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Swelling pressures of some rocks using different test procedures

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ABSTRACT: There are no clearly defined rules for the investigation procedures of swelling rocks. Difficulties are generally met for characterization and testing of swelling rocks and for prediction of the response to tunnel excavation. The waterway tunnels of hydropower projects and other water tunnels are even special since these tunnels are persistently exposed to the moisture changes caused by flowing water. Reported case histories have shown that severe stability problems have been experienced during the operation of hydropower plant caused by swelling of rocks. This important issue needs to be investigated thoroughly. Different laboratory oedometer testing methodologies have been developed and proposed in recent years by different institutions to carry out testing of swelling of the rocks. However, there is no standard methodology to assess the swelling behavior under moisture changes nor the application of the results obtained from powder tests.

The site-specific swelling rock potential including moisture changes should be investigated with effective diagnostic methods, which provide reliable data for the considerations and decisions to be made. The main aim of this manuscript is to provide insight and qualitative description of the laboratory methods in operation at two leading laboratories in rock mechanics; i.e. Norwegian University of Science and Technology (NTNU) of Norway and Karlsruhe Institute of Technology (KIT) of Germany, in order to determine the swelling potential of various rocks through cyclic testing. Oedometer swelling tests on pulverized material as well as intact rock discs have been performed at these two laboratories; i.e. at NTNU and KIT. The manuscript highlights the results of the swelling tests from both laboratories, and comparisons and discussions of the testing methodology at these two institutions are made.

Key words: Water tunnels, hydropower, swelling of rocks, stability issues

1 INTRODUCTION

The determination of the swelling potential of rocks is necessary to make adequate choices on the dimensioning of the tunnel support. However, from swelling tests it is difficult to estimate the in-situ swelling pressure necessary in the design phase of a project (Galera et al. 2014). In the case of hydropower tunnels, the surrounding rock mass will be exposed to cyclic wetting and drying processes during the life-time of the hydropower-project. In several cases, swelling zones or rock mass containing swelling minerals have caused tunnel collapse, which has resulted in considerable additional construction costs and delays in completion of the projects (Selmer-Olsen & Palmstrøm 1989). The cyclic moisture changes and swelling of rocks may be replicated in the laboratory and the main patterns of the swelling behavior can be assessed.

The laboratory work presented in this manuscript was performed at two different universities; i.e. at the Norwegian University of Science and Technology (NTNU) and Karlsruhe Institute of

Technology (KIT); with an aim to compare the methodologies used in determining the swelling capacity of the intact rock and rock powder. The results of the tests performed on the same rocks are presented and compared. It is highlighted on the importance of the set-up at each laboratory and the knowledge needed to interpret the results obtained from the test.

2 THE CASE PROJECT AND MATERIAL

The Alimit hydropower plant is currently in its feasibility stage and is located at Ifugao, North Central Luzon in the Philippines. The rocks in the area are primarily volcanic rocks of basaltic and andesitic origin, which have undergone hydrothermal alteration or metamorphic transformation processes and can be found in different weathering stages (SN Aboitiz/Stache 2015). The tested material was obtained from borehole core samples. The rocks were categorized prior to laboratory investigation as "*strong*" and "*weak*" based on the visual inspection and assessment.

2.1 Sample description

The main characteristics for the rock group categorized as "*strong*" are intact core-lengths over 15 cm and low degree of visible disintegration. The majority of the intact cores show appearance similar to the assumed andesitic rock type as of AD-02 (box 12) shown in Table 1. The distribution of grain size and minerals appear as uniform throughout the samples, and the color is medium grey with shades of green (Table 1). The main characteristics of the "*weak*" group of the rock samples are heterogeneity regarding grain sizes and color, and high degree of disintegration. The samples break easily by hand force (Table 2).

