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Centrifuge modelling of the behaviour of Iron Concentrate ore subjected to rolling movement

Modélisation en centrifugeuse du comportement de minerai de fer concentré soumis à un mouvement de roulis

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ABSTRACT: Combination of cyclic loading, fine particles and moisture within a bulk carrier's cargo can result in liquefaction causing the vessel to list or capsize and possibly loss of human life. In order to investigate the origin of cargo liquefaction during transportation, a new device has been developed at Ifsttar in the framework of the Franco-German European LiquefAction project. The device is inspired from the Rolling Test suggested by ClassNK (2012), but has been designed to support similar stresses than those observed in a vessel transporting ore cargo, and can be used in a 80×g macrogravity field in the Ifsttar's 5.5m radius geo-centrifuge. The rolling test device performances are presented, as well as the results of the first test performed on iron concentrate, with a flat geometry and de-aired water as interstitial fluid. High void ratio has been chosen to potentially generate a liquefaction occurrence in some part of the model subjected to rolling movement. The results are analysed in terms of settlement, total stress and pore pressure evolution.

RÉSUMÉ: La combinaison d'un chargement cyclique, de la présence de particules fines et d'humidité au sein d'une cargaison de minerai peut induire un phénomène de liquéfaction, pouvant engendrer une gite excessive, un déséquilibre du navire, voire sa perte et celle de son équipage. Afin de chercher l'origine de la liquéfaction de minerai au cours du transport maritime, un nouveau dispositif expérimental a été développé à l'Ifsttar dans le cadre d'un projet franco-allemand européen LiquefAction. Le dispositif est inspiré des essais de roulis développés par ClassNK (2012), mais dimensionné pour supporter des contraintes similaires à celles observées dans un vraquier transportant du minerai, et peut être utilisé à 80×g, dans un champ de macrogravité généré par la centrifugeuse géotechnique de l'Ifsttar. Les essais réalisés sur du minerai de fer concentré, concernent une surface plate et de l'eau désaérée comme fluide interstitiel. Un indice des vides élevé a été choisi afin de potentiellement générer de la liquéfaction en certains points du modèle réduit soumis au mouvement de roulis. Les résultats sont analysés en termes de tassement, de contrainte totale et d'évolution de la pression interstitielle.

Keywords: Iron concentrate ore, liquefaction, centrifuge modelling
Mots-clefs: Minerai de fer concentré, liquefaction, modélisation en centrifugeuse

1 INTRODUCTION

Combination of cyclic loading, presence of fine particles and variable moisture content within a bulk carrier's ore cargo can result in liquefaction causing the vessel to list or capsize and possibly loss of human life. Several accidents with vessels have been attributed to ore liquefaction, mostly carrying iron, bauxite and nickel (IMO, 1998, IMO 2012). Three elements may generate such a catastrophic event: the cargo properties, the ship design and the sea conditions. In order to investigate the origin of cargo liquefaction during transportation, a new device has been developed at IFSTTAR in the framework of the Franco-German European LiquefAction project.

From a geotechnical point of view liquefaction is a hazardous phenomenon that consists in a change of the soil behavior from "friction" to "liquid". This phenomenon is related to the presence of interstitial water, which under specific loading condition, can generate overpressures on the soil grains, up to a level sufficient to undermine the friction resistance or, in other words, the shear strength. The liquefaction phenomenon occurs "rapidly", it means that the overpressures generated (e.g. by compression) cannot be dissipated due to a very rapid solicitation on medium-low permeability soil. Liquefaction accidents are often observed during earthquakes and may, for instance, involve building foundations, slopes and earth embankments.

