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INFLUENCE OF CYCLIC MOVEMENT ON THE HARDENING PROCESS OF GROUT: CASE OF OFFSHORE WIND TURBINE INSTALLATION

B. DELSAUTE[*], R. FURNÉMONT[†], M. KÖNIGSBERGER[*] AND S. STAQUET[*]

[*] Université Libre de Bruxelles (ULB), BATir departement
Av. Adolphe Buyl, 1050 Brussels, Belgium
e-mail: bdelsaut@ulb.ac.be, mkonigsb@ulb.ac.be, sstaquet@ulb.ac.be

[†] Vrije Universiteit Brussel (VUB), Robotics and Multibody Mechanics (R & MM)
Pleinlaan, 1050 Brussels, Belgium
e-mail: Raphael.Furnemont@ulb.ac.be

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Abstract: The foundation of offshore wind turbines in a rocky seabed is a major technical challenge for engineers. To insure the stability of the wind turbine, the ring between the steel monopile and the seabed is filled with a grout. The objective of this research is to point out the influence of early age movements and deformational restraints on the performance of the grouted connections. Another objective is to evaluate the performance of different grout materials by means of several experimental tests. A first experimental campaign is performed to characterize the behavior of the grout during hardening and to define the stress induced by the restraint of the free deformations. In a second campaign, the behavior of the grout under cyclic displacements since casting is studied. A Temperature Stress Testing Machine (TSTM) has been used to simulate the influence of cyclic horizontal movements by applying cyclic displacements and loadings since casting on samples designed with different grout materials. A segregation device was used to simulate the effect of the waves in the vertical direction. The results of both campaigns are then used to evaluate the risk of damage caused by the movement of the waves during the hardening of the grout. From these newly developed experimental tools, new indicators were developed in order to compare the performance of different grouts under cyclic displacement since casting.

1 INTRODUCTION

The foundation of offshore wind turbines in a seabed, which is built of hard rock, is a major technical challenge for engineers. Several construction processes and types of foundations were developed; the monopile-type foundation is the most often used solution for recent projects. Foundations are carried out in several stages. Firstly, a borehole will be drilled into the seabed to accommodate a steel monopile. The annulus between the drilled borehole and the steel monopile is filled with grout. During the hardening of the grout annulus, severe stresses due to restraint of thermal and autogenous deformation might arise. As soon as the temporary lateral restraints of the monopile are removed, the grout must carry the loadings induced by the waves acting on the monopile. This leads to additional cyclic loadings of the grouted annulus and might induce additional local damage in form of micro-cracks if the stresses are higher than the material strength.

In order to limit the risk of damage at early ages, the DNVGL-ST-0126 [1] standard specifies that, *"If the relative movement at the grout-steel interface exceed 1 mm during the period until **significant grout strength** is reached, the movement shall be limited to maximum 1 mm by implementing suitable means"*. However, it is not always possible to limit this movement to 1 mm. In the context of the Saint Nazaire wind farm, numerical simulations have shown that it is practically impossible to obtain a relative displacement at the monopile-grout interface less than 1 mm when cyclic loadings coming from the waves are applied. In that case, the aforementioned standard states that "*the long-term grout strength should be reduced to a reasonable value. The definition of an additional safety factor due to movements in curing phase has to be proven by test results*". It is therefore necessary to quantify the potential damage of the grout during its hardening when cyclic movements are applied. The Laboratory of Civil Engineering at the Université Libre de Bruxelles was therefore commissioned to study the performance of grout materials subjected to cyclic loading mimicking the waves by means of a comprehensive experimental campaign.

To provide a detailed answer to this problem, the following load cases are considered:

- Restraint of the thermal and autogenous deformations during the hardening process of the grout.
- Impact of cyclic movement induced by

