Journal of Coastal Research	18	2	372–378	West Palm Beach, Florida	Spring 2002

TECHNICAL COMMUNICATIONS

A Portable, Electrically-Driven Dutch Cone Penetrometer for Geotechnical Measurements in Soft Estuarine Sediments

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ABSTRACT

ARE, D.; KEMP, G.P.; GIUSTINA, F.D.; DAY, J.W., JR., and SCARTON, F., 2002. A portable, electrically-driven Dutch cone penetrometer for geotechnical measurements in soft estuarine sediments. *Journal of Coastal Research,* 18(2), 372–378. West Palm Beach (Florida), ISSN 0749-0208.

We describe here a portable, electric penetrometer (PEP) for use in soft estuarine sediments. The PEP measures *cone resistance,* q_C, and local unit side *friction resistance,* f_S. It is composed of three components: the cone, the power drive system, and the data acquisition system. This instrument has a larger, more sensitive cone that can measure values of q_C and f_S in the range of 0–1.5 Kg/cm^2. The cone is forced into the sediments by the power drive system and values of q_C and f_S are logged at 1–4 cm intervals by the data acquisition system. These data can then be used to calculate geotechnical parameters typical of soft clay soils including soil cohesion, c_u; compression resistance, q_u; Young's modulus, E; stress strain modulus, E_{ed}; over consolidation ratio, OCR; and friction ratio; 100* f_S/q_C. Several examples of applications are presented from Venice Lagoon and the Mississippi delta.

ADDITIONAL INDEX WORDS: *Mississippi Delta, Venice Lagoon, wetland soil characteristics.*

INTRODUCTION

We describe here a portable, electric penetrometer for use in soft sediments. During a Cone Penetration Test (CPT), a Dutch cone is forced into the soil by means of a power drive system. The stress necessary for cone penetration is called *cone resistance,* q_C, while the metal sleeve measures adhesion between the soil and the sleeve which is called the local unit side *friction resistance,* f_S.

The use of a cone forced into the soil to identify more resistant and compact layers than those at the surface was first used in 1917 by the Swedish State Railways (CESTARI, 1990). The cone penetration test was developed in the Netherlands in 1934 for stratigraphic purposes to overcome difficulties in the identification and sampling of thin layers of silt-clay sediments. In 1953, Begemann developed a new mechanical cone with a short sleeve (friction sleeve cone) to measure the friction between the soil and the sleeve (BEGEMANN, 1965). In 1948, an improved electric cone was developed, where q_C and f_S were separately and continuously measured by means of transducers in the cone. In the 1970's, the piezo-cone was developed, where a porous septum was added to the electric cone, which measured the pore pressure *u* as well as q_C and f_S (WISSA *et al.,* 1975; TORSTENSSON, 1975).

The use of a Dutch Cone in a CPT is now a standard measurement in the geotechnical analysis of soils (ASTM, 1986) for identifying most soil types and consequently, local stratigraphy. Values of q_C and f_S (BEGEMANN, 1965) provide information about grain size which makes it possible to identify the lithologies present at a specific site. Based on empirical observations, there is a relationship between q_C and Friction Ratio values (FR = 100 × f_S/q_C) which can identify not only the lithology but also the consistency of the levels (ROBERTSON and CAMPANELLA, 1983).

Lithology and stratigraphy are two important aspects of soils for different kinds of geological and ecological studies, but it is also often necessary to know other physical properties of soils. For this reason, geotechnical tests are often carried out in the laboratory on soil samples to measure a num-

01129 received and accepted in revision 3 January 2002.

