The Legacy of Michele Jamiolkowski to Geotechnical Engineering

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ABSTRACT

Michele Jamiolkowski was deeply interested in many topics in geotechnical engineering. The link between his many contributions to the discipline was his deep appreciation for the need to develop techniques for predicting the performance of real structures. This focus on real structures was pervasive in all of his research, and led to his attention to experimental investigation of natural soils. Jamiolkowski recognized the importance of *in situ* tests to site characterization of natural soils, and consequently this paper focuses on this topic. Jamiolkowski was involved in many challenging projects, and he always considered each project as an occasion to improve the state of the art, to develop novel approaches in site characterization, to develop new *in situ* test interpretation methods, and to obtain quality experimental data. The paper summarizes major improvements to the state of the art that resulted from his contributions, as well lessons learned from major and iconic projects in which Jamiolkowski was involved.

Keywords: Calibration Chamber; CPT; PMT; DMT; Geophysical tests; Shear wave velocity.

1. Introduction

Michele Jamiolkowski was involved in a variety of projects, including iconic projects, such as the stabilization of the Tower of Pisa. But his most enduring contributions to geotechnical research will likely be his work in the area of site characterization and *in situ* testing.

The relevance of site characterization in geotechnical engineering stems from the need to deal with natural materials that are characterized by a complex mechanical response to external actions. This response reflects many factors, including:

- mineralogy,
- grain size and shape,
- state (porosity, state of stress, soil fabric),
- geological history,
- chemistry, and
- hydraulic conditions.

Indeed, soils are porous materials that are intrinsically multiphase materials. The interaction between the solid, liquid and gas phases of soil plays a fundamental role in determining its response to a variety of thermal, hydraulic or mechanical actions.

Laboratory and *in situ* tests are the tools for site characterization that precede tackling virtually any geotechnical application. The attention paid to site characterization assumes a crucial role, especially in complex geological settings and in work related to iconic projects.

Deep knowledge of the site and of material behaviour are indeed a fundamental prerequisite for understanding ongoing processes and for the forecast of the response of new and existing constructions. Moreover, the growing ability to model and simulate processes with advanced constitutive models and sophisticated numerical tools requires high quality input data to produce meaningful results.

Since the beginning of his scientific and technical career, Michele Jamiolkowski devoted his work to innovation and improvement of soil characterization practice. When involved in large projects, he always insisted on performance of site characterization at the highest standard in terms of quality and applicability. The interplay of *in situ* and laboratory tests in experimental soil mechanics was summarized in his seminal paper on the subject of his theme lecture in the San Francisco ICSMFE conference (Jamiolkowski et al., 1985). Indeed, the strong connection between advanced research and geotechnical practice has always been a focus of Jamiolkowski's vision (Jamiolkowski, 1988).

The present paper discusses innovation in the practice of *in situ* testing that resulted from Jamiolkowski's interests and research activity. Initially, an overview of some iconic projects will be presented, highlighting lessons learned. These case studies are likely the most well-known projects in which Jamiolkowski was involved. Interestingly, they cover a wide range of problematic materials with which geotechnical engineers must deal:

- the Pisa tower (soft clays);
- the Messina Straight Bridge (sands and gravels);
- the Venice Lagoon (silts); and
- the Zelasny Most tailing dam (tailings).

The role of the calibration chamber research program that he led in Italy in advancing the understanding of the relationship between quantities measured in *in situ* tests and soil state and intrinsic variables is then discussed. Some of the work that relied on calibration chamber test data for cross validation—such as the use of cavity expansion theory to offer a theoretical framework for the interpretation on cone penetration tests—is also discussed.

The paper concludes with a discussion of the role of geophysical testing in site characterization.

2. High-Profile Projects

2.1. Pisa Tower

The name of Michele Jamiolkowski is known worldwide in large measure because of his crucial role in safeguarding the Leaning Tower of Pisa (Figure 1) against collapse. Jamiolkowski devoted much of his time and energy to this extremely challenging geotechnical problem from 1990 to 2001, the period during which he chaired the "ad hoc" International Committee to safeguard the Tower. The Committee succeeded in devising a definitive solution that addressed one of the intervention goals: respect for the integrity of the monument (Jamiolkowski, 2001).

Figure 1. The Leaning Tower of Pisa.

The Leaning Tower of Pisa is no doubt the favorite "shorthand" image for the idea not only of Pisa but of Italy. However, the Tower is just a single component of Pisa's amazing religious core, the so-called *Campo dei Miracoli*, that should be better addressed as *Campo delle Mirabilia*, being a sight whose impact no amount of prior knowledge can blunt.

The buildings date from the period of Pisa's greatest prosperity and power: from the 11th to the 13th centuries. Construction of the Cathedral begun in 1063 and ended at the close of the 12th century. Construction of the Baptistery started in 1152, of the bell tower in 1173m, and of the cemetery—the *Camposanto*—at the end of the 13th century. The impressive artistic and religious elements of this complex are such that the Tower would have been astonishing even if not leaning.

However, since the early stages of construction, the tower suffered significant differential settlements that induced a marked rigid rotation of the basement. With the potential for acceleration of the rotation of the Tower that was observed in the 1980s and 1990s, detailed analyses of the problem were undertaken. These studies, and the sophisticated numerical model used to calibrate the response of the Tower and the underlying ground required significant site investigation and experimental laboratory testing programmes. This, in combination with the data collected during the activities of previous committees, allowed identification in detail of subsoil conditions and determination of the mechanical properties of different soil layers. A schematic stratigraphy is reported in Figure 2.

Horizon A, about 10m thick, is composed of soft estuarine deposits of sandy and clayey silts laid down under tidal conditions. Horizon B consists of soft sensitive normally consolidated marine clay extending to a depth of about 40m. Because it is very sensitive, this material loses much of its strength if disturbed. Horizon C is dense marine sand extending to a depth of about 60m. An upper perched water table in Horizon A is encountered between 1m and 2m below the level of Piazza dei Miracoli corresponding to elev. +3.0 above m.s.l. The contact between Horizon A and the marine clay of Horizon B is dished beneath the Tower, indicating that it experienced average settlements between 3.0m and 3.5m.

A summary of OCR data collected over the times, together with the results of an example of CPT sounding, is shown in Figure 3.

Based on cone penetration testing done at the site, it is possible to conclude that the lean to the south of the Tower of Pisa is likely due to the differences in the soil in Horizon A on the north and south sides (Salgado 2022b). On the north side, near the ground surface, the soil is mostly sand, whereas on the south side, the soil ranges from silty sand to clayey silt. This reflects on the values of cone resistance measured on the south and north sides of the Tower (Jamiolkowski 2006), as seen in Figure 4. The CPTs on the south side of the Tower (DH4 and DH5) actually suggest the complete disappearance of the sand layer on the south side, while it is clearly visible in the other CPTs, which is consistent with an initial lean to the south, which then intensified because of increased consolidation and settlement caused by the driving moment associated with the weight of the tower.

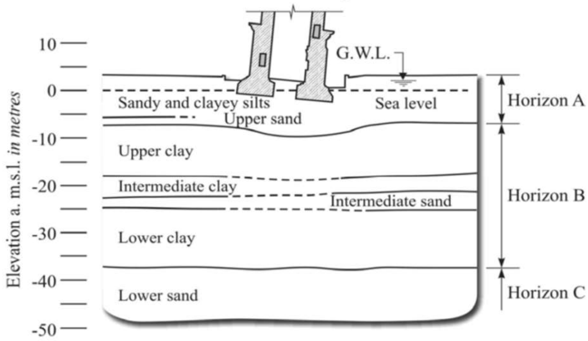


Figure 2. Sketch of soil stratigraphy at the site of Pisa Tower.

