DETERMINING THE CORRELATION BETWEEN UNIAXIAL COMPRESSIVE STRENGTH, MODULUS OF ELASTICITY AND POINT LOAD STRENGTH INDEX OF ROCKS

KAYAÇLARIN TEK EKSENLİ BASINÇ DAYANIMI, ELASTİSİTE MODULÜ VE NOKTA YÜK DAYANIM İNDEKSİ ARASINDAKİ KORELASYONUNUN BELİRLENMESİ

ABDULKADİR ÇİNTESUN

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Graduate School of Science and Engineering of Hacettepe University
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ÖZET

KAYAÇLARIN TEK EKSENLİ BASINÇ DAYANIMI, ELASTİSİTE MODULÜ VE NOKTA YÜK DAYANIM İNDEKSİ ARASINDAKİ KORELASYONUNUN BELİRLENMESİ

ABDULKADİR ÇİNTESUN

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Berna UNUTMAZ

Haziran 2023, 146 Sayfa

Nokta yükü dayanım indeksi, tek eksenli basınç dayanımı ve elastisite modulü kayaçların dayanımlarına göre sınıflandırılmasında ve geoteknik hesaplamalar için kullanılan yaygın parametrelerdir. Bu parametreler geoteknik mühendisliği alanında yapılan pek çok hesaplamayı doğrudan etkilemektedir. Kayaya soketli kazıklar, kaya stabilite analizleri, tünel analizleri gibi pek çok önemli geoteknik hesaplama için kaya dayanım parametreleri gerekmektedir.

Sondajlardan elde edilen numuneler üzerinde yapılan testler ile bu parametrelerin belirlenmesi mümkündür. Ancak yeterli numune olmaması, kaya yapısının durumu, kullanılan makine-ekipman kalitesi bu parametrelerin direkt elde edilmesini bazı durumlarda mümkün kılmamaktadır. Bu durumda korelasyonların kullanılması ve parametreler arası dönüşümlerin yapılması gerekmektedir.

Bu tez kapsamında ülkemizde yer alan belirli formasyonlara ait kayaların korelasyon katsayı değerlerinin tespit edilmesi ve bu değerlerin literatür çalışmaları ile karşılaştırılması hedeflenmiştir. Literatürde yer alan korelasyonlar arasında büyük sayısal farklılıklar bulunmaktadır. Tez kapsamında belirli kabul değerleri için sonuçlar grafikler ile verilmiştir. Korelasyonların kullanılmasında dikkat edilmesi gereken hususlar hakkında tez içeriğinde tavsiyeler verilmiştir. Geoteknik mühendislerinin bu tavsiyeleri dikkate alması hesaplamalarının daha güvenli ve daha gerçekçi olması açısından faydalı olacaktır.

Anahtar kelimeler: Nokta yükü dayanım indeksi, tek eksenli sıkışma dayanımı, elastisite modülü, modül oranı, istatiksel analiz.

ABSTRACT

DETERMINING THE CORRELATION BETWEEN UNIAXIAL COMPRESSIVE STRENGTH, MODULUS OF ELASTICITY AND POINT LOAD STRENGTH INDEX OF ROCKS

ABDULKADİR ÇİNTESUN

Degree of Master of Science, Department of Civil Engineering

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In order to classify rocks according to their strengths, point load strength index, uniaxial compressive strength and modulus of elasticity are the most commonly used parameters. They are used in geotechnical calculations very often and affect many calculations in the field of geotechnical engineering. Rock strength parameters are required for many important geotechnical calculations such as rock socket piles, rock stability analyses, tunnel analyses etc.

It is possible to determine these parameters with the tests performed on the samples obtained from the boreholes. However, the lack of sufficient samples, the condition of the rock structure, the quality of the machinery and equipment used do not make it possible to obtain these parameters directly in some cases. In this case, it is necessary to use correlations and make conversions between parameters.

Within the scope of this thesis, it is aimed to determine the correlation coefficients of the rocks belonging to certain formations in our country and to compare these values

with the literature. There are significant numerical differences among the correlations in the literature. Within the scope of these thesis, the acceptable ranges for the specified parameters are presented graphically. Suggestions are given in the content of the thesis about the points to be considered in the use of correlations. It will be beneficial for geotechnical engineers to consider these suggestions for safer and more realistic designs.

Keywords: Point load strength index, uniaxial compressive strength, modulus of elasticity, modulus of ratio, statistical analysis.

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Abdulkadir ÇİNTESUN

June 2023, Ankara

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SYMBOLS AND ABBREVIATIONS

Symbols

A	Area
E_i	Modulus of Elasticity (Young's modulus)
E_{av}	Average Modulus of Elasticity
E_{sec}	Secant Modulus of Elasticity
E_{tan}	Tanget Modulus of Elasticity
I_s	The Uncorrected Point Load Strength Index
$I_{s(50)}$	The Corrected Point Load Strength Index
ε	Strain
R	Coefficient Correlation
R^2	Coefficient of Determination
σ_c / sigci/ δ_{uc}	Uniaxial Compressive Strength
L	Length
W	Width
D	Depth or Diameter
D_e	Equivalent Core Diameter
P / F	Failure Load
C	Correlation Factor
L / D	Cylindrical Sample Length/Diameter Ratio

Abbreviations

UCS	Uniaxial Compressive Strength
PLI	Point Load Index
PLT	Point Load Test
ASTM	American Society for Testing and Materials
ISRM	International Society for Rock Mechanics
RMR	Rock Mass Rating
RQD	Rock Quality Designation
MR	Modulus Ratio
MTA	Maden Tetkik ve Arama Genel Müdürlüğü (General Directorate of Mineral Research and Exploration)
GSI	Geological Strength Index
TS	Turkish Standard
TS EN	Turkish Standard - Europen Norm
FHWA	Federal Highway Administration
AASHTO	American Association of State Highway and Transportation Officials
MPa	Megapascal
kPa	Kilopascal

1. INTRODUCTION

Rock strength parameters are very important and often critical for geotechnical calculations. Many geotechnical calculations are related to the strength parameters of the rock.

Rock parameters are required for the following geotechnical calculations;

- Rock socket pile calculations
- Slope stability analysis and designs (and rock bolt designs)
- Rock mass analysis,
- Shoring systems analysis
- Tunnel portal calculations & tunnel class determination
- Important material standards (for example ballast or back fill material)
- Preliminary designs (with rock samples)
- Dams and other important engineering structures etc.

Rock parameters required for geotechnical calculations are obtained directly if the conditions are suitable. In the absence of suitable samples, correlations are helpful in making calculations.

The following conditions cause the need for correlations;

- If the rock is highly weathered and has low RQD
- If lack of adequate technical equipment and personnel
- If basic information is needed for preliminary design studies
- If cross-checking of all studies is desired

In this thesis, the relationship between "uniaxial compressive strength", "modulus of elasticity" and "point load index" of rocks are examined. These relationships are different for each rock type. There are correlation suggestions for approximate rock types in the literature. Some of these correlations in the literature were determined by a small number of experimental results. It is important to carry out correlation studies with a large number of samples in a certain region in order to find the closest value to the truth. As can be seen from the map below (Figure 1.1), the mineral structure and tectonic history of the rocks are different for each region in Türkiye. Even if the definition of the rock is the same, factors such as tectonic history and mineral structure affect the correlations. For this reason, academic studies containing detailed information about the rock are important and realistic resources in the use of correlations.

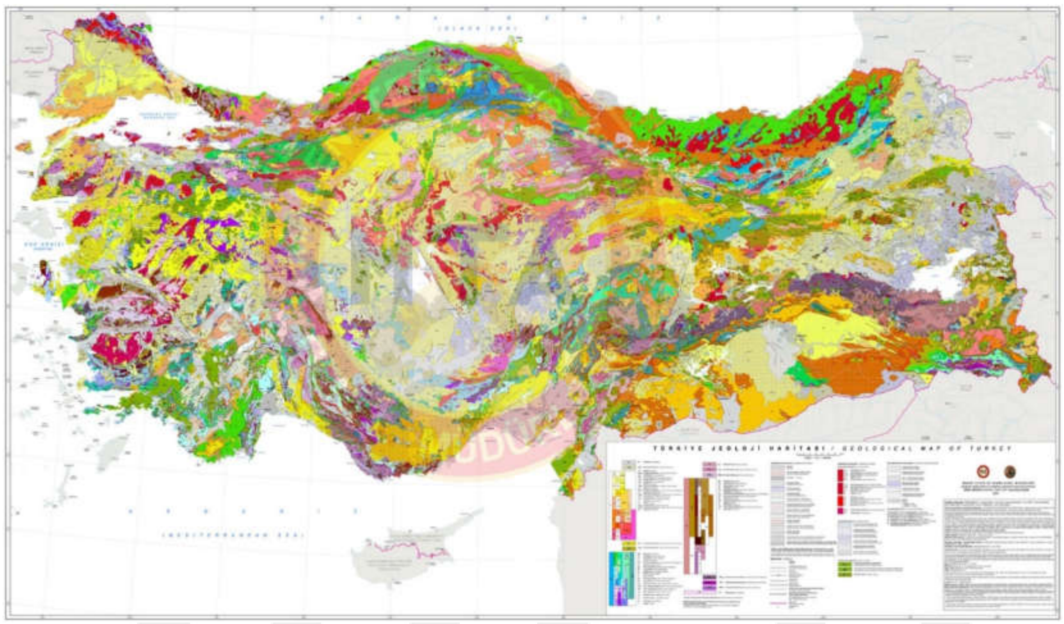


Figure 1.1 Turkey Geology Map (from MTA)

1.1. Scope of Thesis

The studies planned within the scope of this thesis consist of the following stages;

- Classification of test results obtained according to the structure and type of rocks.
- Obtaining correlations from classified test results.
- Comparing the obtained correlations with the literature and testing their accuracy.
- Making detailed descriptions of the formulations that are considered to be the most suitable to be a reference for future studies.

Within the scope of the thesis, the correlations mentioned above are evaluated for the rock types all over the world are discussed in the relevant chapters. After this introductory Chapter 1, in Chapter 2 information on rock classification techniques, mechanical properties of rocks, rock test procedures, and regression analysis methods are presented.

In Chapter 3, information about important studies in the literature on correlations, which is the main subject of the thesis, is presented.

In Chapter 4, many data such as all numerical data, graphics, photographs, mechanical and physical condition evaluations of rock types, correlation coefficients of suggestions are presented under sub-titles.

In Chapter 5, summary, major conclusions and important suggestions of this study are presented.

2. CLASSIFICATION OF ROCKS

Rock mechanics represents a scientific domain that combines theoretical and practical aspects of the mechanical characteristics exhibited by rocks and rock masses. Compared to geology, this branch of mechanics concentrates on the analysis of how rocks and rock masses react to the force fields present within their physical surroundings.

Figure 2.1 shows the details of the evaluation of the rock as a material. The scope of this thesis includes the determination of approximate correlations on the relationship between the mechanical characters of the rocks.

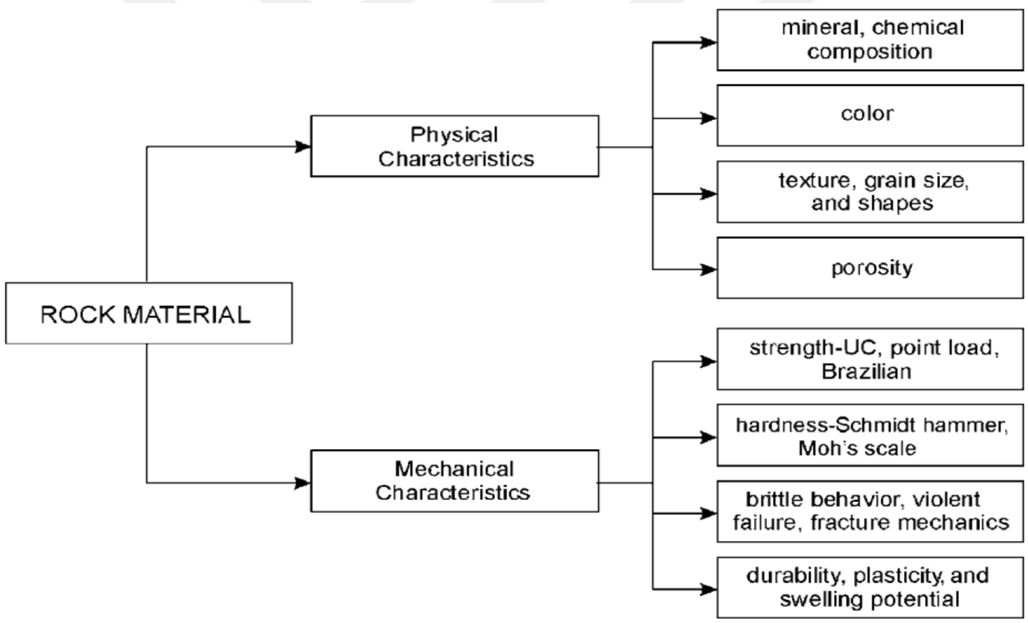


Figure 2.1 Material Characteristics of Rocks (Singh and Goel - 2011)

2.1. Rock Classification

There exists three primary classifications of rocks found in the natural environment: sedimentary, igneous (volcanic), and metamorphic. Each of these rock types is formed through physical transformations and possesses distinct properties. Rocks are formed from multiple accumulations of a single mineral or combination of different minerals.

2.1.1. Sedimentary Rocks

Sedimentary rocks develop through the collection, consolidation, and binding of fragments from other rocks and potential organic material. Sedimentology is the branch of science that studies the sedimentation and reclamation processes and products. Sedimentary rocks are divided into three groups as clastic, chemical and organic.

2.1.2. Igneous (Volcanic) Rocks

Igneous rocks originate from the cooling and crystallization of magma, which occurs either on the Earth's surface at volcanic sites or within the crust before solidification. Classification of igneous rocks, depends on how the magma has cooled. If cooled slowly, the rock will have a granular texture. If cooled rapidly, the rock will have a glassy texture.

2.1.3. Metamorphic Rocks

Metamorphic rocks have undergone transformations due to heat, pressure, and chemical reactions, typically at significant depths beneath Earth's surface. These intense conditions have resulted in changes to the rocks' mineral composition, structure, and chemical makeup.

Table 2.1 Rock Type Classification - 1

(Adapted from AS 1726 – 1993, Mayne, 2001 and Geoguide 3, 1988)

Description		*Sedimentary*					*Pyroclastic*
Superficial deposits	Grain size (mm)	Clastic (Sediment)			Chemically formed	Organic remains	
Boulders		Rudaceous	Conglomerate (Rounded fragments) Breccia (Angular fragments)				Agglomerate (Round grains) Volcanic Breccia (Angular grains)
	200						
Cobbles							
	60						
Coarse gravel							
	20						
Medium gravel							
	6						
Fine gravel					Halite Gypsum		
	2						
Coarse sand		Arenaceous	Sandstone Quartzite Arkose Greywacke		Limestone Dolomite		Coarse grained Tuff
	0.6						
Medium sand							
	0.2						
Fine sand							
	.06						
Silt		Argillaceous	Mudstone	Siltstone		Chalk, Lignite, Coal	Fine grained Tuff
	.002						
Clay			Shale	Claystone			Very fine grained Tuff

Table 2.2 Rock Type Classification - 2

(Adapted from AS 1726 – 1993, Mayne, 2001 and Geoguide 3, 1988)

Description		*Igneous (quartz content)* *Pale* --→ *Dark*			*Metamorphic*	
Superficial deposits	Grain Size (mm)	Acid (Much)	Intermediate (Some)	Basic (Little to none)	Foliated	Non- Foliated
Boulders		Granite Aplite	Granodiorite Diorite	Gabbro Peridotite	Gneiss Migmatite	Marble Quartzite Granulite Hornfels
	200					
Cobbles						
	60					
Coarse gravel						
	20					
Medium gravel						
	6					
Fine gravel						
	2					
Coarse sand		Micrograinte	Microdiorite	Dolerite	Schist	Serpentine
	0.6					
Medium sand						
	0.2					
Fine sand						
	.06					
Silt		Rhyolite Dacite	Andesite Quartz Trachyte	Basalt	Phyllite Slate	
	.002					
Clay						

2.2. Mechanical Properties of Rocks

The mineral structures of the rocks, their formation processes and the differences in natural conditions cause each rock type to have different physical properties. The degree of weathering of rocks in their conditions state is important in determining the tests that can be applied.

These differences are evaluated below in terms of strength and degree of weathering.

2.2.1. Rock Strength

Table 2.3 contains information about the ranges of uniaxial compressive strength of some rocks. In general, it is known that the strength of volcanic rocks is high. However, as explained above, features such as the tectonic history of the rocks and their mineral structure directly affect the strength. Different strengths can be obtained in different locations among the same rock type. In order to draw attention to this situation, correlation evaluations according to the results of the same rock type in different locations are also presented in this thesis.

Table 2.3 Variation of Rock Strength (Berkman, 2001)

Uniaxial compressive strength (MPa)	*Strength*	*Rock classification*		
		Sedimentary	*Metamorphic*	*Igneous*
15	Lowest			Welded Tuff
20	↑	Sandstone		Porphyry
25		Shale		Granadiorite
30		Sandstone		
45		Limestone	Schist	
60		Dolomite		Granadiorite
70			Quartzite	Granite
80				Rhyolite
90		Limestone		Granite
100		Dolomite, Siltstone, Sandstone	Schist	
150				Granite
200	↓		Quartzite	
220	Highest			Diorite

2.2.2. Rock Quailty Designation (RQD)

The rock quality designation (RQD) percentage serves as an indicator of fracture extent. It is utilized to assess rock properties such as weathering depth and degree, areas of rock vulnerability, and the extent of fracturing. This data is vital for calculating foundation depths, rock bearing capacities, settlements, and other geotechnical computations.

For instance, standards like FHWA and AASHTO provide equations based on uniaxial compressive strength and RQD values for rock-socket bored piles. An extremely low RQD value indicates inadequate sampling, necessitating calculations using correlations.

To determine RQD, the International Society for Rock Mechanics (ISRM) suggests using a core size of at least NX (54.7 mm) drilled with a double-tube core barrel and a diamond bit. All artificially created fractures must be disregarded when measuring the core length for RQD. Additionally, drilling at a slower pace will yield improved RQD results.

RQD valuation ranges and calculation method are given in the Table 2.4 and Figure 2.2.

Table 2.4 Rock Quality Designation (Burt G. Look Geotechnical Handbook, 2014)

RQD (%)	*Rock description*	*Definition*
0–25	Very poor	$\text{RQD (\%)} = \dfrac{\text{Sound core pieces} > 100\,\text{mm}}{\text{Total core run length}} * 100$
25–50	Poor	
50–75	Fair	
75–90	Good	
>90	Excellent	

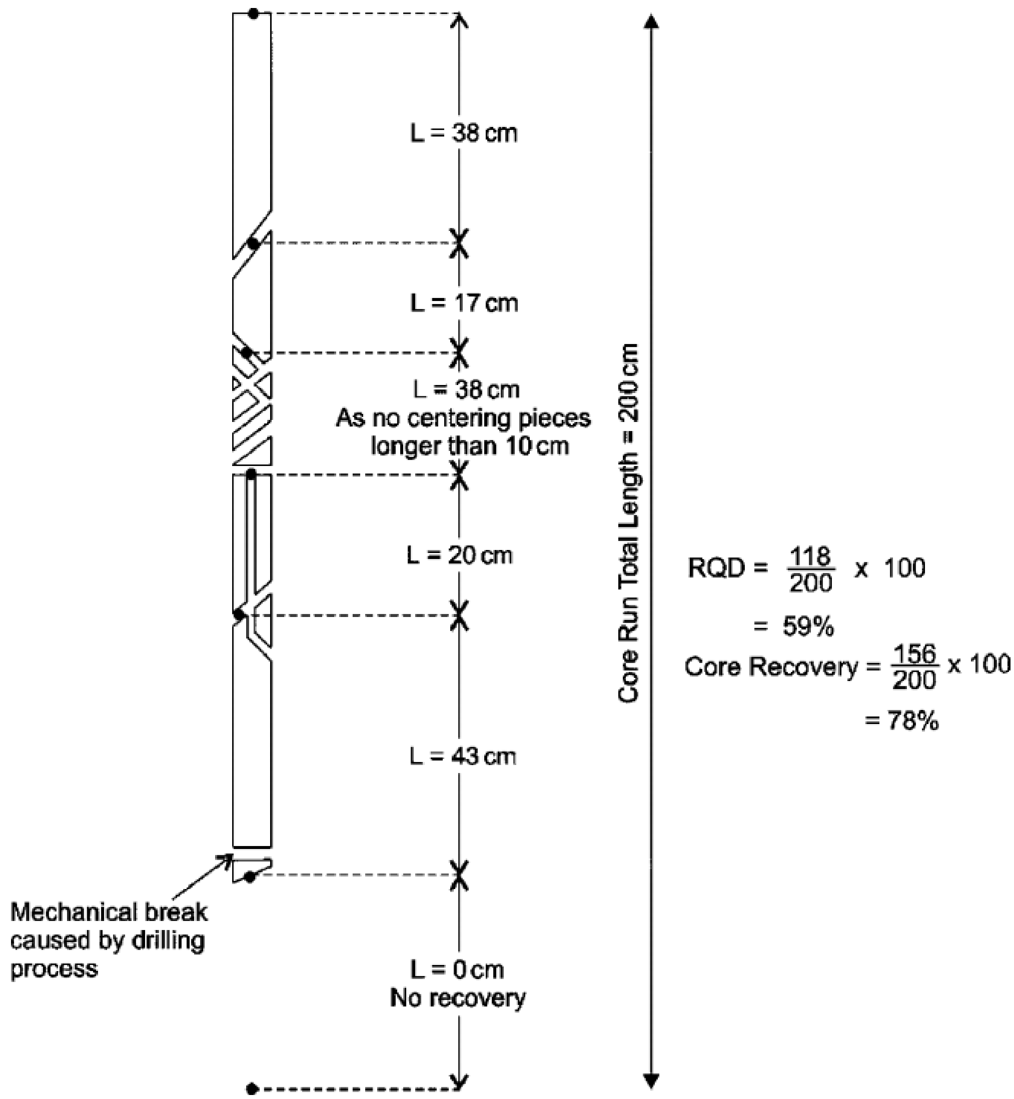


Figure 2.2 Procedure for Measurement and Calculation of Rock Quality Designation (RQD) (Deere, 1989)

2.3. Point Load Index Test (PLT)

The point load test is a prevalent method for assessing rock strength in geotechnical applications. It is frequently utilized for highly weathered rocks exhibiting low RQD values.