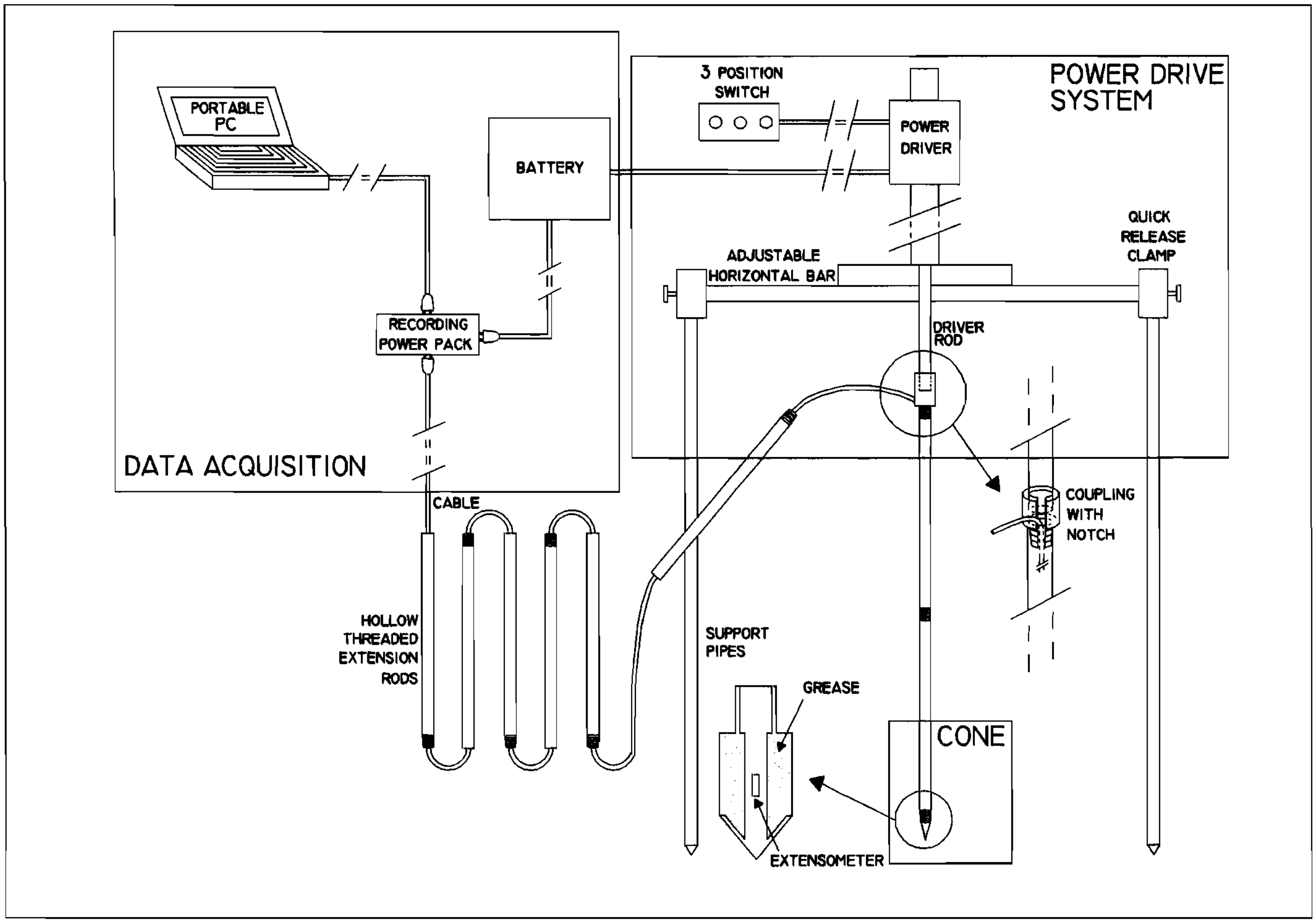

Figure 1. Diagram of the Portable Electric Penetrometer showing the three main components of the instrument: the power drive system, the cone and the data aquisition system.

ber of physical characteristics of the soil (water content, liquid and plastic limit, particle size analysis, coefficient of permeability determination, consolidation test, triaxial test, direct shear test, *etc.*, BOWLES, 1988). Geotechnical tests can also be made on site, from simple vane tests and pocket penetrometer strength determinations to more complicated types of investigations such as the field vane test, dilatometer test, static plate load test, and others. These tests often have technical and operational difficulties and they are often very expensive. Because of this, they are used only when a thorough knowledge of soil geotechnical parameters is necessary, for example, because of major construction.

The CPT is faster and less expensive than other types of tests and it permits the calculation of several important geotechnical parameters. For granular soils, there is a relationship between cone and friction resistance and different physical properties including relative density, shear strength, stress strain and Young's modulus (SCHMERTMANN, 1970; ROBERTSON and CAMPANELLA, 1983). Other relationships exist for clay soils where q_C and f_S give information about shear strength, compression parameters such as the stress strain modulus, Young's modulus and the compression index, the consolidation history of the soil, the coefficient of consolidation and the coefficient of permeability (SCHMERTMANN, 1975; ROBERTSON and CAMPANELLA, 1983).

