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New direct shear testing protocols and analyses for fractures and healed intrablock rockmass discontinuities

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ABSTRACT

Modern geotechnical numerical design is limited by conventional characterization and data collection practices, which do not capture detailed parameters of intact rock and rockmass structure that are necessary for input to sophisticated and powerful simulation tools. Furthermore, as modern underground excavations go deeper and enter into more high stress environments with complex excavation geometries and associated stress paths, healed structures within initially intact rock blocks such as sedimentary nodules and hydrothermal veins (termed intrablock structure, where conventional fractures are termed interblock structure) are having an increasing influence on rockmass behaviour and should be included in modern geotechnical design. The role of sedimentary nodular intrablock structure in the Cobourg limestone on rockmass behaviour is an important consideration for the design of Canadian Deep Geological Repositories (DGRs) for the permanent storage of nuclear waste. This direct shear test program provides valuable laboratory data results for mechanical properties of targeted fracture surfaces and intrablock features in the Cobourg limestone for application to the numerical geotechnical design of prospective DGRs. Measurements of normal stiffness (K_n), shear stiffness (K_s), shear strength (in terms of cohesion (c) and friction angle (ϕ) from the Mohr-Coulomb shear strength criterion), and initial dilation angle (ψ) parameters are assessed and critically evaluated. These established parameters for fractures are applied to the tests on intrablock structures to provide a consistent basis for comparison and to enable the use of existing mechanical parameters in numerical model inputs. The implications of normal and shear stiffness property selection are evaluated at the excavation scale using finite element models with explicit rockmass structure. The critical analyses of conventional calculations of parameters results in improved calculation methods with mechanistic reasoning for the ultimate application of the data to sophisticated numerical models with explicit or discrete rockmass structure.

1. Introduction

Conventional rock characterization and analysis methods for geotechnical assessment in mining, civil tunnelling, and other excavations consider only the intact rock properties and the discrete fractures that are present and form blocks within rockmasses. Field data logging and classification protocols are based on historically useful but highly simplified design techniques, including direct empirical design and empirical strength assessment for simplified ground reaction and support analysis. Given the comparatively complex, sophisticated, and powerful simulation and analysis techniques now practically available to the geotechnical engineer, this research is driven by the need for enhanced characterization of joints and other fractures (termed interblock structure). Furthermore, as modern underground excavations go deeper and enter into more high stress environments with complex excavation geometries and associated stress paths, healed structures within initially intact rock blocks such as sedimentary nodules and hydrothermal veins, veinlets, and stockwork (termed intrablock structure) are having an increasing influence on rockmass behaviour and should be included in modern geotechnical design. Due to the continuing reliance on geotechnical classification methods which predate computer aided analysis, these complexities are ignored in conventional design. Intrablock structure governs stress-driven behaviour at depth, gravity driven disintegration for large shallow spans, and controls ultimate rockmass fragmentation.

Material parameter selection and modelling strategy challenges exist within heterogeneous sedimentary rocks such as those being considered for long-term nuclear waste storage in Ontario, Canada. The service design life for Deep Geological Repositories (DGRs) is one million years in order to sufficiently isolate the waste radionuclide

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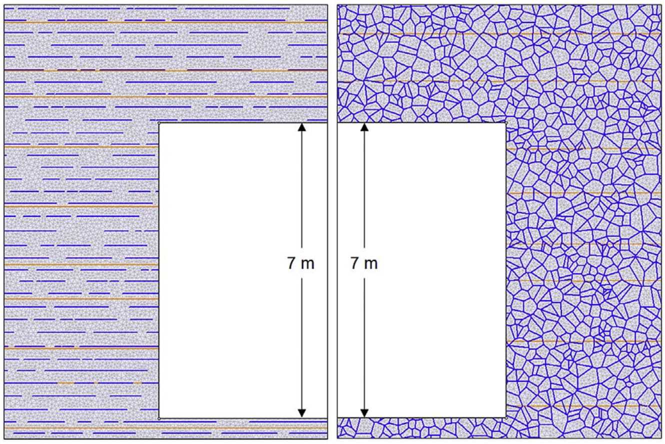

Fig. 1. Examples of strategies to include explicit sedimentary intrablock structure in a FEM model at the excavation scale using RS2 software (RocScience, 2015); interblock bedding is represented in both models with horizontal persistent structure elements (orange); intrablock structure can be represented by (left) non-persistent horizontal parallel structure elements or (right) Voronoi element geometry.

contaminants for their lifespan, which is by far the longest design life for any human engineered project. A prerequisite for the host rock where tunnels are constructed is stability in the geology, in situ stress system, jointing, and faulting. It is therefore critical to determine geomechanical properties of the host rock for effective geotechnical design of the repository excavation. With modern computer simulation tools, it is possible to have a variety of simulation strategies to consider this intrablock complexity using explicit or discrete representations of rockmass structure, as shown in Fig. 1. The finite element method (FEM) numerical models shown in Fig. 1 have a three node triangular mesh throughout the continuum material and use Goodman joint elements (Goodman et al., 1968a, b) to represent explicit rockmass structure. The explicit Goodman joint elements require sophisticated input properties for normal and shear stiffness, as well as cohesion, friction angle, and tensile strength from the Mohr-Coulomb strength criterion. These numerical models of an underground excavation also require the radius of the model to the external boundary to be large enough to simulate in situ stress conditions with no induced stresses occurring at the external boundary, and to have zero displacement conditions applied to the external boundary.

