Gazi Üniversitesi
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PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 14(X): XX-XX (2026)

Prediction of Deformation Modulus of Graphiteschist: The Assessment of In-Situ Test and Empirical Methods for a Gravity Dam Foundation

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Article Info

Research article
Received: 06/02/2026
Revision: 08/05/2026
Accepted: 21/05/2026

Keywords

Deformation Modulus
In-Situ Testing
Empirical Methods
Graphiteschist

Makale Bilgisi

Araştırma makalesi
Başvuru: 06/02/2026
Düzeltme:08/05/2026
Kabul: 21/05/2026

Anahtar Kelimeler

Deformasyon Modülü
Yerinde Deney
Ampirik Yöntemler
Grafitşist

Graphical/Tabular Abstract (Grafik Özet)

Deformation modulus of grafhiteschist was determined as function of common suggested empirical methods using rock classification systems, GSI, RMR and RQD, derived from in-situ test by Rock pressuremeter test, and is compared with each other. / Grafitşistin deformasyon modülü, kaya kütlesi sınıflandırma sistemleri olan GSI, RMR ve RQD kullanılarak ampirik yöntemlerle ve in-situ testlerden kaya presiyometre deneyinden eşde edilen verilerle değerlendirilmiş ve karşılaştırılmıştır.

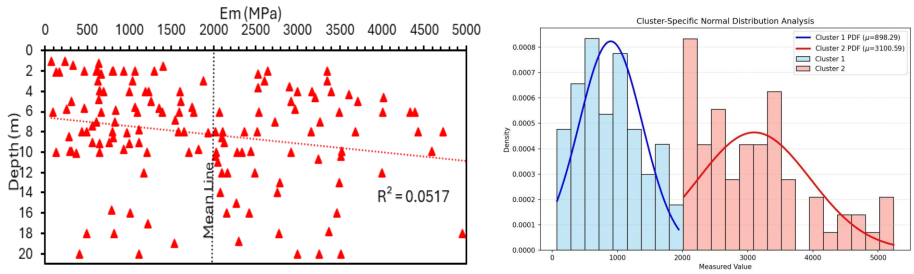

Figure A: *(a) The Mohr-Coulomb (M-C) and (b) E_m deformation modulus distribution by two-cluster. /* ***Şekil A:*** *(a) Mohr-Coulomb (M-C) ve (b) küme analizi ile deformasyon modülü dağılımı*

Highlights (Önemli Noktalar)

- *Rock Pressuremeter Test / Kaya Presiyometre*
- *Empirical Methods / Ampirik Yaklaşımlar*
- *Deformation Modulus / Deformasyon Modülü*
- *Gravity Dam / Ağırlık Barajı*

Purpose (Amaç): *This study aims to determine both in-situ and empirical values of deformation modulus of grafhiteschist rock mass and compare with each other for structure and safety for proper design aspects. / Bu çalışma, grafitşist kaya kütlesinin uygun yapı güvenliği ve tasarımı bakımından önemli parametrelerden olan deformasyon modülünün hem yerinde deneyler hem de ampirik yaklaşımlarla belirlemesi ve karşılaştırılmasını amaçlamaktadır.*

Theory and Methods (Teori ve Metot): *Empirical methods commonly available in the literature and in-situ test, rock pressuremeter tests results were analyzed and compared with each other for a unique gravity dam foundation. / Beznersiz bir beton ağırlık barajının temeli için grafitşist kaya kütlesinin deformasyon özellikleri literatürde yaygın bullanılan ampirik yöntemler ve yerinde deney, kaya presiyometre deneyi, sonuçları ile karşılaştırılmıştır.*

Results: *In-situ test reveals a wide data scatter, empirical methods have resulted in different deformation modulus ratio depending on rock mass properties such as GSI, RMR, Elasticity modulus of intact rock. / Kaya presiyometre deney sonuçları geniş bir aralıkta dağılım ortaya çıkartırken, ampirik yöntemler ise ana kayanın GSI, RMR ve elastisite modülü gibi kaya kütlesi özelliklerine bağlı olarak farklı deformasyon modülü değerleri vermektedir.*

Conclusion (Sonuç): *Empirical methods provide preliminary deformation modulus value in early stages of project assessments. In-situ tests provide a powerful estimation and realistic deformation modulus for site. Combination of in-site tests and empirical methods ensure more reliable and accurate deformation modulus value for a rock mass. / Ampirik yaklaşımlar, proje değerlendirmelerinin erken aşamalarında kaya kütlesinin öncül modül değeri sağlar. Yerinde yapılan deneyler ise saha için daha gerçekçi değerler ortaya çıkartır. Yerinde yapılan deneyler ve amiprik yöntemlerin birleşimi, kaya kütlesi için daha güvenilir ve doğru bir deformasyon modülü değeri ortaya çıkartır.*

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DOI: 10.29109/gujsc.1882792

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Prediction of Deformation Modulus of Graphiteschist; The Assessment of In-Situ Test and Empirical Methods for a Gravity Dam Foundation

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Abstract

The deformation modulus, E_m, of rock masses is a key factor for geotechnical engineering and indispensable parameter in the design and safety assessments of foundations, slopes, supports systems, dams, tunnels and mining operations. Accurate estimation of modulus is essential for the determination of behavior of rock mass under different loads. Nevertheless, determining that behavior is inherently challenging due to heterogeneity of the rock mass. This study investigates the deformation modulus of graphiteschist through a combined approach, integrating empirical estimation methods with in-situ testing. Rock Pressuremeter Test provides direct assessments of deformability of rock mass under actual stress conditions. These measurements were, then compared with deformation values stemmed from several empirical methods related to characterization methods of rock mass including RMR, RQD and GSI based correlations. Comparative analysis reveals significant variability among empirical methods and in-situ tests, influenced by disturbance factors, and classification systems limitations. This study highlights the importance of combination of diverse empirical methods and in-situ measurements to enhance the reliability of deformation modulus estimations. Integrating multiple empirical methods allows for cross check and better characterization of mechanical behavior of complex rock masses. Such an approach is particularly valuable for critical structures such as dams for ensuring structural and foundation stability and safety.

