Mechanical behaviour of concrete piles affected by sulphate attack

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Summary

This paper present results from testing of two concrete piles affected by sulphate attack in marine environment. A multi method approach going from micro scale to structural level has been applied. The crack propagation was monitored during loading by means of Digital Image Correlation (DIC) and Acoustic Emission (AE). After the test cracks were studied using fluorescence microscopy. Furthermore, finite element analysis was used to study the influence of the chemical attack on the response of the piles.

Keywords: Marine constructions, experiment, finite element analysis, microscopy, Digital Image Correlation, Acoustic Emission.

1. Introduction

This paper concerns with two concrete piles damaged by external sulphate attack to different degrees. The piles have been exposed to the marine environment for about 40 years. Both piles have the dimension of 320 x 320 mm^2 in cross section and were cut to a length of 900 mm. The less damaged pile and the severely damaged pile are denoted Pile A and Pile B, respectively. External sulphate attack is characterized by formation of ettringite and a reduction of Ca^{2+} in the the cement paste. This results in expansion and crack formation. Three-dimensional non-linear finite element analysis (FEA) at the structural level were applied to study the behaviour of the concrete piles. The influence of damage was taken into account by adapting material properties. The results from numerical analysis were verified with the results from mechanical testing with respect to global behaviour and load-carrying capacity.

2. Mechanical testing

2.1 Material testing

The concrete properties of the two piles were determined by tests on core-drilled cylinders. The tensile strength, fct, and fracture energy, GF, were obtained from direct tensile tests, performed on notched cylinders (Ø 100 x100 mm^2) with fixed end-conditions. The Young's modulus, E0, and compressive strength, fcc, were obtained by compression tests on cylinders (Ø 100 x 200 mm^2).

During the compression tests the full-field deformation field was monitored at the surface of the cylinders by means of DIC. The deformation field was used to quantify how the damage to the concrete changes with distance from the exposed surface by analyzing the stiffness degradation in segments along cored concrete cylinders. The results show that in Pile B the stiffness in concrete cover area is about 30-50% lower compared with the core area inside the reinforcement, while in Pile A the concrete cover area is instead 30-50% stiffer compared with the core area. The cracking process was also recorded by two AE-sensors. Pile A show significantly more AE-activity compared with Pile B.

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2.2 Pile testing

The compression tests of the stub pile specimens (h 900 mm) were carried out under displacement control with a rate of 0.3 mm/min, using moment stiff loading plates. The cracking process, monitored at one side of the specimen during the loading by means of DIC and the AE activity, was also recorded by a total of six AE-sensors.

Pile A exhibits a higher stiffness, a relatively linear behaviour in pre-peak response and a higher capacity compared to Pile B. Cracks were observed earlier by the DIC measurements for Pile B compared with Pile A; this explains the stiffness loss observed in Pile B in the pre-peak response. For Pile B, the crack formations were mainly located to pre-existing vertical cracks along the reinforcement. In both cases the final failure was caused by vertical cracks due to spalling of the concrete cover. The maximum load capacity was 5.14 MN and 4.44 MN for Pile A and Pile B, respectively. As in the compression tests on the cores, the AE activity was significantly higher for Pile A compared with Pile B, both in number of hits and absolute energy.

3. Analysis of crackpatterns in the cross sections

Plane polished samples with an area covering about 2/3 of the cross section of the pile were produced before and after the test. These samples were impregnated with fluorescent epoxy which made it possible to identify cracks from micro scale.

Pile B showed a complex surface parallel zonal porosity pattern of the cement paste. The main crack patterns of this pile were cracks radiating from the reinforcement bars and going out to the surface but also diagonally through the center of the pile. Ettringite filled cracks especially in the contacts to the aggregate particles were frequent. After testing, pre-existing diagonal cracks had further developed and a shear crack had propagated between the reinforcement bars parallel to one side. The number of cracks formed during testing was much lower in this pile. Pile A showed a less complex zonal pattern of the cement paste porosity than Pile B. The cement paste was less porous outside the reinforcement. There were cracks radiating out from the reinforcement bars. The main cracks were centimeters to decimeters long going diagonally. Adhesion cracks in the ITZ were frequent; however, ettringite filled cracks were not. The main cracks, formed during testing, were a system of cracks connecting the reinforcement bars going adjacent to the stirrups and also cracks going from the bars to the surface of the pile. The ITZ had mostly open cracks after the test but the cracks, to a large extent, had also propagated through the aggregate.

4. Numerical modelling

Three-dimensional non-linear finite element analysis at the structural level has been used to study the mechanical behaviour of the stub pile specimens under compression. As the reinforcement arrangements in the piles were not symmetric, the entire piles were included in the FE model. Concrete was modelled with three-dimensional pentahedron solid elements. A constitutive model based on non-linear fracture mechanics, with a smeared rotating crack model based on total strain, was applied. The longitudinal bars and stirrups were embedded in the concrete elements, corresponding to a perfect bond between the rebar and concrete. The concrete material properties from the compression test and direct tensile test were used in the analysis. The reinforcement was modelled as elasto-plastic.

The analyses sowed good correspondence to the experimental results. Yielding of stirrups at a load level of about 2.5 MN caused several cracks in Pile B. However, the crack pattern was different from that observed in the experiment. This was because the crack pattern in pile B was highly influenced by the pre-existing cracks; while these cracks were not included in the analysis. A better agreement between experimental and numerical crack patterns was seen in the case of Pile A. The failure of both piles was triggered by yielding of one longitudinal bar, with least concrete cover, preceded by crushing of concrete.