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Testing and modeling of cyclically loaded rock anchors

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ABSTRACT

The Norwegian Public Roads Administration (NPRA) is planning for an upgrade of the E39 highway route at the westcoast of Norway. Fixed links shall replace ferries at seven fjord crossings. Wide spans and large depths at the crossings combined with challenging subsea topography and environmental loads call for an extension of existing practice. A variety of bridge concepts are evaluated in the feasibility study. The structures will experience significant loads from deadweight, traffic and environment. Anchoring of these forces is thus one of the challenges met in the project. Large-size subsea rock anchors are considered a viable alternative. These can be used for anchoring of floating structures but also with the purpose of increasing capacity of fixed structures. This paper presents first a thorough study of factors affecting rock anchor bond capacity. Laboratory testing of rock anchors subjected to cyclic loading is thereafter presented. Finally, the paper presents a model predicting the capacity of a rock anchor segment, in terms of a ribbed bar, subjected to a cyclic load history. The research assumes a failure mode occurring in the interface between the rock anchor and the surrounding grout. The constitutive behavior of the bonding interface is investigated for anchors subjected to cyclic one-way tensile loads. The model utilizes the static bond capacity curve as a basis, defining the ultimate bond τ_{bu} and the slip s_1 at τ_{bu}. A limited number of input parameters are required to apply the model. The model defines the bond-slip behavior with the belonging rock anchor capacity depending on the cyclic load level ($\tau_{max\ cy}/\tau_{bu}$), the cyclic load ratio ($R = \tau_{min\ cy}/\tau_{max\ cy}$), and the number of load cycles (N). The constitutive model is intended to model short anchor lengths representing an incremental length of a complete rock anchor.

1. Introduction

The Norwegian Public Roads Administration (NPRA) is planning to upgrade the E39 coastal route in Norway, a distance of about 1100 km. Fixed links at seven fjord crossings along this route will replace ferry connections. The fjord widths range up to 5 km and the depths reach 1300 m. Large bridge structures will be required to cross the fjords. A variety of bridge concepts might be used, whereas the most successful is determined by the local metrics. Suspension bridges, submerged tunnels, fixed bridges, floating bridges and combinations of these structures are conceivable alternatives. Two alternative concepts are illustrated in Figs. 1 and 2.

Anchors for suspension bridge main cables, floating bridge abutments or anchoring of buoyancy forces from the submerged tunnel are one of the challenges related to these structures. The complexity of this subject is depending on the boundaries, offshore/onshore installation, load characteristics (size, static, cyclic), ground conditions among the others. Different alternatives may be used to anchor the loads: gravity based structures (GBS), suction piles, driven piles, drilled piles, rock anchors and so on. Howard et al. (2013) presented the deep water anchors designed to anchor the pontoons of the new Evergreen point floating bridge (Seattle, USA). Drilled shaft anchors, gravity anchors, and fluke anchors are used. Large gravity anchors are traditionally applied to anchor suspension bridge main cables when there is large depth to firm bedrock. The anchor block at the west side of Akahsi Kaikyo is a large cylindrical foundation constituting the following metrics: 75 m depth, 85 m diameter, 2.2 m thick retaining wall, constructed using a slurry trench method, backfilled with concrete inside the cylinder (Furuya et al., 1994).

Suspension bridge main cables are commonly fixed using “end-anchored” grouted rock anchors when rock is accessible. The “end anchors” are accessible through inspection tunnels. The Hardanger

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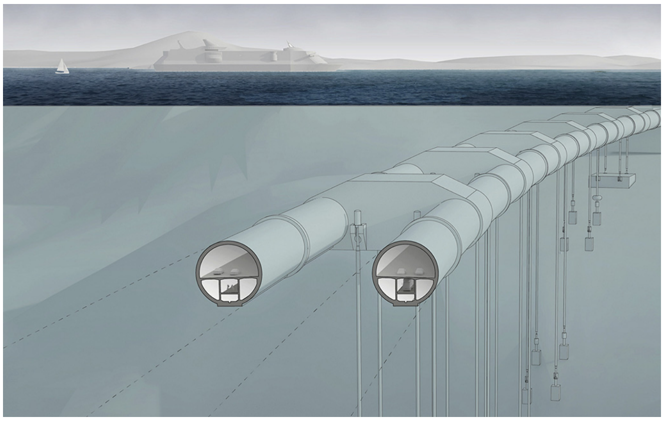

Fig. 1. Submerged floating tube bridge anchored to seabed, conceptual illustration (NPRA).

