CONTRIBUTIONS OF CANADIAN EXPERIMENTS TO THE DEVELOPMENT OF PRESSUREMETER TECHNIQUES

CONTRIBUTIONS DES EXPÉRIENCES CANADIENNES AU DÉVELOPPEMENT DES TECHNIQUES PRESSIOMÉTRIQUES

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1. Introduction

This paper aims at presenting Canadian contributions to the pressuremeter techniques by reporting experiments of three Canadian companies, which have being closely involved in the spreading of these techniques in North America. These companies are: *Roctest Ltd* and *Geopac Tech Inc*, both based in Québec, and *Hughes Insitu Engineering Inc*, based in British Columbia.

Professor Rochette, from the *École polytechnique de Montréal,* conducted the first pressuremeter tests (PMT) in Canada with the collaboration of one of the authors of the present paper. Over the next forty years, and following an exclusive dealing agreement between *Techniques Louis Ménard* and *Roctest,* new types of pressuremeters were developed and marketed, and thousands of tests were performed throughout North America. Main contributions resulting from this are:

- the use of pressuremeter tests in specific applications where conventional geotechnical investigation methods are ill adapted or downright impossible to use;
- the development of unique implementation methodologies, specifically in the field of dynamic compaction;
- the design of a new range of equipment, better suited to local conditions and easier to operate, which among other things lead to the possibility of testing hard rock with new types of dilatometers.

2. Specific applications

In Canada, the progression of pressuremeter techniques has been slow due to strong implementation of generally accepted geotechnical investigation techniques.

In the '60s, most geotechnical investigations were performed by drilling companies and monitored by soil laboratories. These drilling companies were not always equipped to execute undisturbed boreholes. The use of bentonite slurry was almost non-existent, as was the use of Menard D9000-type auger drills. Borings were mainly performed by driving-in. The standard penetration test (SPT) and Shelby tube samplings used in conjunction with laboratory testing were the generally accepted methods. Also the vane testing, using a rudimentary instrument fixed directly on top of the casing, was a frequent application. This test disturbed the soil considerably. Later came the Swedish vane test, with its slip ring and much more efficient thin vanes. The static penetration test (CPT) was occasionally used, mostly in Western Canada.

Geological formations encountered in Eastern Canada often consist of sensitive clay layers, sometimes varved, on top of dense coarse tills, which make PMT borings very complicated. PMTs were quickly confined to situations where conventional methods proved ineffective:

- the study of coarse fills, specifically in cases of dynamic compaction works where PMT reveals itself as an ideal control method. This type of ground control has lead to the development of unique implementation methodologies, with test results validated by settlement measurements after construction;

- the study of soft rocks, specifically in the design of caisson anchorings and of power line towers submitted to overturning forces;
- the implementation technique of retro-jet probes in ultra-sensitive clays, which have produced remarkable results. The purpose of these tests was to compare cohesion values obtained from vane tests with those obtained with the pressuremeter. The PMT has not been utilized for soil characterization essentially as a precaution;
- the methods involving self-boring probes. These methods, requiring sophisticated equipment such as Cambridge in-situ, are used mainly by companies in Western Canada. A simple self-boring pressuremeter, designed by Roctest and involving Menard-type hollow probes and two strings of rods, was also utilized in fine sands deposits. Finally, model PAF self-boring pressuremeters from the *Ponts et Chaussées* of France were used –with the participation of Baguelin and Jézéquel– especially by the California Department of Transportation. Despite the quality of the obtained results, the equipment cost and complexity limited its distribution.

The following sections present some examples of PMT applications.

2.1. Control of dynamic compaction using slotted casings

At its beginning, dynamic compaction (densification), which was first used in North America in the ’70s, was closely related to the PMT for ground control (Dumas and Morel, 1995). However, a recent trend was observed; it consist in limiting ground control to purely empirical methods such as penetration tests performed with Becker-type earth-boring machines (BPT).