For all of the tests described above, the great majority of work has been carried out in well-drained, upland areas where soils information is required for construction activities. However, the sensitivity of these measurements is not sufficient to determine geotechnical characteristics in soft wetland and estuarine sediments. The importance of soil geotechnical measures for wetland soils is generally unrelated to construction but related to wetland processes such as accretion, soil formation and development, consolidation, paleogeology, and wetland vegetation growth and survival. To obtain such information, it is necessary to measure lithology, stratigraphy, and geotechnical properties of a site. The CPT allows the determination of the depth and thickness of either the most soft and compressive level or the most resistant and compact one. These data and the geotechnical parameters, especially the compressive indices, can be used to calculate

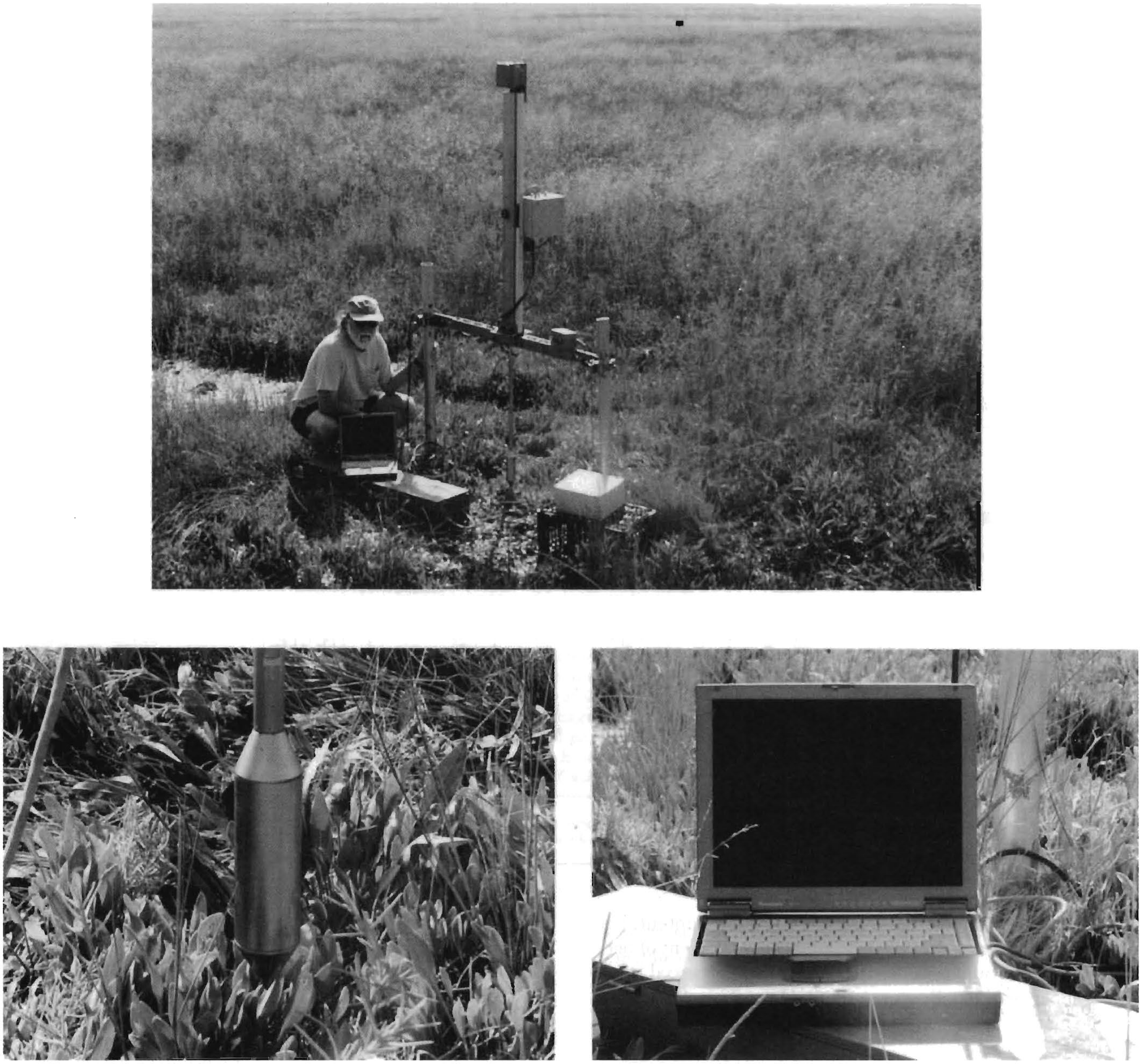

Figure 2. Photograph of the system being used in the field showing the general layout and details of the cone and computer read-out. Refer to the diagram in figure 1 for names of the different components.

the consolidation of the wetland with time in the case of wetlands created with dredged spoil, and optimal soil characteristics. The CPT can also give information about water and organic matter content in very soft sediments. Such information is critical, for example, to determining the ability of a wetland at a specific site to survive sea level rise.

We developed a portable, electric penetrometer because of difficulties in the measurement of cone (q_C) and friction (f_S) resistance in soft, coastal sediments using a standard penetrometer. Coastal sediments are generally very soft, so a standard penetrometer often does not log data until reaching depths greater than 5 to 6 m, where there are sediments which are more resistant and compact than the surficial layers. Thus, as part of geological investigations associated with several important wetland restoration and creation projects in Venice Lagoon, the portable electric penetrometer (PEP) was developed. This instrument has a larger, more sensitive cone that can measure lower values of q_C and f_S which can then be used to calculate geotechnical parameters typical of soft clay and organic soils.

Table 1. *Technical characteristics of the portable electric penetrometer.*

THRUST SYSTEM	
Length:	1450 mm
Rod's diameter:	20 mm
Rod's mechanical stroke:	550 mm
Velocity feed:	2 cm/sec ± 10%
Power engine:	20 Watt
Feeding motor voltage:	48 Vdc
Feeding motor current:	2.4 A max
Gear motor couple:	40 Nm
Gear mtor's number of revolutions:	10 Rpm
