In-situ experimental tests for shallow foundation design using dynamic penetration testing method

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ABSTRACT

To develop an advanced and innovative method for shallow foundations design with the aid of dynamic penetration testing technique, several in-situ tests are realized on various experimental sites to enrich the available database and to valid the computed results. This communication presents the field tests consisting of the Foundation Loading Tests and the Dynamic Cone Penetration Tests (DCPT): their performance, operation principles, equipment and results obtained. A direct method for bearing capacity prediction based on the measured data is also proposed, then compared to other approaches already standardized. Therefore, this study contributes to the improvement of the shallow foundations design method by providing full-scale experimental results and discussing their findings.

Keywords: In-situ test; Shallow foundation; Direct design method; DCPT.

1. Instruction

In-situ experimental tests hold an important role in the geotechnical domain either for scientific research aspect or for engineering applications (e.g. foundation design, tunnels, excavations, embankments). Ground investigation using these direct measurements from field tests are always needed as they help to identify soil properties and to classify them according to different geomaterial groups. Moreover, the prediction of soil behaviour and strength when interacting with buildings or other man-made structures can also be performed using soil data from the in-situ techniques which provides results in a more feasible and instantly way. (Greenwood 2005) has therefore classified in-situ tests into three groups:

1. empirical tests for which the results are strongly based on operator experiences or scientific experiments such as the Standard Penetrometer Test (SPT).
2. semi-empirical tests for which relationships between parameters and measurements have already been established, but that still have limitations such as the Cone Penetrometer Test (CPT).
3. analytical tests that are more advanced and that include control and monitoring of measurements (especially in the stress path) such as the Pressuremeter Menard Test (PMT).

Shallow foundations are the most common geotechnical structures, as they are simple to construct and low-cost. Because of these advantages and its popular application, an advanced design method is essential, especially since the current techniques are based on empiric or semi-empiric approaches providing only approximate results. For that reason, two in-situ tests equipped with advanced devices to control parameters (the Foundation Loading Test (also called the Plate Loading Test) and the P.A.N.D.A. test (*from French Pénétromètre Autonome Numérique Dynamique Assisté par ordinateur*), a Dynamic Cone Penetration Test (DCPT) developed recently in (Benz Navarrete et al. 2013)) are then employed in this study to develop a sound and innovative design method for shallow foundations.

Thus, this paper presents the operation principles, equipment scheme, and results obtained from these in-situ tests: the Dynamic Cone Penetration Test and particularly, the Plate Loading Test. A proposition for a new design method is then introduced. The conclusion from this study contributes considerably to the development of a direct design method for the shallow foundations.

2. In-situ tests presentation

2.1. Dynamic cone penetration test

The P.A.N.D.A. is a lightweight portable dynamic cone penetrometer driven by a hand-hammer mass providing variable energies which adapts to different stiffnesses of soil layers. The energy is delivered by each blow and the overall penetration depth is directly measured. The penetrometer possesses rods with diameter and length respectively 14 mm and 500 mm. An overflowing conical tip with a cone apex angle of 90° and a cross-section of 2 or 4 cm² (15.9 or 22.5 mm in diameter, respectively) helping to avoid the effects of skin friction. Moreover, jacking or mud injection can be implemented if needed. The test procedure and output, the dynamic cone resistance (or dynamic tip resistance) obtained by means of the modified Dutch formula, are based on (ISO-22476-2 2005).

Developed recently, the third generation of this apparatus, called P.A.N.D.A.3 (Benz Navarrete et al. 2021) is more advanced, including new sensors (accelerometers, strain gauges and displacement measurement). Moreover, this version integrates computations for solving wave equations; along with other advance devices for data acquisition, storage, and display. It is the version used for this study. Fig. 1 shows the schematic representation as well as the operation principle of the dynamic penetrometer P.A.N.D.A.3.