Grafitşistte Deformasyon Modülü Belirlenmesi: Ağırlık Beton Baraj Temelinde Yerinde Deney ve Ampirik Yönemlerin Değerlendirilmesi

Makale Bilgisi

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Öz

Deformasyon modülü, kaya mühendisliğinin temel bir parametrelerinden olup, temel, baraj, şev iyileştirme, destek sistemleri, tüneller ile madencilik gibi yeraltı yapılarının tasarımı ve güvenlik değerlendirmelerinde önemlidir. Kaya kütlelerinin farklı yükler altında davranışlarının güvenilir bir şekilde tahmin edilebilmesi için kaya kütlerinin deformasyon modülünün doğru belirlenmesi gereklidir. Ancak, kaya kütlelerinin heterojen yapıları nedeniyle deformasyon modül değerlerinin belirlenmesi oldukça zordur. Bu çalışma, grafitşist kaya kütlesinin deformasyon modülünü, ampirik tahmin yöntemleri ile yerinde deney yöntemlerinden elde edilmesi ve elde edilen değerlerinin karşılaştırmasını kapsamaktadır. Yerinde deneyler, kaya kütlesinin doğal gerilme koşulları altındaki deformasyon durumunu doğrudan değerlendirme imkanı sunmaktadır. Elde edilen deformasyon modülü değerleri, Jeolojik Dayanım İndeksi (GSI), Kaya Kalite Belirlemesi (RQD) ve Kaya Kütle Derecelendirmesi (RMR) gibi kaya kütlesi sınıflandırma sistemlerine dayalı önerilen çeşitli ampirik yaklaşımlardan elde edilen deformasyon modülleri karşılaştırılmıştır. Karşılaştırmalı analiz, yerinde deney sonuçları ile ampirik yöntemlerden elde edilen deformasyon modülü değerlendirmeler yapılarak, ampirik yöntemlerde kullanılan bozulma faktörleri ve sınıflandırma sistemlerinin sınırlamaları gibi etkenlerden kaynaklanan önemli farklılıklar olduğu belirlenmiştir. Bu çalışmada deformasyon modülü tahminlerinin güvenilirliğini artırmak için farklı ampirik yöntemler ve yerinde deney sonuçlarının birlikte değerlendirilmesinin önemini vurgulanmaktadır. Bu durum verilerin çapraz kontrolleri sağlamakta ve kaya kütle davranışlarının daha iyi karakterize edilmesine yardımcı olacaktır. Bu yaklaşım, özellikle baraj gibi kritik yapılarda temel ve yapı tasarımı için oldukça önemlidir.

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1. INTRODUCTION (GİRİŞ)

Deformation modulus of a rock mass is a key parameter used by geotechnical engineers when assessing the rock masses subjected to various load conditions in projects such as the foundation of dam tunnels, and rock slopes [1-5]. It can be determined via in-situ tests (direct methods) or empirical approaches (indirect methods). In-situ tests, such as rock pressuremeter test/ dilatometer test, and plate loading test, are the most accurate way to determine the deformability of rock masses, which are considered the best approach to obtain reliable estimations. Nevertheless, these types of in-situ methods are often limited by their high expense of implementation, time-consuming, and the applicability challenges associated with mobilization, complex installation and testing procedure as well as advanced equipment requirements [1]. To overcome those challenges, numerous researchers have suggested various empirical approaches to estimate the deformation modulus based on established rock mass classification methods. These methods include, intact rock properties, Rock Quality Designation (RQD) [1], Rock Mass Rating (RMR) [7,8], the Tunneling Quality Index (Q-System) [59], and the Geological Strength Index (GSI) [9,10]. These empirical methods employ many variables, such as the elasticity modulus, unconfined compressive strength of intact rock, point load index, weathering degree of discontinuities, disturbance factor for excavation, discontinuity condition rating as well as joint conditions, block size, and joint spacing [11-17]. Furthermore, as presented by Gokceoglu et al. [18,33], the deformation modulus can be calculated using advanced computational techniques such as artificial neural networks, neuro-fuzzy models, and genetic programming among others. Despite these advancements, determining the modulus of any given rock mass using empirical methods can be controversial to estimate accurately, as these approaches are inherently governed by using their specific datasets. Consequently, empirical estimations need to be validated using more than one proposed methodology for cross-control and possibly compared with the in-situ testing whenever possible, such as rock pressuremeter tests, to ensure their reliability for structure design.

In this research, an assessment of the deformation modulus of schist rock mass is carried out through combining the use of selected empirical methods and in-situ test results. Empirical methods were applied using various equations inputting the relations among rock mass classification systems, RMR, RQD, GSI, disturbance factor, intact rock elasticity modulus, and the compressive strength of the intact rock. Afterwards, as in-situ test, rock pressuremeter test were carried out to determine the in-situ deformation. Finally, deformation modulus is derived from empirical approaches is compared with the findings from the in-situ testing, rock pressuremeter, results. The rock mass is highly heterogeneous, particularly at the scale of rock pressuremeter testing, due to the varying orientations and thicknesses of foliation and schistosity planes, as well as the presence or absence of quartz veins. In order to represent the rock mass within the large-scale volume affected by the dam body, average values were adopted for the rock mass classification parameters RMR, GSI, and RQD. Due to the structural heterogeneity and core recovery challenges at the depths where rock pressuremeter tests were conducted, classification parameters could not be determined for each specific test level.

