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Innovative Technologies for the Control of Soil Compaction: Review of the State of the Art and Experiences in Chile

Felipe HERRERA[a,1], Raúl ESPINACE[a,b] y Juan PALMA [b]
[a] *Geotecnia Ambiental, Chile*
[b] *Pontificia Universidad Católica de Valparaíso, Chile*

Abstract. The company Geotecnia Ambiental together with the Geotechnical Group of the Pontificia Universidad Católica de Valparaíso, with financing from INNOVA-CORFO of Chile, approached the challenge of adapting innovative, efficient, environmentally sustainable and precise technologies as alternatives in the process control of soil compaction of Chilean road infrastructure and backfill projects, through an investigation from 2012 and 2014. During the investigation more than twenty state of the art control technologies that exist on a world level were reviewed. Based on the background information dynamic lightweight penetrometer PANDA and the dynamic load plate LFG Pro were selected, of French and German engineering respectively, for use in Chile. Advantages and disadvantages for each system, as well as fields of application, output parameters and proposed methodology were all considered for use in future compaction control projects.

Keywords. soil compaction, compaction control, modulus of dynamic compaction, dynamic lightweight penetrometer PANDA, dynamic load plate LFG Pro, tip resistance to dynamic penetration.

1. Introduction.

It is habitual practice in many civil works projects that the level of compaction that is specified in the design will be directly associated to the method through which it is controlled, that is to say the Proctor percentage of compaction or the Relative Density, more than the desired properties or improving the soil, be it the resistance, deformability, permeability, durability or others.

However, for those who design with consideration for the aforementioned properties, as well as stability during the life cycle of the compacted backfill, it has been a constant worry suitably control constructions of this type, that improve the present compaction control of sand cone or nuclear density gauge methods, which are broadly used, but with great deficiencies defining the desired properties. Only one example achieves the previous, that is the check by Espinace, 1984, [1], where he shows the influence of the state of compaction on sandy fillings, in deformability by static and cyclical actions, obtained for compacted soil on the wet and dry sides of the compaction curve or with diverse levels of energy. This was measured through triaxial static and cyclical tests, simple shear tests, collapsing tests and others.

[1] Corresponding Author: Ingeniero de Proyectos, Geotecnia Ambiental, Blanco 1733 oficina C1, Edificio Costanera Pacífico, Valparaíso, Chile; E-mail: fherrera@geotecniaambiental.cl.

If the importance of calculating with parameters that permit simulating the behavior of the compacted material during the service life of a backfill is considered, it is understandable what brought the investigators to the development of new technologies for the in situ quality control of the compaction of soils.

Currently in Chile as in many other countries, parameters of quality control are applied, including the grade of compaction referring to a maximum objective density, obtained using the Proctor method (Standard or Modified) and/or the maximum or minimum density method or Relative Density. However measurement of the density in situ has employed tests that have been maintained unchanged for tens of years, as is the case of the sand cone test, and more recently the nuclear density gauge test.

Unlike these methods, the innovative technologies focus on the mechanical response of controlled ground before the applied forces, being closer to the criteria of design specified in its construction and to the behavior that the soils will have during the service life of the Project. For example, in countries in the European Union, like Germany, France and Spain, the current tendency is that both the design and the acceptance of the fillers used in the works of flexible pavements and railroads are performed in accordance to its stress-strain behavior. [2][3][4].

2. Existing Techniques at the World Level for the Control of Compaction.

Over the past years, the forces in the world have focused on the development and perfection of a great number of non-destructive technologies that permit the performance of quality control of compaction through improving technically, economically, and environmentally. Among the diverse technologies that have been developed it is possible to distinguish the following groups:

- P**ortable dynamic penetration** devices, equipment that evaluate the state that the solid is compacted by its resistance to penetration. These technologies base their functionality on the application of an impact (dynamic energy) which can be either constant or variable, which permits the driving of a series of bars with a conical point at its end. The dynamic lightweight penetrometers which use a known constant energy are **DCP-Standard, DCP-Utility and PANDITO**, while in the variable energy group there is the **PANDA** penetrometer. The parameter received from these penetrometers is the soil resistance opposing the dynamic penetration of the point, which can be correlated to the level of compaction and other mechanical properties of the material.
- Measuring devices that utilize the **stress-strain relationship**, that base their function on the application of a dynamic and/or static force over the material through a load plate, evaluating the response of the soils in accordance to the elastic deformation generated. Within these devices are the **load plate tests with static plates and dynamic lightweight and the falling weight deflectometer (FWD)**. From this methodology the modulus of deformation and stiffness of the compacted material are obtained, as are the parameters that are related with the level of compaction and mechanical properties of the soil.
- The **seismic methods**, which based their operation on the measurement of the solid stiffness by means of their response to elastic high-frequency waves

applied to the compacted material. Considered in this group of devices, are the **Portable seismic property analyzer (PSPA), Soil Stiffness Gauge (GEOGAUGE), Soil Compaction Supervisor (SCS) and the Intelligent Compaction (IC).**

- Finally there is the **electric equipment**, which bases their functions on the obtainment of the density and moisture content of the ground from the measurement of electric properties like conductivity, resistance or impedance of the soil. Within this category there are the **Moisture Density Indicator (MDI), Soil Density Gauge (SDG) y Electrical Density Gauge (EDG)**.

