Development of a liquefaction risk assessment methodology using an instrumented lightweight dynamic penetrometer: calibration chamber tests

S. López Retamales
Ecole des Ponts ParisTech, Paris, France, sebastian.lopez-retamales@enpc.fr

J. Canou[1], J.C. Dupla[2]
Ecole des Ponts ParisTech, Paris, France, jean.canou@enpc.fr[1], jean-claude.dupla@enpc.fr[2]

M. Benz Navarrete
Sol-Solution, Riom, France, mnavarrete@sol-solution.com

ABSTRACT: Soil liquefaction is one of the most destructive phenomena caused by earthquakes. Nowadays, it has been mainly studied regarding the risk assessment trough in-situ penetration tests (SPT, CPT) that allow identification of potentially liquefiable layers. However, most of these techniques are limited by site accessibility, cost and amount of information collected during the survey. Development of portable, cost effective and efficient equipment as well as the methods to assess cyclic resistance ratio (CRR) are necessary. This paper presents the first results aimed at establishing a pseudo-empirical laboratory methodology for liquefaction risk assessment of sandy soils through a lightweight instrumented dynamic penetrometer. A series of dynamic test on sand samples were performed in calibration chamber. Filling material of each sample is sand of Fontainebleau, different density and overburden pressure has been reproduced. On each sample, a dynamic penetration test was conducted and for each hammer blow, strain, forces, acceleration and displacement were recorded as well as dynamic penetration resistance (q_d^{P3}), computed by wave equation analysis, are obtained. At the end, graphs or charts for correlating qd, density index and overburden pressure are presented in order to assess CRR of soil.

Keywords: Dynamic penetration, liquefaction, density index.

1. Introduction

Due to the negative effects resulting from the occurrence of liquefaction, the evaluation of the potential of liquefaction in the field becomes necessary. Different methods of evaluation in the field have been developed and several of these are based on both static and dynamic penetration tests. Each test equipment has advantages and disadvantages take in account the different conditions of the site, the equipment and its operation are considered, so the development of new methods based on other equipment is necessary. The present article presents the first results of dynamic penetration tests carried out by means of a instrumented light dynamic penetrometer variable energy, on a clean fine sand in a calibration mold system.

The light dynamic penetrometer of variable energy used in the study is the PANDA 3® [5], which allows to obtain resistance to dynamic ground penetration. This equipment has been used in a wide range of geotechnical applications, including the development of some methodologies for liquefaction risk analysis based on correlations with other penetrometers which have been mainly used in the analysis of mining tailings dams [4].

The execution of this study is aimed at analyzing the behavior of the soil against the dynamic penetration of variable energy, considering the effects of relative density and vertical pressure. This information allows validating the use of this type of penetrometers in the auscultation of soils that can be liquefied under different conditions.

The knowledge of the relationship between the tip resistance (q_d^{P3}), density index (I_d) and vertical consolidation stress (σ'_{vc}), allows to predict the behavior of the soil under similar conditions and develop increasingly precise analyzes regarding the expected behavior of the soil.

The dynamic penetration tests were carried out on specimens of Fontainebleau sands, reconstituted in a calibration mold at different density index. The penetrometer used was configured with a conical tip of 4 cm^2 area. The calibration mold allows the application of vertical consolidation stress conditions.

Currently, the evaluation of the liquefaction potential is carried out in the field with penetration equipment and other geophysical equipment, however, the use of the equipment is difficult in some geological configurations and locations. The lighter penetrometer allows auscultation of soils more easily and faster. Although the PANDA 3® penetrometer has been used in a wide range of geotechnical applications, the analysis of results has been based on tests up to 6 meters deep. The execution of tests under higher overload conditions allows the analysis of soil behavior versus dynamic penetration at greater depths.

This article presents the results of dynamic penetration tests carried out with light dynamic penetration equipment instrumented with force and wave acceleration sensors (PANDA3®), on sand specimens built at different density index and vertical consolidation stress. The results allowed to present an equation that relates the 3 parameters of the soil considered.