Ore cargo liquefaction is a complex and still not fully understood phenomenon. It is not necessarily similar to seismic liquefaction even if analogous effects can be observed. It could be related to different hypotheses ascribable to cyclic loading, fluid migration, and soil initial state. Of course, the type of material, loading conditions and water content are the main parameters that influence the triggering of this phenomenon. To identify the risk of cargo liquefaction, several tests can be found in the literature (ClassNK, 2012, IMSBC 2013): flow table test (derived from ASTM C230), penetration test, weight penetration test and rolling test. The latter consists in a 0.3×0.3×0.3m Perspex cubic box, which is rotated around a horizontal axis located in the middle of the box base. The Rolling period simulated is 10s, the maximum rotation angle of rolling is ±25°, and the test duration is limited to 5 min. All those tests are focused on the identification of the Transportable Moisture Limit (TML) of the ore cargo. The TML is the maximum Moisture Content (MC) of the ore cargo for which there is no risk of "flow".

Atkinson & Taylor (1988) have developed a small scale model for studying in centrifuge the stability of iron ore concentrate. The box was 0.35m large and 0.16m high. The tests were performed at 100×g, using a silicon fluid, but the device allowed only to reach a roll angle of 40° in 20s at the model scale. Laue (1997, 1998) has developped a „shaker", which consists in a 0.3×0.5m table installed on springs allowing the movements of rotation and vertical translation. The model, instrumented with pore pressure transducers and displacement sensors, is observed with video camera through a glass window. The maximum frequency of the jacks that control the displacement is 100Hz. A water tank delivers water to simulate raining process. The g-level of the experiments was 50, and the dynamic tilting reached 4° under a frequency of 5Hz. GBWG (2017) mention centrifuge tests on bauxite performed at 50×g using a rolling table (with a container size of 0.6×0.2×0.45m), applying a maximum angle of 25° during 20 cycles at a frequency of 5Hz (Evans et al. 2018). The hydraulic fluid is pressurized in actuators located in the centrifuge basked, allowing only a set of 20 cycles.

Liquefaction in ore cargoes is still an open problem; no observations being possible during the shipment. In this sense physical modelling is a useful tool to observe the evolution of the material during shipment by artificially reproducing conditions similar to those occurring on the oceans.

2 EXPERIMENTAL SETUP

The Rolling Test Device presented here has been designed to be used in the IFSTTAR's geotechnical centrifuge (Figure 1), the target is the reproduction of similar movement, stresses and pressures on the sample inside the vessel.

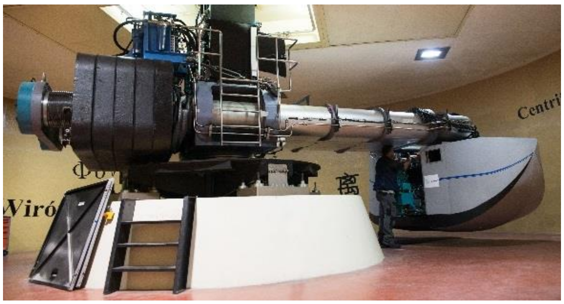

Figure 1 : 200×g-tons & 5.5m radius IFSTTAR's geo-centrifuge

2.1 Rolling test device

The device has been developed in order to simulate a rolling movement of a ship that transports possible iron ore cargo.

2.1.1 Rolling box

The box itself (**Error! Reference source not found.** and 3) is designed similarly to the Rolling Test Equipment suggested by ClassNK (2012), but it has been reinforced in order to support the stresses induced by the macrogravity field. A transparent face allows the observation of phenomena occurring inside the box during the movement. Inside the box, the two other lateral walls (port and starboard sides) have been designed with special features that allow different boundary conditions (rough, smooth, drained…).

The box is fixed in a rotating cradle (radius = 400 mm), placed on an assembly including rolls and hydraulic rotary actuator. A cog-wheel, linked to the actuator, moves a rack and pinion fixed on the cradle. The axis of rotation of the box is perpendicular to the centrifuge rotation axis.