2. SITE GEOLOGY AND TESTING (SAHA JEOLOJİSİ VE TESTLER)

The construction site of this study is in the northwest of Bursa, Türkiye. The bedrock of the region mainly forms metamorphic units belonging to Sakarya continent [56, 57]. The site is predominantly underlain by Paleozoic Era green meta-tuffs, metavolcanics, and schist rock units, particularly graphite schist, calcschist and micaschist, all of which exhibit complex schistosity and foliation structures. As presented in Figure 1, the dam foundation is predominantly composed of graphite schist along with other schist units including mica schist and calc-schist. These schist units exhibit quartz veins along the joints and foliation/ schistosity planes with varying thickness. Measuring discontinuities along the rock mass presents a challenge due to the intense foliation/ schistosity planes revealing S-wave structure formed during regional metamorphism. Hence, it is challenging to follow the direction of discontinuity. The presence of multiple rock joint sets and instance schistosity/ foliation planes contributes to significant structural anisotropy. Nevertheless, several discontinuity orientations (dip direction/dip angle) were measured at the thalweg section of the dam: 258°/58°, 264°/48°, 262°/57°, 249°/54°, 260°/76°, 267°/32°, and 253°/52°. The main global discontinuity orientation is determined as 257°/54°. The discontinuity surfaces are generally slightly weathered to unweathered and are characterized by quartz infilling with thicknesses ranging from 1 mm to 2000 mm1.

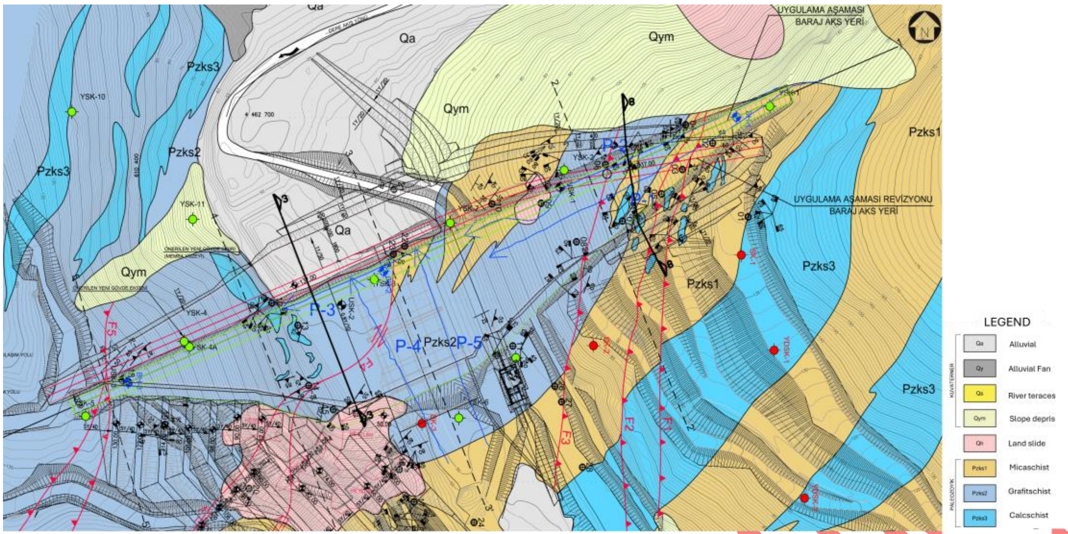

Figure 1. Geological map of the dam axis, Qa: Aluvion, Pzks1: Graphiteschist, Pzks2: Micaschist, Pzks3: Calcschist [58] (Baraj ekseninin jeoloji haritası, Qa: Alüvyon, Pzks1: Grafitşist, Pzks2: Mikaşist, Pzks3: Kalkşist [58])

For this research, the foundation of the dam was investigated by conduction drilling workings along the dam axis to depths ranging from 40 m to 75 m down from the surface. Rock core samples were extracted from various locations and depths to determine the engineering characteristics of the intact rock, including elasticity modulus, the uniaxial compressive strength (UCS), Poisson's ratios and unit weight. After that, the deformation modulus of the rock mass was evaluated using several empirical methods, and rock pressuremeter tests were carried out in construction site to assess in-situ values by given guideline of Roctest [36]. Rock pressuremeter tests were conducted in 23 different boreholes up to 20 m down from the surface located at the thalweg section of the dam. The rock pressuremeter test was specifically conducted within the graphite schist units upon which the dam is directly constructed.

3. ROCK MASS CHARACTERIZATION (KAYA KÜTLE SINIFLAMASI)

The rock core samples and borehole logs are analyzed to classify rock mass based on RQD, RMR, and GSI classification systems. RQD % values are calculated for each borehole along the dam axis, varying from 9% to 100% with the mean of 45%. Thereafter, for the rock mass, RMR value is calculated as 40 assigned as a poor rock mass. Subsequently, the GSI rate is determined as 35 by using GSI=RMR-5 (RMR > 23) proposed by Marinos et al. [35]. Depending on RQD % and RMR ratings, schist units are assigned to poor rock mass conditions [7,65]. It should be highlighted that the values of RMR, GSI and RQD represent mean values for rock mass beneath the dam to calculate deformation modulus by empirical method

3.1. Intact Rock Parameters (Sağlam Kaya Parametreleri)

Comprehensive laboratory tests were conducted to determine engineering properties of intact rock based on their standards. Rock core samples were selected to various depths and locations to accurately represent the dam foundation beneath the dam. In total, 76 specimens were tested for Uniaxial Compressive Strength (UCS) tests by [60-61], 35 samples for Elasticity Modulus (E_i) by [60-61], and 28 samples for Unit Weight by [64]. The maximum and minimum tests results are presented in Table 1. The UCS values range from 1.64 to 20.82 MPa, whereas the elasticity modulus changes from 3.3 to 32.5 GPa. Table 1 presents maximum, minimum, the mean values and standard division of the laboratory testing. The mean value of the compressive strength is 10 MPa, elasticity modulus is 12000 MPa, Poisson's ratio is 0.18, and unit weight is 27.21 kN/m^3. These means values are utilized to determine deformation modulus via empirical methods.