2. Materials and methods

2.1. Fontainebleau Sand

Fontainebleau sand is a light beige granular material, mostly silicon ($SiO_2 > 98\%$)) of uniform graduation (**Figure 1**) [1]. The individualized grains have a rounded to semi-rounded shape and very resistant to breakage. The properties of this arena are summarized in **Table 1**.

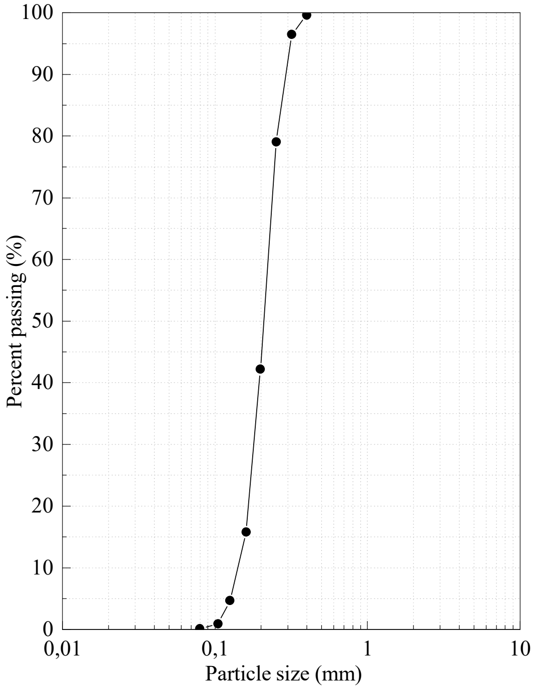

Figure 1. Fontainebleau sand granulometry [2].

Table 1. Fontainebleau sand parameters.

Parameter	Value
Specific gravity (ρ_s)	2,65 g/cm^3
D_{50}	0,21 mm
C_u	1,52
γ_{min}	1,37 g/cm^3
γ_{max}	1,72 g/cm^3

Maximum and different minimum void ratio values have been reported in the available bibliography. For this study, the values of $e_{min} = 0{,}55$ y $e_{max} = 0{,}85$ have been obtained and adopted.

2.2. PANDA 3®

The PANDA 3® (**Figure 2**) is a dynamic penetrometer of variable energy, in which the tip resistance analysis is based on the theory of elastic waves in a rod and its interaction with the soil (eq. 1).

$$\frac{\partial^2 u}{\partial t^2} - c_t^2 \frac{\partial^2 u}{\partial x^2} = \frac{R(x,t)}{E_t A_t} \qquad \text{(eq.1)}$$

With:
$R(x,t)$ = External system resistance.
c_t = Wave velocity.
E_t = Elastic modulus of rods.
A_t = Cross section of rods.

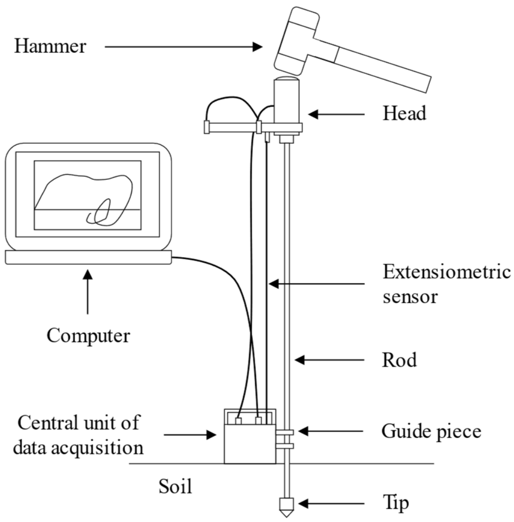

Figure 2. PANDA 3® dynamic variable energy light penetrometer scheme.

The PANDA 3® penetrometer is instrumented with sensors that allow the recording of the variation of the strain $\varepsilon(x,t)$ and the acceleration $a(x,t)$ caused by the passage of the compressional wave generated by the dynamic blow. For the generated wave, the downward (ε_d) and returning (ε_r) wave is decoupled allowing the calculation of the tip penetration ($s_p(t)$) and the stress ($F_p(t)$) during the penetration work, then, it is possible to obtain the load-penetration curve ($\sigma_p - s_p$) [3], [4] (**Figure 3**).

