Borehole expansion tests: State of the art of ISO standardization

Essais d'expansion en forage : état de l'art de la normalisation ISO

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ABSTRACT

Borehole expansion tests refer to various equipment and procedures. Their implementation is now covered by four international ISO standards, allowing a distinction between Ménard pressuremeter tests and other expansion tests, whether prebored, self-bored or performed with a full displacement pressuremeter. Especially, standards covering pre-bored tests have recently evolved to provide a coherent framework for their execution for any type of grounds (soils and rocks), with specific loading programme dedicated to parameter identification for reliable ground model, making borehole expansion tests a recognized technique for ground characterization, in line with the ongoing revisions of Eurocode 7.

RESUME

Les essais d'expansion en forage impliquent des matériels et protocoles très différents. Leur réalisation est désormais couverte par quatre normes internationales ISO, permettant de distinguer les essais au pressiomètre Ménard des autres essais d'expansion en général, qu'ils soient réalisés i) en préforage, ii) au pressiomètre autoforeur ou encore iii) mis en œuvre par refoulement. En particulier, les normes ISO couvrant les essais en préforage ont évolué, et permettent de fournir un cadre cohérent pour leur réalisation, quelle que soit les terrains (sols et roches), avec des programmes de chargement dédiés à l'identification de paramètres pour un modèle géotechnique plus fiable, permettant d'inscrire pleinement les essais d'expansion en forage parmi les techniques de caractérisation des terrains pertinentes et en phase avec les révisions en cours de l'Eurocode 7.

Keywords: Standardisation, Eurocodes, Eurocode 7, Ménard pressuremeter tests, Soil, Rock, Self-boring pressuremeter, Full displacement pressuremeter

1. Introduction

This paper provides an overview of history and current situation of the ISO standardization of borehole expansion tests *i.e.* pressuremeter test used for geotechnical soil characterization. The main types of tests are now governed by ISO 22476 series. The paper outlines the evolution of these standards in connection with the ongoing revision of Eurocode 7. Recent revisions of ISO 22476-4 and -5 standards are underlined, and subsequent clarification of their scope, harmonization of their procedures and enhancement of pressuremeter tests reliability are emphasized.

2. Context

2.1. History and early developments

Borehole expansion tests have been developed since Louis Ménard's 1955 patent for the Ménard pressuremeter device (Ménard 1955), which included both equipments (probe and pressure volume controller) description, a loading procedure and methods for calculating the derived test parameters of compressibility and failure. The history of these pioneering years was recalled after the inventor's very young death (Kérisel 1979, Gambin 1980, 2005, Lopes Dos Santos 2023, Reiffsteck et al. 2023 and 2024). Early in the history of the equipment, Ménard proposed a field memorandum detailing the equipment, the insertion of the pressuremeter probe in test cavity and fixing the loading procedure to carrying the pressuremeter test (Ménard, 1958).

2.2. Testing protocols and standards

As Ménard pressuremeter parameters were early introduced in efficient design French methods of foundations, they become widely used in daily French practice, that led firstly to a French administrative protocol (LCPC 1971) formalising the cited Ménard document, itself supplemented by a brochure on drilling methods (D10, 1970). The establishment of this protocol can be considered as an initial standardization (Kérisel, 1979), and the development of the main advances in direct design with the Ménard pressuremeter was based on these practices, the first "true" standardization not having taken place until 1991: through the first official national standard, NF P94-110 : Sols : reconnaissance et essais, Essai pressiométrique Ménard (AFNOR 1991). This standard was focused on and limited to probes used in France, and then very prescriptive on the interpretation method and let very few possibilities to the operator. This trend was confirmed with the revision of NF P94-110, becoming NF P94-110-1 (AFNOR 2001), with the imposition of digital recording of measurements, and the development of generalized computed assisted interpretation procedures, that was written in way that every user would derive the same interpreted Ménard parameters for a given set of pressure-volume measured data.

