**Geomechanics and Engineering**, *Vol. 26, No. 1 (2021) 63-75*
https://doi.org/10.12989/gae.2021.26.1.063

# Deformation modulus of rock foundation in Deriner Arch Dam

Davut Yılmaz[1a], Ahmet C. Altunışık*[2] and Süleyman Adanur[2b]

*[1]Department of Civil Engineering, Ankara Yıldırım Beyazıt University, Ankara, Turkey*
*[2]Department of Civil Engineering, Karadeniz Technical University, Trabzon, Turkey*

*(Received April 3, 2021, Revised June 14, 2021, Accepted June 24, 2021)*

**Abstract.** Civil engineering structures such as gravity concrete dams, arch dams, pressure tunnels, foundations of high-rise buildings and bridges are generally founded on rock. Design and performance of these structures are highly dependent on the deformation modulus of the rock mass so that expected deformations and/or differential settlements stay within the tolerable limits of the structures. In situ deformation modulus measurements of rock masses are generally performed by using the borehole dilatometer and plate loading tests in Turkey. The diameter of plate loading test device is 30-35 cm. Tests are performed in small unlined tunnels excavated in different elevations of dam abutments. The deformations upon loading are measured on the loading plate in the plate loading tests. It is not possible to exclude the effect of excavation disturbed zone since deformations are not measured with these devices. Large diameter plate test system may have multiple level extensometers set in drill holes opened perpendicular to loading plates. Reading from these extensometers may be utilized to exclude the effect of disturbed zone close to surface together with stress distribution estimated by using elastic theory. There are several field test methods for determining deformation modulus and each method has its own shortcomings. The optimum methodology to correlate plate loading test results with corresponding in-situ deformation modulus values is to back-calculate deformation modulus by using settlements measurements during the construction of dam body. In this paper, Deriner Arch Dam settlements measured during the construction are used to back calculate deformation modulus. It is found that in situ deformation modulus is about two times higher than the average value determined by plate loading tests. This finding will have important effects on the depth of foundation excavations, concrete layers to fortify structure foundations and the amount of consolidation grouting.

**Keywords:** deformation modulus; excavation disturbed zone; plate loading test

## 1. Introduction

Deformability dictates the behavior of rock masses (Deere *et al.* 1968). The relationship between the applied load and the corresponding deformation designates deformability. The ratio of stress to measured strain; including both elastic and inelastic behavior is defined as the modulus of deformation of rock mass. Tests performed on small rock specimens in the laboratory generally do not give the deformability data representing the whole rock mass due to the natural discontinuities in the rock mass. Smaller specimens have fewer discontinuities. Thus, a smaller specimen may produce a higher modulus values. The gap in between laboratory results and rock mass behavior not only depends upon the fracture frequency but also weathered and soft zones in the rock mass.

There are various empirical methods for predicting the overall deformation data of a rock mass from the results of laboratory tests on small samples (Coon and Merritt 1970, Bieniawski 1978, Serafim and Pereira 1983, Palmström and Singh 2001, Hoek and Diederichs 2006). These methods can be used for preliminary design purposes, however, it need to be verified by in-situ tests. Small size specimens should not only be taking into account for the determination of deformation modulus but also in situ testing of rock under natural environmental conditions as far as stress conditions, natural discontinuities and variations in rock characteristics with distance are concerned.

In-situ tests are needed for major projects, like dams, to determine rock mass deformability although the tests are expensive and time consuming. However, there are many controversial issues concerning in-situ tests such as the effect of the excavation disturbed zone on measured strains and the diameter of loading plate (Deere *et al.* 1968, Serafim and Guerreiro 1968, Dodds and Schroeder 1974, Palmström and Singh 2001, Angın 2016, Zhang *et al.* 2018, Lee 2019). Not only do the diameter of the loading plate need to be increased in highly stressed rocks in deeper zones, but also displacements with depth from the loading plate must be measured to observe their change with corresponding stresses. The increasing of the diameter of the plate cause to increase the capacity but then it may not be possible to carry the test machine by workers since it becomes too heavy to transfer it to remote places where there is no road.

Since heavy test devices require access roads to carry test equipment, this creates another problem because there are no roads, no materials handling equipment, and no help of manpower at the early stages of the investigation (Wallace *et al.* 1970). Deformation modulus data obtained by Borehole Lateral Load Test (LLT) in boreholes are only

---

*Corresponding author, Professor
E-mail: ahmetcan@ktu.edu.tr
[a]Assistant Professor
[b]Professor

ISSN: 2005-307X (Print), 2092-6219 (Online)

used for roughly estimating deformation modulus and not effectively used for detailed design (Ito *et al.* 2007). Therefore, an effective procedure to check validity of the test results is to back calculate deformation modulus using measurements taken during dam construction.

There are a limited number of studies in the literature dealing with the numerical and experimental assessment of deformation modulus of rock masses in arch dams. Palmström and Singh (2001) compared the in-situ test and indirect estimated results to determine the deformation modulus of rock masses. Kayabaşı *et al.* (2003) indicated a comparative study about the estimation of the deformation modulus of rock masses. Galera *et al.* (2005) evaluated the deformation modulus of rock masses by comparison of pressuremeter and dilatometer tests. The feasibility of columnar jointed basalt used for high-arch dam foundation is published by Wei *et al.* (2011). Zhou *et al.* (2014) showed the influence of deformation modulus of fault rock masses on dam foundation stability. Agharazi *et al.* (2015) presented a case study about a numerical assessment on plate-loading test results using equivalent-continuum model for the Bakhtiary Dam. Fat *et al.* (2015) proposed the excavation optimization design for foundation surface in Xiluodu arch dam on the basis of feasibility study. Li (2017) conducted an experimental study on the whole deformation process of arch dam rock foundation. Liu *et al.* (2017) evaluated the long-term stability of an arch dam with time-dependent deformation reinforcement theory. Shen *et al.* (2017) discussed the some main problems in rock mass utilization for the foundation surface of high arch dams in medium or high geo-stress regions. Wu *et al.* (2019) suggested approach for deformation modulus mechanism of super-high arch dams. Qi *et al.* (2019) correlated the deformation modulus and wave velocity of the Wudongde dam foundation rock mass. Aksoy *et al.* (2020) studied the change of elastic rock mass with time under constant load. Tan *et al.* (2020) researched on the deformation and failure pattern of rock masses in dam foundations. Tayarani *et al.* (2020) predicted to deformation modulus of rock masses by combination of artificial neural networks and numerical modeling. This study was carried out in order to contribute to the deficiency in the related field.

For this purpose, in this paper, Deriner Dam settlement measurements were used and compared with plate loading test results. Before back calculating deformation modulus and evaluating the test results, the depth of Excavation Disturbed Zone are reviewed in Section 2 and the stress change under loading plate with depth is discussed. The effect of consolidation grouting are evaluated in Section 3. Section 4 are summarized the back calculation of deformation modulus using settlement measurements. Then it is commented the discrepancy between the back calculated and measured test values.

## 2. Excavation disturbed zone

A typical load-deformation curve for plate load test is shown in Fig. 1. This figure shows the dependability of pressure and deformation for four cycles of loading and unloading. The maximum deformation measured at the fourth cycle is called as total deformation and is labeled $\delta_d$. $\delta_e$, which is called as elastic deformation, represents the returning part of deformation after unloading. The difference in between $\delta_d$ and $\delta_e$ is named as the permanent deformation $\delta_t$. The modulus of deformation, $E_d$, is calculated by using total deformation $\delta_d$. If $\delta_e$ is used in calculating the modulus, it is as called the modulus of elasticity and is marked $E_e$.

