An analysis on the slaking and disintegration extent of weak rock mass of the water tunnels for hydropower project using modified slake durability test

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Abstract

Water tunnels built for hydropower passing through weak and heterogeneous rock mass pose challenges associated to slaking and disintegration, as they are first exposed to dry condition during excavation and are then filled with water to produce hydropower energy. Over the period of operational life, these tunnels are drained periodically for inspections and repair leading to drainage and filling cycles. The weakening of rock mass caused by cycles of drying, saturation and drainage may lead to the propagation of instabilities in the tunnels. Therefore, it is important to study the slaking and disintegration behavior of the weak rock mass consisting of clay and clay-like minerals. This paper assesses the mineralogical composition of flysch and serpentinite from the headrace tunnel of Moglicë Hydropower Project in Albania. Further, to determine the slaking and disintegration behavior of these rocks, extensive testing using both the ISRM, Int J Rock Mech Min Sci Geomech Abstr 16(2):143-151, (1979) suggested test method and a modified variant of this test are performed. Finally, comprehensive assessments, discussions and comparisons are made. It is found that the modified slake durability test better suits for the tunnels built as water conveying systems such as hydropower tunnels.

Keywords Weak rocks · Mineralogy · Slaking and disintegration · Water tunnels for hydropower project

Introduction

Weak and weathered rocks are well known for their sensitivity to changes in moisture content. These rocks can disintegrate and rapidly change from rock-like to soil-like materials upon exposure to water, leading to numerous stability problems to engineering constructions (Rincon et al. 2016). The structure and initial degree of micro-fracturing exerts an important control on the rate of water ingress into the material and are factors which separates durable from non-durable rocks otherwise similar (Russell 1982; Olivier 1991; Dick and Shakoor 1992). Santi et al. (1997) define weak rocks as “either intact, unweathered to slightly weathered materials that have low compressive strength or rocks that are highly fractured”, and weathered rocks as “materials that show significant deterioration”. Nickmann et al. (2006) define weak rocks as an intermediate state between hard rocks and soil, whereby the borders between them are variable and linked to complex processes. Moreover, disturbances on the original rock material structure due to changes made by the excavation methods applied such as drill and blast method of excavation, may further degrade the rock material properties. The rate of degradation of an intact rock depends on both the properties of the rock material and the exposure to environmental agents such as water, and this interrelation is crucial in every stability assessment of a construction project, especially the water tunnels for hydropower. Throughout this paper the term “weak rock” is used for the rocks vulnerable to deterioration and disintegration.

Cyclic wetting and drying is considered as one of the main processes that can induce micro-fissures in the rock material which may lead to the failure to the construction work (Dick et al. 1994; Erguler and Shakoor 2009). The process of disintegration upon wetting and drying is known as climatic slaking (Franklin and Chandra 1972), a phenomenon which is a
result of shearing produced by volume change associated with hydration and dehydration (Panthi 2006). Okamoto (1993) defines slaking as the structural breakdown of a mass to small size particles in response to change in moisture content. The process of wetting and drying stresses the skeletal framework of the rock and acts to enlarge and extend pores. Taylor (1988) attributed slaking in less indurated mudrocks to a combination of air pressure increase, as water invades narrow capillaries, and tensile failure of weak inter-crystalline bonds due to drying induced pore water suctions. The failure may not be immediate but induced after repeated cycles of wetting and drying, especially if cementing material is removed during the cyclic process (Hudec 1982; Czerewko and Cripps 2001).

Water-weakening effects on rocks have been a major research topic in rock engineering field due to high practical values. Moisture sensitive rocks tends to degrade easily when in contact with water, and the strength loss is related to the saturation degree of the rock material (Bauer et al. 1981; Chugh and Missavage 1981; Goodman et al. 1982; Molinda et al. 2006; Erguler and Ulusay 2009; Karakul and Ulusay 2013; Wong et al. 2016; Vergara and Triantafyllidis 2016). In general, the strength and stiffness of a rock are reduced with increasing water content, spanning from nearly negligible in quartzite to over 90% reduction of uniaxial compressive strength (UCS) in shale and mudrocks (Vergara and Triantafyllidis 2016; Wong et al. 2016). On the other hand, dehydration caused by high temperature can also contribute to rock decay if the thermal stress exceeds the tensile strength of the rock (Hu et al. 2017). Due to higher temperatures, more water will evaporate from the rock pores and fissures, resulting in tension cracks which in turn provides channels for water. The extent of the degradation due to both temperature effects and moisture changes vary among rock types due to considerable variations of mineralogical composition, texture, and lithology (Erguler and Ulusay 2009; Wong et al. 2016; Cano et al. 2017).

Various slaking tests are in use to quantify or qualify the degree of degradation and disintegration due to altering moisture content of rocks. Among many others, the slake index test (Deo 1972), static slaking immersion test (Sadisun et al. 2002), and the slake durability test (Franklin and Chandra 1972) have been proposed, where the latter is most widely used and accepted method to assess durability of the rock material (Erguler and Ulusay 2009). Czerewko and Cripps (2001) investigated the durability of mudrocks and reviewed various tests that have been used for predicting the slaking potential. Their study shows that the standard slake durability test as proposed by Franklin and Chandra (1972) is too aggressive to assess the behavior of weak rocks and lacks sensitivity when it is used to distinguish between durable and non-durable mudrocks. Therefore, several authors have proposed modified variants of the test to address weaknesses in the proposed methods. Erguler and Shakoor (2009) introduced the disintegration ratio ($D_R$) based on particle size distribution curves aiming to better reflect the actual disintegration of samples exposed to static wetting and drying cycles in the laboratory. As an extension of this work, Gautam and Shakoor (2013) proposed a method in which the disintegration ratio ($D_R$) is calculated from particle size distribution curves of samples exposed to natural climatic conditions for a year. Heidari et al. (2015) introduced a nested mesh drum apparatus with different mesh openings, enabling sieving of different grain sizes during the slake durability test. However, methods that embraces both the actual climatic conditions of the engineering project and the need for a relatively quick slake durability analysis are limited.

This paper presents results of the laboratory analyses on the extent of slaking and disintegration of weak rocks prevailing along the headrace tunnel of a hydropower project under construction. To do so, both the ISRM (1979) suggested method for slake durability test, and a modified version of the slake durability test have been used. The ISRM (1979) suggested slake durability index (SDI) is defined as the percentage ratio of the final to initial dry sample masses after two standard cycles of wetting and drying. Following this procedure, the samples are completely dehydrated both initially and between the wetting cycles. On the other hand, the modified slake durability test (MSDI) is an adjusted version of the slake durability test where samples are not completely dried but drained instead to reflect the condition prevailing in a water tunnel. Both methods were extended to four repeating cycles so that long-term slaking behavior of the rocks tested can be achieved. In addition, the paper presents mineralogical analysis to investigate the linkage with the content of water sensitive clay mineral components. Particle size distribution analyses are also presented in order to assess the degree of disintegration after both slake durability test procedures.

**Modifications on the ISRM slake durability test for water tunnels**

The ISRM (1979) suggested method does not distinguish project types and long-term exposure to environmental condition that a real project is subjected to, such as a water tunnel for hydropower projects. The environmental setting imposes an important control on the behavior of the rocks; therefore, some modifications on the original ISRM test procedure are considered herein.