In the same period, standardization in foreign countries follow the expansion of Ménard company. We can cite among others:

- GOST 20276-85 Soils, field method for determining deformation characteristics (GOST, 1985),
- JGJ 69-90, specification for prebored pressuremeter test, professional standard of Peoples's Republic of China (MOHURD 1990),
- ASTM 4719 Standard Test Method for Prebored Pressuremeter Testing in Soils (ASTM 2020 / originally published 1987, see also Briaud et al 1986).

In parallel, pressuremeter testing in general has been introduced in several standards and generalized, enlarging the initial scope of test, to concern both soils but also rocks, addressing the ground response during unload-reload loops, and we can quote the following:

IRSM Suggested Method for Deformability Determination Using a Flexible Dilatometer (IRSM 1987),

AFNOR, XP P94-110-2, Sols : reconnaissance et essais - Essai pressiométrique Ménard - Partie 2 : essai avec cycle, 12/1999

AFNOR, XP94-443-1 & 2, Roches - Déformabilité - Essai dilatométrique en forage - Partie 1 : essai avec cycles et Partie 2 : essai de fluage après le premier cycle, AFNOR 2002).

2.3. Current organization of international standardization

In conjunction with the implementation of the Eurocodes, which are design standards for structures—specifically EN 1997 series, Eurocode 7, related to geotechnical design (Parts 1 and 2, respectively CEN 2004 and 2006), geotechnical testing ISO standards have been developed jointly by CEN and ISO (leading to EN ISO standard in the CEN countries).

Initially, four different ISO standards have been proposed to cover borehole expansion tests, organized as follows:

- ISO 22476-4 – Ménard Pressuremeter Test (ISO 2012)
- ISO 22476-5 – Flexible Dilatometer Test (ISO 2012)
- ISO 22476-6 – Self-bored Pressuremeter Test (ISO 2018)
- ISO 22476-8 – Full Displacement Pressuremeter Test (ISO 2018)

Initial versions of these standards were fully developed under the auspices of CEN and its Technical Committee (TC) number 341. This ensured that the drafting aligned both in spirit and in the practical notations used in the Eurocodes.

Recent changes have led to these standards now being developed under ISO\TC182, although drafting principles remain unchanged—particularly the alignment with Eurocode writing philosophy.

3. Revision of pre-bored testing ISO standards

3.1. Scope of the recent revisions

The first two standards mentioned above—covering the Ménard pressuremeter and flexible dilatometer—have reached their first natural revision "cycle, fixed to five years. The revisions aim to update the scope of the documents to clearly and explicitly cover all borehole pressuremeter tests.

Thus, the scope of ISO 22476-4 edition 2 (ISO, 2021) remains the Ménard pressuremeter test. Conversely, ISO 22476-5 (ISO, 2023) is now renamed as the "Pre-bored Pressuremeter Test," distinguishing it explicitly from the previous standards, and from ISO 22476-6 and -8 (ISO 2018a, 2018b), which deal with self-bored and full displacement pressuremeter tests, respectively. The scope of different PMT-related ISO standards are summarized in Table 1.

Tableau 3-1: scopes of ISO standards

ISO 22476-i	PMT scope	Publication date	Edition
4	Ménard	2021	2
5	Prebored	2023	2
6	Selfbored	2018	1
8	Full-displacement	2018	1

It's worth mentioning that the revision work of ISO 22476-4 and -5 has been conducted in parallel to ensure consistency.