Since many dynamic compaction applications are on fills which include boulders or blocks of various sizes, traditional borings are difficult to perform. Figure 1 shows that the developed technique requires (1) a 14-cm diameter borehole to be drilled, (2) to fill it with gravel, and (3) to drive in a slotted casing. After compaction, (4) pressuremeter tests are conducted inside the slotted sections (at every 1.5 m). In some cases, to prevent the slotted sections from crushing during compaction, packers are temporarily inserted into the casing. Most of these tests generate exploitable results. The four following case histories are examples where this technique was used.

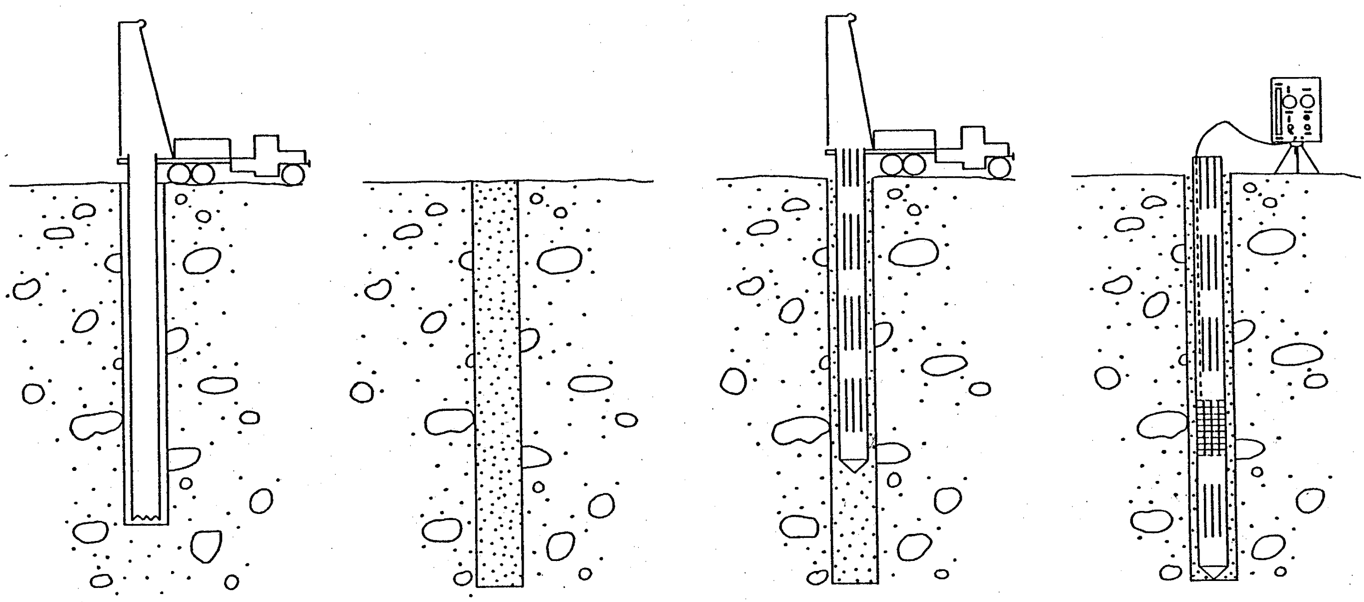
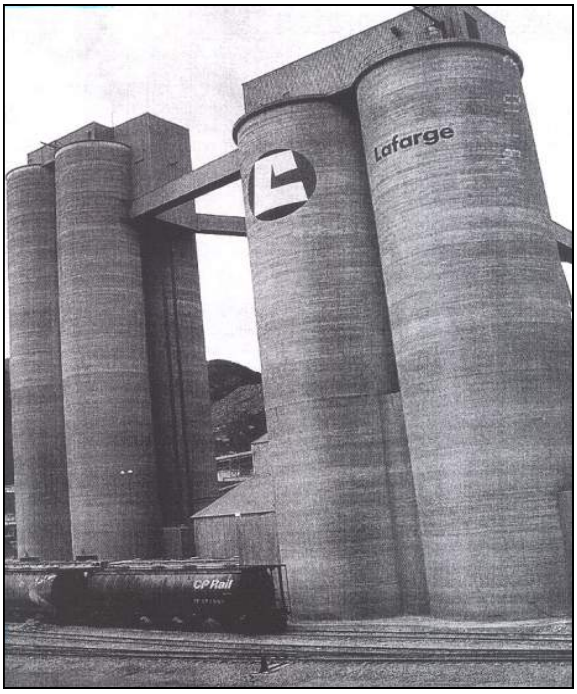