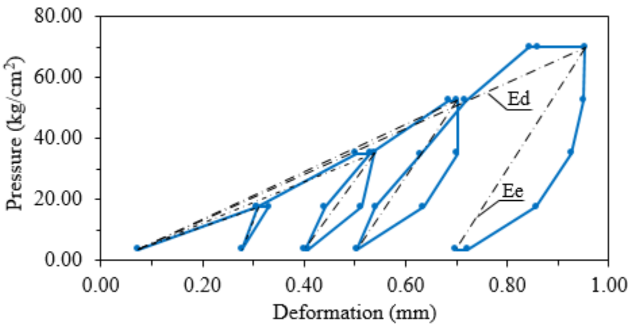


Fig. 1 Load-deformation relationship for a plate loading test in Gallery TC-2(2) in Yusufeli Arch Dam (DSI 2015)

Fig. 2 Actual photo taken during the plate loading testing at Yusufeli Dam site (DSI 2015)

Fig. 2 shows an actual photo taken during the tests conducted at the Yusufeli Arch Dam. Yusufeli Arch Dam is being constructed at about 50km upstream of Deriner Arch Dam. Both Deriner and Yusufeli Arch Dams are arch dams having heights of 249 m, and 270 m, respectively. Same plate loading test devices and procedures were used in both dams during feasibility and design stages. A schematic drawing of the plate loading test executed in Yusufeli Dam site was shown in Fig. 3. The measurements of deformations at a depth behind the plate jacking tests are important to determine the rock mass modulus unaffected by blasting of rock to open test gallery and by relief of in-situ stresses. The decrease in the ratio of elastic deformation to total deformation at the peak stress close to the face of the adits or loading plates was regarded as a reduction in rock quality due to excavation disturbed zone (Hall *et al.* 1974, Rocha 1970, Serafim 1964).

Hall *et al.* (1974) reported that the surface gages were highly affected by near surface fractures created by excavation of the adits for the plate jack test results for Dworshak Dam site. A total of 24 plate jack tests were performed at the adits opened in the abutments. The tests

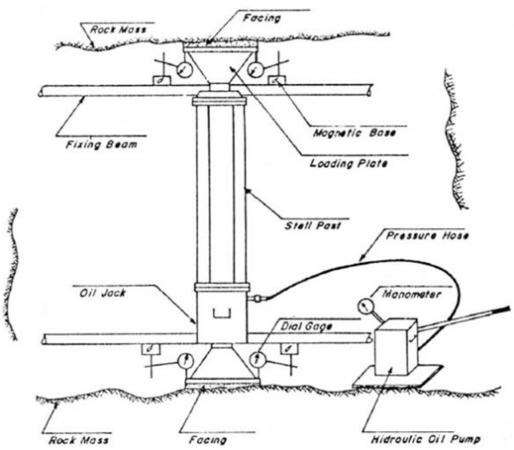


Fig. 3 A schematic drawing of the plate loading test executed in Yusufeli Dam site (DSI 2015)

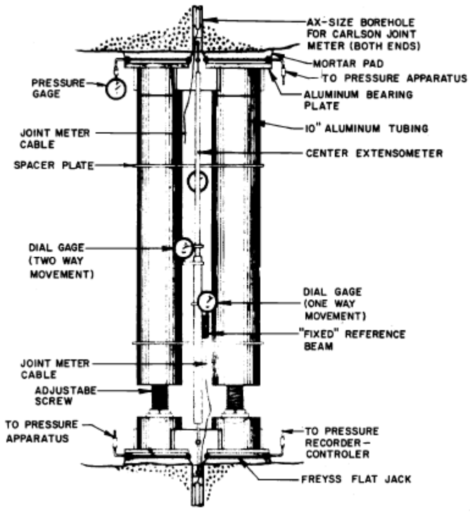


Fig. 4 Plate jacking test system (Shannon and Wilson. Inc. (1964)

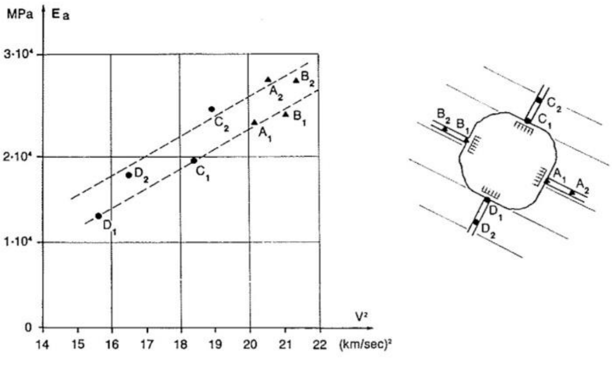


Fig. 5 Plate bearing tests in exploratory adit. Correlation between deformability modulus (E) and square of sonic velocity (V2) measured at the depths of 7 cm and 50 cm from loading surfaces (Oberti *et al.* 1979, Oberti *et al.* 1986)

were performed using 34-inch diameter Freyssinet pressure pads as shown in Fig. 4. It is concluded that modulus determined using the results of surface gage readings seems too low to be used for representing the dam foundation. Therefore, a conclusion was reached that the best way to determine deformation modulus of the foundation was to use the buried gages. The corresponding stress distribution with depth can be determined by using elastic theory. The deformation modulus is determined from the pressure deflection relations with depth by using corresponding measured displacements.

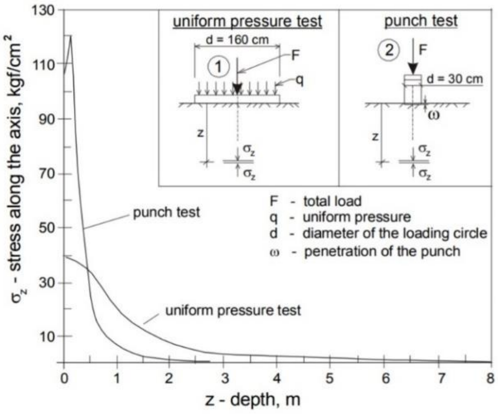
Several plate loading tests were executed in the adits in the directions parallel and normal to stratifications to determine the deformation modulus of dam foundation for Ridracoli Dam (Oberti *et al.* 1986). Pressures up to 6MPa were uniformly applied by flat jacks having a diameter of 60cm. Extensometers installed inside 7.5cm diameter boreholes drilled at the center of the loading plate were used to measure the deformation. Two of the plate jacks were set parallel to stratification while the other two were placed perpendicular to layers (Fig. 5). Sonic velocity (V) and sonic logging tests were performed inside the boreholes drilled in the center of the loading so that they could be compared with deformation moduli values E measured by using plate bearing tests. Velocity measurements were made by receivers installed at depths of 7 cm and 50 cm surfaces to determine excavation disturbed zone around the adits. It was found that loosened zone extends to about 500 mm (Oberti *et al.* 1979, 1986).

Deformability moduli $E_d$ acquired by using plate bearing test were correlated with square of sonic velocity measurements performed inside the boreholes at different depths from loading surface (7 cm and 50 cm). The correlation between E and V shown in Fig. 5 indicates that lower values of E and V close to the face of the adit are due to the excavation disturbed zone created during opening of the test gallery (Oberti *et al.* 1979, Oberti *et al.* 1986).

The zone which is highly affected by excavation of the test adit is called as Excavation Disturbed Zone (EDZ). The effect of EDZ on test results could be better understood by studying the stress change with depth as the diameter of the test loading plate changes. The ratio of the applied stress by flat jacks drops to approximately 25 percent below the depth exceeding three times the diameter of the loading plates as shown in Fig. 6 (Serafim and Guerreiro 1968, Palmström and Singh 2001). Therefore, it could be said that the stresses and corresponding displacements for 30-35cm flat jack are highly affected by 0.5-1.0 m thick zone right underneath the loading plate.