**The environmental setting of waterway tunnels for hydropower**

In underground engineering, the environmental condition is highly controlled by the type of construction project with respect to the exposure of rocks to moisture, temperature and air,
and especially the periodical changes on these parameters. Heterogeneous rock mass undergone different degrees of metamorphism and weathering exhibit changed geotechnical properties related to disintegration and degradation when exposed to environmental agents (Cano et al. 2017; Vivoda Prodan and Arbanas 2016) such as air and water. Caution is required for the prediction of the response of the rock material to the disturbances brought up by the excavation, as this depend on the present weathering state and the rate at which the properties change in response to the environmental changes (Czerewko and Cripps 2001). Therefore, selection of appropriate test procedures will help to improve the assessment of long-term durability.

The major difference in water tunnels compared with other underground engineering projects is the intensity of exposure to water during the life-time of the project. The rock mass is first at the stage of drained condition during construction period due to contentious ventilation and heat released by the moving construction equipment. Once the construction is completed, the waterway system (tunnels) is filled with water for the generation of hydro-electricity. Dewatering of the waterway system is carried out periodically to inspect the stability condition of the tunnels which mainly are supported by thick layers of sprayed concrete (shotcrete). During operation, the rock mass near the tunnel periphery and below the hydrostatic line is fully saturated. For the time of the operational life of the hydropower plant, several watering and dewatering cycles will take place. The cycles of dewatering are relatively short, and the temperature is relatively stable, resulting in draining effects rather than a complete dry-out of the rocks near the tunnel periphery. This periodical exposure to wetting and draining is assumed to amplify the weakening and degradation of the rock material, especially the weak and/or clay bearing rocks. In addition, the water tunnels for hydropower are subjected to dynamic pressure fluctuations caused by cyclic change in the production magnitude of the power plant. The response of the rock mass to complete saturation, cyclic drainage under relatively stable temperature conditions, and dynamic pressure fluctuations are of main interest when assessing the degradation behavior of the rocks which influences the long-term stability of the water tunnels.

**Review of the ISRM slake durability test**

Franklin and Chandra (1972) developed a slake durability test methodology at laboratory scale where the boundary conditions are standardized for quantification and comparison purposes. The technique itself has been discussed in detail by Franklin and Chandra (1972), Koncağül and Santi (1999), Czerewko and Cripps (2001), Erguler and Ulusay (2009) and is also the ISRM suggested method for determination of the slake-durability index (ISRM 1979). The test procedure is designed in such a way that the samples are first completely dried, which is achieved by leaving the prepared lumps in an oven at 105 °C until no more weight loss, whereby 2–6 h are regarded as sufficient time (ISRM 1979). After drying, the samples are kept in a specially designed drum for a wetting period of 10 min in a slow rotating mode. The samples are again dried in the oven and weighted, and the material loss is measured. The method aims to accelerate weathering to a maximum by combining the processes of slaking and sieving whereby the latter requires some motion in the test process.

In general, it is fair agreement between a low durability and high degree of disintegration. Although material has broken down during the test, a high slake durability index value may arise because it is not recorded as having done so if it does not pass through the 2-mm mesh test drum (Czerewko and Cripps 2006). In fact, the prepared lumps prior to the slake durability test have a diameter of approximately 30–50 mm, and extensive disintegration may occur within the span of particle sizes greater than 2 mm. In addition, the shape of the grains comprising the retained material may produce misleading results since splintered grains less likely pass the 2-mm square openings of the mesh. This means that the slake durability index is not necessarily reflecting the actual disintegration degree during the test, and rocks with similar slake durability index may show very different disintegration behavior.

Franklin and Chandra (1972) thoroughly explained the rationale of the suggested test with the description of different features of the testing procedure. They argued that other processes than climatic wetting and drying, such as mechanical abrasion, leaching, solution, and chemical alteration, can locally result in short-term damage where the environment is particularly severe or where the rock is already in an advance state of “geological” weathering. Further, they stated that the ideal way of assessing the slake durability is to compare complete particle-size distributions before and after slaking, but concluded that for most practical purposes, a single sieve gives a satisfactory index.

**Introduction to the modified ISRM slake durability test**

The suggested modifications of the ISRM slake durability test are based on the extraordinary conditions met in a water tunnel discussed in “The environmental setting of waterway tunnels for hydropower”-section. The modified test has the same framework and follows similar standardized steps as the ISRM test with two main deviating boundary conditions. First, the lump samples are immersed in water to achieve full saturation prior to the first cycle of rotation in the drum, and then the samples are drained at 30 °C between the cycles instead of drying at high temperatures as suggested in ISRM (1979). Draining is performed by leaving the samples in a drying cabinet for 24 h between the cycles. The samples will not be completely dried out neither will they be exerted to
temperatures higher than what is expected maximum during the construction of the tunnels. In order to calculate the slake durability index, however, dehydration is accomplished by drying the samples at 50 °C as a part of the preparation and additionally after the completed test. This enables a comparison of the slake durability indices obtained from both test methods. In addition, a particle size distribution analysis on the material after a completed test procedure is introduced in order to assess the actual degree of disintegration, which may vary between different rock types.

Materials

The rock material in this research is sampled from two different core boreholes extracted from the headrace tunnel of the Moglicë hydropower project in Albania. The rocks are dominated by flysch, a sequence of sedimentary rock formation, and ophiolite belonging to magmatic rock formation.

The nature of the studied rock types

The flysch sequences contain claystone, siltstone, marls, and sandstones with varying degrees of weathering and alterations (Selen and Panthi 2018). The material is best described as very heterogeneous in terms of color and fabric, with sections of intact cores alternating with sections of partly or totally disintegrated rock material (Fig. 1). The heterogeneous nature of the flysch results in a great variation of material properties within meters down to centimeters of the material. In terms of evaluating the locational degradation potential of the rock mass surrounding a tunnel, it is not distinguished between claystone, siltstone, sandstone, marl, or other sub-types of rock material type in this connection.

The ophiolitic rock mass comprehends highly weathered serpentinite. Serpentinite forms as a result of serpentinization of ultramafic rocks by hydration of ferromagnesian silicate minerals during low-temperature metamorphic processes (Moody 1976). The common alteration assemblage produced by serpentinization is lizardite, chrysotile, and kaolinite, occasionally together with brucite, antigorite, and clay minerals. The material is of moderately disintegrated to lumps of varying sizes, but otherwise apparently homogenous in terms of color and fabric (Fig. 2).

The nature of these two rock types are complex, resulting from their depositional and tectonic history, which means that they cannot easily be classified in terms of widely used rock mass classification systems. Both rock types are categorized as weak and contains clay minerals, which means they are vulnerable to exposure to environmental conditions and weathering.

The selection of samples

Despite of varying material composition, one core meter of rock material is regarded as a sample representing the expected behavior of this rock type at the particular section of the tunnel. Some segments of the sample material are strong and required further preparation to achieve lumps of appropriate shape and sizes. Other segments included splintered and weak material, and preparation of lumps had to be done carefully to not to shatter the whole sample to splinters. Fig. 3a–c illustrates the outcome of the preparation of sample Flysch 8.

The serpentinite material is already disintegrated to lump-sizes at arrival. At some locations, the lumps were too small compared with the preferred sizes for the slake durability test, i.e., less than 40 g. Therefore, lumps with sizes 40–60 g were chosen from one to two core meters at these locations. An overview of all the selected samples and visual characteristics, including heterogeneity, is given in Table 1.