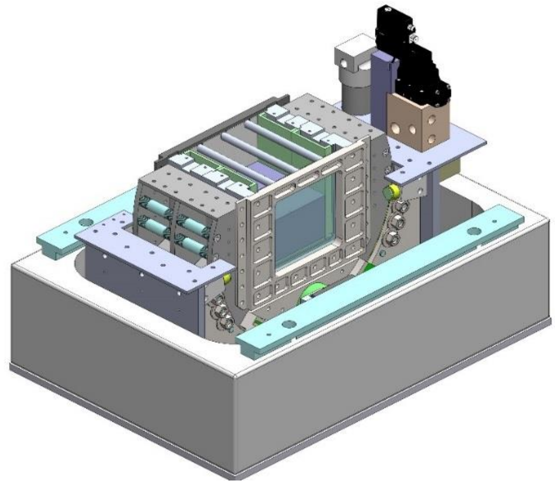

Figure 2 : Scheme of the device.

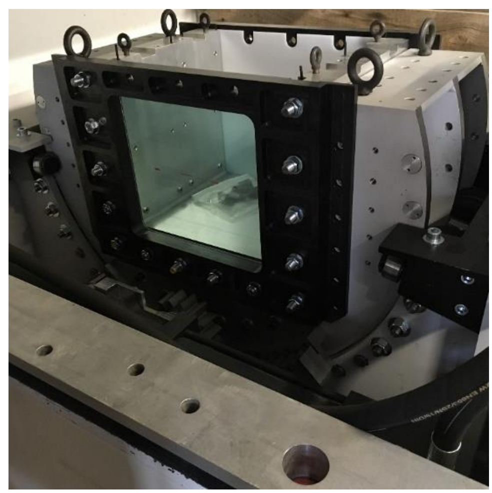

Figure 3 : Detail of the IFSTTAR's Rolling box

The elevation of the box (Figure 4) may be adjusted in order to simulate the rolling movement in different cases: when the centre of gravity is higher than the axis of rotation (light ship) or when the centre of gravity is lower than the axis of rotation (heavy cargo). The elevation is fixed before the test by adjusting wedges of different thicknesses.

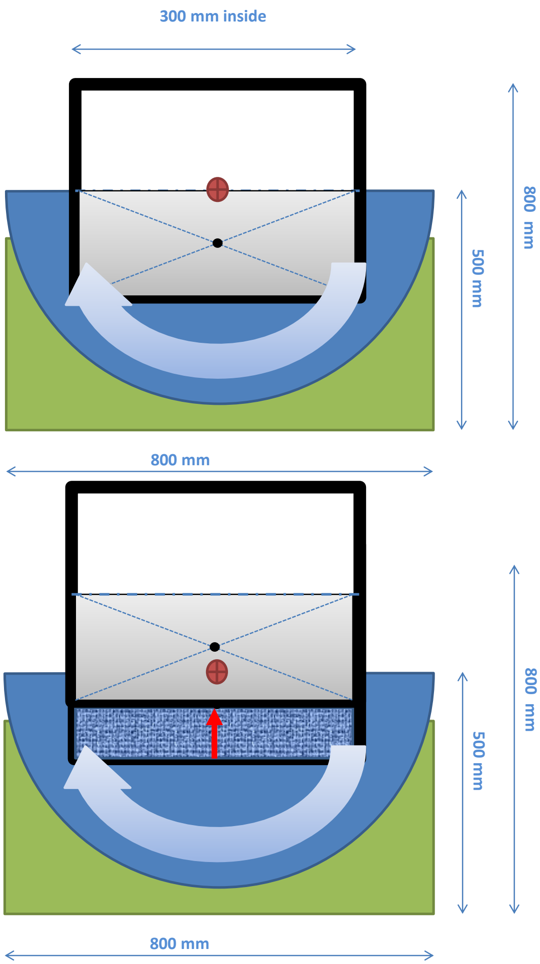

Figure 4: The axis of rotation (fixed) may be relatively more (top) or less (bottom) elevated than the cargo's center of gravity. The red arrow represents 112.5mm maximum.

