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Dilatometer tests in deep boreholes in investigation for Brenner base tunnel

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ABSTRACT: Results from more than one-year of in-situ deep borehole dilatometer testing and data evaluation for the Brenner base tunnel geotechnical investigation project are presented. The principle of dilatometer measurements is explained. Dilatometer measurements describe deformation properties of rock massif. Deformation modulus and modulus of elasticity are determined in relationship to applied pressure. Equipment for testing in deep boreholes with diameters ranging from 96 to 158 mm is described. Information needed prior to measurements, testing procedures as well as evaluation of recorded data are discussed. Examples of in-situ dilatometer measurements are presented. Range of use of gained results is discussed and conclusions are drawn.

1 INTRODUCTION

The Brenner base tunnel will be a significant part of European railway axis Berlin – Napoli – Palermo. The 55.6 km long tunnel route will be built from Austrian Innsbruck to Italian Franzensfeste (Fortezza). Numerous deep boreholes up to 1351 m depth were simultaneously drilled during the second phase of geological exploration in 2004–2005. Depth of the boreholes required drilling in several sections with decreasing diameter. Other reason for various borehole diameters was that six different drilling companies participated in the project. To comply with the proposed procedure of "drilling – logging – measuring", Solexperts AG was obliged to perform tests in boreholes with diameters ranging from 96 mm to 158 mm.

Several types of borehole measurements were performed: geophysical logging, packer tests, stress measurements using hydraulic fracturing and dilatometer measurements. In this paper we focus on in-situ determination of deformation properties of rock massif using Solexperts dilatometer.

2 SOLEXPERTS DILATOMETER SYSTEM

The dilatometer probe developed by Solexperts AG has been successfully used for more than 30 years (Thut 1977). Determination of the mechanical properties of the rock mass is based on real-time measurement of the applied pressure and the resulting deformation – the change of the borehole diameter.

The dilatometer probe consists of a metal core, which holds three potentiometeric displacement transducers placed in the centre of the core, Figure 1. The axes of the transducers are oriented 120° to each other and vertical distance between the transducers is 75 mm. The borehole wall is loaded by means of a reinforced packer sleeve fixed to the core of the probe at its both ends. The packer can be expanded by compressed nitrogen or air via a high-pressure hose connected to either nitrogen bottles or a compressor. The dilatation of the borehole wall is directly measured by the transducers, which contact the borehole wall through steel pins with spherical heads. The applied pressure is measured at the surface using a pressure sensor. The electronic signals of the displacement transducers are transmitted to the dilatometer logger through a coaxial cable within the high pressure-hose. The probe can be additionally equipped with a compass for oriented strain measurement or with two pressure sensors: one measuring the formation pressure underneath the probe and the other measuring the pressure inside the packer. To simplify installation and minimize risk of damage when retrieving the probe from the borehole a steel cone is attached to the lower end

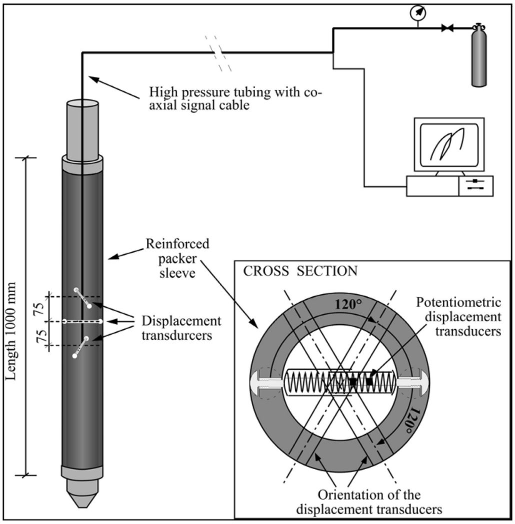

Figure 1. Scheme of the Solexperts dilatometer.

Table 1. Diameters of Solexperts dilatometer.

Diameter		
Unexpanded probe mm	Borehole – minimum mm	Sign
92	96	HQ
95	101	
118	122	PQ
142	146	
148	152	

of the probe and an open type bailer, called sedimentation tube, to its upper end in order to prevent blocking the probe by loose material falling down the drill hole.