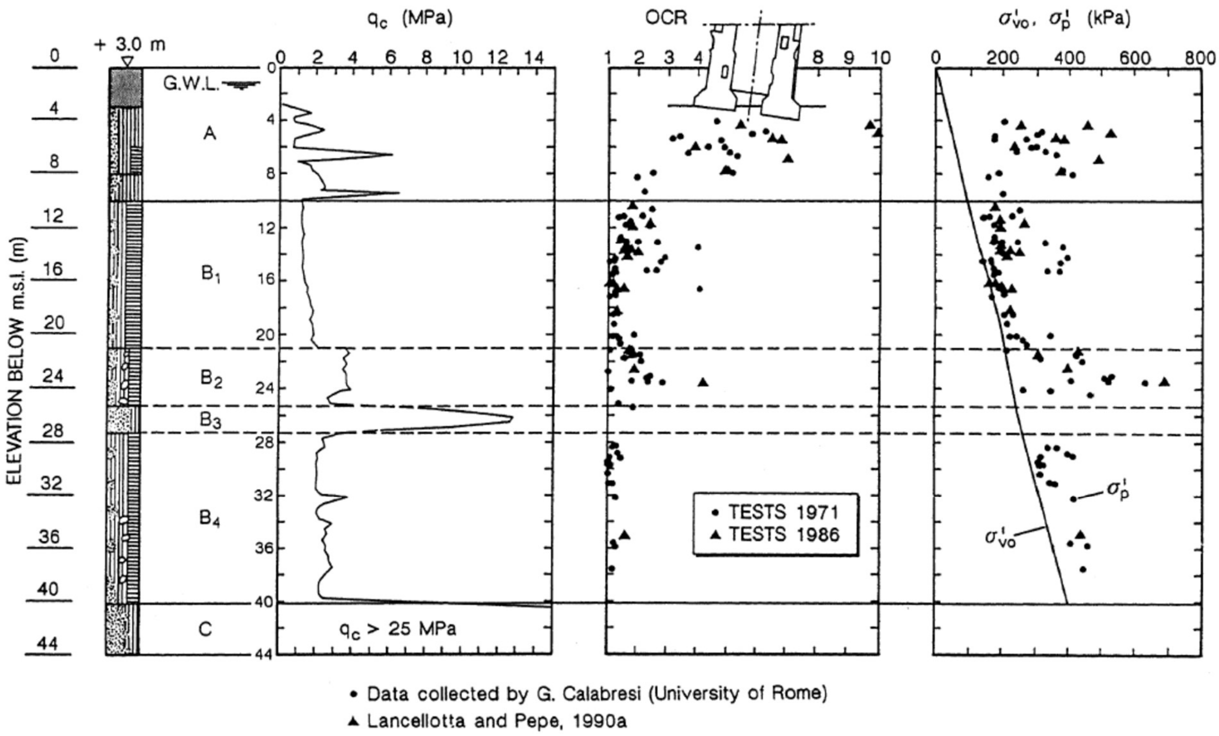


Figure 3. Experimental evidence of OCR at the site of Pisa Tower (Jamiolkowski et al. 1993).

After a period in which the construction stopped because of extraneous factors, the construction was completed with a deviation from a straight axis to partially compensate for that rotation. Over the centuries, the Tower continued to lean, leading to increasing concerns about its stability. This, in turn, led to the appointment of several committees to study the causes of the lean, to assess the tower stability, and to propose interventions for securing it. Eventually, an international committee was appointed in the 1990s, which was led by Jamiolkowski.

Historical studies proved to be most valuable in arriving at suitable stabilization measures. The first was a study of the history of inclination of the Tower during and subsequently to completion of construction. The second study was of measurements of movement made since 1911, that revealed an unexpected potential mode of collapse: leaning instability. This constrasted with previously held ideas that centered around bearing capacity failure. Leaning instability could develop not due to insufficient shear strength and bearing capacity, but due to insufficient ground stiffness (Lancellotta 1993; Burland and Viggiani 1994; Burland et al. 2021). The mechanics of leaning instability is further discussed in Potts (2003).

The realization that leaning instability was the likely mechanism of collapse, if it were to occur, drove the committee to use the method of underexcavation - originally proposed by Terracina (1962) and successfully implemented to reduce the damaging differential settlements within the Metropolitan Cathedral of Mexico City (Ovando-Shelley and Santoyo 2001) - to stabilize the Tower of Pisa.

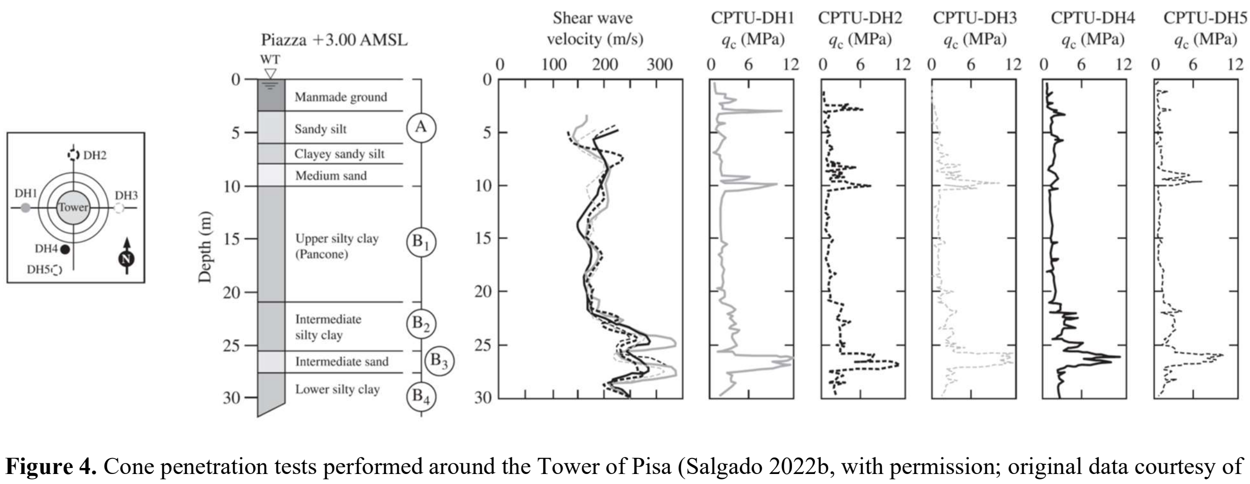


Figure 4. Cone penetration tests performed around the Tower of Pisa (Salgado 2022b, with permission; original data courtesy of Michele Jamiokowski).

Because the application of this method to a tower that was possibly on the point of falling over was rather challenging, the method was studied first by means of physical models, then by numerical modelling, and finally by means of a large-scale trial, in which preliminary and limited ground extraction from Horizon A (figure 2) beneath the Tower itself was performed to observe its response. After the very positive results of the preliminary underexcavation, the Committee agreed to proceed with the full underexcavation (Burland et al., 2003).

2.2. **Mose Barrier**

Venice is one of the most well-known landmarks of Italy. The town was built on a group of islands within a lagoon to provide safety against invasions. However, its peculiar location makes it very vulnerable to high tides, and large stretches of the historical city centre are periodically subjected to full inundation, causing significant disruptions to daily life and damage to structures and services. In order to protect the city against these events, which are likely to become even more frequent because of climate change effects and the worldwide rise of sea water level, a set of moving barriers has been constructed for temporary isolation of the lagoon water from the open sea (Figure 5).

Design of the barrier system (Figure 6) posed major issues with respect to the stability and serviceability of the foundations, considering that the tolerance of the complex moving system to settlements is very limited. Characterization of the marine sediments and predictions of the expected consolidation settlements required therefore a significant effort during the design stage.

One of the major challenges in the characterization was associated with the very complex stratigraphy of the sedimentary estuarine deposits with the presence of predominant silt fractions interbedded by clayey and sandy layers (Jamiolkowski et al., 2009).

For the prediction of consolidation settlements, a large testing embankment was therefore built inland on sediments very similar to those existing below the expected foundations. A very large experimental campaign with a large number of *in situ* tests was implemented for the characterization of the site and thereafter to monitor the evolution of pore water pressure and settlements.


Figure 5. Mose Barrier in Venice (Italy).

