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Numerical Modeling of Determination of in situ Rock Mass Deformation Modulus Using the Plate Load Test

A. Khodabakhshi, A. Mortazavi

Abstract**—**Accurate determination of rock mass deformation modulus, as an important design parameter, is one of the most controversial issues in most engineering projects. A 3D numerical model of standard plate load test (PLT) using the FLAC3D code was carried to investigate the mechanism governing the test process. Five objectives were the focus of this study. The first goal was to employ 3D modeling in the interpretation of PLT conducted at the Bazoft dam site, Iran. The second objective was to investigate the effect of displacements measuring depth from the loading plates on the calculated moduli. The magnitude of rock mass deformation modulus calculated from PLT depends on anchor depth, and in practice, this may be a cause of error in the selection of realistic deformation modulus for the rock mass. The third goal of the study was to investigate the effect of testing plate diameter on the calculated modulus. Moreover, a comparison of the calculated modulus from ISRM formula, numerical modeling and calculated modulus from the actual PLT carried out at right abutment of the Bazoft dam site was another objective of the study. Finally, the effect of plastic strains on the calculated moduli in each of the loading-unloading cycles for three loading plates was investigated. The geometry, material properties, and boundary conditions on the constructed 3D model were selected based on the in-situ conditions of PLT at Bazoft dam site. A good agreement was achieved between numerical model results and the field tests results.

Keywords**—**Deformation modulus, numerical model, plate loading test, rock mass.

I. Introduction

THE static deformation modulus of rock mass is a key parameter in the design of geotechnical structures like dams, tunnels, and caverns. This parameter represents the deformational behavior of rock mass in response to any loading and unloading. Empirical relationships which relate the rock mass deformation modulus E_{rm} to different rock mass classifications, are estimations which can be used in the preliminary stages of the design [1]. Furthermore, these relations do not indicate modulus anisotropy in different directions. Because of the effect of discontinuities in rock mass, the modulus obtained from laboratory tests for intact rock does not represents the in-situ deformational behavior of the rock mass. Therefore, in-situ tests are typically more reliable procedures and employed in important rock engineering projects.

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Among these tests, the PLT is of a specific importance, because this test includes a large volume of rock mass to be loaded. The load is applied by two circular steel plates to the surface of rock mass in opposite directions in a test gallery. Displacements are measured in a borehole beneath the plates. Then elasticity theory (Boussinesq relation) for semi-infinite medium is used to calculate the deformation modulus. This is the suggested method by International Society of Rock Mechanics (ISRM) to calculate the deformation modulus of the rock mass [2].

Due to the fact that the employed assumptions in the ISRM method are not thoroughly applicable to real conditions, the validation of calculated modulus using this method is questionable. In this method, the rock mass is assumed to deform as a continuous, homogenous, isotropic, and linear elastic material with a semi-infinite geometry [2]. Typically, these situations are not met in test galleries in jointed rock masses. Furthermore, in every loading-unloading cycle, some plastic deformations occur within the rock mass that violate the elastic behavior of the media. In this paper, the PLT conducted at Bazoft dam site in Iran are simulated numerically to demonstrate the governing test mechanisms and how to interpret data for the determination of deformation modulus. Moreover, the effect of plate diameter, location of anchors and the amount of plastic strains in each loading-unloading cycle on the values of moduli were investigated.

II. PLT Technique Principles

PLT is based on applying cyclic load to rock mass or soil in small tunnels, adits or at ground surface and measuring displacements within the rock mass or at surface. In rock engineering practices, two areas, each approximately 1 m in diameter are loaded simultaneously using jacks positioned across the tunnels. Deformations of rock mass are measured within a borehole beneath each loading area (see Fig. 1). Two types of PLT exist: “flexible plate loading method” which is associated with uniform stress boundary conditions and “rigid plate loading method” which implies uniform displacement boundary conditions. Using a stiff plate is more suitable when testing soil or soft rock. In hard rock masses, if the plate diameter is large (i.e. 1 m or more), then the plate may not have adequate stiffness and makes the stress distribution complicated. So, the plate stiffness should be at least 100% more than the stiffness of the rock mass [3].