By analyzing the load-penetration curve and the soil-tip interaction, it is possible to obtain different geotechnical parameters, such as: Dynamic stiffness (k_d^{P3}), resistance to dynamic penetration (q_d^{P3}) and static (q_c^{P3}) deformation module (E_d^{P3}), Smith's linear damping coefficient (j_S) and ground wave velocities (C_p^{P3} and C_s^{P3}) [3]–[6].

The PANDA penetrometer also allows soil characterization by correlation between the tip resistance (q_d^{P3}) and the dry density (γ_d) or the density index (I_d). In the case of a PANDA penetrometer, a representative equation of adjustment has been defined (eq. 2) [7].

$$I_d = A \ln(q_d^{P3}) + B \qquad \text{(eq. 2)}$$

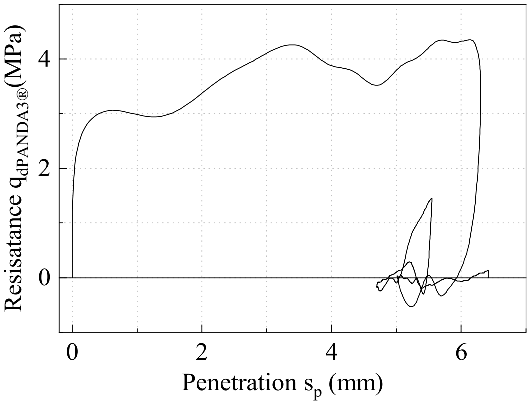

Figure 3. Strength–penetration curve PANDA 3®.

2.3. Calibration mold

The specimens were constructed in a calibration mold system (Figure 4). The mold is composed of a base, two cylinders and an upper cover that together allows the construction of a 73 cm high specimen and 54,7 centimeters in diameter. The system is closed by means of spun bars that are fixed both on the top and bottom by means of nuts. Under the top cover and at the top of the specimen, a hydraulic pressure system is installed that expands to exert vertical pressure. The pressure is induced by a pressure cell (Figure 4).

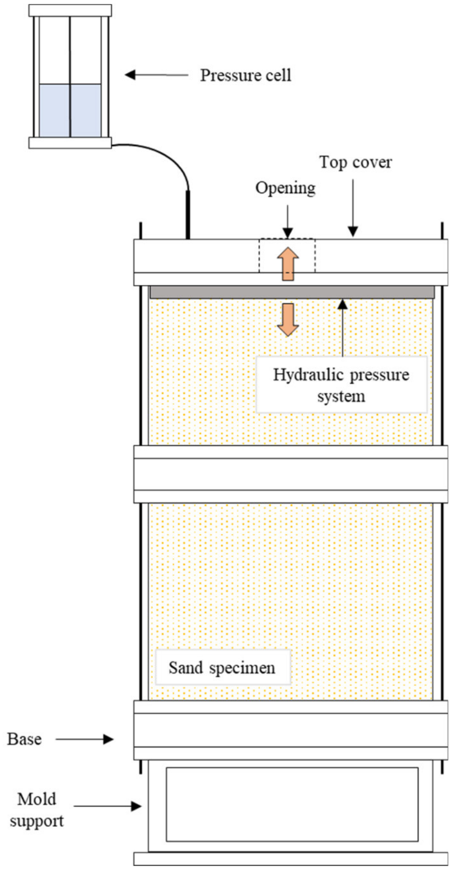

Figure 4 – Calibration mold system.

2.4. Test procedure

Dynamic penetration tests have been carried out in 3 steps: (1) Construction of a specimen in a calibration mold, (2) application of vertical consolidation stress and (3) execution of PANDA 3® dynamic penetration tests.

For the construction of the specimen, the target density index for the test was previously defined and constructed using uniform layers of dry sand deposited according to the index of density specified. Density index between 0,30 and 0,90 were considered, due to the difficulty of constructing specimens of lower density.

For the application of vertical stress, the pressure system is opened until the preset pressure in the test is reached.

For the execution of penetration tests, the conical tip is inserted through an opening arranged in the upper cover of the calibration mold (Figure 4). Once the tip is installed and the test is configured through wave analysis software (Dynawave®)[8], the dynamic striking begins until the pre-set depth and level of vertical stress is reached. This procedure is replicated for all preset vertical stress levels.