Studies on the EDZ reported by Barton (2007) show that the thickness of the EDZ could easily reach 0.5-1.0m and even beyond. It depends upon the type of excavation, the type of the rock, joints, bedding planes in the rock, and stress condition around the adit. Therefore, the plate loading tests having 30-35cm diameter are highly affected by the thickness of the EDZ zone. This is the main reason why first loading cycle in plate loading in Turkey have been omitted by some practitioners in evaluating the results of plate loading tests. In fact, the pressure applied in the first cycle can close the cracks created by the EDZ as it could be seen by observing concave up deformation line in the test shown in Fig. 1. Therefore, excluding the deformations measured in the first cycle for the determination of the deformation modulus have also been supported by Palmström and Singh (2001).

It is well known that excavation for the foundation



| DEPTH (z) | STRESSES ($\sigma_z$) | | |
|---|---|---|---|
| | Test results of Serafim and Guerreiro | | Assumed for the 0.8 m loading plate of the PJT |
| | uniform pressure test | punch test | |
| 0 m | 100% | 100% | 100% |
| 0.5 m | 85% | 121% | 80% |
| 1 m | 52% | 24% | 40% |
| 2 m | 37% | 1.5% | 15% |
| 4 m | 8% | 0.5% | 3% |

Fig. 6 The distribution of the stresses along beyond loading plates (Serafim and Guerreiro 1968, Palmström and Singh 2001)

disturbs the rock because of the two reasons. One of them is the effect of the blasting on surfaces close to the blasting agents. The thickness of this zone would not exceed a couple of meters under normal conditions. The other is the decompression created by excavation to reach to the base of the foundation. Seismic measurements made in Cine Dam (Eroglu and Yilmaz 2005) showed that the decompression zone could reach about 12-15 m perpendicular to the face of excavation. This is the reason why the depth of consolidation grouting executed underneath the dam foundations is usually equal to or less than 15 m (Tanchev 2014).

The depth of disturbed zone created either by the strains because of blasting or by decompression may have a limited impact on dam behavior for a couple of reasons. First, the base width of the dam is usually much larger than the depth of disturbed zone and/or the depth of decompression region. Second, this disturbed zone underneath the dam has a relatively small thickness when it is compared with the depth of pressure bulb created by the dam loading. Third, not only is the effect of the excavation disturbed zone ameliorated by shallow consolidation grouting and but also decompression due to excavation is compensated by the weight of the dam body during construction. Therefore, the excavation disturbed zone and decompression region has a small effect on the dam behavior. On the other hand, the surface gages in plate loading test were strongly affected by near-surface fractures especially for those tests having small diameter loading plates.

Deere *et al.* (1968) proposed a method for obtaining a weighted deformation modulus by taking into account the rock mass quality (RQD) and stress distribution underneath loading plate. They also suggested that deformation measurements be made with depth to consider excavation affected zone close to the face of excavation. If their advice is followed, it can be seen that excavation disturbed zone heavily affects the result of plate jacking test results as the diameter of the loading plate gets decreased to 30 to 35cm, which is the loading plate diameter used in Turkey by State Hydraulic Works of Turkey (DSI) and Electrical Research Institute (EIE). If the test results are directly used for determining deformation modulus of dam foundations, either the depth of excavation to reach foundation level will be increased and/or a layer of concrete cushion below dam body will be used like Yusufeli Dam (ARQ Consulting 2016). Besides there may be unrealistic consolidation grouting applications in the dam foundations to increase, so-called, low deformation modulus of the dam foundations.

Excavation disturbed zone and/or change of measured deformation modulus with depth below a dam foundation can be considered by calculating an equivalent foundation modulus (Scott 1990). Firstly, stress change with depth is calculated by using Boussinesq stress distribution below a rectangular area. Secondly, the ratio of calculated stress with depth to the foundation pressure is computed to the depth where boundaries of the stress bulb created by the dam loading are reached. Thirdly, modulus of each layer with depth is multiplied by the stress ratio calculated to find out the equivalent foundation modulus. By doing this approximation, it is possible to take into account the effect of excavation disturbed zone. It must be emphasized that as the foundation width increases, the effect of excavation disturbed zone on the equivalent deformation modulus gets decreased. Therefore, it is fair to say that plate loading tests having small diameters of 30-35 cm mostly measure the characteristics of the excavation disturbed zone. Therefore, there needs to be an adjustment as suggested by Palmström and Singh (2001) for the plate loading test to be used in the analyses, when the width of the dam, the depth of the stress bulb created below the dam and the consolidation grouting in the excavation disturbed zone are all considered. This suggestion is also verified by data gathered from the monitoring of Deriner Arch Dam in Turkey.

Other than those plate loading tests, the Elastmeter and the Dilatometer tests were performed in Deriner dam site right after construction works were tendered. Although there was a good agreement between the results from the Plate-Load and the Dilatometer tests, the discrepancy between the results of the Elastmeter tests and two other type of tests was very high. It was concluded that the Elastmeter test or the interpretation of its raw data might not have been performed properly. Therefore, the Elastmeter test results were not taken into account (Stucky Synthesis Report 1999). On the other hand, the determination of deformability of rock masses by using dilatometer tests has limitations not only because of the small volume of the rock mass tested but also cracks created due to tensile stresses in the borehole. Therefore, deformation modulus values determined by the dilatometer may be 2-3 times lower than the in-situ values obtained by using the plate bearing tests (Rocha 1974, Bieniawski 1978).

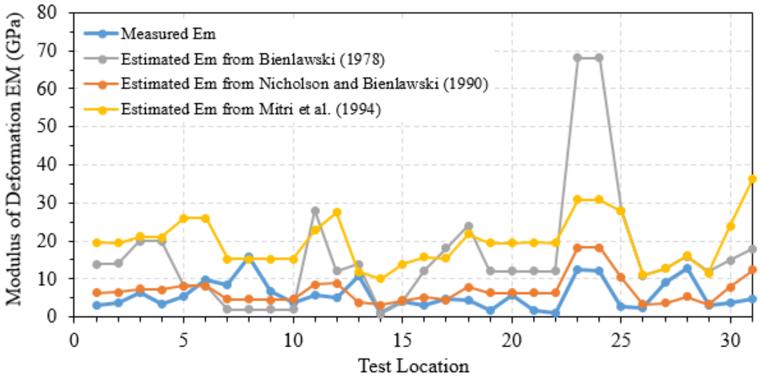


Fig. 7 Measured and estimated modulus of deformations for Deriner Arch Dam (Kayabasi *et al.* 2003).

Hence, all the tests utilized have number of disadvantages to be taken into account. These tests, seismic measurements, lab tests and empirical correlations all were considered to determine average deformation modulus as 9GPa to be used for the analysis although it was measured 5.1 GPa by EIE (Fig. 7) (Kayabasi *et al.* 2003). However, settlement measurements during the construction and impounding of the dam create an excellent opportunity to check the validity of assumptions and evaluations.

Deriner Dam monitoring during construction presents an excellent opportunity to back calculate deformation modulus since zero measurements were done after dam body was raised enough to compensate the effects of decompression due to dam foundation excavation. Besides that, zero measurements were executed during the time when dam body concreting works were halted about one year due to financial reasons. This created opportunity for creep deformation to take place. The dam was raised enough before first settlement readings to calculate additional loading on the foundation between zero and first readings without taking into account loads basically created on the abutments in higher elevations.