Table 1. Intact rock engineering properties (Sağlam kayanın mühendislik parametreleri)

Test Methods	Min.	Max.	Mean	Std. Dev.
Elasticity Modulus (MPa)	3300	32500	12000	8185.80
Poisson ratio, ν	0.11	0.28	0.18	0.054
Unit Weight (kN/m^3)	25.79	27.44	27.21	0.66
UCS, σc (MPa)	1.64	20.82	10.00	9.18

3.2. In-Situ Testing for Deformastion Modulus
(Yerinde deney ile Deformasyon Modülü)

The rock pressuremeter tests were performed through 23 exploration boreholes yielding a total of 145 measurement points for the direct estimation of the deformation modulus of rock mass along the dam foundation. It should be noted that measurements could not be successfully completed at certain test intervals due to extremely weak rock mass conditions, localized borehole wall disturbance, and operational difficulties. The depths of the boreholes are for these specific tests ranged from 10 to 20 m, with most of the usable data collected within 10 m of the subsurface. For these test locations, the in-situ rock mass deformation modulus was subsequently calculated from the rock pressuremeter test data using the relationship suggested by [36]. The results indicate that the in-situ deformation modulus ranges from 74 MPa to 5238 MPa. The overall mean of deformation modulus (E_m) was calculated to be 1916 MPa, with a standard deviation of 1298 MPa. Notably, the majority of the data points were acquired within 10 m of the surface, a zone identified as the critical depth where potential foundation failure is most likely to occur. As illustrated in Figure 2, the rock mass deformation modulus exhibits significant scattering. In order to determine dependency of deformation modulus to depth a linear regression analysis was conducted. As can be seen in Figure 2, the coefficient determination, R^2, is extremely low, therefore it is evident that deformation modulus does not depend on depth. Histogram plot is presented in Figure 3. The distribution of deformation modulus is positively skewed. It means that there is a high concentration of deformation modulus in the lower ranges (74-1000 MPa) along the tail extended towards 5238 MPa.

To further analysis, the deformation modulus values gathered from rock pressuremeter testing were analyzed using two-step clustering algorithms. Two step cluster analysis is an investigative statical algorithm proposed to reveal natural profiling within a continuous dataset and the number of clusters is automatically determined. This type of analysis helps to understand unique characteristics of each cluster [62-63]. The deformation modulus of rock mass is classified within a group that tends to be similar to each other. Additionally, it can be categorized as how the deformation modulus values distribute among the datasets. Therefore, it can be detected possible lower and upper boundary limits of deformation modulus of rock mass for proper foundation and structure designs. The analysis successfully grouped the deformation modulus into two major clusters presented in Figure 4. The dataset was distributed with approximately equal percentage with each other. In Cluster-1, the deformation modulus is tightly grouped between 74 MPa and 2000 MPa, which accounts for 53.8% of the data, yields a mean deformation modulus of 898.28 MPa with a standard deviation of 487.62 MPa. In Cluster-2, the deformation modulus is more separated, distributed from 2000 MPa to 5238 MPa, representing the remaining 46.2% of the dataset, exhibits a distinctly higher mean of 3100.58 MPa with a standard deviation of 866.09 MPa in Figure 4.

This demonstrates that the in-situ data is distributed in roughly equal proportions between a weaker and a stiffer rock mass response. In this regard, cluster analysis is highly effective technique, demonstrating the efficiency of classification criteria in distinguishing data into homogenous groups. Two clusters might show the influence of heterogeny of rock mass deformability. Ultimately, the overall mean of deformation modulus is 1916 MPa, aligning closely with the recommended deformation modulus ranges for mid-height concrete gravity dams proposed by [37]

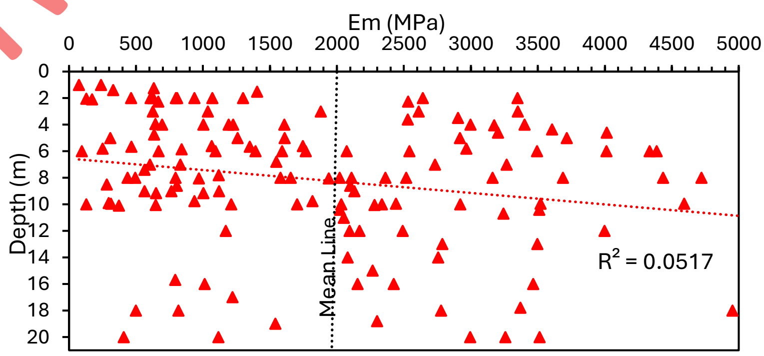

Figure 2. Distribution of deformation modulus, E_m by depth (Derinlikle deformasyon modülü, E_m, dağılımı)