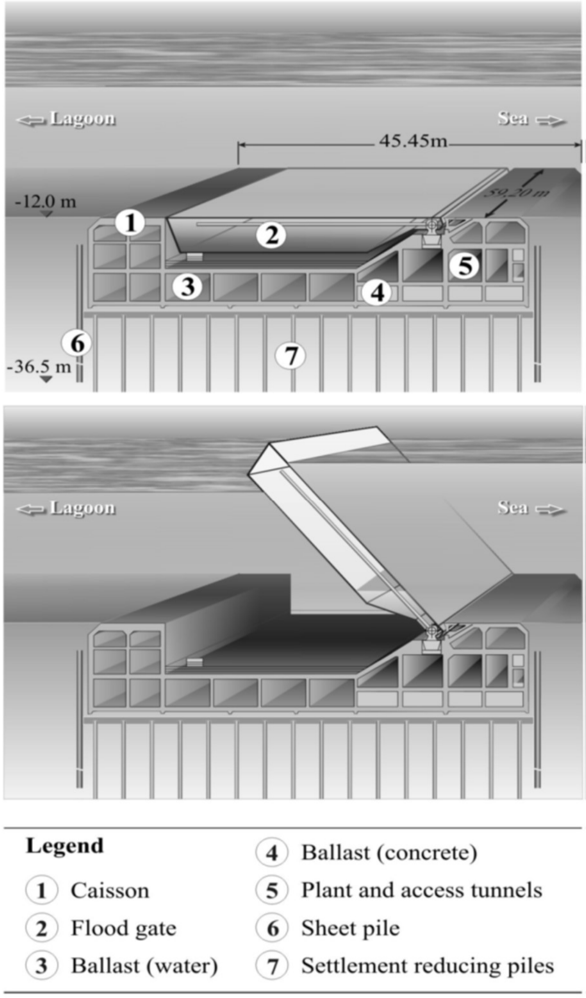


Figure 6. Schematic representation of one of the barriers of Mose (Jamiolkowski et al., 2009).

Combination of in situ and laboratory test results and back-analysis of the instrumented trial embankment allowed for the calibration of advanced soil models for the prediction of settlements of the four barriers, accounting for the temporal construction sequence and evolution in time after end of construction (Jamiolkowski et al., 2009).

2.3. **Zelasny Most Tailings Dam**

Zelasny Most copper tailings disposal facility (Figure 7) is the largest in Europe and one of the largest in the World. Enlargement of the dam to accommodate greater quantities of tailings from the copper mine raised important questions about its stability, also in the view of the possible dramatic consequences of its failure. Indeed, tailings dams are notoriously prone to failure, with failure rates being so high that, in many jurisdictions, defendants are subjected to more stringent legal standards when there is a failure (Salgado 2022a). For this reason, an international committee of experts was set up, including Michele Jamiolkowski, to study the stability of the dam and to supervise construction with the observational method.

The foundation soils consist of Pleistocene deposits deeply affected up to large depths by glacio-tectonic phenomena. In this complex geological setting, deep seated movements with several sub-planar shear surfaces cause significant horizontal movements to be considered for the stability. Continuous and enhanced monitoring is therefore a fundamental requirement (Jamiolkowski, 2014).

Because of their inherent nature, being freshly deposited materials, tailings usually present peculiar mechanical behaviour and specific characteristics that makes their characterization challenging. Often these materials are indeed deposited in a slurry state and their composition makes the sedimentation and consolidation processes critical.

The main questions that were addressed by the site characterization program and related *in situ* tests were (Jamiolkowski, 2014):

- spatial variability of the tailings;
- depth of the saturation surface;
- *in situ* state of tailings (to assess their susceptibility to static liquefaction).

Gel-push sampling was widely used in this project to provide undisturbed sample to be tested in the lab in order to assess the susceptibility of the tailings against liquefaction (Jamiolkowski and Masella, 2015).

The collected data allayed concerns regarding the likelihood of flow liquefaction considering the position of the phreatic surface and the observed contractive-dilative or dilative behaviour of the tailings in laboratory tests.

Figure 7. Zelasny Most tailing dam (Poland).

2.4. Messina Straight Bridge

Connection of Sicily to mainland Italy (Figure 8) is a longstanding goal and would be a challenging project if constructed. Indeed, technical difficulties posed by the distance to be covered with a single span bridge are made harder by a complex geological and hydraulic setting in a high-seismicity zone with emerging faults.

The subsoil conditions on both sides of the Messina Strait consist of gravelly deposits of Holocene and Pleistocene age underlain by soft rocks of Pliocene and Miocene age (Crova et al., 1993; Jamiolkowski and Lo Presti, 2003). On the Sicilian shore, sand and gravel deposits extend to a depth beyond 180 m below the existing ground level. In particular, at the location of the anchor block required by the bridge design, the soil consists of sand and gravel of medium Pleistocene age from the ground surface down to the depth of 180 m. This deposit is locally called Messina Gravel Formation (MGF).

At the location of the bridge tower, the upper part of the soil profile consists of sand and gravel of Holocene age, having a thickness ranging from 35 to 67 m. This deposit is called the Coastal Plain Deposit (CPD).

The possibility of investigating both formations (the MGF and CPD), deposited in similar environments and exhibiting similar grading and mineralogical composition, but of substantially different age, offered a unique opportunity to check the influence of the age of the deposit on penetration resistance and shear wave velocity.

Considering the limitations imposed by the gravelly nature of the soil, the SPT was considered to be the only practical test in preliminary investigations. However, a larger spoon sampler (ID=110 mm; OD = 140 mm) was used as a penetration tool (Crova et al. 1993).

The results obtained from the testing proved that the penetration resistance in the CPD was on average 10 to 20% lower than that obtained in the MGF. A complete picture of the impact of aging on the behavior of the material emerged from the shear wave measurements, from which the shear modulus of the MGF was as much as 5 times greater than that obtained in the CPD.

To complement these results with geologic data, a number of outcrops of MGF were carefully investigated. These showed (1) weak to strong bonding due to cement agents like calcium carbonate and iron oxides; and (2) no sign of liquefaction events in the past.

The conclusion based on the geotechnical investigation was that the complex structure that developed in the natural soil could not easily be replicated in the laboratory, nor could its effects be completely investigated using penetration resistance. Geophysical testing was essential.

Undisturbed samples were also obtained at a later stage with the ground freezing technique used for large diameter triaxial tests both in cyclic and monotonic conditions. The tests yielded valuable information regarding the susceptibility of the sandy gravel to cyclic mobility and plastic strain accumulation during earthquake loading (Fioravante et al., 2012).

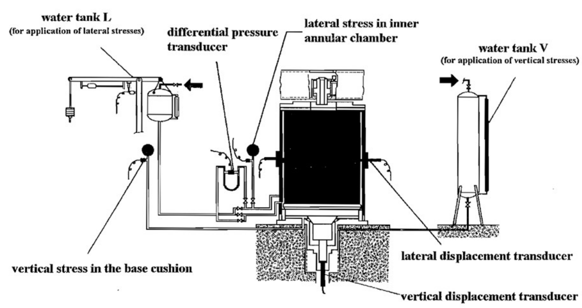
Figure 8. Rendering of the proposed Messina Bridge, Italy (www.webuildgroup.com).

3. Geotechnical *In situ* Tests

Michele Jamiolkowski was an early and enthusiastic advocate of *in situ* testing for geotechnical site characterization (Jamiolkowski et al. 1985). *In situ* tests provide data that enable engineers to infer the state and mechanical response of soils without recovery of soil samples. The value of *in situ* testing is even greater in characterization of hard-to-sample materials, such as coarse-grained soils, or in complex stratigraphic conditions. However, a limitation in developing relationships for the interpretation of geotechnical *in situ* tests is given by the lack of control of boundary conditions during field experiments and the limited knowledge of "ground truth" on the actual state of soils.

The challenge in *in situ* test interpretation of developing the relationships that link measurements made with a particular type of test to the variables that we wish to determine or estimate has been the focus of considerable research. In sands, these unkown are typically soil state variables, such as relative density D_R and the coefficient K_0 of lateral effective stress at rest. Jamiolkowski led a large, long-lasting experimental research program whose main aim was to develop methods to interpret various *in situ* tests, chiefly the cone penetration test, in sand. This research program involved performing tests under controlled conditions in calibration chambers. In a calibration chamber (Figure 9(a)), it is possible to prepare a large sample of sand at a known relative density and subject it to a known stress state. Boundary conditions are strictly controlled during sample consolidation and testing by an intricate system (Figure 9(b)) that allows setting either fixed or traction boundary conditions (Salgado et al. 2007) on any of the sample surfaces.

(a)



(b)

Figure 9. Calibration chamber system (Baldi et al. 1986).

By performing a large number of tests covering a wide range of soil states, a relationship can be based on correlating these variables, or the data can be used to validate theoretically derived relationships (e.g. Jamiolkowski et al., 2003).