Table 1. Samples of the category "strong"(Selen 2017)

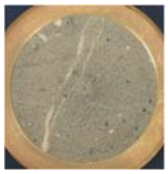
	AD-02, box 12 ~ 40.35–44.05 m	**AD-06, box 25** ~ 86.30–87.30 m	**AD-07, box 12** ~ 38.3 –41.00 m	**AQD-02, box 12** ~ 42.25–45.60 m
Rock type *strong*	 	 	 	 
	Andesite	Andesite/basalt	Altered andesite	Altered basalt

Table 2. Samples of the category "weak" (Selen 2017)

	AQD-02, box 5 ~ 16.70 – 20.60 m	**AQD-02, box 6** ~ 20.60 – 24.60 m	**APH-02, box 18** ~ 59.80 – 63.40 m
Rock type ***weak***			
	No disc able to be prepared		
	Volcanic agglomerate/breccia	Volcanic agglomerate/breccia	Altered andesite/basalt

3 THE OEDOMETER SET-UP AND PROCEDURE AT NTNU AND KIT

Different variations of oedometer-tests are being used around the world, whereas many of them are based on the work performed by Huder and Amberg (1970) and Grob (1972) (Wittke-Gattermann &Wittke 2004). The oedometer swelling tests method described by ISRM (1977 and 1989) were updated several times (Madsen 1999). The suggestions include recommendations on preparation, apparatus configuration, procedures and reporting of the results. The maximum swelling pressure test suggested by ISRM (1977 and 1989) are the modified swelling tests of the method suggested by Huder and Amberg (1970). The oedometer swelling tests can be performed both on pulverized and intact rock samples. However, there is no methodology to assess the swelling behavior of the intact rock from the results obtained from powder tests. No consistent procedures on the preparation and testing of intact rock specimen are found. This may be due to the fact that different institutes construct the odeometer with some modifications of known standards, in this case the ISRM standards. No characterization system for swelling test results on intact rock specimen is developed yet. The results obtained are therefore difficult to compare directly, since the test results are influenced by both the apparatus used and the methodological constituency. This issue also applies to the results obtained from the tests performed at NTNU and KIT.

3.1 *Oedometer test configurations*

The swelling apparatus configuration should allow to obtain either swelling pressure or swelling strain (deformation) or combination of both. To obtain the characteristic swelling strain-pressure relationship, measurements on both strain (deformation in axial direction) and swelling force are needed. Some frequently used test-configurations are described in Table 3.

Table 3 Overview of conditions under which radially constrained swelling pressure tests may be performed in oedometers

Method variations	Test configuration	Output
1) Zero volume change/zero deformation (ISRM, 1977 and 1989) (maximum swelling pressure tests)	Single test (one wetting phase)	Maximum swelling pressure in axial direction under constant volume.
2) Swelling under constant load followed by unloading stages in stress control (ISRM, 1999)	Single test (one wetting phase)	Swelling stress-strain relationship
3) Zero volume change followed by unloading stages in stress or strain control (Updated ISRM 1989 by Pimentel, 2007)	Single test (one wetting phase)	Maximum swelling pressure in axial direction Swelling stress-strain relationship First stage differs from method 2
4) Cyclic tests with controlled axial deformation (Updated ISRM 1989 by Vergara et al 2014) (cyclic swellintests)	Multiple tests in cycles, often starting with one or more wetting and drying cycles allowing zero deformation (as for 1)). Further unloading stages can be performed. The deformation allowed is fixed in each cycle (as for 2 or 3).	Swelling stress-strain-relationship is obtained Changes in swelling capacity between cycles may be evaluated.

3.2 The NTNU method

There exists a long tradition of testing the swelling potential of rock material at NTNU, due to the well documented problems with swelling gouge in weakness zones in different types of engineering projects (Nilsen 2016). The established form of oedometric swelling test at NTNU is maximum swelling pressure tests under conditions of zero volume change (Table 3, method 1a). The majority of tests have been carried out on the swelling potential of gouge material, and to some extent pulverized and compacted mixed soil/rock samples. In some cases, intact rock structure specimen has also been assessed, as in the study of Skippervik et al (2014). The principle of the swelling pressure test developed at NTNU follows the method for determining maximum axial swelling stress for swelling rocks as suggested by ISRM (1977). The swelling pressure-swelling strain relationship cannot be obtained by the use of the current version of the oedometer at NTNU. Hence, single swelling pressure tests are performed on both powder and intact rock specimen. The procedure is similar for both powder- and intact rock structure specimen and is based on the ISRM (1977). The swelling test principle is illustrated in Figure 1.