Adopted testing approach

Each sample was divided in two duplicate sets of 10 lumps, whereby one set underwent the standardized ISRM slake durability index test (SDI) and the other set underwent a modified slake durability index test (MSDI). In both tests, 4 cycles
of wetting and drying/draining were performed aiming to evaluate the long-term slaking behavior of the material tested. The mineralogical composition of all samples was investigated by XRD analysis with aim to link the results with the content of water sensitive material components. At last, particle size distribution analyses were carried out in order to assess the degree of disintegration after both test procedures.

**Mineralogical assessment by XRD analysis**

The first step in detecting the potential of a rock to degrade and slake is to evaluate the mineralogical composition of the rock itself. X-ray diffraction (XRD) analysis is a method used in identifying and determining the mineralogical composition of the rock samples. It is common to perform a bulk analysis of the mineralogical content, and then treat the fine-fraction powder of the material with ethylene glycol to detect swelling minerals. Every mineral or compound has a characteristic X-ray diffraction pattern, call it “fingerprint”, which can be matched against a database of over thousands of recorded phases (Dutrow and Clark 2012). Identification and quantification of minerals is carried out by comparing relative peak heights of the crystalline phases. However, weathering may cause a destruction of the crystalline structures of the minerals, seen as amorphous reflections in the X-ray diffraction patterns. Although a semi-quantitative deviation between

| Sample name | Rock type    | Visual characteristics                             | No. of lumps |
|-------------|--------------|----------------------------------------------------|--------------|
| Flysch 6    | Flysch       | Homogeneous, intact, strong.                       | 20           |
| Flysch 7    | Flysch       | Homogeneous, intact, strong                        | 20           |
| Flysch 8    | Flysch       | Heterogeneous, schistose, partly disintegrated, weak| 20           |
| Flysch 9    | Flysch       | Heterogeneous, schistose, partly disintegrated, weak| 20           |
| Flysch 10   | Flysch       | Heterogeneous, schistose, partly disintegrated, weak| 20           |
| Flysch 11   | Flysch       | Heterogeneous, schistose, partly disintegrated, weak| 20           |
| Serp 5      | Serpentinite | Homogeneous, disintegrated, moderate strength      | 20           |
| Serp 6      | Serpentinite | Homogeneous, disintegrated, moderate strength      | 20           |
| Serp 7      | Serpentinite | Homogeneous, disintegrated, moderate strength      | 20           |
| Serp 8      | Serpentinite | Homogeneous, disintegrated, moderate strength      | 20           |
crystalline and amorphous phases is approximate and questionable (Tijhuis 2018), it reveals valuable information on the variable degree of weathering of the samples.

The XRD analysis was conducted at NTNU with a Bruker D8 ADVANCE. Only crystalline phases were quantified, while a semi-quantitative deviation between crystalline and amorphous phases is performed to indicate the amount of weathered minerals. Identification of crystalline phases is done with DIFFRAC.SUITE.EVA software combined with PDF-4+ database. Quantification of the minerals is done by Rietveld refinement in Topas with an accuracy of 1–2 percent (%). Further, glycolation is used on fraction sizes of < 6 μm to identify swelling clays, but quantification on the amount of swelling minerals based on this method is highly questionable and is not performed. The detected swelling minerals are therefore only indicated as “detected” or “not detected”.

It is assumed that the most moisture sensitive rock components are clay minerals as smectite and kaolinite. In addition, clay-like minerals such as chlorite and mica are susceptible to weathering agents and may transform into clay minerals or intermediate states of these mineral groups (Wilson 2004). To enable a distinction between the different moisture sensitive minerals and their properties, pervasive mineral and swelling analyses must be confirmed. In this study, in terms of defining moisture sensitive rock components in the context of the slake durability assessment, it is not distinguished between clays and clay-like minerals.

The procedure of the ISRM suggested slake durability test

The sample is placed in a clean drum with a standard mesh of 2 mm and dried to a constant weight at 105 °C (A). The drum plus the sample is then put in the slaking container with tap water at 20–25 °C, and the drum is rotated at 20 rpm for 10 min. The drum plus the retained portion of the sample is removed from the container and dried to a constant weight at 105 °C (C1). The procedure is repeated, and the dry weight C2 of the drum plus retained portion of the sample is recorded. The dry weight of the drum, D, is then used to calculate the slake-durability index (SDI) of the sample after two cycles of drying and wetting. The slake-durability index (SDI) is the percentage ratio of final to initial dry weights of rock in the drum:

$$SDI_2 = \frac{C_2 - D}{A - D} \times 100$$  \hspace{1cm} (1)

The slake durability test as suggested by ISRM (1979) uses the second cycle as slake durability index (SDI2) in the assessment of the degradation potential of rocks, which describe the short-term effect of wetting and drying. For long-term evaluations, the cycles can be repeated i times to better reflect the evolution of weathering over time. As suggested by Selen and Panthi (2018), the above formula can be extended to apply for i cycles of drying and wetting:

$$SDI_i = \frac{C_i - D}{A - D} \times 100$$  \hspace{1cm} (2)

The number of cycles used in this study is 4, where 2 h of drying between the cycles is chosen of practical reasons as explained previously. Minor amounts of water may be retained after 2 h; therefore, an extended phase of drying is included after the last cycle and before the final calculation of SDI4.

The procedure of the modified ISRM slake durability test

As a part of the preparation, the sample is placed in a clean glass container and dried in a drying cabinet at 50 °C until no more weight loss, and the initial dry weight of the sample plus the dry drum is recorded (A). The static wetting phase is then performed by leaving the samples in a container filled with tap-water having temperature between 20 and 25 °C for 72 h. Visual signs of disintegration are described and photographed. The wetting phase is not regarded as a part of the slake durability test itself but rather a separate phase after preparation of the lumps and prior to the first cycle.

After the static wetting phase, the sample is gently moved from the glass container to a clean and wetted drum (D (wet)) with a standard mesh of 2 mm. This is performed by placing the drum in a glass container and carefully pouring the sample and water solution into the drum, whereby the portion of the sample > 2 mm is sieved by the drum mesh. Dependent on the rock type, some of the material dissolve and/or disintegrate to less than 2 mm and is therefore removed from the sample before the first slake cycle. This material is dried and recorded for control and further analyses. The wet sample (> 2 mm) and the wetted drum are weighted (A (wet)) for further testing.

The drum containing the sample is put in the slaking container with tap water at 20–25 °C, and the drum is rotated at 20 rpm for 10 min. The drum plus the retained portion of the sample is removed from the container and weighted (Ci) before a draining phase in a drying cabinet at 30 °C for 24 h. The procedure is repeated i times, meaning i cycles of wetting, weighting, and draining. After the last cycle, in this case after 4 cycles, the sample is dried in the oven at 50 °C to a constant weight. The dry weight of the drum plus the retained portion of the sample is recorded (Ci). Table 2 summarize the notations used for the weight records used in the calculations.