Pinion diameter:	40 mm
Total force:	200 Kg
Power supply:	No. 4 batteries 12 Vdc 7Ah
Fuse for motor batteries:	12A
Fuse for measuring plant:	2*12 A
Battery weight:	17 Kg
ELECTRIC CONE	
Cone angle:	60°
Cone area:	18.47 cm^2
Friction sleeve length:	124 mm
Friction sleeve area:	188.9 cm^2
q_C max:	3 kg/cm^2
f_S max:	3 kg/cm^2
q_C resolution:	0.01 kg/cm^2
f_S resolution:	0.01 kg/cm^2
Q_T resolution:	1 kg/cm^2
RODS	
Length:	50 cm
External diameter:	21.3 mm
Internal diameter:	13.84 mm

DESCRIPTION OF THE INSTRUMENT

The PEP99 (this is the designation of the penetrometer described in this paper) is composed of three components (Figure 1, 2). The total weight of the three components is about 60 Kg. Technical characteristic of the PEP are given in Table 1. A detailed description of each component follows. The senior author can provide a more detailed description of the construction and use of the instrument. Estimated cost of the PEP is $15–20 thousand USD.

Cone. The electrical cone developed for the PEP is larger than those used for dry soils. This was necessary so that the cone was sensitive enough to measure geotechnical parameters of soft soil formations such as soft clay, organic soils, and silty clay. To achieve the necessary sensitivity, the surface area of the tip of the cone was increased to 18.47 cm^2 compared to 10 cm^2 for the standard cone used in typical soil geotechnical applications. The higher surface area of the cone allows logging of values of cone (q_C) and friction (f_S) resistance in the range of 0–1.5 Kg/cm^2, considerably lower than can be measured by standard penetrometers (1.5–200 Kg/cm^2).

The prototype penetrometer, which was initially constructed to investigate the wetland soils of Venice Lagoon, derives from the "FUGRO" type piezo-cone (CESTARI, 1990). To increase the cone's sensitivity, the wall thickness of the cone was reduced to 1 mm, using salt-resistant, ISO 304 stainless steel. The rods, which force the cone into the ground, also are constructed of ISO 304 stainless steel. The load cells located inside the cone are constructed with a complete bridge called a "strain gauge", each of which is composed of eight extensometers with 350 ohms of electric resistance. To minimize friction during tests, the clamping ring in this prototype was eliminated and the cone is sealed with lithium grease. The load cells have a breaking load >1000 kg in terms of total stress. The amplification factors are designed for a maximum value of 3 Kg/cm^2 for cone (q_C) and friction (f_S) resistance, while on the portable computer monitor, the maximum value has been reduced to 1.5 Kg/cm^2 to achieve better accuracy in case of very low resistance values.