3.3 The KIT method

At KIT, the ISRM suggested methods of 1989 is used for the laboratory set-up and the apparatus and methodology was modified several times. The latest changes on the oedometer apparatus configuration at KIT was made based on Pimentel (2004) and Vergara et al. (2014). This oedeometer allows to control the deformation or the load on the specimen in order to perform stress or strain swelling tests. In addition, cyclic swelling tests can be performed at KIT where the sample is subjected to dry and wetting cycles. These tests are performed under controlled axial deformation of the intact rock specimen (Table 3, method 4), and data on both swelling stress and swelling strain are obtained. The oedometer configuration is illustrated in Figure 3.

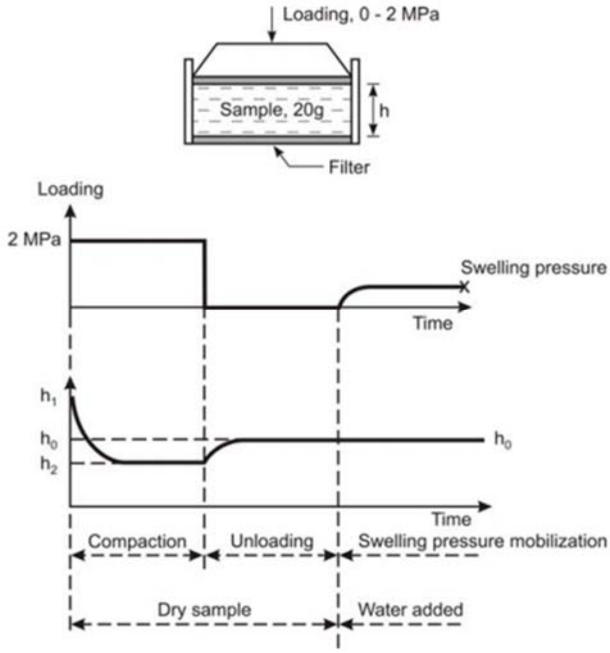


Figure 1. Principle for testing swelling pressure at constant volume (Nilsen 2007)

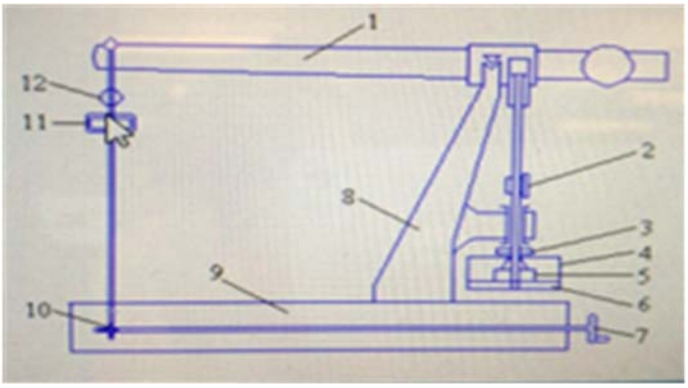


Figure 2. Apparatus at NTNU. 1) Balance lever, with the ratio of 1:10. 2) Dial gauge with a sensitivity of 0.001 mm to measure the height (volume) of the specimen. 3) Adjustment screw. 4) Container. 5) Cylindrical test cell. 6) Steel base plate of the container. 7) Wheel. 8) Frame. 9) Base. 10) Worm gear. 11) Pressure ring. 12) Dial gauge

The procedure of the cyclic swelling tests is summarized as following:

The axial swelling pressure developed by the specimen under conditions of zero volume change is recorded over the time, and after no noticeable change in the pressure is observed, the first cycle is assumed completed and the water is removed. As an effect of drying, the axial pressure produced by swelling decreases until a constant value is reached, marking the “finish-point” of the drying process. In case if swelling pressure does not increase after about 3 cycles, further cycles are performed with an increased deformation to see if it is an effect on the swelling behavior. Cycling is repeated until the pressure is stabilized. The adjustments to keep the desired volumes during the tests and the recording of swelling pressures are performed manually. The oedometer configuration is illustrated in Figure 3.

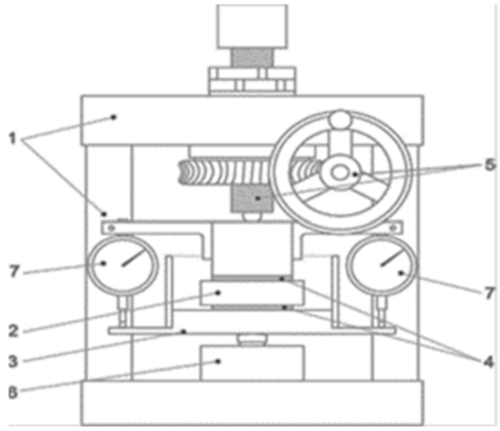


Figure 3. Modified oedometric apparatus at KIT (Vergara et al. 2014 and 2015). 1) rigid frame, 2) ring with rock specimen, 3) watering cell, 4) porous metal plates, 5) spindle, 6) load cell and 7) dial gauges.