Figure 1. Dynamic Compaction Control, Steps (1) to (4)

2.1.1. Cement Silos Worksite at the Exshaw Plant – Alberta

Constructed in 1989, these four 68-meter high silos rest on 27-meter diameter slabs. Weighing 45,000 tons, the silos apply a maximum surface pressure of 575 kPa (Figure 2). The foundation consists of 50 meters of soil, the first 18 meters being alternate layers of sand, silty sand, and gravel in loose to dense conditions of compaction. Between 18 and 40 meters, medium compacted sand and gravel is found on top of a bed of stiff clay.

The quality of compaction was controlled with PMT and BPT. Calculated total and differential settlement levels were 41 mm and 21 mm respectively, whereas observed settlements 500 days after the end of construction were 55 mm and 3 mm.



Test Results & Post Construction Measurements

	Required	Calculated	Observed
Bearing Capacity	575 kPa	660 kPa	-
Total Settlement	75 mm	41 mm	55 mm
Differential Settlement	38 mm	21 mm	3 mm

Figure 2. Cement silos at the Exshaw Plant in Alberta, with test results

2.1.2. Delta-Whistler Hotel Worksite – British Columbia

The construction of this important hotel, built at the foot of one of North America’s premier ski resorts, ended in 1980. This hotel is comprised of two independent 9-storey high buildings located on top of two-level parkings (Figure 3). Maximum load on the columns is 4,500 kN. The soil consists of 20 meters of various layers of fluvioglacial materials. The geotechnical investigation, consisting of BPTs because of high levels of stones and boulders, had revealed areas of weak penetration resistance in the first 12 meters.

The maximum total settlement calculated with PMTs after compaction was 6 mm whereas observed settlement is less than 4 mm.

2.1.3. Duke Point Sawmill Worksite – British Columbia

Duke Point industrial park covers 155 hectares. It is on a plateau built from cuts and fills located between 2 sandstone ridges separating the Northumberland Channel from the Nanaimo River. The sawmill, covering over 12,000 m², is founded on an 18-meter thick fill comprised of sandstone blocks of various sizes up to 1.0 m³.

Maximum settlement allowed under the terms of the contract was 13 mm for a footing of specified dimensions and loaded at 300 kPa, with a settlement ratio inferior to 1:1000.

Given the type of material, only 50% of the 87 tests performed were conclusive. Slotted AW casings were installed in BW casings previously drilled, and then removed.

Calculated results vary from 6.5 mm to 12.5 mm, whereas settlements observed after the end of construction were all inferior to these results.

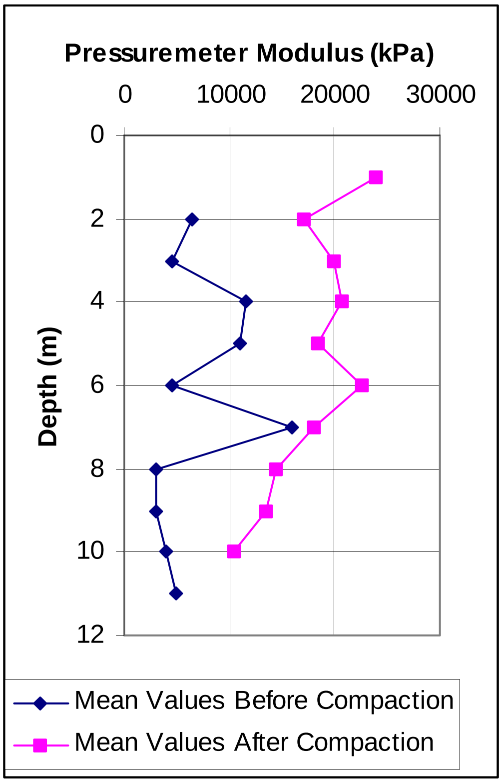


Figure 3. Delta-Whistler Hotel – British Columbia, with test results

2.1.4. Alumina Silos Worksite on Pier 51 in Québec City Harbour – Québec

The project started in 1997 included two dome-shaped silos 60 meters in diameter (Figure 4).