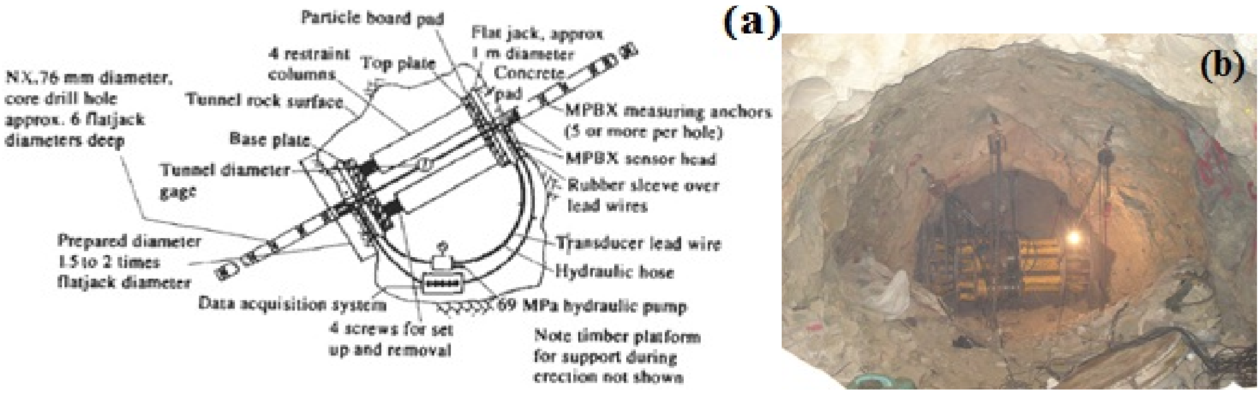

Fig. 1 PLT setup, (a) ISRM suggested method [2], (b) Bazoft dam site

Incremental and cyclic loading provide data for the calculation of loading and unloading deformation moduli. Based on elasticity theory, deformations measurements for various load cycles are utilized to compute the deformation moduli. Depending upon the type of the test, i.e. rigid or flexible loading, the following equations are used, respectively [4]:

$$w = \frac{aq\left(1+\vartheta\right)}{2E}\left[2\left(1-\vartheta\right)cot^{-1}\left(\frac{z}{a}\right)+\frac{az}{z^{2}+a^{2}}\right] \quad (1)$$

$$w = \frac{zq\left(1+\vartheta\right)}{E}\left[1-z\left(a^{2}+z^{2}\right)^{-1/2}\right]+\frac{2q\left(1-\vartheta^{2}\right)}{E}\left[\left(a^{2}+z^{2}\right)^{1/2}-z\right] \quad (2)$$

where w is the vertical displacement, a is the radius of loading plate, q is the applied stress, E is the modulus of elasticity, ϑ is the Poisson's ratio, and z is the depth of deformation measurement along the loading plate axis.

III. Fundamental Errors in PLT Data Interpretation

There are several parameters influencing test results that can lead to an inappropriate calculation of the deformation modulus. These parameters can be classified into two major categories [4]: "operational factors" directly related to the quality of the test such as the resolution of the measuring instruments, quality of site preparation and proper installation of the test apparatus. Blast damage and rock disturbance around test gallery are important examples of this category. In this case, the effect of blast damage will vary with several features, such as rock properties, amount of explosive used, number of holes detonated at the same time, quality of site preparation, etc. [1].

The second source of errors comes from theoretical aspects which correspond to incompatibility between theoretical basis test assumptions, and actual conditions of the rock mass. ISRM assumes rock masses as homogenous, isotropic and continuum material with linear elastic behavior which are not met in rock masses. Also, the effect of local stress state is not considered in calculations. In addition, these equations require prior knowledge of Poisson's ratio of the rock mass as an input parameter. Estimation of this parameter at a rock mass scale is very difficult.

Another typical problem in the interpretation of PLT results, using ISRM suggested method, is the dependency of modulus magnitude to the depth of displacement measurement in the borehole. Because of this fact that load is measured just at the surface of the plate and displacements are measured at different depths within the rock mass, there is an apparent trend of increasing moduli with depth of deformation measurement for a given test. In some cases, this may lead to calculate rock mass moduli much greater than the actual of modulus of rock mass.

IV. Numerical Simulation of PLT

The first objective of this study was to numerically simulate the PLT and look in to mechanism involved in the test. Moreover, the effects of plate diameter and depth of displacement measurements on the calculated moduli were evaluated. Accordingly, a sophisticated 3D model of the test conditions was constructed. The advanced 3D finite difference code FLAC3D was used for the modeling. The code is a developed by ITASCA consulting Inc. and is equipped with sophisticated mesh generation, material behavior modeling, etc. capabilities [5].