On the other hand, there was no consolidation grouting before zero measurements to complicate back calculation of the deformation modulus. There were also enough data to show that consolidation grouting effects could be neglected after zero measurements since there were no decrease in lugeon values in water pressure tests and no considerable change in grout intakes when compared with values before grouting. Therefore, before making any assessment, the effect of consolidation grouting made after zero readings was evaluated.

## 3. Effect of consolidation grouting

Another important issue related to the modulus of deformation of the rock masses is the effect of consolidation grouting in enhancing the deformation modulus. Before evaluating the effect of consolidation grouting, the time of consolidation grouting, the time of the initial (zero) readings, the extent of decompression zone due to the effect of foundation excavation, the time and the effect of dam dead loading, groutability of the rock mass by considering the Lugeon Tests results are all need to be taken into account.

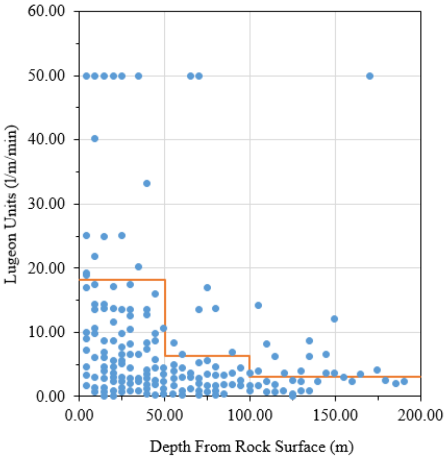


Fig. 8 Profile of the Lugeon values, for the entire Deriner dam site, as a function of depth (Stucky Synthesis Report 1999)

Zero readings were taken on April 20th, 2007 after concrete works for the dam body had been temporarily halted almost for five months. No consolidation grouting was executed before zero readings. The relaxation zone created by removing of the rock masses by excavation to reach foundation level and by blasting during this excavation caused some existing cracks or fissures to open up or new ones to be created. Some of the cracks or fissures which reduce the deformation modulus are closed by the loading of the dam dead weight as the dam was raised. This effect is similar to that of the first cycle or cycles during the plate loading tests. In other words, recompression of the rock mass was achieved by the preceding loading of the rock mass with dead weight of the dam body before consolidation grouting applied for the purpose of filling-in of the cracks and fissures with cement.

Water Pressure Tests (WPT, Lugeon type) are generally performed on the dam axis to determine the water tightness of rock masses during geological investigations. Water take measured per minute per unit length of the borehole under 1MPa water pressure corresponds to the Lugeon Units (1 [LU] = 1[l/min/m]). The Lugeon Units near unexcavated ground surface are generally much larger than those in deeper zones as shown in Fig. 8 for Deriner Arch Dam.

Much larger Lugeon Values in the upper 50 m are

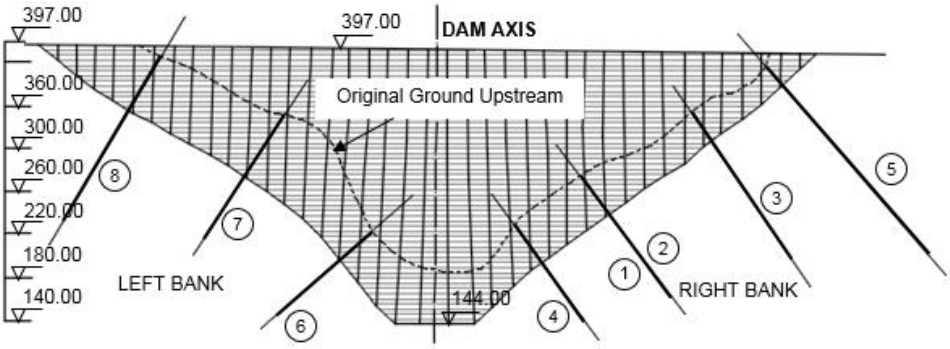


Fig. 9 Final foundation elevations together with natural ground levels for Deriner Arch Dam. (Deriner Dam Application Design Drawings, various dates)

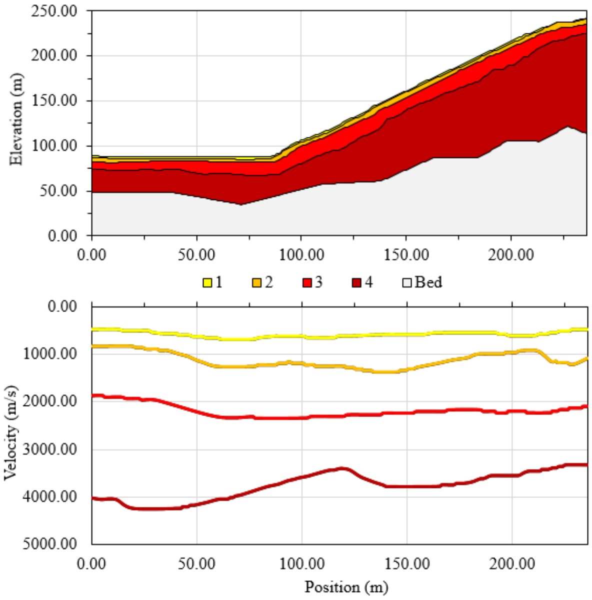


Fig. 10 Seismic velocity measurements at Cine Dam after foundation excavations (Eroğlu and Yılmaz 2005)

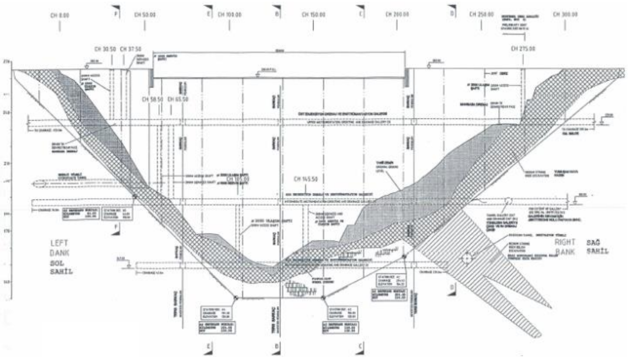


Fig. 11 Final foundation elevations together with natural ground levels for Cine Dam (Geoconsult, GIBB and ARQ, 2000)

observed because of the open fractures created mainly by the relaxation during valley forming process in the geologic time. But these types of cracks are not only decreased in numbers due to increase in distance from valley surface but also get closed because of the stress increase in the deeper zone of the ground. On the other hand, rock quality increases with depth. Therefore, the Lugeon Units drop with

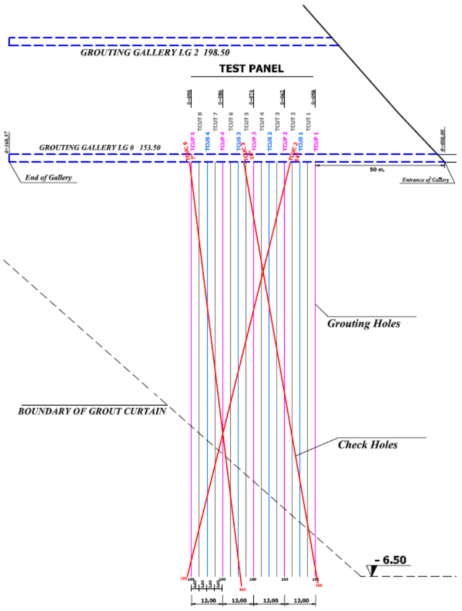


Fig. 12 Grout curtain test panel in the left bank of Deriner Dam executed in the gallery LG 0 -153.50, the bottom gallery at the foundation level (Ünal 2007)

Table 1 Specific injection grout consumption (Deere 1976)

| | |
|---|---|
| Very High | >400 |
| High | 400-200 |
| Medium High | 200-100 |
| Medium | 100-50 |
| Medium Low | 50-25 |
| Low | 24-12.5 |
| Very Low | <12.5 |

depth. Much of the natural rock in the upper 50 m zone was excavated during the foundation excavation of the dam as shown in Fig. 9.