The equipment and process involved in the point load test allow for cost-effective testing of core or bulk rock samples in both field and laboratory environments. Its popularity is often attributed to its straightforward and widely recognized testing procedure.

Estimating the uniaxial compressive strength (UCS) becomes effortless using point load strength index tests on rock cores and rock lumps directly at the drilling site, as there is no need to cut and polish the ends of rock specimens

Rock samples, which can be in the form of cores (for diametral and axial tests), cut blocks (for block tests), or irregular chunks (for irregular lump tests), undergo testing by applying focused pressure through two truncated, cone-shaped platens. Minimal to no sample preparation is necessary.

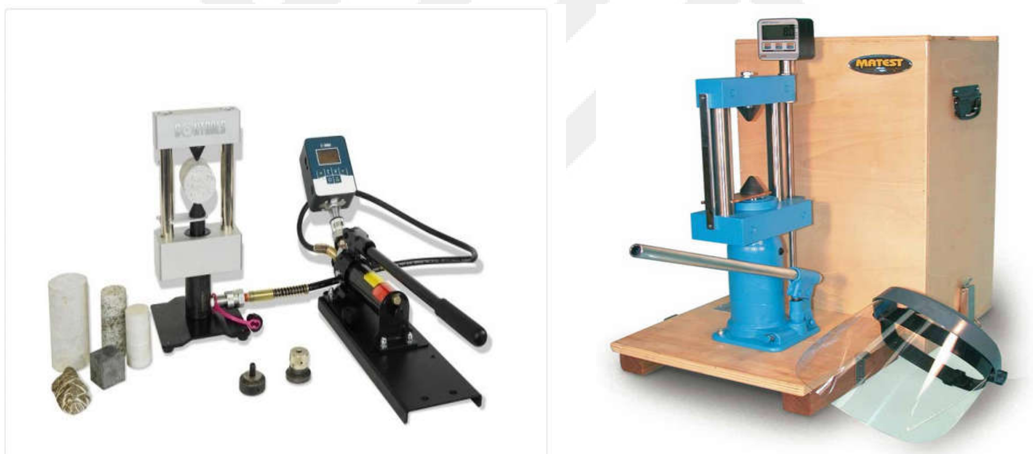


Figure 2.3 Point Load Index Test Apparatus

In accordance with ASTM D 5731 – 95, it is recommended that a minimum of 10 samples of the analyzed material be tested to ensure reliable results, with a greater number of samples necessary when dealing with anisotropic or heterogeneous rocks. The distance parameter, denoted as D, should be recorded with an accuracy of ±2%. Additionally, the applied load should progressively increase to ensure specimen failure within a timeframe of 10 to 60 seconds.

"Rock specimens in the form of either core (the diametral and axial tests), cut blocks (the block test), or irregular lumps (the irregular lump test) are tested by application of concentrated load through a pair of truncated, conical platens. Little or no specimen preparation is required". (ASTM D 5731 – 95)

PLT test can be performed on rocks with different geometries;

2.3.1. Diametral Test

Diametral point load tests are performed on cylindrical specimens, with the length-to-diameter ratio (2L/D) required to exceed unity. The specimen is situated in the loading apparatus and subjected to loading perpendicular to its central axis, ensuring that the platens come into contact along the diameter. The spacing between the contact points and the free end must surpass 0.5D. Subsequently, the distance between the contact points, which ought to be equivalent to the diameter, is documented, and the specimen is loaded until failure.

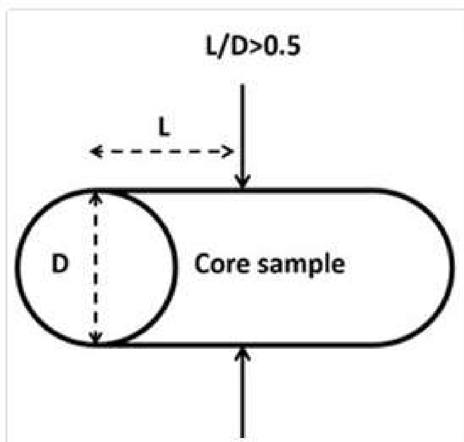


Figure 2.4 Diametral Point Load Test

2.3.2. Axial Point Load Test

The axial point load test is performed on cylindrical specimens characterized by a comparatively shorter length. The proportion of the specimen's length to its diameter should fall within the 0.3 to 1.0 range. The sample is positioned in such a way that the loading plates align with its central axis. Prior to commencing the test, the distance between the contact points is measured.

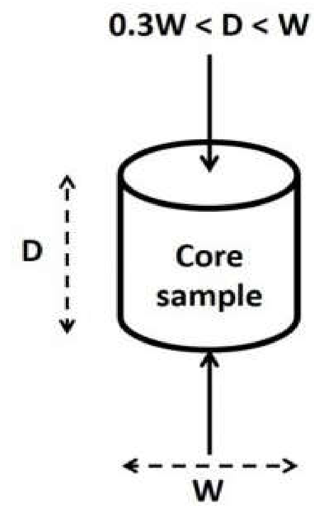


Figure 2.5 Axial Point Load Test

2.3.3. Block Lump Test

Block lump tests are conducted on rectangular prism specimens, preferably with dimensions of 5.0 ± 3.5 centimeters. The specimen is arranged in the apparatus such that its smallest dimension interacts with the loading plates. The ratio of diameter to width should be within the 0.3 to 1.0 range, and the spacing between the contact points and the unrestricted end of the sample must surpass 0.5D.

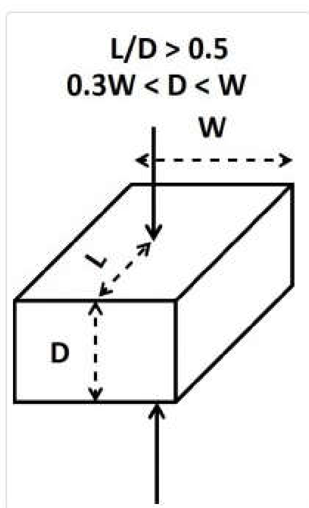


Figure 2.6 Block Lump Point Load Test

2.3.4. Irregular Lump Test

Point load tests can additionally be conducted on irregular blocks approximating the geometry of a rectangular prism. In such instances, a specific block's cross-section is regarded as a trapezoid featuring parallel top and bottom bases (W1 and W2) and a constant height (D). An average width is computed (W=(W1+W2)/2), and the loading procedure is akin to that employed in the block lump test.

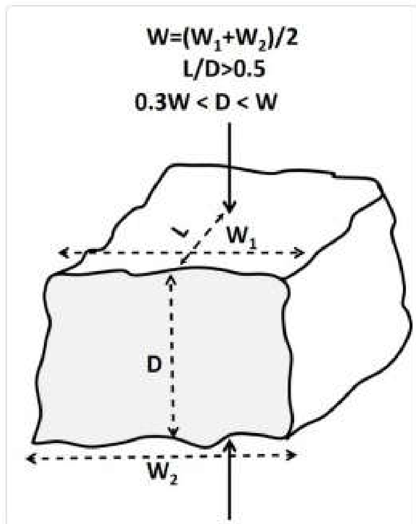
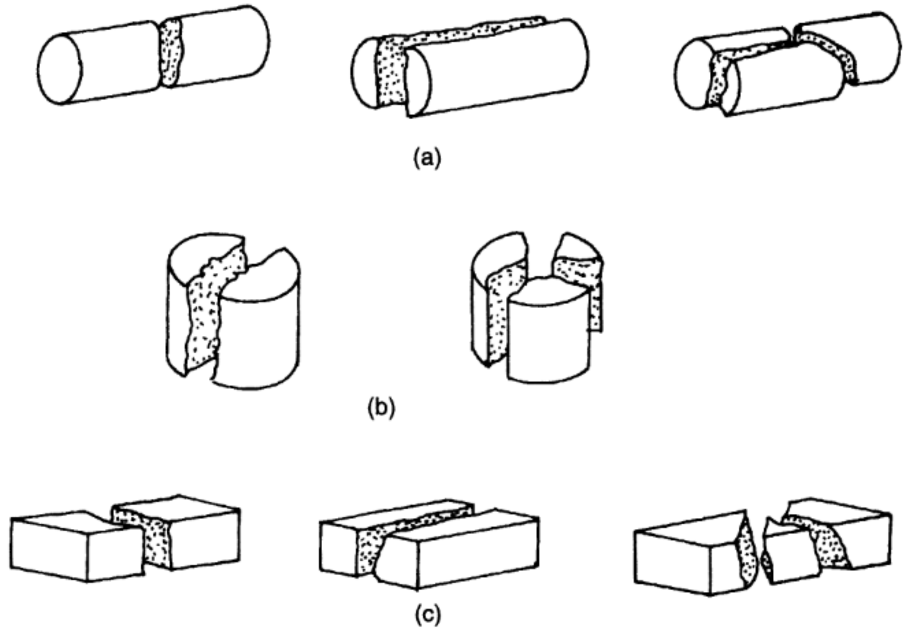


Figure 2.7 Irregular Lump Point Load Test

Rock specimens are categorized according to their rock type and anticipated strength. For core or block samples, a minimum of ten specimens is chosen, while for irregularly-shaped specimens obtained through other methods, at least 20 specimens are selected. Core samples are preferred for a more accurate classification.

The external dimensions of the specimen should be no less than 30 mm and no more than 85 mm, with an ideal size of approximately 50 mm.



a) valid diametrical test
b) valid axial test
c) valid block test

Figure 2.8 Typical Modes of Failure for Valid and Invalid Test (IS-8764)

Uncorrected Point Load Strength Index;

The uncorrected point load strength Is is calculated as:

$$I_s = P/D_e^2 \quad \text{(MPa)} \qquad \text{Equation 2-1}$$

Where:

P = Failure load, N,

D_e = Equivalent core diameter

D = For diametral tests, m,

$D_e^2 = D^2$ for cores, mm^2,

$D_e^2 = 4A/\pi$ for axial, block, and lump tests, mm^2;

A = WD = Minimum cross-sectional area of aplane through the platen contact points

In the diametral test, I_s changes based on D, while in axial, block, and irregular lump tests, it varies according to D_e. Thus, a size adjustment is necessary to achieve a singular point load strength value for the rock specimen, which can be utilized for rock strength classification purposes.

The adjusted point load strength index, $I_{s(50)}$, for a rock sample is determined as the Is value that would be observed in a diametral test where D equals 50 mm.

$$I_{s\,(50)} = F \times I_s \qquad \text{Equation 2-2}$$

The “Size Correction Factor F” can be obtained from the chart in Figure 2.9, or from the expression:

$$F = (D_e / 50)^{0.45} \qquad \text{Equation 2-3}$$

For tests near the standard 50 mm size, only slight error is introduced by using the approximate expression:

$$F = \sqrt{(D_e / 50)} \qquad \text{Equation 2-4}$$

Table 2.5 Standard Size and Designation of Casing, Core Barrel, and Drill Rod

Casing and core barrel designation	Outside diameter of core barrel bit (mm)	Drill rod designation	Outside diameter of drill rod (mm)	Diameter of borehole (mm)	Diameter of core sample (mm)
EX	36.51	E	33.34	38.1	22.23
AX	47.63	A	41.28	50.8	28.58
BX	58.74	B	47.63	63.5	41.28
NX	74.61	N	60.33	76.2	53.98

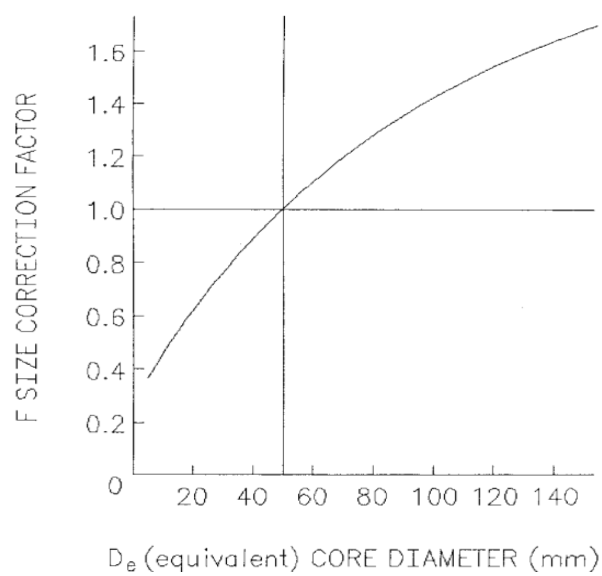


Figure 2.9 Size Correction Factor Chart (ASTM D 5731 - 95)

2.4. Uniaxial Compressive Strength Test

The uniaxial compression test is a laboratory procedure employed to determine the uniaxial compressive strength (UCS) of a rock specimen. The UCS represents the maximum axial compressive stress that a specimen can withstand in the absence of confining stress. This parameter holds significant importance within geotechnical design practices.

According to ASTM D7012 – 14;

- “These four test methods cover the determination of the strength of intact rock core specimens in uniaxial and triaxial compression. Methods A and B determine the triaxial compressive strength at different pressures and Methods C and D determine the unconfined, uniaxial strength.”
- “Methods A and B can be used to determine the angle of internal friction, angle of shearing resistance, and cohesion intercept.”
- “Methods B and D specify the apparatus, instrumentation, and procedures for determining the stressaxial strain and the stress-lateral strain curves, as well as Young’s Modulus, E, and Poisson’s ratio, υ. These methods make no provision for pore pressure measurements and specimens are undrained (platens are not vented). Thus, the strength values determined are in terms of total stress and are not corrected for pore pressures. These test methods do not include the procedures necessary to obtain a stress-strain curve beyond the ultimate strength.”

A rock core sample is prepared by cutting it to the required length and machining the ends to achieve flatness. The specimen is positioned within a loading frame, and if needed, situated in a loading chamber where it is subjected to confining pressure. In cases where the test is performed at varying temperatures, the specimen is either heated or cooled to the desired temperature prior to test initiation. The axial load exerted on the specimen is progressively increased and continuously measured. Deformation measurements are not acquired for Methods A and C; however, they are recorded as a function of load until peak load and failure are attained for Methods B and D.

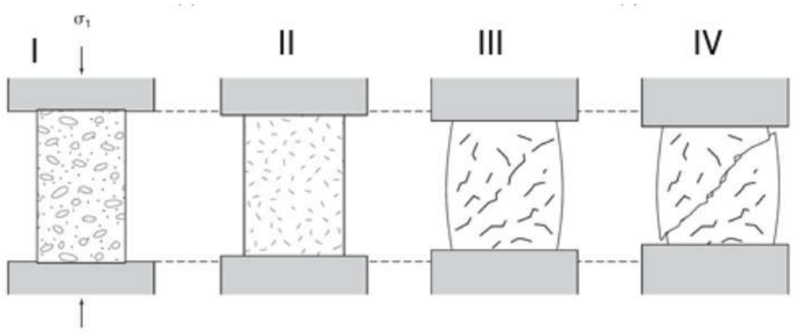


Figure 2.10 Rock Failure Under Axial Load (https://www.usb.ac.ir)

The compressive strength of the test sample is determined according to the following equation:

$$\sigma = \frac{P}{A} \qquad \text{Equation 2-5}$$

σ_u = Uniaxial compressive strength (MPa),

P = Failure load (kN),

A= Cross-sectional area (mm^2)

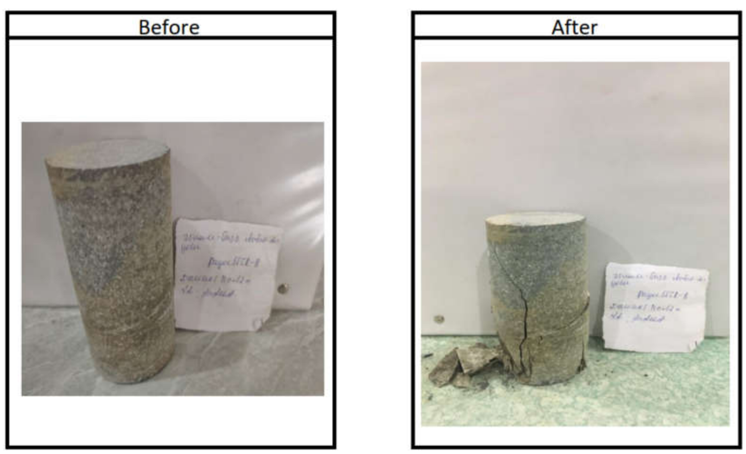


Figure 2.11 UCS Test Sample Process

The UCS value is directly related to the sample geometry. Hoek and Brown have prepared the chart in Figure 2.12 for these situations. A sample diameter of 50 mm is accepted as a standard. Necessary corrections should be made for larger or smaller diameters.

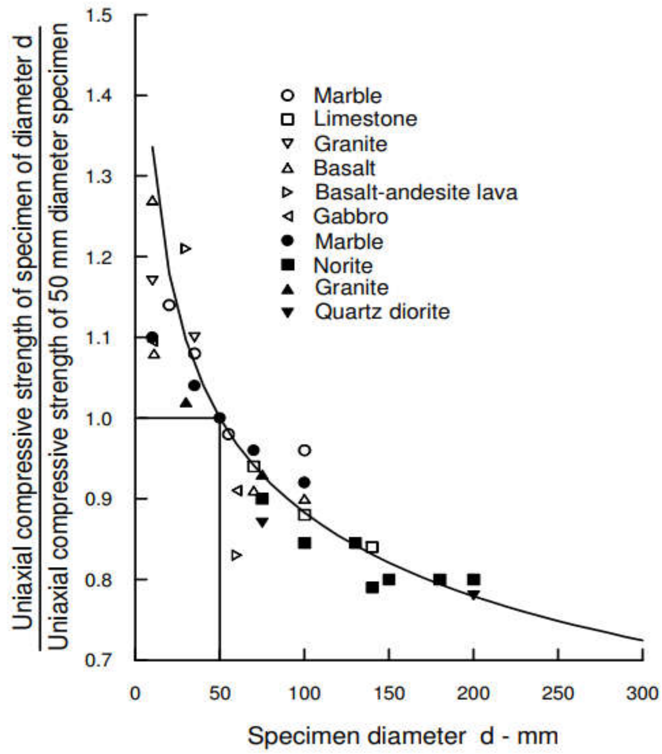


Figure 2.12 Influence of Specimen Size on The Strength of Intact Rock (Hoek and Brown, 1980)

2.5. Elastic Modulus of Rocks

Through the uniaxial compression test, it is possible to ascertain the Young's modulus of elasticity and Poisson's ratio of a rock specimen, provided the stress-strain behavior is captured until the peak point. The slope of the stress-strain curve directly yields the elastic modulus of the specimen.

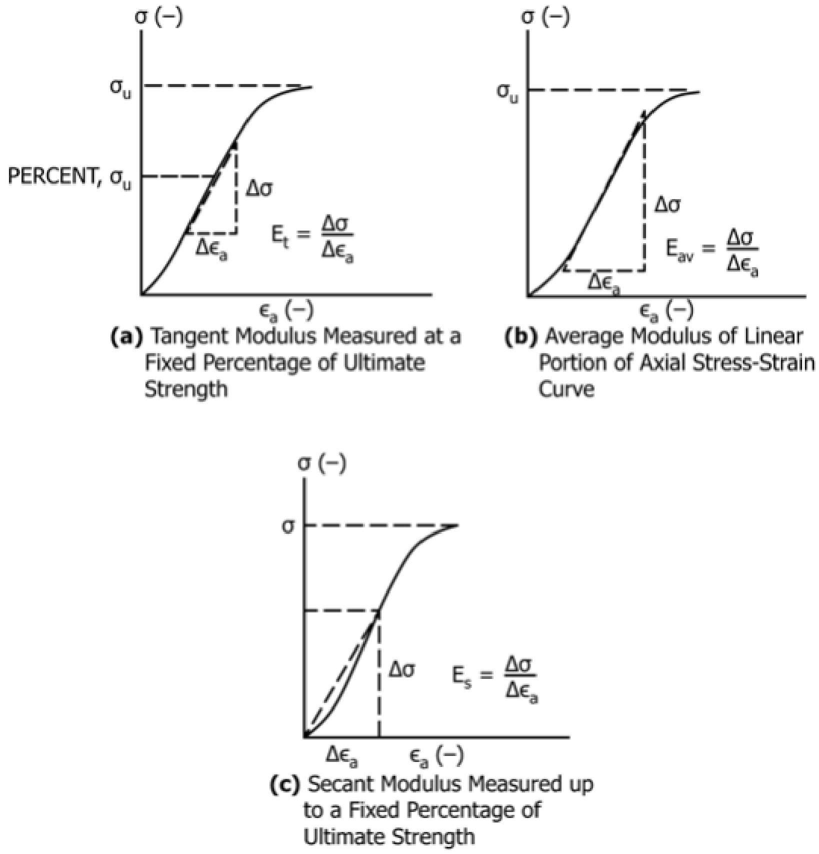


Figure 2.13 Methods for Calculating Young's Modulus from Stress - Strain Curve

Young's modulus, defined as the ratio of the change in axial stress to the rate of axial strain induced by the stress alteration, can be calculated utilizing various methods plotted on the stress-strain curve. The tangent Young's modulus is determined at a specific stress level, usually a fixed percentage of the ultimate strength (as depicted in Figure 2.13a). Conversely, the secant Young's modulus is measured from zero stress to a predetermined percentage of the ultimate strength, commonly set at 50% (as shown in Figure 2.13b).