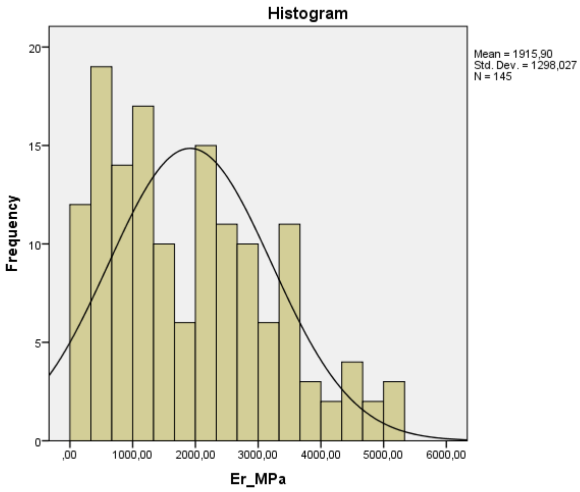

Figure 3. Histogram of deformation modulus, E_m, (Deformasyon Modülü E_m'nin histogram dağılımı)

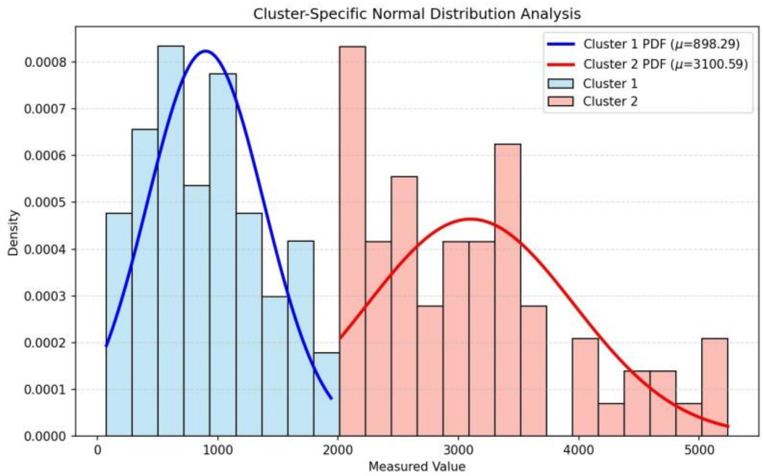

Figure 4. Distribution of deformation modulus, Em, by cluster analysis (Küme analizi ile deformasyon modülü E_m dağılımı)

3.3. Estimation of Deformation Modulus by Empirical Methods (Ampirik Yaklaşımlar ile Deformasyon Modülü Hesaplaması)

Numerous empirical methods have been proposed to determine the deformation modulus of rock mass. These methods incorporate various rock mass classification systems, including RQD, RMR, GSI, the Q-system, and combinations thereof. Furthermore, these approaches integrate structural and engineering properties of both the intact rock and the overall rock mass, by utilizing parameters such as the intact rock elasticity modulus, degree of weathering, disturbance factor for excavation, and other site-specific characteristics to estimate the deformability situation across a wide range of rock masses. One of the most commonly preferred empirical methods for estimating the deformation modulus was proposed by [13], known Hoek and Diederich method, which incorporates the Geological Strength Index (GSI), unconfined compressive strength, elasticity modulus and the disturbance factor (D). The concept of the disturbance factor was first introduced by [38] and subsequently integrated into the Generalized Hoek-Brown failure criterion by [39]. The value of D directly affects the estimation of the deformation modulus. It varies from 0 for undisturbed rock masses to 1 for highly disturbed rock masses, with descriptive guidelines provided by [40].

In this study, the factor of D was initially considered to be zero (representing an undisturbed, upper-bound condition) due to the use of mechanical strip excavation methods along the dam axis, which theoretically minimizes blast-induced or mechanical damage along the rock mass as the foundation is classified as a poor quality-weak rock mass. Conversely, Romano [41] argued that the D factor should be assigned a very low value for a gravity dam foundation, yet it should not be zero. It is suggested it should be greater than zero to account for stress relief and decompression effects during excavation or explosion. Specifically, Romano [41] suggests a D value of 0.2 for poor rock masses subjected to mechanical excavation, Nevertheless, Demirdogen and Yildirim [42] provided a descriptive framework for selecting appropriate D factor for the analysis of dam foundations that have been constructed across Türkiye. It is stated that the primary guidelines for selecting D values were

originally developed for open-pit mining, tunneling, and slope stability rather than massive foundation loading, so it is concluded that a sensitivity analysis must be conducted. This ensures the appropriate selection of D, which remains a highly critical input for safe and optimized dam design. For the purposes of this study, disturbance factor is assigned as 0 (zero) for the primary reference value for empirical methods. Furthermore, the D=0.2 value suggested by Romano [41] was employed to assess the sensitivity of the estimated modulus to excavation-induced disturbance.

Figure 4 and Figure 5 illustrate the normal stress versus shear stress failure envelopes for both D=0 and D=0.2, providing a visual comparison of how the angle of friction and cohesion vary with the assigned disturbance factor. The coefficient of determination, R^2, is close to 1.0, indicating a good fit for both disturbance factor value. That means the M-C fit line shows a good linear fit for the Hoek-Brown shear strength envelop with in this specific normal and shear stress ranges. The corresponding shear strength parameters and Hoek-Brown criterion constants are summarized in Table 2. Based on the empirical model proposed by Hoek and Diederichs [13], the deformation modulus is estimated to be 1360 MPa for an undisturbed rock mass (D=0) and 1025 MPa for a slightly disturbed rock mass (D=0.2). The analysis reveals that applying a disturbance factor of 0.2 results in an approximate 25% reduction in the deformation modulus in comparison to factor of D is set as zero. Additionally, the angle friction and cohesion simultaneously tend to slightly reduce due to the disturbance factor increment.