Although the excavation of upper 50 m natural ground for foundation was performed, this huge excavation might have created new cracks in the rock just below the foundation of the dam because of relaxation created by stress relief and blasting effects on rocks. These stress relief and blasting effects of excavation on foundation rock was measured for Cine Dam by using seismic measurements. It

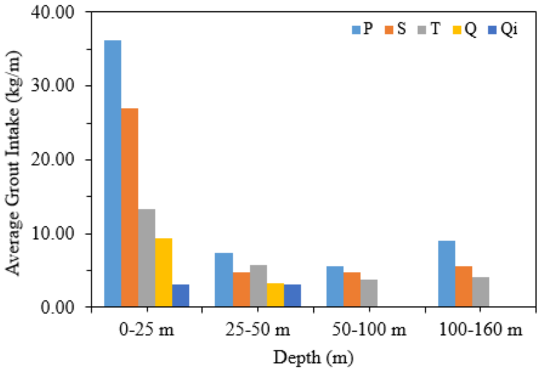


Fig. 13 Grout intakes with depth in the test panel executed in the gallery LG 0 -153.50, the bottom gallery at the foundation level (Ünal 2007)

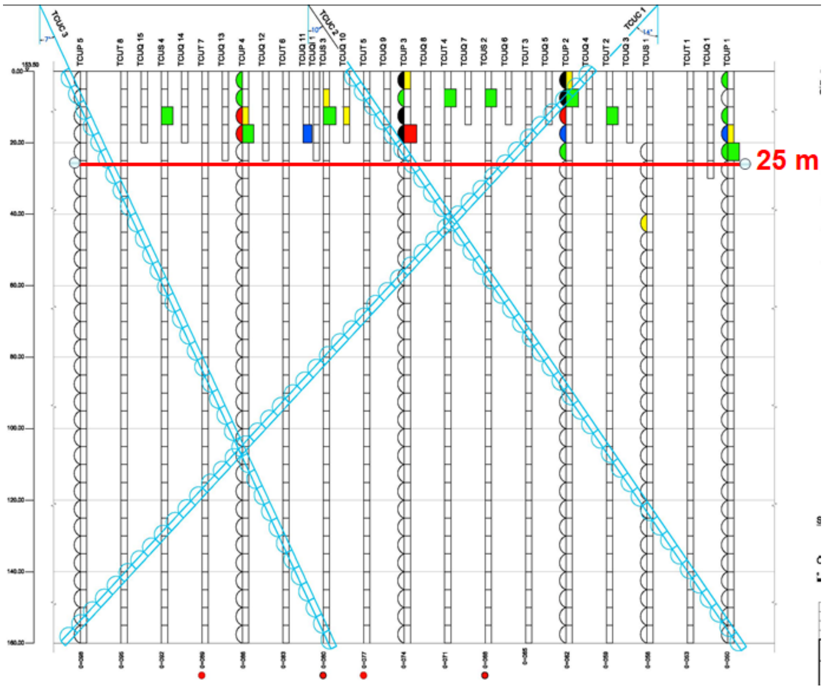


Fig. 14 Grout intakes with depth along the length of the test panel the gallery LG 0 -153.50, the bottom gallery at the foundation level (Ünal 2007)

was shown that the depth of affected zone could reach to about 20 m in vertical direction (Fig. 10). The average depth of excavation in vertical direction is about 30m in terms of the unexcavated rock unit weight (Fig. 11), where those measurements were executed. The ratio of the depth of excavation to the depth affected zone because of relaxation is about 1.5.

"Grout Curtain Test Panel" was executed in the left bank – gallery LG 0 – 153.50 to evaluate the effective-grouting radius in between grout holes, penetrability rate of used grout mixes, penetrability rate of used grout mixes, suitability and effectiveness of applied grouting pressures,

and the achieved rate of grout curtain permeability. The beginning of the panel was at 50 m from the entrance of the left bank – gallery LGO – 153.50. The length of "Grout Curtain Test Panel" was 48m and the depth of grout holes extended to 160 m from the bottom of the gallery as shown in Fig. 12.

The excavation effect together with the excavation of the gallery where the tests were performed could be evaluated by considering the grout intakes in the grout curtain test panel. Fig. 13 shows that grout intake in the upper 0-25 m depth reaches 35 kg/m for primary holes and then drops to less than 8 kg/m below the depth of 25m. That is a very low value according to Deere (1976) (Table 1). As pointed out by Nonveiller (1989), any grout take less than 10kg/m is a waste of time and resources since approximately 10 kg/m and 5 kg/m grout is needed to fill 1m of a hole 70 mm and 46 mm in diameter respectively. The diameter of primary holes is 76 mm whereas the diameter of secondary and tertiary holes is 59 mm in the test panel.

The average excavated rock cover depth above the test panel is about 80 m over the test panel. Rock cover above the test panel starts with 50 m in the entrance side of the gallery and reaches about 100 m at the end of the gallery. The ratio of the rock cover above test gallery to excavated rock depth is about 1.5 at the beginning of the test panel and

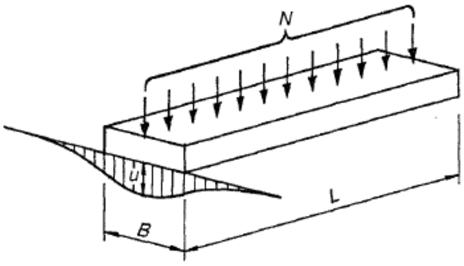


Fig. 15 Ground deformations due to loading of strip foundations (Herzog 1999)

(a) Photo taken on February 7, 2006 (b) Photo taken on October 12, 2006

Fig. 16 Deriner Dam concreting works at foundation level. Gallery G0 at elevation 153.50 m

reduces to 0.8 at the end. The high ratio of excavated rock depth to rock cover over the gallery could be understood as a sign of relaxation due to excavation. This ratio at the beginning of the panel is almost the same that was measured in Cine Dam. Hence, the gallery was built on the boundary of the relaxation limit but there is also the effect of excavation of the gallery as far as the disturbance of the ground is concerned.

The thickness of disturbed zone could theoretically reach up to two excavated tunnel diameters. In addition to that, since there is a removal of some portion of rock due to construction of the gallery, the depth of affected zone because of tunneling could extend to the deeper elevations. It is interesting to note that possible cracks created during the excavation of the gallery might have closed by the induced stresses due to high rock cover towards the end the gallery. Therefore, there was no important grout intake in this zone close to the end of the gallery.

It can be said that there is no considerable effect of the grouting test gallery exceeding a depth of 25m under the gallery not only because high rock stresses exist but also the excavation disturbed zone due to the opening of the gallery could not reach to that depth. Besides the quality of rock increases with depth as observed in water pressure tests. The elevation of test gallery (153.50) lies about one 100m to 180 m down from natural ground surface. The change of Lugeon water pressure test results with depth given in Fig. 8 shows that undisturbed rock in the place of the test gallery before any grouting executed is highly impermeable and average Lugeon values are about 3-4. Therefore, Lugeon units reached 30-40 in the test panel up to 25 m below gallery (Fig. 14) cannot be attributed to undisturbed rock foundation. In conclusion, high Lugeon units and high grout intakes observed in the test panel just below the grouting gallery up to 25 m depths cannot define the characteristics of undisturbed dam rock foundation at that elevation. Those values were observed because of decompression and disturbance created by gallery excavation. Therefore, there is a drastic decrease in the amount of grout intake with depth exceeding 25 m below the gallery.