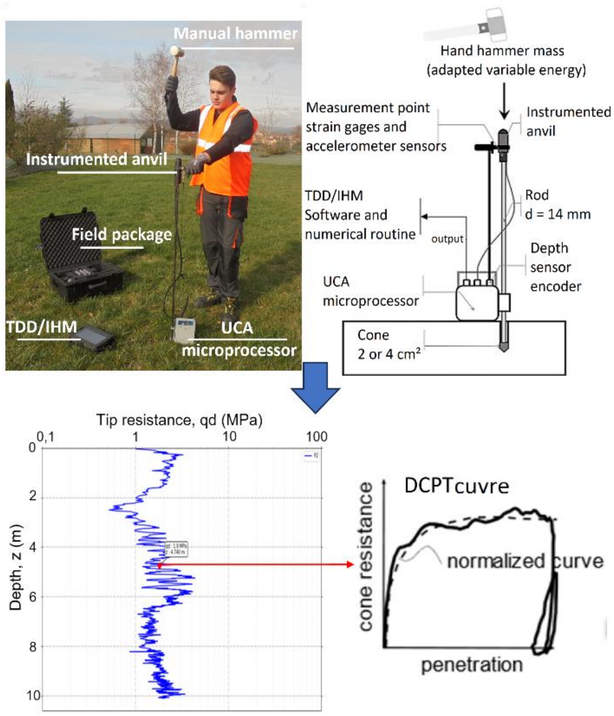


Figure 1. Description and principle of the dynamic penetrometer P.A.N.D.A.3

The dynamic tip resistance profile (or the penetrogram) is obtained for each test sounding. From each point of displacement generated by hammer impact, the plot of DCPT curve shows cone resistance $q_d(t)$ as a function of cone penetration $s_p(t)$. By using a nonlinear elastic-plastic model such as the Simplified Hyperbolic with two input parameters: the limit resistance, q_{lim} presented in (Reiffsteck et al., 2021) and the elastic modulus for dynamic penetrometer, E_d, a model can be then established by fitting the experimental DCPT curves.

2.2. Foundation loading test

Foundation Loading Test (or Plate Loading Test) is a classic geotechnical experiment. The test is either carried out to determine the bearing capacity of soil or the quality of a backfill compaction by measuring the displacements (or the soil settlement) corresponding to stresses applied through the plate with a variable loading program. The soil bearing capacity and its deformability are evaluated by studying the load-displacement relationship. Equipment scheme of this in-situ test is presented in detail in Fig. 2. It comprises:

1. a rigid metallic plate which simulates a shallow foundation. The shape of the plate can be either squared with the width B ranging from 0.71 to 1 meter or circular with a diameter B of 0.6 meter. The circular form is the one used for this specific test system.
2. a loading system which consists of a hydraulic jack for loading with a pushing capacity of 100 tons; and a non-deformable metallic reaction frame with a hollow cube shape and weighing 0,7 ton, anchored into the soil by auger-type anchors (89 mm and 1500 mm of diameter and length respectively). Anchors are situated at the frame four arm corners to fix and to ensure the stability of the structure during the test (Fig. 3). To ensure the anchoring resistance during the loading test, the anchor properties are also considered, such as its diameter and the anchoring depth. According to (Vézole 2002) the resistance F that can be mobilized for passive anchoring in granular soil contains two compositions: skin resistance (lateral friction) and volume resistance (repressed soil), according to Mohr-Coulomb criterion:

$$F = \pi h \gamma (\frac{h^2}{3} tan^2(\varphi) + \frac{D^2}{4}) \quad (1)$$

Where h the anchoring depth, γ the unit weight of soil, φ the friction angle of soil, and D the anchor diameter.
Another advantage of the system is that it is also a mobile station that can be transported by trailer and vehicle to diverse experimental sites.
3. a system of data acquisition and display; different devices and sensors for parameter monitoring and data measurement. The system allows to measure the vertical effort applied on the plate, and its corresponding axial displacement vis-a-vis initial surface level.

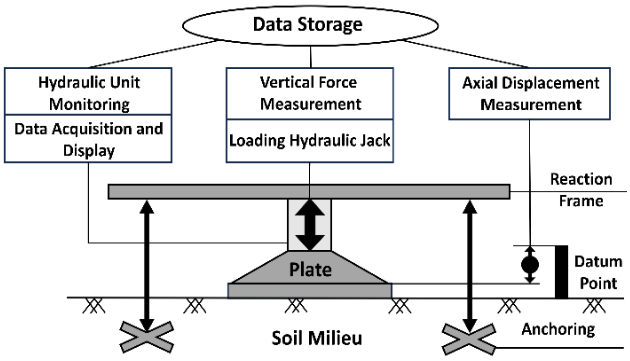


Figure 2. Equipment scheme of foundation loading test

The foundation test is performed following a step loading program corresponding to the monotone case (vertical and centered applied force). The loading protocol is presented in Fig. 4 and described as follows:

- bearing capacity of soil is firstly estimated based on data obtained previously from different investigation tests (e.g. DCPT, CPT or PMT) on the site to predict the maximum load value;