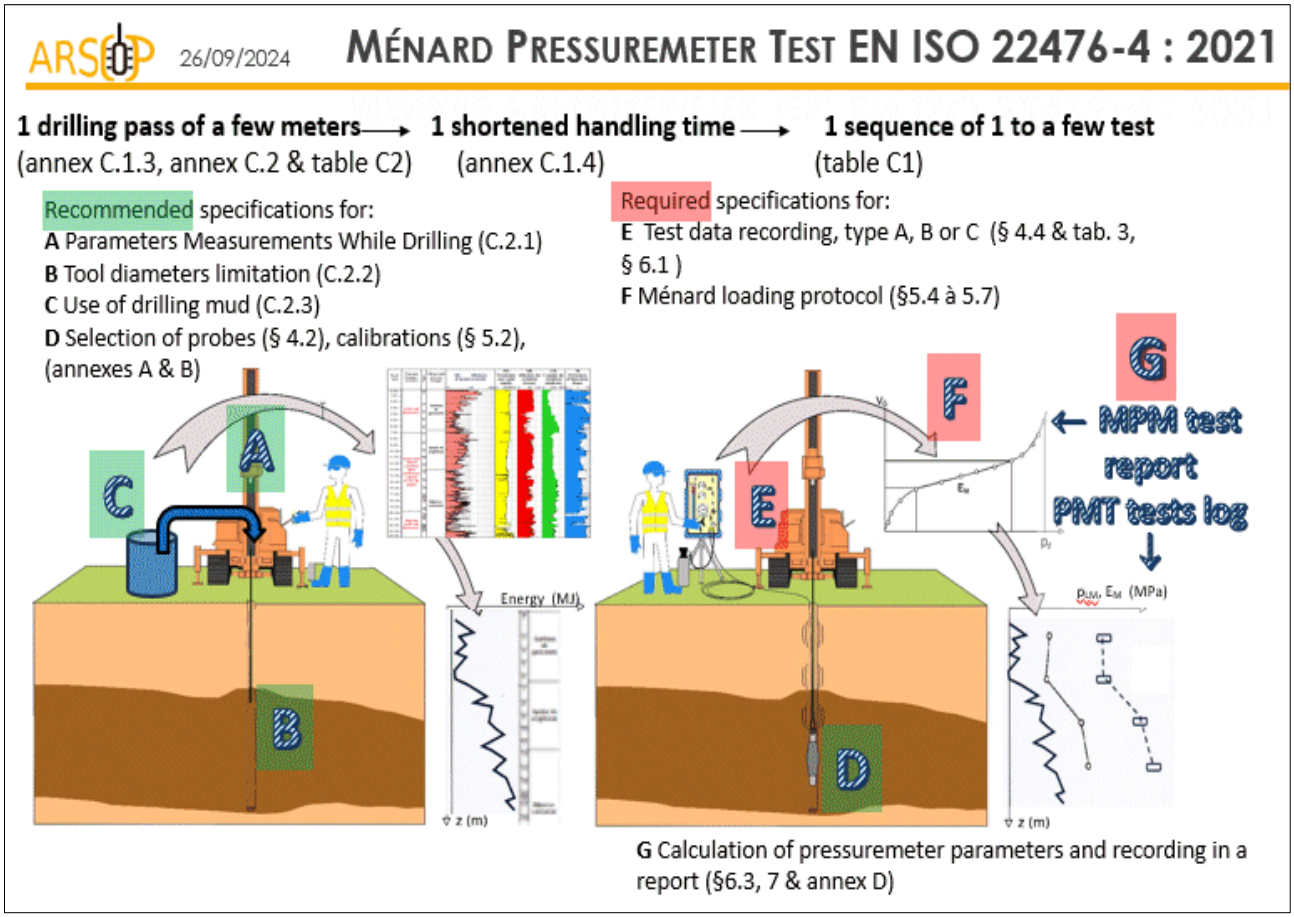

Figure 1. Summary of the main provisions of the standard "Ménard Pressuremeter test" (ARSCOP final meeting, Paris, 2024)