The stresses induced in the cargo are similar to those existing in a vessel, as the maximum height of cargo is 0.3 m in the box, which corresponds to 24 m at a centrifuge acceleration of 80×g.

2.1.2 Hydraulic rotary actuator

The rotary actuator has been selected in order to apply the required torque in the worst work condition, when the centre of gravity is less elevated than the centre of rotation and taking into account the required frequency.

The model selected is a Parker HTR45 hydraulic rotary actuator, which allows a torque of 2000 N·m and a maximum service pressure of 80 bar. It contains an oil volume 1.8 l, which requires an oil debit of 21 l/min at 0.1 Hz, or 105 l/min at 0.5 Hz. Those performances require of course an adequate hydraulic power supplied by a high-pressure hydraulic pump with a flow of more than 100 l /min. Due to hydraulic constraints, the frequency cannot be scaled. So it has been chosen to reproduce the same range of frequency than in situ.

2.1.3 Control-command

The macrogravity field in the centrifuge basket precludes any human intervention. All on-board equipment is remotely guided from the control room.

The movement applied to the Rolling box is controlled by a servo-controller manufactured by MOOG. A control-loop was created with the rotation sensor, which is an absolute single turn encoder with a precision of 21bits. The software associated with the controller allows a real time control of the movement applied to the Rolling box. The movement could be a sine signal, or other signal as required.

2.1.4 Instrumentation

The data acquisition system HBM Spider enables conditioning and digitizing measurements by means of synchronous 8-channel modules that may be linked. Any type of sensor may be conditioned: full bridge, half-bridge, voltage source, temperature probe… The sampling frequency reaches up to 1.2 kHz.

Pore pressure measurements are necessary to evaluate the overpressure generated by the mechanical solicitations and to compare to the effective stress for liquefaction analysis. The sensors used classically are Druck or Measurement sensors with a range of 700 kPa.

Earth pressure sensors Kyowa (200 and 500 kPa) will be installed on the walls of the box and at the bottom.

A digital camera will be installed in front of the glass of the container. This one will turn with the rolling box to observe the movement of the cargo. This full HD color camera allows observation and measurement of the phenomenon. If measurement needs more precision, a higher definition camera will be installed.

Small size B&K IEPE accelerometers could be installed in the cargo.

Roll angle can be measured with the rotation sensor installed to control the Rolling box.

Pressure sensors are installed on the hydraulic inputs of the actuator to verify the approximate torque issued by the system.

2.1.5 Performances

The performances have been selected to simulate one degree of freedom of a rigid vessel rolling movement during shipment. Thanks to the centrifuge technique, the stresses and pressures are similar to the ones encountered in the vessel. The technical characteristics are presented in **Error! Reference source not found.**.

Table 1: Performances of the centrifuge Rolling Test Device

Max. g-level	80
Maximum angular velocity [°/s]	60
Maximum rotation angle of Rolling [°]	±25
Mass of the box (empty) [kg]	140
Maximum mass of material in the box [kg]	40
Maximum moving mass [kg]	400
Total mass of the device (empty) [kg]	1485*

*Including centrifuge container

A first proof test has been performed up to 80×g. The box, filled with water, has been tested at the lowest elevation under a frequency of 0.4Hz. The movements follow a sine signal and pressures in the system were in line with the expectations (Figure 5). A second series of proof tests have been realized with an empty box and with dry sand inside. The Figure 6 shows the envelope curve that links the maximum frequency to the maximum roll amplitude. All the combinations below this curve are available.