The calculation of the modified slake durability index (MSDI) is based on the dry weights of the sample prior to the first cycle and after a complete test cycle. The slaking trend during the cycles can be obtained by calculating the slake...
trend index (STI) after each cycle; however, the weight records include water to an unknown amount. Three different parameters are possible for evaluations of the wetting effect:

Wetting index, I_wetting, which describes the material loss < 2 mm during static wetting for 72 h of the sample. The index is calculated based on the dry weight of the material passing through the drum after wetting subtracted from the initial dry weight of the sample (C_wetting).

\[
I_{\text{wetting}} = \frac{C_{\text{wetting}} - D}{A - D} \times 100
\]  

(3)

Slaking trend index, STI_i (wet), which describe the evolution of material loss < 2 mm during repetitive cycles of wetting and draining. The index is calculated based on the wet weight of the retained material of cycle i compared with the initial wet weight of the sample after wetting. Since the amount of water in the samples is unknown, the trendline numbers do not reflect the exact material loss.

\[
\text{STI}_i(\text{wet}) = \frac{C_i(\text{wet}) - D(\text{wet})}{A(\text{wet}) - D(\text{wet})} \times 100
\]

(4)

Modified slake durability index, MSDI_i, which describe the material loss < 2 mm after i cycles of wetting and draining, whereby the initial state of the samples is saturated. The index is calculated based on the dry weight of the retained material after the last cycle (C_i) compared with the initial dry weight of the sample after wetting (A'). The index is only to be calculated after a complete test procedure of i cycles. The index can be compared with the ISRM slake durability index (SDI_i) when the number of slaking cycles is similar.

\[
\text{MSDI}_i = \frac{C_i - D}{A' - D} \times 100
\]

(5)

By computing the slake trend index (STI) after each cycle, one can evaluate the evolution of slaking during the test. The slake trend index after first cycle will indicate the weakening effect of the static wetting phase prior to the mechanical exposure in the rotating drum. The complete trendline during i cycles can further be compared with the trendline of the ISRM test so that any behavior change related to the different initial moisture state of the samples is detected. It should be noted that the slake trend index is calculated by comparing wet weights of the sample prior to and after the cycles, while the modified slake durability index (MSDI_i) is calculated based on the dry weights. The slake trend index after the i-th cycle is therefore not directly comparable with the modified slake durability index due to the water content.

**Particle size distribution analysis**

To enable an assessment of eventual differences in the degree of disintegration in the performed slake durability tests, a particle size distribution analysis is performed on the samples after the completion of the test procedures. The analysis is performed by sieving both the retained material in the drum (> 2 mm) and the material left in the slaking container (< 2 mm). Sieves with quadratic mesh openings spanning from 62 to 0.063 mm are used, and a cumulative weight % analysis is performed on all samples in both slake durability tests. The particle size analysis enables further assessments on the extent of disintegration of the rock material after the complete slake durability test cycles when this is desired. Similar approaches of disintegration analysis have also been carried out by authors such as Erguler and Shakoor (2009), Gautam and Shakoor (2013), Heidari et al. (2015), and others.

**Laboratory test results**

**XRD results**

The mineralogical composition of the all samples prior to slake durability tests is determined. In addition, the composition of the dissolved and disintegrated material < 2 mm during wetting in the modified test is also assessed for the samples where the material loss is higher than 0.5% (samples Flysch 7–11). Only minerals presenting > 2% in at least one sample is accounted for, and the values are rounded up to nearest %.

The main constituents of the flysch samples are quartz, chlorite, calcite, plagioclase, and mica, with smaller amounts of k-feldspar. The composition is varying between the different samples, where high amounts of quartz and plagioclase are related to lower amounts of mica, chlorite and amorphous phases, and vice versa. The deviation between crystalline and amorphous phases is semi-quantitative. The results are given in Table 3.

The mineral constituents of the serpentinite samples were difficult to assess by the XRD analysis, due to highly amorphous diffraction patterns. This means that the

| Object | Notation |
|--------|----------|
| Dry drum | D |
| Wet drum | D (wet) |
| Dry sample + dry drum | A |
| Dry sample – material loss wetting + dry drum | A' |
| Wet sample (initial) + wet drum | A (wet) |
| Dry material > 2 mm after wetting | C_wetting |
| Dry sample + dry drum after cycle i | C_i |
| Wet sample + wet drum after cycle i | C_i (wet) |

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**Table 2** Notations used for the weight records in the calculations of the slake durability indices
original crystal structures are broken which indicate extensive weathering of the rock material. As a very high percentage of the mineral structures are destroyed, the quantification of even the crystalline phases is approximate (Tijhuis 2018). Based on the experience of the analyst at NTNU, the main crystalline constituents are recognized as chrysotile, lizardite, kaolinite, and nepouite, with smaller amounts of pyrope, brucite, calcite, dolomite, and magnetite. In addition, sample Serp 6 contains enstatite and fosterite. The chrysotile and lizardite diffraction patterns are overlapping and not distinguished. The only sample where swelling clay is detected is sample Serp 5, with an unknown amount of corrensite. Due to a high degree of weathering/crystal destructions of the samples, the quantification of both crystalline and amorphous phases is approximate. The results are given in Table 3.

The composition of the dissolved and disintegrated material (< 2 mm) sieved after the wetting phase of the modified slake durability test is assessed. Only the samples Flysch 7–11 have a material loss exceeding 0.5%. The

### Table 3 XRD bulk analysis of flysch samples and serpentinite samples, given in %

| Flysch sample no. | Serp sample no. |
|------------------|----------------|
|                  | Semi-quantitative analysis* | Approx. deviation of phases* |
|                  | Crystalline phases | Amorphous phases | Swelling clay** |
|                  | 77 | 72 | 63 | 60 | 57 | 52 |
|                  | 23 | 28 | 37 | 40 | 43 | 48 |
|                  | yes | yes | yes | no | yes | no |

|                  | Quantitative analysis of crystalline phases |
|------------------|---------------------------------------------|
| Brucite          | -   | -   | -   | -   | -   |
| Calcite          | 19  | 19  | 40  | 21  | 17  | 15 |
| Chlorite         | 8   | 12  | 23  | 27  | 32  | 30 |
| Chrysotile + Lizardite | -   | -   | -   | -   | -   | -   | 30  | 23  | 42  | 46 |
| Enstatite/Fosterite | -   | -   | -   | -   | -   | -   | -   | 7/25 | -   | -   |
| K-feldspar       | 3   | 3   | 1   | 2   | 2   | 1   |
| Kaolinite        | -   | -   | -   | -   | -   | -   | 29  | 19  | 22  | 18 |
| Magnetite        | -   | -   | -   | -   | -   | -   | 1   | 1   | 4   | 2   |
| Mica             | 5   | 6   | 7   | 14  | 14  | 20  |
| Népouite         | -   | -   | -   | -   | -   | -   | 9   | 4   | 5   | 6   |
| Plagioclase      | 17  | 17  | 6   | 11  | 11  | 12  |
| Pyrope           | -   | -   | -   | -   | -   | -   | 5   | 5   | -   | -   |
| Quartz           | 48  | 43  | 23  | 25  | 24  | 22  |

Approx. quantification of crystalline phases

|                  | Calcite | Chlorite | K-feldspar | Mica | Plagio-clase | Quartz |
|------------------|---------|----------|------------|------|-------------|--------|
| Flysch 7         | 2       | 21       | 4          | 15   | 21          | 36     |
| Flysch 8         | 3       | 32       | 4          | 16   | 6           | 29     |
| Flysch 9         | 9       | 34       | 3          | 19   | 11          | 24     |
| Flysch 10        | 7       | 36       | 3          | 16   | 12          | 26     |
| Flysch 11        | 10      | 21       | 4          | 23   | 13          | 27     |

