A review of pile drivers for testing in centrifuge

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Abstract :

The use of centrifuge modelling offers another way for geotechnical engineers to investigate the loaded driven pile behaviours. It is well known that centrifuge tests take the place of in site tests to perform parametric studies useful to get a data base for recommendations and to improve design codes. To accurately simulate loaded driven pile behaviour, some conditions must be satisfied. A fundamental one is the checking of similitude laws linked to the pile driving, the second concerns an experimental aspect *i.e.* the installation of driven pile. To study and to fill these conditions, centrifuge pile hammers must be developed. A first difficulty is to conceive a miniature hammer supporting macro gravity effects and to achieve a model pile driving in flight. The paper describes the similitude laws linked to the driving of a pile and some of them have been already checked and validated during a pile driving centrifuge tests using a miniature pile driver. A recap of centrifuge pile drivers is proposed before to describe in details the last two pile drivers used the LCPC centrifuge. One has been developed to check similitude laws inherent to a pile driving; a second miniature pile driver directly adapted on the top of the pile has been also tested. For both pile drivers, limits and performances of them are given and tacking into account them, a concept of a new one pile driver is given able to drive and to load the model pile.

Keywords :

Piling – Centrifuge testing – Similitude laws – Miniature pile driver – Centrifuge equipment.

Résumé :

La modélisation en centrifugeuse permet de réaliser des essais de comportement de pieux chargés et ainsi offre une alternative aux essais en vraie grandeur qui restent très onéreux et parfois difficiles à mettre en œuvre. Au-delà de l'essai lui-même, des études paramétriques peuvent être menées en centrifugeuse dans des conditions d'essais parfaitement maîtrisées ce qui n'est pas le cas sur site. L'apport de tels essais intéresse non seulement la recherche mais sert à améliorer les codes ou les relatives aux lois de similitude. La validation de ces lois dans le domaine du battage ont été étudiées ce qui a nécessité la mise au point d'un moyen de battage sous macro gravité de manière à

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respecter les conditions d'installation de pieux modèles. La conception et le développement de matériel spécifique pour battre les pieux modèles en centrifugeuse a donné lieu à la création de deux batteurs miniatures. L'utilisation du premier associé à un dispositif de chargement axial a permis d'étudier et de valider les lois de similitude à l'aide d'essais de battage, ce qui est rappelé dans l'article. Dans le cadre du développement de ces deux batteurs miniatures, il a été entrepris un récapitulatif de ces dispositifs de battage utilisés ou disponibles au niveau des centrifugeuses installées dans le monde. Ces données sont ici détaillées avant de décrire les deux batteurs miniatures mis au point et testés sur la centrifugeuse du LCPC. Le second batteur miniature a été développé pour être plus autonome avec une installation directe en tête de pieu. Pour les deux batteurs, les limites et performances sont décrites. En reconsidérant celles-ci, un nouveau batteur a été proposé capable de battre en tête de pieu et en fond de trou et réaliser des essais de chargements axiaux.

Mots-clés :
Battage – Modélisation en centrifuge – Lois de similitude – Batteur miniature – Matériel d'essai en centrifuge.

1. Introduction

Face to the expensive costs and the difficulties to install bearing capacity tests in site, geotechnical designers carry out these tests at a reduced scale. But the similitude laws must be checked so as the model-pile behaviour is representative of the prototype pile one. In geomechanics, some data results obtained from reduced scale tests can not be transferred in prototype data, mainly when scale effects occur. With these test limitations coming for instance from normal gravity testing, the centrifuge modelling is revealed to be a testing method well fitted for the geotechnical studies. For driven piles, the installation method must be similar to the model and prototype piles. Thus the model pile will be driven in flight and a miniature pile driver is needed. A first recap is given on the validation of similitude laws during driving (impact, energy, and wave propagation). Another one is dedicated to miniature pile drivers which have been developed and used to perform specific centrifuge studies till now. A new type of pile driver is presented which is conceived to drive on top and tip of a pile and to have the ability to bear this driven pile.

2. Technical aspect on industrial hammers

The usual hammers for top pile driving are mainly diesel or hydraulic ones to lift the striking mass. Considering small industrial hammers by the delivered energy limited to 150kJ among 5 manufacturers (Guo, 2007), the blow rates are ranged from 30 to 100 blows per minute. The table 1 recaps the numbers of hammers versus the available energy.