The maximum measurement range of the displacement transducers is 25 mm, also due to their high accuracy of 0.001 mm. The packer is designed for this range of strain too. To perform tests in boreholes with diameters ranging from 96 mm to 158 mm there had to be either a single probe for each diameter or one type of probe, where the packer element and transducer extension pins could be easily changed. Solexperts has developed a dilatometer probe body (core), which can be equipped by packer elements of different diameters. A set of corresponding sedimentation tubes and calibration tubes have also been provided, Table 1. The probe is installed with so called hydro-frac tubing of 1″ using a drilling rig.

The high-pressure hose containing signal cable is wound on a winch on the surface. The hose/cable was manufactured in sections of 200 m with the appropriate connectors. Connecting multiple sections, made it possible to perform measurements up to 1400 m in depth. One or more 200 m sections of the hose/cable can be replaced, if needed.

The inflation pressure is manually regulated and automatically measured at the control panel with a pressure sensor. Additionally it can be observed together with the pressure in the system and the rest pressure in the nitrogen bottle (or compressor) with mechanical pressure gauge in the control panel. For special long-term dilatometer experiments a fully automated monitoring system (the Solexperts GeoMonitor II) can be used. In this case however, the dilatometer system is pressurized with silicon oil.

The pressure sensor and the signal cable from the probe are connected to special dilatometer data acquisition system, which is controlled by a computer via the software program DilatoII developed by Solexperts. This program provides data acquisition, testing control, graphical and numerical real-time data presentations, as well as test analysis and reporting.

3 DILATOMETER TESTS

3.1 *Planning and preliminary information*

To comply with a “drilling – logging – measuring” procedure requires a significant planning, decision making and preparation is necessary prior to execution of each series of tests.

In-situ testing i.e. dilatometer measurements or hydraulic tests using a double packer system can be done during the drilling phase or after the entire length of the borehole has been drilled. Performing measurements according to the state of drilling progress may be difficult to manage especially when several boreholes are being drilled simultaneously, as it was for the Brenner exploration project.

In most cases however, measurement campaigns are carried out after the drilling has been successfully finished. The geologist in charge usually overviews the entire borehole and specifies the borehole sections of interest. Results of tests might be affected by “borehole history effect” (especially affecting the hydraulic tests results). Another problem to be considered for testing after drilling is the stability of the borehole. Especially, investigation of faults and shear zones is of interest for the design of planned excavation. In cases of poor borehole stability only the “measurement-while-drilling” approach can be applied.

The approach chosen for the geotechnical and hydrogeological investigation for the Brenner base tunnel was a compromise of the presented possibilities: a series of test measurements was done after a first section of the borehole with one diameter was drilled.

Borehole logging and geophysical measurements were carried out at the beginning of a testing campaign.

The logs were used to decide about the subsequent testing strategy and number of tests. For the dilatometer tests the most important information was:

– nominal borehole diameter,
– test depths,
– type of rock / inspection of borehole cores,
– dipping of shistosity,
– calliper log for actual borehole diameter or
– borehole scan for geologic structure and
– ground water table / hydrostatic pressure at each test depth.

The calliper log and/or the borehole scan provided information about the true borehole diameter as well as the possible existence of caverns, discontinuities, large cracks and fractures of the massif. Uneven borehole walls result in higher risk of packer damage and, in the extreme case, the possible blockage of the borehole by an irretrievable probe. Additionally, to high artesian water pressure (determined by the hydrogeological tests) can cause difficulties during the tests.

3.2 *Test procedure*

The dilatometer probe must be calibrated prior to testing. The calibration is done by inflating the probe inside a steel tube of known diameter. The DilatoII software then records the data from each displacement transducer and calculates offsets so that a "zero reading" corresponds to the known inner diameter of the tube. The actual borehole diameter can then be precisely determined. It is needed for control of the probe expansion state during the test and for test analysis.

The test sequence usually begins at the lowest test position in the borehole. During installation into deep boreholes the probe must be partially inflated in order to counterbalance the acting hydrostatic pressure. After lowering the probe to the depth given by the geologist, the dilatometer measurement can start. The actual borehole diameter can be determined with the dilatometer probe in cases where the calliper log shows significant variations in borehole diameter along the borehole section selected to be the test position, or the borehole cores showed discontinuities, but especially if no core could be retrieved. The actual diameter can be determined by inflating the probe just enough to overcome the hydrostatic pressure and the stiffness of the packer. Then the packer is in contact with the borehole wall. Under low inflation pressure there is no danger for the probe even if a cavern or fracture exists at this borehole section. The risk of damaging the equipment can be minimized by selecting a test position with an appropriate diameter after measuring the borehole diameter at several locations along the test zone using the described procedure.