Table C.2 — Guidelines for pressuremeter probe placement technique

Probe placing in the soil			WITHOUT SOIL DISPLACEMENT :									Probe placing by pushing out soil	
LEGEND			Pre-drilling technique										
Soils & rocks types ↓	***	Recommanded	$1 < d_t/d_c \leq 1{,}1$ (V_A < 90 m/h ; P_l < 500 kPa ; Q_l < 15 l/min ; V_r < 60 rotation par minute)									$d_t/d_c \leq 1$	
	**	Suited											
	*	Acceptable											
	-	Non suited	ROTARY DRILLNG				ROTARY-PERCUSSION			SPLIT TUBE		PUSHED/DRIVEN PROBE	
according to ISO 14688 (all parts), and ISO 14689		Non covered by the standard	OHD Open Hole Drilling (+mud)	HA Hand Auger (+mud)	CFA Continuous Flying	CD Core Drilling	RP Single ROTARY PERCUSSION	RPM ROTARY PERCUSSION +	STDTM SELFBORING SLOTTED TUBE	PT Pushed Tube	DT/VDT Driven or Vibrodriven Tube	PUSHED PROBE	DST (Vibro)Driven Slotted Tube
FINE	CLAYS	sludge to soft	**	***	*	*		-	*	***	-	*	-
		soft to firm	***	***	**	**	-	*	**	**	*		
		stiff	***	*	***	***	*	**	**	*	*		
	SILTS	DRY	***	***	***	**	-	*	**	**	*	-	-
		UNDER WATER TABLE	***	**	-	*	-	*	**	-	-	*	*
COARSE	LOOSE SANDS	DRY	***	***	**	*	-	**	**	-	-	-	-
		UNDER WATER TABLE	***	**	-	-	-	**	**	-	-	*	*
	SANDS & GRAVELS	Medium to Dense	***	**	***	**	*	***	***	-	*	-	**
		Gravels	**	-	-	*	*	***	***		*	-	***
		Cobbles	**			**	**	***	**		-	-	**
INTER- MEDIATE	COARSE COHESIVE		**	-	*	**	*	***	**		*	-	*
	NON HOMOGENEOUS		**	*	*	*	*	**	**	-	*	*	**
H.S.S.R.	CHALK		***	*	**	**	**	**	**		*		
	SOFT ROCKS		***	-	*	***	**	**	**		-		
ROCK	SOUND ROCKS		**		-	***	***	***	*		-		
		SCORE * by drilling method	39	21	19	26	14	30	30	8	8	4	12

Figure 2. ISO 22476-4: 2021. Presentation of table C2 guidelines for pressuremeter probe placement techniques (ARSCOP final meeting, Paris, 2024)

3.2. Second edition of ISO 22476-4 – Pressuremeter test by Ménard procedure

The second edition of ISO 22476-4 (ISO 2021) has been published in September 2021.
It incorporates especially the following modifications (Fig. 1):

- Opening to a wide range of probes, to overcome the previous limitations to historical "French type of probes", including:
  - Overall set-up of the probe: type of measurement of the cavity expansion, volumetric vs radial.
  - Tricellular Ménard probes with guard cells or monocellular probes with length / diameter slenderness conditions,
  - Dimensions, open from very small diameters (mini pressuremeters) to large diameters required for internal sensor systems.
- Suitable drilling techniques, consistent with the international standardization drafting philosophy (see Fig. 2 & 3) and drilling lengths before performing the test, designed to minimize decompression time before a test inside preliminary drilling,
- Suggestion to practice Measurement While Drilling (MWD) during PMT preboring,
- Distinction of 3 types of PMT control and recording units, types A, B & C:
  - Type A for historical Control Units with manual data collection
  - Type B for Control Units equipped with digital data recording for pressure and volume
  - Type C for Control Units equipped with automatic pressure regulation and digital data recording
- Generalized loading program, including the criteria to stop the test,
- Limit pressure p_{lM} (opening to different fitting and extrapolation techniques, as far they are considered relevant) and pressuremeter creep pressure p_f,
- Clarification of terms, notations and symbols.

