil parameters from DMT are based on the "conventional" determination of p_0.

Future developments of iDMTs should eventually tend toward standardization of probes and procedures, in order to translate cautiously the available experience into new interpretation models. The development of modified iDMTs providing full pressure-displacement curves has the undeniable merit of permitting a deeper insight into the non-linear soil response and is a potential opportunity to improve the interpretation of soil properties. Notably the same Authors (Shen et al. 2016) are involved in an ongoing project using the 3D printing technology for manufacturing an iDMT probe, an innovative frontier application of this technology in the field of geotechnical testing.

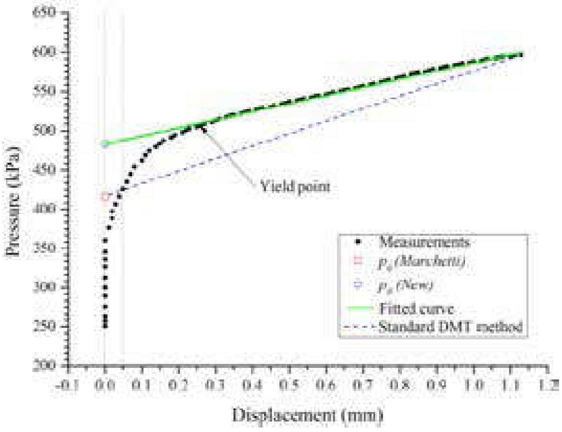

Figure 10. Application of the proposed p_0 interpretation technique to test data from Akbar et al. (2005) (Shen et al.)

3 DISCUSSION AND FURTHER DEVELOPMENTS (FOR PMT AND DMT)

Regarding PMT, all papers presented in this symposium show that pressuremeter has still a great interest for practice in basic application such as classification of ground mass or quality control but also for deriving parameters or to develop and fit behavior law needed for finite element modeling. For this purpose as pointed out by Briaud (2013) in his Ménard lecture, simple techniques can be used to recreate the small strain early part of the curve lost by the decompression-recompression process associated with the preparation of the Ménard pressuremeter borehole. The use of the Ménard pressuremeter test unload-reload modulus can be also a reliable way to derive small strain modulus.

In order to continue the development of the pressuremeter, the National Project ARSCOP initiated in France aims to provide on the one hand, test procedures and tools for a better ground investigation and, on the other hand, values of soil and rock properties and calculation methods ensuring more reliable geotechnical design. Concerning test procedures and tools, the main issues are: the measurement of the pore pressures around the probe in order to perform total and effective stress analysis, the development of cyclic procedures for off-shore applications especially with the implementation of cyclic p-y curves, the development of procedures to quantify liquefaction susceptibility, etc.

As to the DMT, many papers presented in this conference confirm its utility as a fast, simple to operate and repeatable in situ test, which provides estimates of a variety of soil parameters for design. Major distinctive contributions that the DMT can offer in a routine site investigation are information on stress history and on "working strain" stiffness. In addition the SDMT provides also measurements of V_S, hence information on small strain stiffness.

Current trends and ongoing developments of DMT research and practice addressed in this conference include:

- increasing application of a multi-parameter/multi-test approach, with combination/comparisons of DMT/SDMT and other in situ tests (mostly CPT);
- increasing interest in methods for deriving in situ G-γ decay curves from SDMT;
- updates in the interpretation of geotechnical parameters, particularly in "non-textbook" soils;
- validation of methods for liquefaction assessment based on DMT/SDMT;
- technological innovation of the testing equipment (instrumented DMT, upgrade of seismic probe).

4 CONCLUSIONS

This report includes a brief summary of the papers received for the ISC'5 Conference for pressuremeter and dilatometer tests. Some of the more interesting topics covered are presented and discussed in order to give an overview of the current practice of pressuremeter and dilatometer tests. These two expansion tests can provide very detailed information about the soil behavior especially in terms of stiffness. They seem to be complementary to penetration tests that can provide strength parameters.

5 REFERENCES

Abchir, Z., Burlon, S., Frank, R., Habert, J. & Legrand, S. (2016) t-z curves for piles from pressuremeter test results. *Géotechnique*, 66(2): 137-148.

Akbar, A., Kibria, S. & Clarke, B.G. (2005) The Newcastle Dilatometer testing in Lahore cohesive soils. *Proc. XVI ICSMGE, Osaka*, 2: 651-654.

Amoroso, S., Monaco, P., Lehane, B.M. & Marchetti, D. (2014) Examination of the Potential of the Seismic Dilatometer (SDMT) to Estimate *In Situ* Stiffness Decay Curves in Various Soil Types. *Soils and Rocks*, 37(3): 177-194.