Table 4. Main differences in methodology between NTNU and KIT (Selen 2017)

	NTNU	KIT
Preparation of rock specimen	- Core drilling (overcoring) -Use of trimming ring to fit specimen to oedometer ring	- Keep the core diameter if possible and remove the external surface by a lathe - Use of lathe to fit ring to specimen
Preferred test conf. (cf. Table 3)	Method 1)	Method 1) and 4).
Placement of dial gauges	- One dial gauge placed about 20 cm above the specimen. - Limited correction of the deformation of apparatus components between the dial gauge and specimen during the tests.	- Two dial gauges placed at opposite diameter ends of the loading plate. - Deformation of apparatus is avoided by abutting of dial gauges and sample, and by manual corrections during the tests.
Administration during tests	- Automatic volume control. - Automatic recording of swelling displacement and pressure.	- Manual volume control by reading the dial gauges and manually increasing/decreasing the load. - Manual recording of swelling displacement and pressure.
Sample size/mass (dry condition)	Powder - Mass: 20 g - Height: not measured - Diameter: 20 mm Rock - Mass: not measured - Height: ~5 mm - Diameter: 35,7 mm	Powder - Mass: 100 g - Height: ~18 mm - Diameter: ~60 mm Rock Mass: ~135 g Height: ~18.5 mm Diameter: ~60.5 mm
Pre-loading before tests	Yes, on both powder and intact rock structure samples with 2 MPa.	No, except 0.1 kN in order to ensure contact.
Number of wetting (and drying) cycles	Normally one.	Normally three or more.
Swelling stress and strain relationship	None	Yes, by allowing deformation (volume expansion in axial direction) in a stepwise manner in the conventional or in the cyclic tests.

3.4 Main differences between NTNU and KIT

The methodologies in operation at NTNU and KIT differ in several ways. The main differences include on the method, and on the internal modifications on apparatus and test procedures. Table 4 summarizes the main differences. Figure 2 and Figure 3 show the apparatus configurations.

The main difference in the methodologies in the powder tests, is the sample preparation. The sample dimensions are 2-4 times higher at KIT compared with the procedure used at NTNU. In addition, there is no pre-loading on the procedure used at KIT while a pre-loading of 2 MPa is carried out at NTNU. It is not known to which degree these differences appear in the results, but it is assumed that the influence is significant.

The main difference in the apparatus set-up is the placement of the dial gauge(s). At NTNU, the dial gauge is placed about 20 cm above the specimen, so it is unknown to which degree the deformation due to swelling pressure is absorbed in the apparatus between the specimen and the dial gauge. At KIT, the dial gauges are placed only a few millimeters from the specimen assuming that most of the swelling pressure induced by the specimen are detected by the gauges.

4 COMPARISON OF TEST RESULTS

The results comprise the comparison of oedometer swelling test results between NTNU and KIT. The swelling pressure test results on the powder material, whereby the tests were performed under conditions of zero volume change at both NTNU and KIT, are shown in Table 5. Since cyclic tests are not performed at NTNU, there is no comparable results for this type of test.

Table 5 Maximum swelling pressures in oedometer powder tests (Selen 2017)

	Samples	**Maximum swelling pressure(powder), MPa**	
		NTNU	**KIT**
«weak» “strong”	AD-02, box 12 (1)	0.33	4.88
	AD-06, box 25	0.06	0.38
	AD-07, box 12	0.10	2.42
	AQD-02, box 12 (1)	0.10	0.41
	AQD-02, box 5	0.43	3.03
	AQD-02, box 6	0.35	2.87
	APH-02, box 18	0.12	0.82

Table 6 Overview of tests on discs. All values are given in MPa (Selen 2017)