Table 1 presents a summary of the main advantages and disadvantages perceived from the reviewed equipment in the context of this research project.

Table 1. Advantages and disadvantages perceived between the main equipment considered in the review of information. Sources: [2][5][6][7][8][9].

Equipment	Advantages	Disadvantages
Dynamic lightweight penetrometers using constant energy (DCP, PANDITO)	Correlations with resilient modulus (Mr). Economical equipment. Simple to use. Standardized methodology in Chile.	Requires two operators Requires previous calibration for the soil as a control (grade of compaction and moisture level). Does not detect layer thickness Results depend on operator.
Dynamic lightweight penetrometers using variable energy (PANDA)	Detects layer thickness. Depth of up to 6m. Management and storage of information internally. Standardized methodology in Chile.	Requires previous calibration for the soil as a control (grade of compaction and moisture level). High initial investment.
Dynamic lightweight load plates (Models LFG-Pro, Prima 100)	Simple to use. Verifies the parameters of design (Mr) through correlation. Correlation between the distinct dynamic lightweight plates, the FWD and the static load plate. Standardized methodology.	Requires previous calibration for the soil as a control (grade of compaction and moisture level).
Falling weight deflectometer (FWD)	Permits control of multilayers systems Verifies the parameters of design (Mr) through back-analysis. Correlates between the distinct dynamic lightweight plates and the static load plate. Standardized methodology.	Requires a trailer for transport Can not be employed in confined spaces High initial investment.
Seismic Method, GeoGauge	Compact equipment of smaller size. Standardized methodology.	Low depth of evaluation (less than 30 cm) Needs previous ground parameters (G and E)
Electrical devices (MDI, SDG y EDG)	Compact equipment of smaller size. Returns the density and the moisture content. Standardized methodology.	Difficult to drive the bars into the grain size Chilean base. A complex calibration Calculation models require a wide variety of variables.

3. The Dynamic Lightweight Penetrometer PANDA and Dynamic Plate LFG Pro.

Based on criteria such as: the previous experiences in Chile, relation of simplicity of use and necessary calibrations versus quality of delivered information, amount and quality of existing studies at a world level, regulatory support and technical manuals that regulate and recommend the use of the technology and employability in a wide variety of soils that exist on a national level the following were selected from all the previous methods as the equipment used in the investigation: the dynamic lightweight penetrometer PANDA and the dynamic lightweight load plate LFG Pro (see figure 1).

Figure 1. Dynamic lightweight plate LFG- Pro (left) and Dynamic lightweight penetrometer PANDA (right).

3.1. Dynamic Lightweight Penetrometer PANDA.

The PANDA (Pénétromètre Autonome Numérique Dynamique Assisté par Ordinateur) equipment is a pile driving device utilizing a group of rods with a conical point. The energy is provided by human force against a standardized hammer blow (See figure 1). This equipment belongs to the variable energy dynamic lightweight penetrometer family. The PANDA measures the penetration and applied energy for every impact and using an incorporated microprocessor the device outputs the soil tip resistance (qd [MPa]), calculated using the Dutch formula for pile driving (Eq. 1) [10]. This equation considers the mass of the standardized hammer (M), the energy applied in every hammer blow (E) which is measured by the device, the penetration of the point in the soil (e) which is also measured by the device and the mass of the rods, the point and the impact head (P) which is registered by the user. Also required is the surface area of the conical tip (A_c), which can be two distinct values depending on the use; it can be 2 cm^2 and 4 cm^2 which allows a maximum penetration depth of approximately 1.5 m and 6.0 m respectively.

$$q_d = \frac{1}{A_c} \times \frac{E}{e} \times \frac{M}{M+P} \tag{1}$$

The equipment presents diverse uses: quality control and surveys of the soils. The French norm XP P 94-105, regulates the use of the equipment in the control of compaction, recognized three functions: **Function A**, recognizing of compacted layer thickness; **Function B**, control of compaction based on the calibration in laboratory of the parameter qd for the dry density of the material; **Function C**, compaction control based on the in situ calibration of the parameter qd for the dry density of the material.