The boreholes indicated the presence of a fill layer approximately 7-meter thick, mainly composed of sand with traces of silt. Inter layers of wood chips of variable thicknesses were encountered. These materials lie on a medium-density sand deposit sitting on a till deposit. The bedrock starts approximately 40 meters down.

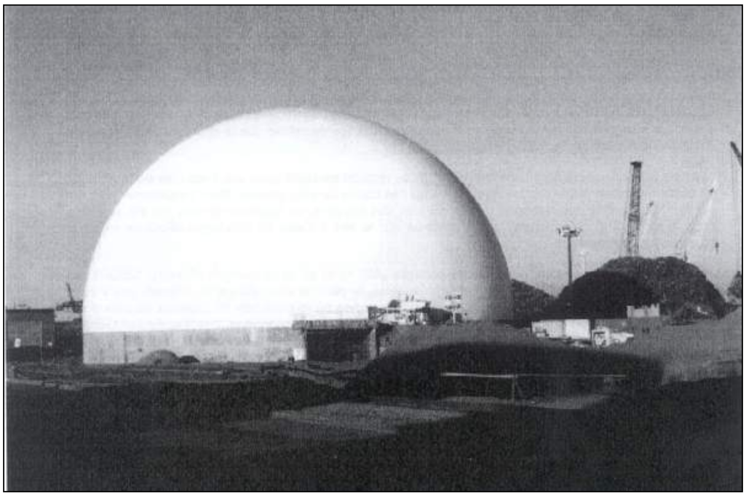
After selective excavation of wood chips, 74 groups of 7 columns of crushed stone were built to form 3-m diameter piles.

Post-compaction tests were comprised of 66 PMTs performed inside 7 boreholes.

Maximum settlement allowed under the terms of the contract was 50 mm. Calculated maximum settlement based on pressuremeter test results was 44 mm, while observed settlement over the following years varied between 10 and 20 mm, depending on silos loads.

2.2. Using the retro-jet technique

The use of the simple but delicate retro-jet technique was limited to research programs on varved clays conducted by *École polytechnique de Montréal* and *Laval University* of Québec City. Although promising, test results had no follow-up mainly because the use of cohesion and friction angle estimated with PMTs never received complete approval from consulting engineers to perform slope stability. The high level of expertise required to implement this technique also restricted its promotion.



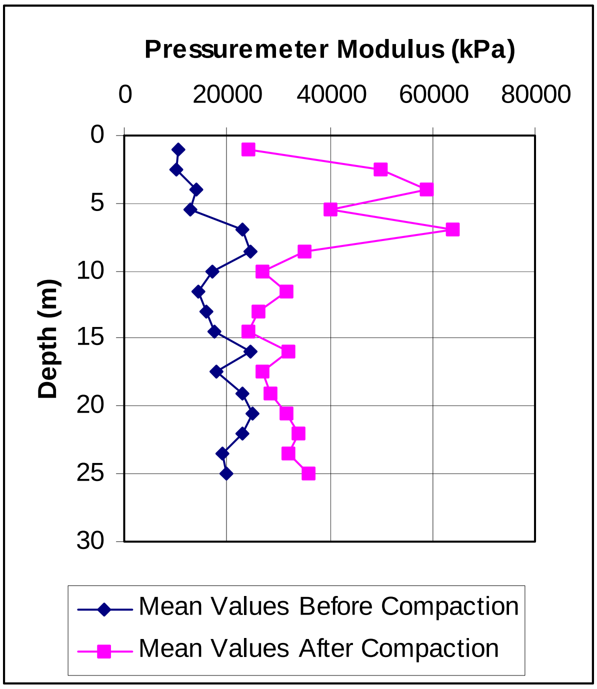


Figure 4. Alumina silos – Pier 51 – Québec City Harbour, with test results

2.3. PMT in soft rock

Tests conducted in soft rocks according to the suggested method for deformation determination using a flexible dilatometer (ISRM, April 1987), have revealed the PMT as a suitable and useful testing method in such materials (Gill and Leite, 1995).