A. Numerical Modeling of Bazoft Dam PLT

The Bazoft dam and hydropower project is located 200 km south-west of Shahrekord, Iran. Bazoft dam will be a double curvature concrete dam with over 180 m height. Based on conducted geological and geotechnical assessments, the rock mass of the right abutment consists of massive limestone. According to the conducted laboratory and in situ tests, the physical and mechanical properties of intact rock and rock mass for the right abutment were determined and summarized in Table I. Two exploration galleries excavated in the right abutment and in situ PLT were carried on in these galleries. The calculated Poisson's ratio and RMR for the rock mass were 0.3 and (68-78), respectively [6].

To model the PLT numerically, a simplified 3D model of the right abutment of the Bazoft dam and its test gallery was constructed. The geometry and dimensions are as those of the Bazoft dam site. Fig. 2 illustrates the 3D view of the constructed model of right abutment and the lower test gallery. Fig. 3 shows a close-up view of the constructed numerical model of jacking test location and the measurement borehole. Displacement measurement points are located in different depths along the borehole.

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF THE BAZOFT DAM RIGHT ABUTMENT ROCK [6]

Materials \ Properties	Density (gr/cm^3)	UCS (MPa)	Elastic/deformation Modulus (GPa)	Cohesion (MPa)	Friction (deg)
Intact rock	2.62	48.2	14.2	2.8	41
Rock mass	2.6	7.3	9.6	2.1	42

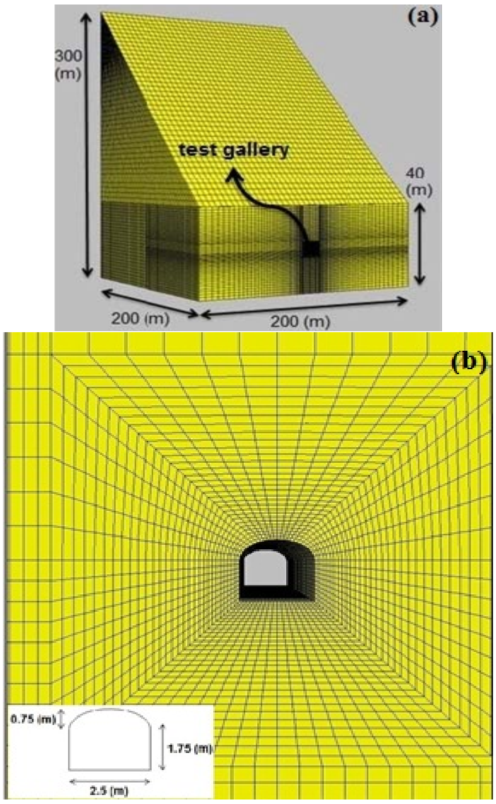

Fig. 2 3D view of the constructed model: a) right abutment of Bazoft dam, b) test gallery

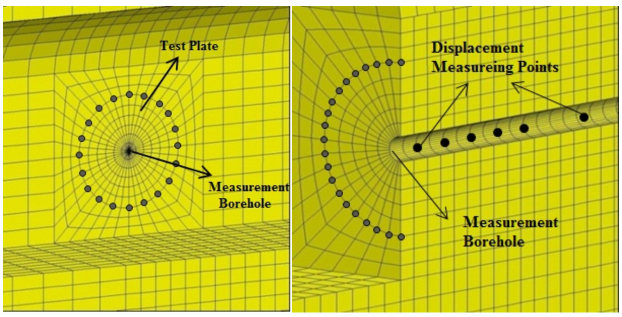

Fig. 3 3D view of horizontal plate loading test and measurement borehole intest gallery

With regard to the conditions and nature of the plate loading test, the constitutive model for material behavior was assumed to be plastic Mohr-Coulomb model. Due to plastic deformation associated with load-unload cycles which affects the slop of stress-strain curve (deformation modulus), this model selected for the PLT simulation. The failure envelope for this model corresponds to a Mohr-Coulomb criterion (shear yield function) with tension cutoff (tension yield function) [5]. The geometry, material properties and boundary conditions used in the analysis were selected based on Bazoft dam site. To obtain the load-displacement curve, five load-unload cycles were carried out. At the last cycle, the rock mass loaded up to 25 MPa. The simulated circular loading area had a diameter of 80 cm which is equal to the diameter of plates used in the actual test.