The design of a miniature top pile driver for centrifuge testing up to 100g impose a prototype mass superior to 5 tons, so the more representative and adapted industrial hammer corresponds to the APE 10-60 type which the main characteristics are given below in table 2.

Table 1.Distribution of industrial top pile driving hammers (delivered energy <150kJ).

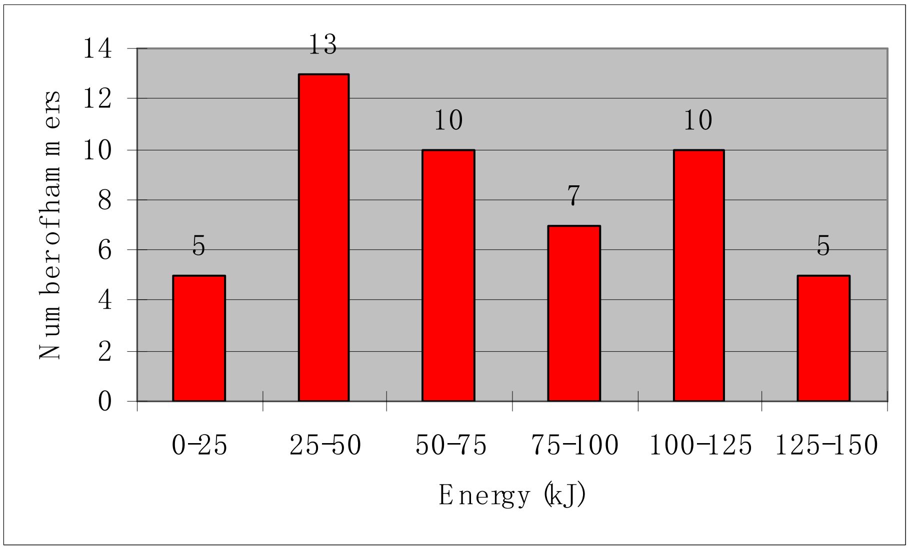


Table 2. Energy parameters of the APE 10-60 type top pile hammer.

Mass (t)	Free fall (m)	Energy (kJ)	Blow count (blow/min)
9	1.2	108	30

A recent type of industrial hammers concerns the toe pile hammers which drive tubular piles by striking the toe of the piles. Respectively with the considered energy less than 150kJ, a toe pile driver from the manufacturer IHC is available. It is the S-150 hydraulic hammer type which the energy parameters are in table 3.

Table 3. Energy parameters of the IHC S-150 type toe pile hammer.

Reference	Type	Mass (t)	Free fall (m)	Energy (kJ)	Blow count (blow/min)
IHC S-150	Hydraulic	7.5	2.02	149.24	44

3. Similitude conditions in pile driving application

Considering the materials for the soil pile model and the full scale prototype pile are identical, to have a similar non linear soil response imposes that it is necessary to have for both the same level of stress and deformation. So as the scale factor of gravity g* is in inverse ratio to the lengths x* or displacements u* scale factor. It is the basis principle for geo centrifuge testing. If we note N the scale factor for the gravity, all the scale factors can be easily found. They are summarized in the following table 4.

To study the soil pile behaviour during and after driving by centrifuge, other scale factors complete the list of the table 4. Considering a free fall hammer which impacts a pile, the driving characteristics are linked to the hammer energy E_0 and the impact velocity v_0 just before the contact, given by the following equation:

$$E_0 = Mm\ g\ H = \tfrac{1}{2} Mm\ v_0^2 \qquad (1)$$

Mm is the hammer mass and the free fall height H.

If the stress wave propagates in a linear elastic pile at rest, an equation gives the relation between the stress and the particle velocity as follows:

$$\sigma = z\ v \quad (2)$$

z is the mechanical impedance of the pile depending on its physical properties (E elasticity modulus and ρ density) as the stress velocity c:

$$z = (E\rho)^{½} \text{ and } c = E^{½}\rho^{-½} \quad (3)$$

In a particular simple case, when the hammer impacts a pile made with the same materiel and having the same section, the duration of the rectangular stress wave τ_0 and the amplitude σ_0 are:

$$\tau_0 = 2\ Lm/c \text{ and } \sigma_0 = ½(z\ v_0) \quad (4)$$

Here Lm is the hammer length.

So two other scale factors are deduced in the case of the model and prototype piles are made with the same material:

$$z^* = 1 \text{ and } c^* = 1 \quad (5)$$

Table 4. Main scale factors for geo centrifuge testing.