2.6. Standards of Tests

The test results used in this study were obtained by performing the following standards.

- Natural Unit Weight (ISRM)
- Modulus of Elasticity (TS 2030 / ISRM)
- Uniaxial Compressive Strength (TS EN 1926 / ISRM)
- Point Load Strength Index (TS 699)

2.7. Regression Analysis

Regression analysis represents a statistical technique employed to evaluate the association between dependent variables. This method is utilized to determine the intensity of the correlation between variables and to predict their future interactions. Various forms of regression analysis exist, such as linear, exponential, logarithmic, and power, among others.

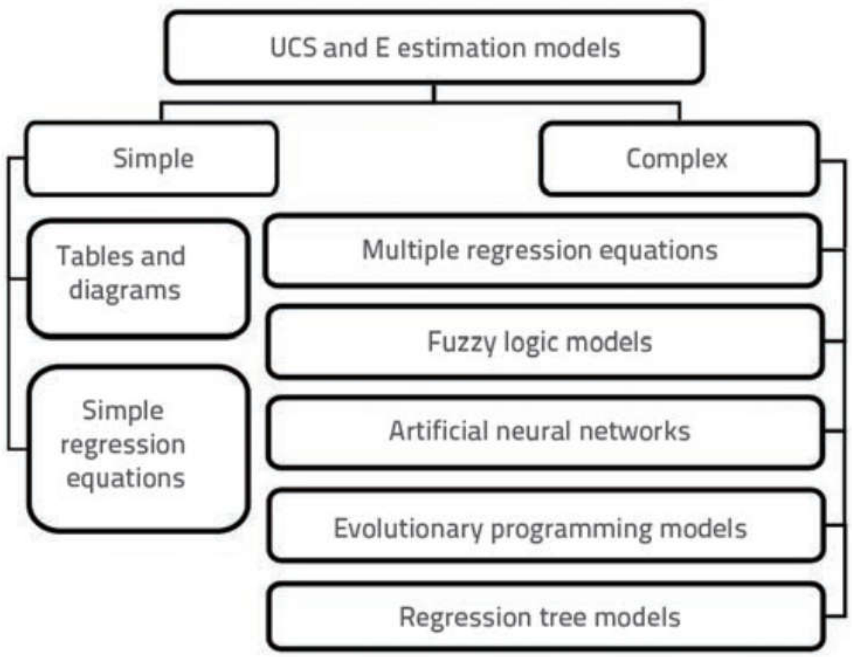


Figure 2.14 Classification of Methods for Estimating Physicomechanical Properties of Intact Rock Material (Brisevac Z., Hrzenjak P., Buljan R.,2016)

Simple regression analyzes for each independent variable were performed within the scope of the thesis study. Among the relationships obtained, the relationship that best represents the experimental results was determined. (R^2 value).

$$R^2 = 1 - \frac{\sum_{i=1}^{m} (X_i - Y_i)^2}{\sum_{i=1}^{m} (\bar{Y} - Y_i)^2}$$

The R-squared value consistently ranges from 0 to 1, where;

- A value of 0 signifies a model that fails to account for any variation in the response variable surrounding its mean. In this case, the dependent variable's mean serves as a predictor as effectively as the regression model.
- A value of 1 indicates a model that captures all the variation in the response variable around its mean.

Although simple regression equations yield relatively accurate estimation results, their efficacy depends on the specific rock type for which they have been devised. Moreover, even within the same rock type, these equations may not encompass all property variations

The estimation of UCS or E values can be accomplished through simple methodologies employing diagrams, tables, or relying on specific index tests. Conversely, complex approaches employ multiple types of test results as the foundation for prediction, necessitating the use of intricate computer programs to implement such methods.

The UCS value is calculated using the PLI value, and the E value is calculated using the UCS value.

UCS value = PLI * C   C = variable coefficient (as in ASTM)

E value = UCS * MR   MR = modulus of rock (Hoek and Diederichs, 2006)

3. UCS – E and UCS – PLI CORRELATIONS in LITERATURE

3.1. UCS – E Correlations

There are many studies in the literature about the relationship between uniaxial compressive strength and modulus of elasticity. Most commlonly used ones will be evaluated in this chapter. However, as some of the studies has limited number of samples and/or they do not contain the rock samples within the scope of the thesis, they are not included within this chapter.

The results tables of the studies, which are generally accepted in the literature and include the rock types within the scope of the thesis, are presented. The following correlations has been tabulated taken from the sources their original status. (Table 3.1, Table 3.2 and Table 3.3)

“The most common parameter used in engineering practice for easy evaluation of Young’s Modulus is the modulus ratio MR”. (Hoek & Diederichs, 2006) The MR value is the ratio of the E value to the UCS value.

“The modulus ratio, defined as the ratio of the Young Modulus (E) to the Uniaxial Compressive Strength (σ_c), is a useful parameter for estimating E from σ_c. This ratio varies in the range of 100 - 1000, depending on the rock type.” (Ameratunga, J., Sivakugan, N., and Das, B.M.,).

Typical values for the modulus ratios as suggested by Hoek and Diederichs (2006) are summarised in Table 3.1, Table 3.2 and Table 3.3.

Table 3.1 Typical Values of Modulus Ratios - Sedimentary Rocks (Hoek and Diederichs - 2006)

	Texture			
	Coarse	**Medium**	**Fine**	**Very Fine**
Sedimentary	Conglomerates	Sandstones	Siltstones	Claystones
	300 - 400	200 - 350	350 - 400	200 - 300
	Breccias		Greywackes	Shales
	230 - 350		350	150 - 250[a]
				Marls
				150 - 200
	Crystalline limestone	Sparitic limestone	Micritic limestone	Dolomite
	400 - 600	600 - 800	800 - 1000	350 - 500
		Gypsum	Anhydrite	Chalk
		(350)[c]	(350)[c]	1000 +

Table 3.2 Typical Values of Modulus Ratios - Metamorphic Rocks (Hoek and Diederichs - 2006)

	Texture			
	Coarse	**Medium**	**Fine**	**Very Fine**
Metamorphic	Marble	Hornfels	Quartzite	
	700 - 1000	400 - 700	300 - 450	
		Metasandstone		
		200 - 300		
	Migamatite	Amphibiolites	Gneiss	
	350 - 400	400 - 500	300 - 750	
		Schists	Phyllites / Mica Schist	Slates
		250 - 1100[a]	300 - 800[a]	400 - 600[a]

Table 3.3 Typical Values of Modulus Ratios - Igneous Rocks

(Hoek and Diederichs - 2006)

	Texture			
	Coarse	**Medium**	**Fine**	**Very Fine**
Igneous	Granite[b]	Diorite[b]		
	300 - 550	300 - 350		
	Granodiorite			
	400 - 450			
	Gabro	Dolerite		
	400 - 500	300 - 400		
	Norite			
	350 - 400			
	Porphyries		Diabase	Peridotite
	400[c]		300 - 350	250 - 300
		Rhyolite	Dacite	
		300 - 500	350 - 450	
		Andesite	Basalt	
		300 - 500	250 - 450	
	Agglomerate	Volcanic Breccia	Tuff	
	400 - 600	500[c]	200 - 400	

"[a] Highly anisotropic rocks: the modulus ratio will be significantly different if normal strain and/or loading occurs parallel (high modulus ratio) or perpendicular (low modulus ratio) to a weakness plane. Uniaxial test loading direction should be equivalent to field application."

"[b] Felsic granitoids: Coarse grained or altered (High modulus ratio), fine grained (low modulus ratio)."

"[c] No data available; Estimated on the basis of geological logic."

Roclab software, which is frequently used by geotechnical and geological engineers, simply presents the MR ratio between UCS and E values. Roclab software uses the MR value ranges given in Figure 3.1.

Modulus of elasticity (Intact Modulus E_i) = UCS * Modulus Ratio

For example, if the calculation is made for andesite rocks;

UCS (sigci) = 30 MPa

MR Value (modulus ratio) = 400 (average value)

E_i = 30 * 400 = 12.000 MPa

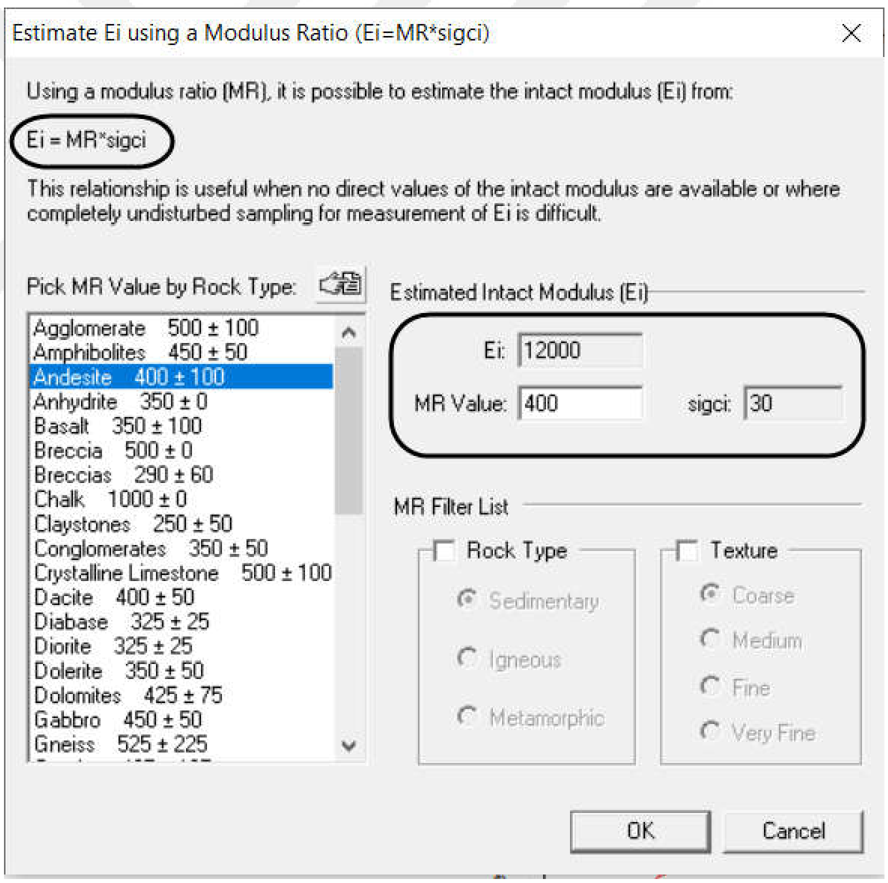


Figure 3.1 Roclab Software's Modulus Ratio Input Page

Deere and Miller in their book "Engineering Classification and Index Properties for Intact Rock (1966)" have prepared different charts for the modulus ratio. In this book, UCS values are divided into five categories as A,B,C,D and E, modulus ratio values are divided into three categories as high, average and low.

Table 3.4 Rock Classification Tables (Deere and Miller, 1966)

Class	**Description**	**UCS (lb / in²)**
A	Very High Strength	Over 32.000
B	High Strength	16.000 – 32.000
C	Medium Strength	8.000 – 16.000
D	Low Strength	4.000 – 8.000
E	Very Low Strength	Less Than 4.000

Class	**Description**	**Modulus Ratio**
H	High Modulus Ratio	Over 500
-	Average Modulus Ratio	200 – 500
L	Low Modulus Ratio	Less Than 200

Classify rock as B, BH, BL, etc.

According to Deere and Miller (1996) ;

Modulus Ratio : E_t / σ_a (ult.)

Where E_t = tangent modulus at 50 % ultimate strength

σ_a = uniaxial compressive strength

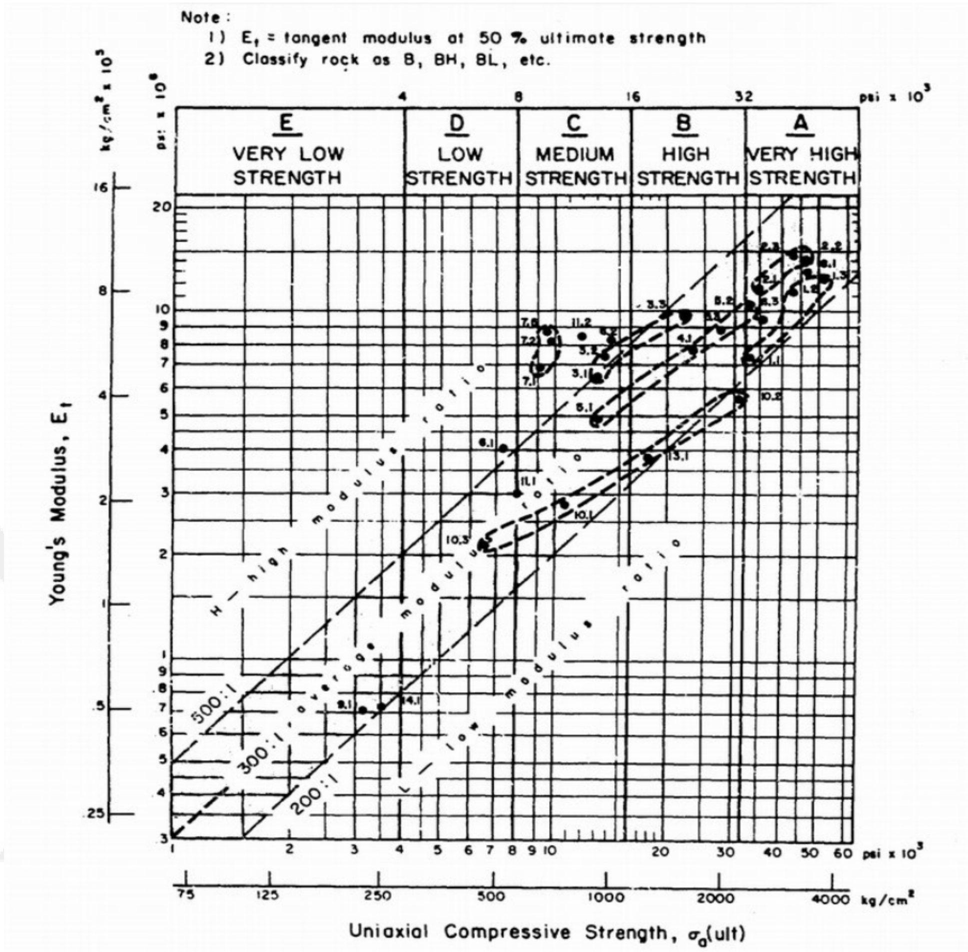


Figure 3.2 Engineering Classification of Rocks (Deere and Miller, 1966)

Table 3.5 Rock Modulus Values (According to Deere and Miller, 1966)

*E/q*u	*Material*	*Comments*
1000	Steel, concrete	Man-made materials
500	Basalts & other flow rocks (Igneous rocks) Granite (Igneous) Schist: low foliation (Metamorphic) Marble (Metamorphic)	*High modulus ratio – UCS > 100 MPa* Metasediments 730 in SE Qld Basalt in Brisbane was 300 and 680 in SE Qld Granite in Queensland was 640 Phyllite (foliated metamorphic) in Brisbane was 500 Tuff (Pyroclastic Igneous) in Brisbane was 150
200	Gneiss, Quartzite (Hard metamorphic rocks) Limestone (Sedimentary) Dolomite (Calcareous sedimentary: Coral)	*Medium modulus ratio – UCS = 60–100 MPa*
100	Shales, Sandstones (Sedimentary rocks) Schist: steep foliation	*Low modulus ratio – UCS < 60 MPa* Horizontal bedding: Lower the E values Sedimentary 370 in SE Qld

Table 3.6 Modulus Ratio MR According to Some Studies (E and UCS in MPa)

Rock Type	Reference	Number of Samples	MR (range)
Claystone	Hoek & Diederichs,2006	nda	(200 - 300)
	Malik & Rashid,1997	30	141 (87 - 228)
	Małkowski & Ostrowski,2017 (Carboniferous)	81	E_{tan}274 (118 - 657)
			E_{av}276 (77 - 606)
			E_{sec}269 (79 - 616)
Siltstone	Hoek&Diederichs,2006	nda	(350 - 400)
	Malik&Rashid,1997	30	137 (79 - 190)
Mudstone	Małkowski&Ostrowski,2017 (Carboniferous)	70	E_{tan}232 (59 - 421)
			E_{av}242(61 - 500)
			E_{sec}203(45 - 436)
Sandstone	Hoek&Diederichs,2006	nda	(200 - 350)
	Bell&Lindsay,1999	27	372 (141- 680)
	Malik&Rashid,1997	30	119 (76 -157)
	Sabatakakisetal.,2008	36	303 (120 - 727)
	Małkowski&Ostrowski,2017 (Carboniferous)	86	E_{tan}223(139 - 381)
			E_{av}236(141- 491)
			E_{sec}187(82 - 379)

3.2. UCS – PLI Correlations

There are many studies in the literature about the relationship between uniaxial compressive strength and point load index. Since it does not include the rock samples within the scope of the academic thesis, it was not evaluated. Since the correlations in the literature in general are made with a limited number of samples, its use in geotechnical calculations has risks. Also, in some academic publications, correlations have been determined for all rocks or for a certain rock class.

In the relevant parts of the thesis, the relationship between sample depth and the variation of the correlation coefficient has been examined. Deep exploration drilling is generally applied in underground structures such as mining and tunnels. As stated in the specifications, shallower drillings are made in bridges, buildings and similar engineering structures.

It is also seen that correlations are formulated with different physical and mechanical properties of the rock in some academic studies. There is some justification for this approach. Rocks of the same type with different void ratio or porosity are likely to have different correlation values. This also applies to the degree of saturation.
The results these studies, which are widely accepted in the literature and include the rock types within the scope of the thesis, are presented in Table 3.7.

Table 3.7 Correlating Equations for UCS and PLI Given by Previous Researchers

Rock Type	Author (s)	Correlations
Various rock types	Broch and Franklin (1972)	UCS=23.7 * PLI
Sandstones	Bieniawski (1975)	UCS=23.9 * PLI
Sedimentary rocks	Hassani et al (1980)	UCS=29 * PLI
Sedimentary rocks	Read et al (1980)	UCS=20 * PLI

Rock Type	Author (s)	Correlations
Basalts	Read et al. (1980)	UCS = 18 * PLI
Granites, Igneous Rocks	Lumb (1983)	UCS = 22 * PLI
Sedimentary rocks	Gunsallus and Kulhawy (1984)	UCS = 16.5 * PLI + 51
-	ISRM (1985)	UCS = (20, …, 25) * PLI
Granites, Limestones	Brook (1985)	UCS = 22 * PLI
Basalts	Brook (1985)	UCS = 20 * PLI
Siltstones	Das (1985)	UCS=14.7 * PLI
Sandstones	Das (1985)	UCS=18 * PLI
Shales	Das (1985)	UCS=12.6 * PLI
Limestones	Hawkins and Olver (1986)	UCS=26.5 * PLI
Sandstones	Hawkins and Olver (1986)	UCS=24.8 * PLI
Sedimentary rocks	O'Rourke (1988)	UCS=30 * PLI
Sandstones	Vallejo et al (1989)	UCS=17.4 * PLI
Granites	Ghosh and Srivastava (1991)	UCS=16 * PLI
Quartzite	Singh and Singh (1993)	UCS=23.4 * PLI
Sandstones	Ulusay et al (1994)	UCS=19 * PLI+12.7
Granites, Tuffs	Chau and Wong (1996)	UCS=12.5 * PLI

Rock Type	Author (s)	Correlations
Sandstones / Limestones	Smith (1997)	UCS = 24 * PLI
Sedimentary Rocks	Brautigam et al. (1998)	UCS = 20.4 * PLI
Igneous Rocks	Brautigam et al. (1998)	UCS = 14.2 * PLI
Shales	Rusnak and Mark (1999)	UCS=21.8 * PLI
Siltstones	Rusnak and Mark (1999)	UCS=20.2 * PLI
Sandstones	Rusnak and Mark (1999)	UCS=20.6 * PLI
Limestones	Rusnak and Mark (1999)	UCS=21.9 * PLI
Igneous Rocks	Tugrul and Zarif (1999)	UCS=15.25 * PLI
Mixed	Sulukcu and Ulusay (2001)	UCS=15.3 * PLI
Sedimentary rocks	Tsiambaos and Sabatakakis (2004)	UCS= 7.3 * $PLI^{1.71}$
Shales, Limestones, Sandstones	Kahraman and Alper (2006)	UCS = 17.91 * PLI + 7.93
Igneous Rocks	Basu and Aydin (2006)	UCS = 18 PLI
Sandstone, Limestone, Marl	Akram and Bakar (2007)	UCS=11.076 PLI
Sedimentary (hard rocks)	Akram and Bakar (2007)	UCS = 22.792 * PLI + 13.295
Sedimentary rocks	Sabatakakis et al. (2008)	UCS = 25.3 * PLI
Metamotphic	Diamantis et al. (2009)	UCS=19.79 * PLI
Igneous Rocks	Kahraman and Gunaydin (2009)	UCS = 8.2 * PLI + 36.43

Rock Type	Author (s)	Correlations
Limestones	Singh et al (2012)	UCS=22.3 * PLI
Shales	Singh et al (2012)	UCS=14.4 * PLI
Mixed	Kohno and Maeda (2012)	UCS=16.40 * PLI
Basalts (saturated)	Endait and Juneja (2015)	UCS = 18 * PLI
Basalts (dry)	Endait and Juneja (2015)	UCS = 24 * PLI
Basalts	Sharo and Al Tahawa (2019)	UCS = 23.52 * PLI
Igneous Rocks	Kallu and Roghanchi (2015)	$UCS=90.14 * PLI^{0.92}$
Granitoid	Tandon and Gupta (2015)	UCS = 5.602 * PLI + 4.38
Mixed	Mohamad et al. (2015)	UCS = 12.291 * PLI + 5.892

According to ASTM - D 5731 – 95;

Estimation of compressive strength;

The estimated uniaxial compressive strength can be obtained by using the following formula;

$$\delta_{uc} = C * I_{s\,(50)} \qquad \text{Equation 3-1}$$

δ_{uc} = uniaxial compressive strength,

C = factor that depends on site-specific correlation between δ_{uc} and $I_{s\,(50)}$, and

$I_{s\,(50)}$ = corrected point load strength index

Table 3.8 Generalized Value of "C"[A]

Core Size, mm	Value of "C" (Generalized)
20	17.5
30	19
40	21
50	23
54	24
60	24.5

[A] From ISRM Suggested Methods.[3]

Suarez-Burgoa (2012), states that there are uncertainties due to the variation of the correlation coefficient in a wide range, and it should be avoided to indirectly switch to uniaxial compressive strength by using the result found in the point load strength index test. It states that the strength index values determined by point load test should be classified among themselves and without using any correlation.