3.1. The Cone Penetration Test (CPT)

The calibration chamber research program had considerable impact on the development of methods of cone penetration test (CPT) interpretation. The resulting data has been used to: (1) provide direct correlations between cone resistance and sand relative density and effective stress state; and (2) validate theoretical penetration resistance analyses.

Initial focus of the calibration chamber work was to find the coefficients in correlations of the type (Jamiolkowski et al. 2012):

$$q_c = C_1 \exp(C_2 D_R)\sigma_v'^{\,n} \tag{1}$$

where C_1, C_2 and n were typically fit to the calibration chamber data, which include cone resistance q_c, vertical effective stress σ'_v and relative density D_R.

This presumed dependence of cone resistance on vertical effective stress was the state of the art in the eighties and nineties. It was carried over from correlations that had been developed for the standard penetration test (SPT) by, for example, Liao and Whitman (1986). Data from the Italian calibration chamber tests (Salgado et al. 1997) and from other sources (Houlsby and Hitchman 1988) suggested otherwise. It became apparent that it was not the vertical effective stress σ'_v, but the lateral effective stress σ'_h that controlled cone resistance.

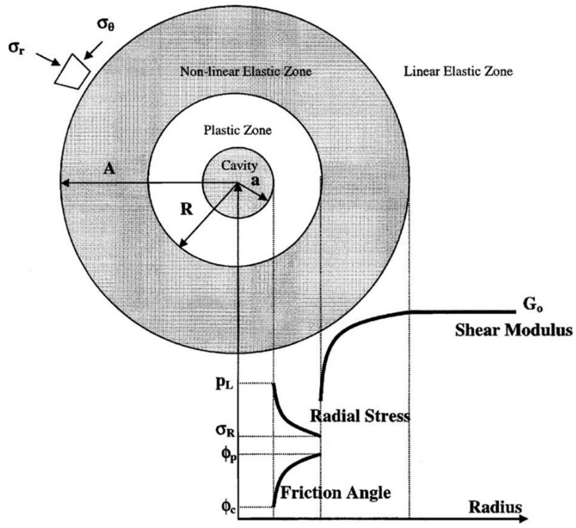
This led to the use of cylindrical cavity expansion to relate cone resistance to relative density and lateral effective stress (e.g., Salgado et al. 1997; Salgado and Prezzi 2007; Salgado and Randolph 2001). Use of cavity expansion theory to calculate cone resistance involves first calculating a cavity limit pressure, and, from it, the cone resistance. It is based on the requirement that the cone must expand a cylindrical cavity in the soil to advance. Based on cavity expansion analysis (Figure 10), validated by comparison of its predicted cone resistance values with values measured in the calibration chamber, it was now possible to use it to develop correlations that better reflected the relationship between q_c and soil state (Salgado and Prezzi 2007):

$$\frac{q_c}{p_A} = 1.64\, exp[0.1041\phi_c + (0.0264 - 0.0002\phi_c)D_R]\left(\frac{\sigma'_h}{p_A}\right)^{0.841-0.0047D_R} \tag{2}$$

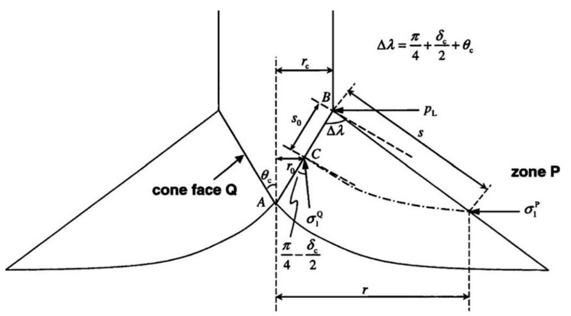
where ϕ_c is the critical-state friction angle of the sand, D_R is the relative density, σ'_h is the horizontal effective stress and p_A is the atmospheric pressure.

This equation is only a single equation to determine, for an overconsolidated sand, two variables: the relative density and the lateral effective stress. The required additional equation could come from geophysical tests, discussed in a later section. It is also possible that stress history is known from geologic studies. If the soil's overconsolidation ratio is known, then the coefficient of lateral earth pressure at rest will be in the 0.4-0.5 range, and the lateral effective stress can be computed independently.

Another possible approach to CPT interpretation is direct interpretation. Direct interpretation aims not to determine the state in which the soil exists, but an intermediate or final quantity of interest. This can be the bearing capacity of a footing or pile, or it can be stiffness or shear strength of a soil. For example, Baldi et al. (1990) established correlations between drained secant Young's modulus E'_s measured in the triaxial test at 0.1% axial strain and cone resistance q_c measured in a calibration chamber (Figure 11). The correlation takes into account the impact that sand aging and overconsolidation has on the relationship between the two variables. Baldi et al. (1990), however, discuss the various other variables that could affect the relationship, including inherent and stress-induced soil fabric.



(a)



(b)

Figure 10. Cavity expansion analysis for cone resistance calculation involves calculating the pressure associated with creation of a cavity in the ground, which involves (a) overcoming soil stiffness and shear strength around the expanding cavity and (b) calculating cone resistance from cavity limit pressure (Salgado and Prezzi 2007).

The existence of high-quality calibration chamber data for the CPT inspired—together with other developments, such as increasing computer power and general progress in computational geomechanics—research aiming to model cone penetration resistance theoretically.

Arroyo et al. (2011) used the discrete element method (DEM) to perform a 3D simulation of cone penetration in a calibration chamber. The simulation produced results that compared very favorably with the results of the test. Salgado (2022b) reviews other attempts to simulate cone resistance, with the Material Point Method (MPM) showing great promise. The calibration chamber tests performed as part of the Italian program remain an important reference for validation of all such attempts at simulating the cone penetration process.

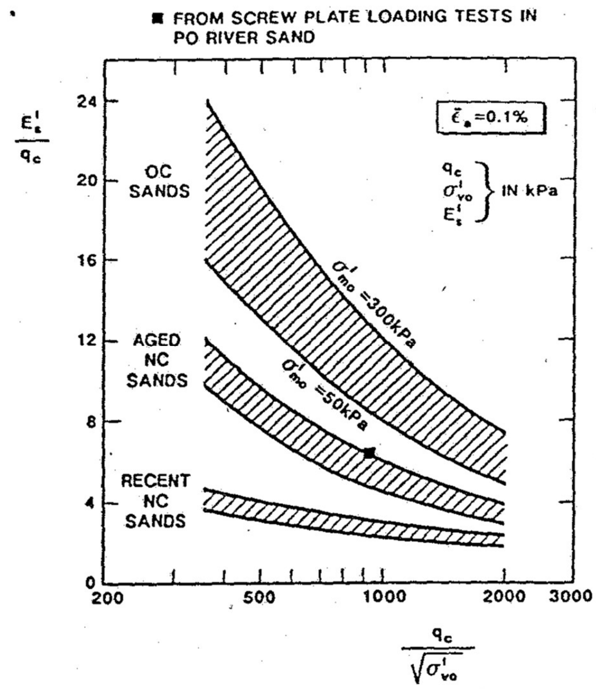


Figure 11. Drained secant Young's modulus of silica sand versus cone resistance measured in calibration chambers (Baldi et al. 1990).

Another great interest of Michele Jamiolkowski in connection with the CPT has been the estimation of pile capacity from q_c., another example of direct interpretation. Jamiolkowski and co-workers clearly differentiated between the response of nondisplacement and displacement piles. For example, Colombi et al. (2006) performed centrifuge tests to study the differences in shaft and base resistance of displacement and nondisplacement piles, finding a much stiffer response, particularly in base resistance, in displacement piles.

Interest was strongest in determining the correlation between pile unit base resistance q_b and cone resistance q_c. Ghionna et al. (1994) performed plate load tests in the calibration chamber. The plates were pre-installed, and so modeled the installation of nondisplacement piles. The tests were used to validate numerical analyses (Lee and Salgado 2000) that were later used to compute pile unit base resistance and relate it to cone resistance (Salgado et al. 1998). These initial results established a solid reference for future work in this area (see, e.g., Lee and Salgado 1999) also involving numerical analyses. The fact that the numerical analyses, validated by the extensive Italian calibration chamber test program, were so successful in predicting correct values of cone resistance and pile base resistance was powerful confirmation of the quality and usefulness of the experimental research in calibration chambers.