Physical parameter	Symbol	Scale factor
Stress	σ^*	1
Density	ρ^*	1
Gravity or acceleration	$g^* = a^*$	N
Length or displacement	$x^* = u^*$	N^{-1}
Deformation	ε^*	1
Time	t^*	N^{-1}
Energy	E^*	N^{-3}
Velocity	v^*	1
Force	F^*	N^{-2}
Mass	M^*	N^{-3}
Displacement per blow	δ^*	N^{-1}
Blow count	n^*	1
Frequency	f^*	N

4. Centrifuge testing and validation of similitude conditions

An experimental study has been performed in centrifuge on pile driving to check the theoretical scale factors listed above in table 4. Using a hydraulic jacketed pile driver, see after figure 2, a model of modelling has been run on a prototype closed ended steel pile in sand (pile diameter = 0.5m; pile length = 12.5m; hammer mass = 5 tons; free falling height = 1m). Various diameters for the pile model has ranged from 8 to 16mm, see table 5, and each one were driven in a loose dry fine sand (Fontainebleau d_{50} = 0.2mm; density index I_D = 0.36). To investigate the wave propagation during the pile driving, each model pile was equipped with strain gauges at the pile top and measurements of the pile displacement and number of blows was recorded.

Among the checked similitude conditions, one is concerning the wave propagation through the pile *i.e.* up and down stress travels (see figure 1). Other scale factors have been checked and reported by Levacher and Sieffert (1996)

Table 5. Hammers and piles characteristics.

Type of piles →	**Prototype**	**Model**			
Gravity level (g)	1	31.2	41.7	50	62.5
Hammer and pile diameter (mm)	500	16	12	10	8
Pile length (mm)	12500	400	300	250	200
Hammer length (mm)	3263	104.5	78.3	65.3	52.2
Hammer free fall (mm)	1000	32	24	20	16
Hammer mass (kg)	5000	0.1638	0.0691	0.04	0.0205
Theoretical energy (J)	49100	1.607	0.678	0.392	0.211

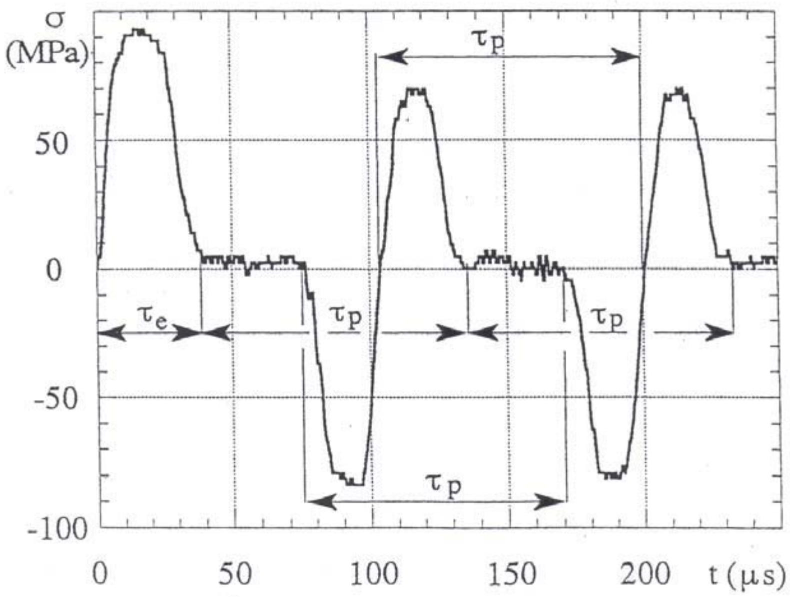


Figure 1. Typical recorded stress wave signal for the model pile of 10mm diameter (τ_p is the up and down travel time, τ_e is the impact duration).

Following the driving of the pile for a given embedded depth, the miniature pile driver (figure 2) mounted on the hydraulic jack allows to perform axial loading tests. So, using the adequate scale factors, it has been demonstrated by Levacher and Sieffert (1996) that the bearing capacities obtained from the loading tests run out on each model pile at various gravity level, were the same. Any scale effect was observed for the different used model piles.

But the authors have compared the bearing capacities obtained with a model pile installed at 1g level, with a bored pile and with a driven pile driven at the required gravity level, differences have been observed. The bored and driven at 1g give a very close bearing capacity, clearly inferior to the driven pile at the required gravity level one. So any driven pile behaviour centrifuge study must be conducted only on model pile driven at the required level of acceleration. This fully justifies the development of miniature pile drivers for centrifuge pile driving and driven pile behaviour studies.