It may be concluded that there is almost no effect of consolidation grouting except the zone disturbed by blasting, which may be considered a couple of meters close to the dam foundation since the depth of dam foundation excavation was enough to reach sound rock conditions, because the Water Pressure Tests and grout intakes corresponding to the foundation level was limited, and for the dead weight of the dam body and the time passed before zero readings were enough to close decompression cracks not only by the stress created but also by the effect of creeping. Besides, the depth of the blast affected zone is small when compared with the width of the dam. Thus consolidation grouting may have negligible effect on back calculated deformation modulus values.

## 4. Back calculation of deformation modulus from settlement measurements

Boussinesq's theory of elastic semi-space could be used to deduce a formula for ground deformations (Herzog 1999). Normal displacement (settlement) can be calculated by Eq. (1).

$$u = \frac{N}{L}\left(\frac{L}{B}\right)^{\frac{1}{3}} \tag{1}$$

(a) Photo taken on July 4, 2006 (b) Photos taken February 5th, 2009

(c) Photo taken February 5th, 2009 (d) Photo taken June 8th, 2010

Fig. 17 Deriner Arch Dam concreting works

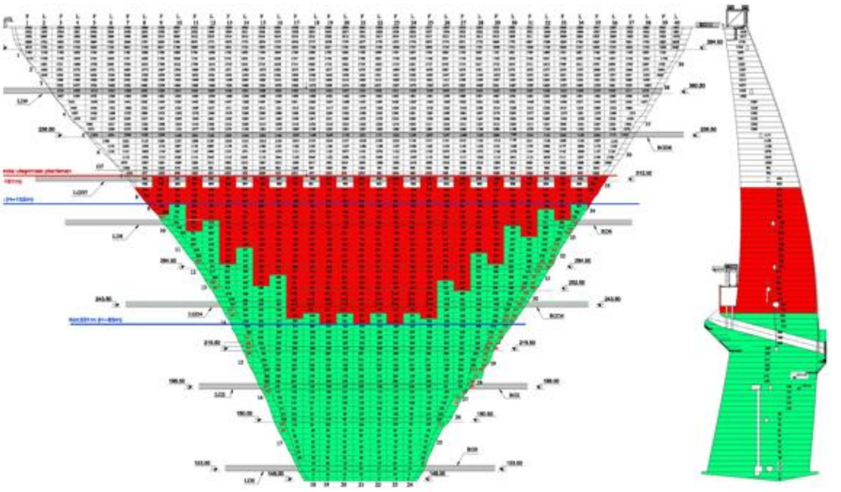


Fig. 18 Deriner Dam concrete progress as of March 2009

where; u is the normal displacement, L is the length of the foundation, B is the width of the foundation and N is strip loading as shown in Fig. 15.

Early construction stages of dam body were shown through the Figs. 16 and 17. Concrete progress for all dam body was shown in Figs. 18 and 19. Settlement measurements together with dates and reservoir water level were shown in Fig. 20 and Table 2 (Electrowatt and Dolsar 2014). The Geodetic Deformation Monitoring System used in Deriner Dam was given by Konakoğlu *et al.* (2020).

The crown cantilever section and abutment thickening of the dam were given in Figs. 21 and 22. The dead weight corresponding to settlement measurements could be calculated. This information could be used for detailed back calculation of modulus by dam modelling at any stage but

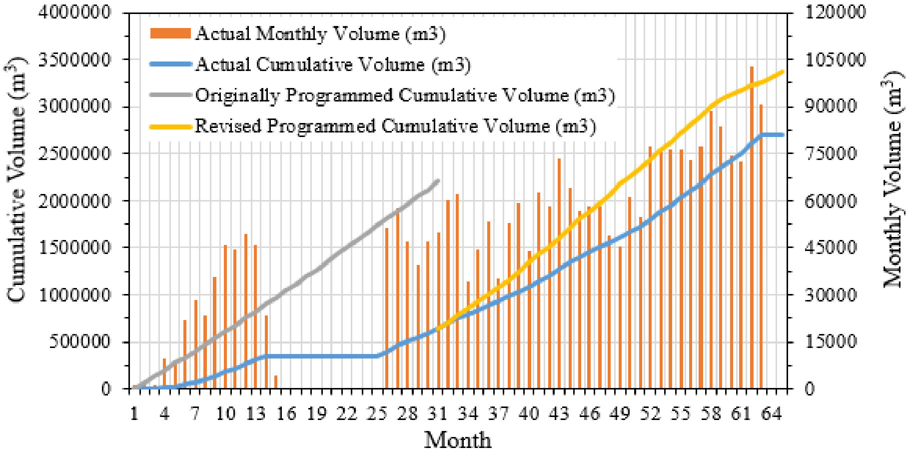


Fig. 19 Deriner dam body mass concrete placement progress

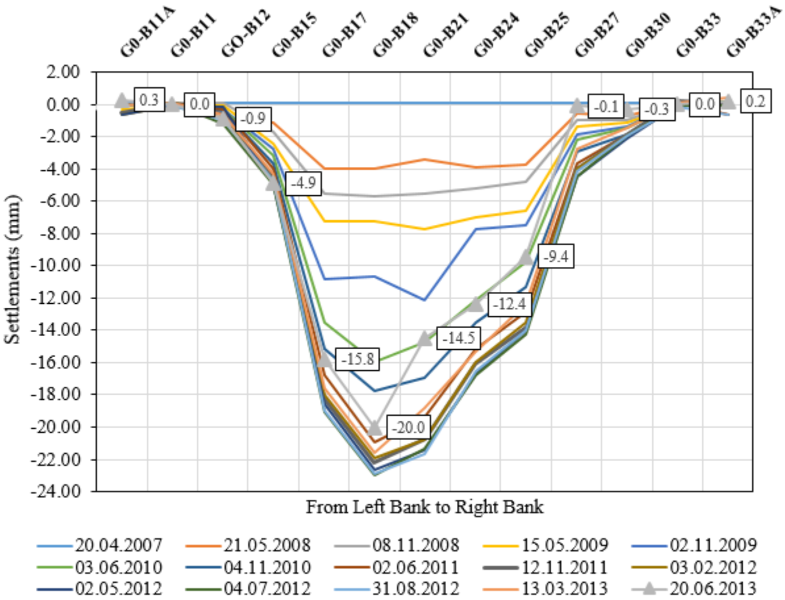


Fig. 20 Deriner Dam settlements measured in gallery G0 at elevation 153.50 m (Electrowatt and Dolsar, 2014)