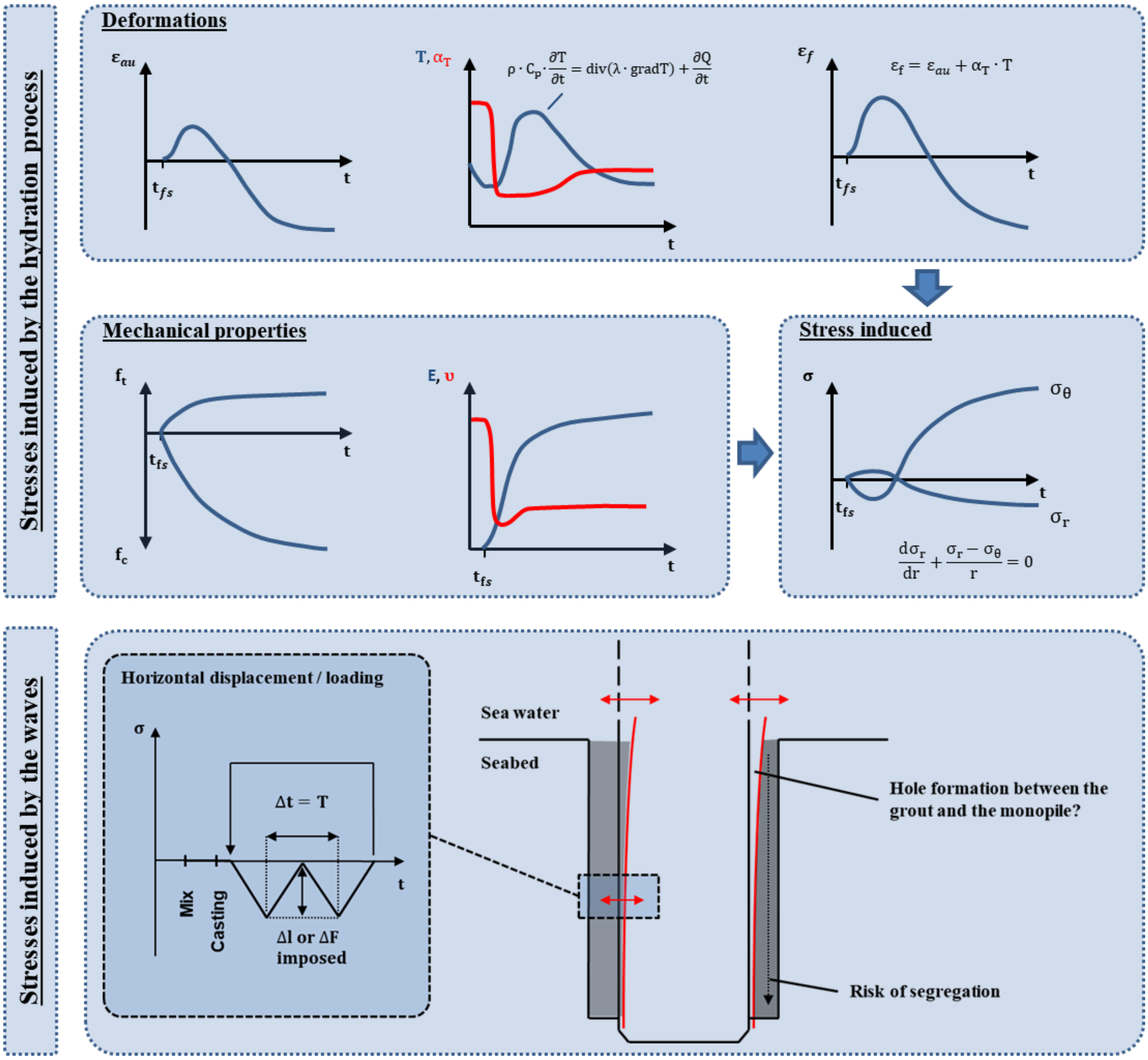

Figure 1: Load cases in the grout annulus induced by the hydration process and the waves motion

the waves.

To assess material damage, cumulated stresses resulting from both load cases must be compared to the grout strength during the whole hardening process of the material, from very early ages directly after setting to material ages of several days. The damage might accumulate over time and might eventually lead to a significant reduction of the local mechanical strength and local durability properties of the grout.

Firstly, restraint stresses are discussed. The temporal evolution of restrained strains is composed of two periods: a heating period followed by a cooling period (Figure 1). The heating period starts after the initial setting when the mechanical properties of concrete start to develop. During and after the setting, a large amount of heat is produced by the hydration reaction which leads to an increase of the temperature inside the grout and thus to an increase of the thermal strain. In parallel, autogenous strains start to develop. Autogenous deformations can result in both swelling or shrinkage depending on the mixture proportion and the composition itself [2]. However thermal strains are frequently dominant in case of high performance grout used for the foundations of offshore wind turbines. Thus a general free expansion of the grout is expected during the heating period. The cooling period starts when the heat of hydration decreases rapidly. During this period, both free autogenous and thermal strains decrease. As a result of the restriction of the strains of the grout in the annulus, stresses are induced. During the heating period, the structure is typically in compression and, inversely, during the cooling period the concrete is submitted to tension in the circumferential direction. In the radial direction, the stresses are of opposite sign and of lower magnitude. Tensile stresses in the grout entail a risk of cracking. To properly characterize this risk, it is necessary to quantify the thermochemical properties (heat release, coefficient of thermal expansion, thermal conductivity, specific heat and autogenous strain) to determine the free deformations and the mechanical properties (mechanical strength, elastic and creep behaviour) and then the stress associated to the restraint of the free deformations since the final setting time t_{fs}. In this study, creep and relaxation phenomena were not considered. These phenomena have the effect to globally reduce the magnitude of the stresses [3–6].

Secondly, the stresses induced by wave motion are calculated according to the specifications of DNVGL-ST-0126 [1]. The movement of the monopile during the first 24 hours after the casting of the grout is determined by considering the state of the sea with the most severe conditions (maximum wave height and associated period depending on the location of the wind turbine). With numerical simulation, it is then possible to define the displacements of the grout (before setting) or the stresses taken up by the grout (after setting). But other risks which are associated to wave loading include segregation of the grout [7] and ovalization of the grout annulus induced by an accumulation of irreversible deformations taking place during each cyclic displacement/loading. All of these phenomena are shown schematically in the bottom of Figure 1.