5. Background recap on centrifuge pile drivers

5.1 One blow loading system

Many techniques have been developed last recent years to model the dynamic pile testing on site such as the Statnamic test. A typical load pulse corresponding to the modelled dynamic test is applied to the pile and the resulting measurements are analysed by the researchers. In fact, the pulse is obtained from a unique blow which is repeated. So, it is difficult to regulate the cadence of blows or the blow rate.

5.2 Multi blows loading system

It is interesting before developing the last used miniature pile driver referenced "Pivert" and giving the concept of a new prototype of a universal pile driver and the associated load system, a complete sum up of centrifuge pile drivers is drawn. In table 6, the list concerns the different centrifuge pile drivers used or available in different centres of centrifuge testing.

Figure 2. The "DLM" pile driver without the jacketed load system

Table 6- Recap of centrifuge pile drivers.

Date	Origin	Type of pile driver	Energy	Ram mass (g)	Drop height (mm)	Blow count (N/min) or frequency (Hz)	Pile number	Pile arrangement	Type of axial loading test	Innovation out of pile driving installation	References
1984	Caltech (USA)	Mechanical and pneumatic pile driver	Pneumatic jacket	-	- Double acting hammer	4Hz	1	Single pile and only one	Compressive	Combined pile driving and pushing mechanism	Allard Allard *et al* (1984)
1988	Cambridge (UK)	Pneumatic pile driver	Pneumatic jacket	95	62 Double acting hammer	2.5Hz	1	Single pile	Compressive or tensile tests	Independent loading system	Nunez *et al* (1988)
1991	Florida Univ. (USA)	Drop weight Pile driver	Electro-magnet	-	- Free fall	1 blow/3min	1	Single pile or set of piles as a group	Any	-	Bloomquist *et al* (1991)
1991	Florida Univ. (USA)	Stepping motor pile driver	Stepping motor				1or 5 Fixed spacing	Single pile or set of piles as a group	Compressive on a single or a set group of piles	Pseudo dynamic insertion method	Bloomquist *et al* (1991)
1991	Florida Univ. (USA)	Multiple pile driver	Stepping motor				1-5 (one by one) free spacing	Single pile or set of piles as a group	Compressive on a single or a group of piles	Pseudo dynamic insertion method	Bloomquist *et al* (1991)
1991	Boulder Univ. (USA)	Pile driving hammer	Pneumatic	170	50 Free fall and/or spring action	27.7Hz	1		Compressive or tensile tests	Single and double acting operation	Cyran *et al* (1991)
1994	Florida Univ. (USA)	Multiple pile driver					1-9	Group of piles 3x3	Compressive or lateral tests on a single or a row of piles	Row of piles: individual and row displacements	Mc Vay *et al* (1994)
1994	UWA (Australia)	Pile driving actuator	Pneumatic	Max. value: 70	0-20 Free fall	0-20 Hz Individual blow or Continuous driving	1	Piles in line (one by one)	Compressive or tensile tests	Pipe piles: plug measurement	De Nicola *et al* (1994)
1994	LCPC (France)	Pile driving actuator	Electro-magnet	163.8	0-32 Free fall	10 blows/min	1		Compressive		Levacher & Cottineau (1996)
1996	LCPC (France)	Electro-magnet hammer	Electro-magnet		0-25 Free fall		1			Free installation on top of the pile	Levacher & Cottineau (1996)
1998	Tsinghua (Chine)	Hydraulic jacket					1	Circular group			Pan *et al* (1998)

6. Recent developments of miniature pile drivers

6.1"Pivert" pile driver

A recent miniature pile driver has been tested only for its ability to drive single model piles in centrifuge. The concept of this pile driver was inspired by the industrial electromagnetic hammers (Demichelis *et al*, 1995). Its main characteristics are the following ones: a variable blow rate, a free fall hammering, a quick and easy installation on the top of the pile by clamping, a possible driving for a range of pile diameters.

Figure 3. The "Pivert" electromagnet hammer.

The hammer is moved up by the electromagnetic force and stays at a constant level above the top of the pile. And after switching the supply, the hammer is free falling down. The pile driver is directly centred upon the top of the pile. A special bearing or pulling load system could be adapted on the top of the pile driver, see figure 3..

