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Evaluation of the hydro-mechanical properties and behavior of Opalinus Clay

Author(s):
Wild, Katrin M.

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Evaluation of the hydro-mechanical properties and behavior of Opalinus Clay

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presented by

KATRIN MIRJAM WILD

MSc ETH in Earth Sciences, ETH Zurich
born on 11.12.1987
citizen of Remetschwil, Switzerland

accepted on the recommendation of

Prof. Dr. Simon Löw (examiner)
Prof. Dr. Derek Elsworth (co-examiner)
Dr. Florian Amann (co-examiner)

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Abstract

Argillaceous rock formations are considered as favorable host rocks for nuclear waste repositories due to their low permeability, high sorption capacity, and potential for self-sealing. Damage caused by the construction of underground excavations, however, may alter the beneficial properties of the rock and affect its natural barrier function negatively. In order to assess the performance of a repository and its safety, it is therefore essential to understand the processes that occur during and after excavation and to predict the behavior of the rock mass around man-made underground cavities. Due to the low hydraulic conductivity and complete saturation in the in-situ state, argillaceous rocks usually show a strong hydro-mechanical coupling. Thus, the characterization of the hydro-mechanical properties and behavior is of particular importance.

In Switzerland, Opalinus Clay, a Mesozoic clay shale formation, has been chosen as host rock formation for a nuclear waste repository. In this dissertation, consolidated drained and undrained triaxial tests on back-saturated specimens of Opalinus Clay were conducted to study the hydro-mechanical properties and gain a better understanding of the processes that control the rock mass behavior around an excavation in this formation. Of particular interest were:

- the characterization of the poroelastic properties,
- the determination of the drained and undrained elastic properties,
- the description of the stress-strain or pore pressure evolution under compressive loading conditions and their dependency on the stress path,
- the measurement of the effective strength properties.

To highlight the importance of back-saturating the specimens and to deepen the understanding of the impact of suction (or partial saturation) on the geomechanical properties of Opalinus Clay, a preliminary study was conducted. Specimens were equilibrated to different levels of relative humidity to establish the water retention characteristics, the influence of suction on ultrasonic p-wave velocity and geomechanical properties (e.g. Young’s modulus, Poisson’s ratio, onset of dilatancy, unconfined compressive strength, and Brazilian tensile strength). The results of this study showed that suction has a significant influence on these properties. Both stiffness and strength, for example, increased significantly (by a factor of 2-3) with increasing suction. In addition to the importance for the performance of a nuclear waste repository during the open-drift and long-term phase, this influence also emphasizes the need for tests on back-saturated specimens to characterize the material properties and behavior for in-situ conditions before and during an excavation.

In order to back-saturate the specimens, a multi-stage testing procedure is necessary. Before the actual shearing phase, a saturation and a consolidation phase are required. For the purpose of elaborating a testing procedure that allows the determination of representative material properties, a review of the major key aspects and challenges associated with laboratory testing of low permeable clay shales was performed. Theoretical background for each stage (i.e. saturation, consolidation, and shearing) is given.
and the testing procedure was applied to a series of Opalinus Clay specimens to illustrate the applicability.

The specimens were back-saturated with the help of elevated back pressure, consolidated at effective confinements between 0.5 and 16 MPa and subsequently sheared under drained or undrained conditions using a standard triaxial stress path. P-specimens (loaded parallel to bedding) and S-specimens (loaded normal to bedding) were used to characterize the influence of the anisotropy of the material. The measured pore pressure response during undrained tests and the effective geomechanical properties were additionally analyzed with respect to their dependency on the confinement.

The results show that Skempton’s pore pressure parameter $A$ and $B$ and the Young’s moduli depend on both the confinement and the anisotropy. Additionally, a change from overconsolidated to normally consolidated behavior was observed with increasing confinement. Specimens consolidated at lower effective stresses (i.e. heavily overconsolidated specimens) show a dilatant behavior in the pre-peak region and a significant post-failure stress drop. Specimens consolidated at higher effective stresses (i.e. slightly overconsolidated to normally consolidated specimens) show compaction from initial loading until post-peak and a brittle-ductile post-failure behavior. The changes could be correlated to a non-linear appearance of the effective peak strength envelope. The dilatant structure of the material is proposed as possible explanation for this non-linearity.

To investigate the influence of the stress path on the hydro-mechanical behavior of Opalinus Clay, a second series of specimens was subjected to different stress paths approximating a tunnel excavation. Three different stress paths were applied to both P- and S-specimens: a two-dimensional stress path with isotropic initial stress conditions (i.e. pure shear compression), a two-dimensional stress path with anisotropic initial stress conditions, and a three-dimensional stress path. An influence of the stress path and the anisotropy on the hydro-mechanical response of the specimens was observed. The application of the two-dimensional stress paths on S-specimens revealed positive excess pore pressure whereas P-specimens showed negative excess pore pressure. Dilation associated with yielding was observed for all specimens. The results of the tests using the three-dimensional stress path conceptually reproduced the pore pressure evolutions usually observed during tunnel excavations. With regards to the effective peak strength of the specimens, no significant difference compared to the standard triaxial tests was found. However, the state of failure is affected by the transversal isotropy, which is related to the different hydro-mechanical response of the specimens and is reflected by different effective stress paths. S-specimens fail at lower effective stresses compared to P-specimens.