The dilatometer tests for Brenner base tunnel project were performed with four loading cycles. At first, the probe was inflated to a base pressure, which was about 0.5 MPa higher than the hydrostatic pressure at the test position in order to establish a good contact between the packer and the borehole wall. The first cycle consisted of initial loading and subsequent unloading to the base pressure. The following cycles consisted of reloading up to the maximum pressure of the previous load cycle, initial loading to a higher level and then unloading to the base pressure level.

The maximum level of loading pressure has to be chosen with respect to the rock type, its assumed compressibility and the aim of the test. In case of measurements for a future base tunnel, the applied pressure should reach the same order as the horizontal pressure at rest in the mountain massif. One of the aims of a good dilatometer test is to describe the ratio of plastic and elastic deformations together with general behaviour of the rock, which can be also mostly elastic or plastic. The range of applied pressures should be chosen so, that the maximum of elastic deformation phase of the rock is used, but causing massive plastification or fracture of the rock is to be avoided if possible.

After the test is finished, the probe is unloaded under the level of acting hydrostatic pressure and raised to the next higher measurement zone.

3.3 *Evaluation of dilatometer test*

The moduli are calculated based on Lamé's equation for a tube with infinite wall thickness (1):

$$E = \frac{\Delta p * d * (1+\nu)}{\Delta d} \tag{1}$$

where Δp = pressure difference; d = borehole diameter; Δd = change of borehole diameter; ν = Poisson's ratio. In case where no results of laboratory tests are available for the tested rock formation, we assume the Poisson's ratio of 0.33 with respect to rock quality.

The deformation modulus (V) is calculated based on data of initial loading from each load cycle. The modulus is computed using a linear regression along the corresponding section of the curve. The deformation modulus from reloading phase of each cycle is calculated in a similar manner.

The modulus of elasticity (E_1) is calculated from the slope of a secant connecting the first and the last point of the unloading phase, which corresponds to the initial loading range for each cycle. However in cases of very step slopes which correspond to very small elastic deformation of the borehole wall and thus to very high moduli, it appears to be more appropriate to calculate E_2 (Fig. 2) from the entire unloading curve for each load cycle.

The averaged displacement measurements of the all three transducers are mainly used for the calculation

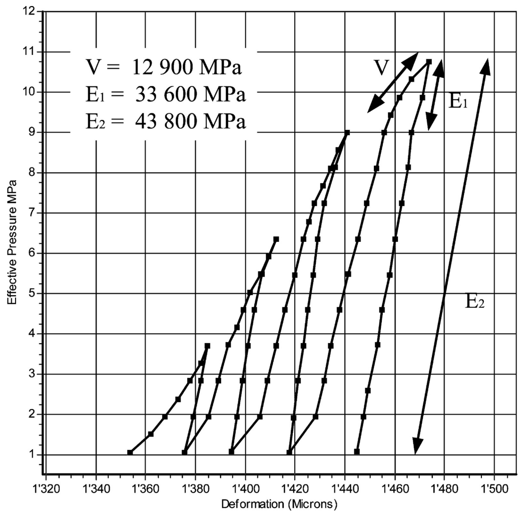

Figure 2. Dilatometer test in borehole Va-B-03/04s, 986.5 m depth, chlorite schists. Graphical representation from the DilatoII software program: average from deformation measurements of all three extensometers.

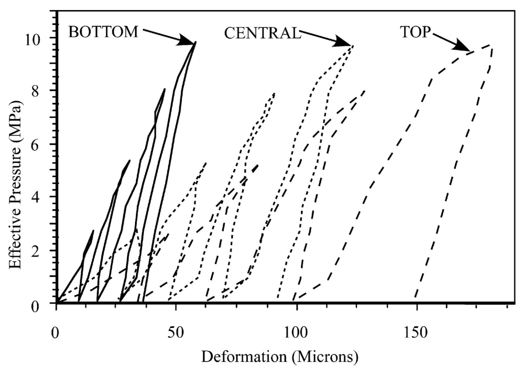

Figure 3. Dilatometer test in borehole Va-B-03/04s, depth 986.5 m. Comparison of pressure/deformation graphs for three extensometers.

of the moduli. Based on comparison of all three pressure / deformation graphs, conclusions on elastic or plastic behaviour of the rock massif can be drawn and estimates of anisotropy can be made. Figures 2 and 3 show a dilatometer test in chlorite schists at 986.5 m depth. The borehole Va-B-03/04s is inclined 30° from vertical.