V. SIMULATION RESULTS

In order to understand the mechanism of PLT, three PLT were simulated according to the location of actual in situ tests conducted in Bazoft dam right abutment. To compare the test results with numerical simulation, the load-displacement curves were calculated along ten measuring points within the rock mass and below the loading plate. Fig. 4 shows the load-displacement curve of a simulated test at a point located 60 cm beneath the loading plate.

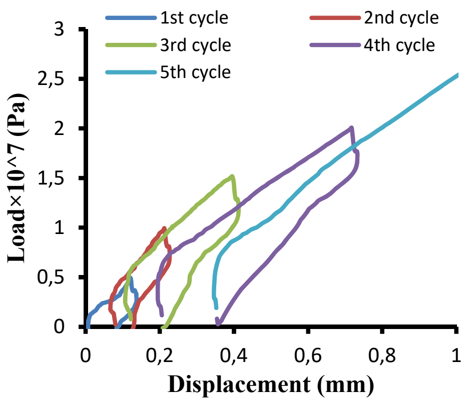

Fig. 4 Load-displacement curve determined at 60 cm below the loading plate

A. Determination of the Deformation Modulus Using Stress-Strain Curve

In order to calculate the deformation modulus, a linear strain variation was assumed during loading-unloading cycles. Fig. 5 shows a stress-strain curve of a measurement point at the depth of 60 cm beneath the plate. The slope of each loading and unloading cycles represents the loading and unloading deformation modulus, respectively.

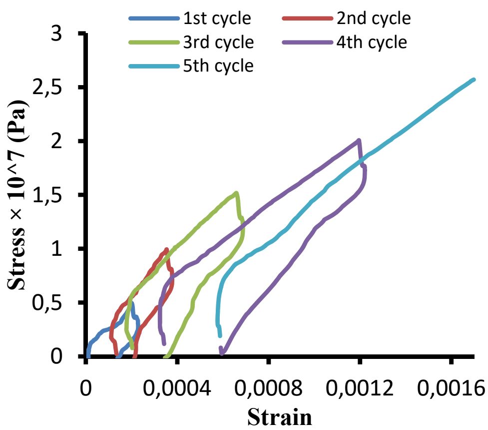

Fig. 5 Stress-strain curve determined at 60 cm below the loading plate

A linear fit function was used to approximate the slope of each curve. Note that, these linear functions should be fitted in the linear part of the curves. As shown in all of above curves, the beginning part of each loading or unloading process is approximately vertical, i.e. the modulus is infinitive in these parts. This phenomenon, which is observed in both field and numerical data, is not the behavior of rock mass. This is because of a delay between loading and unloading step in each cycle. At the beginning of unloading, due to a time lag between loading and unloading phases and with regard to the distance between plate and the measurement points, stress relaxation associated with plate movement at the beginning of unloading process is not transferred to the measurement points instantaneously. So, displacement contours near plate move back to the direction of the plate movement (unloading direction), but displacement contours far from plates move in the opposite direction (loading direction) due to the loading process at the previous cycle. There is a transitional zone with zero displacement contours between these two areas (Fig. 6). This transitional zone causes vertical slope in the beginning parts of all unloading cycles. Similarly, when the unloading process is finished, and a new loading cycle is initiated, this phenomenon causes a vertical slope at the beginning part of the loading curves. Linear fit functions for five load-unload cycles at the depth of 60 cm below loading surface are shown in Fig. 7.