Prior to the use of PMT, allowable bearing capacities in building codes, such as Toronto's, were extremely low because of a lack of in-situ testing. Despite limitations relative to the parasitic dilatation of the equipment, PMT gave a minimal safe value for the modulus and limit pressure applicable to this type of material. In some cities, these values allowed for a revision of the building codes. One of the first examples of this is the Toronto's Manulife building, where PMTs multiplied by 3 the allowable end bearing capacity for the caissons.

Comparative tests were conducted simultaneously with other in-situ rock mechanics testing methods, such as plate load and Goodman Jack, in various worksites (Montréal Olympic Park, the Revelstoke Dam in British Columbia, etc). Table I gives comparative modulus test results obtained with high-pressure PMTs and plate load tests conducted by *Roctest* in serpentinite at Guatemala's Chulac Dam worksite. The moduli consist of those obtained from the first loading measured between 2000 and 4000 kPa.

Table I. Moduli comparison

TEST TYPE	E Max (MPa)	E Min (MPa)	E Avg (MPa)
Pressuremeter	4.5	0.09	2.3
Plate Load	3.6	0.4	2.0

Dilatometer tests performed with a PROBEX (Figure 6) for Ohio's Ironton-Russel Bridge project confirmed the E_{Labo}/E_R ratio of 3, the generally accepted ratio for moduli obtained from core samples in laboratory and in-situ tests (Table II).

Table ll. Rock Mechanics Test Results – Ironton-Russel Bridge Project
(Courtesy of DLZ Corp., Columbus, Ohio)

Lithology	E_{Labo} (GPa)	E_R (GPa)	E_{Labo} / E_R
Fine-grained sandstone	15	5.6	2.68
	15	3.9	3.85
	11	4.2	2.62
Average:	14	4.6	3.04

Following demonstrations such as the one of Mouchaorab et al. (1995) that shows that the PMT simulates accurately the radial behaviour of rock-socketed piers surrounding medium, we assist to a growing number of applications of pressuremeters in soft rock, notably for the calculation of the reacting modulus for the design of towers or piles subjected to overturning forces

The present trend of using the soft rock modulus for design work is reflected by new regulations recommending this practice. The recent edition of the Canadian Highway Bridge Design Code (CAN/CSA-S6-00, 2000) is an example of that. This trend seems also to spread among some U.S. Departments of Transportation.

3. Specific use of the pressuremeter from a Western-Canada perspective

The view outlined in this section is from the perspective of *Hughes Insitu* company.

As mentioned previously, North America has a well-established system of obtaining data for geotechnical projects. Conventional samples can be efficiently obtained or in-situ tests can be conducted with the SPT or the electric cone to provide information from which satisfactory solutions can be made for almost all engineering problems. However there are situations in which conventional testing methods do not yield satisfactory economic solutions. These situations usually occur when samples either cannot be obtained or those that are obtained are badly disturbed. The prime example of this situation is in attempting to obtain data in weathered or fractured rock or weakly cemented material. In these types of material, that are too hard or stiff for in-situ penetration tests, the pressuremeter test is paramount. The majority of the pressuremeter testing conducted by our company is concentrated in those materials that are difficult to test by conventional means. Generally this type of testing is deemed worthwhile only on large significant projects. As a result, they are spread over a wide geographical area from Eastern Europe to Australia as well as most States in the U.S. For such materials, the conventional methods of pressuremeter analysis, based on empirical correlations of the field performance in similar materials, are not always applicable. Without prior experience in a particular geological formation, the unload reload modulus, as obtained from electronic pressuremeters with minimal compliance corrections, is a particularly valuable parameter.