Table 2. *Example of the output of the Data Acquisition System from Punta Vecia in Venice Lagoon. Cone resistance (q_C) and friction (f_S) resistance are measured directly. The other geotechnical parameters (soil cohesion, c_U; compression resistance, q_U; Young's modulus, E; stress strain modulus, E_{ED}; over consolidation ratio, OCR) are calculated. OC is over consolidated, LC is lightly consolidated, NC is normally consolidated.*

Consorzio Venezia Nuova
Site: Venice Lagoon-Punta Vecia
Date: 01/04/99
CPT N.2—Water level = 0.55 m

Depth m	q_C kg/cm^2	f_S kg/cm^2	c_U kg/cm^2	q_U kg/cm^2	OCR	E kg/cm^2	E_{ED} kg/cm^2
0.10	0.29	0.07	0.02	OC	0.05	0.57	1.57
0.20	0.60	0.23	0.05	OC	0.10	1.19	3.28
0.30	0.60	0.22	0.05	OC	0.09	1.20	3.29
0.40	0.60	0.21	0.05	OC	0.09	1.20	3.30
0.50	0.49	0.16	0.04	LC	0.07	0.98	2.68
0.60	0.50	0.16	0.04	LC	0.07	1.00	2.75
0.70	0.52	0.18	0.04	LC	0.07	1.04	2.86
0.80	0.55	0.19	0.04	LC	0.08	1.10	3.03
0.90	0.57	0.20	0.04	LC	0.08	1.14	3.15
1.00	0.67	0.23	0.05	LC	0.10	1.35	3.70
1.10	0.95	0.35	0.07	OC	0.14	1.89	5.20
1.20	0.95	0.37	0.07	OC	0.14	1.90	5.23
1.30	0.95	0.37	0.07	OC	0.14	1.90	5.21
1.40	0.95	0.37	0.07	OC	0.14	1.89	5.20
1.50	0.93	0.35	0.07	LC	0.14	1.87	5.13
1.60	0.96	0.37	0.07	LC	0.14	1.92	5.28
1.70	0.94	0.36	0.07	LC	0.14	1.87	5.15
1.80	0.89	0.31	0.07	LC	0.13	1.78	4.90
1.90	0.86	0.27	0.06	LC	0.12	1.71	4.71
2.00	0.83	0.26	0.06	LC	0.12	1.66	4.57
2.10	0.82	0.27	0.06	LC	0.12	1.64	4.52
2.20	0.80	0.24	0.06	LC	0.11	1.60	4.39
2.30	0.79	0.23	0.06	LC	0.11	1.57	4.33
2.40	0.75	0.19	0.05	NC	0.11	1.51	4.15
2.50	0.68	0.14	0.05	NC	0.09	1.36	3.75
2.60	0.69	0.17	0.05	NC	0.09	1.38	3.80
2.70	0.71	0.19	0.05	NC	0.10	1.42	3.91
2.80	0.59	0.16	0.05	NC	0.09	1.38	3.78
2.90	0.68	0.16	0.05	NC	0.09	1.36	3.75
3.00	0.71	0.18	0.05	NC	0.10	1.42	3.91
3.10	0.71	0.17	0.05	NC	0.09	1.41	3.89
3.20	0.71	0.17	0.05	NC	0.09	1.42	3.89
3.30	0.70	0.17	0.05	NC	0.09	1.40	3.86
3.40	0.71	0.18	0.05	NC	0.09	1.43	3.93
3.50	0.71	0.17	0.05	NC	0.09	1.42	3.90

Power Drive System. The power drive system consists of a 20 watt motor which drives a double action piston. The motor can be reversed for pulling the rods out at the end of a test. The system is powered by a rechargeable battery. To use the penetrometer in the field, two support pipes are manually forced into the soils to refusal. A horizontal adjustable bar is attached to the support pipes and leveled. Quick release