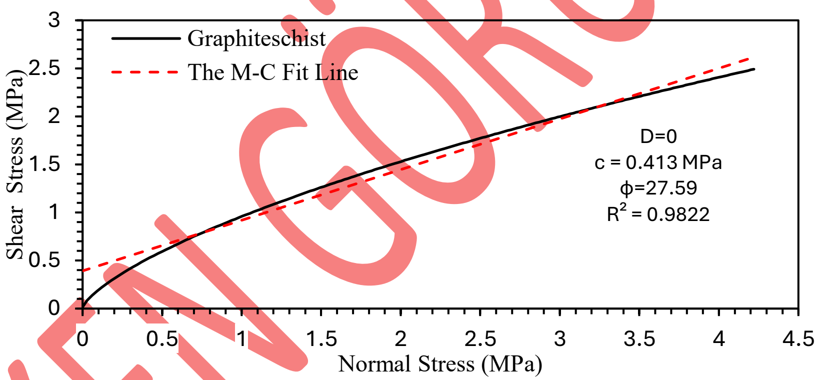

Figure 7. Normal stress versus shear stress for the disturbance of D=0 (Örselenme faktörü D=0 için normal gerilme ve kesme gerilmesi arasındaki ilişki)

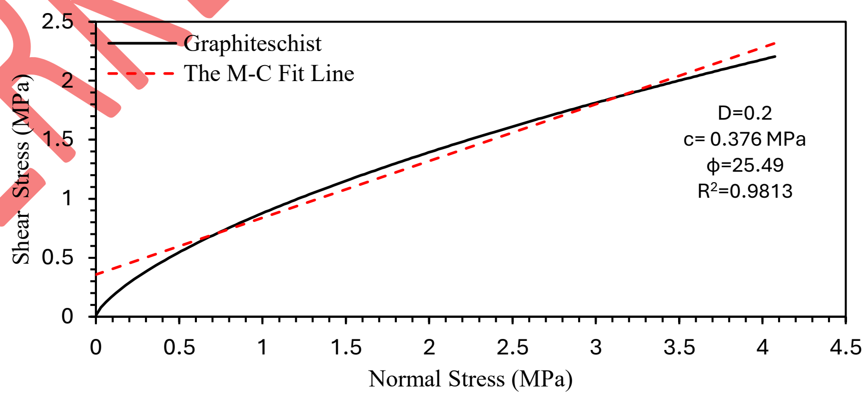

Figure 8. Normal stress versus shear stress for the disturbance of D=0.2 (Örselenme faktörü D=0 için normal gerilme ve kesme gerilmesi arasındaki ilişki)

Table 2. Estimated Mohr-Coulomb and Hoek-Brown fit parameters (Hesaplanan Mohr-Coulomb ve Hoek Brown fit parametreleri)

Lithology	Mohr-Coulomb Fit			Hoek-Brown Criterion			Er
	D	c, kPa	ϕ	mb	s	a	MPa
Graphiteschist	0	413	27.59	1.178	0.000730	0.516	1360
	0.2	376	25.49	0.910	0.000436	0.516	1025

Table 3. Selected empirical methods (Seçilmiş ampirik yaklaşımlar)

References	Equations	Parameters	E_m (MPa)
Bieniawski [7]	$E_m = 2RMR-100$	RMR > 50	N. A
Serafim and Pereira [43]	$E_m = 10^{(RMR-10)/40}$	30|<RMR ≤ 50	5623
Mitri et al. [53]	$E_m = E_i [0.5(1-\cos(\pi * RMR/100)))]$		1443
Aydan et al. [47]	$E_m = 0.1(RMR-10)^3$		2700
Read et al. [44]	$E_m = 0.1(RMR/10)^3$		6400
[a]Gokceoglu et al [18]	$E_m = 0.0736e^{(0.0755RMR)}$		1508
[b]Gokceoglu et al [18]	$E_m = 0.1451e^{(0.0654GSI)}$		1431
Zhang and Einstein [11]	$E_m = E_i 10^{(0.0186RQD-1.91)}$	0≤RQD≤100	1790
Sonmez et al. [12]	$E_m = E_i(s^a)^{0.4}$, s=exp (GSI-100/9-3D), $a=0.5+1/4(e^{-GSI/15}-e^{-20/3})$		2703
Carvalho [55]	$E_m = E_i(s^a)^{0.25}$, s= exp(GSI-100/9-3D)		1972
Galera et al. [48]	$E_m = E_i\, e^{(RMR-100)/36}$		2266
Sonmez et al. [45]	$E_m = E_i * 10[((RMR-100)(100-RMR))/(4000\exp(RMR/100))]$		2992
Hoek and Diederichs [13]	$E_m = E_i[0.02+(1-(D/2))/(1+e^{((60+15D-GSI)/11)}]$	D =0	1360
		D =0.2	1025
Chun et al. [49]	$E_m = 0.003228e^{(0.0495RMR)}$		2246
Ghamgosar et al. [46]	$E_m = 0.0912e^{0.0866GSI}$		3480
Beiki et al. [50]	$Em = \sqrt[3]{RQD log(UCS) tan(\ln(GSI)} \, 0.08e^{0.2513Ei}$		1207
Shen et al [51]	$E_m = 1.14E_i e^{-((RMR-116)/41)2}$		2501
Khabbazi et al. [54]	$E_m = 9x10^{-7}RMR^{3.868}$		1416
Alemdag et al. [29]	$E_m = 0.058e^{0.0785RMR}$		1340
Alemdag et al. [4]	$E_m = 0.00067RQD2+0.00067RQD\sigma+(0.00067RQD\sigma+0.00067\sigma_2)/(RQD+99.5)$		2667
[a]Kıncal and Koca [52]	$E_m = 0.1107e^{(0.0505RQD)}$		2098
[b]Kıncal and Koca [52]	$E_m = 0.0113E_i^{(1.9586)}$		1468