*Crystalline and amorphous phases are calculated percent-based on the sample as a total

**Corrensite is the only detected mineral with known swelling potential in the flysch samples, not quantified

### Table 4 XRD analysis of dissolved and disintegrated material < 2 mm during wetting of the flysch samples in the modified test

| Sample | Material < 2 mm (%) | Semi-quantitative analysis* | Quantitative analysis of crystalline phases |
|--------|---------------------|-----------------------------|-------------------------------------------|
|        |                     | Cryst. phases | Amorph. phases | Swelling clay** | Calcite | Chlorite | K-feldspar | Mica | Plagio-clase | Quartz |
| Flysch 7 | 1,4              | 52  | 48  | Yes | 2   | 21  | 4  | 15  | 21  | 36 |
| Flysch 8 | 0,8              | 36  | 64  | Yes | 11  | 32  | 4  | 16  | 6   | 29 |
| Flysch 9 | 1,7              | 42  | 58  | No  | 9   | 34  | 3  | 19  | 11  | 24 |
| Flysch10 | 1,3             | 38  | 62  | Yes | 7   | 36  | 3  | 16  | 12  | 26 |
| Flysch11 | 0,7             | 37  | 63  | No  | 10  | 21  | 4  | 23  | 13  | 27 |

*Crystalline and amorphous phases are calculated percent-based on the sample as a total

**Corrensite is the only detected mineral with known swelling potential in the flysch samples, not quantified
main constituents of the material are chlorite, mica, and quartz, where the content of chlorite and mica is slightly higher compared with the sample composition prior to wetting. The results are given in Table 4.

### Table 4 ISRM slake durability index results

| Sample | SDI<sub>1</sub> | SDI<sub>2</sub> | SDI<sub>3</sub> | SDI<sub>4</sub> | SDI<sub>4</sub> (dried) | Classification* |
|--------|----------------|----------------|----------------|----------------|----------------------|-----------------|
| Flysch 6 | 99,1           | 98,6           | 98,2           | 97,7           | 97,6                 | High            |
| Flysch 7 | 97,2           | 95,6           | 94,8           | 93,6           | 93,4                 | Medium high     |
| Flysch 8 | 89,1           | 80,7           | 75,5           | 70,9           | 70,8                 | Medium          |
| Flysch 9 | 86,5           | 71,5           | 59,7           | 49,2           | 48,9                 | Low             |
| Flysch 10| 84,2           | 74,9           | 69,9           | 65,0           | 64,9                 | Medium          |
| Flysch 11| 87,0           | 64,6           | 52,0           | 43,4           | 43,3                 | Low             |
| Serp 5  | 98,4           | 97,2           | 95,9           | 94,9           | 93,4                 | Medium high     |
| Serp 6  | 97,4           | 95,4           | 93,4           | 92,1           | 91,8                 | Medium high     |
| Serp 7  | 96,9           | 95,4           | 94,4           | 93,4           | 92,9                 | Medium high     |
| Serp 8  | 96,9           | 93,8           | 92,3           | 90,0           | 89,2                 | Medium high     |

*ISRM (1979) defines slake durability (SDI) as follows: 98 – 100 as very high, 95 – 98 as high, 85 – 95 as medium high, 60 – 85 as medium, 30 – 60 as low and < 30 as very low.

**ISRM slake durability index results**

The slake trend index (SDI<sub>i</sub>) of the ISRM suggested method is calculated after each cycle; whereby, the final calculation of SDI<sub>4</sub> in the dry state is used for classification (Table 5). The results show varying degrees of slaking resistance across different samples, with Flysch 6 and Serp 5 being classified as very high, while Serp 8 is classified as low in slake durability.
the slake durability index is performed after an additional phase of drying. The results are given in Table 5.

The slaking evolution during the test is plotted based on the slake durability indices after each cycle, shown in Fig. 4a (flysch samples) and b (serpentinite samples).

**Modified ISRM slake durability results**

The dissolved and disintegrated material < 2 mm left in the water after the static wetting phase was dried and weighted in order to calculate the material loss. Based on the material loss, the dry weight of the samples after wetting is calculated, and the wetting index ($I_{\text{wetting}}$) is determined. Visual descriptions of the samples are also recorded. The results are given in Table 6.

The samples Flysch 7, Flysch 9, and Flysch 10 show the highest material loss (< 2 mm) during wetting, while Flysch 6 and the serpentinite samples show minor weight loss. However, the visual assessment reveals appreciable disintegration and changes in the samples Flysch 8–11, some

| Sample | $I_{\text{wetting}}$ | Visual assessment after wetting |
|--------|----------------------|--------------------------------|
| Flysch 6 | 99,0 | No disintegration, minor color-changes of water |
| Flysch 7 | 98,6 | Some disintegration, minor color-changes of water |
| Flysch 8 | 99,2 | Moderate disintegration, minor color-changes of water |
| Flysch 9 | 98,3 | Moderate disintegration, minor color-changes of water |
| Flysch 10 | 98,7 | Heavy disintegration, moderate color-changes of water |
| Flysch 11 | 99,3 | Heavy disintegration, moderate color-changes of water |
| Serp 5 | 99,9 | No disintegration, no color-changes of water |
| Serp 6 | 99,9 | No disintegration, no color-changes of water |
| Serp 7 | 99,8 | Minor disintegration, no color-changes of water |
| Serp 8 | 100,0 | No disintegration, no color-changes of water |

**Fig. 5** Visual signs of disintegration during wetting of the samples Flysch 11 and Serp 7
changes of Flysch 7 and Serp 7, and little or no changes in Flysch 6, Serp 5, Serp 6, and Serp 8. The visual changes during wetting are exemplified in Fig. 5, by the photos of Flysch 11 and Serp 7.

After the wetting phase, the samples underwent the modified slake durability test. The results include all the durability indices obtained from the testing procedure, whereby the modified slake durability index (MSDI) is the parameter describing the slaking potential based on the dry weight loss of the samples during cyclic wetting and draining (Table 7). It is reminded that the STI and MSDI are calculated based on two different moisture states of the samples, explaining why the MSDI show slightly higher values compared with the STI for some of the samples.

Based on the slake trend indices calculated after each cycle (wet state), the slaking evolution can be assessed (Figs. 6 and 7).

### Table 7 Durability indices obtained from the modified slake durability test procedure of 4 cycles

| Sample | Wetting | Slake Trend Index (STI) (wet) | Dry state calculation and classification |
|--------|---------|-------------------------------|-----------------------------------------|
|        | $I_{wetting}$ | STI<sub>1</sub> | STI<sub>2</sub> | STI<sub>3</sub> | STI<sub>4</sub> | MSDI<sub>4</sub> | Classification* |
| Flysch 6 | 99,0 | 98,9 | 98,3 | 97,8 | 97,3 | 97,8 | High |
| Flysch 7 | 98,6 | 95,6 | 93,5 | 91,9 | 90,7 | 91,9 | Medium high |
| Flysch 8 | 99,2 | 77,3 | 74,6 | 73,3 | 71,5 | 73,4 | Medium |
| Flysch 9 | 98,3 | 66,5 | 54,0 | 46,9 | 42,7 | 43,9 | Low |
| Flysch 10 | 98,7 | 66,5 | 57,0 | 51,9 | 49,3 | 51,2 | Low |
| Flysch 11 | 99,3 | 72,7 | 51,7 | 39,0 | 32,1 | 31,8 | Low |
| Serp 5 | 99,9 | 99,0 | 97,5 | 96,4 | 96,1 | 96,9 | High |
| Serp 6 | 99,9 | 97,9 | 95,8 | 93,9 | 91,7 | 92,2 | Medium high |
| Serp 7 | 99,8 | 94,8 | 91,8 | 89,8 | 88,9 | 90,1 | Medium high |
| Serp 8 | 100,0 | 97,9 | 95,2 | 93,9 | 92,4 | 92,9 | Medium high |

*ISRM (1979) defines slake durability (SDI) as follows: 98 – 100 as very high, 95 – 98 as high, 85 – 95 as medium high, 60 – 85 as medium, 30 – 60 as low and < 30 as very low.