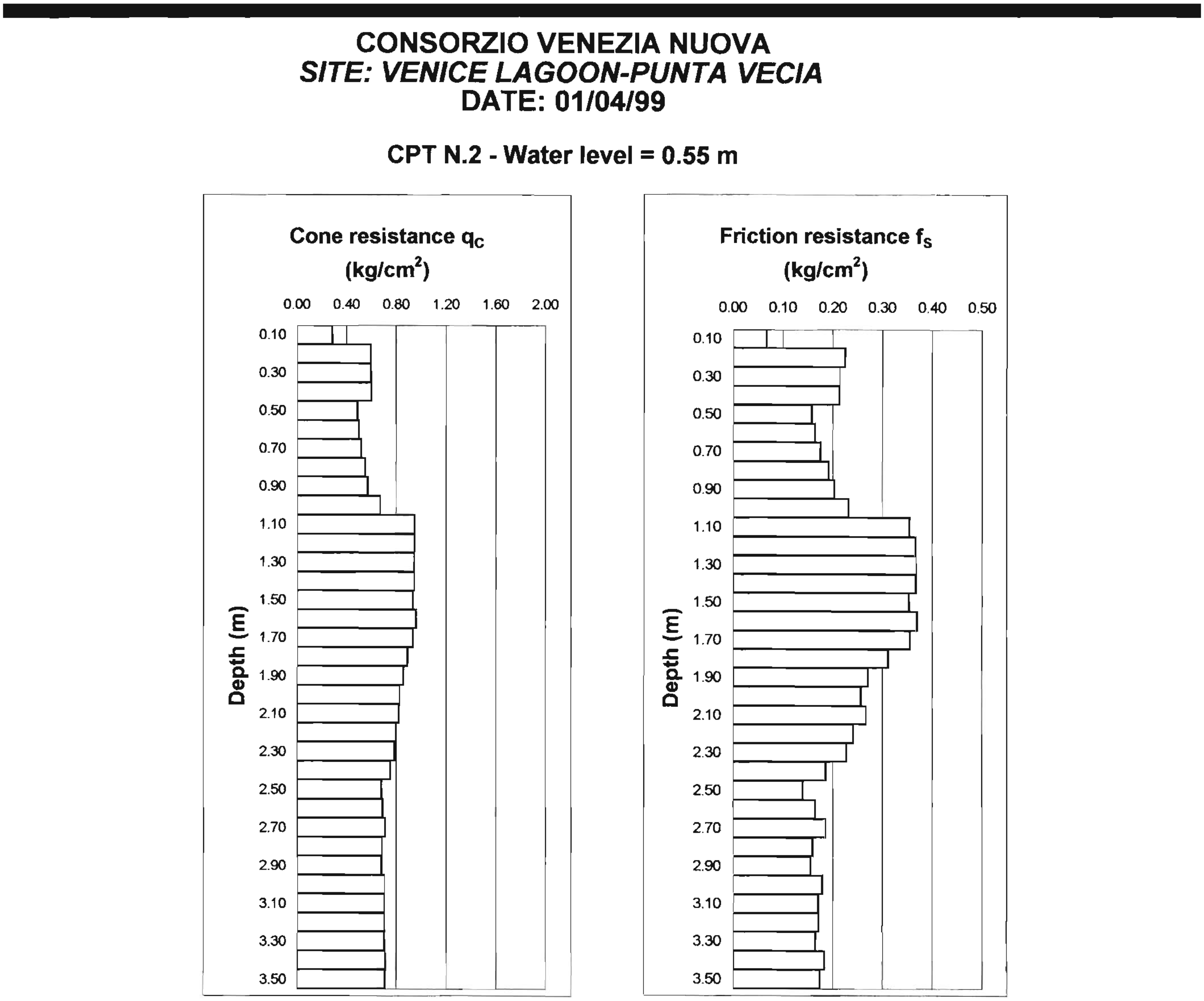

Figure 3. Results of cone resistance and friction resistance from a penetrometer test at Punta Vecia in Venice Lagoon. The strong increase between 0.9 to 2.1 m is due to the presence of a layer with a higher sand content. See text for discussion.

clamps allow rapid assembly and leveling. The cable from the cone passes through a series of hollow threaded rods. During operation these rods are attached one at a time to the piston that forces the cone into the soil. The motor stops automatically when each rod has been pushed into the soil. There is a 3 position switch which allows manual operation of the motor; the three positions are up, down and off. A coupling with a notched opening on the piston rod allows for the passage of the cable. The maximum depth of the penetrometer is six m. Data recorded by the cone passes through the cable to the data acquisition system. Figure 2 shows the PEP being used in the field.