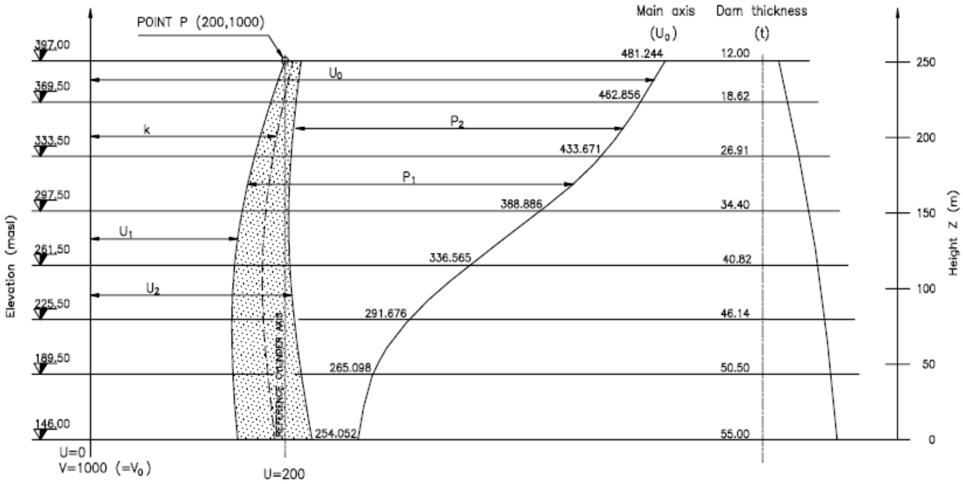


Fig. 21 Definition of main parabolas and crown cantilever section of Deriner Arch dam (Stucky 2000)

that requires not only to know friction coefficient in between dam concrete and rock foundation but also the friction coefficient in between the blocks in the abutments. High slope angle towards abutments will complicate the calculation. Therefore, back calculation of deformation modulus by using Eq. (1) has been done for just horizontal valley section and neighboring blocks.

The depth of foundation excavation and Water Pressure Test results in terms of Lugeon values below foundation level show that rock foundation is almost untreatable by grouting. In other words, consolidation grouting effect in between zero reading and following readings is minimal as far as overall deformation modulus is concerned.

Average elevations at the time of zero measurement and at the time second measurement were about 189.5 m and 219.0 m, respectively. Average additional load in between these days was about 27.23 m. Average load per meter on the foundation is about 3267 ton/m. Measured average deformation was about 3.8 mm. Average length of loading (L) can be taken as 190 m at elevation 189.5 m. Deformation modulus can be back calculated by using Eq. (1). Its value is about 13 GPa.

This is about 2.2 times plate loading tests made by EIEI of Turkey. The diameter of the plate is 35 cm. This back calculated value verifies those conclusions reached by Palmström and Singh (2001). As pointed out by the other studies, Excavation Disturbed Zone (EDZ) created around the adits must have affected the results because the stress change with depth due to test loading is proportional to the diameter of the loading plate. Therefore, smaller diameter loading test setups are more affected by disturbed zones around the adits where the tests are run.

## 5. Conclusions

Small diameter plate loading test with surface displacement measurements gives lower deformation values because the stress bulb created by the plate mainly remains in the excavation disturbed zone. There are many test methods to determine deformation modulus of rock foundations but each one has its own shortcoming or difficulty. Therefore, the best way is to use deformation measurement during the construction of the dam to back calculate deformation modulus. This study about Deriner Dam shows that in-situ deformation modulus calculated by using settlement measurements is about two times higher than those estimated by using the plate loading tests. This is the same conclusion reached by Palmström and Singh (2001). This verification has a lot of important consequences. Some of them are listed below:

- Empirical equations relating rock mass quality to rock mass modulus need to be restudied if the data were obtained from the small diameter test devices. In reality more sites would be appropriate for concrete dams, bridges and high-rise buildings given the low values of the test results for sound rock conditions.

- Low values of deformations modulus would require more excavation to reach appropriate foundation conditions. This extra excavation would increase the cost drastically because of both excavation and backfilling with concrete. In fact, the depth of excavation to meet necessary deformation modulus criteria can be reduced. Besides the amount of concrete backfilling or cushion concrete could be decreased or probably eliminated.

- In recent years, there is a tendency to increase consolidation grouting works not only by extending grout holes into greater depths and widths but also decreasing the distance in between holes. This choice increases the cost and extends the time of construction. Consolidation grouting works for dam foundations may be much needed and justified for the zones affected by blasting. The thicknesses of those zones are much less than consolidation grouting depths practiced today in many dams in Turkey. Besides, the amount of consolidation could be reduced since in situ deformation modulus's are higher than test values because of the plate loading test devices utilized. Therefore, the need to increase deformation modulus by consolidation grouting is diminished.

- Best way to reduce the effect of excavation disturbed zone on test results would be to increase the diameter of plate loading device and to measure displacements with depth during the test.

## References

Aksoy, C.O., Uyar Aksoy, G.G., Guney, A., Ozacar, V. and Yaman, H.E. (2020), "Influence of time-dependency on elastic rock properties under constant load and its effect on tunnel stability". *Geomech. Eng.*, **20**(1), 1-7. http://doi.org/10.12989/gae.2020.20.1.001.

Angın, Z. (2016), "Geotechnical field investigation on Giresun hazelnut licenced warehause and spot exchange", *Geomech. Eng.*, **10**(4), 547-563. https://doi.org/10.12989/gae.2016.10.4.547.

Agharazi, A., Martin, C.D. and Tannant, D.D. (2015), "Numerical analysis of plate-load test results on fractured rocks using an equivalent-continuum model: Case study of the Bakhtiary dam site", *Int. J. Geomech.*, **15**(1), 05014001, 1-11. https://doi.org/10.1061/(ASCE)gm.1943-5622.0000415.

ARQ Consulting. (2016), "Yusufeli dam and HEPP", Report on Dam Foundation Strengthening, Revision-1, Artvin, Turkey.

Barton, N. (2007), *Rock Quality, Seismic Velocity, Attenuation and Anisotrophy*, Taylor and Francis Group, London, U.K.

Bieniawski, Z.T. (1978), "Determining rock mass deformability: experience from case histories", *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **15**(5), 237-247. https://doi.org/10.1016/0148-9062(78)90956-7.

Coon, R.F. and Merritt, A.H. (1970), *Predicting In-Situ Modulus of Deformation using Rock Quality Indexes*, ASTM Special Technical Publication, Philadelphia, U.S.A.

Deere, D. (1976), "Dams on rock foundations, some design questions", *Proceedings of the Rock Engineering for Foundations and Slopes Conference*, Boulder, Colorado, U.S.A.

Deere, D.U., Hendron, A.J., Patton, F.D. and Cording, E.J. (1968), "Design of surface and near-surface construction in rock", *Proceedings of the 8th Symposium on Rock Mechanics (USRMS)*, Minneapolis, Minnesota, U.S.A., September.

Dodds, D.J. and Schroeder, W.L. (1974), "Factors bearing on the interpretation of in-situ testing results", *Proceedings of the 2nd Rapid Excavation and Tunnelling Conference*, San Francisco, California, U.S.A., June.

DSI. (1999), "Deriner dam final design drawings", State Hydraulic Works of Turkey, Ankara, Turkey.

DSI. (2015), "Hydraulic jack and dilatometer test report", Yusufeli

Dam and Hydropower Plant Project, Artvin, Turkey.

Electrowatt Engineering Ltd and Dolsar Engineering Ltd. (2014), Deriner dam and hydroelectric power plant, Geodetic Dam Monitoring I8 Readings After Completion of Impounding, Technical Report, Artvin, Turkey.

Eroğlu, V. and Yilmaz, D. (2005), "Approaches considered to overcome uncertainties at Çine dam", *Proceedings of the ICOLD Annual Meeting*, Iran.

Fan, Q., Zhou, S. and Yang, N. (2015), "Optimization design of foundation excavation for Xiluodu super-high arch dam in China", *J. Rock Mech. Geotech. Eng.*, **7**, 120-135. https://doi.org/10.1016/j.jrmge.2015.03.001.

Galera, J.M., Alvarez, M. and Bieniawski, Z.T. (2005), "Evaluation of the deformation modulus of rock masses: comparison of pressuremeter and dilatometer tests with RMR prediction", *Proceedings of the ISP5-Pressio International Symposium*, France.

