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# Evaluation of monitoring items for adverse ground conditions in subsea tunneling

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ABSTRACT

Three monitoring items, i.e. displacement vector orientation, preceding displacement, and water inflow, were compared to determine which one best provided supplementary and valuable information on the ground ahead of a subsea tunnel face when used with probe drilling. The geotechnical factors affecting tunnel stability were selected from the case studies on the construction of subsea tunnels, and six representative types of adverse ground condition were built with combinations of the factors. The capabilities of monitoring items were compared in depression and weakness zone types that were selected as major adverse ground conditions with three criteria, i.e. the capability of categorizing the type of adverse ground condition, the early-warning time, and the response capability. A three-dimensional finite element analysis program was used to simulate the process of subsea tunnel excavation, and the Analytic Hierarchy Process was used to select the optimum monitoring item. A comparison of the results showed that the vector orientation was the optimum item for categorizing ground type, and the preceding displacement and the water inflow possessed the best capability for early warning according to ground type. The response capability of water inflow was assessed as the best for three types of weakness zones, and that of vector orientation was best for depression type. In 13 cases where the priorities of comparison criteria were different, the vector orientation and the water inflow were respectively chosen in six cases, and there was little difference between the two items in the case where the criteria were equally important. While the application of one item alone may be vulnerable to a specific adverse ground condition, the monitoring capability could be overall improved by the adoption of both items.



## 1. Introduction

Continuous monitoring of the ground conditions ahead of subsea tunnel faces is indispensable for safe and efficient excavation. Because a sea floor is covered with deep water, geotechnical investigation is usually conducted in the limited extent prior to excavation, resulting in insufficient geotechnical data available during tunneling. As a similar case, a new investigation method had to be applied for the construction of a LPG storage terminal underneath a lake in South Korea because of limited information on the geological features of bedrock (Park et al., 2005). Hence, geotechnical investigation should be performed continuously during excavation using the monitoring items specified especially in subsea tunnels. Probe drilling has been one of the most widely applied methods to determine ground conditions during construction of subsea tunnels (Palmstrøm and Huang, 2007). However, for some cases of instability in subsea tunnels, the major weak point was the performance and interpretation of probe drilling and geophysical investigation (Nilsen, 1994, 2011).

The purpose of the present study is to compare existing monitoring items to determine which one can provide supplementary and valuable information on the ground ahead of the tunnel face and reduce the uncertainty of investigation results when used with probe drilling. First, the main geotechnical factors affecting tunnel stability were selected from several case studies on the construction of subsea tunnels, and then six representative adverse ground conditions were built with combinations of the factors. Depression and weakness zone type were chosen as major types of adverse ground, and the monitoring capabilities of each item were assessed under the condition that either of the two grounds was ahead of the tunnel face. Vector orientation, preceding displacement, and water inflow were chosen as the monitoring items. The comparison was conducted with three criteria, i.e., the capability of categorizing adverse ground condition, early warning, and response. The monitoring item must detect the presence of adverse ground and identify its type for planning a detailed investigation, and the detection has to be performed as early as possible to gain more

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time to prepare for hazardous situations. In addition, the monitoring item should respond to a small-scale adverse ground. A three-dimensional finite element analysis program was used to simulate the process of subsea tunnel excavation, and the Analytic Hierarchy Process (AHP) was used to select the optimum monitoring item. The item that could be the most efficient when a specific capability was required in an adverse ground condition was found, and an optimum item or a combination of monitoring items was proposed by considering the priorities of comparison criteria.

## 2. Background

### 2.1. Adverse ground conditions during construction of subsea tunnel

#### 2.1.1. Geotechnical factors affecting tunnel stability

*2.1.1.1. Type of weakness zone.* During the construction of subsea tunnels, the representative types of weakness zones that exist ahead of the tunnel face and cause a hazardous situation are as follows.

- Depression due to erosion of bedrock.
- Fault or weakness zone formed by tectonic activity.
- Fractured zone at contact area between intrusive dyke and rock mass.
- Flat and weak sedimentary rock mass.