In this paper, a new experimental methodology is presented to characterize the grout performance when cyclic displacements/loadings are imposed and, at the same time, when thermal and autogenous deformations of the material are restrained since the grout casting.

In the frame of this study, several grouts from different suppliers were tested and compared. However, the composition and performance of these grouts are confidential and no experimental results can be presented. Only the test methodology for characterizing the performance of grouts under cyclic displacements / loadings is presented in this paper.

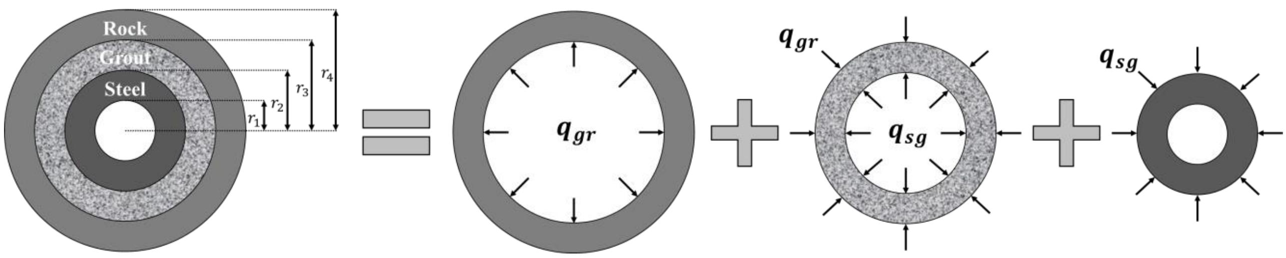

Figure 2: Schematic diagram of the calculation of the restraint of the free deformations.

2 METHODS

Two test campaigns were conducted to determine the influence of cyclic motion on grout hardening. A first test campaign is performed to characterize the performance of the grout in sealed condition during its hardening and to define the stresses associated to the restraint of the autogenous and thermal deformations. A second test campaign is then carried out to characterize the behavior of the grout under cyclic displacements / loadings since its casting.

2.1 Cracking risk induced by the restraint of the free deformations

Analytical solution for stresses in grouted annulus

The free deformations of the grout annulus are restrained by the steel monopile (shrinkage) and the rock (swelling) as shown in Figure 2. As for quantification of stresses, a horizontal section through the annulus is considered (2D calculation), and the steel, grout, and rock are represented as annuli (Figure 2). Radial stresses σ_r and tangential stresses σ_θ must satisfy the equilibrium condition given by Equation 1 while considering the stress-strain relations for a plane stress state (Equations 2 and 3).

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \quad (1)$$

$$\sigma_r = \frac{E}{1-\upsilon^2}\left(\varepsilon_r + \mu\varepsilon_\theta - (1+\upsilon)\varepsilon_f\right) \quad (2)$$

$$\sigma_\theta = \frac{E}{1-\upsilon^2}\left(\varepsilon_\theta + \mu\varepsilon_r - (1+\upsilon)\varepsilon_f\right) \quad (3)$$

with υ, the Poisson's ratio. The boundary conditions are shown in Figure 2. The stress components σ_r and σ_θ can be solved analytically. This requires knowledge of the elastic modulus E and Poisson's ratio υ of the rock, the grout and the steel of the monopile. Free strains ε_f result from autogenous strains ε_{au} and from thermal strains ε_{th}. To quantify the latter, knowledge of the evolution of the coefficient of thermal expansion α_T and of the temperature T is required (Equation 4). The heat equation (Equation 5) [8] is solved numerically (finite differences), where ρ, C_p, λ and Q are the density, specific heat, thermal conductivity and heat release of the grout, respectively.

$$\varepsilon_f = \varepsilon_{au} + \alpha_T \cdot T \quad (4)$$

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \mathrm{div}(\lambda \cdot \mathrm{grad}T) + \frac{\partial Q}{\partial t} \quad (5)$$

Complete details about the stress calculation for such a geometrical configuration is given in Reference [9]. To obtain the restraint stresses, several grout properties must be assessed: E, υ, ε_{au}, α_T, ρ, C_p, λ, Q. In addition, compressive f_c and tensile f_t strength must be quantified to assess the damage risk. The set of methods used to characterize these properties since very early age is presented below. Only the evolutions of C_p and λ have not been determined since the casting of the grout at ULB.

Monitoring of the setting

The initial and final setting times are determined using the FreshCon device, which monitors the P- and S-wave velocity. The samples are completely sealed to prevent drying. The tests are carried out in a climatic chamber in which the temperature is controlled to ± 0.1 ° C. The initial setting time corresponds to the time when the time derivative of the S-wave velocity reaches a maximum. The final setting time corresponds to the time when the time derivative of the dynamic elastic modulus (based on the measurement of the speed of the P- and S-waves) is maximum. A complete description of the device, the test protocol and the data processing is indicated in the references [10,11].