Fig. 2. Suspension bridge with floating towers, conceptual illustration (NPRA).

bridge used this method at both anchors whereas the Yi Sun-Sin bridge is designed with end anchor at one end only (Kim et al., 2012; NPRA, 2013). This method may be feasible for an onshore construction site. It might however be challenging for a deep-water offshore operation. The use of "traditional" large-scale rock anchors might therefore be an alternative. Offshore drilling vessels from the oil and gas industry might be used to drill and install rock anchors at large water depths. Both pre-stressed and passive anchors may be considered.

Experience with rock anchors of this size is elusive. Due to the nature of the loads, the poor availability for inspection and the possible severe consequences accompanying a failure, it is necessary to investigate the effects of cyclic loading combined with sustained loading (tension), creep, anchor-borehole ratio, anchor surface, failure mechanisms and grout properties amongst other factors.

There are in general four principal modes of failure of grouted anchors: (1) rock anchor tensile failure, (2) grout–anchor interface failure, (3) rock–grout interface failure, and (4) shear or uplift failure within the surrounding rock mass (Brown, 2015).

According to Benmokrane et al. (1995a), the failure tends to occur at the rock–grout interface in weak rocks and at the grout–tendon interface in strong rock provided that the tendon is sufficiently strong. The authors also state that the failure mechanism of anchors subjected to repeated loads may be different from those subjected to static loading. This might be caused by plastic strains in the anchor system, especially in the grout surrounding the bar/cable. Thus, when the anchors are subjected to repeated loads, they might suffer cumulative fatigue damage.

This paper investigates the rock anchor–grout interface bond strength reduction caused by cyclic loads. Other failure mechanisms are not evaluated within this paper. The research concerns passive rock anchors. The laboratory testing is performed on full-scale rock bolts to investigate the effects of repeated one-way cyclic loading in tension. The aim of the study is to assess the damage caused by cyclic loads and to establish a basis for prediction of corresponding rock anchor capacity. An empirical model predicting the behavior of incremental lengths of rock anchors subjected to cyclic load histories is presented in the paper. This model can be further developed to represent the full length of an infinitely long rock anchor in e.g. a finite element (FE) code.

A literature study is performed in order to shed light on factors affecting the rock anchor bond–slip relationship. Awareness of these factors and their influence on the holding capacity is crucial both in the laboratory work and in the development of a model describing the rock anchor behavior when subjected to cyclic loads. Research related to rebar in concrete is also evaluated. The study reveals few cross-references between the topic of bond-slip relations for rebar in concrete and grouted rock anchors. Research performed on the bond-slip relation between reinforcing bars in concrete is included in the study because the failure mechanism compares well to that of a grouted rock bolt given similar boundary conditions. The main findings from the literature study are summarized and presented within this paper.

2. Factors influencing bond-slip relationship

The topic of load transfer capability of rock anchors has been investigated in several publications. Standards and codes recommend an average (uniform) bond stress to be used for the complete anchored length (e.g. Brown, 2015). Measurement and theory show nevertheless varying mobilized shear stress along the anchor interface with relative slip between the steel tendon and the surrounding grout. In order to more accurately model the rock anchor capacity with anchored length, it is common to apply bond-slip curves to modeling the locally mobilized shear stress with relative slip between anchor and surrounding grout (Ma et al., 2016). The values of the bond and the corresponding slip depend on several factors, including not only physical factors related to the materials used, but also testing procedures and confinement of the grout surrounding the rock bolt.

Rock anchor bond degradation caused by cyclic loading is an important topic in the context of foundations relying on rock anchors. The consequences of failure in rock anchors might be severe, depending on the utilization of these structures. Only a limited number of data are published within the topic of cyclic degradation of rock anchor capacity caused by cyclic loading. There are apparently more information available with respect to cyclically loaded reinforcing bars in concrete than that about cyclically loaded rock anchors.

Theories and experimental data concerning pullout testing of reinforcing bars in concrete under monotonic and cyclic loads are investigated within this study. Main factors affecting the bond along a grouted rock anchor are presented in the following.

2.1. Length of bar for definition of local bond-slip relation

Several studies, both on rebar in concrete and on rock anchors, concern the local bond-slip relation. In order to isolate the local bond-slip relation from an average curve representing the complete anchor length, only a limited length of the anchor shall be

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