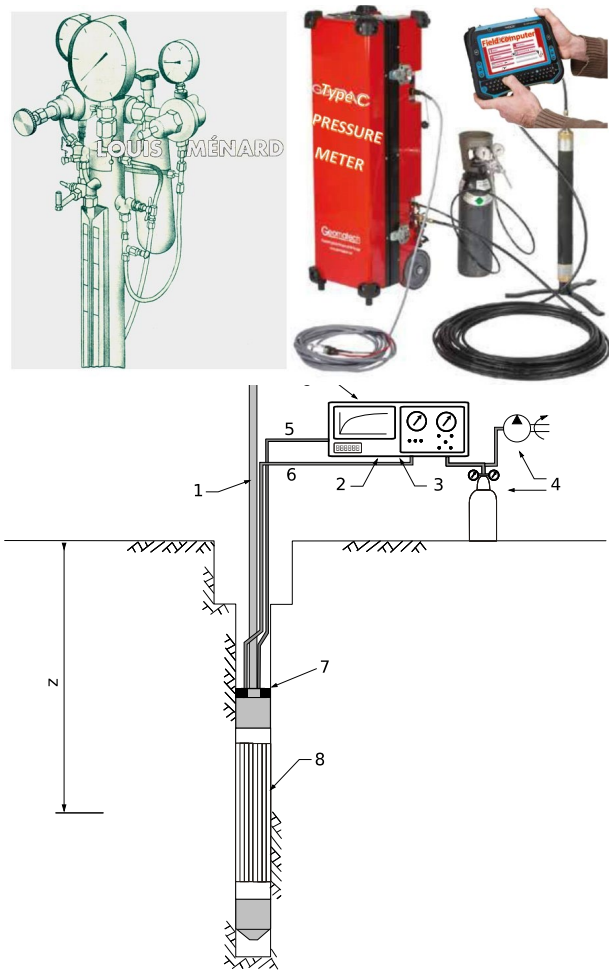

Figure 3. ISO 22476-4: 2021. Placement of the probe for Ménard and prebored pressuremeter techniques

Where:

1 setting rods
2 displacement or volume measuring unit
3 pressure control unit
4 pressure source
5 signal cable
6 connecting line
7 probe rode coupling sediment collection tube
8 pressuremeter probe
9 data logger

3.3. Second edition of ISO 22476-5 – Pre-bored pressuremeter test

The second edition of ISO 22476-5 (ISO 2023) has been published in March 2023.
It's organized in the following philosophy:

- It refers to ISO 22476-4 for clauses related to probe placement in soils,
- From the calibration points of view, the standard:
  - Refers to calibrations described in 22476-4 for limited values of pressuremeter modulus;
  - Introduces additional calibrations procedures to address especially high values of pressuremeter modulus (corresponding to an apparent shear modulus $G_{app} = \Delta p_c/\Delta\gamma_c) \geq 250$ MPa), where p_c is the pressure at the cavity wall, γ_c the shear strain or distortion at the cavity wall), as provided in Figure 4 and also during unloading phase in Figure 5;

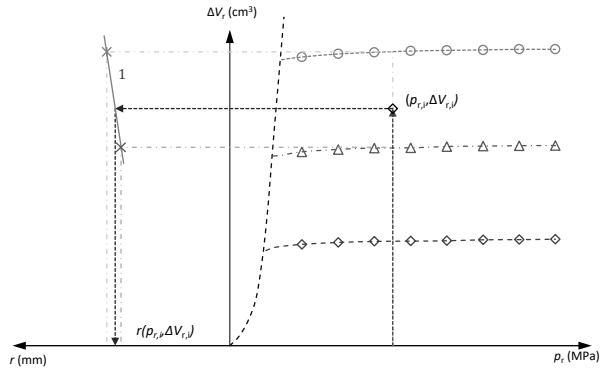

Figure 4. ISO 224376-5/ 2023. Additional calibration with calibration cylinders of different diameters