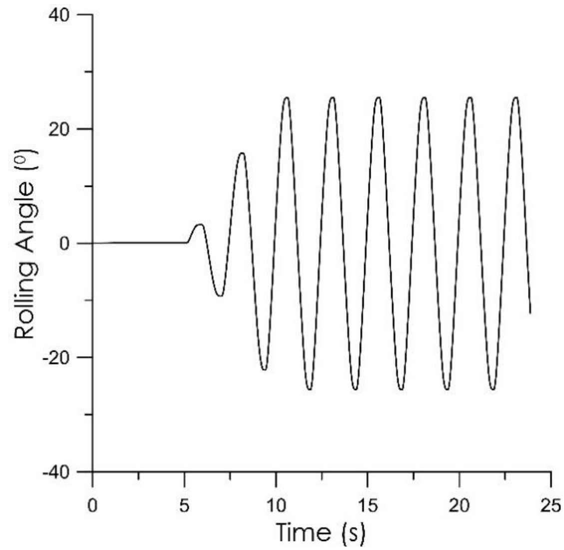

Figure 5: Rolling test frequency response.

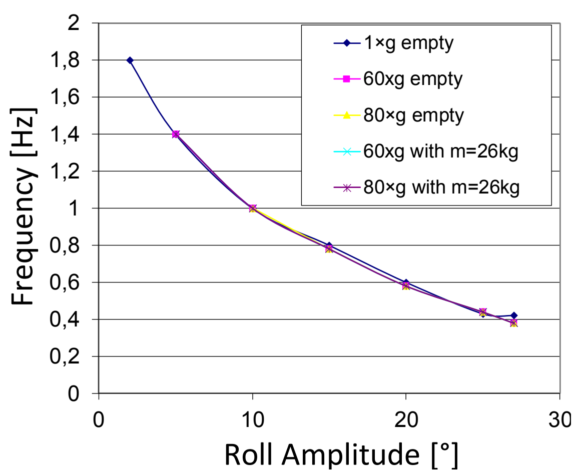

Figure 6: Envelope response curve of the Rolling test (model scale)

2.1.6 Scaling laws

To simulate the movement of the boat on the sea, the dynamic phenomenon should be scaled. This is not possible for this device, so it is assumed that the wave frequency (and the wave period) are not scaled. The scaling factors, in a macrogravity field of N, are then $\ell^*=1/N$ for length, $\sigma^*=1$ for stresses, $t^*=1$ for time and $f^*=1$ for frequency. This is not perfect, but it permits the observation of phenomenon.

An assumption is that, as the movement is quite slow, there is an equilibrium at each instant. So the scaling on dynamic effect would not play any role.

Concerning the flow of water, if it follows the Darcy law, and diffusion effect on time, that is scaled as $t^*=1/N^2$. For water, the Darcy velocity becomes $v^*=\ell^*/t^*=N$. This is too high to avoid turbulent flow or other phenomenon like erosion, so the technique will be to increase the fluid viscosity by $\eta^*=N$.

This parameter will be studied later in the second series of tests.

3 FIRST TESTS

In order to testing the suitability of new device in mimicking the rolling movement of the vessel during maritime transportation, a model constituted by ore iron concentrate was tested under 70×g. This test has, as the main aim, to capture the variation of the stresses and displacements resulting from a rolling of ±25° up to 4600 cycles. This represents according SDA (Significant Double Amplitude, GBWG 2017), the route Australia-China under tropical storm.

The model was instrumented according to Figure 7. The model did not consider the actual shape of the ore pile after being launched in the vessel hold, once this is an investigating test and the stresses are better evaluated with a horizontal surface of the embankment.

The ore in the model had a void ratio of 0.8, corresponding to contractive behavior under shearing and it was saturated with sink de-aired water. The main characteristics of the ore iron are presented in Table 2.