Unfortunately it takes many years for significant projects to reach completion and for measurements to be taken. However settlement predictions based on this parameter for the two highest buildings in Vancouver and Seattle, both over 70 storeys, have been remarkably accurate. The Vancouver Shaw Tower was founded on inter layers of sandstone and coal; the Columbia Center was founded on dense till. The investigation for the Phoenix Airport in cemented gravel is a further illustration of the value of this parameter (Durkee et al., 2005). The restoration of the Historic Breakfast Creep Pub in Brisbane, on the soft estuarine sediments of the Brisbane River, is another example of the use of the unload reload modulus (Fidler, 2002).

The data is not limited to stiffness. The data can be analyzed by inverse modelling whereby the field data is compared to an analytical model. In this manner the full test can be used to determine a set of material parameters that describe the behaviour of the formation and hence, the data can be used as a check on more complex analytical models that are to used to analyze different stress path loading resulting from the particular structure.

Therefore, from Vancouver the experience of this company is to concentrate the use of the pressuremeter on projects in which the material data is difficult to obtain by conventional means. If only disturbed samples are available, the assessment of the material properties must be an informed guess. In many situations of this nature, the pressuremeter is an ideal tool to obtain in-situ test data.

The equipment that we have available are all electronic mono cell pressuremeters with computer data acquisition. Tests have been conducted to over 400 meters in depth, to pressures of 20 MPa. Much more sensitive instruments are used to test soft materials. The equipment is based on that marketed by Cambridge Insitu, England.

4. New equipment designs

The first instrument in use in Canada was the Type G from *Techniques Louis Ménard*. This equipment being available only on loan, combined to the large amount of control valves on its face panel –rendering it unattractive– basically prevented its adoption.

Then, Louis Ménard authorized *Roctest* to design a new model of pressuremeter equipped to meet the needs of North-American users. This resulted in the design of the G-AM Pressuremeter (AM standing for American) on which subsequent GA, GB and GC pressuremeter models built by *Techniques Louis Ménard* were based. With this equipment, setting of the differential pressures became easier. As well, high pressure testing became possible without having to dismantle the pressure gauges.

Under the guidance of Professor Jean-Louis Briaud from Texas A&M University, and with the collaboration of *Roctest*, a mono-cellular unit was developed and called TEXAM (Briaud et al., 1983). Professor Briaud demonstrated that when a probe length-to-diameter ratio is above a specified value, the results obtained are similar to those obtained with a tri-cellular Ménard unit (Briaud, 1992). Main interests of this type of pressuremeter come from its simplicity, its sturdiness and its ease of use. Among other features, it does not require the use of pressurized gas. These characteristics can be determining in the selection of a type of pressuremeter for use in harsh conditions such as those encountered in Northern Canada (Morin, 1995).