To reduce the border effects on the specimen, all those points recorded on 10 centimeters of the bottom and 10 centimeters from the top of the system were excised from the analysis.

The tests performed are summarized in the **Table 2**.

Table 2 – Summary of tests performed.

Test number	I_d	Vertical consolidation stress
Tests 1	0,3	10 Kpa 25 Kpa 50 Kpa 75 Kpa 100 Kpa 200 Kpa 300 Kpa 400 Kpa
Tests 2	0,4	
Tests 3	0,5	
Tests 4	0,6	
Tests 5	0,7	
Tests 6	0,8	
Tests 7	0,9	

3. Dynamic penetration test results

3.1. Density index effect

In the case of the conditions considered in this study, a good fit is observed between q_d^{P3} and I_d (**Figure 5**) for all the conditions of vertical effective stress (σ'_{vc}). The values of factors A and B for different stress conditions are presented in **Table 3**.

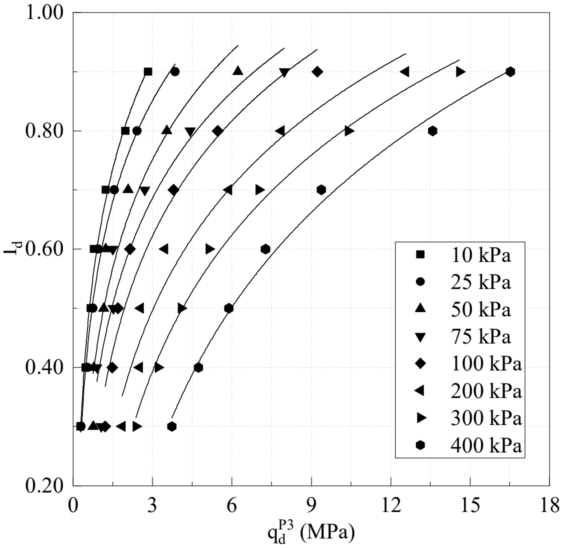

Figure 5 –q_d^{P3}- I_d relationship under different vertical stress conditions.

Table 3 – Correlation factor for q_d^{P3}- I_d (eq. 2).

σ'_{vc}	A	B	R^2
10	0,26642	0,62738	0,98757
25	0,24611	0,58034	0,98942
50	0,26436	0,4607	0,91699
75	0,25909	0,40141	0,8872
100	0,28058	0,31383	0,94336
200	0,30293	0,16344	0,94955
300	0,33288	0,02731	0,99017
400	0,39534	-0,20666	0,99197

3.2. (q_d^{P3} - σ'_{vc} - I_d) relationship

The analysis of the results of penetration tests with different vertical overload pressures (Figure 6), shows that the results can be well adjusted using a potential equation (eq. 3).

$$\sigma'_{vc} = A \cdot (q_d^{P3})^B \qquad \text{(eq. 3)}$$

Through the analysis of non-linear adjustment through iterations, it was possible to obtain an equation that correlates the effective vertical stress (σ'_{vc}), the density index (I_d), and the resistance to dynamic penetration (q_d^{P3}) (eq. 4).

$$I_d = \log_{0,016}\left(\frac{\sigma'_{vc}}{137{,}64\left(q_d^{P3}\right)^{1{,}9}} + 0{,}011\right) \qquad \text{(eq. 4)}$$

The correlation obtained is valid for the material considered in this research, for a dry wet state and for a range of density index values between $0{,}3 \leq I_d \leq 0{,}9$.