RQD: Rock Quality Index, RMR: Rock Mass Rating, GSI: Geological Strength Index, E_i: Intact Elasticity Modulus, Em: Deformation Modulus, D: Factor of Disturbance, σ: Compressive Strength, mb s and a: Hoek Constants N.A: None applicable

To derive the deformation modulus by empirical methods, the mean values of intact rock parameters presented in Table 1 are preferred. Empirical methods have inherent limitations depending on their foundational datasets, preferring the rock mass classification systems, and the specific input parameters that require for the estimation of deformation modulus. In this study, rock mass classification systems, RMR, RQD, and GSI were utilized to estimate the deformation modulus of the rock mass.

Table 3 provides a summary of the empirical methods developed between 1973 and 2019, each offering a distinct approach to E_m estimation for structural and dam foundation design. As presented, since the RMR value of the rock mass is assigned as 40 to represent whole rock mass. The deformation modulus could not be calculated using the equation proposed by Bieniawski [7], which is one of the earliest relationships but is precisely applicable only for RMR > 50. Conversely, Serafim and Pereira [43] suggested an equation applicable to rock mass if RMR is 30 < RMR ≤ 50; however, use of this approach, one of the highest modulus values of 5623 MPa is yielded. The method of Read et al. [44] reveals the highest one as well. Both empirical methods lead to a potential overestimation of rock mass stiffness. Similarly, the models proposed by Sonmez et al. [45], and Ghamgosar et al. [46] significantly overestimate the deformation modulus when only relying on the RMR and GSI values and Hoek-Brown constants of the rock mass. In contrast, the methods developed by Alemdag et al. [4], Sonmez et al. [12], Aydan et al. [47], Galera et al. [48], Chun et al. [49], Beiki et al. [50] and Shen et al. [51] compute deformation modulus of rock mass ranging between 2000 and 2700 MPa. Among these, the approaches by Beiki et al. [50] and Alemdag et al. [4] are characterized by high complexity, utilizing multiple input parameters to enhance accuracy. Equations proposed by Zhang and Einstein [11], Alemdag et al. [4], and [a]Kıncal and Koca [52] particularly proved useful estimation where only borehole data (such as RQD) is available, even if detailed multi-parameter rock mass classifications such as GSI, RMR and the UCS values, have not been fully applied in such rock mass conditions, yet moth methods reveals higher deformation modulus. The method by Alemdag et al. [29] yielded approximately similar modulus value as Hoek and Diederichs [13] approach. It should be note that Alemdag et al. [29] uses RMR value; by contrast Hoek and Diederichs [13] preferred GSI, disturbance factor, UCS values as input parameters. The remaining methods resulted in relatively consistent deformation modulus estimations with each other, changed from 1207 to 1972 MPa. Notably, Mitri et al. [53] by using E_i and RMR, Gokceoglu et al. [18] by using GSI and RMR, and Khabbazi et al. [54] by using RMR produced highly similar modulus estimations, despite utilizing fundamentally diverse rock mass classifications and intact rock parameters. Moreover, the equation by Carvalho [55] which incorporates GSI, Hoek-Brown criterion constants, and the disturbance factor (D) yields a deformation modulus closely matching the mean value of the in-situ rock pressuremeter test results, yet it is higher than Hoek and Diederichs [13].

As demonstrated in Table 3, the estimated deformation modulus ranges from 1025 MPa to over 6400 MPa based on selected empirical approaches. This highlights that empirical methods are inherently influenced the specific datasets, rock types, and site conditions upon which they were originally developed. The choice of input parameters, along with the use of linear, exponential or nonlinear mathematical models, heavily influences the final estimated modulus. The contrasting results between Carvalho [55] and Sonmez et al. [12] serve as clear evidence of this sensitivity. Many of the empirical approaches presented in Table 3 include the intact rock elasticity modulus (E_i) to estimate the fundamental stiffness of the rock mass. More recently proposed methods attempt to generalize across diverse geological conditions by integrating multiple input parameters and nonlinear behavioral effects of the rock. Nevertheless, RMR, GSI, the disturbance factor (D), and the intact elasticity modulus (E_i) remain the preferred parameters for accurate estimation of the rock mass deformability. Because all these parameters are derived by geological and geomechanical testing, site observations, and engineering judgment, they are required to fundamentally enhance the reliability of the estimation for design purposes.

Ultimately, the wide range of estimated modulus values is primarily attributed to differences in the selected input parameters and the inherent assumptions of each empirical approach. For instance, approaches developed primarily using intact rock parameters or data from slightly fractured rock masses tend to severely overestimate the deformation modulus when applied to heavily jointed or poor rock masses, such as the graphite schists encountered in this study. Based on empirical methods, Carvalho [55] offers the best estimated deformation modulus value in comparison to mean value of rock pressuremeter testing. Kıncal and Koca [52] results in slightly higher than in-situ mean value; by contrast Zhang and Einstein [11] reveal slightly lower than in-situ mean value. The most common method proposed by Hoek and Diederichs [13] is approximately 30% lower than the deformation modulus in comparison to in-site mean values for This specific schist rock mass. Consequently, geotechnical designers must employ multiple empirical methods, carefully cross-reference the results while consider the geological condition of the site, data availability, and the specific limitations of each chosen equation.