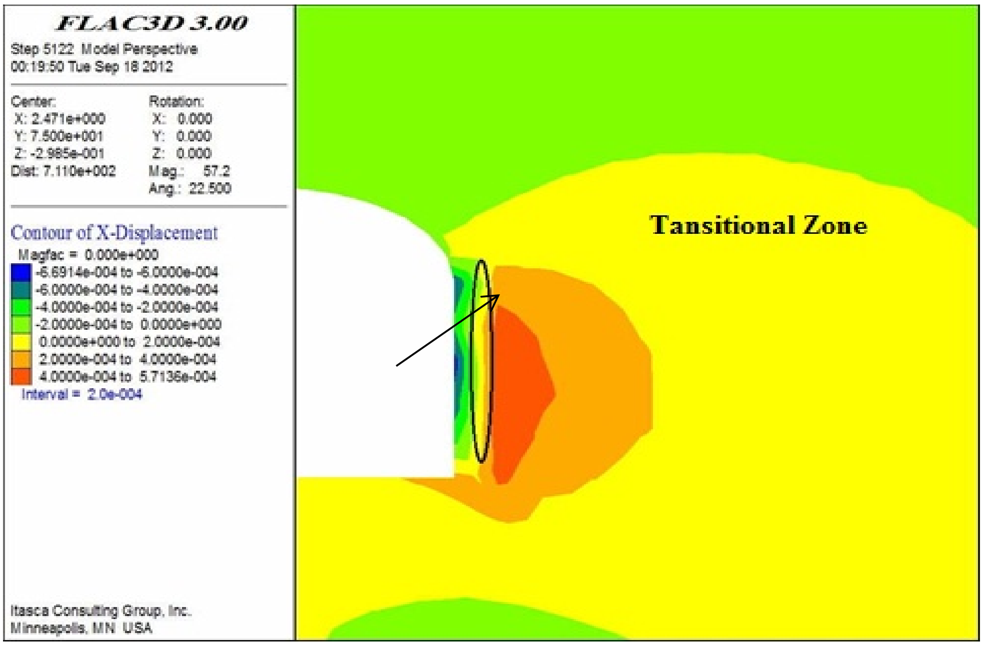

Fig. 6 Displacement contours at the beginning of unloading phase.

Unal [7] suggested a new method for the determination of rock mass modulus based on least square method. This method postulates an advantage to use all displacement measurements in modulus calculation, but as mentioned earlier, some portion of the displacement measurements should not be taken into account for modulus calculations.

B. The Influence of Measurement Depth on Calculated Deformation Modulus

Because of this fact that load is measured just on the surface of the plate and displacements are measured at varying depths into the rock mass, there is an apparent trend of increasing moduli with depth of deformation measurement for a given test. In some cases, this will cause significant error such that calculated rock mass moduli are much greater than that of the

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intact rock. Fig. 8 shows the relation between calculated modulus and measurement depth. It is observed that at a depth of equal to plate diameter, calculated modulus is greater than that of the intact rock. This is the maximum depth of measurement that should be taken into account for rock mass deformation calculations. The main problem is to determine the optimum depth of measurement. For this purpose, a PLT with three different plate diameters of 60, 80, and 100 cm were simulated. Although there are several parameters that influence the maximum measurement depth, it is observed that maximum measurement depth is approximately equal to the plate radius. In the subsequent parts, the results of PLT with three different plate diameters are presented.