Monitoring of the heat flow and the adiabatic temperature

The heat flow of the grout is measured continuously with two types of devices. A quasi-adiabatic calorimeter (QAB) is used to measure the evolution of the temperature of the grout in quasi-adiabatic conditions and to define both the heat flow and the temperature evolution in adiabatic conditions [12]. The tests are carried out on cylindrical specimens (dimension: Ø16x32 cm). A TAM-Air isothermal calorimeter composed of 8 measuring channels was used to measure the heat release in isothermal condition [13]. 4 samples per composition are tested and have a total mass of about 20 g.

Monitoring of the autogenous strain and the coefficient of thermal expansion

The autogenous strain is monitored using the Autoshrink device [14]. The device has been adapted at ULB concrete laboratory to monitor the coefficient of thermal expansion by means of thermal variation during the test [15]. The samples are placed horizontally on the test rig just after the grout has been cast in a corrugated mold. The autogenous deformations can then be defined since the casting of the grout. During the test, repeated thermal variations of ± 3°C are applied to the sample to determine the coefficient of thermal expansion. A complete description of the device as well as the test methodology is given in the references [15,16].

Monitoring of the elastic properties

The elastic properties are monitored on cylindrical specimen (dimension: Ø97x550 mm). For the simultaneous monitoring of free deformations and temperature, a second sample, having the same geometry, is produced. Two aluminum foils surround the specimens to keep them sealed during the test. The tests are performed with an electromechanical press with a capacity of ± 100 kN. Longitudinal and lateral deformations are measured with Invar© extensometers. Each extensometer consists of two rings spaced 350 mm apart and three bars placed at 120° on which displacement sensors are fixed. Three anchors with elastic blade are placed on each ring. The entire device is placed in an air-conditioned room where both temperature and humidity are controlled. For the monitoring of the elastic modulus and Poisson's ratio, repeated loadings are applied every 30 minutes after the end of setting during the first 24 hours. Each loading corresponds to 20% of the compressive strength of the grout obtained at the age at loading. Then loads are applied at ages of 2, 3, 7, 14 and 28 days. A complete description of the device, the test protocol and the data processing is indicated in [4,17,18].

Determination of the activation energy

The temperature variations in the grout and, consequently, its aging are dependent on the temperature of the sea when it is cast. Tests were carried out at 3 curing temperatures to define the influence of the sea temperature on the evolution of the grout properties. These 3 temperatures correspond to the minimum, average and maximum temperatures observed during the years preceding the installation of the wind turbines. It is then possible to determine the impact of the cure temperature on the evolution of the properties of the grout by considering the equivalent time t_{eq} (Equation 6). Equivalent time is based on the Arrhenius equation and is function of the age of the material t, the evolution of the temperature T (°C), a reference temperature T_r (here 20°C), the universal gas constant R (=8.314 J/mol/K) and the apparent activation energy E_a (J/mol).

$$t_{eq}(t,T) = \int_0^t \exp\left(\frac{E_a}{R}\cdot\left(\frac{1}{273+T(s)} - \frac{1}{273+T_r}\right)\right)\cdot ds \quad (6)$$

For each test, the temperature of the grout is recorded from the end of mixing until the end of the test.

2.2 Grout properties under cyclic loading/displacement since casting

The strength of the grout and consequently the bearing capacity of the grout annulus can be altered by cyclic displacements since casting. Three major phenomena must be considered according to Lohaus, et al. [7]. Horizontally, the application of cyclic displacements / loadings can lead to damage to the grout and to irreversible deformations that can induce the formation of a hole at the grout-rock and grout-monopile interfaces. Vertically, the application of cyclic displacement/loading can lead to a risk of sedimentation and grout segregation. Each of these phenomena is a function of the magnitude and frequency of the cyclic displacements/loadings and of the composition of the grout. Two types of devices were used to define the influence of these cyclic loadings. A TSTM device has been used to simulate the influence of cyclic movement / loading horizontally. A second device has been developed to simulate the effect of waves in the vertical direction. These two devices are presented below.

Cyclic loading under compression

The TSTM (Temperature Stress Testing Machine) is a device which has been developed for the monitoring of restrained