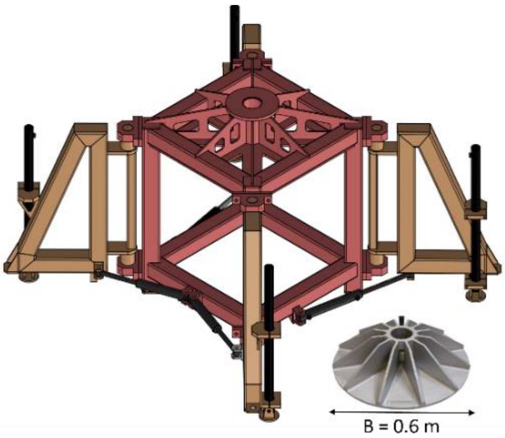


Figure 3. Reaction frame (SOMAC) and circular plate

- loading program is then set incrementally up to the predicted value of soil resistance, with an average of 10 steps of equal magnitude; to take into account the creep effect in soil, the load is kept constant at each level for a conventional maximum duration of 30 minutes, or until the curve representing deflection as a function of the logarithm of the time is linear. The comparators are distributed symmetrically around the plate to measure the deflection and affixed to a support frame independent of the loading system as a reference beam;
- the test terminates either when the settlement of the plate is measured equal to one-tenth of its width B, the value defined conventionally as failure settlement of soil as presented firstly in (Canépa and Despresles, 1990), or when reaching the limit of measurement devices. Settlement values are also measured by steps during the unloading phase of the test. The aim is to understand the elastic property of the soil under unloading phase.

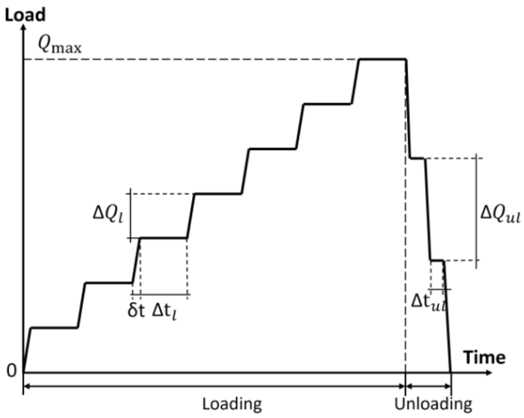


Figure 4. Loading program protocol

As presented in Fig. 4, Q_{max} is the predicted maximum loading value (estimated as the bearing capacity of soil under a loaded plate with a given dimension), ΔQ_l is the transition value of applied load on plate and Δt_l is the duration (30 minutes maximum) for each step in the loading phase; ΔQ_{ul} is the transition value of uncharged load and Δt_{ul} is the duration (5 minutes) for each step in the unloading phase; δt is the duration for step transition (less than one minute).

As an in-situ test of full-scale structure, which is somehow complex, time-consuming and costly to carry out, the setting-up of the test is therefore significant. Fig. 5 shows an example of an installation plan for the experimental campaign performed in Montfavet, France. During a three day campaign, three plate loading tests were performed consecutively and adjacently to the locations where P.A.N.D.A. test (named PD) were already performed. Besides these DCPT tests, other ground investigation tests such as PMT or CPT were also carried out before or during the foundation tests. The tests were carried out in the experimental zone situated within 3 to 5 m of the first tests. The aim is to define a geotechnical model of the terrain. The organization of test installation is similar to other experimental campaigns carried out on other sites.

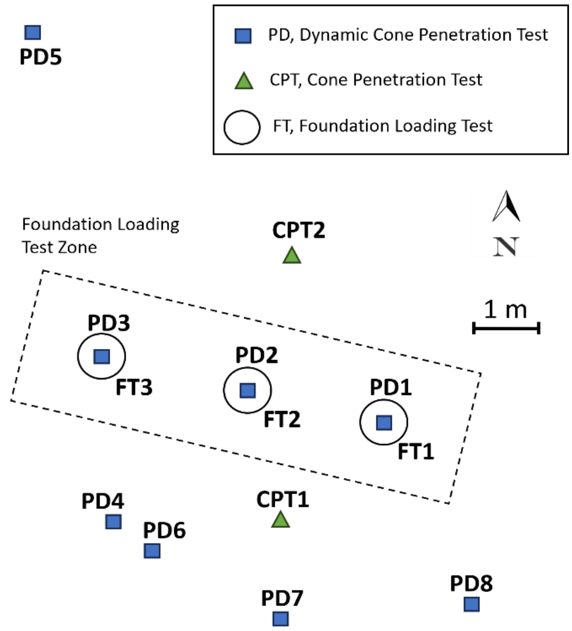


Figure 5. Plan of experimental tests in Montfavet, France

Findings acquired from the foundation tests are the evolution of the plate displacement (or soil settlement) as a function of the force (or stress) applied. This result expresses the reaction and the behavior of soil against the plate loading. The results are presented and discussed in the next section.