3.2. The flat DilatoMeter Test (DMT)

The introduction and development of the Flat Dilometer (DMT) for soils is due to the innovative research by the late Prof. Silvano Marchetti, an early collaborator of Michele Jamiolkowski, who strongly promoted the use of this tool. Since its introduction (Marchetti, 1980), the empirical correlations based on DMT readings have proven to be effective in the evaluation of constrained modulus for the prediction of settlements and for an assessment of stress history of soils. Further studies and the inclusion of a seismic tool for the execution of down hole tests in parallel to the penetration of the blade widened over the time the scope and the application of the test.

An example of SDMT test at the site of the Treporti trial embankment (Mose project) is reported in Figure 12.

Tests in calibration chamber were carried out on Toyoura sand to check the effectiveness and significance of moduli estimated with DMT in sand (e.g., Baldi et al., 1986; Bellotti et al., 1997; Fretti et al. 1992).

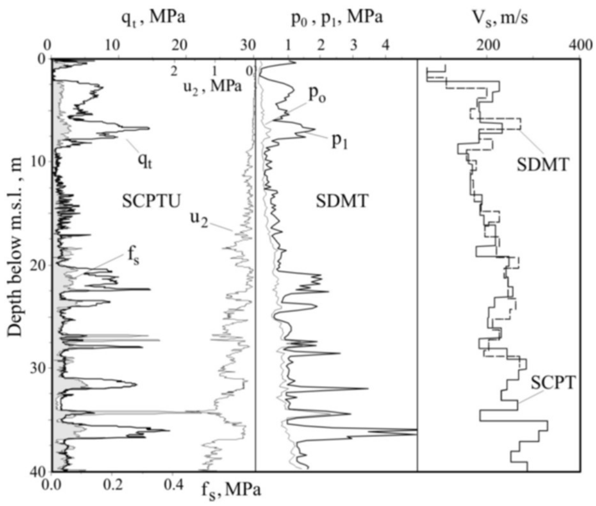


Figure 12. Results from SCTP and SDMT at Treporti Testing Site for the design of Mose Barrier system in Venice (Jamiolkowski et al, 2009).

3.3. The PressureMeter Test (PMT)

Research on self-boring pressuremeter on Italian clays and silty sands in the 1980s was an attempt to clarify scope and limit of applicability. Attempts to use the self-boring pressuremeter (Camkometer) to estimate the permeability with strain-holding and stress-holding tests were also reported by Fioravante et al. (1994).

Test in the calibration chamber were also performed to assess the reliability of the pressuremeter test in sands (Bellotti et al., 1989). The authors performed 47 self-boring pressuremeter tests in the ENEL-CRIS calibration chamber (Bellotti et al., 1987) and 25 tests in a natural sand deposit at the PO River site in Italy (Bruzzi et al., 1986). A significant conclusion was that results depended strongly on disturbance during device installation, and that moduli backcalculated from loading could not reliably be correlated with measurements of moduli made in the laboratory. Whereas moduli measured during unloading proved more reliable, that was only true if unloading occurred after the pressure was increased sufficiently for a significant plastic zone to form around the pressuremeter, undoing the influence of disturbance that occurs during installation.

4. Geophysical tests

Geophysical tests enable the characterization of soils in their natural state. A wide variety of methods are available to help in the reconstruction of soil stratigraphy and underground geometry (electric resistivity tomography, ground penetrating radar, electromagnetic surveys, microgravity surveys, time domain reflectometry, etc.); however, the most widely used methods are seismic methods, because they also provide quantitative information on the mechanical response of soil (mainly in terms of the very-small-strain shear modulus, which is associated with the shear wave velocity of propagation). Seismic tests are a must for site characterization in geotechnical earthquake engineering, but their role in any geotechnical engineering project has been steadily increasing over the years.

The velocity of propagation of shear waves (V_S) being directly associated to solid skeleton allows for a direct estimation of the very-small-strain stiffness of soils in their natural state in situ. Moreover, it can be used for a quantitative assessment of sample disturbance if the field value is compared to laboratory measurements.

The velocity of propagation of compressive waves (V_P) is often considered less informative, because the interaction with the fluid phase in saturated soils prevent a direct use in term of mechanical response of the soils. However, its sensitivity to saturation conditions can be informative in some applications. Additionally, the interpretation of seismic wave velocities in the framework of Biot's theory for porous media (Biot 1956) can provide an estimate of soil porosity for saturated soils (Foti et al. 2002, Foti and Lancellotta 2004).
The relevance and the role of geophysical testing in geotechnical site characterization has been the topic of the De Mello Lecture in 2011 (Jamiolkowski, 2012). Some examples are reported in the following sections with specific reference to the iconic projects discussed in section 2.

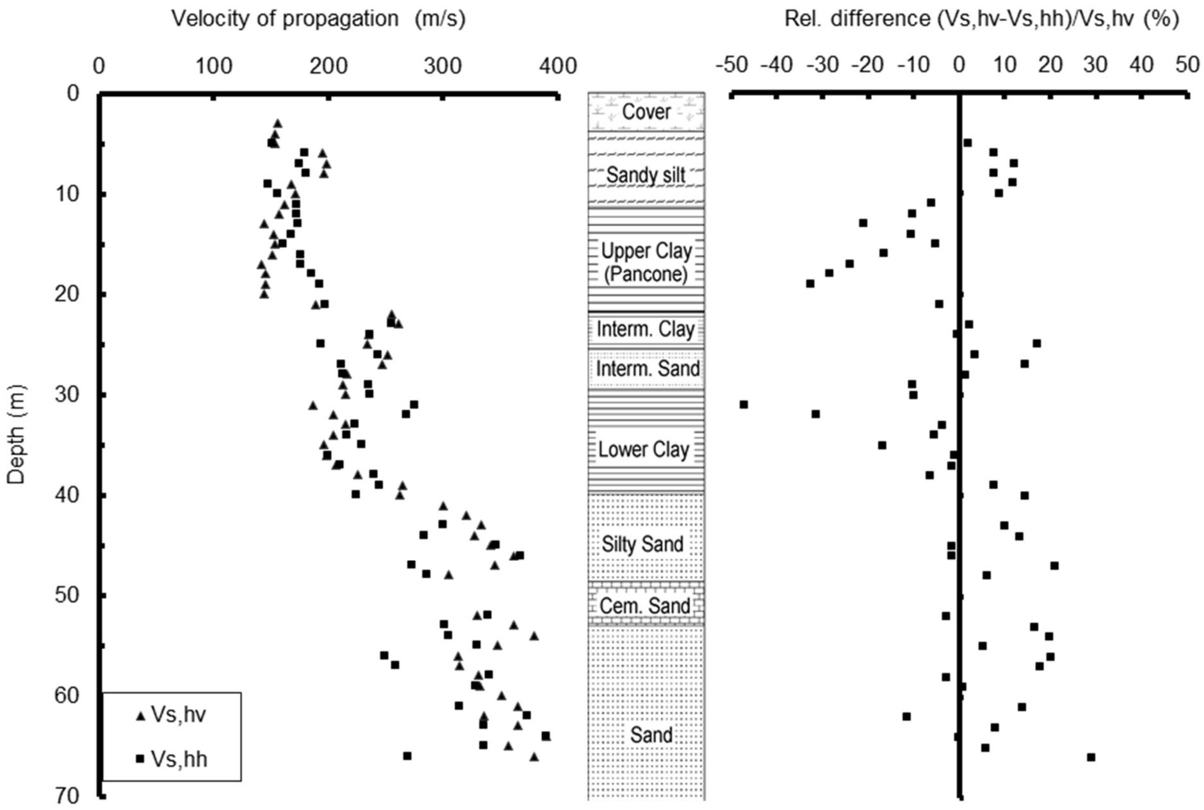


Figure 13. Evidence of anisotropy from seismic velocities at the Pisa Tower site (original data courtesy of M. Jamiolkowski).

4.1. **Stiffness at very small strain**

The very-small-strain stiffness of soils and rock at their in situ state is typically assessed though direct or indirect measurements of the velocity of propagation of shear waves with geophysical methods.