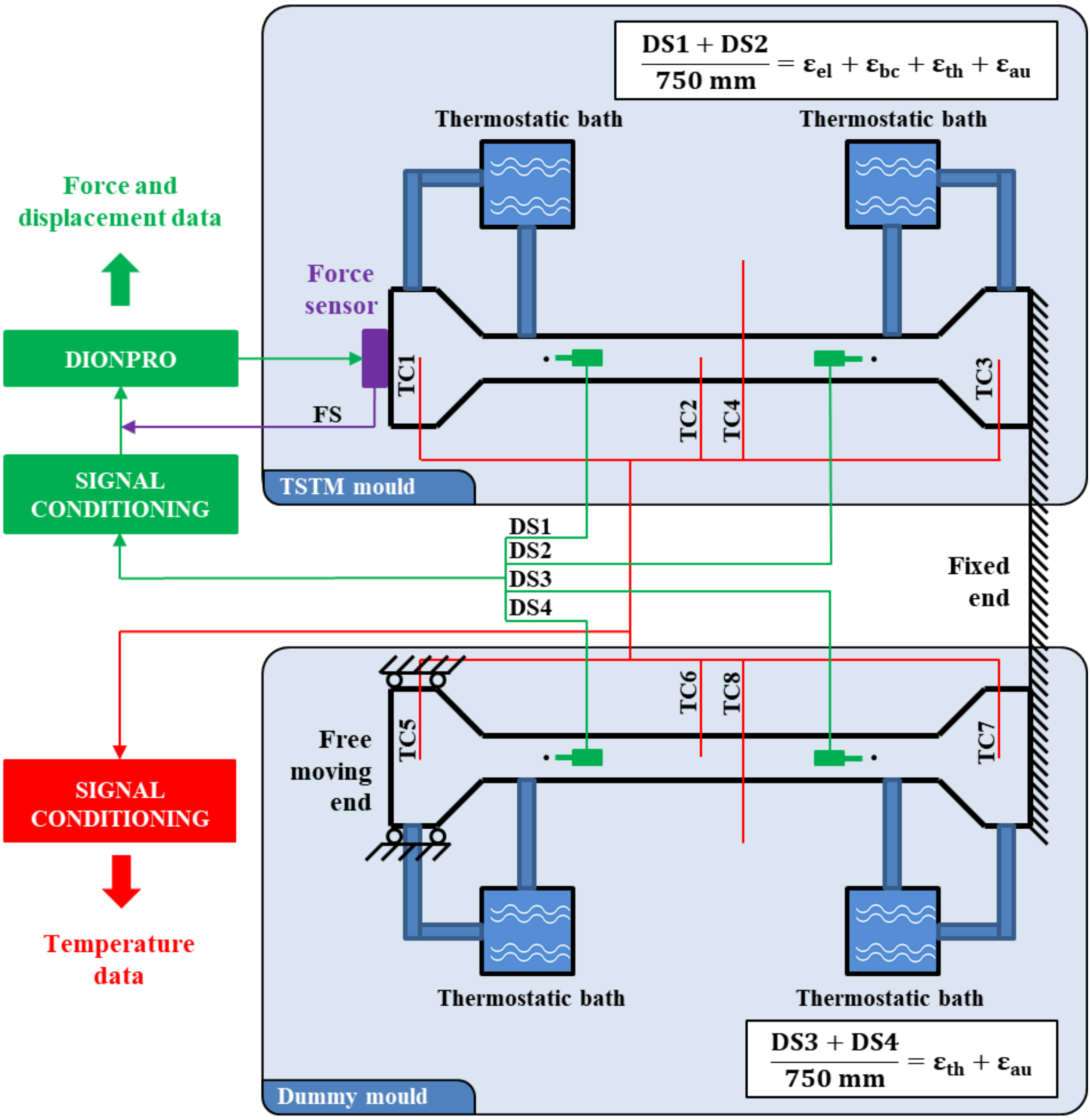

Figure 3: Overview of the TSTM device [4].

shrinkage. A revised design has been developed at ULB for extending its use to other applications such as creep and relaxation [19,20]. Loadings in tension and compression can be applied on a sample confined in a mold. The TSTM is an electro-mechanical testing machine with a capacity of ±400 kN. The machine is fully programmable and controlled by computer (force and displacement at the moving end). The scheme of the TSTM device is shown in Figure 3. The test specimen is bone-shaped and is composed of a central span 1 meter long and a square section of 100 mm side. The temperature is monitored with a thermocouple in the middle of the span. A watertight plastic film and PTFE (poly-tetra-fluoroethylene) sheets cover the mold and the crossheads, allows reducing the friction between the concrete and the mold. The mold is surrounded by a thermal regulation and a thermal insulation which ensures the control of the temperature inside the sample. All equipment is in an air-conditioned room. Within the central prism section of the mold, displacements are measured by two contact-less Foucault current sensors placed on invar supports which are fixed on steel bars. The distance between both sensors is 750 mm (where deformations are uniforms in the sample). Free deformations are monitored on a dummy specimen with exactly the same dimensions as the first one. The only difference comes from the free movement of one head.

Segregation test

The test device developed at the ULB is inspired by the work of Lohaus, et al. [7]. This device was developed to simulate the effect of cyclic movements of the monopile induced by the waves on the hardening of the grout until the end of setting. The 120x80x50cm large frame (total volume of 442 dm^3) is made of wooden formwork and is divided into two equal parts by a wooden board (Figure 4). The wooden plate in the middle of the frame is attached to the bottom of the mold with two joints allowing the central board to tilt. The top of the wooden board is attached to a bar connected to a motor which itself is attached to the frame. The engine has a capacity of 75Nm. In this way, the movement of the grout caused by displacements of the monopile can be simulated. The test device is shown in Figure 4.