3. Applications and results

Experimental campaigns using the DCPT, and the Foundation Loading Tests were recently undertaken on several sites in France with various soil lithologies: marine clay in Cran, sand in Messanges, silt in Aulnat and dry silt in Montfavet, and numerous data were obtained.

Fig. 8 shows dynamic tip resistance (q_d) and dynamic modulus (E_d) profiles obtained with the dynamic penetrometer for each experimental site. Mean values and error bars (standard deviation) for each layer of 1 m are also presented on the graphs. The shape of all penetrograms are typical of homogeneous soils, except for the strong layer at one meter depth in Messanges.

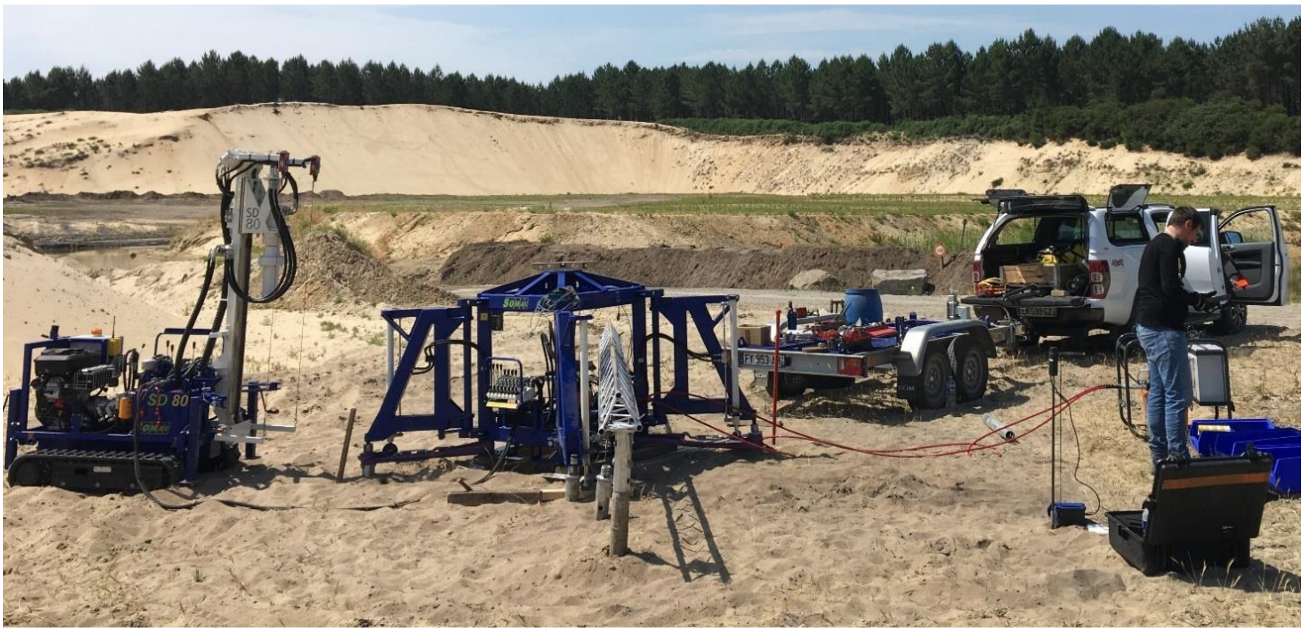


Figure 6. Sideview of setting-up for an in-situ test campaign in Messanges, France with mini drilling rigs, loading frame with datum bar, trailer and P.A.N.D.A.3 (from the left to the right)

This indicates experimental sites examined are pretty homogeneous. In the first two meters of depth, q_d and E_d results in Messanges and Montfavet are generally higher than that in Cran and Aulnat. However, for deeper zones, the density of sands in Messanges decreases while silts in Aulnat significantly increase their resistance with depth.

The application of Foundation Loading Test and its results are also presented. Fig. 7 shows the experimental load-settlement curves carried out on four sites: three tests on Aulnat (AU) and Montfavet (MO); and two tests on Cran (CR) and Messanges (ME). All ten loading tests were performed with a 0.6 m circular footing which means the value of settlement defined as rupture equals to 60 mm. Two groups of curves are observed in the figure: curves in warm color with points and other curves in cold color with asterisks. The warm color curves decline slower than the cold color one. This indicates that soils in Messanges and Montfavet are more resistant than that in Cran and Aulnat when considering the zone of influence of the circular plate, which is rather located in the superficial depth of the soils. This is in accordance to DCPT results discussed above.