The instrument can log resistances of q_C and f_S between 0 and 1.5 Kg/cm^2, with an accuracy of 0.01 Kg/cm^2. It has a velocity feed of 2 cm/s and, during operation, it is possible to choose different intervals to calculate values for the geotechnical parameters. The instrument resolution allows logging of resistance values in surficial sediments, where very soft sediments (with high water and organic matter content) are present.

Data Aquisition System. The data acquisition system consists of a data logger connected to a portable computer. The data logger is powered by the battery. The computer software is called PENTRO4.EXE. This program reads the electrical signal from the cone and displays the output on the computer monitor in real time. The program also stores the results from CPT and calculates the various soil geotechnical parameters. The program is available from the senior author.

During a test, resistance values with depth are displayed on the computer monitor that is connected to the instrument. The data analysis software program, written specifically for the penetrometer, plots q_C and f_S with depth in two histo-

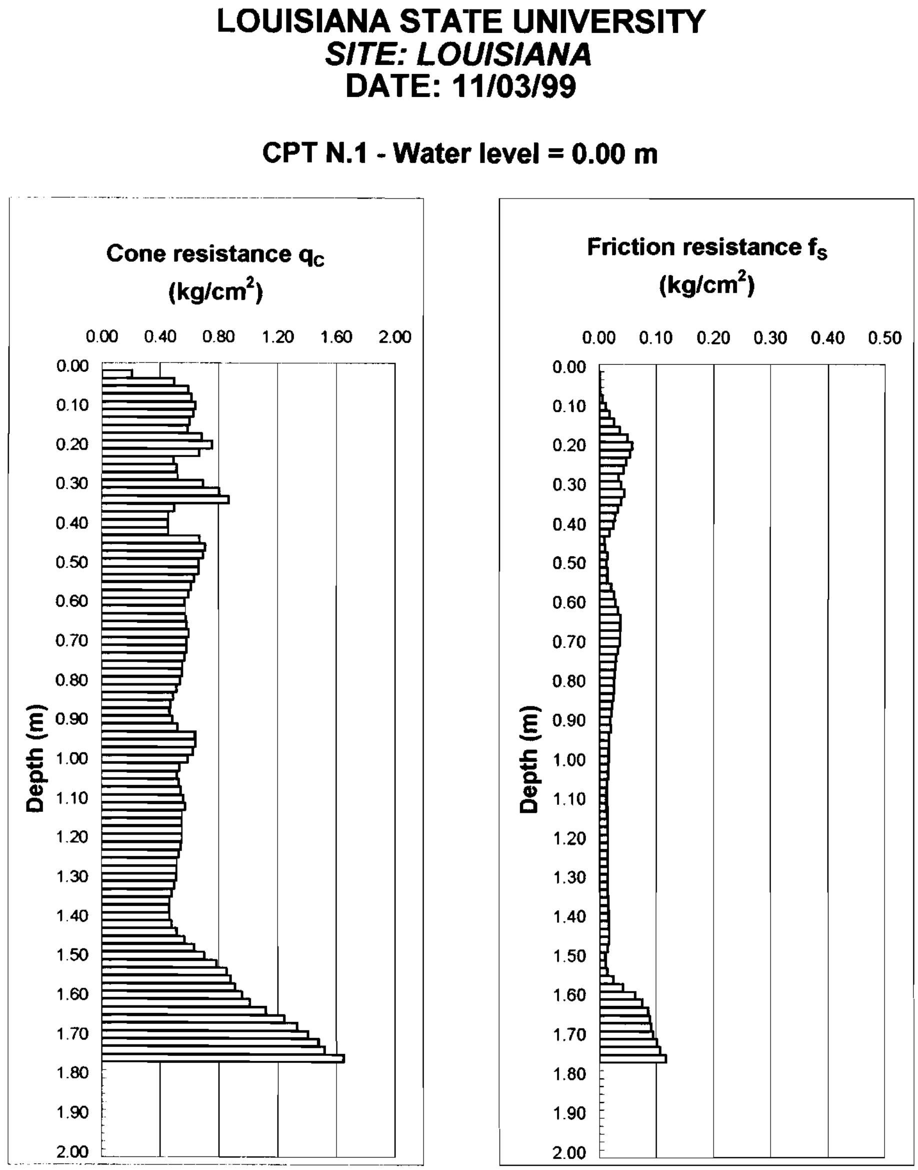

Figure 4. Results of cone resistance and friction resistance from a penetrometer test in a Mississippi delta coastal marsh. The strong increase in the two parameters at 1.5 m is due to the presence of a clay layer associated with an old channel of the Mississippi River. See text for discussion.

grams. Thus it is possible to observe soil characteristics during a test, and at the end of a test, the data can be reviewed and saved. The software program also calculates several important geotechnical parameters (soil cohesion, c_u; compression resistance, q_u; Young's modulus, E; stress strain modulus, E_{ED}; over consolidation ratio, OCR; and friction ratio; $100^* f_S/q_C$).

APPLICATION EXAMPLES

We present here several examples from Venice Lagoon and the Mississippi Delta to demonstrate the kind of results produced by the system. In Venice Lagoon, a number of wetland creation and restoration projects are being implemented by the Consorzio Venezia Nuova, the main organization responsible for environmental management of the lagoon. A knowledge of soil geotechnical characteristics was required for these projects.

Geotechnical measurements were made at Punta Vecia, where dredged spoil was used to create marsh, in order to determine the best position of piles driven into the sediment to contain the fluid pumped sediments (Figure 3). The sediments were obtained during routine maintenance dredging of channels in Venice Lagoon. The cone penetration tests were carried out along the external boundary of the area to identify the physical characteristics of sediments at the site and the depth of the most resistant and compact layer. This was very important because it helped in the planning of the layout of the pilings, avoiding particularly soft sediments, and the depth to which the piles were driven (and thus, the right length for the piles). The results show that both cone resistance and friction resistance increased significantly at 1.10 m due to a more compact soil layer with a high sand content. Table 2 is presented as an example of the output from the data acquisition system. It shows that all the geotechnical parameters also increased at 1.10 m. It was therefore decided to drive the piles greater than two meters into the soil through this compact layer.

