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CENTRIFUGE ROLLING TEST FOR ORE LIQUEFACTION ANALYSIS

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Abstract.
To study the development of liquefaction in ore cargo, a new Rolling Test has been designed to support similar stresses than those observed in a vessel. It can be used in an 80×g macrogravity field in the 5.5m radius Ifsttar geo-centrifuge. Its main characteristics are presented.

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. 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; it consists in a change of the soil behavior from "solid" to "liquid" (the meaning of the word "liquefaction" is different than in physics, where a change from gas phase to liquid phase is observed). This phenomenon is related to the presence of interstitial water which, under specific loading conditions, can generate overpressures on the soil grains, up to a level sufficient to eliminate the contacts between the grains. The liquefaction phenomenon occurs "rapidly", it means that the overpressures generated (e.g. by compaction) cannot be dissipated due to a very rapid solicitation or to medium-low soil permeability. Liquefaction accidents are often observed during earthquakes and can for instance involve building foundations.

Ore cargoes liquefaction is a complex and not fully understood phenomenon, it is not necessarily similar to seismic liquefaction even if similar effects can be observed. It could be related to different hypotheses basically ascribable to cyclic loading, fluid migration, and soil compaction. 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 ([1], **Erreur ! Source du renvoi introuvable.**): flow table test (derived from [3]), 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". MC is linked to the water content w by: MC=w/(1+w).

Liquefaction in ore cargoes is still an open problem; the phenomenon is not yet totally understood, 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 reproduce conditions similar to those occurring during sailing.

2 EXPERIMENTAL SET UP

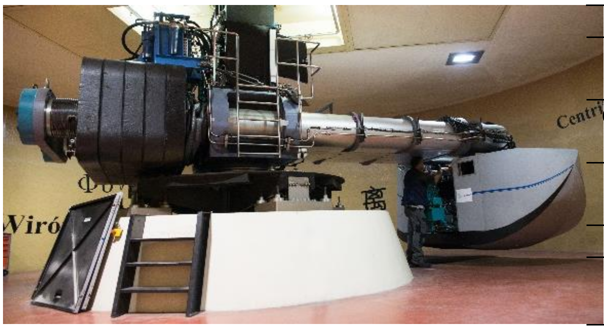
The Rolling test presented here has been designed to be used in a geotechnical centrifuge, which allows the reproduction of similar stresses and pressures on the sample than inside the vessel.

2.1 Geotechnical centrifuge

Centrifuge modelling of geotechnical structures (foundations, tunnels, etc.) using physical models requires respecting the scaling laws (e.g. [2],[5]) that correlate the (reduced scale) model, placed in a macrogravity field, with the (full-scale) prototype targeted by the simulation exercise. This method has become quite wide-spread [6] and enables conducting parametric studies, ultimately taking structures to their failure, observing and understanding phenomena and obtaining data that can be applied either for drawing comparisons with actual structures or for calibrating numerical models. One of the strengths of this approach lies in its compatibility with the stress and strain states between two similar (homologous) points on both the reduced-scale model and prototype structure. This condition must in fact be satisfied since the soil behaviour and, more generally, the behaviour of all granular materials depends to a great extent on the applied stress level.

The primary scaling laws have been listed on Figure 1, with N representing the macrogravity intensity (or g-level). As an example, an experiment conducted at N=80 corresponds to a macrogravity field of 80×g and to a reduced model scale of 1/80.

The centrifuge acceleration ($\omega^2 \cdot R$) depends on both the angular rotation speed ω and the radius R at which the model is positioned.



Scaling laws	
Length, displacement	$L^*=1/N$
Centrifugal, seismic acceleration	$g^*=N$
Stress, pressure	$\sigma^*=1$
Strain	$\varepsilon^*=1$
Force	$F^*=1/N^2$

Figure 1 : 200×g-tons & 5.5m radius Ifsttar's geo-centrifuge and main scaling laws

2.2 Rolling test device

The device has been developed in order to simulate a rolling movement of a ship that transports possible iron ore cargo. In this case, the grain density reaches up to 4.8, when the dry density is about 3.

Rolling box

The box itself (Figure 2) 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 studying 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 rotative 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.