Table 1 synthetizes results obtained from DCPT and loading tests for each experimental site. Soil nature and number of tests performed is also included. The dynamic tip resistance q_d in superficial soil layers (from 0 to2 meter depth) is presented with the mean and standard deviation values. For foundation tests, the maximum load value, Q_{max} and the equivalent settlement are shown. Once again, it is important to note that the plate applied is all circular type with the diameter B equals to 0.6 m and carried out with a null embedment.

Numerous experimental campaigns of the Foundation Loading Test were also carried out by other research organizations and universities with various soil natures in France or in different countries around the world. These results are available in the bibliography: for example (Canépa and Despresles 1990) and (Ménard 1963) presented 107 tests using the plate with width B = 0.7 – 1 meter on stiff silty, dune sand and altered chalk on sites of Jossigny, Labenne, Lognes, Provins and Châtenay in France. Similarly, (Larsson 1997, 2001) presented 9 tests using plate with B = 0.5 – 2 m on clay and silty soil on sites of Vagverket, Vattahanmar in Sweden. In addition, (Viana da Fonseca 2001) showed a square footing test of 1.2x1.2 m² embedded on the surface on a silty sand site of Porto in Portugal. Other examples are (Tand et al. 1986), (Lutenegger and De Groot 1995) and (Nordlund and Deere 1970) (Briaud and Gibbens 1999) who presented 14 tests with various footing dimensions on sand, silty clay, and silty sand on sites at Alvin, Texas, FHWA in USA etc.

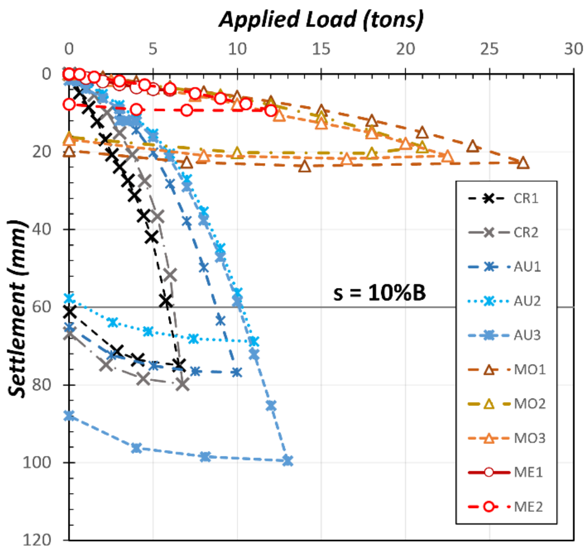


Figure 7. Load – settlement curves of foundation loading test for all sites.

Table 1. List of experimental sites with results obtained from the DCPT and the Foundation Loading tests.

Site	Soil nature	DCPT tests		q_d (z = 0-2 m) (MPa)			Loading tests				
		Number of tests y	z max (m)	Mean μ	SD δ	Number of loading tests	Number of loading steps	ΔQ_l (kN)	Q_{max} (kN)	ΔQ_{ul} (kN)	s max (mm)
Cran	Marine clay	7	6.5	0.86	0.37	2	13	4 – 5	65.4	12 – 27	75
							9	7.5	67.5	22	80
Messanges	Sand	10	4.5	6.86	3.93	2	6	10	60	-	4
							8	15	120	40	9.5
Aulnat	Silty	5	3.7	2.71	1.02	3	10	10	100	25	77
							11	10	110	25	69
							13	10	130	40	99.5
Montfavet	Dry silty	6	2	7.27	1.88	3	12	20 – 30	300	70	23.5
							8	30	240	80 – 100	20
							10	25	250	80	22