Measurements were also made in two wetlands created when dredged sediments were pumped into an enclosed area at sites called Buello and Ravaggio. A series of cone penetration tests were carried out in the wetlands and a number of sediment samples were taken for geotechnical laboratory tests. The tests were done before the dredged material was deposited (1995) and 3 years later, so that geotechnical characteristics could be obtained before dredge material deposition and after a period of consolidation. The main objective of these measurements was the evaluation of the coefficient of yield. This index is a function of the consolidation of the pre-existing sediments and the compaction of dredged sediments. The cone penetration tests allowed the identification of local vertical stratigraphy and the different kinds of soils, especially the presence of compressible cohesive sediments. From the geotechnical parameters calculated from q_C and f_S values, we calculated the settlement of the soil and then the coefficient of yield. The results of the geotechnical measurements were confirmed by measurements of settlement of the soil surface made with staff gauges located inside the two wetlands.

In the Mississippi Delta, cone penetration tests using the PEP were carried out in a stable marsh near an old distributary of the Mississippi River that was active in the 18th century. There is currently regular input of sediments resuspended from nearby bay bottoms and the site has firm soils with a high bearing strength. We measured a rapid increase in both cone resistance and friction resistance at about 1.5 m (Figure 4). Soil cores taken at the site showed the presence of a clay layer of low organic matter content ($<5\%$) overlain with a more organic soil with a high density of living and dead root material. We concluded that the clay layer was deposited when the distributary channel was active. Results such as these would be useful in coastal marsh restoration decisions where, for example, the presence of the clay layer indicates this site could support the placement of dredged spoil.

ACKNOWLEDGEMENTS

This work was supported by the Consorzio Venezia Nuova through funds provided by the State Water Authority of Venice, the Magistrato alle Acque di Venezia and by the Louisiana State Board of Regents. We thank M. Masriqui and the field operations personnel of the Coastal Studies Institute at LSU for their invaluable assistance. We would like to thank Giuseppe Bassato for technical support in equipment construction.

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