EVALUATING ROCK MASS BEHAVIOUR IN DILATOMETER TESTS

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ABSTRACT: The rock mass deformation modulus can be measured by different methods including field and laboratory testing and considering the relation between the applied load and resulting deformation. The dilatometer is one of the most versatile instruments used for this purpose. Defining an absolute value for the deformation modulus based on this test may be difficult or inaccurate and the aim should rather be the definition of a magnitude for the modulus. However, interpreting the results of dilatometer tests is a matter of engineering judgment that requires an understanding of the rock mass behavioural pattern during the test which is discussed in this paper. Examples of dilatometer test results from Roudbar-Lorestan dam site in Iran are also presented.

KEYWORDS: Dilatometer, Deformation, Elasticity, Rock behaviour.

1- INTRODUCTION

The deformability is one of the most important properties that represent the mechanical behavior of rock masses and is used in various rock engineering projects including underground and surface structures. It is characterized by a modulus which describes the relation between the applied load and the resulting strain. The commission of terminology, symbols and graphic representation of the International Society of Rock Mechanics has given the following definitions [1]:

- Modulus of deformation of a rock mass is the ratio of stress to corresponding strain during loading of a rock mass, which includes both elastic and inelastic behavior.
- Modulus of elasticity of a rock mass is the ratio of stress to corresponding strain during loading of a rock mass which only includes the elastic behavior.

The rock mass deformation modulus can be measured by different methods including field testing and laboratory testing. It is known however that the measured or estimated values in virtually all methods of field modulus measurement vary from laboratory results. Since rock masses usually contain discontinuities, their mechanical behavior is different to that of small rock specimens tested in the laboratory. The variation in blockiness or degree of jointing in rock masses may often be the cause of such variation. Part of it may also occur from changes in test boundary conditions, from poor test design or incorrect analysis. For instance, Farmer and Kemeny [2] have found that the deformation modulus of intact rock samples is in the order of 5 to 20 times higher than in-situ values and Pinto de Cunha and Muralha [3] showed the effect of the volume involved in the test of the deformation modulus measured. Hence large scale techniques offer advantages by testing at a more reasonable scale. However, few projects feature a sufficient number of different tests to allow a meaningful comparison of in-situ test data and very different in-situ results may be obtained depending on the test method. Even in an extensive in-situ test program in fairly uniform and good quality rock mass conditions, deformability data may feature a deviation of 25% or as much as 10 GPa for an average in-situ modulus of 40 GPa [4]. Therefore the use of more than one indirect procedure has also been proposed by many other authors, so that the results obtained can be compared and their reliability checked. In this regards the Borehole Expansion Tests, mostly Flexible dilatometers, were found to be one of the most suitable in-situ tests for the determination of the rock mass deformation modulus [5].

2- THE DILATOMETER TEST

The dilatometer test is a conventional method among in-situ tests and is based on the theory of elasticity which considers the rock mass as an elastic, isotropic and homogeneous medium. The dilatometer is one of the most
versatile instruments used for determining the in-situ modulus of deformation. These devices are capable of applying hydraulic pressure on the rock mass in boreholes through a flexible membrane. During the test it is possible to define the deformational characteristics of rock mass with regard to the relationship between the pressure and deformation by imposing pressure on the wall of borehole. Using the test results allows one to anticipate the behavior of rock masses when exposed to changes under loading and unloading conditions. The testing method has been described in detail in the suggested methods of the International Society of Rock Mechanics [6].