### Particle size distribution curves

After the last cycle, each sample is sieved in aiming to analyze the actual disintegration. Particle size distribution curves are obtained by plotting the cumulative weight of each fraction of the sample passing the respective sieves, with mesh openings spanning from 62 to 0.063 mm. The results are illustrated in Fig. 8 a (flysch samples) and b (serpentinite samples).

### Overall analyses

**The effect of initial wetting on the slake durability index**

A detailed assessment on loss of durability due to initial wetting is performed by comparing the slake durability indices, where the initial state before the tests is dry (SDI of the ISRM...
test) and wet (MSDI of the modified test). Abundant differences in slaking behavior are observed during the first cycle of the two test procedures, illustrated in Fig. 9. It should be noted that the slake durability indices obtained after the first cycle may not be directly comparable due to different moisture content, still, the obtained values demonstrate a tendency of relative disintegration. The samples Flysch 8–11 show extremely reduced resistance to the mechanical impact imposed by the rotation of the drum, while the other samples show minor deviating results when comparing the two test methodologies. This indicates that the samples have different material properties and vulnerability to changes in moisture content in terms of water-weakening effects due to saturation.

The slake durability indices after 4 cycles, calculated based on dry weights, can be compared directly (Fig. 10). The samples Flysch 8–11 show the lowest durability in both test procedures, while Flysch 6–7 and the serpentinite samples show relatively high durability. The

Fig. 7 Slaking evolution of the serpentinite samples in the modified test

Fig. 8. a. Particle size distribution of flysch samples. b. Particle size distribution of serpentinite samples
water-weakening effect of the initial wetting on repeated slaking cycles is prominent in Flysch 9–11 and virtually absent in Flysch 6–7 and the serpentinite samples. A comparison of the slake durability indices of the ISRM method and the modified method is shown in Fig. 10.

**The slake durability index and actual disintegration**

Although the slake durability index is an indicative material parameter on disintegration, it may fail to detect the disintegration behavior of rock materials where at least one diameter
of the disintegrated particles exceeds 2 mm. Even at high slake durability indices, major size and mass reductions of the lumps can be the case. A comparison of the slake durability index and the cumulative weights of particle sizes > 2 mm capture this feature. Table 8 show a comparison the slake durability indices and weight % of particles < 16 mm and < 4 mm after the tests.

A fair correspondence between slake durability indices and disintegration require a low weight % of fractions less than the initial diameter of the samples (~ 40 mm) for high slake durability index values. For the samples Flysch 6 and Flysch 7, both the slake durability indices correspond fairly to the weight % of material less than 16 mm and 4 mm, meaning that the low actual disintegration is the reflection on the high slake durability index.

In the case of sample Flysch 8, the slake durability indices are $SDI_4 = 70.8$ and $MSDI_4 = 73.4$, i.e., medium slaking. However, the disintegration is quite extensive compared with the slake durability index, with 32.8–33.8 % of the grains being less than 16 mm and 26.5–30.1 % of the grain less than 4 mm in the modified test and ISRM test, respectively.

For the samples Flysch 9–11, the slake durability indices indicate low durability (< 60). However, based on the weight % of the particles passing through the 16 mm and 4 mm sieves, the slake durability indices are relatively high compared with the actual disintegration of the rock material. Flysch 11 show the most extensive disintegration whereby most of the particles of the retained material pass the 16 mm sieve (83.0 % in the ISRM-test and 97.5 % in the modified test) and the 4 mm sieve (67.5 % in the ISRM test and 85.6 % in the modified test). In addition, the grains are splintered, a factor contributing to misleading results even after the grain size analyses due to the quadratic openings of the sieves (Fig. 11).

The limited correspondence between the slake durability index and actual disintegration is obvious for some of the samples and may cause underestimated disintegration potentials. For example, the serpentinite samples and Flysch 7 achieve similar slaking indices, but the disintegration behavior is considerably different when the material is assessed by visual inspection. The deviating disintegration behavior despite quite similar slake durability indices is illustrated in Fig. 12.

The effect of material composition on the slake durability indices

The sensitive components (i.e., the clay/clay-like minerals) and the slake durability indices of all samples were calculated and compared (Fig. 13) in order to detect eventual patterns in rock material composition and water-weakening effects. A general trend is that an increasing degree of weathering,
indicated by high estimates of clay and clay-like mineral content (left axis), result in a lower slake durabilities (right axis). The lower slake durability indices in the modified test is pronounced in the flysch samples where the clay content exceeds 20% (samples Flysch 9–11).

A similar analysis was performed with respect to the actual disintegration, whereby the cumulative weight of particles passing through the 16-mm sieve is used to exemplify this trend (Fig. 14). An increasing content of clay and clay-like minerals correlates with increased disintegration and larger span between the ISRM test results and modified test results.

Discussions

**The slake durability index as support design parameter**

The ISRM slake durability test is useful as a general comparison of the slaking properties of different rock types. In terms of support design of a tunnel, however, it is crucial to obtain material parameters based on assessment obtained as close to the environmental conditions of the actual project as possible. As Franklin and Chandra already mentioned in 1972, other mechanisms than simple drying and wetting may have
considerable effect on the deterioration of geologically weathered rocks if the environment is particularly severe.

In general, rock mass classification systems for engineering purposes combine findings from observation, experience and engineering judgment to provide a quantitative assessment of rock mass quality (Williams 1997). These can be used either to simply characterize rock properties and thereby facilitate the application of information into a design or relate findings to the determination of actual design parameters. For a classification system to be successful, the parameters must be relevant to their application, especially if the findings are to be related to the determination of actual design parameters.

The rock mass surrounding an underground opening will, dependent on the construction method, be disturbed and degraded already during the construction phase of the project. In terms of stability assessments of a tunnel traversing a heterogeneous and disturbed rock mass, the behavioral characterization of the material at a defined location is considered as more helpful than general parameters of a specific rock type. Further, eventual changed behavior resulting from the exposure to degrading agents such as water in water tunnels during operation is crucial information for the support design analysis.

The duration of 10 min in the slake durability test exposes the rock samples to a limited wetting phase, where the saturation degree of the lumps is variable and uncertain. As a result, only an unknown % of the rock material is saturated and exposed to the slaking effect. The modified slake durability index (MSDI) test aims to bridge this gap and to specify the environmental effects on the slaking properties of rocks in water tunnels for hydropower projects, without significantly reducing the simplicity and comparability of the established ISRM procedure. Firstly, the slaking properties of the material constituting a defined location are assessed rather than the properties of a single rock type. This enable an evaluation of heterogeneous and disturbed rock mass where the material properties may change within very short distances. Secondly, by introducing the samples to an extensive wetting
phase prior to the test, the slaking effect of moisture changes is assessed closer to the in-situ condition of water tunnels. Thirdly, the rock material is not exposed to artificially high temperatures or dehydration states during the test, which potentially can change the material behavior. In addition, the method allows a separation between the effect of static wetting and mechanical abrasion, which opens up a possibility for an early assessment of the moisture sensitivity of the tested material.