The method of analysis described above allows assessing one dilatometer test at a time. The stiffness of the examined rock can be classified according to the values of deformation and elasticity modulus from the last loading cycle. For this purpose we use the classification based on E-modulus values, which was proposed by AFTES (1993).

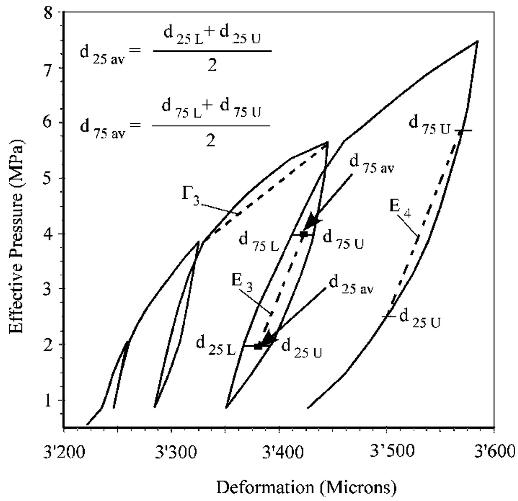

Figure 4. Schema for computation of E and Γ for Schneider's criterion. Graph: Test in borehole Pf-B-03/05, depth 39 m, quartzphyllite. Average from deformation measurements of all three extensometers.

Another approach, Schneider's criterion (1967), also uses the Lamé's equation, but allows interpretation and comparison of series of dilatometer tests from a wide range of rocks. Development of the deformation properties can be evaluated with respect to acting pressure. Measurements with four loading cycles are required for the Schneider's criterion, which describes the relationship of a factor of permanent deformation C_p (2) to a ratio of elasticity modulus E to deformation modulus Γ (3):

$$C_p = \frac{d_p}{p_{max}} \tag{2}$$

$$\frac{E}{\Gamma} \tag{3}$$

where d_p = permanent deformation after a complete loading cycle; and p_{max} = maximum loading pressure applied with this cycle. The factor of permanent deformation is calculated for each loading cycle.

The modulus of elasticity E is defined as a slope of a straight line, which connects points $d_{25\,av}$ and $d_{75\,av}$. These points represent average deformation from unloading ($d_{25\,U}$, $d_{75\,U}$) and reloading ($d_{25\,L}$, $d_{75\,L}$) phase of the corresponding load cycle (see Fig. 4). Values of d_{25} and d_{75} are determined at pressure levels of 25% and 75% from the maximum pressure applied in the loading cycle. The E moduli are calculated for the first to the third load cycle. The calculation of E-modulus from the last (fourth) cycle is based on data from the unloading phase only. These calculations

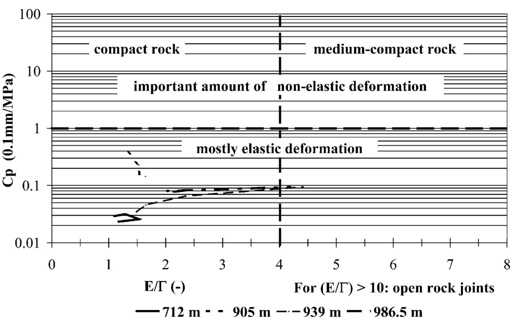

Figure 5. Schneider's criterion, after Schneider (1967). Graph: dilatometer tests in shales, borehole Va-B-03/04s.

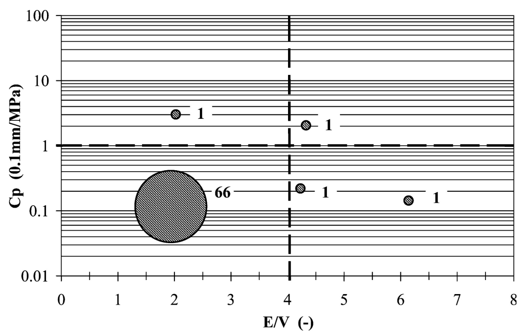

Figure 6. Modified Schneider's criterion. Distribution of 70 test results. The position of the points corresponds with average of E/V and C_p for each presented rock class. The size of points relatively depicts the number of tests.

can be done by interpolation between the data points recorded during the measurement (see Figure 2) or estimated in the chart. The analysis data presented in this article were interpolated. The deformation modulus Γ is determined as the slope of a secant, which connects the first and last point of an initial loading phase of a load cycle, Figure 4.