A current injected through a cupper bobbin excites a core which is the hammer. A cage non conductive in polycarbonate hollow where the bobbin is installed receives the hammer which is free moving along the hollow. In the nose the diameter is bored out to the diameter of the model pile to drive. So the pile driver follows perfectly the displacement of the pile. The height of each blow is maintained constant but this height is adjustable by acting on the amplitude of the electromagnet force.

6.2 A new development of pile driver and pile load system

Based on the « Pivert » pile driver model which has been tested only to drive a model pile, new developments are proposed to have the following abilities with the new one:

-to make a top pile driving on a model pile in flight for centrifuge testing, see right figure 4;

-to make a toe pile driving on a model tubular pile in flight for centrifuge testing, see left figure 4;

-to load axially the driven pile model for bearing capacity tests;

-to load axially the driven pile model for uplift capacity tests;

-to perform cyclic tests on the driven pile model.

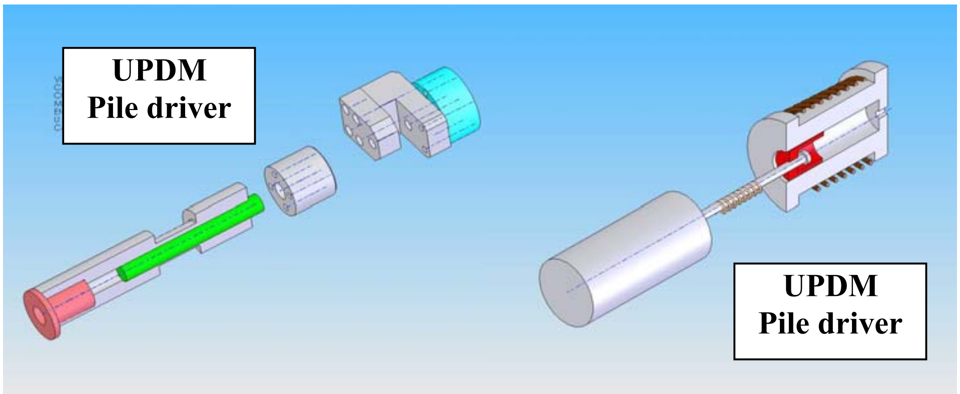
Considering the centrifuge machine *i.e.* LCPC centrifuge, due to the free space in the swinging basket and the container for testing, some geometric limitations are imposed. The main are concerning the length of the model pile (limited embedded depth = 300mm) including the effects of the walls and bottom of the container, the rotation of the swinging basket.

If the pile diameter is kept constant *i.e.* 18mm, some driving parameters are recapitulated in the following table 7, for a range of possible accelerations. It will be possible to install in each container a line of 3 pile models for to rows with the respect of the minimal distance between them.

Table 7. Main parameters for driving with new pile driver.

Acceleration level (g)	**Embedded depth (mm)**	**Free fall (mm)**	**Hammer mass M_m (gram)**	**Ng hammer weight (N)**	**Hammer diameter (mm)**	**Hammer length (mm)**
30	300	51.4	259.3	77.8	16	165.3
35	300	34.3	209.9	73.5	16	133.8
40	300	30	140.6	56.3	16	89.6
45	300	26.7	98.8	44.4	16	63.0
50	300	24	72.0	36	16	45.9
55	300	21.8	54.1	29.8	16	34.5
60	300	20	41.7	25	16	26.6
65	300	18.5	32.8	21.3	16	20.9

A special hammer has been conceived to model the mass impacting the pile at the toe, see left figure 4. The hammer model is composed in two parts *i.e.* a steel cylinder corresponding to the hammer toe pile driver prototype mass and in the upper part, a steel hollow cylinder core. A damping system is installed between these two parts so as to eliminate after the impact, the influence of upper part (core). The position of the two parts is adjustable.



UPDM top pile driver version *UPDM impact toe pile driver version*

Figure 4. Schematic views of the Universal Pile Driver Model – UPDM.

7. Conclusions

Many miniature drivers for centrifuge modelling are continuously developed in centres of research where centrifuge machines are installed. Also, the increasing investigations on single or group of driven piles behaviours subjected to axial or lateral loads require these equipments. The development of "DLM" and "Pivert" pile drivers has brought many interesting results as follows:

-the validity of similitude laws in stress and wave propagation;
-no scale effect for bearing capacity;
-repeatability of tests confirming the soil installation by pluviation and the driving installation method;

Founded on these results, a new pile driver is in progress to make a top and tip pile driving and finally to run out axial bearing tests. Other driving equipments such as helmets, anvils, and so and could be also installed on the top of pile but mechanical characteristics of the materials might be adapted referring the similitude aspects.