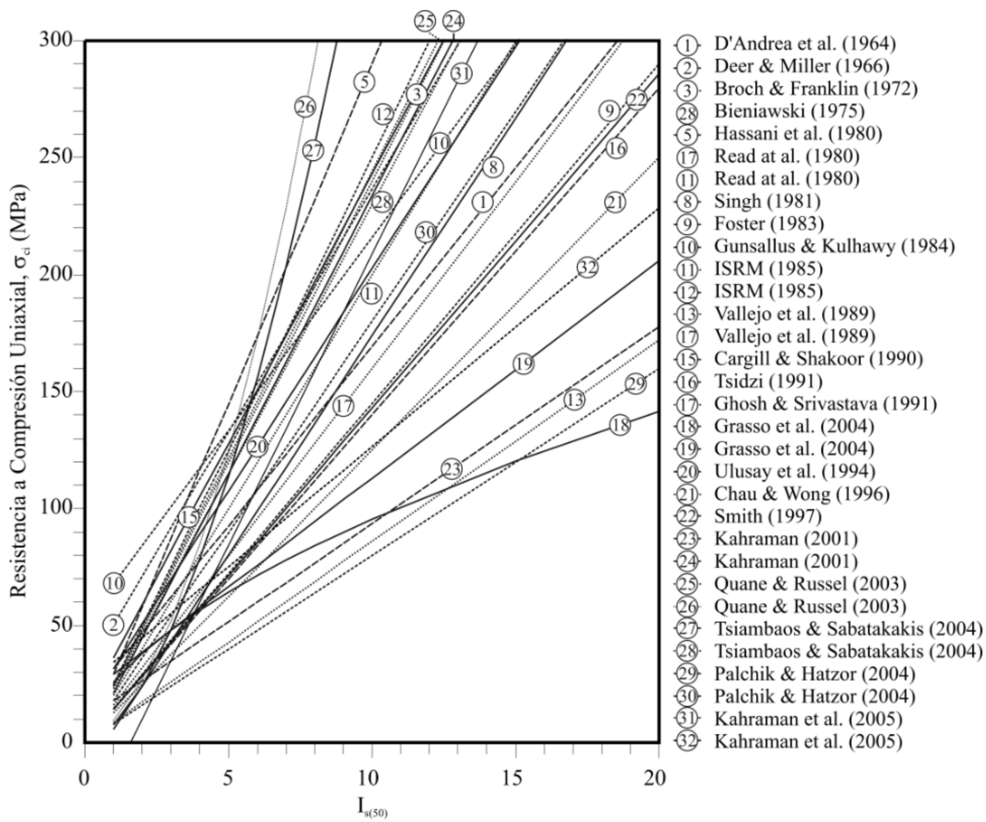


Figure 3.3 Variation of UCS with PLI (Suarez- Burgao, 2012)

4. DETERMINATION OF CORRELATIONS

Within the scope of this thesis, different rock types belonging to different regions of Turkey were examined. Uniaxial compressive strength, point load index and elasticity modulus values for each rock type are listed depending on the depths. The rocks have been grouped considering that their formation information is the same. As a result of the studies, it is aimed to determine the closest correlation for some soil formations named by MTA in Turkey. The locations where the rock samples were taken are indicated on the map presented in Figure 4.1.

Figure 4.1 Location of All Samples Points

MTA formation information of each rock sample point is also given below.

Rock Type - 1 : Beydaglari Formation

Rock Type - 2 : Elmali Formation

Rock Type - 3 : Erenler Mountain Volcanic Complex and Dilekci Formation

Rock Type - 4 : Kaçkar Granodiorite I & II and Catak Formation

Rock Type - 5 : İhsaniye Formation

In the scope of the thesis, it is aimed to propose correlations determined specifically for the formations which will be more suitable references for future engineering studies.

Within the scope of the thesis, five rock types belonging to different formations are examined. The summary table of the number of samples used for correlations is given in Table 4.1.

Table 4.1 Number of Samples Summary Table (All Rock Types)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 1	Limestone	836	886	392	392
Rock Type - 2	Alternation of Shale - Sandstone - Claystone	559	287	267	267
Rock Type - 3	Andesite	340	134	155	155
Rock Type - 4	Granite, Granodiorite	233	125	113	113
Rock Type - 5	Claystone	-	-	262	262

The definitions of rock types in the borehole logs are as follows;

Rock type - 1: Light gray – light beige colors, generally medium weak - weak and occasionally medium strength, very and moderately weathered, very often fractured crystallized limestone. Unit weight value is in the range of generally 2.50 - 2.70 gr/cm^3.

Rock type - 2: Light gray-greenish gray color, medium weak - weak strength, very moderately weathered in general, shale - claystone - sandstone alternation. Unit weight value is in the range of generally 2.20 - 2.60 gr/cm^3.

Rock type - 3: Gray - beige color, medium - medium weak strength, moderate - highly weathered, highly fractured - fragmented, discontinuity surfaces rough, poor - very poor rock quality andesite. Unit weight value is in the range of generally 2.10 - 2.60 gr/cm^3.

Rock type - 4: Black colored, moderately weathered, medium weak strength, fragmented-fractured, fractured surfaces with wavy roughness, very poor rock quality basalt. Grayish-grey colored less weathered, partly moderate-highly weathered strength-medium strength, partly weak-strength massive-very sparsely fractured, partly fragmented-fractured granite. Unit weight value is in the range of generally 2.30 - 2.60 gr/cm^3.

Rock type - 5: Gray-fume color, densely fractured structure, moderately weak strength, slightly-moderate weathering, good rock quality claystone. Unit weight value is in the range of generally 2.20 - 2.50 gr/cm^3.

4.1. Rock Type - 1 (Limestone)

In this section, correlation studies related to limestones are presented. The samples were taken from Isparta - Burdur - Antalya in the Western Mediterranean region. The working area is marked on the map below (Figure 4.2).

Figure 4.2 Location of Samples (Rock Type – 1)

As indicated in the geological maps below (Figure 4.3, Figure 4.4, Figure 4.5) the presence of limestones is evident in the general formation of the region.

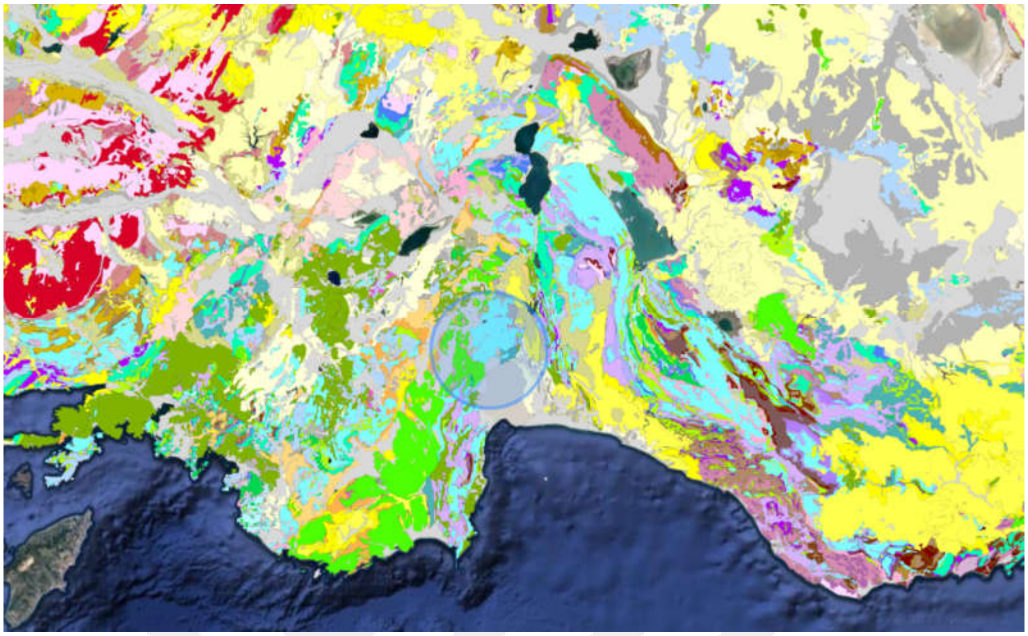


Figure 4.3 Formation Information (from MTA website)

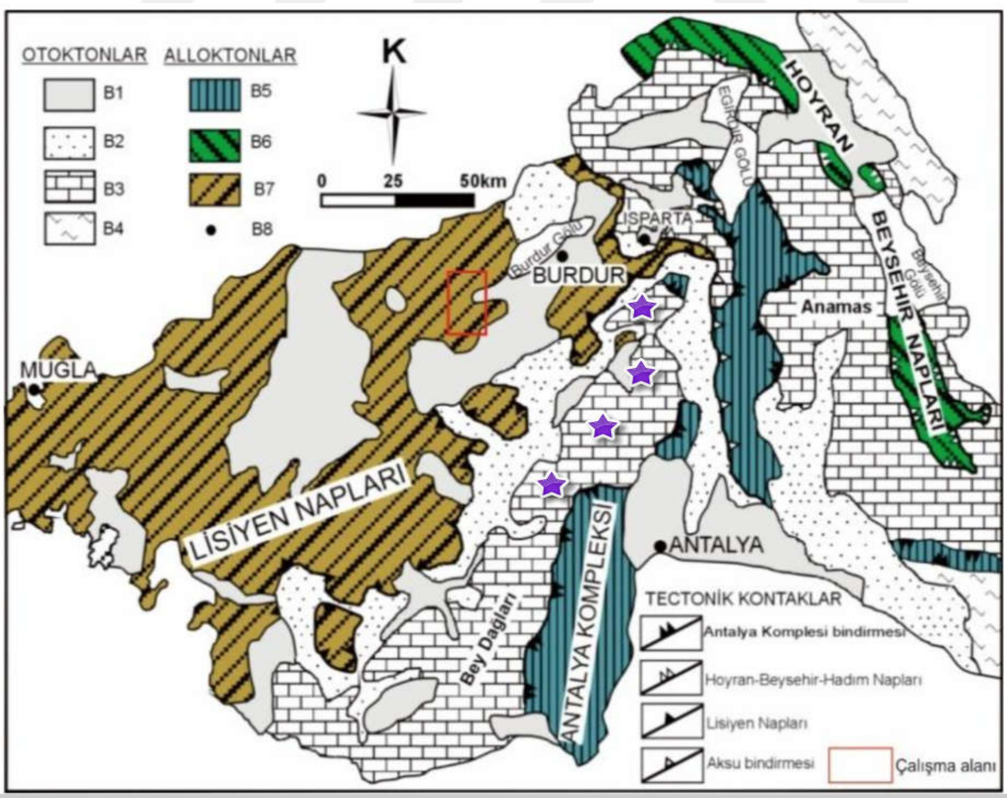


Figure 4.4 Simplified Geologic Map of the Isparta Angle (Modified From MTA 1/500000 Scale Geological Map of Turkey) (Alpan et al.,1964)

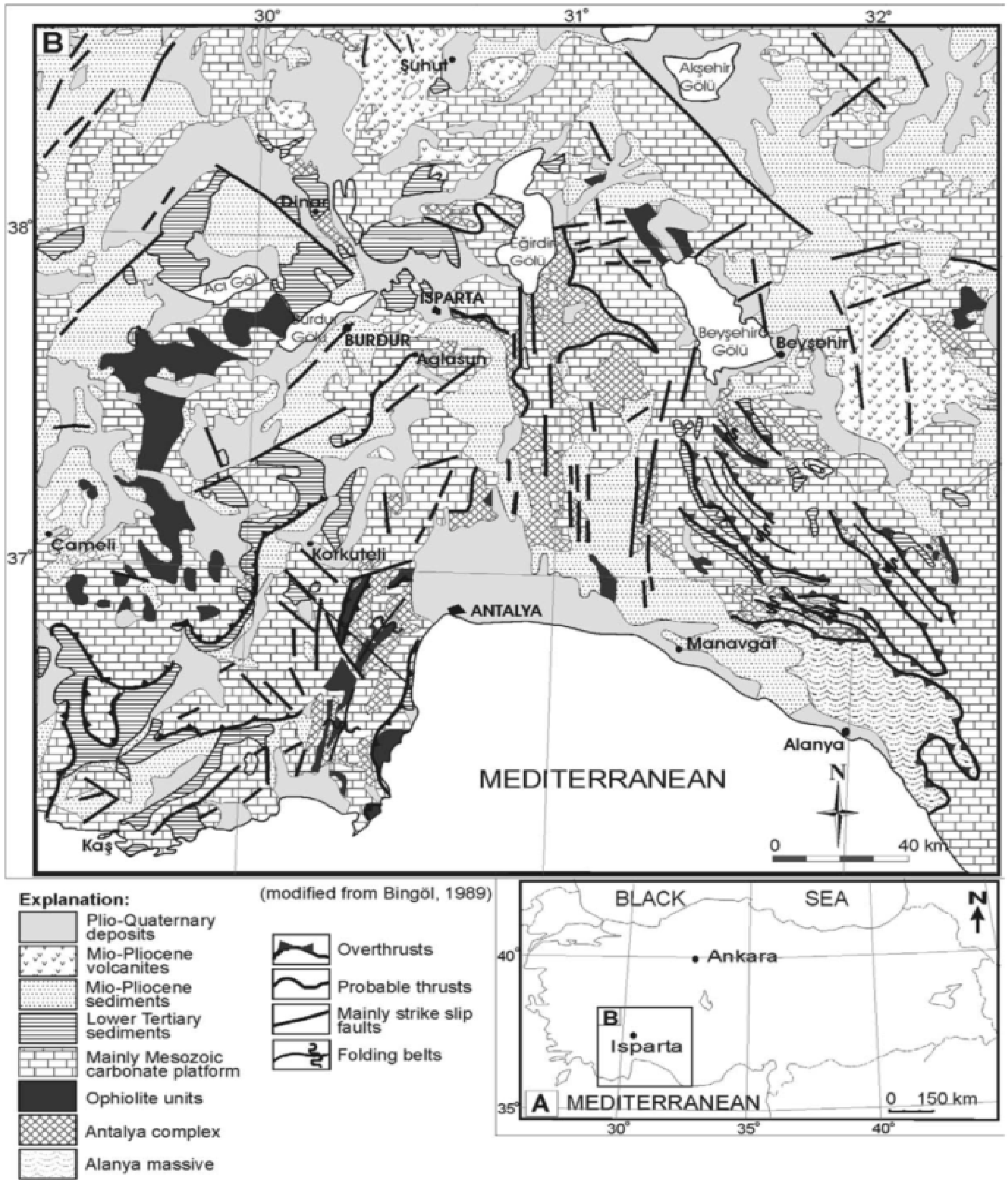


Figure 4.5 Geological Map of the Isparta Angle (Modified from Bingol, 1989)

Although the formation structures of the rocks are the same, the degree of weathering is different for each borehole.

While there are enough samples for each test in some soundings, a limited variety of tests were carried out in boreholes with advanced degree of weathering.

Some core sample box pictures of these rock samples are presented in Figure 4.6.

Figure 4.6 Core Sample Boxes (Rock Type - 1)

4.1.1. Depth of Samples

Within the scope of the thesis, it is also aimed to examine the effect of sample depth on correlations. The graphs (Figure 4.7, Figure 4.8 and Figure 4.9) below show the percentage distribution of the depth ranges of the samples.

Table 4.2 Number of Samples Summary Table (Rock Type – 1)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 1	Limestone	836	886	392	392

With the increase of the cover depth; it is determined that the weathering degree of the rock and the PLI percentage are decreasing.

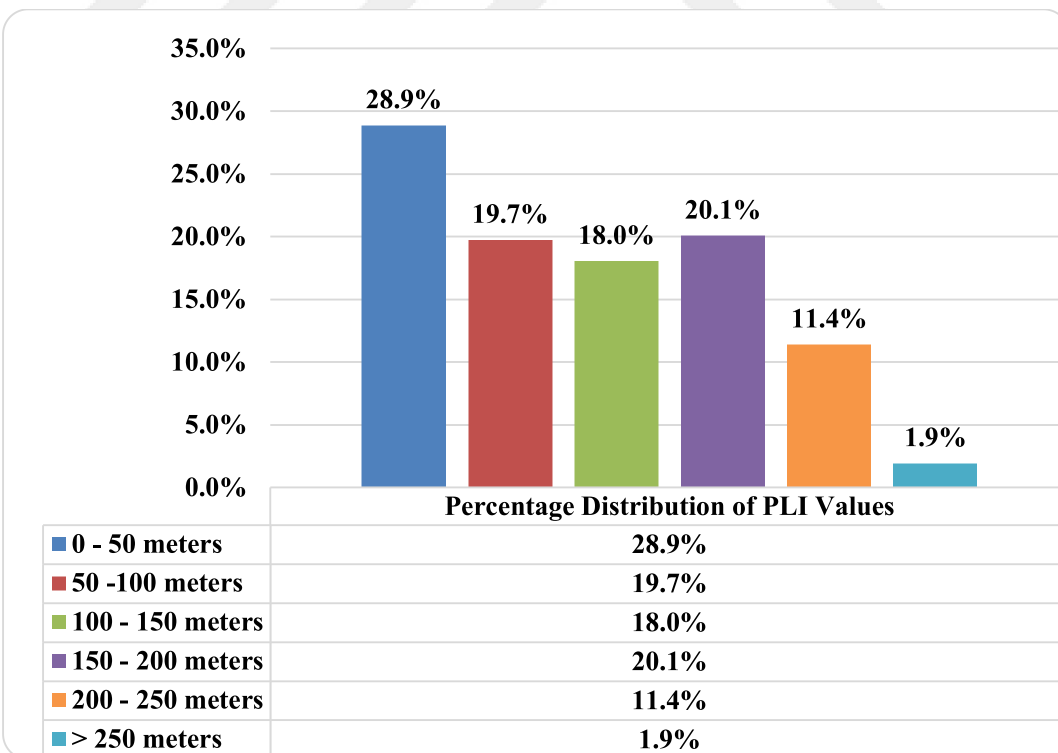
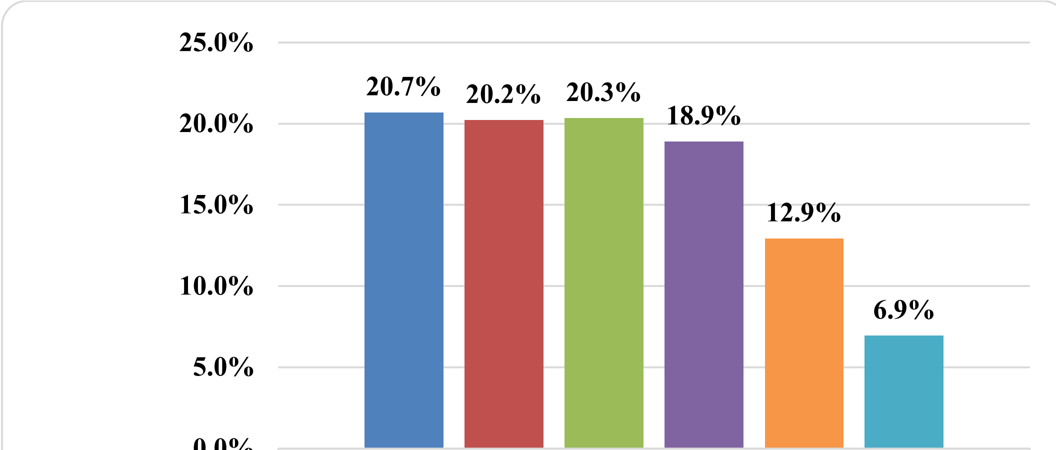
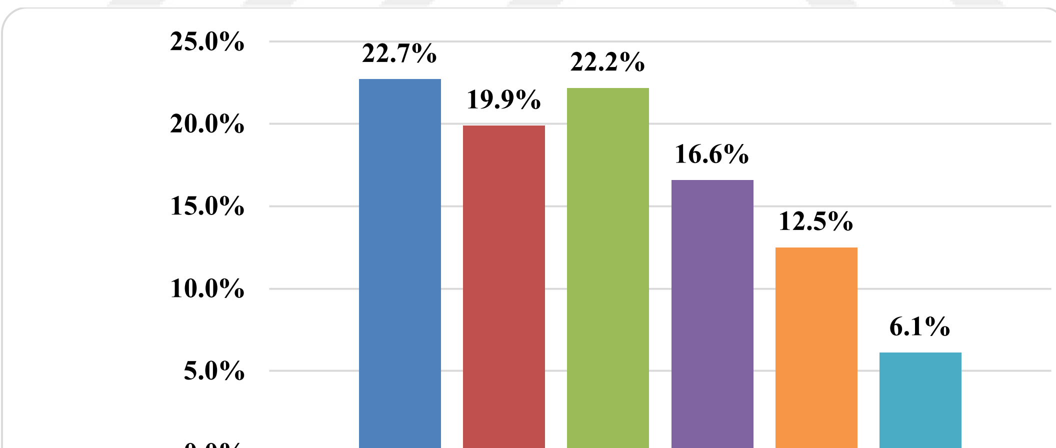


Figure 4.7 Percentage Distribution of PLI Values by Depth (Rock Type – 1)