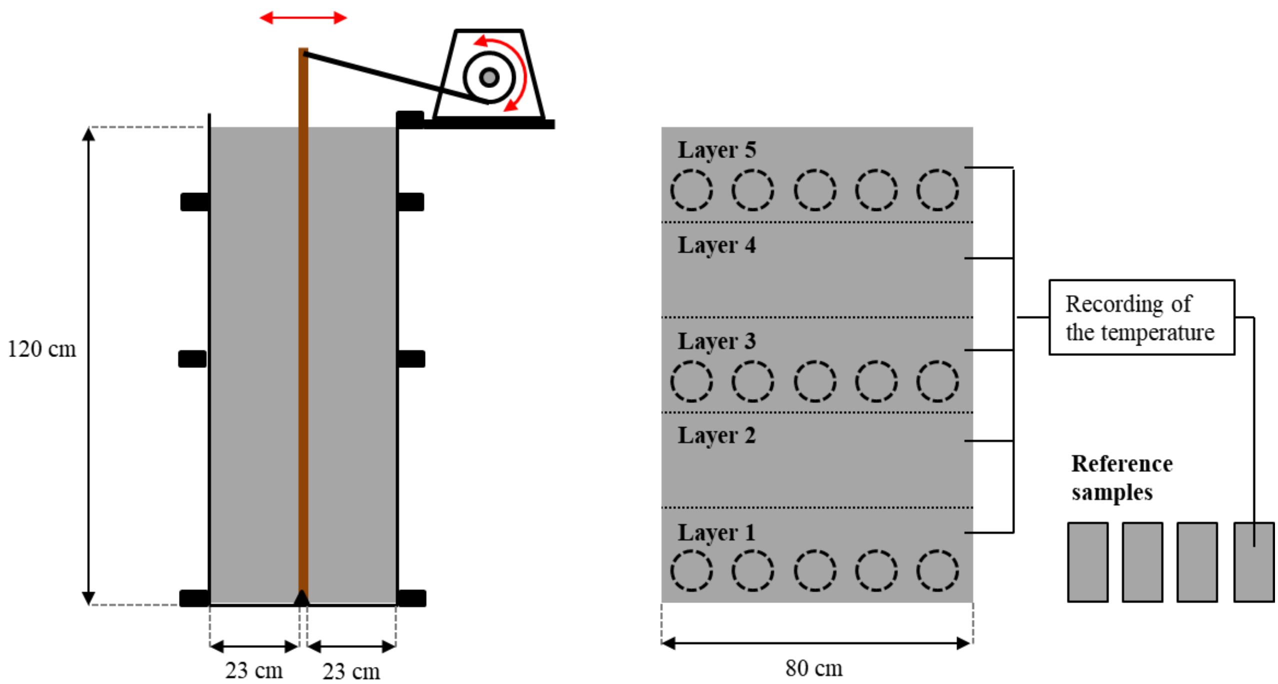

Figure 4: Overview of the segregation device.

3 TEST PROTOCOL AND DATA ANALYSIS

The amplitude and the frequency of the deformations / stresses applied on the grout resulting from the movement of the monopile induced by the wave have been defined by finite element simulation of the whole foundation (rock, grout and monopile). The frequency and amplitude of the waves are defined by means of readings made during the years preceding the installation of the wind turbine. These data are then used as input data for the test protocols presented below.

3.1 TSTM test

Cyclic displacement and cyclic loading tests were applied on samples since an age of 1 hour until an age of 24 hours with the TSTM device at 3 curing temperatures corresponding to the minimum, average and maximal temperature measured on site. For each test, a dummy specimen with exactly the same dimension is cast to measure the free strains. The test protocol was developed in order to reproduce the displacement/loading imposed by the waves on the grout annulus during the construction process. Firstly, cyclic displacements with a magnitude d_s and a period p are applied. The force and the total displacement of the TSTM specimen were recorded during this period. Secondly, when the load induced by the cyclic displacement became higher than a force threshold F_s, the control of the device was changed. Cyclic loadings with a magnitude F_s and a period p are applied. At this moment, displacement sensors were activated to monitor the displacement in the straight part of the sample. The displacement d_s corresponds to the maximum relative displacement at the grout-monopile interface. The force F_s is the maximum force applied on the grout during its hardening. These parameters were calculated by numerical simulation. At an age of 24 hours the cyclic loadings were stopped. The test protocol used with the TSTM follows the scheme indicated in Figure 5.