This dissertation aims at a systematic, experimental characterization of the hydro-mechanical properties and behavior of Opalinus Clay. The findings, including (poro)elastic properties, stress-strain behavior in combination with the pore pressure response, the dependency of these properties and behavior on the confinement and the stress path, and the non-linear effective peak strength failure envelope, present a valuable contribution to the geomechanical understanding of the material itself and the interpretation of observations around test galleries at the Mont Terri Underground Rock Laboratory. The newly gained
understanding of the hydro-mechanical properties and behavior of Opalinus Clay contributes to the development, the implementation and the validation of new constitutive models which are able to adequately represent and predict the short- and long-term behavior of the rock mass around underground excavations in the Mont Terri Underground Rock Laboratory. Furthermore, such a constitutive model would substantially add value to the geotechnical and safety assessment of a nuclear waste repository in Opalinus Clay.
Zusammenfassung


Opalinuston, ein mesozoisches Tongestein, wurde in der Schweiz als Wirtsgestein für ein Tiefenlager für radioaktive Abfälle bestimmt. Zur Untersuchung seiner hydro-mechanischen Eigenschaften und um ein detaillierteres Verständnis für die Prozesse während des Tunnelvortriebes zu erhalten, wurden in der vorliegenden Doktorarbeit konsolidierte, drainierte und undrainierte Triaxialversuche an rückgestättigten Proben durchgeführt. Im Fokus standen dabei:

- das Bestimmen der poroelastischen Eigenschaften,
- die Beschreibung des drainierten und undrainierten elastischen Verhaltens während des Scherens,
- die Charakterisierung des Spannungs-Dehnungs-Verhaltens und der Porenwasserdruck-Entwicklung unter kompressiver Differntialspannungserhöhung,
- das Ermitteln der Spitzenfestigkeit des Opalinustons.

Diese Eigenschaften wurden auch auf ihre Abhängigkeit gegenüber der Einspannung und des Spannungspfades hin untersucht.

In einer Vorstudie wurden mehrere Prüfkörper in Exsikkatoren mit verschiedenen relativen Luftfeuchtigkeiten ins Gleichgewicht gebracht. Damit konnte der Einfluss von partieller Sättigung auf die p-Wellengeschwindigkeit und die geomechanischen Eigenschaften (Elastizitätsmodul, Poissonzahl, einaxiale Druckfestigkeit und indirekte Zugfestigkeit) gezeigt werden. Mit zunehmender Saugspannung (bzw. zunehmender Entsättigung der Probe) nehmen beispielsweise sowohl die Steifigkeit als auch die Festigkeit signifikant zu (um einen Faktor von 2-3). Dies ist einerseits relevant in Bezug auf das längerfristige Verhalten des Gesteins um einen Lagerunsstollen. Andererseits impliziert es die Notwendigkeit einer kompletten Sättigung der Probe zur Bestimmung von hydro-mechanischen Materialeigenschaften, die als repräsentativ für die Beurteilung des Verhaltens des Opalinustons vor und während des Tunnelvortriebs herangezogen werden können.

Die Prüfkörper wurden mithilfe von erhöhtem Wasserdruck gesättigt und bei effektiven Einspannungen zwischen 0.5 und 16 MPa konsolidiert, bevor die axiale Spannung unter gleichbleibender radialer Spannung erhöht und der Prüfkörper somit gesichert wurde. Um den Einfluss der Anisotropie des Materials auf die Eigenschaften und das Verhalten untersuchen zu können, wurden sowohl P-Proben (Hauptbelastungsrichtung verläuft parallel zur Schichtung) als auch S-Proben (Hauptbelastungsrichtung verläuft senkrecht zur Schichtung) getestet. Zudem wurde der Einfluss der Einspannung auf die Porenwasserdruck-Entwicklung während der undrainierten Versuche und auf die effektiven geomechanischen Eigenschaften studiert.


beobachtet wird, konzeptionell nachgebildet werden. In Bezug auf die Spitzenfestigkeit konnte kein signifikanter Unterschied im Vergleich zu der vorhergehenden Testreihe (d.h. den Triaxialversuchen unter Verwendung eines Standard-Spannungspfades) festgestellt werden. Jedoch wird das Eintreten des Bruches stark durch die Anisotropie des Opalinustons beeinflusst und kann auf das unterschiedliche hydro-mechanische Verhalten der P- und S-Proben zurückgeführt werden, welches sich in den unterschiedlichen Spannungspfaden zu erkennen gibt. Obwohl im Ganzen gesehen ein gemeinsames Bruchkriterium festgestellt wurde, brechen S-Proben im Vergleich zu P-Proben grundsätzlich bei geringeren effektiven Spannungen.