	Percentage Distribution of UCS Values
0 - 50 meters	20.7%
50 -100 meters	20.2%
100 - 150 meters	20.3%
150 - 200 meters	18.9%
200 - 250 meters	12.9%
> 250 meters	6.9%

Figure 4.8 Percentage Distribution of UCS Values by Depth (Rock Type – 1)



	Percentage Distribution of E Values
0 - 50 meters	22.7%
50 -100 meters	19.9%
100 - 150 meters	22.2%
150 - 200 meters	16.6%
200 - 250 meters	12.5%
> 250 meters	6.1%

Figure 4.9 Percentage Distribution of E Values by Depth (Rock Type – 1)

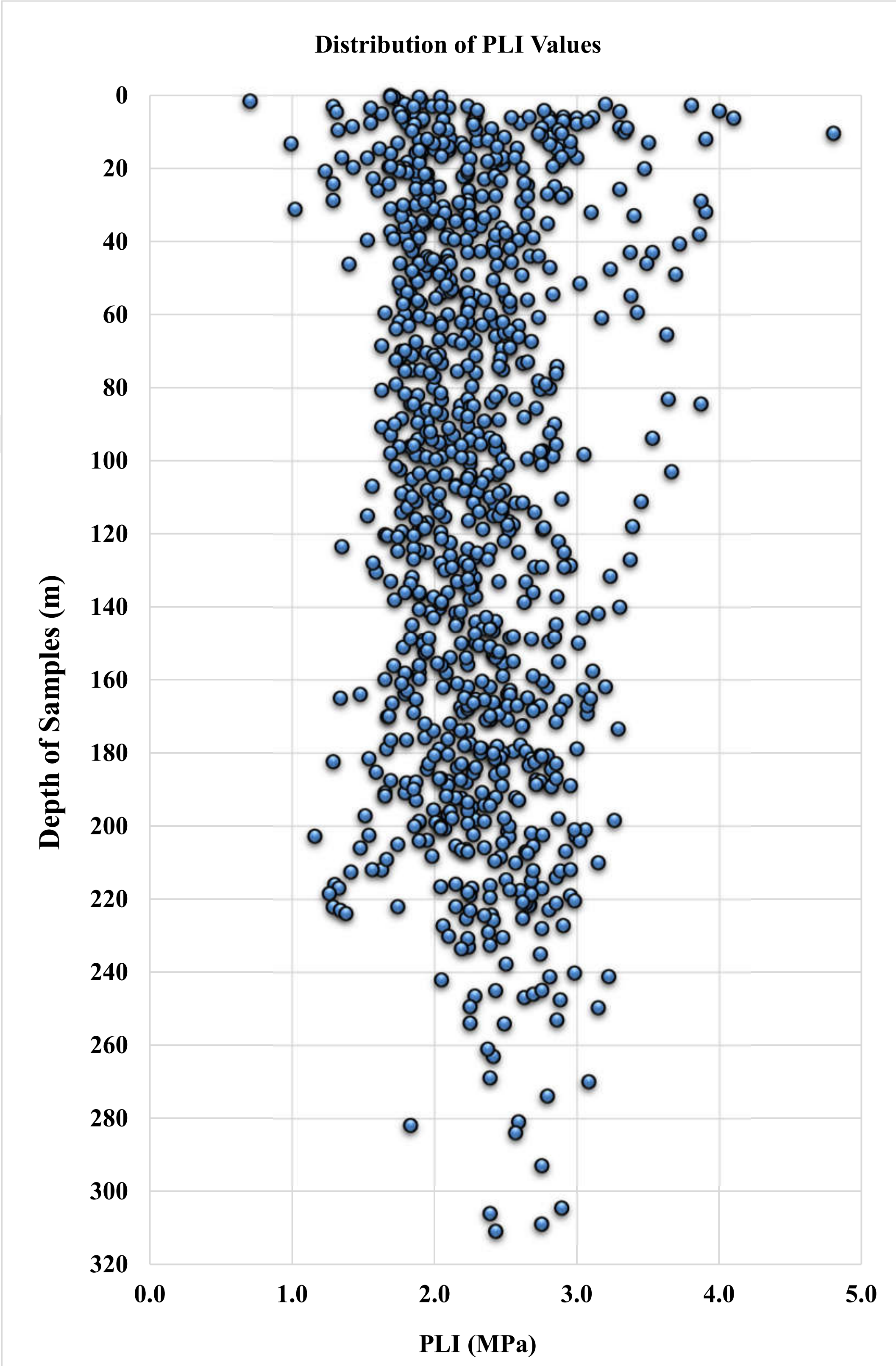


Figure 4.10 Distribution of PLI Values by Depth (Rock Type – 1)

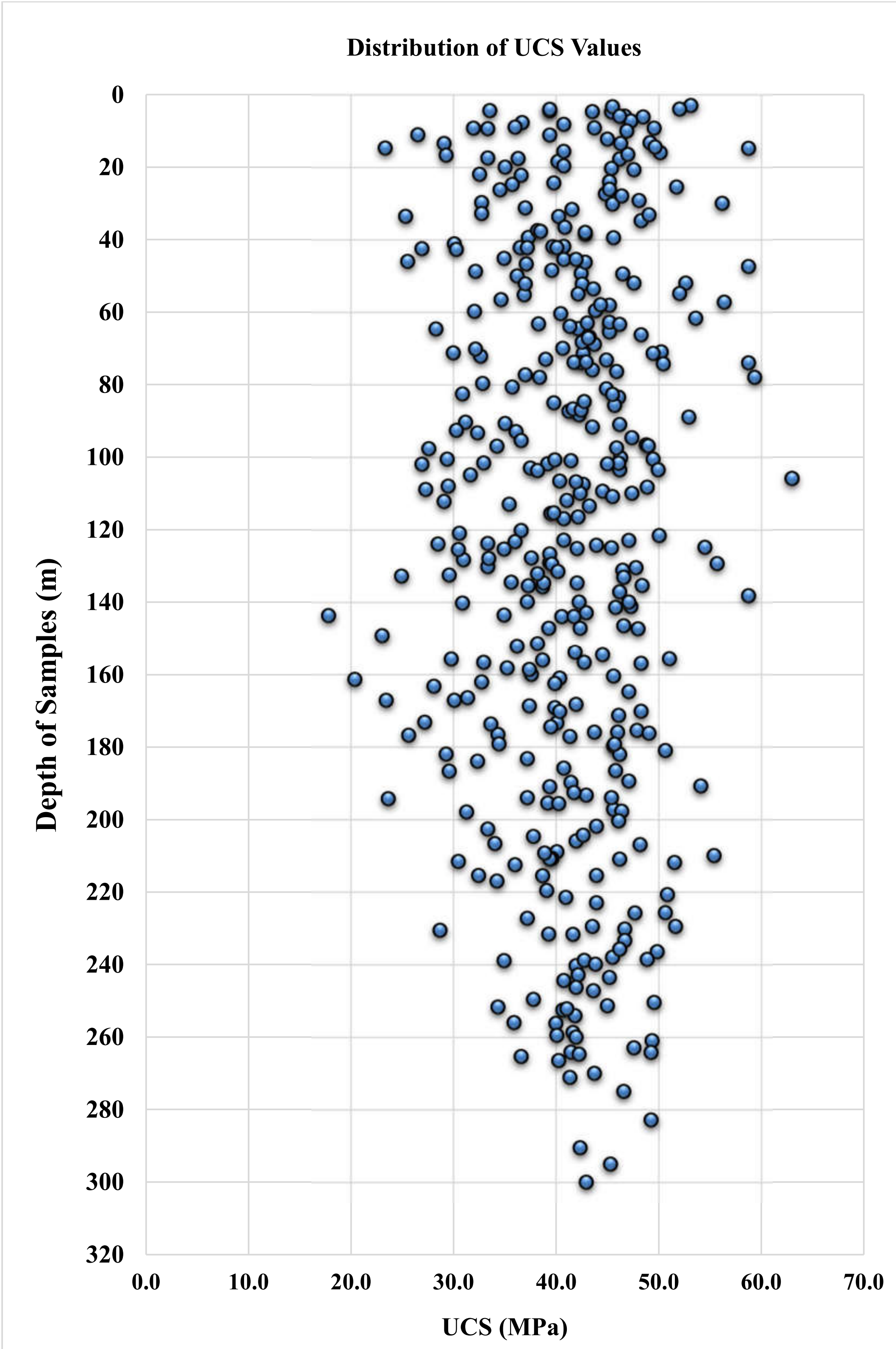


Figure 4.11 Distribution of UCS Values by Depth (Rock Type – 1)

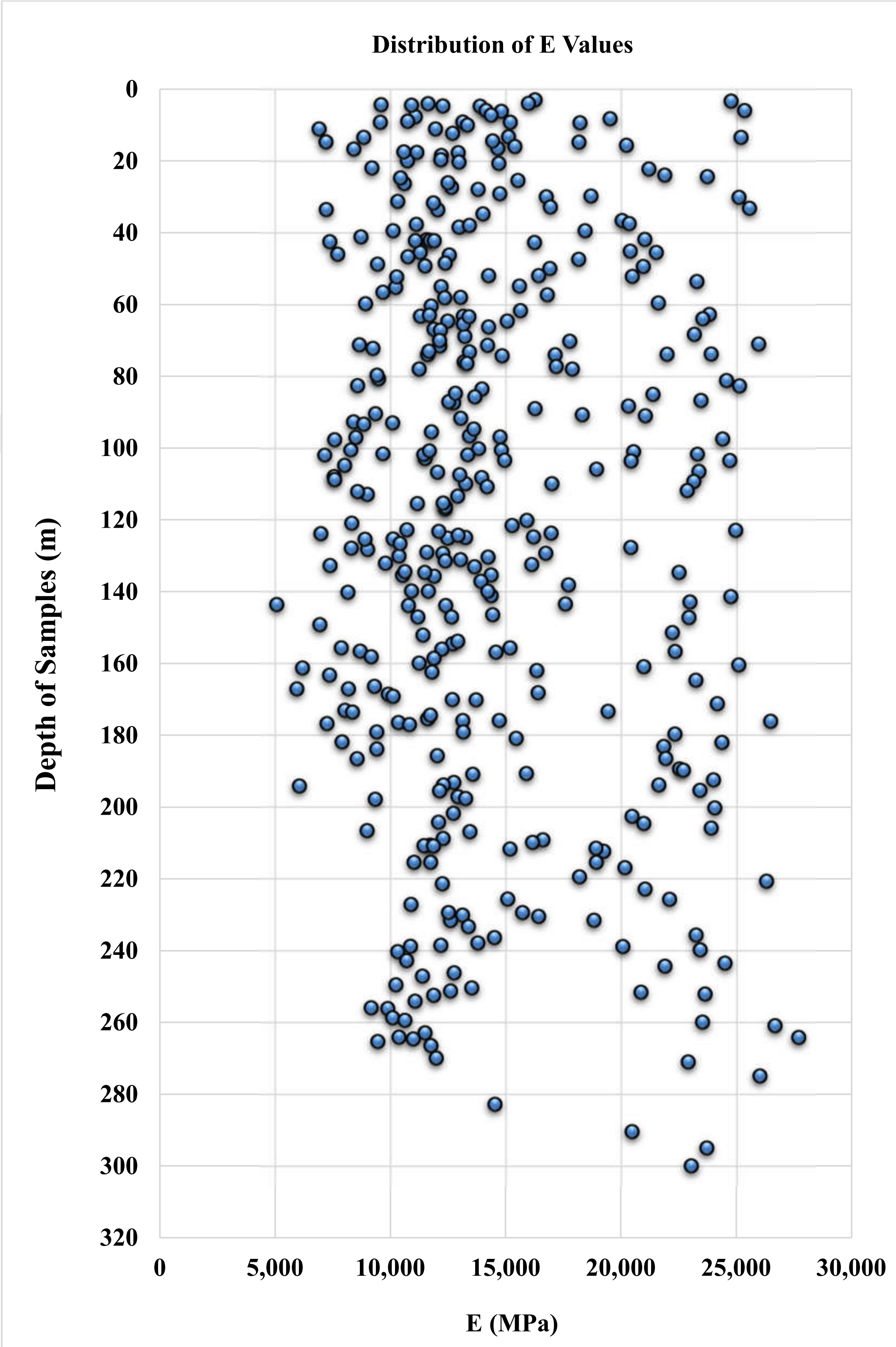


Figure 4.12 Distribution of E Values by Depth (Rock Type – 1)

4.1.2. Correlation of UCS and E Values

Uniaxial compression test was applied on 392 samples. In these tests, the modulus of elasticity values was also measured. In this section, individual UCS tests were not taken into account for correlation study.

The distribution of the uniaxial compressive strength values are given proportionally. Approximately 85.0 % of the total sample has compressive strength between 30-50 MPa. There are samples with strengths different from the average at low rates.

Table 4.3 Field Estimates of Uniaxial Compressive Strength and Point Load Index (Hoek and Marinos – 2001)

Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown [2]
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results.

According to Table 4.3, the majority of the samples are considered "Strong - medium strong" among this database.

When the UCS values of the samples are classified;

- Minimum UCS test value : 17.90 MPa
- Maximum UCS test value : 63.00 MPa

Quantity of observations within the specified interval;

- 0-20 MPa : 1 sample (% 0.3)
- 20-30 MPa : 28 samples (% 7.1)
- 30-40 MPa : 127 samples (% 32.4)
- 40-50 MPa : 206 samples (% 52.6)
- >50 MPa : 30 samples (% 7.7)
- Total samples : 392 samples

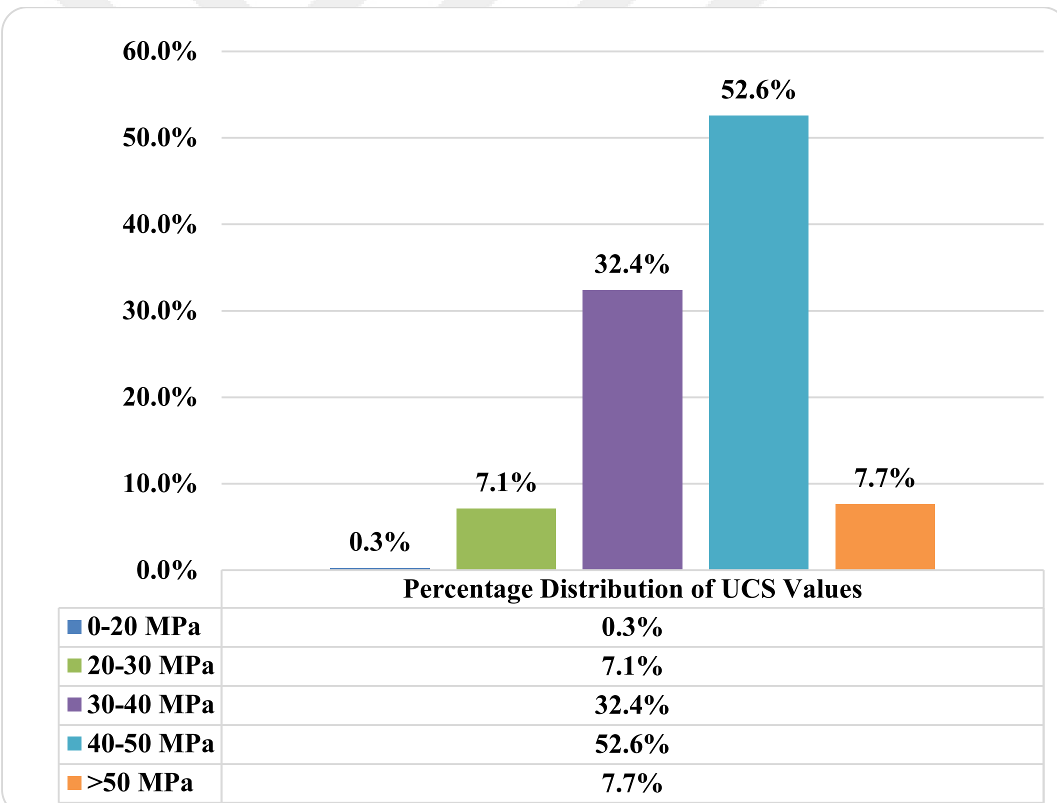


Figure 4.13 Percantage Distribution of UCS Values (Rock Type – 1)

When the E values of the samples are classified;

- Minimum E test value : 5.070 MPa
- Maximum E test value : 27.667 MPa

Quantity of observations within the specified interval;

- 5.000 – 10.000 MPa : 64 samples (% 16.3)
- 10.000 – 15.000 MPa : 191 samples (% 48.7)
- 15.000 – 20.000 MPa : 54 samples (% 13.8)
- 20.000 – 25.000 MPa : 71 samples (% 18.1)
- > 25.000 MPa : 12 samples (% 3.1)
- Total samples : 392 samples

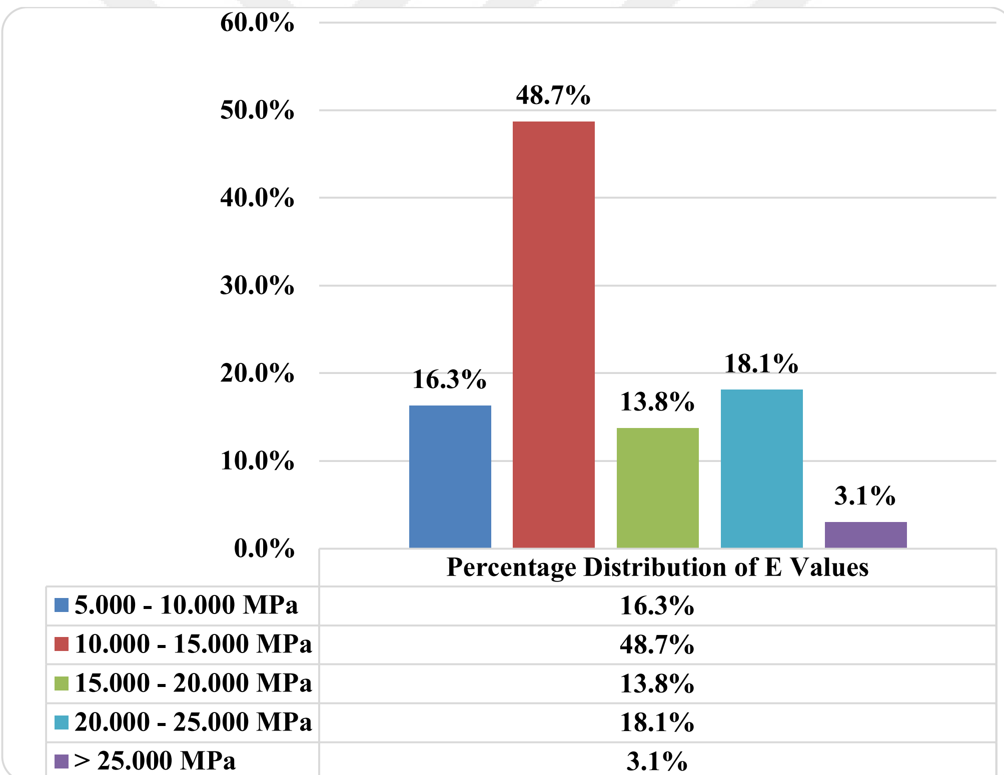


Figure 4.14 Percantage Distribution of E Values (Rock Type – 1)

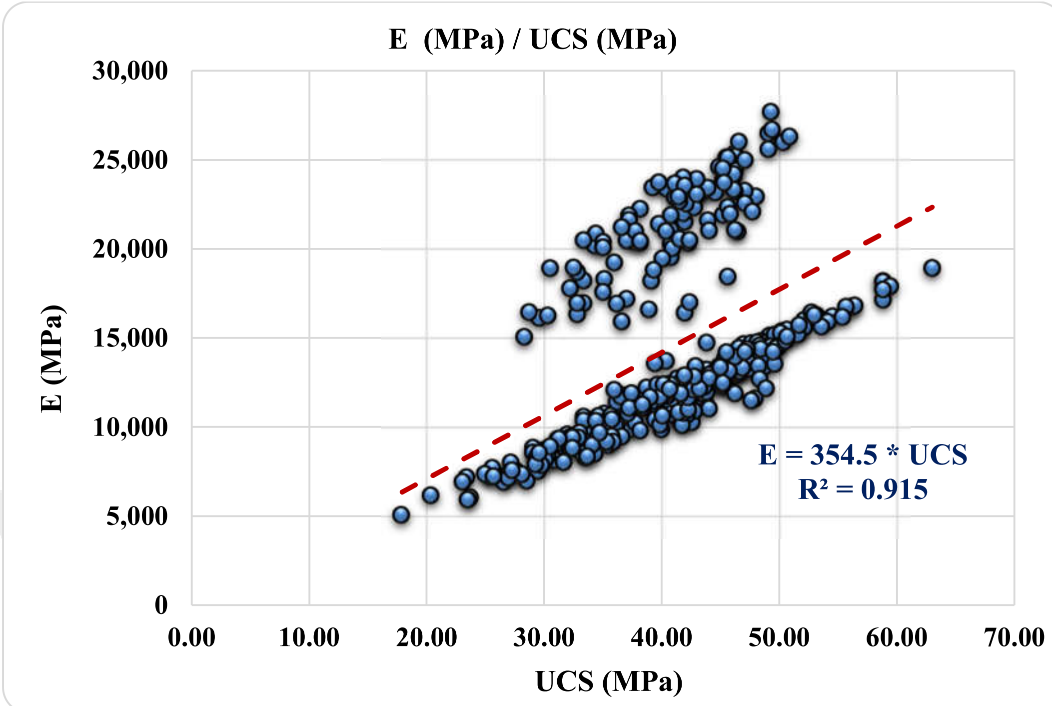


Figure 4.15 Chart of E (MPa) / UCS (MPa) Correlation (Rock Type – 1)

Arithmetic Mean of All E Results	:	14563.69 MPa
Arithmetic Mean of All UCS Results (MPa)	:	41.03 MPa
Ratio (E / UCS)	:	354.95

Geometric Mean of All E Results (MPa)	:	13724.68 MPa
Geometric Mean of All UCS Results (MPa)	:	40.36 MPa
Ratio (E / UCS)	:	340.05

According to the above graphical and mathematical calculation results;

Modulus of elasticity value = 340 - 355 x UCS value

MR (modulus ratio) ~ 340 – 355

Table 4.4 Comparasion with Hoek - Diederichs (Rock Type – 1)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range (Hoek - Diederichs)
Rock Type - 1	Limestone	340 - 355	400 - 600

The correlation range obtained as a result of studies with Hoek and Diederichs (2006) is similar.