In Chile this equipment has been used for more than 10 years of in the compaction control of tailings dam, estimating the potential for liquefaction of tailings sands and natural sands in Chile, as well as tests for the verification of soil behavior in depth for civil works projects [11][12][13][14]. Furthermore there are Chilean norms regulating the use in Chilean Mining [**NCh 3261 of 2012**].

3.2. Dynamic Lightweight Plate LFG-Pro.

The dynamic lightweight plate originated in Germany in the 1980's, and was designed to evaluate road structures using an adaptation of Boussinesq's analytic solution (Eq. 2). The equipment consists of three main parts (See figure 1). The load plate, which is responsible for transferring the stress generated by the fall of the mass to the ground, the impact generating assembly, the parts that produce the dynamic force over the ground using the guided fall of a standard mass; and the settlement sensor, which is located in the center of the plate, aligned perpendicularly to the ground, and measures the deformation in the ground at the center of the plate.

$$E = \frac{(1-\nu^2) * \sigma_0 * r}{s_0} * f \tag{2}$$

The Boussinesq analytic solution calculates settlements under rigid, circular foundations. One of the first necessary assumptions is that the dynamic modulus of deformation (E_d) for the LFG-Pro equipment will be equivalent to the modulus of deformation for static loads (E) used in the Boussinesq solution. The solution of the dynamic modulus of deformation (E_d) (Eq. 2) will be expressed as a function of Poisson's modulus of the ground (ν), the force applied on the ground by the plate of the LFG-Pro (σ_0), the plate radius (R), a shape factor that describes the stress-strain relationship between the plate and the ground (f) and the ground deformation under the center of the plate due to the dynamic force (s_0). The LFG-Pro only has sensors to measure the settlement generated under the plate (s_0 [mm]), therefore it is necessary to assume that the other variables in equation 2 remain constant with the pre-established values from the manufacturer, resulting in a value of 22.5.

The devices norms exists in Germany (TP BF-StB Parte B 8.3), and Spain (UNE 103807-2:2008) and also is standardized ASTM (E2835-11). The procedure indicated allows the measurements direct the modulus of dynamic deformation of the material, and therefore serves as an indirect measurement of the grade of compaction of the controlled soils. The main job given to this technology at an international level corresponds to the verification of road works and railroad designs through the correlation of the LFG-Pro dynamic modulus with the results obtained for the load test with a static plate. The LFG Pro is also used for compaction control in service trenches. [3][4].

4. Experiences of Innovation in Chile and Cases.

A series of visits to diverse works were performed as research for this study. The following are presentations of some of the results.

4.1. Case Study; Site N°1.

This case correspond to two embankment constructed with silty sand (named locally "maicillo") characteristic of the central zone of Chile; one was an existing embankment where the level of compaction at depth was unknown and the adjacent embankment was new and compacted. The series of tests were completed with the dynamic lightweight penetrometer PANDA, dynamic lightweight plate and in-situ density using a nuclear densimeter.

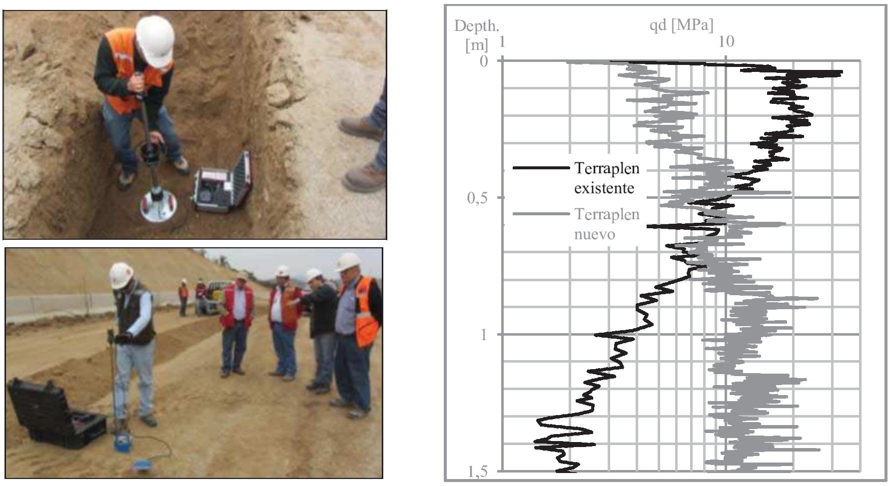

Figure 2. Tests with technologies in the study site (left) and Penetrogram received from the dynamic lightweight penetrometer PANDA on study site (right).