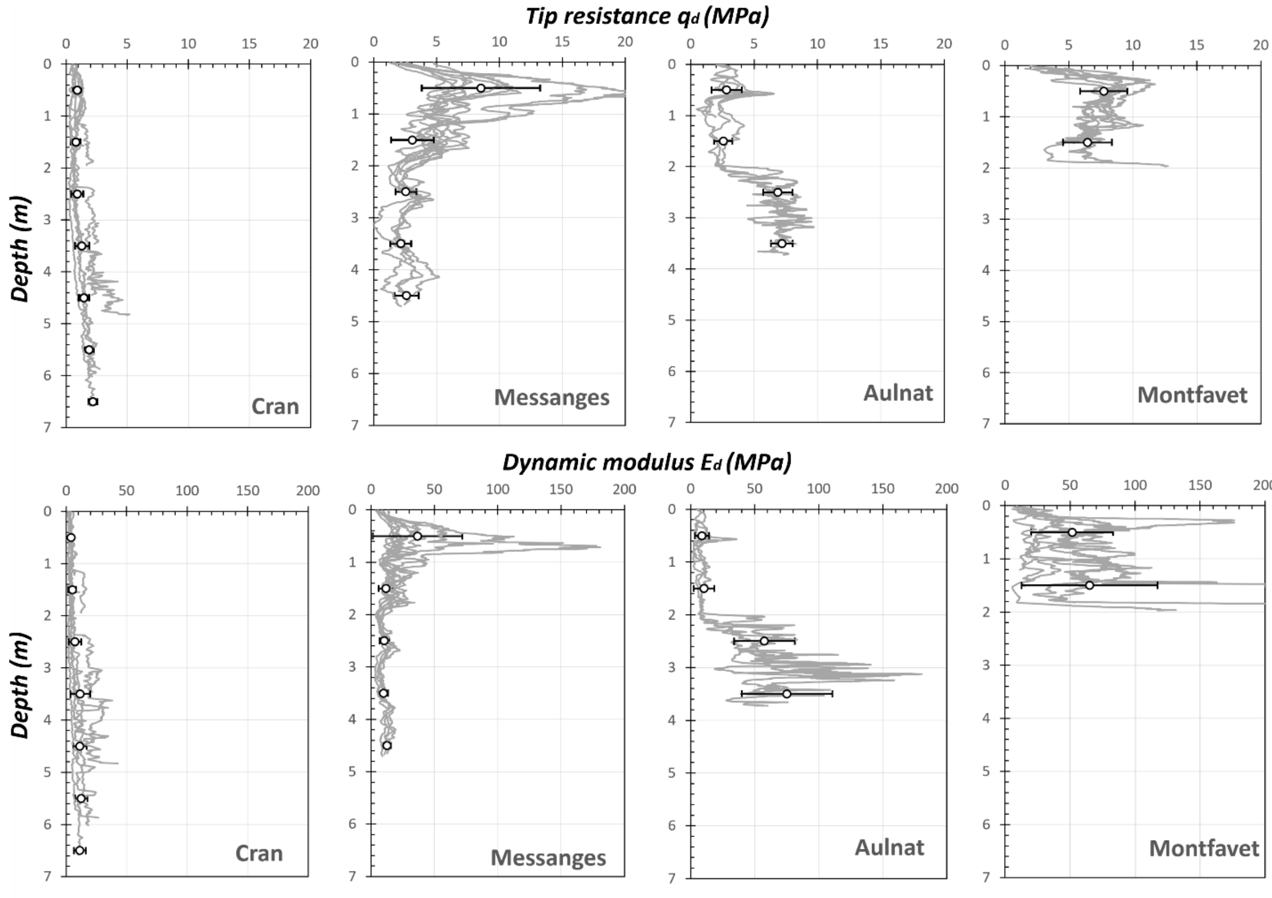


Figure 8. Dynamic tip resistance and dynamic modulus profiles obtained with P.A.N.D.A.3 for all sites

4. Shallow foundation design using DCPT

A direct method for shallow foundation design is proposed in this section: bearing capacity assessment and settlement prediction are derived from dynamic penetrometer data and method is based on the in-situ experimental test findings. Then, the method is applied to experimental sites and a comparison to other existing approaches is provided.

4.1. Bearing capacity assessment

Beside the most used one, the c and φ method of (Skempton 1951 ; Terzaghi 1943), other direct methods for bearing capacity assessment using soil data from Pressuremeter Menard Test (PMT), Cone Penetrometer Test (CPT) or Standard Penetrometer Test (SPT) are already standardized and introduced in Eurocode 7. With a slight modification from the CPT method in (AFNOR, 2013), bearing capacity of foundations may also be evaluated by results obtained from its dynamic version, the DCPT test, as shown in the following formulas:

$$q_{net} = q_0 + k_d \cdot q_{de} \quad (2)$$

$$k_d = k_{d0} + \left(a + b.\frac{D_e}{B}\right) \cdot \left(1 - e^{-c.\frac{D_e}{B}}\right) \quad (3)$$

Where q_{net} is the net pressure or the bearing capacity, q_0 the total vertical stress after projet without foundation, k_d the bearing capacity factor for dynamic penetrometer, q_{de} the equivalent dynamic tip resistance, D_e and B, the equivalent embedment depth and the width of foundation respectively and k_{d0}, a, b, and c coefficients varying in accordance with the type of soil and the shape of the foundation.

4.2. Settlement prediction

Inspired partly from the Load Settlement Curve Method introduced by (Briaud, 2007) for PMT, a novel method using dynamic penetrometer for settlement prediction is proposed which considers the similarity of the tip resistance – penetration curve of DCPT (as mentioning in section 2.1) and the load – settlement curve of shallow foundation.