When the relationship between the correlation coefficient and the depth is examined;

Table 4.5 Summary Table According to Depth (Rock Type – 1)

Sample Depth Range	MR Value (according to chart)	MR Value (according to arithmetic mean)	MR Value (according to geometric mean)
0 – 100 meters	348.98 (R^2 = 0.9237)	350.30	338.28
100 – 200 meters	350.44 (R^2 = 0.9194)	348.41	332.11
200 – 300 meters	374.03 (R^2 = 0.8953)	377.97	361.18
All Depths	354.5 (R^2 = 0.9150)	354.95	340.05

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

As can be seen in Figure 4.16, the correlation value is different for some of the samples. There basically two sets of different correlations in this graph. When investigated deeply, there seems no specific difference between the samples in these two groups.

they were taken from three different boreholes which are distributed at different places along the route of the tunnels, i.e., they are not the adjacent boreholes. There was no specific depth correlation among the samples. Therefore, it was decided to separate these two sets to find the upper and lower bounds for the correlation between E and UCS for this specific rock type. Figures 4.18 to Figure 4.20 are provided as useful example of how the correlation coefficient may be in a wider range than anticipated.

Figure 4.18 represents 65-70% of all samples, whereas Figure 4.20 represents the remaining 30-35%. As can be seen from these two figures, the range of the correlation coefficient has become wider, in the range of 288.56 to 452.46.

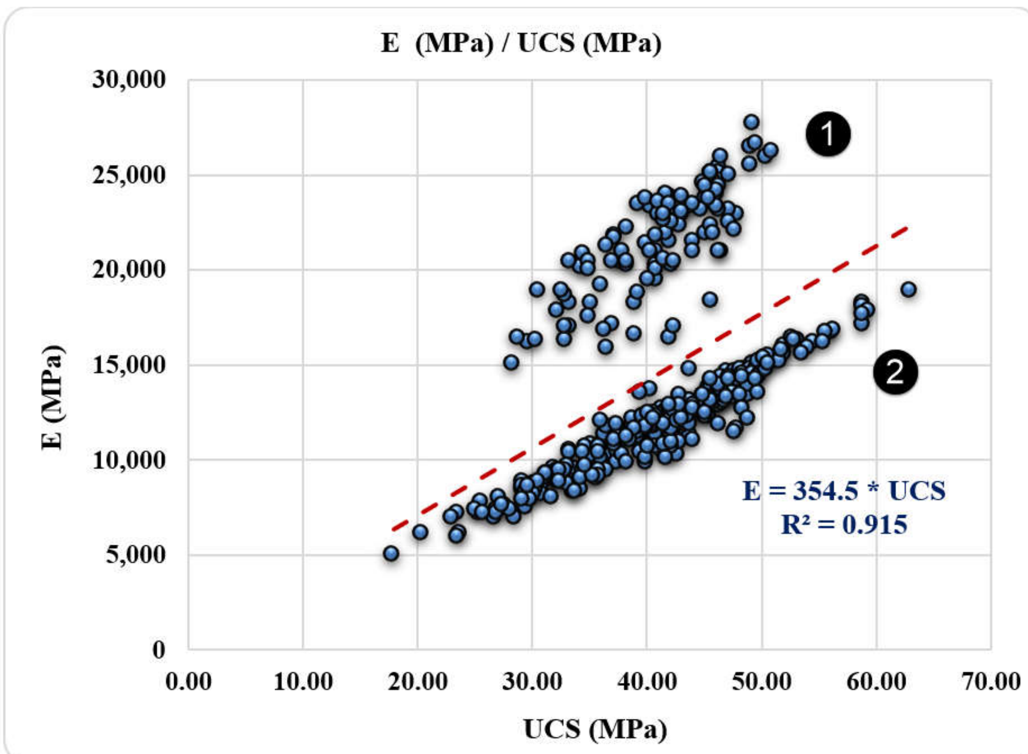


Figure 4.16 E (MPa) / UCS (MPa) Correlation for Two Groups (Rock Type – 1)

As can be seen from the box pictures (Figure 4.17, Figure 4.19) there is no significant difference in the physical conditions of the rocks.

Figure 4.17 Core Sample Boxes for the Samples in Figure 4.16

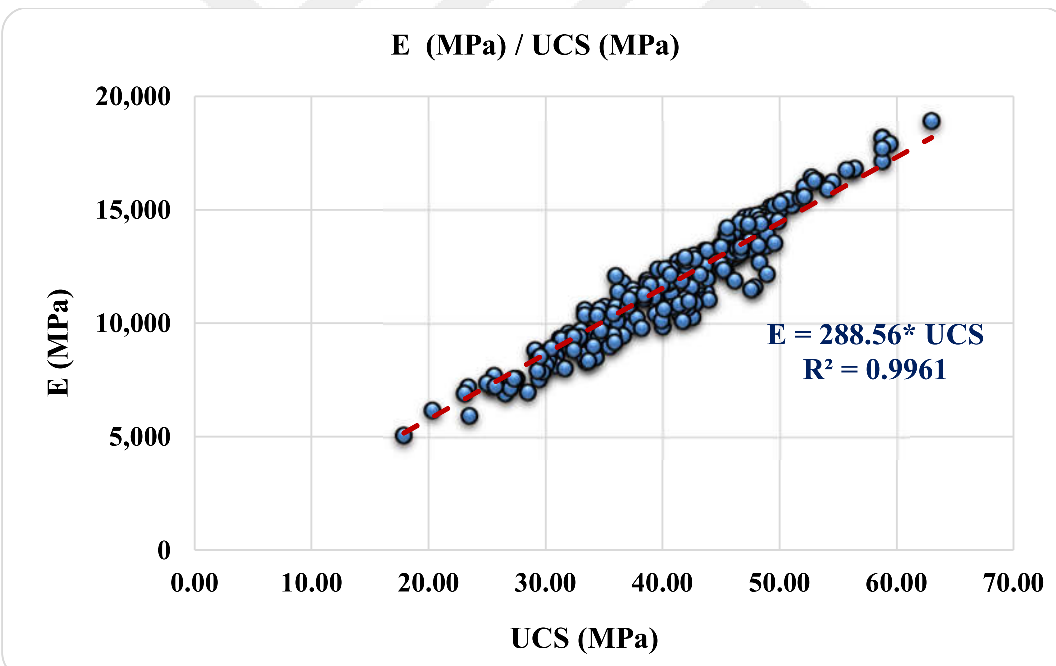


Figure 4.18 E (MPa) / UCS (MPa) Correlation (group - 1)

Figure 4.19 Core Sample Boxes for the Samples in Figure 4.18

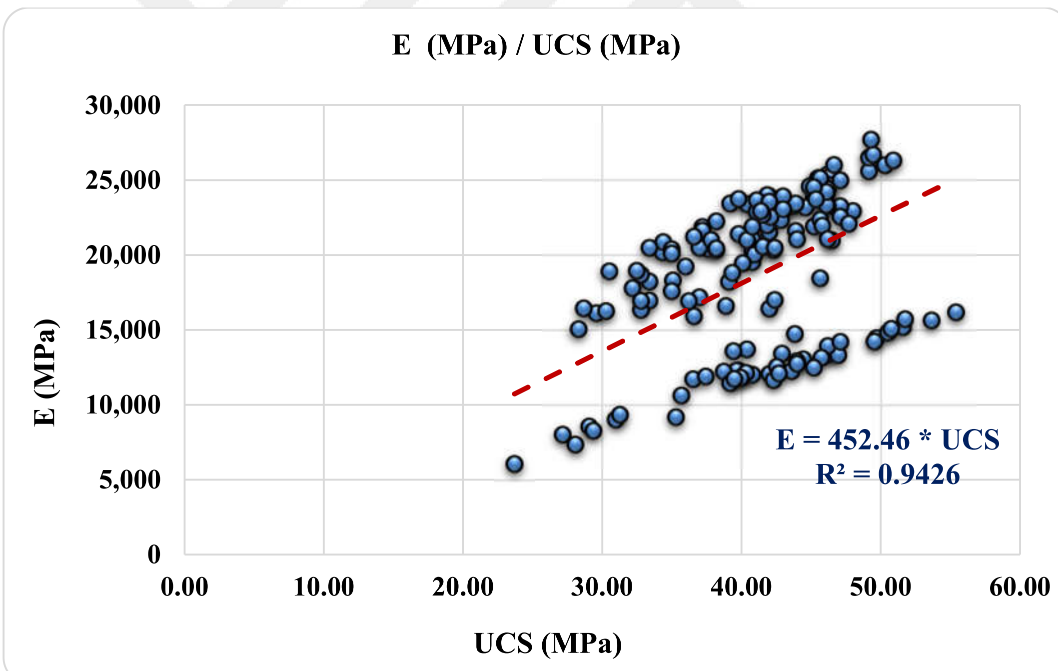


Figure 4.20 E (MPa) / UCS (MPa) Correlation (group - 2)

4.1.3. Correlation of PLI and UCS Values

Point load index test was applied to 886 samples. The UCS test was applied on 836 samples within the scope of the project.

When the PLI values of the samples are classified;

- Minimum PLI test value : 0.70 MPa
- Maximum PLI test value : 4.80 MPa

Quantity of observations within the specified interval;

- 0.5-1MPa : 2 samples (% 0.2)
- 1-1.5 MPa : 24 samples (% 2.7)
- 1.5-2 MPa : 246 samples (% 27.8)
- 2-2.5 MPa : 361 samples (% 40.7)
- 2.5-3.0 MPa : 194 samples (% 21.9)
- >3.0 MPa : 59 samples (% 6.7)
- Total samples : 886 samples

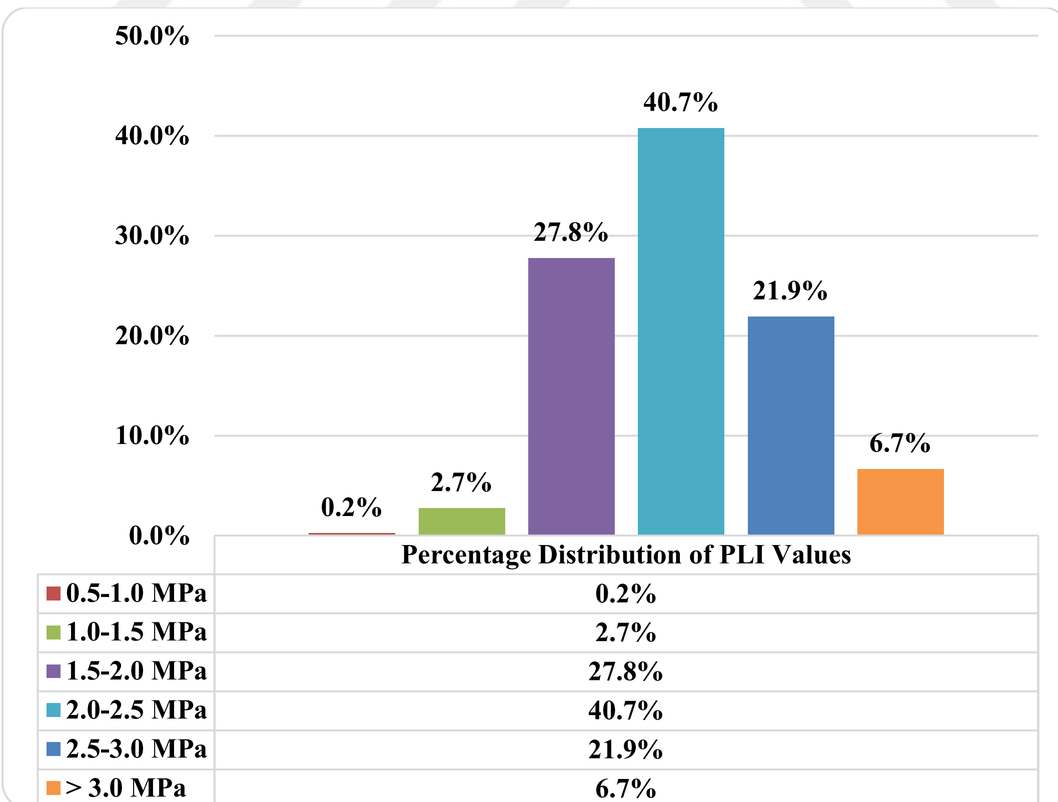


Figure 4.21 Percantage Distribution of PLI Values (Rock Type – 1)

When the UCS values of the samples are classified;

- Minimum UCS test value : 17.90 MPa
- Maximum UCS test value : 66.50 MPa

Quantity of observations within the specified interval;

- ➢ 0-20 MPa : 2 samples (% 0.2)
- ➢ 20-30 MPa : 54 samples (% 6.5)
- ➢ 30-40 MPa : 271 samples (% 32.4)
- ➢ 40-50 MPa : 445 samples (% 53.2)
- ➢ >50 MPa : 64 samples (% 7.7)
- ➢ Total samples : 836 samples

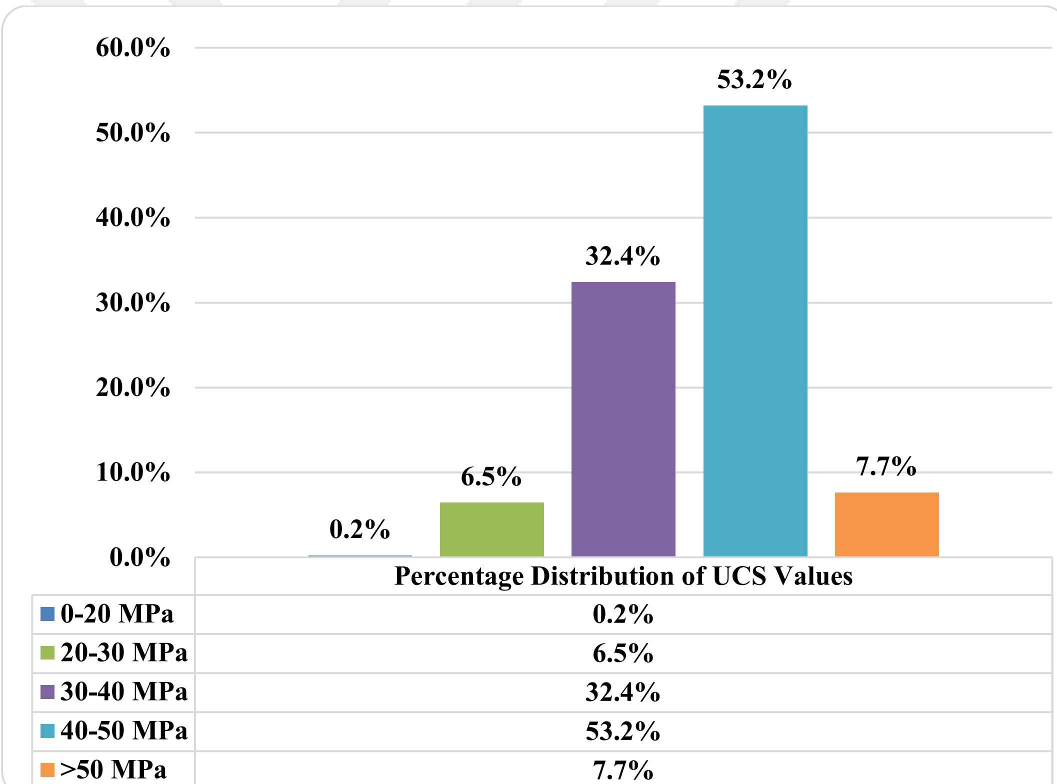


Figure 4.22 Percantage Distribution of UCS Values (Rock Type – 1)

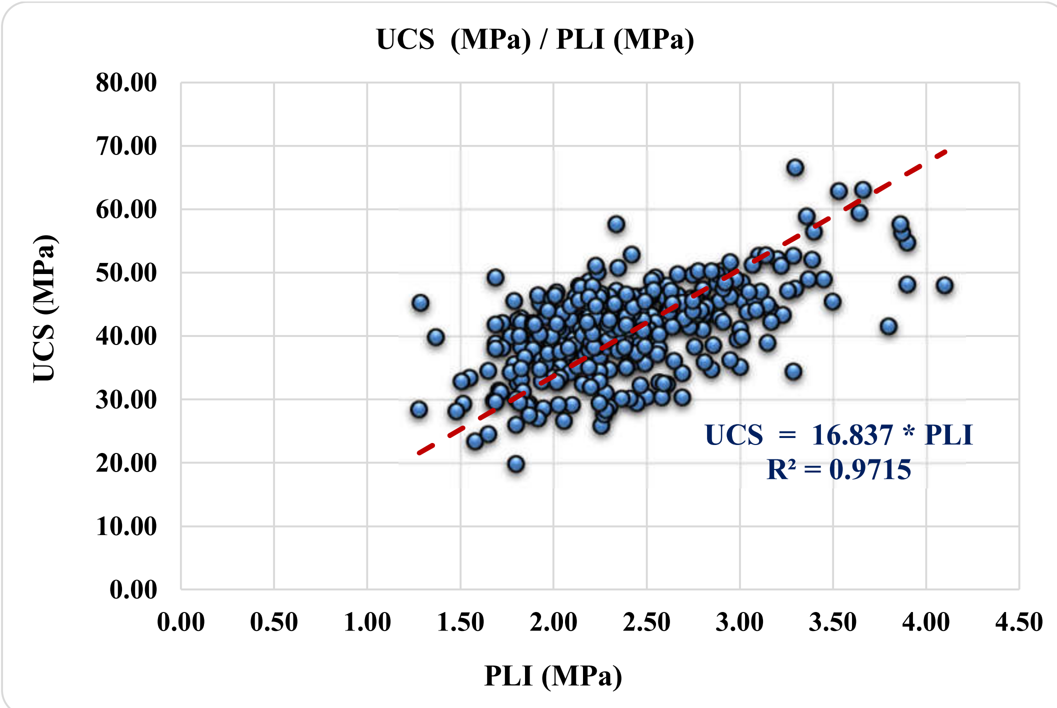


Figure 4.23 Chart of UCS (MPa) / PLI (MPa) Correlation (Rock Type – 1)

Arithmetic Mean of All UCS Results	:	41.18 MPa
Arithmetic Mean of All PLI Results	:	2.29 MPa
Ratio (UCS / PLI)	:	17.98

Geometric Mean of All UCS Results	:	40.55 MPa
Geometric Mean of All PLI Results	:	2.23 MPa
Ratio (UCS / PLI)	:	18.18

According to the above graphical and mathematical calculation results;
*Uniaxial Compressive Strength ~ 17 - 18 * PLI value*

Some of the samples were included for regression analysis and all of them were included for mathematical calculations. Because regression analysis requires UCS - PLI matches and this is not available for all depths.

When the relationship between the correlation coefficient and the depth is examined,

Table 4.6 Sample Depth Range for C Values (Rock Type – 1)

Sample Depth Range	C Value (according to arithmetic mean)	C Value (according to geometric mean)
0 – 100 meters	18.23	18.42
100 – 200 meters	17.68	17.67
200 – 300 meters	17.91	18.19
All Depths	17.98	18.18

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

Correlations in the literature for this rock type are listed below.

Mohamad et al. (2015) : *UCS = 12.291 * PLI + 5.892 (mixed)*

Kohno and Maeda (2012) : *UCS=16.40 * PLI (mixed)*

Singh et al (2012) : *UCS=22.3 * PLI (limestones)*

Sabatakakis et al. (2008) : *UCS = 25.3 * PLI (sedimentary rocks)*

Akram and Bakar (2007) : *UCS = 22.792 * PLI + 13.295 (sedimentary rocks)*

Akram and Bakar (2007) : *UCS=11.076 * PLI (sandstones, limestones, marls)*

Kahraman and Alper (2006) : *UCS = 17.91* PLI + 7.93 (limestones)*

Tsiambaos and Sabatakakis (2004): *UCS=7.3 * $PLI^{1.71}$ (sedimentary rocks)*

Sulukcu and Ulusay (2001) : *UCS=15.3 * PLI (mixed)*

Rusnak and Mark (1999) : *UCS=21.9 * PLI (limestones)*

Brautigam et al. (1998) : *UCS = 20.4 * PLI (sedimentary rocks)*

Smith (1997) : *UCS = 24 * PLI (sandstones / limestones)*

O’Rourke (1988) : *UCS = 30 * PLI (sedimentary rocks)*

Hawkins and Olver (1986)	*:*	*UCS = 26.5 * PLI (limestones)*
Brook (1985)	*:*	*UCS = 22 * PLI (granites, limestones)*
ISRM (1985)	*:*	*UCS = 20 - 25 * PLI (all rocks)*
Gunsallus and Kulhawy (1984):		*UCS = 16.5 * PLI + 51 (sedimentary rocks)*
Read et al. (1980)	*:*	*UCS = 20* PLI (sedimentary rocks)*
Hassani et al (1980)	*:*	*UCS = 29 * PLI (sedimentary rocks)*
Broch and Franklin (1972)	*:*	*UCS = 23.7 * PLI (various rock types)*

In Figure 4.24, UCS values are calculated with the assumption of PLI = 1 MPa.

As can be seen from Figure 4.24, significant differences emerge between the correlations and the value obtained in this study falls within that range with a value of 18. This fact should be kept in mind while using the correlation coefficients. It is recommended to evaluate with more than one correlation in order to minimize the error.