Disc	**NTNU**	**KIT**							
	-	1.cycle	2.cycle	3.cycle	4.cycle	5.cycle	6.cycle	7.cycle	8.cycle
	ε = 0	ε = 0	ε = 0	ε = 0	ε = 0.5%	ε = +0.5%	ε = +0.5%	ε = +0.5%	ε = +0.5%
AD-02, box 12	1.33	**2.08**	1.68	1.58	1.74	1.91	1.85	0.61*	-
AD-06, box 25	0.01	**0.05**	0.04	**0.05**	-	-	-	-	-
AD-07, box 12	0.22	0.13	0.14	0.15	0.17	**0.18**	-	-	-
AQD-02, box 12	0.09	0.04	0.04	0.04	-	-	-	-	-
AQD-02, box 5	-	**0.38**	0.26	0.25	0.13*	0.20*	-	-	-
AQD-02, box 6	0.08	0.17	0.17	0.18	0.09*	0.14*	**0.19***	0.18*	0.05*
APH-02, box 18	0.04	0.49	0.48	0.52	0.17*	0.52*	0.48*	0.57*	**0.74***

* = Controlled deformation allowed by reducing the load acting on the specimens.

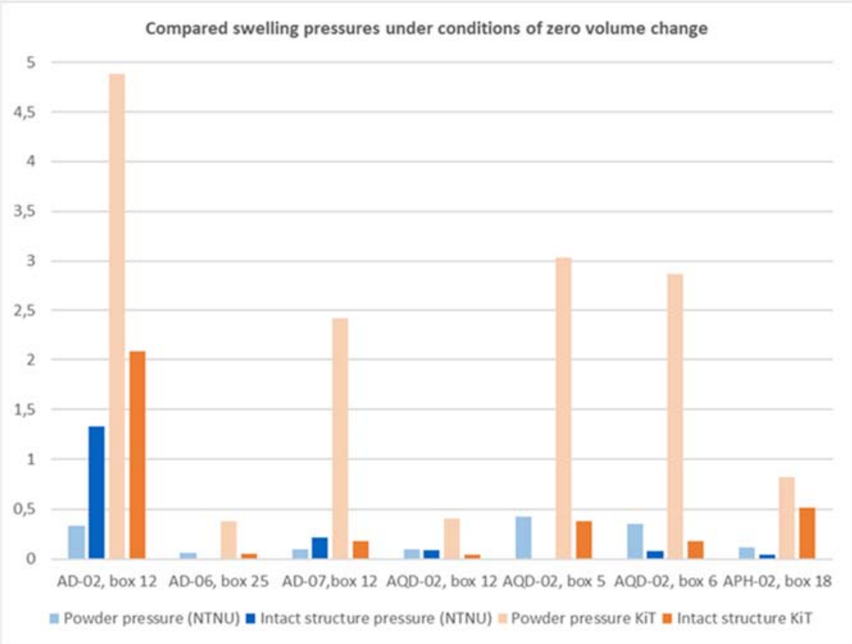


Figure 4. Compared swelling pressures in MPa of powder samples and intact rock samples (Selen 2017)

An overview of the intact rock structure (disc) swelling results is given in Table 6. The results from NTNU are obtained by single “zero volume change” tests. The results from KIT are obtained by cyclic tests, where some samples underwent cycles under conditions of “controlled deformation” as marked with “*”. The maximum swelling pressure obtained in each cycle is presented. The highest value obtained by the cyclic tests is marked with bold text.

The obtained swelling pressure magnitudes from KIT are 2 to 4 times higher than for the corresponding tests carried out at NTNU. The differences in the magnitudes between powder tests and intact rock structure tests is also found higher at KIT. Figure 4 shows a comparison of the swelling pressures under conditions of zero volume change measured at both NTNU and KIT. The highest swelling pressures from the cyclic tests under conditions of zero volume change are representing the values obtained at KIT. Powder sample results are colored light blue (NTNU) and light orange (KIT), while intact rock structure results have corresponding strong blue and orange colors. The vertical axis shows the swelling pressure in MPa.

As can be seen from Figure 4, the NTNU method gave much lower swelling pressure potential of most of the intact rock samples compared KiT. Moreover, the swelling pressures obtained from the powder samples are also lower than that of the KIT results.

5 Conclusions

The comparison of the oedometer testing methodologies in operation at NTNU and KIT uncovered important differences. The deviations apply on both the apparatus used, and the procedures of swelling tests that is being practiced. The differences include the version of the ISRM suggested methods (1977 and 1989), and internal modifications on both apparatus and procedures made at each institution. The fact that different institutes operate with intern modifications of methodologies and apparatus configurations, leads to different results for similar rock types.