The resulting data is plotted in a semi-logarithmic graph, which is also used for rock classification, after Schneider (1967), Figure 5. All four data sets presented in this example indicate compact rocks with mainly elastic deformation behaviour.

Data analysis for Schneider's criterion is not integrated into the analysis part of DilatoII program. Therefore the analysis was made with a spreadsheet program, which is rather time consuming. Further, presentation of a large number of tests in a diagram according to Schneider can become confusing. For these reasons we propose a modified version of Schneider's criterion based on the values from the last (fourth) loading cycle only. The results of a complete dilatometer test are reduced to only one point in the Schneider's graph, instead of a polygon line in the original Schneider's criterion. This method allows a quick comparison of rock properties in a large set of dilatometer tests. This procedure does not depict the development of the moduli and the amount of plastic deformation with respect to pressure changes during the test but makes evaluation of the distribution of measured moduli much easier.

We use the data of V (deformation modulus calculated as regression) and E (elasticity modulus) computed by the DilatoII program in the modified Schneider's analysis. The E_2 modulus calculated from the entire unloading phase of the fourth loading cycle was chosen, because it is closer to the original Schneider's criterion than the E_1 value determined from the upper part of the corresponding unloading phase only, Figure 2. This simplifies determination of coefficient E/V (instead of original E/Γ), whereas the coefficient C_p remains unchanged. All results are then displayed in Schneider's graph. To get a better overview of the distribution of test results, the average is calculated for each rock class. Seventy dilatometer tests executed during the exploration campaign for Brenner base tunnel project are shown in Figure 6.

The proposed analysis and graphic presentation gives an overview of the deformation properties along the whole project. Based on the modified Schneider's criterion, it is obvious, that that about 95% of the tests indicate a compact rock, of mainly elastic behaviour in the range of applied pressures. Only four tests (roughly 5%) represent rock with partly plastic deformation behaviour. In the next step, these tests should be reviewed in detail and further investigation might be considered if these results appear to be critical for the project.

This approach might be helpful for decision making in the early stages of geological and geotechnical survey. The knowledge gained from the modified Schneider's criterion may be used:

- as another point of view for preliminary characteristics the rock mass,
- to find areas, where further investigation may be required,
- to obtain an overview of the deformation properties of the rock mass and
- to estimate suitable tunnelling techniques and the type of primary tunnelling supports.

4 APPLICATION OF RESULTS

For the determination of the stiffness parameters of the rock mass at the Brenner base tunnel various formulas given in the literature such as Hoek et al 2002 have been used. Results obtained revealed a considerable scatter. The results of the dilatometer tests have been used to verify calculated results. Due to the fact that dilatometer tests represent the deformability of sections of rock mass of less than 1 m, whereas during excavation stress redistributions affect sections of up to 10 m results of dilatometer tests have been regarded as an upper limit taking into consideration the scale effect.

5 CONCLUSIONS

Results of dilatometer in-situ measurements describe deformation properties of rock mass. A large number of tests were performed during the second phase of geological exploration for the Brenner base tunnel in 2004–2005. The borehole diameters were ranging from 96 to 158 mm and the boreholes were reaching to depths of more than 1300 m. The results from the provided dilatometer tests were used to verify calculated stiffness parameters of the rock mass at the Brenner base tunnel. Based on our experience with test analysis and interpretation, a modification of Schneider's analysis of dilatometer tests has been created in order to allow quick overview and comparison of numerous dilatometer tests. The most important modifications are: moduli calculated only from the last loading cycle are directly used. Each dilatometer test is then represented by only a single point in the Schneider's graphical classification. Even large series of tests covering the whole explored area of interest can be assessed. Evaluation of the distribution of points in the resulting graph allows characterization of the major type of rock mass deformability. The rock classes where few tests occur can indicate areas to be reviewed or further investigated.

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