The depression type of ground was found in the Oslofjord tunnel in Norway, where it was formed so deep in the bedrock by glacial erosion and filled with soil that there was no rock cover over a short section of tunnel (Blindheim et al., 2005). The second type was reported in the construction cases of the Vardø tunnel, Bjorøy tunnel, and Ellingsøy tunnel, where faults or weakness zones possessing weak clay minerals were under sufficiently high water pressure to cause a stability problem (Dahlø and Nilsen, 1992; Nilsen et al., 1999; Nilsen and Palmstrøm, 2001). The narrow fractured zone created at the contact area between an intrusive dyke and a rock mass was the main factor in the increase of tunnel supports in the Hvalfjørdur tunnel and the cave-in in the subsea outfall tunnel of the Lysaker outlet overflow system (Grøv and Haraldson, 1999; Strande and Birgisson, 1999). Finally, in the case of the North Cape tunnel, the poor stability caused by flat and weak sedimentary rocks required comprehensive supports and reduced tunneling progress (Nilsen et al., 1999).

*2.1.1.2. Geotechnical condition of weakness zone.* When one of the foregoing weakness zones is present around the proposed alignment of tunnel, it affects the stability of the excavation differently according to its size, orientation, and distance from the tunnel face. The strength of materials filling the weakness zone also influences the stability, and their permeability determines the role of the weakness zone in water inflow. If a recently formed weakness zone is loosely filled with soil, gravel, and crushed rocks, the zone has considerable potential to become a channel connecting excavated space and the sea. However, when the weakness zone is clogged with heavily crushed rocks and clay, seawater flow can be obstructed. The amount of seawater that flowed into the Hitra tunnel was smaller than expected due to the low permeability of major discontinuities (Nilsen and Palmstrøm, 2001). Channeling was shown in the Oslofjord tunnel, where large volumes of grout material had been pumped into a weakness zone, but it had been difficult to control the result of grouting due to the presence of permeable channels. A freezing method was applied for the stabilization of the zone before excavation in the end (Backer and Blindheim, 1999).

*2.1.1.3. Geotechnical condition of surrounding rock mass.* The surrounding rock mass should have adequate strength for excavation because a subsea tunnel is under high water pressure and additionally have a low possibility of discontinuities that can act as channels for seawater. Øvstedal and Melby (1992) mentioned that the factors governing leakage were rock type, crack pattern, and the amount of clay in the cracks, based on experience from the first eight subsea tunnels in Norway. Furthermore, they stated that leakages were more dependent on rock type than the thickness of rock cover.

*2.1.1.4. In situ rock stresses.* The in situ stresses of a rock mass may have an adverse effect on tunnel stability in a specific circumstance. Nilsen and Palmstrøm (2001) reported that the water inflow in a subsea tunnel could be increased by the low minor principal stress of unfavorable orientation with respect to main discontinuities and such adverse stress conditions actually caused a large amount of water inflow and pre-grouting grout consumption during the construction of the Godøy tunnel.

*2.1.1.5. Rock cover.* A rock cover is the thickness of the rock mass between the tunnel roof and bedrock surface under the sea (Palmstrøm, 2002), and sometimes it means the rock mass between them. It has to be sufficiently thick to support the pressure of seawater and give rise to the arching effect during the excavation of subsea tunnels, but thinner rock cover is more effective in reducing construction cost because the total length of the subsea tunnel is closely dependent on the tunnel depth. Therefore, the rock cover should be properly planned in view of both excavation stability and cost.

#### 2.1.2. Six types of adverse ground condition

Six representative types of adverse ground condition in subsea tunnels were built with combinations of these geotechnical factors, and they are listed as follows.

- Water inflow through fractured rock cover (type 1 in Fig. 1) – When the sea floor is generally flat and rock cover is sufficiently thick, there is little or no impermeable clay deposit above the bedrock as a blocking layer, and a tunnel face is approaching the section where quite a number of discontinuities are present. The discontinuities are not filled with clay or other materials, and the orientation and magnitude of the in situ stresses are in favor of water inflow.
- Tunnel instability in depression (type 2) – A tunnel face is approaching a bottom of a depression without recognizing the presence of a soil deposit because of limited prior information on the surrounding rock mass. The thickness and strength of the rock cover are insufficient to excavate the tunnel.
- Water inflow and tunnel instability in depression (type 3) – There exists a fractured zone below the bottom of a relatively shallow depression. The inflow of seawater through discontinuities can be markedly increased by tunnel excavation and lower the strength of rock cover at the same time.
- Water inflow and tunnel instability by weakness zone ahead of tunnel face (type 4) – The stability of tunnel excavation is influenced by the size, location, orientation, and strength of the weakness zone ahead of the tunnel face. Seawater flows through openings in the weakness zone loosely filled with soil, gravel, and crushed rocks.
- Water inflow through fractured zone formed during dyke intrusion (type 5) – Seawater flows through the fractured zone at the contact area between an intrusive dyke and a rock mass. Tunnel excavation can make the narrow zone a major channel connecting the working area and the sea.