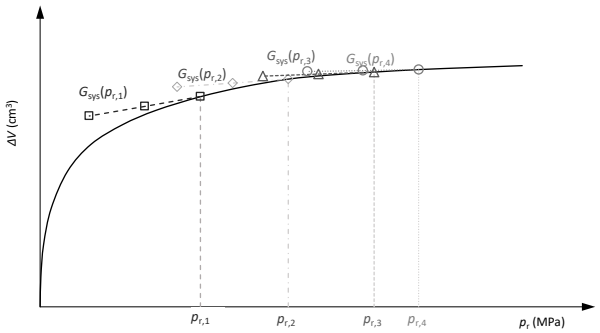

Figure 5. Additional calibration during unloading phases

The standard accepts the use of a wide range of equipment, as well as for probes and for pressure volume controllers.
The expansion of the borehole shall be monitored by volume or diametral or perimetral displacement measurement. The probe shall have a cover in a shape of monocellular (examples II and III Figure 6, middle and right) or tricellular (example I Figure 6, left) probe.

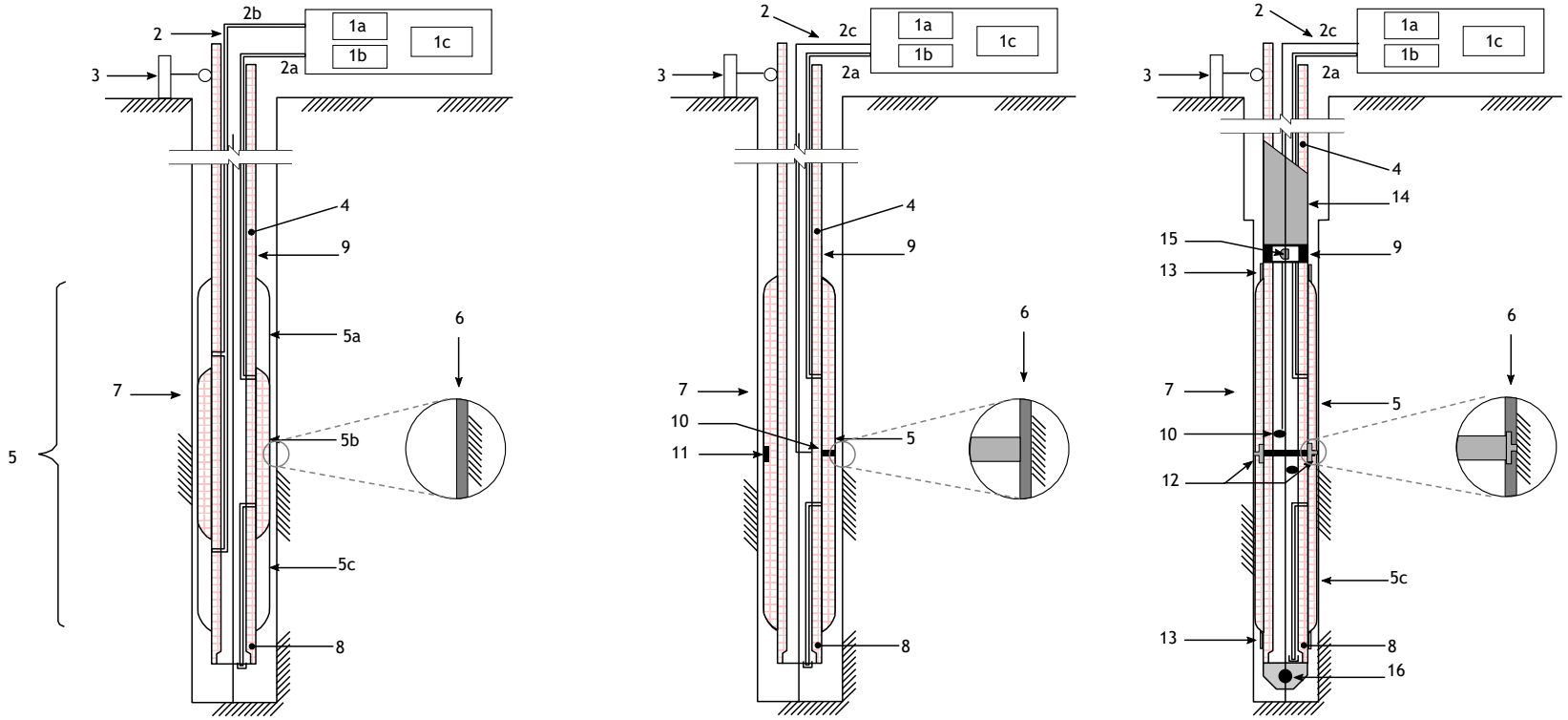

Figure 6. ISO 22476-5/ 2023. Sketch of pressuremeter (not to scale) - Example I II and III

1 control unit (CU): 1a - pressurization, differential pressurization (if any) and injection devices / 1b - pressure and displacement or volume measuring devices / 1c - acquisition, storage and printing out of the data (required for CU type B and C)

2 connecting lines: 2a - line for liquid injection / 2b - line for gas injection /c 2signal cable

3 depth measurement system

4 setting rods

5 pressuremeter probe: 5a - upper guard cell / 5b - central measuring cell / 5c - lower guard cell

6 ground

7 pressuremeter test pocket

8 probe body, hollow

9 probe rod coupling

10 and 11 displacement transducers

12 metal insert at the extremities of the displacement transducers

13 membrane clamping ring

14 sediment collection tube

15 pressure transducer (if applicable)

16 compass (if applicable)

- It introduces four reference procedures, as shown in Figure 6, A to D;
    - Procedures A and B covering tests with a limited number of unload-reload loops,
    - Procedure C corresponding to creep and dissipation tests,
    - Procedure D introducing cyclic tests,