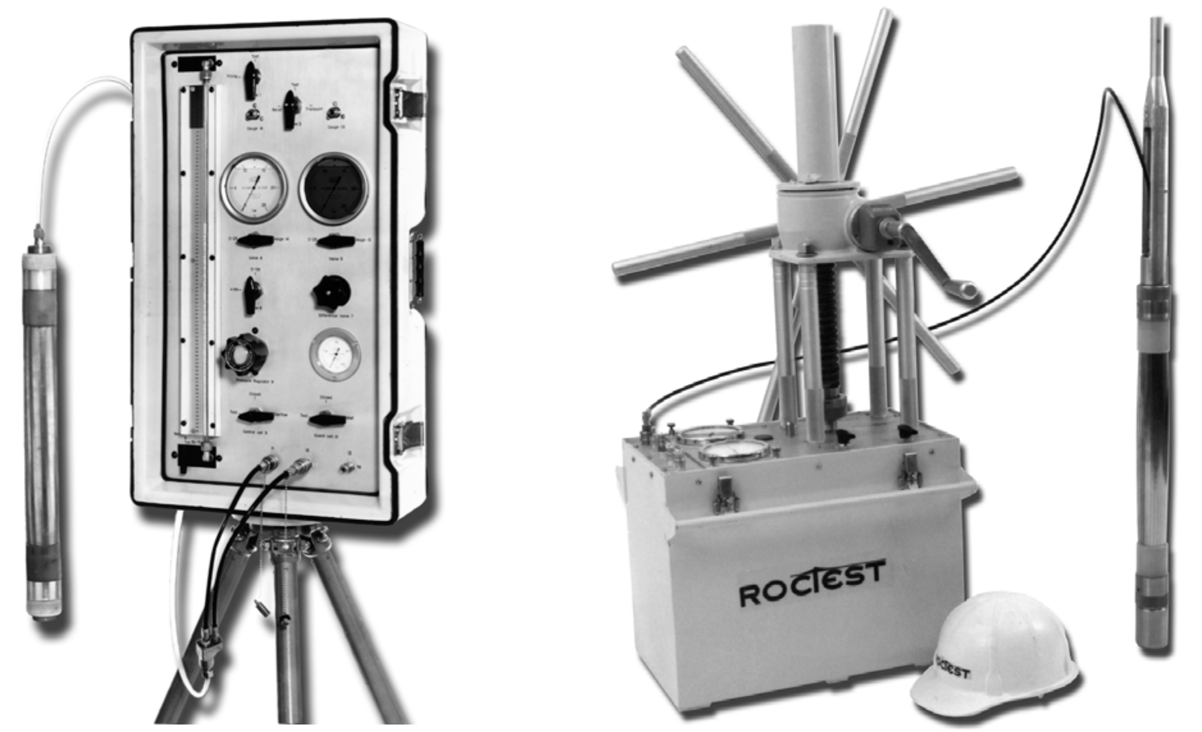


Figure 5. G-AM and TEXAM pressuremeter models

Other simplified equipment was developed such as the PENCEL, which is derived from the pavement pressuremeter. One advantage of this pressuremeter over the others is that it can be used in series with an electrical static cone penetrometer.

Another interesting achievement is the PROBEX, which is becoming a standard in the study of rock caissons subjected to overturning forces. This pressuremeter-dilatometer combination is equipped with a hydraulically inflated mono-cellular probe, a system for volume measurement, and computer data acquisition.

Figure 6. PENCEL pressuremeter and PROBEX dilatometer

5. On-going development

Following the success of the TEXAM pressuremeter, an on-going R&D program has been put in place by *Roctest* in order to design a much lighter and entirely automated unit.

Another result from research work on pressuremeter techniques is Professor Ladanyi's conical probe, which is based on an interesting but difficult to execute concept (Ladanyi et al., 1995).

An automated PENCEL is also under development through a research program sponsored by an American DOT (TRB, 2003).

Finally, we may consider that due to the importance that the PMT gives to the measurement of the in-situ moduli of deformation, it acted as an indirect trigger to the development of a new range of in-situ equipment, such as the BCD. This new apparatus would allow direct measurement of soil moduli for compaction control (Briaud and Li, 2004).

6. Conclusion

In Canada, geotechnical investigation techniques using Louis Ménard pressuremeter began in the mid '60s. Its introduction was slow due to the strong implementation of generally accepted techniques such as SPT, CPT, vane tests, and sample testing in laboratories. PMT was therefore limited mainly to situations where conventional methods proved economically or technically difficult to perform, such as soft rock testing and dynamic compaction control.

Although PMT progression in North America was slow, it has proven to be steady. Contributions of Canadian companies to the pressuremeter techniques have been significant in the design of better-adapted types of instruments, in the development of unique implementation methodologies –especially in the field of dynamic compaction– and, by extension, in the acknowledgment of the role that soil and rock moduli measurement plays in the control and design of structures.

7. Acknowledgements

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8. References

Briaud J.L., Babb L., Capelle J.F. (1983) The Texam Pressuremeter. *Geotechnical Testing Journal of the American Society for Testing and Materials*.

Briaud J.L. (1992) *The Pressuremeter*, A. A. Balkema, Rotterdam, Brookfield, 322 pages.

Briaud J.L., Li Y. (2004) A BCD for Compaction Control, *Journal of Geotechnical and Geoenvironmental Engineering of the ASCE*, Version 1.

Canadian Highway Bridge Design Code (2000) CAN/CSA-S6-00.