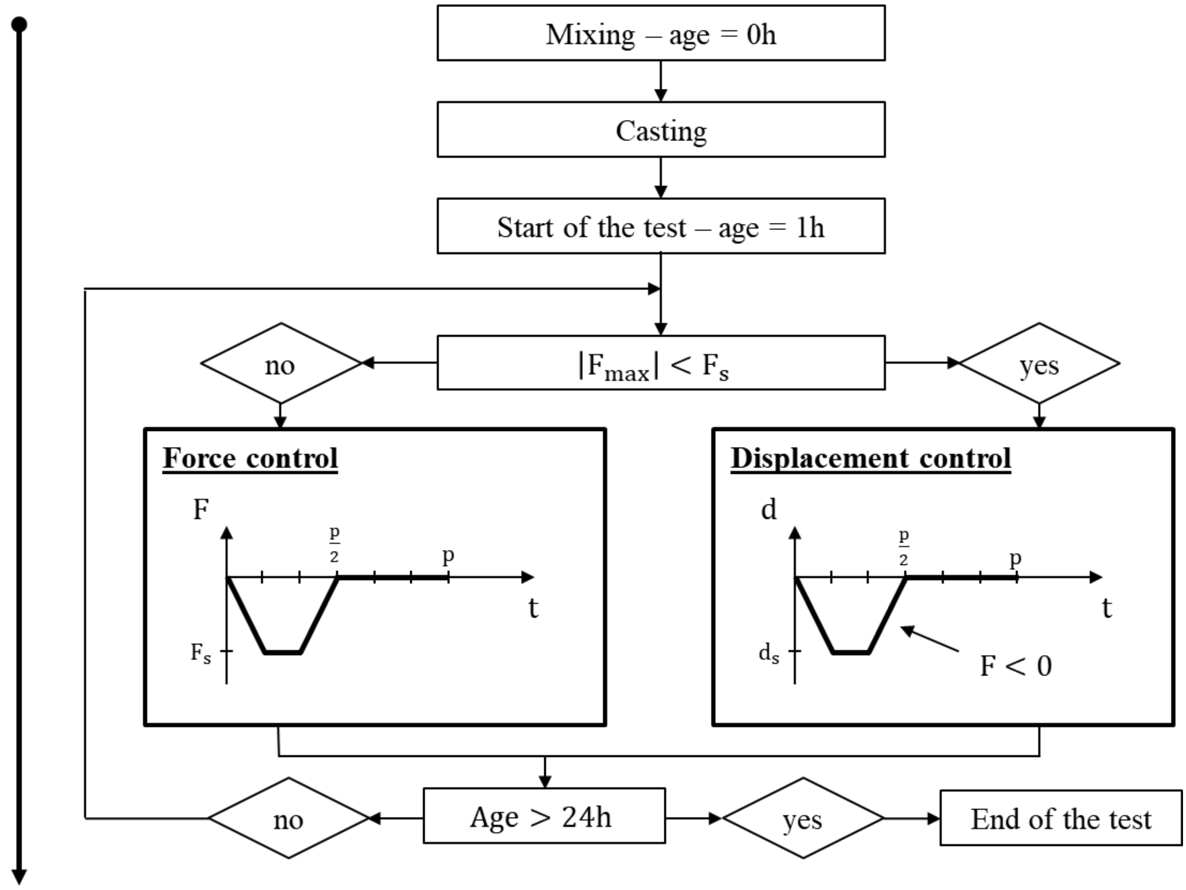

Figure 5: Test protocol used in the TSTM device.

From the recordings of the force during the cyclic displacements, the decrease of workability and the start of the setting of the grout are observed based on the evolution of the maximum force applied for each cyclic displacement. From the recordings of the force and the grout displacement during the cyclic loading, the E-modulus has been computed for each loading and unloading. These results are then compared to the E-modulus results obtained with the repeated loadings to define the potential damage of the grout induced by the cyclic displacement/loading. In addition, the strains of the loaded specimen at the end of each cycle are compared to the strains of the dummy specimen. This comparison quantifies the irreversible strains induced by the application of cyclic loadings. At the end of the test, the prismatic part of the TSTM and dummy specimens were removed from the mold and were cut in several cubes of 10 cm side length for compressive strength tests. This way, the influence of cyclic displacement/loading on the strength development of the grout material is studied since casting. Based on the results obtained, an additional safety factor related to the strength and the stiffness of the grout can be defined.

3.2 Segregation test

When producing an offshore wind turbine, the grout is produced continuously. To best represent the offshore conditions, the filling of the segregation test device in the laboratory is carried out in 5 phases. After placing the first grout layer, cyclic displacements are continuously applied. The other layers follow each other at regular intervals until complete filling of the mold. The total filling duration of 5 hours corresponds to the time of casting of the grout on site. Five thermocouples were inserted into the mold halfway up each layer to follow the evolution of the grout temperature. The test is stopped when the last layer of grout