**Discussion on the slake durability parameters in the modified test**

Three slake durability parameters are obtained in the modified test: the wetting index ($I_{\text{wetting}}$), the slake trend index (STI), and the modified slake durability index (MSDI).

The wetting index in combination with visual characterization intend to indicate the resistance of the material to dissolution and disintegration due to static wetting and may function as a first-hand determination on the moisture sensitivity of the rock material. By visually comparing the lumps before and after the wetting phase, one can qualitatively assess the rock material (Fig. 5). By comparing the color of the water, eventual structural changes and disintegration of the lumps, a first prediction of the water sensitivity can be made already at this stage. By examining the dissolved and disintegrated material by XRD, one can also indicate which components of the material are more sensitive to the water exposure. Based on the calculation procedure of the slake durability index generalized in both the ISRM procedure and the modified procedure, the wetting index is computed from the weight of retained material after sieving the material passed through 2-mm mesh of the drum. As shown in Table 6, the wetting index is very high for all samples. However, some of the lumps disintegrates heavily during wetting into rock pieces > 2 mm, such as sample Flysch 11 (Fig. 11). Similar as for the slake durability index, the variation between the samples in regard of the actual disintegration behavior during wetting is not reflected in the weight records, since the calculations are based on the weight of particles less and larger than 2 mm only. This weakness is connected to the calculation procedure rather than the test procedure itself and can be solved by descriptions and/or photographs of the retained material. A first-hand determination on the water-weakening effect can therefore be made at this stage, but the wetting index should be evaluated together with visual observations of the material. If the samples show heavy disintegration due to the static wetting phase, an analysis procedure and classification system as suggested by authors describing static slaking tests can be chosen, and the test can be closed already at this stage.

The slake trend index intends to produce values to evaluate the evolution of slaking during repeated cycles of changed moisture conditions. This enables an evaluation of the water-weakening effect on the samples when they are introduced to minor mechanical forces, and an assessment of the slaking progress due to repeated cycles. The slake trend indices in the modified test are calculated when the samples are partly saturated by water and cannot be compared with the slake trend indices of the ISRM procedure directly. However, the trends may be compared in order to uncover eventual changes in slaking behavior due to the initial moisture state. In cases where the STI is low after one or few cycles, the test can easily be closed by drying the retained material and calculate the slake durability index. This is recommended in cases where time saving is crucial and where the durability is obviously lower than a specified support design limit.

The modified slake durability index intends to quantify the slake durability of samples exposed to an extensive wetting phase prior to cycles of changed moisture content under stable temperatures. The index is calculated after drying the retained material at 50 °C until no more weight loss and is therefore also comparable with the ISRM slake durability index. The index and its precedent procedure are recommended in cases where abundant water exposure is natural in terms of project type, as in hydropower.

**Comparison of the slake durability indices in the two procedures**

In order to assess eventual differences in slaking behavior of saturated rocks compared with dry rocks, the modified test has the same framework and follows similar standardized steps as the ISRM suggested method, and both procedures are performed on similar samples. This enable a comparison of the slake durability indices, whereby the main deviating test conditions are the initial moisture state of the samples and the temperature exerted on the rock material during the test.

The wetting phase in the modified test revealed a significantly lowered slake durability of some samples compared with the ISRM test, which is very useful information for the water tunnels. The effect is varying between the samples tested, where the heterogeneous flysch samples are extensively affected compared with the homogeneous samples. The homogeneous samples did not show noteworthy different slaking behavior in the two test procedures. This deviation seems to be somehow connected to an increasing content of clay minerals, which may again be linked to the initial degree of weathering. Other factors may also contribute, as fabric, structure, strength, and initial micro-fracturing of the material. The samples in which the water sensitivity is revealed during passive wetting, are similar samples which show a lowered slake durability in the modified test. The lowered durability due to initial saturation is most prominent in the first cycle of the test, when minor mechanical forces are introduced due to collision of the lumps (Fig. 9). This water-weakening
effect is apparently connected to the structure and composition of the samples, and most likely also to the dry strength of the rock material. To verify this, analyses such as strength tests, microscopy, and SEM-analyses are recommended for further research.

As some rocks are more sensitive to moisture changes than others, the modified test is assumed to reflect the degradation potential more efficiently than a test carried out on dehydrated samples as suggested by ISRM (1979). With the proposed modified test, the boundary conditions are closer to the in situ environment of the rock close to the periphery of a water tunnel, which in turn produce more reliable estimates on the behavior to be expected. It is possible to close the test after fewer cycles than of this research, if the samples show an extensive slaking behavior exceeding the support design limit. In order to obtain an index value on moisture sensitivity and slaking behavior, the modified test seems to uncover these features more efficiently than the ISRM suggested method.

**Disintegration analysis as a part of the slake durability assessment**

The practical value of a database with slake durability results of different rock types is significantly reduced if no other disintegration parameters are obtained. The weight % of material fractions spanning from > 2 mm up to the initial lump diameters can be used to assess the linkage between the calculated slake durability indices and actual disintegration of the retained material. Such analyses enable further disintegration parameters to be evaluated if found necessary, based on the purpose of the durability assessment. For example, the retained fragments may be categorized by a disintegration ratio (D₆₅) analysis as suggested by Erguler and Shakoor (2009) or other similar categorization systems. For a complete overview of the disintegration behavior, the material passing the 2-mm mesh of the drum can be included in the disintegration analysis.

As performed in this research, a particle size distribution analysis uncovers noticeable differences between the disintegration behavior of the rock types tested compared with the slake durability indices obtained. The materials which disintegrates the most (Fig. 8a, b) are also the samples that show degradation at the wetting stage of the modified test (Table 6). These samples disintegrate more when exposed to the modified slake durability test procedure compared with the ISRM procedure, which may be connected to the content of clay (Fig. 14). The methodology of integrating the disintegration analysis into the slake durability assessment should be adjusted to the purpose of the analysis, as support design or similar motives.

**Conclusion**

A modified slake durability test has been developed for use in behavioral assessment of weak rocks in hydropower water tunnels. The test is time-efficient, semi-quantitative, reproducible, and seem quite promising. Weathering behavior and the influence of water saturation in slake durability tests can be detected using this method, and the material response to cyclic moisture changes under conditions similar as the in situ condition can be evaluated.

The general pattern is, for rock materials composited of moisture sensitive minerals, that the water-weakening effect of saturation is prominent both in a short-term and long-term perspective. The total degradation of weak rocks is higher in a saturated condition compared with an initial dehydrated state when exposed to repeated cycles of changed moisture conditions. These findings are important to keep in mind when evaluating the durability of rocks in an environment where the exposure to water is abundant for a longer period.