Cross-hole Testing (CHT) can provide the highest level of resolution; it is the geophysical test in which there is the highest control of the experiment. Its straightforward method of interpretation is not affected by the difficulties associated with inverse problems, which are present in methods of interpretation for most geophysical tests. However, the large cost—due to the necessity of drilling and setting-up two or three adjacent holes—limits the use of CHT to large and important projects.

The use of polarized sources also allows for an evaluation of soil anisotropy, considering that both horizontally polarized and vertical polarized waves can be generated in the hole. Travelling along horizontal paths, they provide an assessment of structural stress-induced anisotropy in soils. An example from the Pisa site is reported in Figure 13. It is interesting to notice that, in sandy layers, the stress anisotropy prevails, leading to larger stiffness in the G_{HV} component, whereas in clayey layers, intrinsic anisotropy leads to greater values of the G_{HH} component. A study of the anisotropy of carbonate sands in a calibration chamber using bender element tests is reported by Fioravante et al. (2013), showing the relevant role of stress history, which is typically negligible for silica sands.

Repeatability and accuracy of shear wave velocity measurement is an important question, whether in a practice or research context, and the possibility of having different tools applied to the same site allows for comparisons that provide relevant information in this respect (e.g. Garofalo et al. 2016b). For example, with reference to the assessment of liquefaction susceptibility, the normalized shear wave velocity is considered a relevant parameter. A comparison for Zelasny Most dam is reported in Figure 14, in which the results of Cross-Hole tests repeated at two different times (2011 and 2014) are compared to the results from down-hole tests performed with the Seismic Cone (S-CPTU) and the Seismic Dilatometer (S-DMT). Consistency and stability of the results are a prerequisite for reliable prediction that is often overlooked, but is crucial for higher-profile, higher-consequence projects. The figure shows that a high degree of confidence with respect to these measurements is possible because of the close agreement between them.

In-hole methods are well incorporated in the state of practice, especially because they allow for a very high resolution with depth. However, they provide local values that, for some applications, may be not fully representative of the whole soil deposit.

The Surface wave analysis method was introduced in geotechnical engineering in mid-1980s (Nazarian and Stokoe, 1984) to attempt to fill that gap. It is now widely adopted, especially in geotechnical earthquake engineering applications (Foti et al., 2018). However, one of the major concerns regarding the method is related to the reliability of the test. Several benchmark tests have been carried out at several sites (e.g. Garofalo et al. 2016a). One of the early applications in Italy was at the site of the proposed Messina Strait Bridge. The comparison against the more expensive Cross-Hole test reported in Figure 15 suggests that the method is generally reliable. However, the critical issue of resolution with depth is also emphasized by these results. Indeed, surface wave tests are based on the solution of an inverse problem that is based on measurements made at the ground surface. Specifically, the shear wave velocity profile is obtained from the solution of an inverse problem whose target function is the Rayleigh experimental dispersion curve, but the sensitivity of the dispersion curve to deep stratigraphic features is limited. Therefore, the blindness to thin, deep material layers, even in the presence of significant contrasts of shear wave velocities, is to be accepted as an intrinsic limitation of the method.

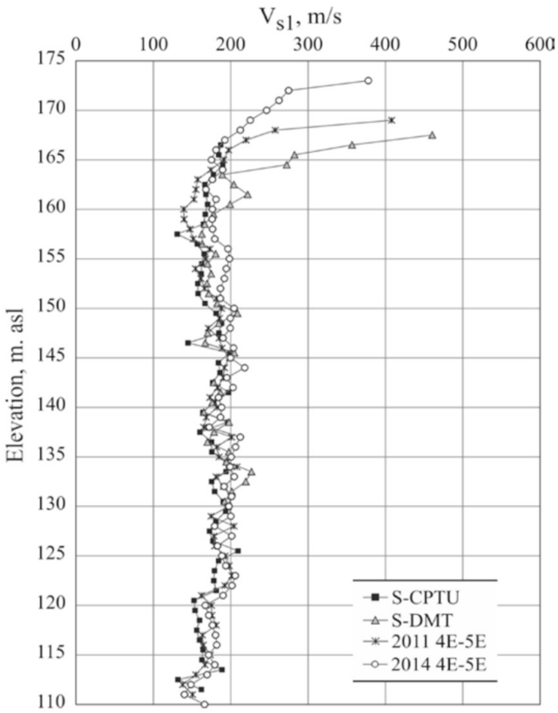


Figure 14. Consistency of normalized shear wave velocity from different methods at Zelasny Most tailing dam. 2011 and 2014 in the legend are the times of 2 repetition of CHT in the same holes (Jamiolkowski and Masella, 2015).

4.2. Sample disturbance

Shear wave velocity can be measured *in situ* for the material in its natural state. Sampling and specimen preparation, even when performed with great caution, inevitably alter the state of stress and the structure and fabric of soils, also when undisturbed sampling is claimed. The possibility of measuring shear wave velocity in the lab with bender elements or to obtain the very-small-strain stiffness in cyclic and dynamic tests allows the proposal of a powerful index of sample disturbance: the ratio between the field and the laboratory values of the shear wave velocity. The closest the ratio is to unity, the more the specimen can be considered of good quality and therefore representative of the behaviour of the soil element in its natural state. In the case of sand and gravelly soils sampled with ground freezing techniques, this aspect is particularly relevant, considering the great attention that has to be taken during the whole process *in situ* and in the lab to guarantee the quality of the samples. Examples from the Messina Straight Bridge project are reported in Figure 16, showing the remarkable correspondence.

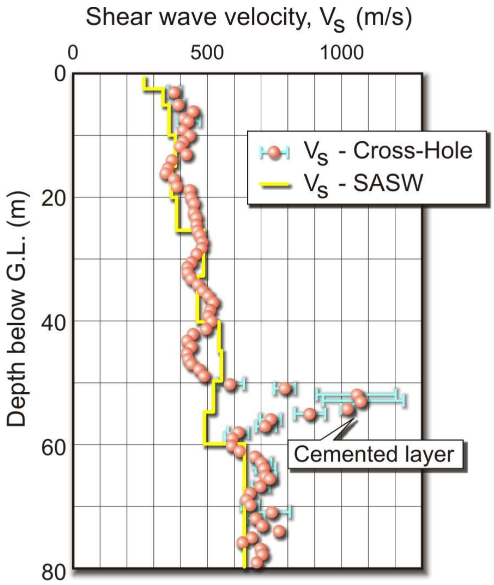


Figure 15. Comparison of shear wave velocities at the site of the foundation of the proposed Messina Straight Bridge in Sicily: CHT vs SASW (Jamiolkowski and Lo Presti, 2003).

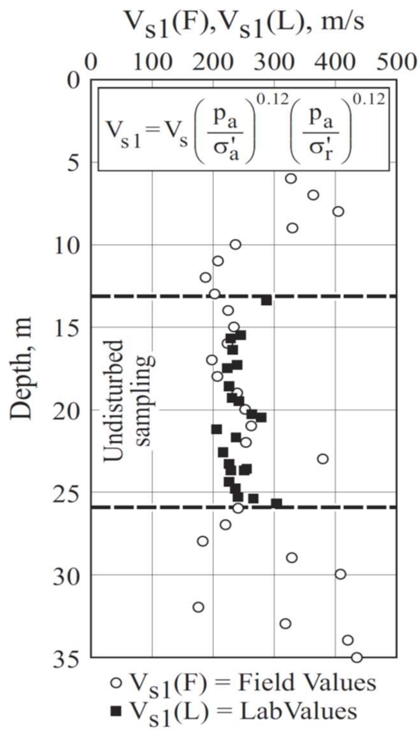


Figure 16. Values of shear wave velocity from CHTs performed in the field and from laboratory tests on undisturbed samples collected with the aid of ground freezing (Jamiolkowski and Lo Presti, 2003).