Table 2: Iron ore properties

D_{50} (mm)	C_u	e	γ_s (kN/m^3)	γ_h (kN/m^3)	fine content (%<0.1mm)
0,2	3	0,8	48,6	28,6	15

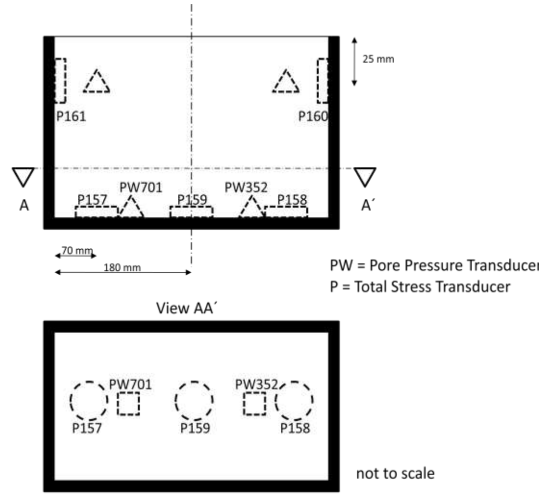

Figure 7. Model and instrumentation: side and top views

The rolling was set up to use a frequency of 0.4Hz following a sine-type signal as shown in Figure 8.

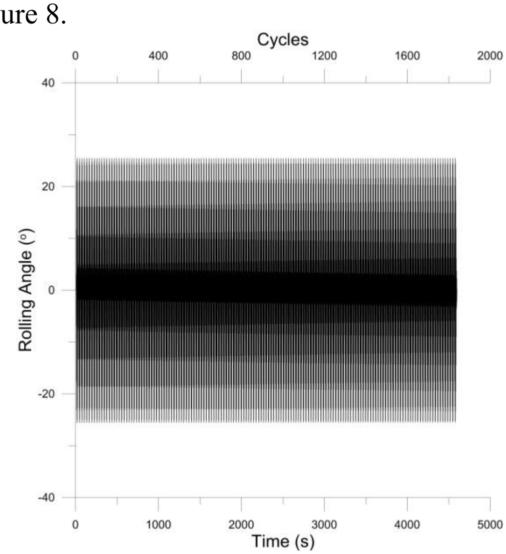

Figure 8. Cycles applied to the model (0.4Hz)

Figure 9 shows the variation of vertical and horizontal total stress during rolling. It can be seen that there is a non-linear relation between the rolling angle and the resulting stress. An extreme variation of the lateral stress up to 200kPa is observed by the lateral stress cells, which is reversible when the movement is in opposite side.

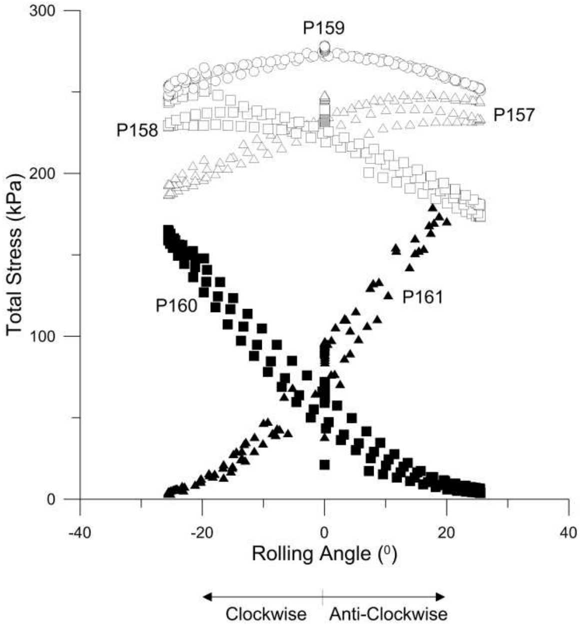

Figure 9. Total stresses recorded during rolling.

As to the development of pore pressure (Figure 10) it can be seen that its variation follows the same pattern of the rolling movements without any accumulation, indicating that the use of sink regular water cannot fulfill the requirements of modeling for diffusion process.