Baguelin, F., Jézéquel, J.F. & Shields, D.H. (1978) The Pressuremeter and Foundation Engineering. Transtech Publications, pp. 618.

Baker, C.N. (2005) The use of the Menard pressuremeter in innovative foundation design from Chicago to Kuala Lumpur. *2nd Menard Lecture, Proceedings of the 5th Int. Symp. on the Pressuremeter – ISP5, Paris, France*, Presses de l'ENPC.

Boulanger, R.W. & Idriss, I.M. (2016) CPT-Based Liquefaction Triggering Procedure. *J. Geotech. Geoenviron. Eng.*, 142(2): 04015065.

Briaud, J.L. (1992) The Pressuremeter. Taylor and Francis, London, pp. 422.

Briaud, J.L. (2013) The pressuremeter test: expanding its use. *Ménard Lecture, 18th ISSMGE, Paris.*

Burlon, S., Roger, F., Baguelin, F., Habert, J. & Legrand,S. (2014) Model factor for the bearing capacity of piles from pressuremeter test results. A Eurocode 7 approach. *Géotechnique*, 64(7): 513-525.

Combarieu, O. & Canépa, Y. (2001) L'essai cyclique au pressiomètre. *BLPC*, 233: 37-65.

Frank, R. & Zhao, S.R. (1982) Estimation par les paramètres pressiométriques de l'enfoncement sous charge axiale de pieux forés dans des sols fins. *Bull. Liaison Labo P. et Ch.*, 119: 17 - 24.

Marchetti, S. (1980) In Situ Tests by Flat Dilatometer. *J. Geotech. Eng. Div.*, 106(GT3): 299-321.

Marchetti, S. (2015) Some 2015 Updates to the TC16 DMT Report 2001. *Proc. 3rd International Conference on the Flat Dilatometer DMT'15, Rome, Italy*, 43-65.

Marchetti, S. (2016) Incorporating the Stress History Parameter K_D of DMT into the Liquefaction Correlations in Clean Uncemented Sands. *J. Geotech. Geoenviron. Eng.*, 142(2): 04015072.

Marchetti, S. & Crapps, D.K. (1981) Flat Dilatometer Manual. *Internal Report of G.P.E. Inc., Gainesville, Florida*.

Marchetti, S., Monaco, P., Totani, G. & Calabrese, M. (2001) The Flat Dilatometer Test (DMT) in Soil Investigations – A Report by the ISSMGE Committee TC16. Official version approved by TC16 reprinted in *Flat Dilatometer Testing*, *Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington DC*, 2006, Failmezger R.A. & Anderson J.B. (eds), 7-48.

Marchetti, S., Monaco, P., Totani, G. & Marchetti, D. (2008) In Situ Tests by Seismic Dilatometer (SDMT). *From Research to Practice in Geotechnical Engineering*, *Geotech. Spec. Publ. No. 180*, ASCE, 292-311.

Mayne, P.W., Coop, M.R., Springman, S.M., Huang, A.B. & Zornberg, J.G. (2009) Geomaterial behavior and testing. *Proc. XVII ICSMGE, Alexandria*, 4: 2777-2872.

Monaco, P., Amoroso, S., Marchetti, S., Marchetti, D., Totani, G., Cola, S. & Simonini, P. (2014) Overconsolidation and Stiffness of Venice Lagoon Sands and Silts from SDMT and CPTU. *J. Geotech. Geoenviron. Eng.*, 140(1): 215-227.

Monaco, P., Marchetti, S., Totani, G. & Calabrese, M. (2005) Sand liquefiability assessment by Flat Dilatometer Test (DMT). *Proc. XVI ICSMGE, Osaka*, 4: 2693-2697.

Monaco, P., Totani, G. & Calabrese, M. (2006) DMT-predicted vs observed settlements: a review of the available experience. *Proc. 2nd International Conference on the Flat Dilatometer, Washington D.C.*, 244-252.

Robertson, P.K. (2012) The James K. Mitchell Lecture: Interpretation of in-situ tests – some insights. *Proc. 4th Int. Conf. on Geotechnical and Geophysical Site Characterization, Porto de Galinhas*, 1: 3-24.

Shen, H., Haegeman, W. & Peiffer, H. (2016) 3D Printing of an Instrumented DMT: Design, Development, and Initial Testing. *Geotechnical Testing Journal*, 39(3): 1-8.

Tsai, P., Lee, D., Kung, G.T. & Juang, C.H. (2009) Simplified DMT-based methods for evaluating liquefaction resistance of soils. *Engineering Geology*, 103: 13-22.