Geoconsult GIBB and ARQ. (2000), "Cine RCC dam", Phase II Design Reports, Volume 1-4, and Final Design Drawings, Artvin, Turkey.

Hall, W.J., Newmark, N.M. and Hendron, A.J. (1974), "Classification, engineering properties and field exploration of soils, intact rock and in situ rock masses", Directorate of Regulatory Standards, US Atomic Energy Commission, USA.

Herzog, M.A.M. (1999), *Practical Dam Analysis*, ICE Publishing, Thomas Telford.

Hoek, E. and Diederichs, M.S. (2006), "Empirical estimation of rock mass modulus", *Int. J. Rock Mech. Min. Sci.*, **43**, 203-215. https://doi.org/10.1016/j.ijrmms.2005.06.005.

Ito, Y., Agui, K., Kikuchi, K., Fujieda, M., Kobayashi, T. and Saito, T. (2007), "Brief and systematic evaluation for deformation characteristics of dam site rock mass by shock response value", *Proceedings of the 11th Congress of the International Society for Rock Mechanics: The Second Half Century of Rock Mechanics*, July, Lisbon, Portugal.

Kayabası, A., Gokceoglu, C. and Ercanoglu, M. (2003), "Estimating the deformation modulus of rock masses: A comparative study", *Int. J. Rock Mech. Min. Sci.*, **40**, 55-63. https://doi.org/10.1016/S1365-1609(02)00112-0.

Konakoglu, B., Cakir, L. and Yilmaz, V. (2020), "Monitoring the deformation of a concrete dam: A case study on the Deriner Dam, Artvin, Turkey", *Geomatics Nat. Hazards Risk*, **11**(1), 160-177. https://doi.org/10.1080/19475705.2020.1714755.

Lee, S.W. (2019), "Experimental study on effect of underground excavation distance on the behavior of retaining wall", *Geomech. Eng.*, **17**(5), 413-420. http://doi.org/10.12989/gae.2019.17.5.413.

Li, W. (2017), "Experiment study on the whole deformation process of arch dam bedrock", *Proceedings of 9th International Economics, Management and Education Technology Conference*, Taiyuan, China, July.

Liu, Y., He, Z., Yang, Q., Deng, J. and Xue, L. (2017), "Long-term stability analysis for high arch dam based on time-dependent deformation reinforcement theory", *Int. J. Geomech.*, **17**(4), 04016092. https://doi.org/10.1061/(ASCE)gm.1943-5622.0000760.

Nonveiller, E. (1989), "Grouting theory and practice", Developments in Geotechnical Engineering, **57**, 1-250.

Oberti, G., Bavestrello, F., Rossi, P.P. and Flamingi, F. (1986), "Rock mechanics investigations, design and construction of the Ridracoli Dam", *Rock Mech. Rock Eng.*, **19**(3), 113-142. https://doi.org/ 10.1007/BF01024952.

Oberti, G., Carabelli, E., Goffi, L. and Rossi, P.P. (1979), "Study of an orthotropic rock mass: Experimental techniques, comparative analysis of results", *Proceedings of the 4th Congress International Society for Rock Mechanics*, Montreux, Switzerland, September.

Palmström, A. and Singh, R. (2001), "The deformation modulus of rock masses-comparisons between in situ tests and indirect estimates", *Tunn. Undergr. Sp. Tech.*, **16**(2), 115-131. https://doi.org/10.1016/S0886-7798(01)00038-4.

Rocha, M. (1970), *New techniques in deformability testing of in situ rock masses, in determination of the in-situ modulus of deformation of rock*, A.S.T.M. Special Technical Publication, 477, 39-54, A.S.T.M., Philadelphia.

Rocha, M. (1974), "Present possibilities of studying foundations of concrete dams", *Proceedings 3rd International Congress on Rock Mechanics*, Denver, Colorado, U.S.A.

Scott, G.A. (1990), "Deformation of rock foundations under dams", *Proceedings of the 10th Annual USCOLD Lecture Series*, New Orleans, Louisiana, U.S.A.

Serafim, J.L. (1964), *Rock Mechanics Considerations in the Design of Concrete Dam*s, in *State of Stress in the Earth's Crust*, 611-650, New York, U.S.A.

Serafim, J.L. and Guerreiro, M. (1968), "Shear strength of rock masses at 3 Spanish dam sites", *Proceedings of the International Symposium on Rock Mechanics*, Madrid, Spain.

Serafim, J.L. and Pereira, J.P. (1983), "Consideration of the geomechanics classification of Bieniawski", *Proceedings of the International Symposium on Engineering Geology and Underground Constructions*, Lisbon, Portugal.

Shannon and Wilson Inc. (1964), "Report on in situ rock tests, Dworshak dam site", US Army Engineer District, Walla Walla, Seattle, Washington, U.S.A.

Shen, X., Niu, X., Lu, W., Chen, M., Yan, P., Wang, G. and Leng, Z. (2017), "Rock mass utilization for the foundation surfaces of high arch dams in medium or high geo-stress regions: review", *B. Eng. Geol. Environ.*, **76**, 795-813. https://doi.org/10.1007/s10064-016-0892-4.

Stucky Consulting Engineers Ltd. (1999), "Deriner dam and HEPP, Additional Geological Investigations", Synthesis Report, Report No. 4353/4115-1, Switzerland.

Stucky Consulting Engineers Ltd. (2000), "Deriner dam and HEPP, Dynamic analysis of the final optimised dam desig"n, Report No. 4353/4265, Switzerland.

Tan, C., Ma, D.H., Liu, Z.F., Gao, Y., Xu, X.C. and Zhang, W. (2020), "Research on the deformation and failure pattern of rock masses in dam foundations controlled by continuous gently inclined and discontinuous steeply inclined unconformities", *IOP Conf. Ser. Earth Environ. Sci.*, **570**, 1-12.

Tanchev, L. (2014), *Dams and Appurtenant Hydraulic Structures*, Taylor & Francis Group.

Tayarani, N.S., Jamali, S. and Zahed, M.M. (2020), "Combination of artificial neural networks and numerical modeling for predicting deformation modulus of rock masses", *Arch. Min. Sci.* **65**(2), 337-346.

Ünal, B. (2007), "Deriner dam and HEPP grout curtain test results", *Proceedings of the Turkey Union of Chambers of Architects and Engineers Second Geotechnical Symposium*, Adana, Turkey, November.

Wallace, G.B., Slebir, E.J. and Anderson, F.A. (1970), In situ methods for determining deformation modulus used by the bureau of reclamation, ASTM Special Technical Publication, 477, 3-26, Philadelphia, USA.

Wei, Y., Xu, M., Wang, W., Shi, A., Tang, M. and Ye, Z. (2011), "Feasibility of columnar jointed basalt used for high-arch dam foundation", *J. Rock Mech. Geotech. Eng.*, **3**, 461-468. https://doi.org/10.3724/SP.J.1235.2011.00461

Wu, B, Niu, J, Su, H, Yang, M, Wu, Z and Cui, X. (2019), "An approach for deformation modulus mechanism of super-high arch dams", *Struct. Eng. Mech.*, **69**(5), 557-566. http://doi.org/10.12989/sem.2019.69.5.557.

Zhang, Y, Ding, X, Huang, S, Qin, Y, Li, P and Li, Y. (2018), "Field measurement and numerical simulation of excavation damaged zone in a 2000 m-deep cavern", *Geomech*. *Eng*., **16**(4), 399-413. http://doi.org/10.12989/gae.2018.16.4.399.

*CC*