8. References

[1] Allard M.A., 1984, *Tests on piles installed in flight on the centrifuge,* Symposium on recent advances in Geotechnical Centrifuge Modelling, University of California, Davis, pp. 18-20.

[2] Allard M.A., Scott R.F., Lee J.R., 1986, *Driveability on piles. Experiments on model piles driven in flight in the centrifuge,* 3rd International Conference on Numerical Methods in Offshore Piling, Nantes, pp. 91-103.

[3] Bloomquist D., Feld T., Townsend F.C., Gravgaard J., Gill J.J, 1991, *Development of a multiple pile driver. Load test device for pile group studies,* Proceeding Centrifuge'91, Editor H.Y. Ko and F.G. Mc Lean, Rotterdam: A.A. Balkema, pp. 355-359.

[4] Brown M.J., Hyde A.F.L., Anderson W.F., 2002, *The influence of loading rate on pile behaviour in clay,* Physical Modelling in Geotechnics: ICPMG 2002, Phillips, Guo and Popescu Editors, pp. 667-672.
[5] Cyran T.C., Mehle J.S., Goble G.G., *Centrifuge modelling of piles,* Proceeding Centrifuge'91, Editor H.Y. Ko, Rotterdam: A.A. Balkema, pp. 377-384.
Demichelis J., Lafont R., Servant D., 1995, *Le marteau électromagnétique*, Report LCPC Nantes, 11p.
[6] de Nicola A., Randolph M.F., 1996, *Development of a miniature pile driving actuator*, Proceedings Centrifuge'94, Editors Leung, Lee and Tan, Rotterdam: A.A. Balkema, pp.473-478.
[7] Guo C., 2007, *Mise en oeuvre et développement d'un marteau pour le battage en tête et en fond de trou de pieux modèles réduits centrifugés,* Master of sciences report LCPC n°RMS/MSC 2007-4-09-1/1-a, *in French*, 69p.
[8] Levacher D., Cottineau L.M., 1996, *Pile driving hammers in centrifuge modelling*, 6th International Conference and Exhibition on Piling and Deep Foundations, Bombay, India, 15 - 17 January, 8p.
[9] Levacher D., Sieffert J.G., 1996, *Physical simulation of the behaviour of piles during and after driving,* Eurodyn'96, 3rd European Conference on Structural Dynamics, Florence, 5 - 8 June, volume 2, pp. 1039-1044.
[10] Mc Vay M., Bloomquist D., Vanderlinde D., Clausen J., 1994, *Studies on laterally pile groups in sand,* Proceedings Centrifuge'94, Editors Leung, Lee and Tan, Rotterdam: A.A. Balkema, pp.479-484.
[11] Nunez I.L., Hoadley P.J., Randolph M.F., Hulett J.M., 1988, *Driving and tension loading of piles in sand on a centrifuge,* Proceeding Centrifuge'88, Editor J.F. Corte, Rotterdam: A.A. Balkema, pp. 353-362.
[12] Pan S.S., Pu J.L., Yin K.T., Liu F.D., 1998, *A new pile driver and loading set for pile group in centrifuge flight,* Proceeding Centrifuge'98, Editor Kimura, Rotterdam: A.A. Balkema, pp. 91-96.
[13] Randolph M.F., Foray P., (1995), *Centrifuge modelling of Euripides pile test,* Report GEO: 95169, University of Western Australia, Department of Civil Engineering, Geomechanics Group.
[14] Sakr M., El Naggar M.H., Nehdi M., 2004, *Novel toe driving for thin-walled piles and performance of fibreglass-reinforced polymer (FRP) pile segments ,* Canadian Geotechnical Journal, volume 41, pp.313-325.
[15] Sieffert J.G., Levacher D., 1995, *Etude de l'effet d'échelle de pieux battus en cours de centrifugation,* Revue Française de Géotechnique, *in French,* n°69, pp.1-15.
[16] Thorel L., Rault G., Garnier J., Murillo C., Gauducheau P., Néel A., Favraud C., 2008, *Mesures en macrogravité sur modèles réduits de structures géotechniques*, Bulletin des Laboratoires des Ponts et Chaussées, n° spécial Instrumentation, *in French, in press*, 75 p.