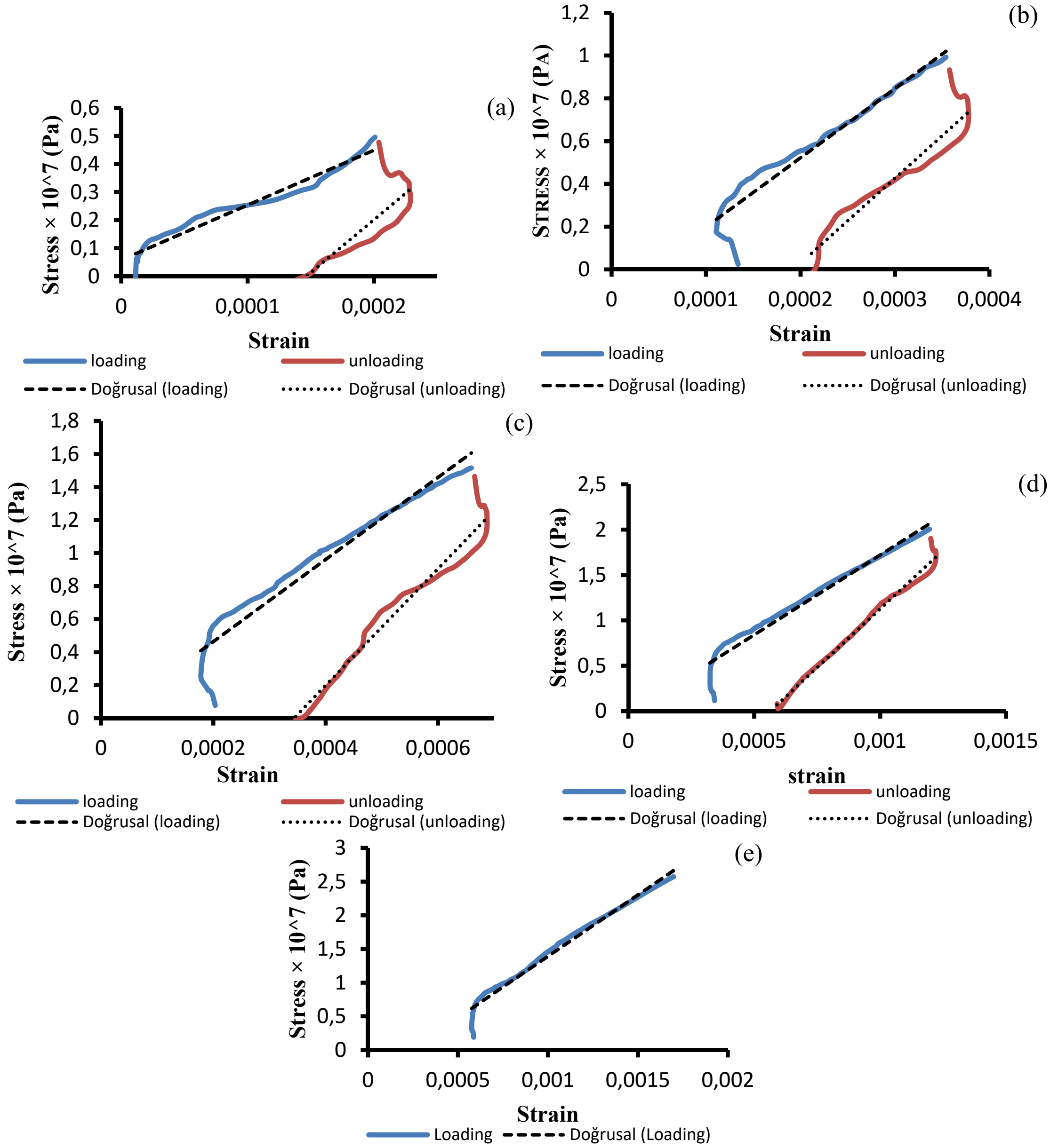


Fig. 7 Linear fit function used for 5 load-unload cycles at depth of 60 (cm), (a) 1st cycle, (b) 2nd cycle, (c) 3rd cycle, (d) 4th cycle, (e) 5th cycle

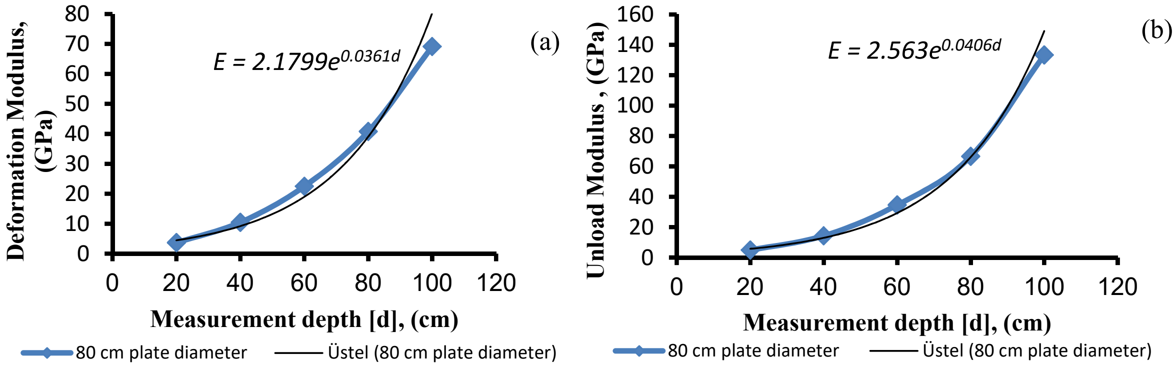


Fig. 8 The relationship between deformation modulus and measurement depth, (a) loading modulus (b) unloading modulus

C. The Influence of Loading Plate Diameter on Measured Deformation Modulus

A PLT with three different diameters was simulated to investigate the effect of plate diameter on calculated rock mass modulus. The results are depicted in Fig. 9. It was concluded that larger plate diameters result in smaller values of moduli. According to simple linear Hooke relation [8]:

$$E = \frac{\sigma}{\varepsilon} = \frac{\sigma l}{\delta l} \tag{3}$$

The displacement (δl) for larger diameters should be greater than that of smaller diameters in the same load at the surface of the plate. To justify this, the stress at measurement points investigated and it was observed that for the same load at the surface of the plate, the stress at an exact measurement point for larger plate diameters is greater than the stress in smaller plate diameters (Fig. 10). This extra stress produces larger displacements at the measurement point and consequently leads to a reduction in the magnitude of modulus. Fig. 9 shows the variation of calculated loading and unloading modulus with three different diameters.