Therefore, to reproduce the experimental curves of DCPT with a non-elastic fitting model, the Simplified Hyperbolic method using parameters A_i as presented in (Baud and Gambin 1992, 2008, 2013) is applied. Based on the elastic theory of Boussinesq, the relationship between displacement and stress is expressed as a function of soil elastic modulus and the characteristics of plate geometry and the soil compressibility. The relationship between penetration and dynamic tip resistance is then described as shown in Eq. (4).

$$s = h_e\left(A_1 + A_2 q + \frac{A_4}{A_6 - q}\right) \quad (4)$$

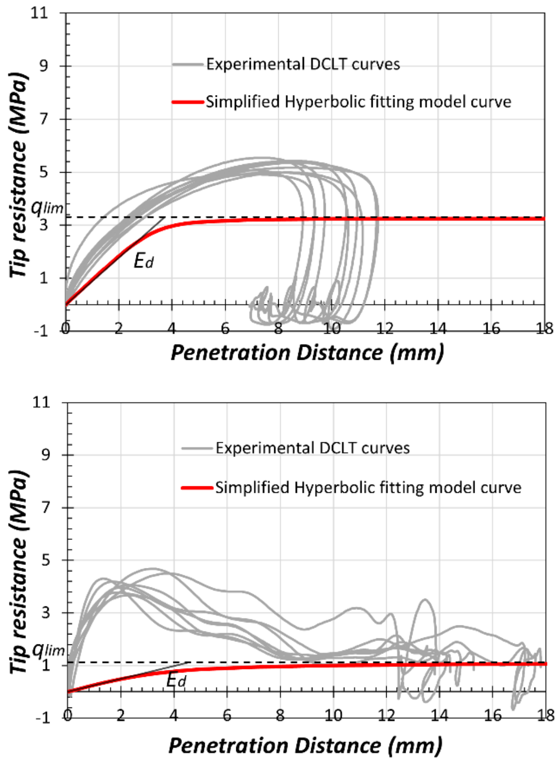
With:

$$A_1 = -\frac{A_4}{A_6} \qquad A_2 = \frac{\alpha B_{HS}}{E_d}$$

$$A_4 = \frac{\alpha(1 - A_{HS})(1 - B_{HS})}{E_d} q_{lim}^2 \qquad A_6 = q_{lim}$$

Where, q_{lim} and E_d are derived from DCPT; $\alpha = (1 - \nu^2)\frac{b}{h_e} C_f$, a non dimensional term, with $C_f = 0.79$ corresponding to the form coefficient of the rigid cone of P.A.N.D.A; $h_e = \frac{\pi R}{4}(1 - \nu^2)$ is the influence depth (Butterfield and Banerjee, 1971); ν is the Poisson coefficient of the soil; b and R are diameters and radius of the cone respectively; A_{HS} and B_{HS} are the parameters related to the transition point from the elastic linear part to the non-linear part of the curve and the initial slope of the curve respectively which also depends on the behavior of soil.

Fig. 9 shows the application of this method for DCPT tests on two experimental sites, Messanges and Aulnat, through the tip resistance–penetration curve. The curves obtained in Messanges present high soil resistances with q_d and q_{lim} of about 5 MPa and 3.5 MPa at approximately 10 mm of penetration. On the other hand, soils in Aulnat are less resistant with values of q_d, q_{lim}, and s are respectively 4 MPa, 1 MPa and 18 mm.



a)
b)

Figure 9. Experimental DCPT curves and the Simplified Hyperbolic fitting curve for a) sand in Messanges and b) silty in Aulnat

4.3. Results and comparison

Ground investigation data obtained from in-situ techniques such as PMT, CPT and DCPT is employed for the bearing capacity assessment of shallow foundation. Bearing capacity assessment is based on different current direct methods: the standardized methods commonly used in the French standards such as NF P94-261, 2011 and DTU 13.2, 1992 (*in French Document Technique Unifié*) which are put in comparison with the proposed one using formulas in Eq. (2) and Eq. (3) and data from the dynamic penetrometer P.A.N.D.A.3. The computed results are then confronted to the measurement results from the Foundation Loading Tests in Fig. 7 which are considered as the reference to evaluated these different method results.