Dilatometer tests have been used in various projects and the results are widely reported [7, 8, 9, 10, 11 and 12]. However, analyzing and interpreting the behavior of rock masses based on pressure-displacement curves resulting from this test are still not being evaluated in a suitable manner and most reports suffice by presenting a numeric value as the modulus of deformation. In order to arrive at the best possible results one must know the limits and problems involved in the tests. It is generally known that in-situ tests are subjected to measurement errors, both from equipment and test location preparation. The type of dilatometer used for testing, its calibration and the measurement accuracy may largely affect the results [13]. Drilling procedures may cause some damages to the borehole walls or cause stress release due to core recovery. In addition to the above, it has been pointed out by several investigations that the in-situ deformation modulus is not constant, but depends on the stress conditions, being generally higher in areas subjected to high rock stresses. However, this may also be due to better rock mass quality where the higher stress occurs [14]. Thus it has been suggested that the aim cannot be to define an absolute value, but rather to define a magnitude for the modulus, even if the modulus of deformation is determined by direct measurement [15]. This is a matter of engineering judgment which requires an understanding of the behavior of the rock mass during a test.

2.1- ROCK MASS BEHAVIOUR DURING TESTING

The interpretation of the dilatometer tests is rather difficult due to the variation of rock mass behavior during testing. Generally the modulus value increases with the increase in applied pressure during the measurement. This is due to the closure of cracks or joints in the rock mass under stress, making the material stiffer at higher stresses. During the application of pressure in a dilatometer test, several stages may occur in the behaviour of the rock mass [16]. In the first stage, if the initial stress of the rock mass is not null, the application of pressure will first decompress the rock mass in a peripheral direction. In the second stage and with the increase of pressure, the peripheral compressive stress will decrease until tensile stresses occur. With further pressure increase a third stage is obtained. During this stage a failure process will start once the rock mass has reached its tensile strength limit, producing a first cracked zone where there is a radial stress of compression with a null peripheral stress, and producing a second zone in which the peripheral stress zone is a tensile one and varies between the tensile strength and zero, and finally producing a third zone in which the stresses are all compressive. If the initial stress of the rock mass is null the test will start from second stage, and if the tensile strength of the rock mass is null a compressive zone will directly be reached from a cracked zone. Considering the above, one the following six stress conditions may occur during a dilatometer test (Figure 1):

Condition 1: The rock mass is under compression.
Condition 2: A zone with tensile peripheral stresses and a compressive zone.
Condition 3: The whole rock mass has peripheral tensile stresses.
Condition 4: A cracked zone and a compressive zone.
Condition 5: A cracked zone and a zone with peripheral tensile stresses.
Condition 6: A cracked zone, a zone with peripheral tensile stresses and a zone under compression.

Figure 1: Possible stress zones occurring in a dilatometer test where $\sigma_t$ is the tensile stress and $\sigma_c$ is the compressive stress
However, the behavioural pattern of a rock mass may change depending on the rock and testing conditions. In this regard various models of rock behaviour have been observed [17]. To be able to interpret the results of a dilatometer test correctly, it is important that the different behavioural patterns of a rock mass are understood.

In a homogeneous elastic rock mass the loading and unloading path is the same which means that the pressure-expansion curve is linear (Figure 2, Type 1).

In case there is a limit to the shear stress that the rock can sustain, the rock behaves as an elastic material prior to failing in shear (Figure 2, Type 2). Once the testing pressure exceeds the pressure required to initiate shear failure, the strain rate will show a substantial increase. The form of the non-linear portion of the pressure-expansion curve will be a function of the shear strength of the rock. On unloading, the rock will behave elastically until the failure strength is reached. At this point the circumferential stress becomes the major principal stress. It should be noted however that the true behavior of the rock is often masked by the disturbance caused by the forming of the borehole or by soft cuttings lodged between the dilatometer and the borehole wall.

In this model it is assumed though that the rock only fails in shear and not in tension. In case the tensile strength of the rock is low then the lateral stress must be high enough to ensure that the rock does not fail in tension and crack.

Most rocks do not have isotropic strength properties and are usually weak in tension and much stronger in compression or shear. If the in-situ lateral stress is low and the shear strength high then tensile stresses may develop during the test. Once the pressure increases the circumferential stress will go into tension and at some stress the rock will crack (theoretically in a radial direction). This is shown in the pressure-expansion curve in form of a distinct step at the initiation of the cracks (Figure 2, Type 3). With further increase in pressure the cracks will grow and the slope of the pressure-expansion curve flattens. On unloading the stress path will follow down the same curve until the cracks close completely from where the curve will follow the initial elastic path.