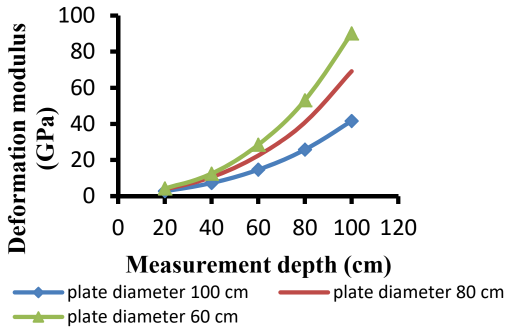
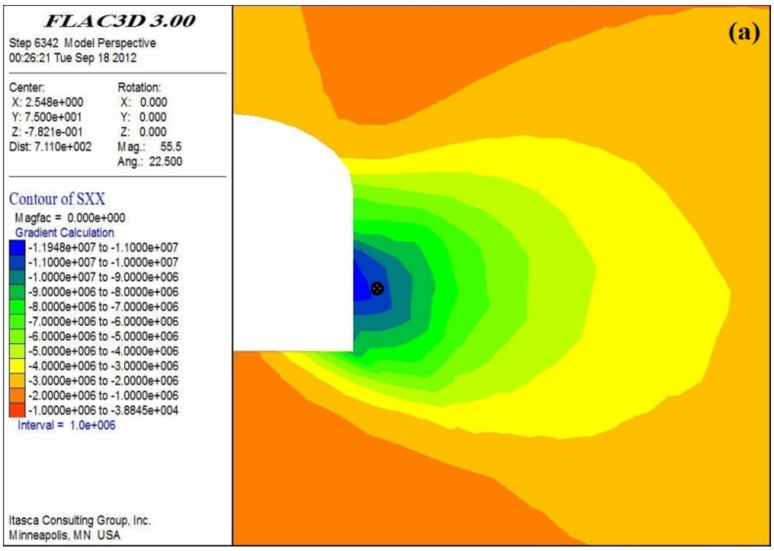


Fig. 9 The effect of plate load diameter on deformation modulus variation as a function of depth



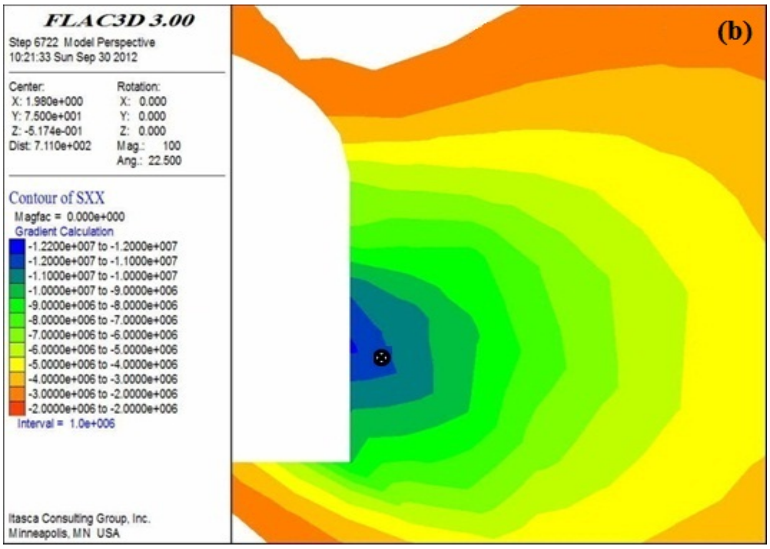


Fig. 10 Induced stress state in the direction of loading for two loading diameters, (a) loading diameter of 80 cm (b) loading diameter of 100 cm

VI. The Effect of Plastic Strains on the Values of Deformation Moduli in Loading-Unloading Cycles

When a sample of intact rock is loaded uniaxially up to a given stress level, linear elastic behavior is observed. The slope of stress-strain curve at this zone represents the elastic modulus of the rock. By increasing the amount of stress, some plastic deformation is occurred. Propagation of micro-cracks and creation of shear bonds within the rock is the major causes of plastic strain [8]. Creation of plastic strains will reduce the stiffness and consequently the deformation modulus of the rock [8]. To understand the effect of plastic strains in each load-unload cycles on the calculated modulus, the values of plastic strains for all of the test cycles were calculated numerically. The results for three evaluated plate diameters are illustrated in Figs. 11-13. As can be seen from figure, by increase in plate diameter, the amount of plastic strains at a given measurement point is increased and leads to the reduction of the rock mass stiffness and consequently deformation modulus. Figs. 11-13 show linear variation of plastic strains as a function of loading diameter.