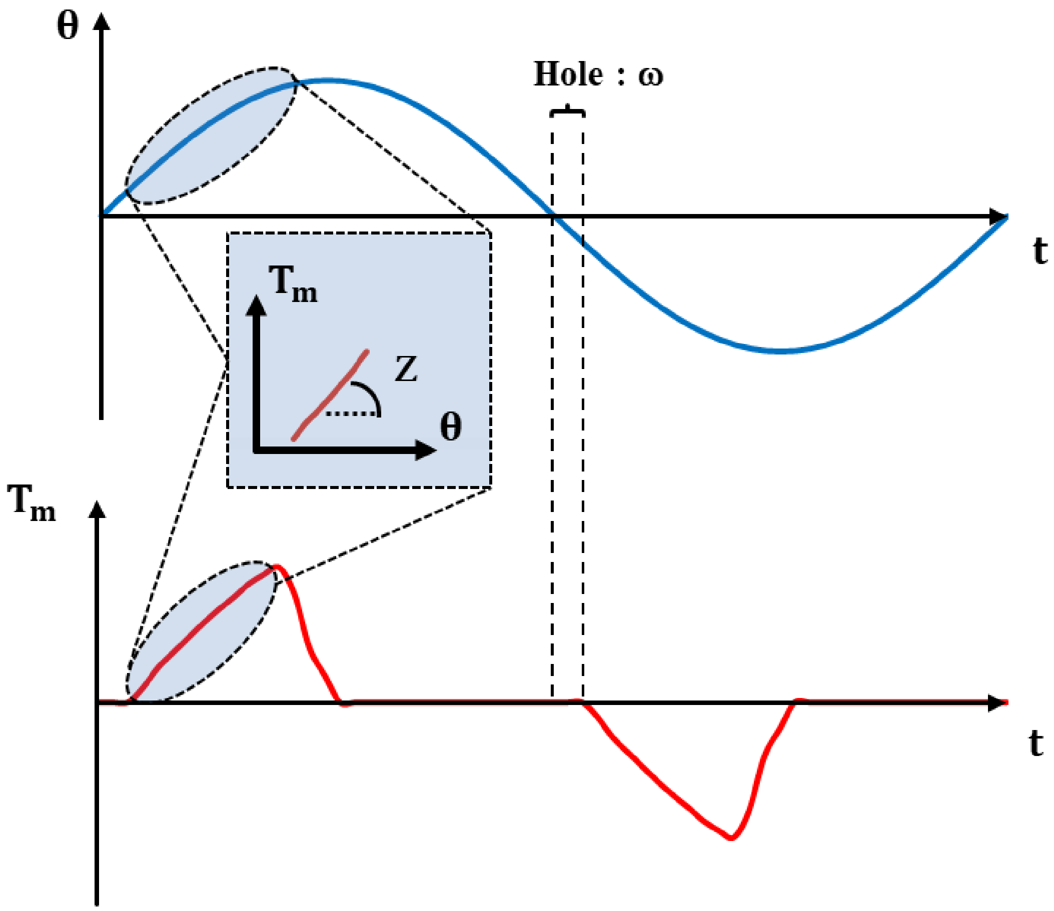

Figure 6: Typical evolution of the position and the torque during one cycle.

has set. During the whole test, the position θ and the torque applied by the motor T_m are recorded every 0.2 seconds. 24 hours after the start of the test, the device is disassembled and 5 cylinders are extracted on the first, third and fifth layers (Figure 4). Additional grout cylinders were cast at the end of the segregation test as reference samples. Two cylinders from each of the three locations and from the reference compositions are tested in compression at ages of 3 days and 7 days, respectively. The last cylinder is cut perpendicular to its axis into ten pieces. Each section is then photographed at ages of 3 and 7 days, respectively. A grey level analysis of the resulting high resolution images allows for assessing sand, binder and void contents in the different layers. By comparing compressive strength as well as void sand/binder/void contents at layers 1, 3 and 5 to the reference, segregation during cyclic displacements can be revealed.

The position and torque records provided by the engine are used to characterize the formation of a potential hole between the removable wooden plate and the grout and the evolution of the stiffness of all the grout layers. For each cycle, the thickness of the hole formed by the cyclic displacements is determined by considering the time interval ω between a position θ = 0 and the beginning of the increase of the motor torque. The stiffness Z of all the grout layers is defined on the basis of the evolution of the engine torque-position relationship during each loading as shown in Figure 6. In addition, temperature measurements can be used to validate results from numerical simulations of temperature based on heat release results.

4 CONCLUSIONS

A new comprehensive experimental methodology is presented to monitor the behavior of grout materials. A first test campaign is carried out to define the grout performance during its hardening and to determine the stress induced by the restraint of autogenous and thermal deformations. A second test campaign is used to characterize the behavior of the grout under cyclic displacements/loadings since its casting. A TSTM device has been used to simulate the influence of cyclic horizontal movement/loading by applying cyclic displacements and loadings since the grout casting. This test allows defining the evolution of the elastic modulus when cyclic loadings are applied. A segregation device was used to simulate the effect of the waves in the vertical direction.

The results of both test campaigns are then used to estimate the damage risk caused by the movement of the waves during the hardening of the grout in the annulus around a steel monopile in the foundations of wind turbines. Moreover, new indicators and safety considerations were developed in order to quantify the performance of grouts under cyclic displacements/loadings since casting.

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