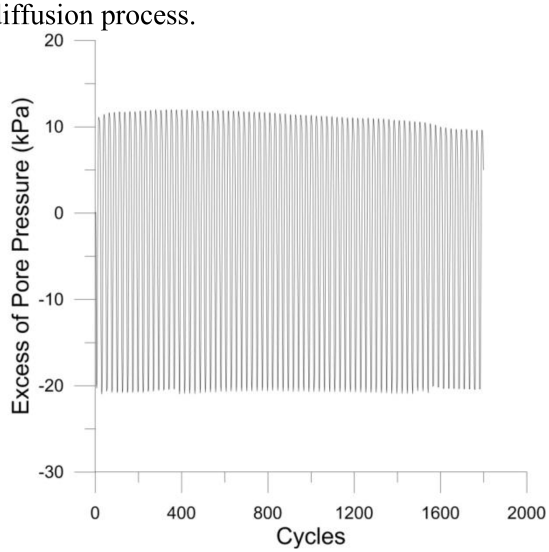

Figure 10. Excess of pore pressure during rolling

Observing the settlement during the cyclic loading (Figure 11 and Figure 12), it is interesting to note that 50% of total settlement take place during the first 20 cycles. This suggests that this material tends to suffer a sudden volume change of its fabric arrangement with cycling loads. This important characteristic is observed for some ores during the maritime transportation.

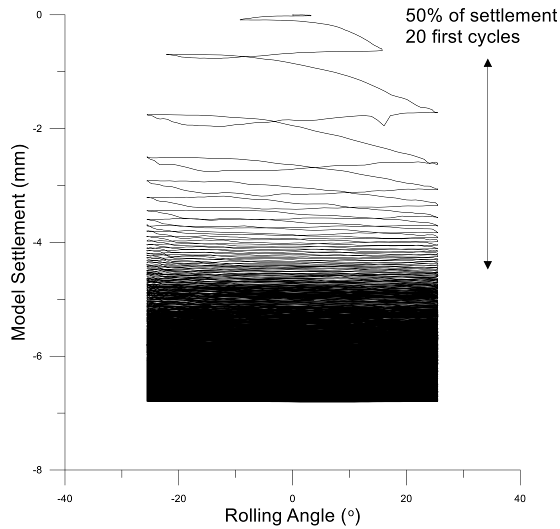

Figure 11. Settlement vs rolling angle.

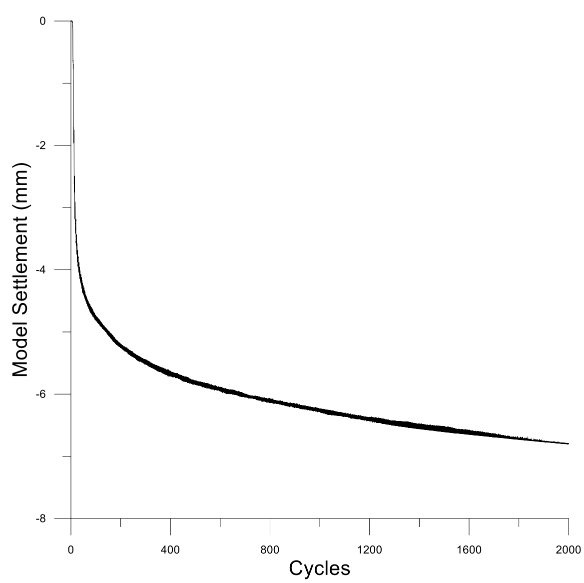

Figure 12. Accumulated settlement during rolling

4 CONCLUSIONS

A new device has been developed to simulate Rolling test for studying the liquefaction hazards of ore cargo. Designed for centrifuge testing at 80×g, it has been successfully tested under those conditions in the framework of approval testing. In the future, the first tests with ore cargo will concern iron concentrate and lateritic-nickel ore. The objectives are: 1) to observe; 2) to understand; 3) to simulate liquefaction of ore cargo and 4) to test counter-measures on small-scale models to avoid this phenomenon.

5 ACKNOWLEDGMENTS

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