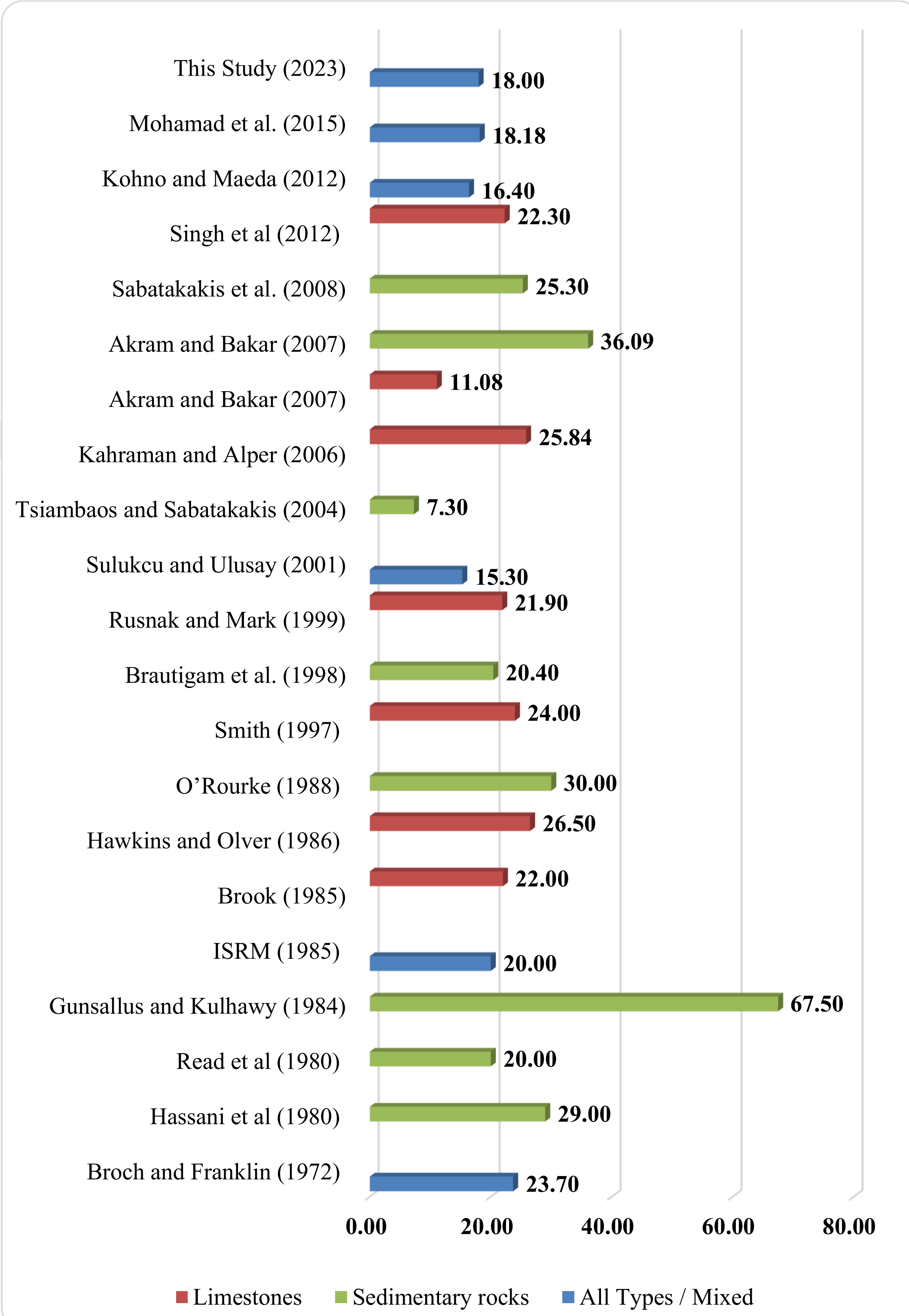


Figure 4.24 Comparison of Some Studies from Literatures for PLI / UCS (For PLI = 1 MPa)

4.2. Rock Type - 2 (Alternation of Shale - Sandstone - Claystone)

In this section, correlation studies related to alternation of shale – sandstone – claystone are presented. The samples were taken from the Isparta - Antalya in the Western Mediterranean region. The working area is marked on the map below (Figure 4.25).

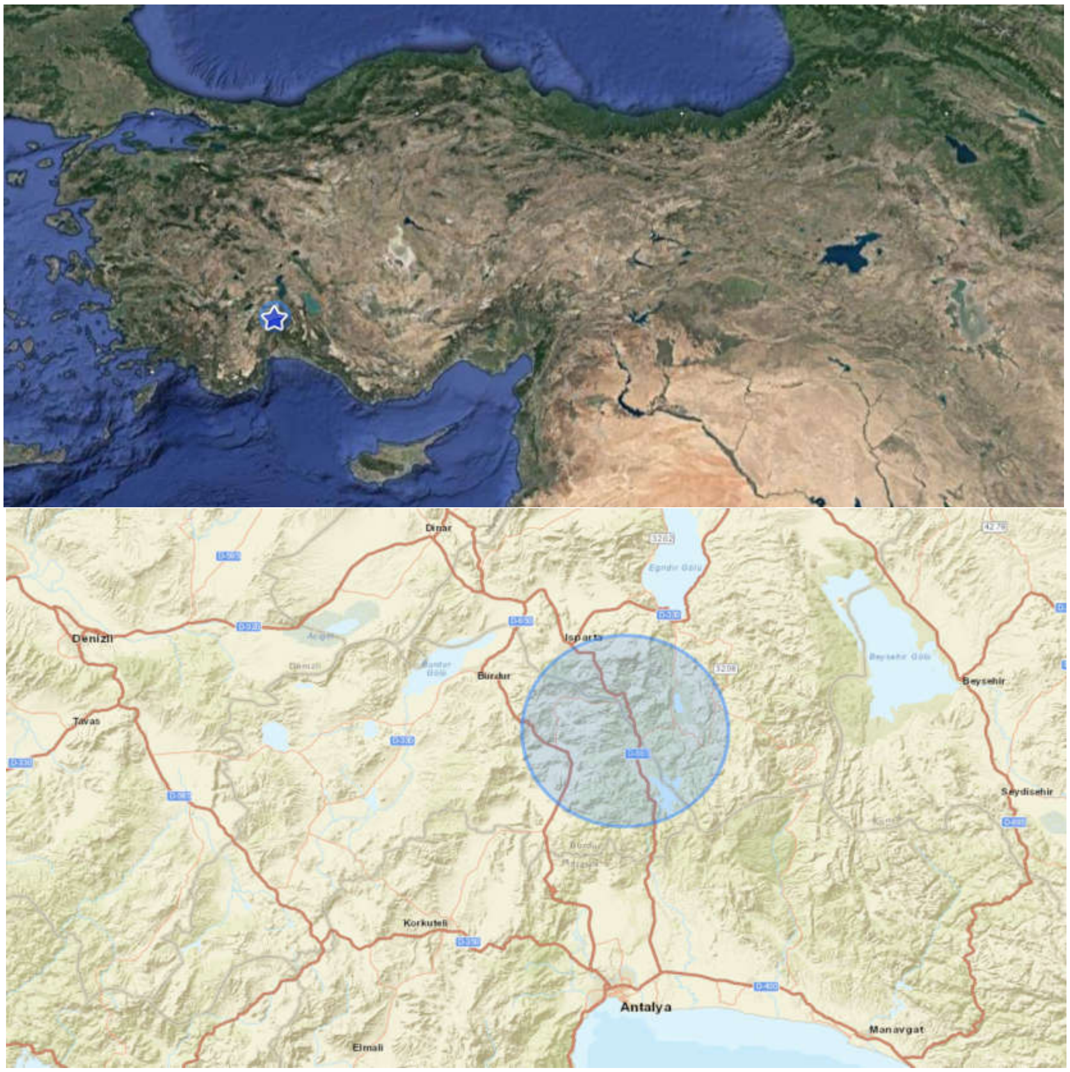


Figure 4.25 Location of Samples (Rock Type – 2)

As indicated in the geological maps (Figure 4.26, Figure 4.27) the presence of alternation of shale – sandstone – claystone is evident in the general formation of the region.

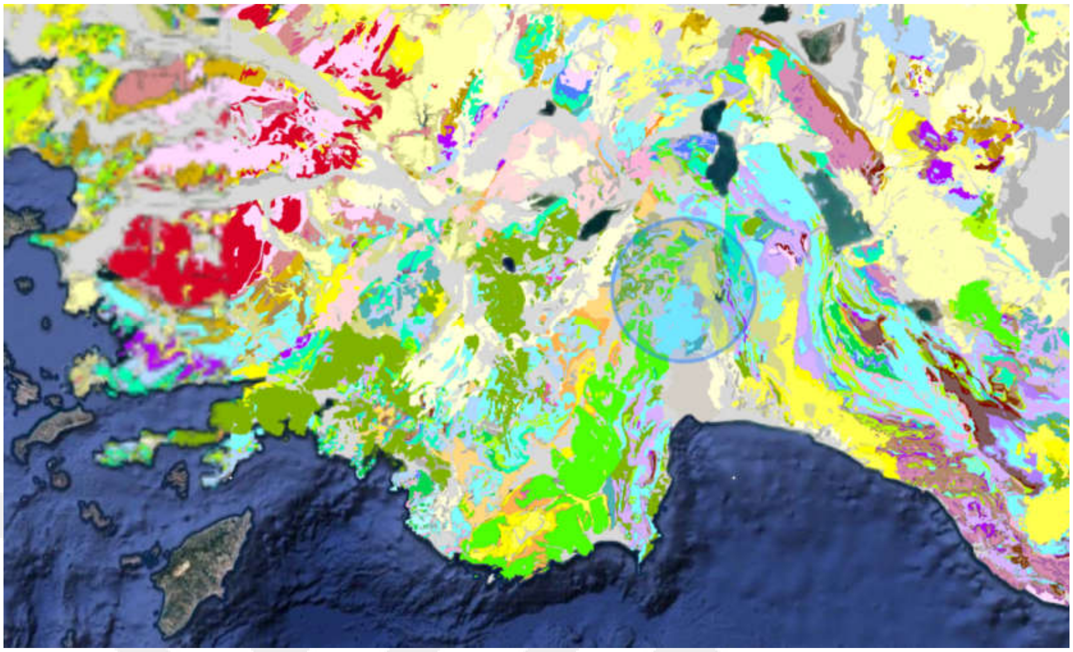


Figure 4.26 Formation Information (from MTA website)

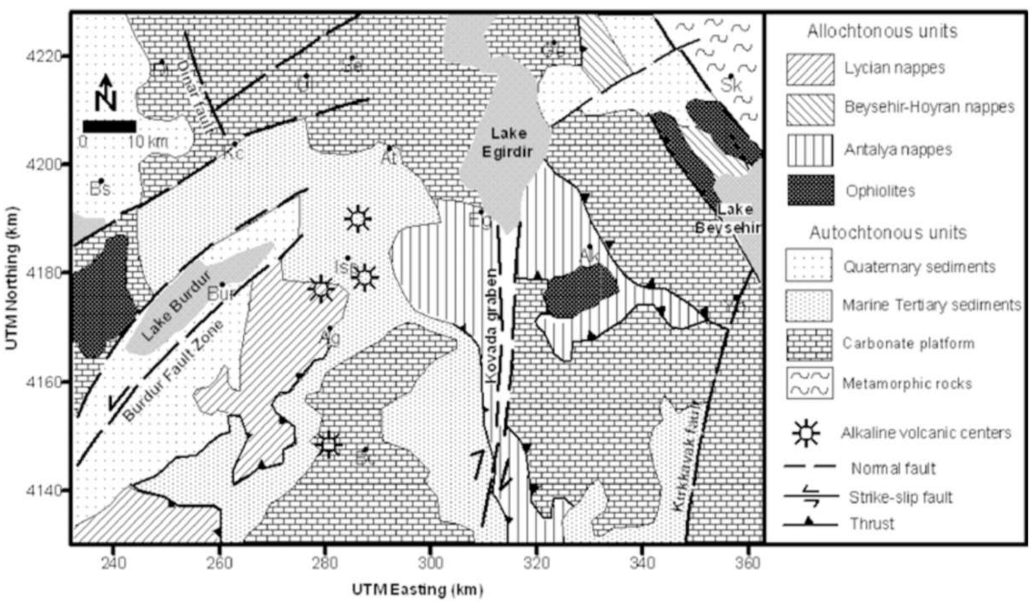


Figure 4.27 Simplified Structural map of the Burdur-Isparta Area
(Modified from Yagmurlu et al., 1997)

Although the formation structures of the rocks are the same, the degree of weathering different for each borehole. While there are enough samples for each test in some soundings, a limited variety of tests were carried out in boreholes with advanced degree of weathering. Some core sample box pictures of these rock samples are given in Figure 4.28.

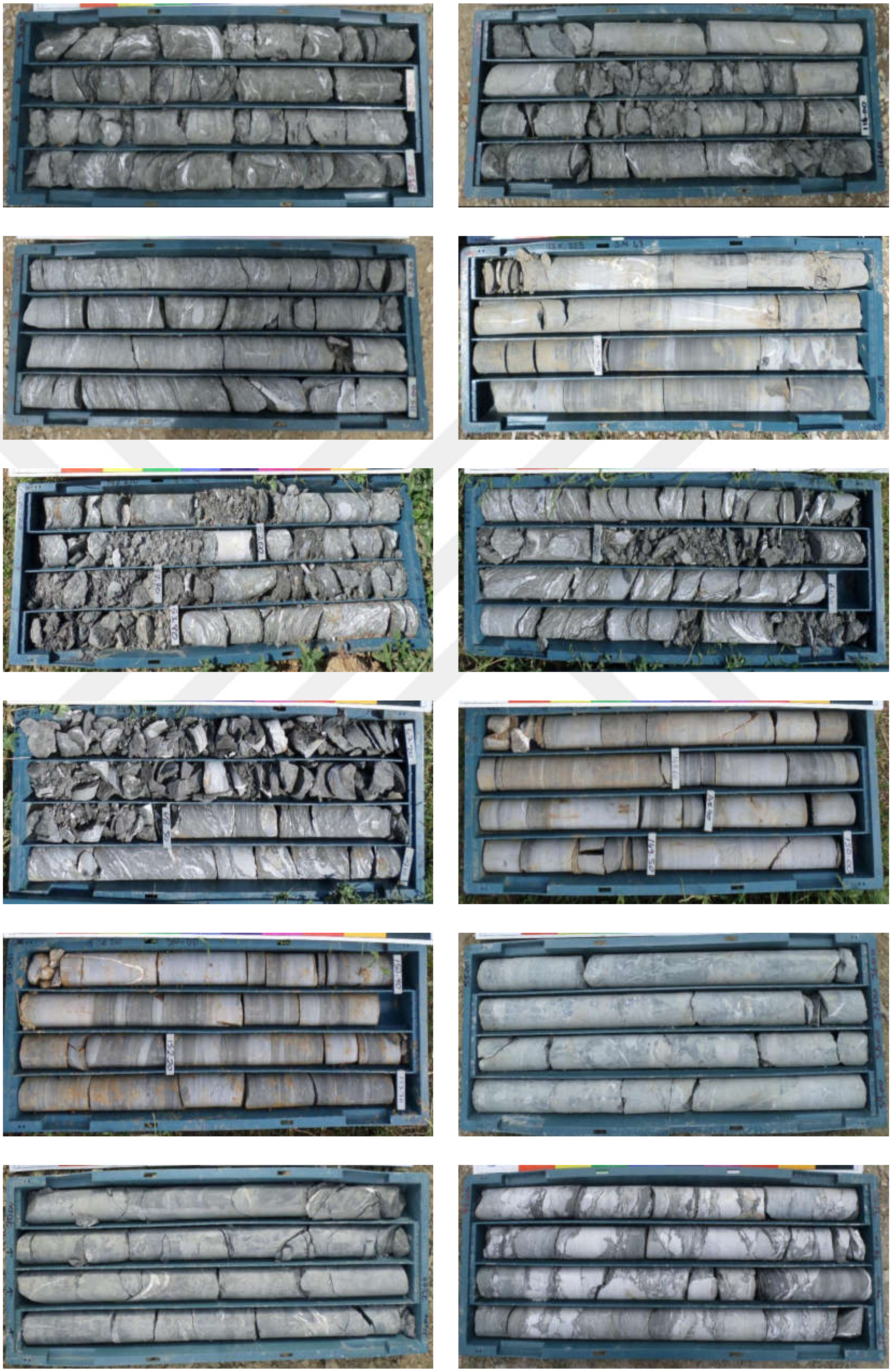


Figure 4.28 Core Sample Boxes (Rock Type - 2)

4.2.1. Depth of Samples

Similar with the previous rock type, the effect of sample depth on correlations is studied for this type of rock. The graphs (Figure 4.29, Figure 4.30 and Figure 4.31) below show the percentage distribution of the depth ranges of the samples.

Table 4.7 Number of Samples Summary Table (Rock Type – 2)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 2	Alternation of Shale – Sandstone – Claystone	559	287	267	267

With the increase of the cover depth; it is determined that the weathering degree of the rock and the PLT percentage are decreased.

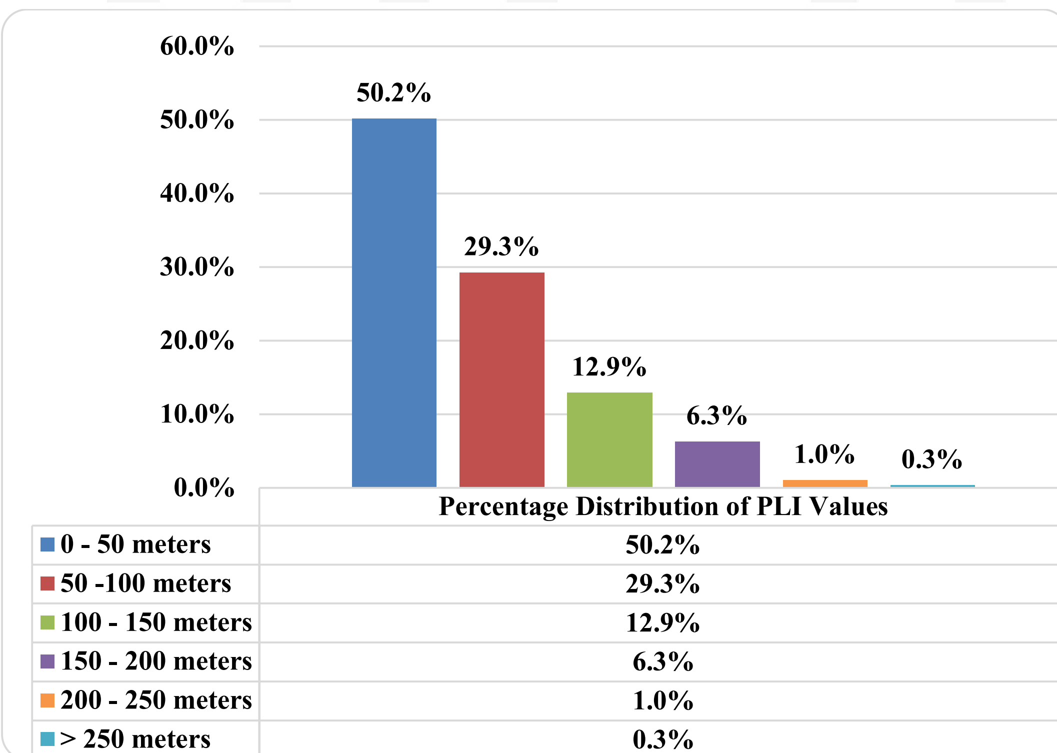
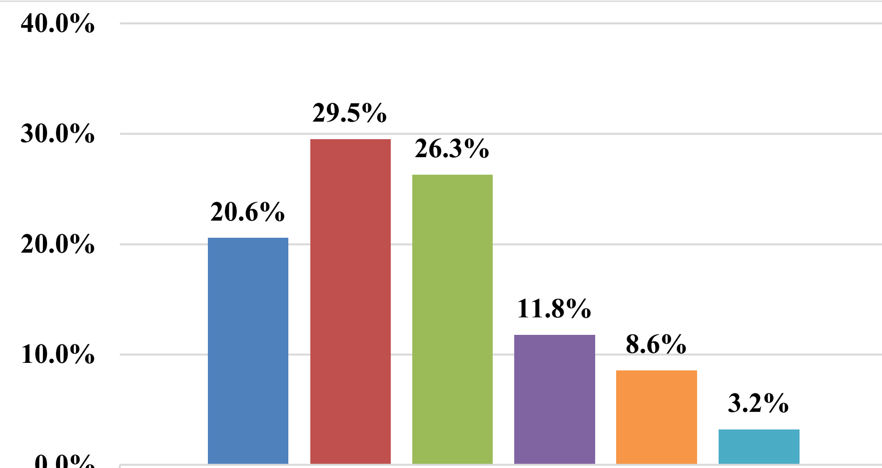
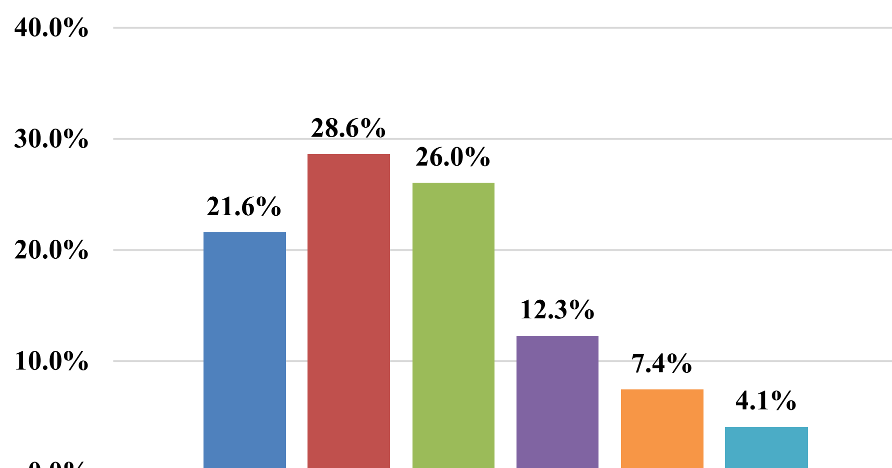