This study uses physical laboratory direct shear testing to define structural stiffness and strength properties for targeted surfaces in the heterogeneous sedimentary Cobourg limestone unit. Conventional joint shear strength properties are evaluated and joint stiffness is separated into normal and shear components. The importance of joint stiffness was recognized more recently (e.g. Goodman et al., 1968a, b) than that of shear strength (e.g. Coulomb, 1776; Mohr, 1900), with the need to describe pre-yield stress-deformation responses for numerical methods with explicit or discrete rockmass structure. Joint stiffness is a challenging parameter to account for and the current use of it is largely inadequate for detailed numerical models in advanced geotechnical design.

A thorough analysis of joint stiffness data of interblock and intrablock structure is conducted in this investigation in an effort to better understand more meaningful stiffness and strength properties. The existing methodologies for strength and stiffness analyses for direct shear testing of joints (ISRM, 1974) are extended here to intrablock structure in order to develop streamlined direct shear test analyses across both interblock and intrablock types of rockmass structure. Consideration of multiple closure laws for normal stiffness (Hungr and Coates, 1978; Zangerl et al., 2008), the reanalysis of shear stiffness determination, and applying a consistent approach across interblock and intrablock rockmass structures aim to provide suitable laboratory testing results for inputs to geomechanical parameters in numerical models with discrete or explicit representations of rockmass structure.

This direct shear laboratory testing program investigates the effects of changing confining stresses and sample sizes for tests through shear surfaces of interblock and shear zones of intrablock structures. The applied maximum normal stresses for these constant normal stress tests include 0.2, 0.5, 1.2, 2, 3, 5, and 8 MPa and the target shear sample sizes have diameters of 50.8 and 76.2 mm (2 and 3 inches). The constant normal stress conditions were selected to provide good data resolution at low confining stresses, which is relevant for fracture behaviour near underground excavation boundaries and the excavation damage zone. The sample sizes were selected to be comparable to standard drill core, to maximize sample numbers that could be extracted from the available rock blocks, and multiple sample sizes enable comparisons of scale for the various mechanical properties. The direct shear testing protocols have been developed at high quality standards that will ultimately be subject to public review with the engineering design of Deep Geological Repositories (DGRs) for the Canadian Nuclear Waste Organization (NWMO). Deep Geological Repositories (DGRs) are intended to be a permanent storage solution for nuclear waste. They typically have design lives of one million years and will be situated at depths on the order of 500 m below ground surface to be isolated from the biosphere.

In order to effectively design repositories for such a large timeframe, the application of state-of-the-art numerical modelling tools is necessary. Therefore, a sound understanding of rockmass properties is required to determine appropriate input properties and effectively predict rockmass behaviour. The selection of mechanical properties of explicitly modelled rockmass structure elements has a significant influence on the model behaviour, so measuring these properties in the laboratory is an essential step toward improving model accuracy and behaviour prediction capabilities. The influence of calcite healed discontinuities (intrablock structure) on rockmass behaviour in granodiorite has been examined using direct shear tests with application to DGR research in France (e.g. Boulon et al., 2002), which demonstrates the importance of the present research for rockmass evaluation of Canadian DGR cases in heterogeneous sedimentary host rocks such as the Cobourg limestone.

2. Source of rock samples

The Cobourg limestone occurs near ground surface at the St. Marys Cement Bowmanville quarry near Bowmanville, Ontario. The limestone sourced from the Bowmanville quarry is an easily accessible occurrence of the Cobourg limestone, which shallowly dips NW and has a large lateral extent at acceptable repository depths. The Canadian Low and Intermediate Level Waste DGR at the Bruce site has been designed to be hosted in the Cobourg limestone at approximately 680 m below ground surface. The occurrence of the Cobourg limestone in the Bowmanville quarry is suitable for extensive geomechanical laboratory testing to characterize the rock with state-of-the-art research tools for future repository design applications. The Cobourg limestone from the Bowmanville quarry is argillaceous and nodular, where light grey nodules of calcite-rich limestone are surrounded by tortuous layers of dark grey, clay-rich rock. The Cobourg limestone unit in southeastern Ontario is also called the Lindsay formation where it occurs closer to ground surface, as is the case at the Bowmanville quarry. These units are stratigraphically equivalent but may exhibit some lateral changes on the kilometer scale, due to differences in depositional environments. For the purposes of this research, the name Cobourg limestone is used.

The dominant orientation of the intrablock structure is horizontal with some vertical connective segments around nodule boundaries, which is evident at the sample block scale (see Fig. 2). This geometry of the nodule boundaries highlights the suitability of Voronoi geometry of explicit rockmass structure in numerical models. When the blocks were wetted with water, preferential drying patterns emerged where the nodules dried first and the intrablock structure dried last, which shows