If the pressure continues to increase the mechanism of failure at the boundary will change to one of a shear failure mode (Figure 2, Type 4). In such case three distinct zones can be seen in the material around the dilatometer: the outer zone in which the rock is un-cracked and behaves elastically, the middle zone in which the rock will have radial cracks and a low circumferential stress, and the inner zone adjacent to the borehole wall where the rock will fail in shear and the voids will be closed.

If radial cracks exist prior to the test, then no tension can develop. If the shear strength of the rock is too high to fail under the maximum pressure of the instrument then the pressure-expansion curve will show a distinct change of curvature when the cracks start to open (Figure 2, Type 5). If the pressure is reduced the curve will retrace itself because the rock behaves elastically at all times. If existing cracks did not dominate, then as soon as a crack forms a sudden increase in expansion can be seen on the pressure-strain curve. This behavior is frequently observed in hard rocks near the surface. In view of the erratic nature of the tensile strength several abrupt steps are often seen in the pressure-expansion curve as the pressure increases (Figure 2, Type 6). Generally the curve will be a straight line containing small steps but with no significant increase in strain (unless the rock begins to fail in shear). On unloading, the curve will follow a similar path to the loading except that it will be smooth and without steps. However, if on loading, the cracks do not remain open and become filled with rock cuttings then the unloading curve will be much stiffer than the loading curve (Figure 2, Type 7). In addition both tension and shear failure could occur with the cracks being filled before unloading. A similar behavior may be observed if the rock fails in tension followed by failure in shear, and the cracks become filled with rock cuttings (Figure 2, Type 8).
Figure 2: Different behavioural patterns of rock masses in dilatometer tests

It should be noted that in the above descriptions, dry testing conditions were assumed. However, water may be present due to the drilling process or from hydrostatic water pressure. If the hydrostatic water table is near the surface then pressure will exist throughout the formation. In such situation the above discussion will still apply with the provision that the stresses considered must be effective rather than total stresses.

In the following section few examples are presented of tests carried out in a site investigation program in order to show the behavioural patterns of a rock mass based on the above descriptions.

3. CASE STUDY

Several dilatometer tests were carried out as part of a site investigation program for the Roudbar-Lorestan Dam Project in the South-West of Iran in order to determine the deformation characteristics of the rock masses in that area. The site under survey is in the Zagros Mountain range in the Lorestan province of Iran and the rocks in this area consist mainly of grey to brownish grey, well bedded limestone and dolomitic limestone, with alternation of marly limestone, shale, and marl. The testing procedure and calculation of results followed the suggested method of the International Society of Rock Mechanics [6]. The device used, a High Pressure Dilatometer HPD73, can apply a pressure of up to 20 MPa to the ground, and can expand from an initial diameter of 73 mm to nearly 100 mm [17]. The expansion of the instrument is measured by means of six circumferentially fixed strain gauged leaf springs that follow the movement of the inside of the membrane and the internal pressure is measured by a transducer within the body of the HPD. The instrument is capable of resolving movements of less than 1 micron and pressure changes less than 1 kPa, however it requires proper calibration and corrections for membrane thinning since the strain arms are covered by the membrane.

Examples of achieved results from these tests are presented in Table 1 together with the corresponding Pressure-Deformation graphs shown in Figures 3 to 7. As suggested by Clerici [15], instead of defining an absolute value, a range for the deformation and elasticity modulus of each test is presented corresponding to different applied pressures.

It can be seen that in the first cycle of the tests a very low modulus values have been observed. This was mainly due to inadequate pressure applied for testing. Since the displacement transducers are covered by a membrane, it is important to not only calibrate the system for membrane compression and membrane thinning, but also to use adequate initial pressure for the full expansion of the membrane before the behavior of the rock can be measured. Hence the low modulus values in the first cycles do not represent the real behavior of the rock mass. In all cycles...
the applied pressure up to 3MPa, shows the behavior of rubber sleeve of the dilatometer in addition to the behavior of borehole wall which affects test results and the shape of the curves.