Dumas J.C., Morel J.F. (1995) Le pressiomètre Ménard, un outil efficace pour la vérification de travaux d'amélioration de mauvais terrains, *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Durkee D.B., Langer J.A., Hughes J.M.O., Smith D.E. (2005) Pressuremeter Tests in Sands Gravels and Cobbles. *Symposium International ISP5/Pressio 2005*

Fidler S. (2002) Design and Construction Monitoring for Breakfast Creek Tunnel, Inner City Bypass Project, Brisbane, Australia, *Geotechnical Aspects of Underground Construction in Soft Ground,* Toulouse, France, Specifique/Lyon.

Gill D.E., Leite M.H. (1995) Dilatometer testing of rock. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

ISRM (April 1987) *Suggested Method for Deformability Determination Using a Flexible Dilatometer*, 125-134.

Ladanyi B., Mchayleh J., Ducharme A. (1995) A continuous pressuremeter test based on the 'sharp cone' principle. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Morin P. (1995) Revue critique et interprétation d'essais pressiométriques rapides dans la glace. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Mouchaorab K.S., Benmokrane B., Rhazi J., Ballivy, G. (1995) Essais au pressiomètre dans un milieu encaissant de pieux en béton moulés dans le roc. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Transportation Research Board of the National Academies (TRB) (2003) Research in progress.

Other Canadian Contributions

Amadei B., Valverde M., Jernigan R., Touseull J., Capelle J.F. (1995) The directional dilatometer: A new option to determine rock mass deformability. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Baguelin F., Jézéquel J.F., Shields D.H. (1978) *The Pressuremeter and Foundation Engineering.* Trans Tech Publications, Clausthal-Zellerfeld, W. Germany.

Capelle J-F (1983) New and simplified pressuremeter apparatus. *Proceedings of the Symposium on Laboratory and Field Tests;* Bangkok, Thailand.

Deshpande S.C., Hughes J.M.O., Singh S.K. (1995) Pressuremeter: Applications in the design of geotechnical structures. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Dumas J., Beaton N., Nowodworski H., Brzezinski L. (1992) Enhansing Dynamic compaction capabilities using select fill displacement techniques. *45th Canadian geotechnical conference*, Toronto.

Hamouche K., Roy M., Leroueil S. (1995) A pressuremeter study of Louiseville sensitive clay. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Knight F.J., Diviney J.G. (1988) Lateral Stress Measurements against the Eisenhower and Snell Locks: Alternatives and their Assessment. *First International Symposium on Penetration Testing,* Florida.

Ladanyi B. (1972) In Situ Determination of Undrained Stress-Strain Behavior of Sensitive Clays with the Pressuremeter. *Canadian Geotechnical Journal*, 9 (3).

Leite M.H., Ladanyi B., Gill D.E. (1995) An extension of the interpretation model for the sharp cone test fort the determination of deformability parameters of rock-like materials. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Roy M., Juneau R., La Rochelle P., Tavenas F. (1975) In Situ Measurements of the Properties of Sensitive Clays by Pressuremeter Test. *ASCE, Spec. Conf. on In Situ Measurement of Soil Properties,* Vol. 1, Raleigh.

Saleh K. (1995) État de contrainte dans un milieu fini lors d'un essai pressiométrique. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Wightman A., Beaton N. (1984) Improvement of a dumped rockfill foundation by dynamic consolidation. *International conference on cases histories in geotechnical engineering,* Saint-Louis.

Shields D.H., Bauer G.E. (1975) Determination of the Modulus of Deformation of a Sensitive Clay Using Laboratory and In Situ Test. *ASCE Specialty Conference on In Situ Measurement of Soil Properties,* North Carolina State University.

Shields D.H. (1995) Predicting the creep-induced lateral displacement of piles from pressuremeter tests. *The Pressuremeter and its New Avenues*, Balkema, Rotterdam, ISBN 90 5410 5453, Ballivy.

Silvestri V. (2001) Interpretation of Pressuremeter Tests in Sand. *Canadian Geotech. J.,* 38, 1155-1165.

Tavenas F., Blanchette G., Leroueil S., Roy M., La Rochelle P. (1975) Difficulties in the In Situ Determination of K_o in Soft Sensitive Clays. *ASCE Specialty Conf. on In Situ Measurement of Soil Properties,* Vol. 1, Raleigh.