Predicting the durability of weak rock materials on the basis of a few index tests is a difficult task, and the modified slake durability test described herein is not intended to replace the ISRM standardized slake durability index test, rather it intends to improve the methodology so that test results reflect more to the environment that prevails in the water tunnel. This is the reason for keeping the framework and test principles of the modified test similar to the ISRM test. The method can be regarded as an informative alternative when evaluating the durability of weak rocks surrounding a water tunnel for hydropower or similar projects where rock mass is continuously exposed to water. The methodology presented in this paper provides insights to evaluate the effect of saturation on the degradation potential of rocks exposed to heavy moisture changes and flowing water, and helps to understand the extent of rock support required in water tunnels passing through weak rock mass conditions.

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References

Bauer SJ, Friedman M, Handin J (1981) Effects of water-saturation on strength and ductility of three igneous rocks at effective pressures to 50 MPa and temperatures to partial melting. Technical Report, Texas A and M Univ., College Station (USA), Center for Tectonophysics. https://doi.org/10.2172/6381419

Cano M, Tomás R, Raquelme A (2017) Relationship between monitored natural slaking behaviour, field degradation behaviour and slake durability test of Marly Flysch rocks: preliminary results. Procedia Eng 191:609–617

Chugh YP, Missavage RA (1981) Effects of moisture on strata control in coal mines. Eng Geol 17(4):241–255

Czerewko MA, Cripps JC (2001) Asssessing the durability of mudrocks using the modified jar slake index test. Q J Eng Geol Hydrogeol 34(2):153–163

Czerewko MA, Cripps JC (2006) The implications of diagenetic history and weathering on the engineering behaviour of mudrocks. International Association for Engineering Geology and the Environment, 2006 Conference Proceedings 118: 1-12

Deo P (1972) Shales as Embankment Materials. Publication FHWA/IN JHRP-72/45, Joint Highway Research Project, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. doi https://doi.org/10.5703/1288284314547

Dick JC, Shakoor A (1992) Lithological controls of mudrock durability. Q J Eng Geol Hydrogeol 25(1):31–46

Dick JC, Shakoor A, Wells N (1994) A geological approach toward developing a mudrock-durability classification system. Can Geotech J 31(1):17–27

Dutrow BL, Clark CM (2012) X-ray powder diffraction (XRD). Geochemical Instrumentation and Analysis. https://serc.carleton.edu/research_education/geochemists/techniques/XRD.html. Accessed 15 November 2019

Erguler ZA, Shakoor A (2009) Quantification of fragment size distribution of clay-bearing rocks after slake durability testing. Environ Eng Geosci 15(2):81–89

Erguler ZA, Ulusay R (2009) Assessment of physical disintegration characteristics of clay-bearing rocks: Disintegration index test and a new durability classification chart. Eng Geol 105(1-2):11–19

Franklin JA, Chandra R (1972) The slake-durability test. In: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 9(3)325-328

Gautam TP, Shakoor A (2013) Slaking behavior of clay-bearing rocks during a one-year exposure to natural climatic conditions. Eng Geol 166:17–25

Goodman RE, Shi G, Boyle W (1982) Calculation of support for hard, jointed rock using the keyblock principle. American Rock Mechanics Association, The 23rd U.S Symposium on Rock Mechanics (USRMS), 25–27

Heidari M, Rafiei B, Mohhjbi Y (2015) Torabi-Kaveh M (2015) Assessing the behavior of clay-bearing rocks using static and dynamic slaking indices. Geotech Geol Eng 33:1017–1030. https://doi.org/10.1007/s10706-015-9884-6

Hu M, Liu Y, Ren J, Zhang Y, Wu R (2017) Temperature-induced deterioration mechanisms in mudstone during dry–wet cycles. Geotech Geol Eng 35(6):2965–2962

Hudec PP (1982) Statistical analysis of shale durability factors. Transp Res Rec 873:28–35

ISRM (1979) Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake-durability index properties: Part 1: suggested methods for determining water content, porosity, density, absorption and related properties. Int J Rock Mech Min Sci Geomech Abstr 16(2):143–151

Karakul H, Ulusay R (2013) Empirical correlations for predicting strength properties of rocks from P-wave velocity under different degrees of saturation. Rock Mech Rock Eng 46(5):981–999

Koncagül EC, Santi PM (1999) Predicting the unconfined compressive strength of the Breathitt shale using slake durability, Shore hardness and rock structural properties. Int J Rock Mech Min Sci 36(2):139–153

Molina GM, Oyler DC, Gurgeni H (2006) Identifying moisture sensitive roof rocks in coal mines. Proceedings of the 25th international conference on ground control in mining, West Virginia University, p 57-64

Moody JB (1976) Serpentinitization: a review. Lithos 9(2):125–138

Nickmann M, Spaun G, Thuro K (2006) Engineering geological classification of weak rocks. In: Proceedings of the 10th International IAEG Congress: 492, 1–9 p

Okamoto T (1993) Testing methods of indurated soils and soft rocks—suggestions and recommendations. In: Technical committee on indurated soils and soft rocks, Intern. society for Soil Mechanics and Foundation Engineering

Olivier HJ (1991) Some aspects of the engineering geological properties of swelling and slaking mudrocks. In: 6th International IAEG Congress: 285, pp 707–712, 6 p. https://doi.org/10.1016/0148-9062/91j0024-G

Panthi KK (2006) Analysis of engineering geological uncertainties related to tunnelling in Himalayan rock mass conditions. PhD thesis, NTNU, Trondheim, Norway

Rincon O, Shakoor A, Ocampo M (2016) Investigating the reliability of H/V spectral ratio and image entropy for quantifying the degree of disintegration of weak rocks. Eng Geol 207:115–128

Russell D (1982) Controls on shale durability: the response of two Ordovician shales in the slake durability test. Can Geotech J 19(1):1–13

Sadusim IA, Shimada H, Ichinose M, Matsui, K (2002) Improved procedures for evaluating physical deterioration of argillaceous rocks. In: Proc. 2nd Intl. Conf. on New Development in Rock Mech. and Rock Eng, p 36–39. https://doi.org/10.13140/2.1.3499.8400

Santi PM, Doyle BC, Shakoor A (1997) The locations and engineering characteristics of weak rock in the US. Association of Engineering Geologist, Denver, Special Publication No 9: 1–22

Selen L, Panthi KK (2018) Influence of slaking and disintegration effect on the stability of water tunnels for hydropower. In: ARMS10 10th Asian Rock Mechanics Symposium The ISRM International Symposium for 2018, 29 Oct-3 Nov, Singapore-proceedings, 1–9

Taylor R (1988) Coal Measures mudrocks: composition, classification and weathering processes. Q J Eng Geol Hydrogeol 21(1):85–99

Tijhuis L (2018) Personal communication during laboratory work. NTNU 2018

Vergara MR, Triantafyllidis T (2016) Influence of water content on the mechanical properties of an argillaceous swelling rock. Rock Mech Rock Eng 49(7):2555–2568

Vivoda Prodan M, Arbanas Ž (2016) Weathering influence on properties of siliststones from Istria, Croatia. Proc: Adv Mater Sci Eng 3073202 15 p

Williams O (1997) Engineering and design-tunnels and shafts in rock. US Army Corps of Engineers, Washington, DC, pp 20314–21000

Wilson M (2004) Weathering of the primary rock-forming minerals: processes, products and rates. Clay Miner 39(3):233–266

Wong LNY, Maruvanchery V, Liu G (2016) Water effects on rock strength and stiffness degradation. Acta Geotech 11(4):713–737

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