Figure 2 shows test conducted with the new technologies and the results obtained with the PANDA penetrometer, where it is possible to estimate that the first 0.5 to 0.7 m of the existing embankment (see "terraplén existente" in figure 2) show a compaction greater than 95% OPM (Modified Proctor Optimum density) in accordance with the results from the nuclear densimeter. After this depth the material shows a reduction in the level of compaction. The aforementioned situation contrasted with the recently compacted embankment (see "terraplén nuevo" in figure 2), which shows a grade of compaction greater than 95% OPM for the whole thickness of the controlled layer (1.5 m). The results show that for zones with compaction of 95% OPM the PANDA registers a value of point resistance greater than 10 MPa. The evaluation performed with the LFG-Pro on the surface showed that the soil compacted to 95% OPM has a deformation modulus greater than 30 MPa, meanwhile the tests performed at a depth of 1 m (test pit) in the existing embankment showed values around 10 MPa.

4.2. Case Study; Sites N°2, N°3 y N°4.

The following presents a summary of three reviews completed in the northern and central zones of Chile. Characterization of materials was performed in all the study sites, as well as evaluations using sand cone, nuclear densimeter, PANDA penetrometer and LFG-Pro dynamic plate (see table 2). Figure 3 shows the results obtained using the PANDA in the three sites with respect to the control curve for gravel with fine silts (GM) compacted to 95% OPM and with moisture less than the optimal compaction moisture (OMC) presented in the analysis software developed by the company Sol Solution. For the LFG-Pro, the results from the three sites show that the deformation modulus is greater than 35 MPa (See table 2), which is the reference value of a level of compaction greater than 95% OPM corresponding to silty gravel in the German technical specifications [3][4].

Table 2. Material characterization and results obtained using Sand Cone, Nuclear Density Gauge, PANDA penetrometer and LFG-Pro dynamic plate.

Site	Soil classification		Max. dry density	OMC [%]	OPM [%]	Moisture range [%]	q_d PANDA [MPa]	E_{vd} LFG-Pro [MPa]
	USCS	AASHTO	[gr/cm^3]					
N°2	GP	A-1-a (0)	2,23	8,1	98	3,4 ± 0,6	7; 18	43,2 ± 7,9
N°3	GP-GM (ML)	A-1-a (0)	2,16	6,3	96	3,1 ± 0,6	13 ; 25	47,4 ± 8,2
N°4	GP-GM (ML)	A-1-b (0)	2,24	6,0	95	6,0 ± 0,4	6 ; 17	44,4 ± 8,5

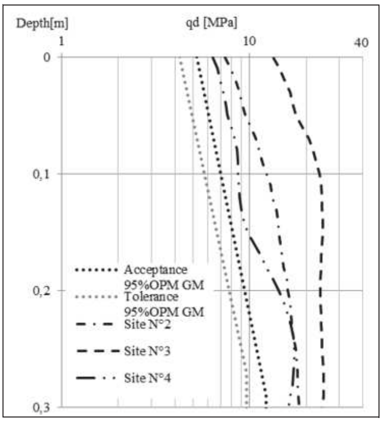

Figure 3. PANDA Penetrogram for sites N°2, N°3 y N°4, compared with French reference curves.

The results obtained using traditional technologies as well as those used in this study, in correspondence with the acceptable criteria of the countries of origins; demonstrate that the gravels studied show a level of compaction greater than 95% OPM.

5. Conclusions.

The compiled worldwide information, the 10 worksites visited in Chile for this study as the motive and experiences with the previous technologies has led to these conclusions:

- The dynamic lightweight load plate LFG-Pro like the dynamic lightweight penetrometer PANDA allows the performance of the indirect control of the grade of compaction of road works. The value that is obtained from these devices according to the existing methodologies is in a direct relationship to the type of material evaluated, and the hydraulic state of the material.
- The use of the penetrometer PANDA is recommended for backfill and multilayer systems for its advantages in reachable depth (up to 6 m) and detection of layer thickness.

- Advantages were observed in the use of the LFG-Pro in the control of layer of up to 30 cm in linear works of a large area, due to its simplicity to transport and speed of execution (less than three minutes).
- The dynamic lightweight load plate LFG-Pro allows the testing of influential parameters of design are directly measured by the stress-strain behavior of road works (Modulus of dynamic deformation).
- The output results of the two technologies are highly dependent on soil water content. While the PANDA penetrometer presents a clearly defined moisture correction criteria the dynamic lightweight load plate LFG-Pro does not. Until there are a sufficient number of tests and experiences to improve the test procedures it is proposed that LFG-Pro uses in a range of ± 2% for the optimal moisture of compaction obtained in the Proctor procedure.
- It is proposed that for now, both technologies will be complementary to the used of the nuclear density gauge, recommending the decrease in control points by this method, and integrating a great number of tests by means of dynamic lightweight plate LFG-Pro and dynamic lightweight penetrometer PANDA that allow identification of deficient zones.

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