<table>
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<th>Mean Deformation Modulus (MPa)</th>
<th>Applied Pressure (MPa)</th>
<th>Mean Elasticity Modulus (MPa)</th>
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At the end of each loading and unloading cycle the curves show that a portion of deformation has taken place during loading that is not recovered during unloading. This is partially due to the closure of cracks and discontinuities and represents the plastic behaviour of the rock mass. Deflection of the weakened rock in the borehole wall periphery occurs mainly due to the borehole wall convergence under the effect of in-situ stress field or swelling of the rock. The presence of discontinuities, inadequate drilling techniques during borehole preparation may cause crushing and weakening of the rock which will have a similar effect on the results. Behavioural patterns of the rock such as elastic response, shear failure, tensile failure, and crack filling explained earlier, can clearly be identified in various cycles of the graphs shown below which also correspond to the modulus values shown in Table 1.

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![Pressure-deformation graph of the test in Gallery LG1 at depth 21.65 m.](figure3.png)
Figure 4: Pressure-deformation graph of the test in Gallery RG1 at depth 7.30 m.

Figure 5: Pressure-deformation graph of the test in Gallery RG1 at depth 22.00 m.

Figure 6: Pressure-deformation graph of the test in Gallery RD1 at depth 27.55 m.

Figure 7: Pressure-deformation graph of the test in Gallery RD2 at depth 14.55 m.
4- CONCLUSION

The dilatometer test is a conventional method among in-situ tests and has widely been used in various projects for measuring the deformation modulus of rock masses. The interpretation of dilatometer tests is rather difficult due to the variation of devices used and inaccuracies during preparation and testing, and also different rock mass conditions. The choice of a design value for the in-situ modulus of deformation is a matter of engineering judgment and it has also been suggested that the aim in such a test should not be to define an absolute value, but rather to define a magnitude for the modulus. This requires an understanding of the rock mass behavior during testing.

The purpose of this paper is to give some useful indications for the interpretation of such tests. Various behavioural patterns of rock masses in a dilatometer test have been reviewed and discussed, along with examples of dilatometer tests carried out at the Roudbar-Lorestan dam site in Iran. Once the behaviour of a rock mass is better understood, the prediction of in-situ parameters becomes closer to actual values and conditions. The test results presented in this paper together with the corresponding pressure-deformation graphs show the effects of rock mass behaviour on the deformation modulus of the rock. The above review and examples could be used as a guide for evaluating rock mass behaviour in dilatometer tests.

5- REFERENCES

6- BIODATA

Dr. Morteza Gharouni Nik graduated and obtained a Ph.D in Geotechnical Engineering (Rock Mechanics) from the University of Newcastle Upon Tyne, England, in 1993. From 1993 to 2002 he worked for a Rock Mechanics company, specialising in Geotechnical laboratory and in-situ tests and performed these tests for design and construction of at least 15 concrete dams in Iran. From 2001 he has been Professor of Tunneling and Rock Mechanics and Rock Engineering at the Iran University of Science and Technology (IUST), where he specialises in Rock Mechanics, Soil Mechanics and Tunnelling.

Dr. Siamak Hashemi has obtained a BSc in Mining Engineering, an MSc in Rock Mechanics, an MSc in Computing and completed his PhD in Soil Mechanics at the University of Newcastle upon Tyne in 2002. He was technical manager of Khak & Sang Geotechnical Consultants until 2006 and works at present for Moshanir Power Engineering Consultants as project manager. He is currently vice president of the Iranian Tunnelling Association and is specialized in site investigations and rock mechanics in-situ testing. He has carried out various tests including dilatometer, plate load and direct shear tests in more than 10 large dam projects in Iran.