4. CONCLUSIONS (SONUÇLAR)

It is challenging to determine appropriate deformation modulus of rock mass due to nature of geological complexity of rock mass. There are two primary approaches to estimate this critical design parameter: in-site testing (direct) and empirical approaches (indirect). Both empirical methods and in-situ tests have played essential roles in estimating the deformation modulus of a rock mass. In-situ tests, such as rock pressuremeter tests, require specialized equipment, experts, and high costs, whereas empirical methods present cost-effective, quick estimations for primary assessments in comparison to the in-situ testing if not applicable initially. Nevertheless, a combined approach is usually ideal to enhance reliability of the estimated design parameters, particularly for complex projects such as concrete gravity dams. Hoek and Diederichs [13] is proposed the most accepted empirical method is proposed to calculate deformation modulus of rock mass. This is why it is considered initial methods to compare with other methods and in situ measurements.

Empirical methods can reveal a wide range of deformation modulus value based on the input, and analytic models even if they cooperate with each other. Some of the methods, Serafim and Pereira [43]; Read et al. [44], and Ghamgosar et al. [46] can lead to overestimating the deformation modulus of rock mass. Nevertheless, Gokceoglu et al. [18] by using GSI; Beiki et al. [50] by using multiple inputs as GSI, UCS, RQD and E_i; [b]Kıncal and Koca [52] by using only E_i; Mitri et al. [53] by using RMR and E_i; Khabbazi et al. [54] by using only RMR result in similar deformation values. Beiki et al. [50] uses multiple inputs to predict the deformation modulus of rock, it reveals the lowest ratio among others, by comparison of Hoek and Diederichs [13] even if they use same inputs due to analytical model differences. Methods with E_i and Rock mass classification such as GSI and RMR perform better either as single or as combined inputs in such poor rock mass. It can be stated that performance of empirical models highly depends on indicators and analytic modes, which is confirmed by [17].

Rock pressuremeter test provides deformation modulus values from a wide range distribution. It is significant to determine accurate distribution of modulus values for proper design parameter selection. Cluster analysis can help to improve the data set quality for proper parameter selection; thus, it can provide lower and upper deformability limits of rock mass. Thereafter, classified modulus values should be compared with others derived from empirical approaches to control their applicability since each method has its own pros and cons. In this study, Carvalho [55] by using GSI and E_i; Zhang and Einstein [11] by using RQD % and [a]Kıncal and Koca [52] by using E_i and RQD % reveal similar deformation modulus in comparison to mean value of in-situ test results. However, the most common empirical approach proposed by Hoek and Diederichs [13] results in deformation modulus 30 % lower than mean value of in-situ test for this particular poor quality rock mass, which may underestimate the deformability of the rock mass for this study. This is why multiple empirical approaches should be utilized to determine deformation modulus of rock mass. Empirical models by Zhang and Einstein [11]; [a]Kıncal and Koca [52] and Carvalho [55] might be cautiously used to determine the deformation modulus rock mass exhibiting similar rock mass properties in this research. This helps to gather pre-design parameters. Based on findings from this study, the following conclusions can be drawn:

- Empirical methods prvide primary estimation of the deformation modulus of rock mass during early stage of foundation and structure design. However, these approaches depend on their specific inputs, assumptions, geological conditions, so that they result in a weide range of predicted values. Due to nature of the compexity of rock mass, empirical approaches should be carefully applied using site geological data, engineering judgement rather than directly adopted into design.

- In-situ tests are the most reliable technique for determining deformation modules since they provide direct estimation and capture the mechanical behavior of rock mass under applied stress and geological conditions. In situ tests consider geological structures which affect deformability of rock mass. Thus, In-site tests often eliminate the uncertainties of empirical models.

- In situ tests data might present a wide range of scatters. To ensure the reliability of data, statical data analysis should be considered during the project design process to determine optimum design parameters for structure and foundation.

- Ultimately, the selection of modulus estimation methods should be based on the project requirements, geological complexity, and acceptable thresholds of design uncertainty. Since both empirical methods and in-site testing presents advantages and distinct limitations. Designers should not be relied on by any single approach. Instead, multiple empirical methods should be selected to catch possible range of deformation modulus of rock mass. In situ tests are essential to proper determination of deformation modulus, yet it should be considered based on the engineering judgments, site investigations and range of empirical methods. However, it is strongly recommended that integrating multiple direct and in direct methods gathering the deformation modulus of rock mass provides more reliable and comprehensive understanding of rock mass deformability. Therefore, it can be facilitated with a more accurate, economic and safer structure and foundation design, particularly for gravity dams and their foundations respectively.

ACKNOWLEDGMENTS (TEŞEKKÜR)

Authors would like to thank to the General Directorate of State Hydraulic Work (DSI), 1st Regional Hydraulic Work (DSI-Bursa), Fugro Consultant, Özkar Construction Company, and other dedicated workers.

Yazarlar, Devlet Su İşleri Genel Müdürlüğü (DSİ), Bursa, DSİ 1. Bölge Müdürlüğü (DSİ Bursa), Fugro Danışmanlık, Özkar İnşaat Şriketi ve diğer özverili çalışanlara teşekkürlerini sunar.

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Nihat Sinan IŞIK**:** He conducted statistical analysis performed the conceptualization, methodology, writing, visualization, editing and reviewing process.

İstatiksel analiz yapmış, sonuçlarını analiz etmiş kavramsallaştırma, methodloji ve maklenin yazım, revisyon ve değerlendirme işlemini gerçekleştirmiştir.

Mehmet SAGNAK**:** He conducted statistical analysis performed the conceptualization, methodology, writing, visualizatin and editing process.

İstatiksel analiz yapmış, sonuçlarını analiz etmiş kavramsallaştırma, methodloji ve maklenin yazım ve revisyon işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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