- It does not provide any provisions for test interpretations. However, it emphasizes that ground and especially soils present a non-linear behaviour during the test, that can be addressed considering non-linear elasticity and that has tobe considered during the test interpretation and the derivation of any relevant modulus;
- It also includes clarification of terms, notations and symbols.

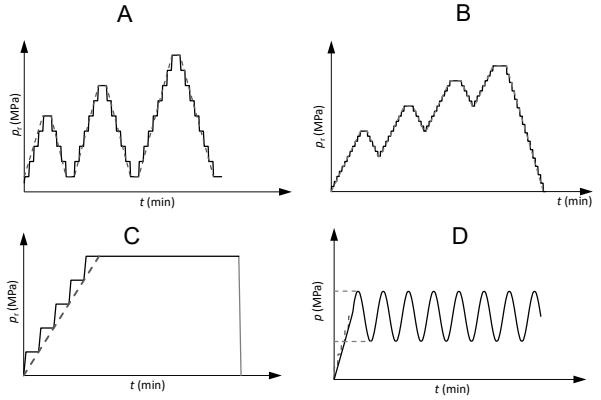

Figure 7. ISO 22476-5. Reference procedures A to D

4. Conclusions

This paper provides an overview of the state of the art in standardization related to borehole expansion tests.

This short text and the references show how national and international standards have gradually integrated the numerous diversifications and modernizations of in situ expansion measurements of a pressuremeter cavity.

At the same time, maintaining a test protocol that has been almost immutable since the beginning guarantees the sustainability of the direct design of foundations resulting from Ménard pressuremeter, as retained in Eurocode 7.

The second edition of the NF EN ISO 22476-4 standard was published in 2021. The second edition of the NF EN ISO 22476-5 standard occurred in 2023.

The next revisions of these standards might include several new items, such as innovative drilling methods allowing to limit remoulding during cavity execution and probe installation or as closely as possible to respect the characteristics of the virgin soil, or add-ons to the loading programmes that would allow to derive the horizontal earth pressure at rest. Overall homogenization of the four pressuremeter ISO standards will also be continuously sought.

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