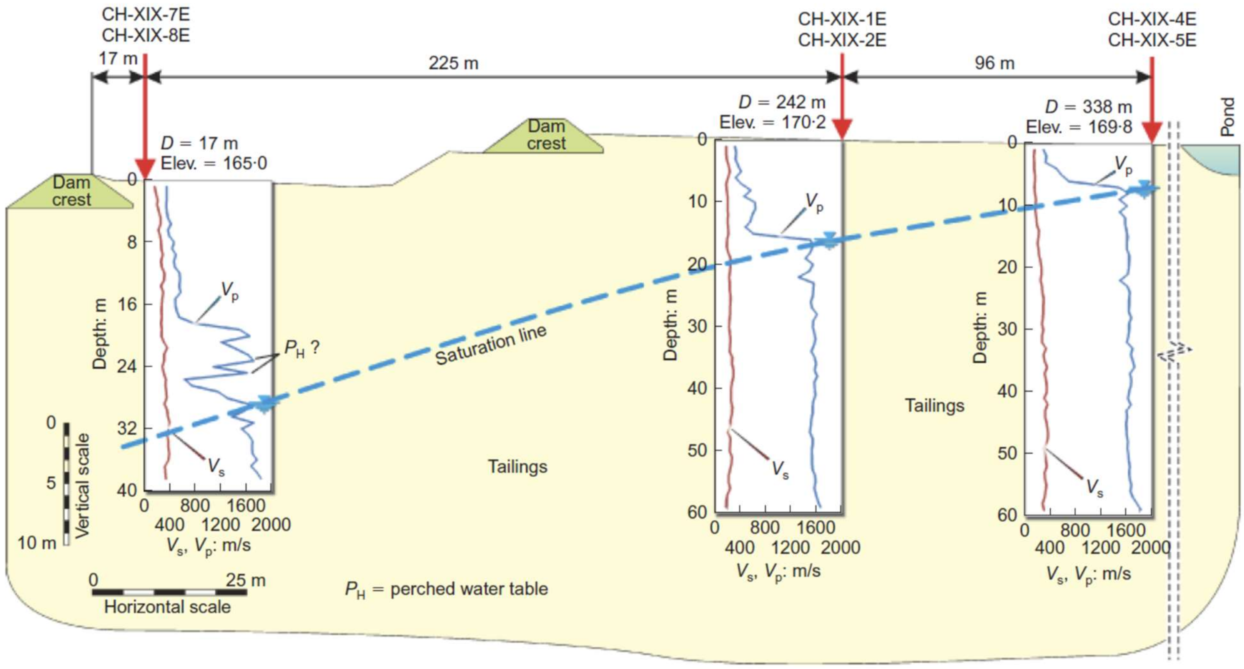


Figure 17. East Dam of the Zelasny Most tailings: location of the saturation line from V_P Measurements (Jamiolkowski, 2014).

4.3. Monitoring saturation conditions

Full saturation is basically a prerequisite for the possible occurrence of liquefaction. While cyclic liquefaction is a relevant problem, especially under the effects of earthquakes, static liquefaction can play a very significant role in tailings, considering that they are often deposited in a very loose state, and that the consequences of failure of such a structure can be catastrophic. Indeed, this was one of the major concerns for the enlargement of Zelasny Most tailing dam. Geophysical tests may provide in this respect powerful tools for assessing saturation condition also in the presence of a perched water table. Indeed, the velocity of propagation of compressive waves (P-waves) is strongly affected by pore water. Even small quantities of gas have a very significant effect on the compressibility of the pore fluid and therefore a marked effect on V_P, which can be easily detected with cross-hole tests. Figure 17 report the results of CHTs performed at different location along a section of the Zelasny Most dam that allow a clear recognition of the position of the water table and the presence of unsaturated zones that are of primary importance when assessing the risk of liquefaction in the tailings. Repeated measurements over time also allow a reliable monitoring of evolution in time.

Interestingly, cross hole tests performed on the sea bottom for the sites of the Mose barriers in the Venice lagoon also showed, even underwater, a significant and relevant presence of unsaturated layers (Figure 18). These unsaturated layers have a significant effect on the stability and expected settlements of the foundations.

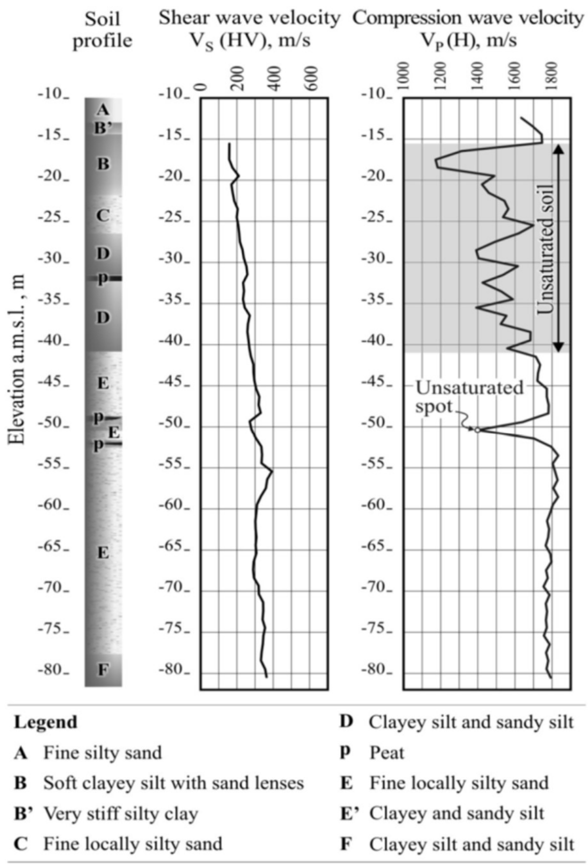


Figure 18. Mose project: results of CHT at Malamocco inlet (Jamiolkowski et al., 2009).

4.4. **Soil porosity**

Assessment of soil porosity (or void ratio) for soils in their natural state is a very difficult task in site characterization, especially for coarse grained materials, for which the possibility of getting undisturbed samples to the laboratory is very limited, typically requiring the adoption of very costly techniques (e.g., ground freezing or gel-push samplers). Additionally, these techniques are highly specialized, demanding very great care and expertise in execution both on site and in the lab.

In this context, the theory of wave propagation in saturated porous media (Biot, 1956) provides the framework for the direct assessment of soil porosity based on measured values of compressional and shear wave velocities (Foti et al., 2002). Examples of application at Pisa (Figure 19), Zelasny Most (Figure 20) and Messina (Figure 21) show the consistency of obtained values against laboratory values in different geological contexts and for different materials.

A key aspect of the evaluation of soil porosity from seismic velocities is related to the reliability of the *in situ* measurements, especially of the velocity of propagation of compressive waves (V_P). In this respect, repeated measurements at Zelasny Most were performed to check the standard deviation associated with results of CHTs (Figure 22). In order to provide a better insight into the quality of the measurements, uncertainties on the measurements of distances and travel times, which are the primary quantities to be measured, are also reported in Figure 23. A procedure for error propagation into porosity estimation was proposed by Foti and Passeri (2016).

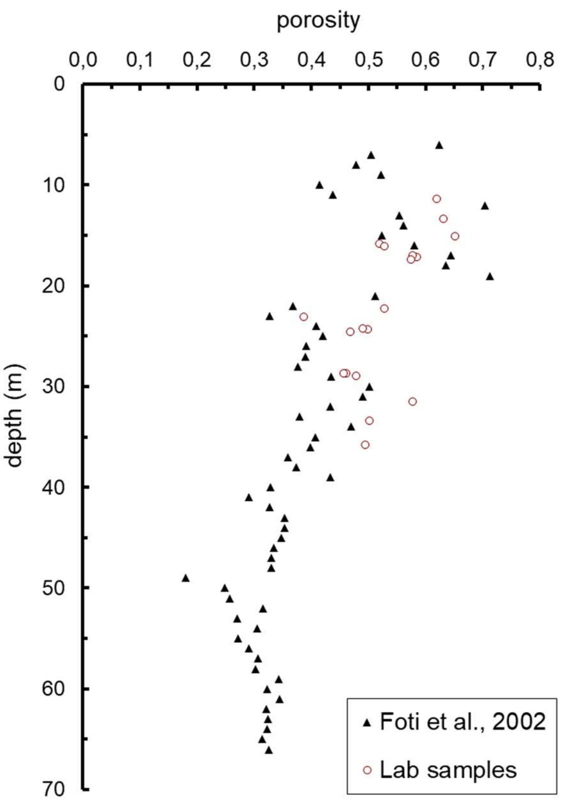


Figure 19. Soil porosity at the Pisa Tower site: predicted values from CHT results vs. laboratory evaluation based on high-quality undisturbed samples in clays.