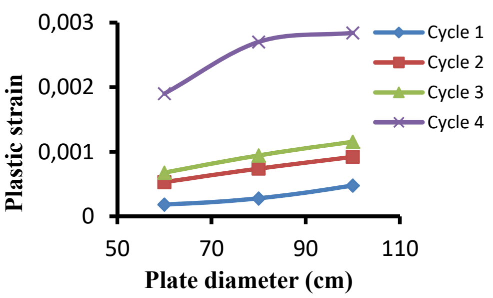


Fig. 11 Plastic strain versus plate diameter curves at a depth of 20 cm beneath the plate

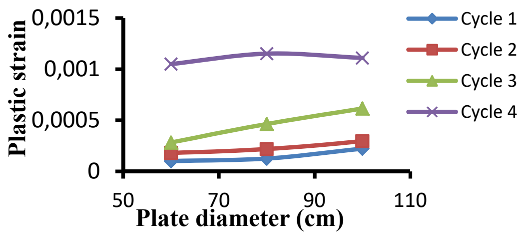


Fig. 12 Plastic strain versus plate diameter curves at a depth of 40 cm beneath the plate

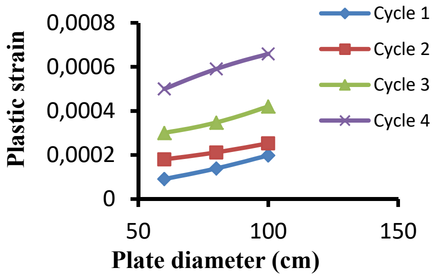


Fig. 13 Plastic strain versus plate diameter curves at a depth of 60 cm beneath the plate

VII. Comparison of Modeling Results with ISRM Suggested Method Results and in situ Field Tests

In this part, a comparison between the ISRM suggested method (based on elasticity theory), the conducted 3D numerical modeling, and the in-situ field test results at the right abutment of Bazoft dam site was provided. Two major objectives were the focus of this comparison. The first goal was to validate the numerical results of the conducted 3D modeling for PLT simulation. The second objective was to compare the calculated modulus from elasticity relations (ISRM method) and plastic Mohr-Coulomb model. Fig. 14 shows the relationship obtained between the calculated modulus and measurement depth from ISRM method, actual test data, and numerical modeling. It is observed that ISRM method determines larger modulus values than other modulus determination methods. Also, it can be seen that for measurement depths of up to the plate radius, there is not a significant difference between numerical and field test results.

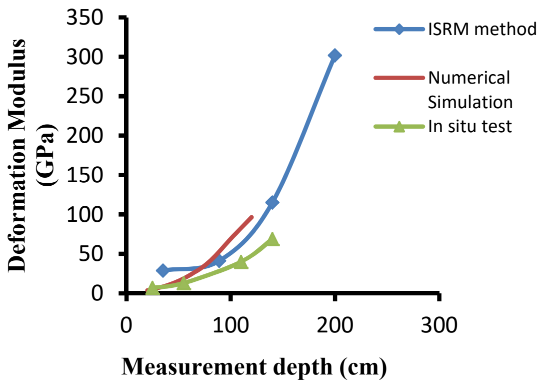


Fig. 14 A comparison of calculated deformation modulus against measurement depth for various methods

VIII. Conclusions

The validity of determination of the rock mass deformation modulus using PLT conducted at Bazoft dam project site was evaluated numerically. The 3D numerical simulation with Mohr-Coulomb constitutive model showed good agreement with field test results.

The analysis showed that the optimum measurement depth for rock mass modulus calculation is approximately equal to the plate radius. Also, it was concluded that larger plate diameters result in smaller values of the moduli. By measuring the plastic strains in each of the load-unload cycles, it is shown that by increasing the plate diameter, the amount of plastic strains for an exact measurement point will be increased leading to the reduction of the rock mass stiffness and consequently deformation modulus. According to the obtained results, it is concluded that the initial vertical parts of the load-displacement curves or consequently stress-strain curves (vertical slope) are due to a time lag between loading and unloading phases and also distance between loading plates and measurement points. Therefore, the vertical parts should not be taken into account in the determination of rock mass modulus.

According to the fundamental errors in the assumptions of elasticity theory which is used by ISRM suggested method in the interpretation of test results, it is concluded that the best way for modulus calculation is the depiction of stress-strain curves and measuring the slope of these curves.

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