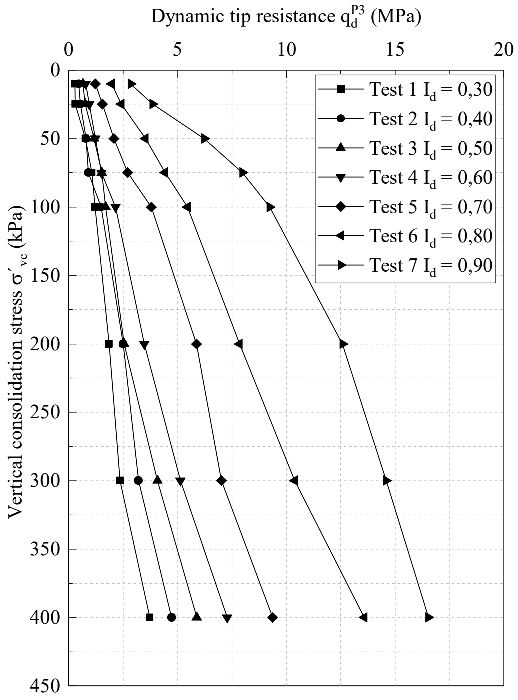

Figure 6 – Dynamic Penetration tests (PANDA 3®) results.

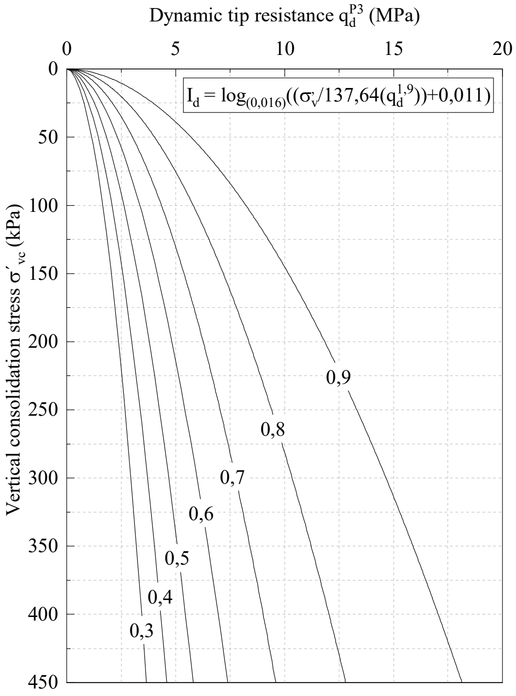

Figure 7 –q_d^{P3} - σ'_{vc} - I_d relationship.

4. Conclusions

This article presents the first results of analysis of resistance to the dynamic penetration of Fontainebleau sands by means of a instrumented penetrometer PANDA 3® that allow wave analysis in an elastic bar. The results show that this analysis technique allows to characterize the geotechnical properties of the soil from the point of view of the soil density index, with a high degree of precision.

The equation obtained based on the tests carried out allows the calculation of the density index as a function of the dynamic tip resistance and effective vertical pressure. The consideration of these variables makes the equation extensible to different soil conditions in site in the case of dry soils in drained conditions, however, progress must be made in the analysis of the effects of suction produced by water content.

References

[1] N. Benahmed, "Comportement mécanique d'un sable sous cisaillement monotone et cyclique : application aux phénomènes de liquéfaction et de mobilité y cylique," Ecole Nationale des Pont et Chaussees, 2001.

[2] J. Alvarado, "Etude des caractéristiques physiques et granulométriques de sables de reference," Ecole Nationale des Ponts et Chaussées, 2000.

[3] M. Benz, "Mesures dynamiques lors du battage du penetrometre panda 2," 2009.

[4] E. J. Escobar Valencia, "Mise au point et exploitation d'une nouvelle technique pour la reconnaisance des sols: le PANDA 3," Université Blaise Pascal, 2015.

[5] E. Escobar, M. B. Navarrete, R. Gourvès, P. Breul, and B. Chevalier, "Dynamic Characterization of the Supporting Layers in Railway Tracks using the Dynamic Penetrometer Panda 3 ®," *Int. Conf. Transp. Geotech. (ICTG 2016)*, vol. 143, no. Ictg, pp. 1024–1033, 2016.

[6] E. Escobar *et al.*, "Reconnaissance dynamique des sites ferroviaires a l'aide du penetrometre PANDA 3®," in *Journées nationales de géotechnique et de géologie de l'ingénieur*, 2014.

[7] L. Chaigneau, "Caracterisation des mileux granulaires de surface al'aide d'un penetrometre," Université Blaise Pascal - Clermont II, 2001.

[8] Sol-Solution, "PANDA 3® LABO Application de recherche micromécanique," Riom, France, 2016.