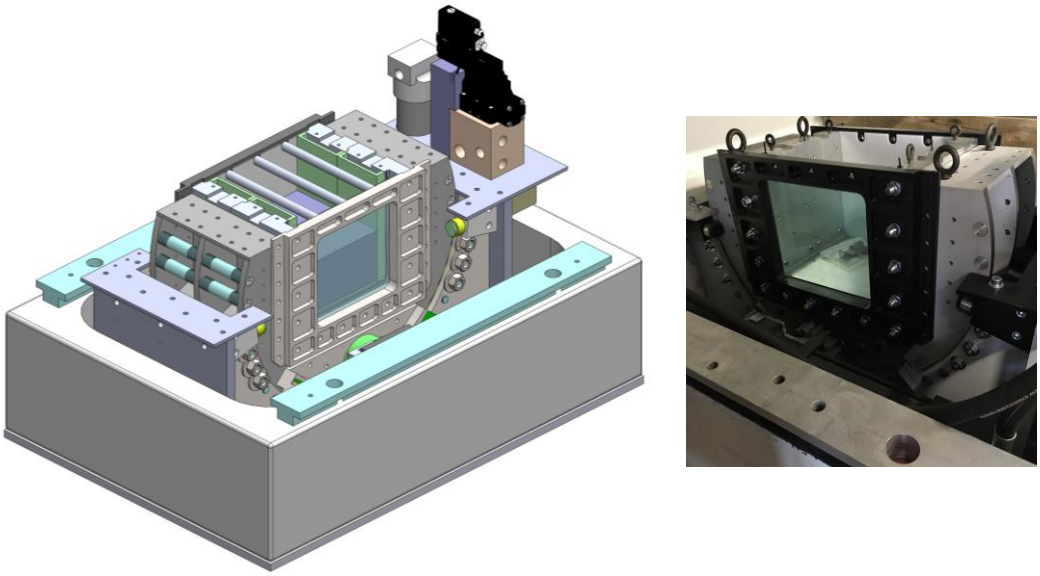


Figure 2 : Scheme of the device (left). Detail of the Rolling box (right)

The elevation of the box (Figure 3) 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.

The stresses induced in the cargo are similar to the ones 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.

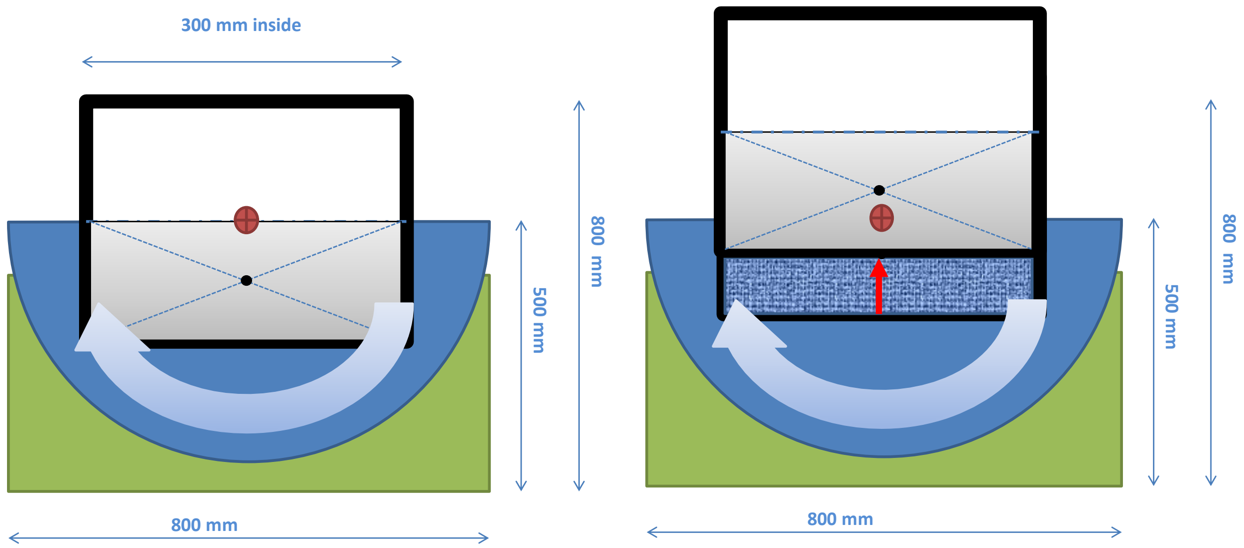


Figure 3 : The axis of rotation (fixed) may be relatively more (left) or less (right) elevated than the cargo's center of gravity. The red arrow represents 112.5mm maximum.

Hydraulic rotative actuator

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

The model selected is a Parker HTR45 hydraulic rotative actuator, which allows a torque of 2000 N·m and a maximum service pressure of 80 bar. It contains an oil volume 1.8 dm^3, which required an oil debit of 21 dm^3/min at 0.1 Hz, or 105 dm^3/min at 0.5 Hz. Those performances require of course an adequate hydraulic power supplies by a high pressure hydraulic pump with a flow of more than 100 dm^3/min.

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.

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 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 colour 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 measure with the rotation sensor installed to control the Rolling box.

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

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 **Erreur ! Source du renvoi introuvable.**.

Table 1: Performances of the centrifuge Rolling Test Device

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

*Including centrifuge container

A 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 0.1Hz. The movements follow a sine signal and pressures in the system were in line with the expectations.

3 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.

4 ACKNOWLEDGMENTS

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