Fig. 10 shows the calculated results, q_u using direct methods with data from various soil investigation techniques versus the measured results, q_r as the load at rupture moment considered conventionally when s equal to 10%B from the loading tests in different sites as Jossigny, Cran, Messanges, Aulnat and Montfavet. This graph shows that the higher the resistance of the soils, the more difference between the computed results of various approaches: the data points from two direct methods in Eurocode 7, NF P94-261 for PMT and CPT demonstrate a good prediction of bearing capacity as their trend lines are fairly close to the symmetric diagonal line of the graph (q_u= q_r). In contrast, the rest two groups of data from methods in DTU 13.2, 1992 and the proposed method both using DCPT indicate an underestimation of calculated results in relation to the measured ones with a factor of two ($q_u \approx 1/2\ q_r$). This could lead to a conservative design for the bearing capacity assessement which would also enhance thesafety aspects in design.

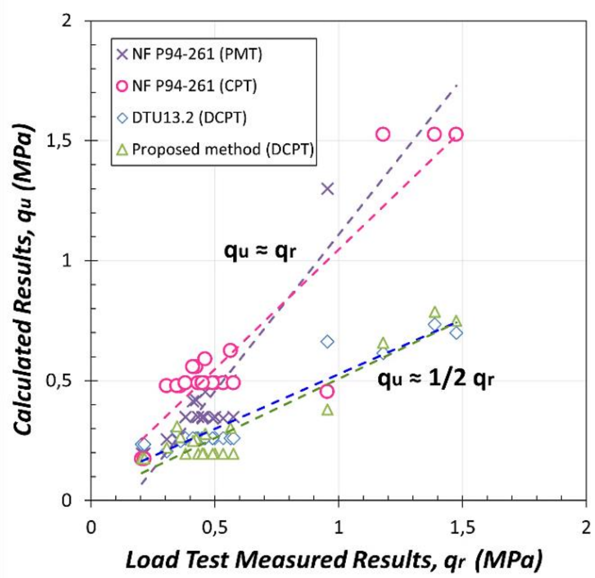


Figure 10. Bearing capacity assessment comparison between methods for shallow foundation design

The synthesis of data from all experimental sites in France as well as from abroad presented in the section 3 is also studied by applying the direct methods in NF P94-261 using PMT and CPT; the method of SPT; and the proposed method using DCPT. This graph in Fig. 11 shows the cumulative distribution function of the ratio between the computed bearing capacity factor from design methods (k_s_cal) and the measured factor from in-situ tests (k_s_mes). The application indicates that the shape of curves is quite similar with a fitting curve using Normal law (mean = 0.92 and standard deviation = 0.27) for all.

When the ratio $k_{s_{cal}}/k_{s_{mes}}$ produced is smaller than 1, it means that the result obtained from methods underestimates the bearing capacity of shallow foundation. A probability equal to about 62% is observed in Fig. 11. However, there is only a small possibility (< 10%) where this ratio equal to 0.5 (equivalent with the results $q_u \approx 1/2\ q_r$ of proposed method as obtained before). Overall, with a considerably larger database of foundation tests and considering various direct methods, the study shows that the method still give a conservative design. This somehow relates to the conclusion obtained from the Fig. 10.

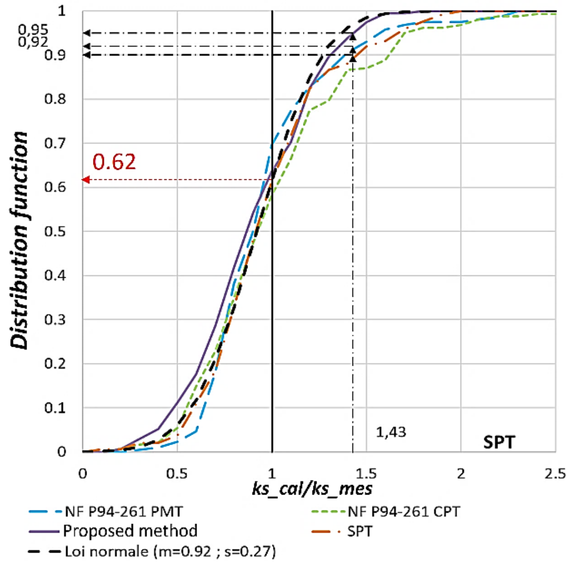


Figure 11. Distribution curves of the experimental and computed bearing capacity ratio applied for all sites

5. Conclusion

An innovative shallow foundations design method based on the use of the Dynamic Cone Penetrometer Test is presented in this communication. Full scale Foundation Load Tests carried out in order to develop this method are also described in detail to enlighten the experimental work.

By comparing this method to other current standardized methods, the bearing capacity assessment results from the proposed method are shown to be quite in accordance with the results obtained from the experimental tests performed all over the world by various authors. Nevertheless, the robustness of this approach needs to be improved with additional field data and more comparisons. Furthermore, other applications for footing settlement prediction will be examined and evaluated in future works to complete the development of this direct method using the dynamic penetrometer test.

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