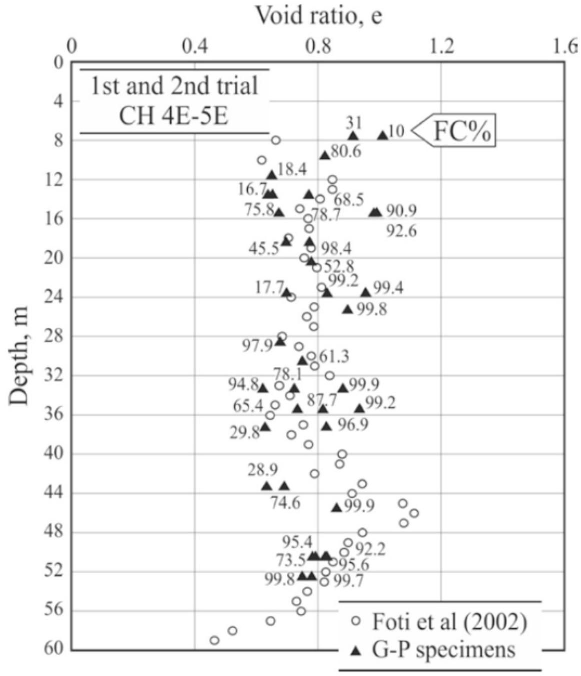


Figure 20. Soil void ratio at Zelasny Most site: predicted values from CHT results vs. laboratory evaluation on undisturbed samples collected with the gel-pushing technique in tailings (Jamiolkowski, 2012).

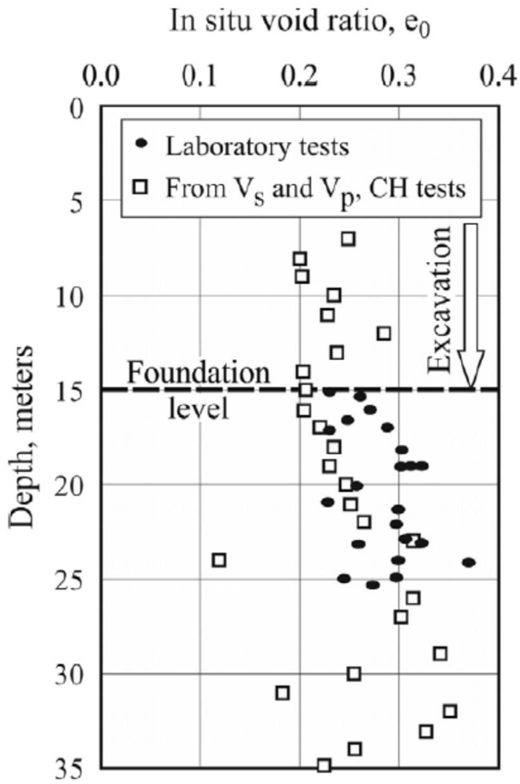


Figure 21. Soil void ratio at Messina Straight Bridge site: predicted values from CHT results vs. laboratory evaluation based on undisturbed samples collected with the ground freezing technique in gravelly sands (Jamiolkowski and Masella, 2015).

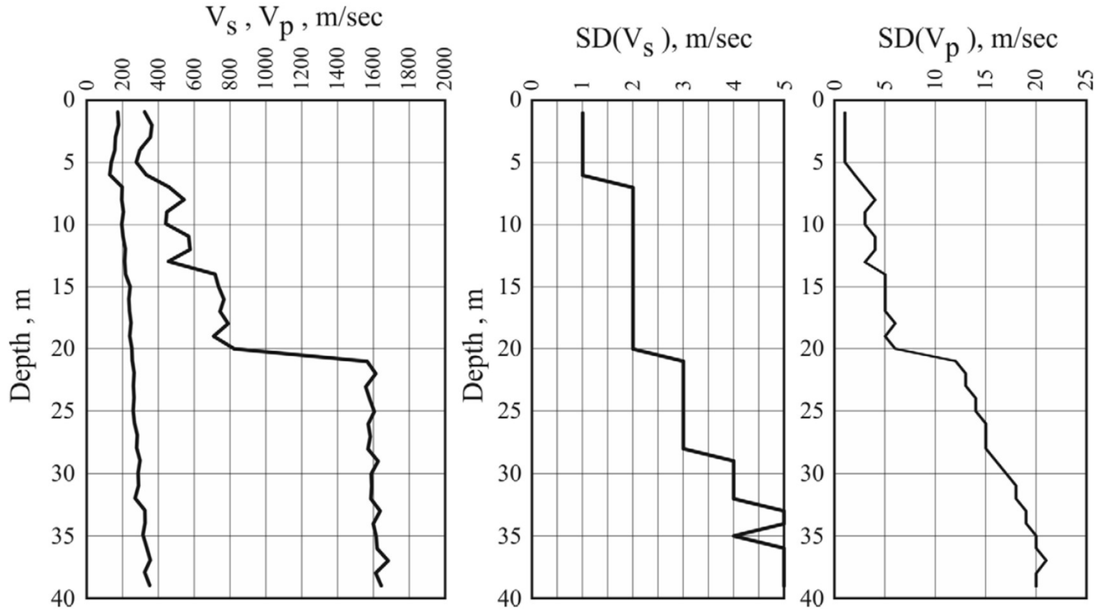


Figure 22. Zelasny Most site: V_S and V_P from CHT tests and their associated standard deviation for 10 repetitions of the test (Jamiolkowski, 2012).

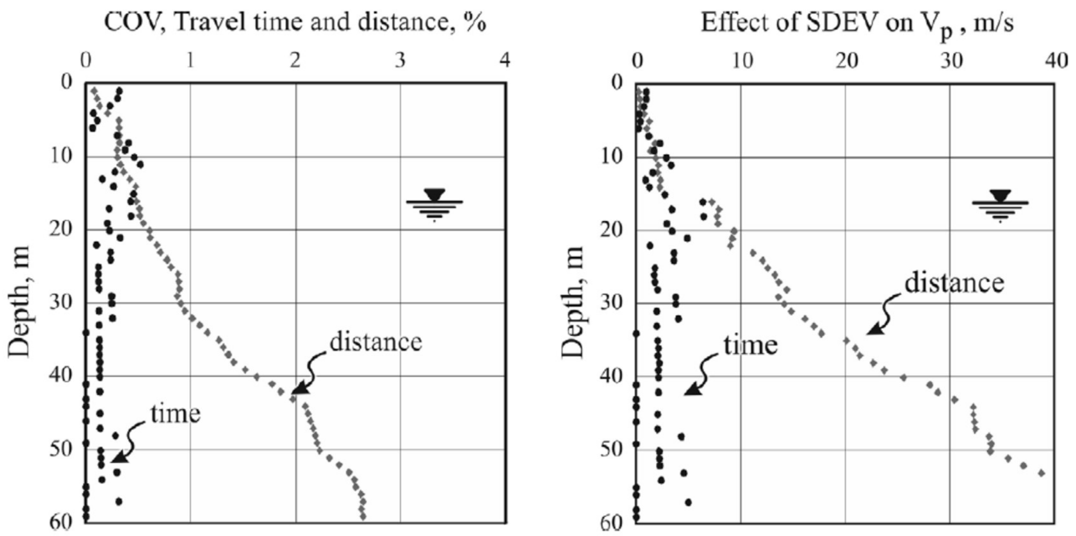


Figure 23. Zelasny Most site: Coefficient of Variation of travel time and distance in CHT tests and their implication of estimated V_P values (Jamiolkowski, 2012).

5. Final Remarks

Site characterization is a key element in the successful completion of geotechnical projects, particularly more challenging ones. Mike Jamiolkowski often and visibly reminded us of this simple but important lesson through his leadership roles in expert panels for many iconic projects that are milestones of modern geotechnical engineering. We have discussed only a few such projects in the present paper. Mike was a much sought-after consultant, and many others could have mentioned.

Mike consistently aimed for quality in *in situ* testing. Through his research with his many collaborators, he pushed the boundaries of the understanding that we have of processes involving *in situ* tests and contributed to the improvement of interpretation methods. Particularly noteworthy was the calibration chamber testing program that he led in Italy, which appreciably helped advance the state of the art in *in situ* testing. He also sought to enlarge the range of available *in situ* testing tools, and helped raise the profile of geophysical methods and raise awareness of their value and importance.

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