It is difficult to conclude on which of the methods is closest to the real swelling potential of the rock mass, since there exists no data on the in-situ swelling behavior. It is important to underline that the swelling pressure test results achieved from each laboratory cannot directly represent the swelling potential of the in-situ rock mass, and therefore must be used as indicative indexes. Each testing institution should classify indexes accordingly based on their data base recorded from actual projects and test results from the lab. This will help to understand on in what swelling pressure category the test results belong to. In the future, if laboratory data could be correlated with in-situ data, it would be possible to make an approach to a methodology appropriate to detect the swelling potential of the actual rock mass. However, it is reasonable to imply that the swelling measurements should be performed by dial gauges as close to the sample as possible. It is also clear that different institutions should agree on a standard method and a standard configuration of the apparatus, so comparisons of laboratory data can be made with lesser degree of uncertainty in the future. For projects where the rock mass is exposed to humid variations, as in hydropower projects, cyclic swelling tests should be included in the testing procedure. By allowing the specimen to deform during the test, data on both swelling stress and swelling strain can be obtained, and a simulation of the rocks interaction with support in a tunnel is possible to evaluate.

Further, it is important to highlight that there is a need for closer communication and cooperation among the institutions so that the swelling pressure test are standardized and differences in the test results are known, as have been made between NTNU and KIT. This cooperation will help to develop an index on the swelling pressure potential of both powder and intact rock discs, that could be translated in the consideration of potential swelling problems in the project. If comparable data on powder samples and intact structure specimen are systematically collected by synchronized test procedures, it may be possible to predict the intact rock behavior from powder test results in cases where the rock quality prevents preparation of intact rock specimens. Evaluations of laboratory testing will then be of higher value in the design of rock support on the tunnels passing through swelling rock mass

REFERENCES

GALERA, J., PAREDES, M., MENCHERO, C. & POZO, V. 2014 Risk Associated with Swelling Rocks in Volcanic Formations in the Design of Hydro-Tunnels. ISRM Regional Symposium-EUROCK 2014.International Society for Rock Mechanics.

ISRM. 1977. Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties. Test Standards by International Society for Rock Mechanics, pp. 89-92.

ISRM. 1989. Suggested Methods for Laboratory Testing of Argillaceous Swelling Rocks. International Journal of Rock Mechanics, Mining Sciences and Geomechanics Abstracts, vol. 26 (5), pp. 415-426.

MADSEN, F. T. 1999 International Society for Rock Mechanics Commission on Swelling Rocks and Commission on Testing Methods, International Journal of Rock Mechanics and Mining Sciences, p 291-306

NILSEN, B. 2007 Reliability of Swelling Pressure Testing for Tunnel Support Evaluation

SKIPPERVIK, C. P., Panthi, K. K. and Dahl F. 2014. Study on the Swelling Potential of some Selected Rocks. Proceedings: Norwegian Tunneling Conference, Oslo 2014.

SELEN 2017 Study on material properties and testing of various rock types, development of investigation procedure and test methodology for future projects. NTNU, Institutt for geologi og bergteknikk.

SELMER, R. & PALMSTROM, A. 1989.Tunnel collapses in swelling clay zones. Tunnels & tunnelling.

SN ABOITIZ/STACHE M. 2015.Geological Report, Olilicon and Alimit HPP's and Alimit pump storage schemes, Feasibility phase. (Unpublished)

VERGARA 2016 Oral discussion.

VERGARA, M. R., BALTHASAR, K. & TRIANTAFYLLIDIS, T. 2014. Comparison of experimental results in a testing device for swelling rocks. International Journal of Rock Mechanics and Mining Sciences, p 177-180.

VERGARA, M. R. & TRIANTAFYLLIDIS, T. 2015. Swelling behavior of volcanic rocks under cyclic wetting and drying. International Journal of Rock Mechanics and Mining Sciences, 80, p 231-240.

WITTKE-GATTERMANN, P. & WITTKE, M. 2004. Computation of strains and pressures for tunnels in swelling rocks. Tunnelling and Underground Space Technology, 19, 422-423.

XANTHAKOS, P. Ground Anchors and Anchored Structures, John Wiley & Sons, 1991, Technology and Engineering, 686 p., p 432.