Figure 4.29 Percentage Distribution of PLI Values by Depth (Rock Type – 2)



	Percentage Distribution of UCS Values
0 - 50 meters	20.6%
50 -100 meters	29.5%
100 - 150 meters	26.3%
150 - 200 meters	11.8%
200 - 250 meters	8.6%
> 250 meters	3.2%

Figure 4.30 Percentage Distribution of UCS Values by Depth (Rock Type – 2)



	Percentage Distribution of E Values
0 - 50 meters	21.6%
50 -100 meters	28.6%
100 - 150 meters	26.0%
150 - 200 meters	12.3%
200 - 250 meters	7.4%
> 250 meters	4.1%

Figure 4.31 Percentage Distribution of E Values by Depth (Rock Type – 2)

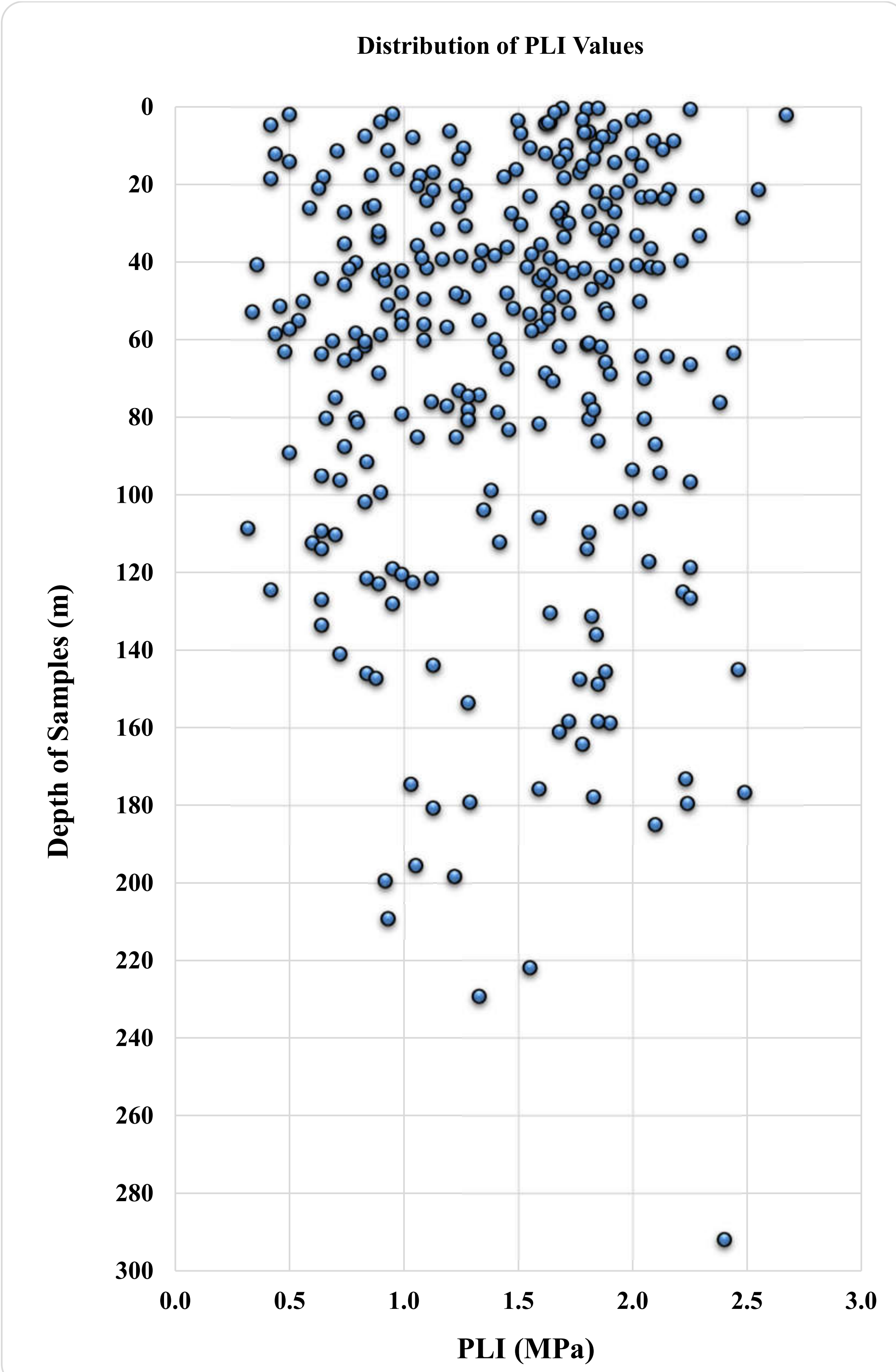


Figure 4.32 Distribution of PLI Values by Depth (Rock Type – 2)

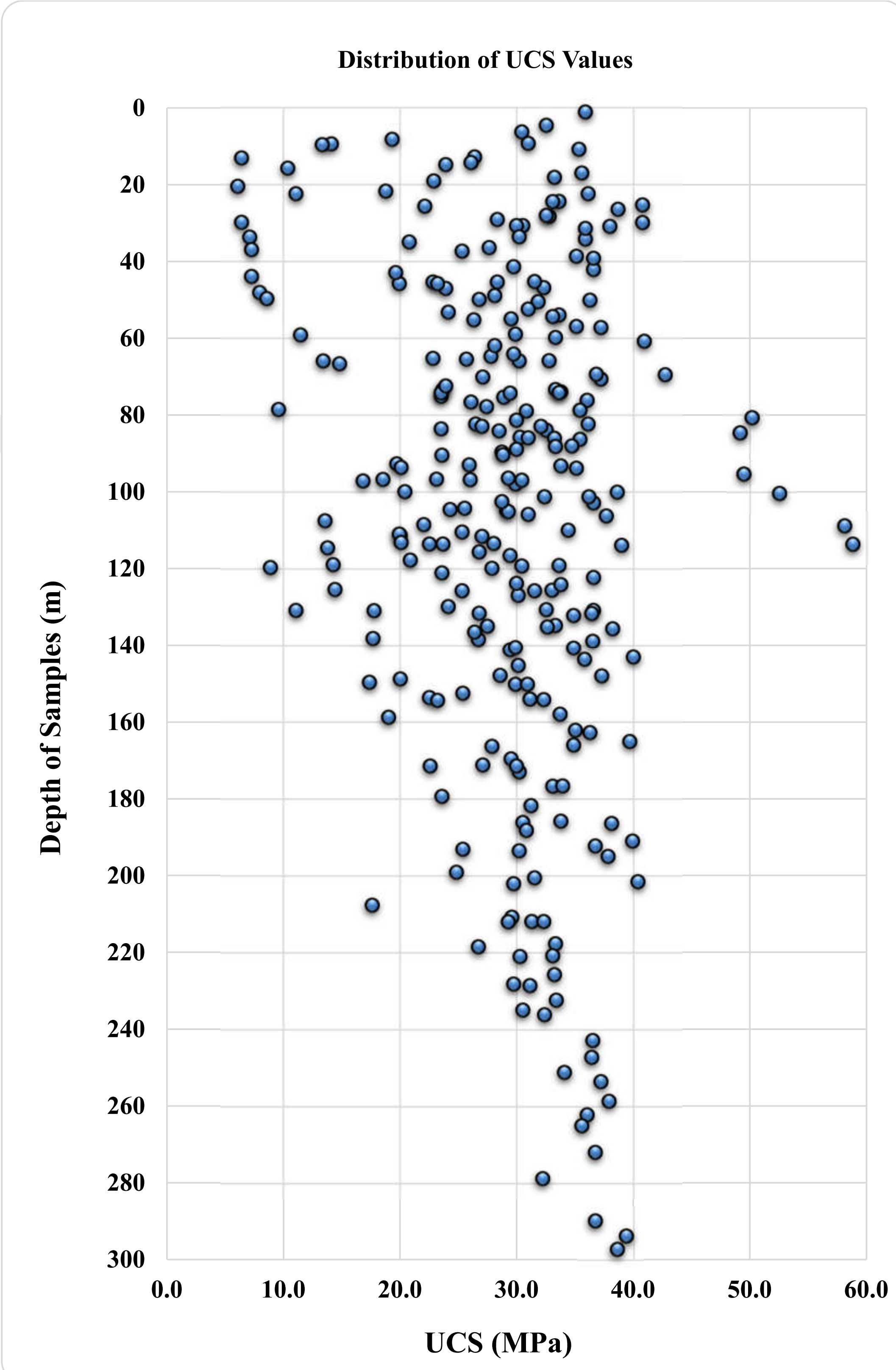


Figure 4.33 Distribution of UCS Values by Depth (Rock Type – 2)

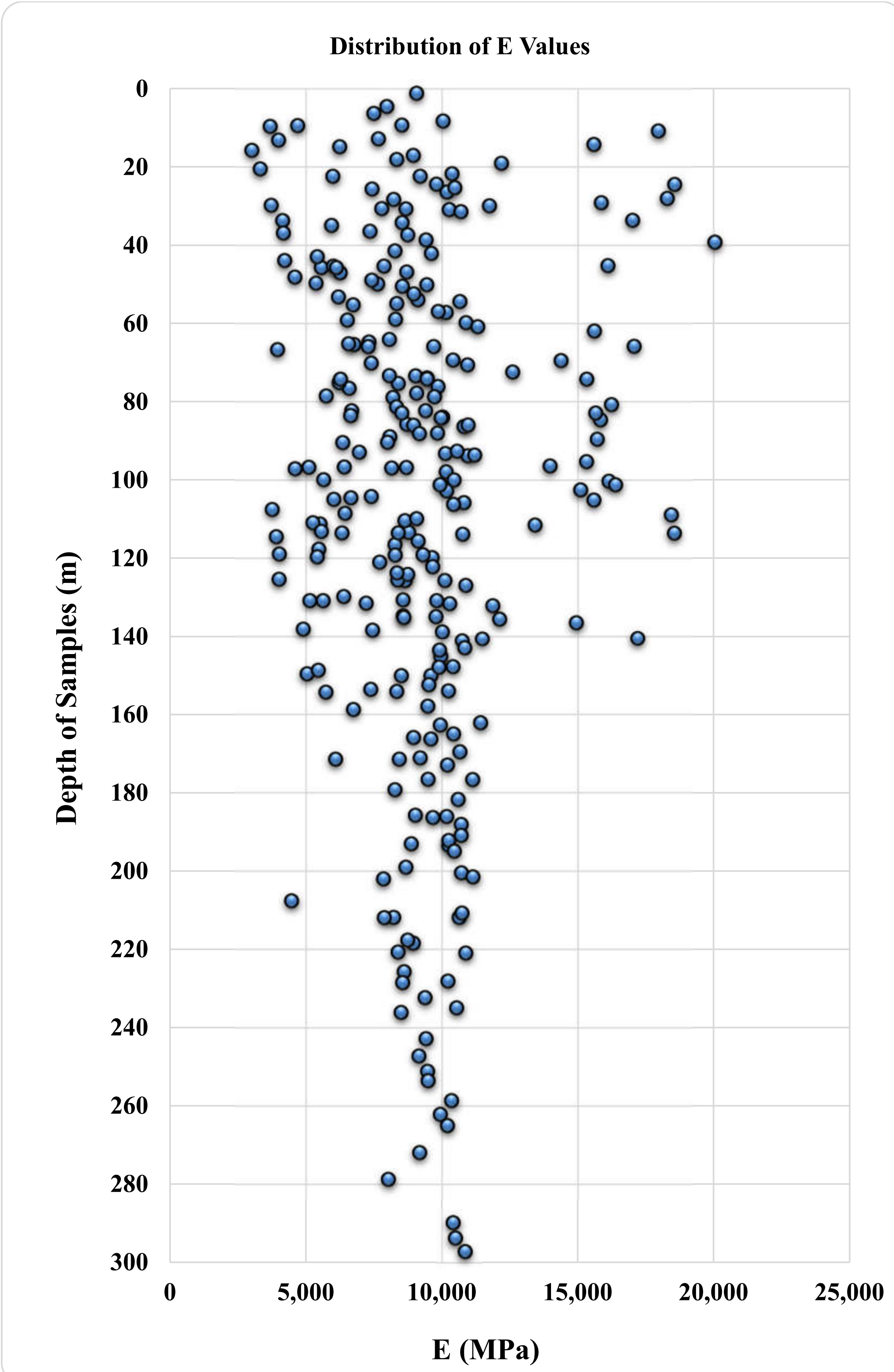


Figure 4.34 Distribution of E Values by Depth (Rock Type – 2)

4.2.2. Correlation of UCS and E Values

Uniaxial compression test was applied on 267 samples. In these tests, the modulus of elasticity values was also measured. In this section, individual UCS tests were not taken into account for correlation study.

The distribution of the uniaxial compressive strength values are given proportionally. Approximately 84.0 % of the total sample has compressive strength between 20-40 MPa. There are samples with strengths different from the average at low rates.

Table 4.8 Field Estimates of Uniaxial Compressive Strength and Point Load Index (Hoek and Marinos – 2001)

Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown [2]
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results.

According to Table 4.8, the majority of the samples are considered "Medium strong" among this database.

When the UCS values of the samples are classified;

- Minimum UCS test value : 6.10 MPa
- Maximum UCS test value : 58.80 MPa

Quantity of observations within the specified interval;

- 0-10 MPa : 10 samples (% 3.7)
- 10-20 MPa : 27 samples (% 10.1)
- 20-30 MPa : 95 samples (% 35.6)
- 30-40 MPa : 124 samples (% 46.4)
- 40-50 MPa : 7 samples (% 2.6)
- >50 MPa : 4 samples (% 1.5)
- Total samples : 267 samples

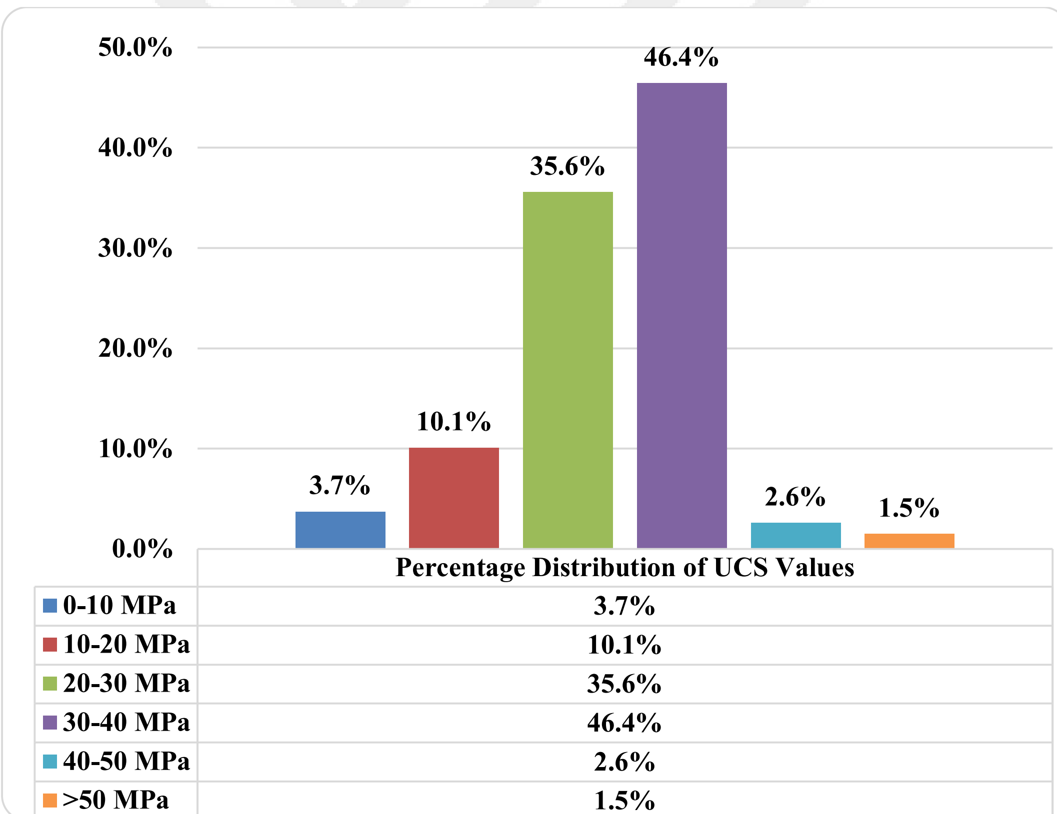


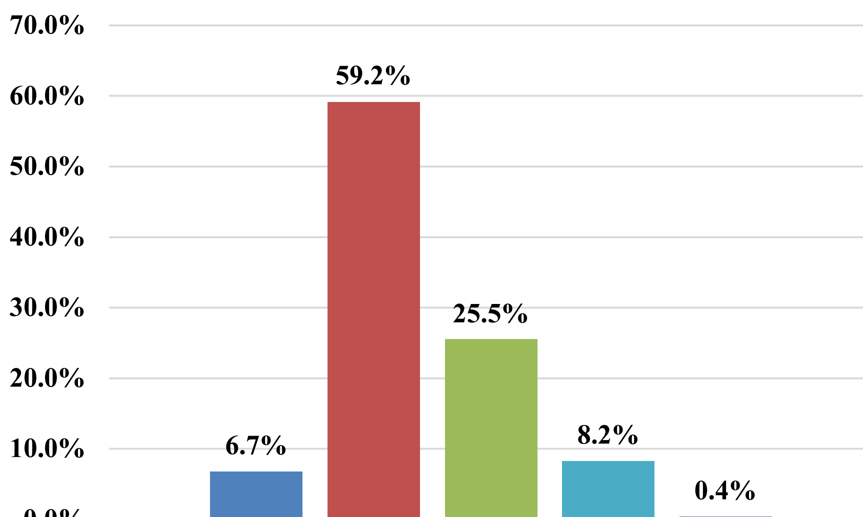
Figure 4.35 Percantage Distribution of UCS Values (Rock Type - 2)

When the E values of the samples are classified;

- Minimum E test value : 3.040 MPa
- Maximum E test value : 20.048 MPa

Quantity of observations within the specified interval;

- 0.000 – 5.000 MPa : 18 samples (% 6.7)
- 5.000 – 10.000 MPa : 158 samples (% 59.2)
- 10.000 – 15.000 MPa : 68 samples (% 25.5)
- 15.000 – 20.000 MPa : 22 samples (% 8.2)
- > 20.000 MPa : 1 sample (% 0.4)
- Total samples : 267 samples



	Percentage Distribution of E Values
0.000 - 5.000 MPa	6.7%
5.000 - 10.000 MPa	59.2%
10.000 - 15.000 MPa	25.5%
15.000 - 50.000 MPa	8.2%
> 20.000 MPa	0.4%

Figure 4.36 Percantage Distribution of E Values (Rock Type - 2)

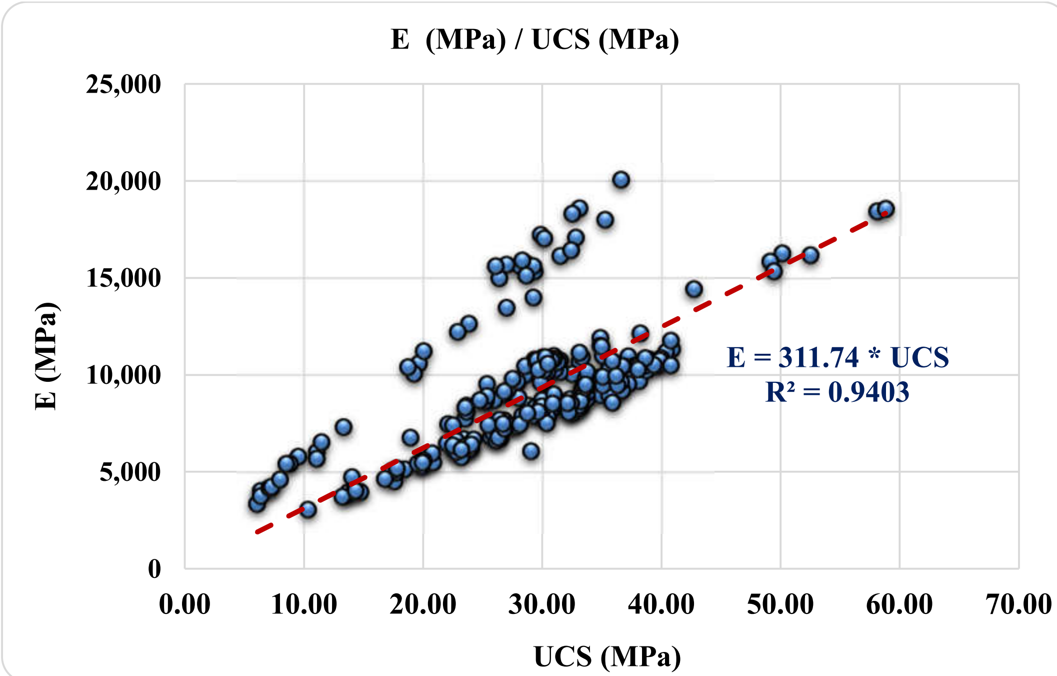


Figure 4.37 Chart of E (MPa) / UCS (MPa) Correlation (Rock Type - 2)

Arithmetic mean of all E results	:	9239.82 MPa
Arithmetic Mean of All UCS Results (MPa)	:	29.12 MPa
Ratio (E / UCS)	:	317.33

Geometric Mean of All E Results (MPa)	:	8732.88 MPa
Geometric Mean of All UCS Results (MPa)	:	27.49 MPa
Ratio (E / UCS)	:	317.63

According to the graphical and mathematical calculation results;

Modulus of elasticity value = 311 - 318 x UCS value

MR (modulus ratio) ~ 311 – 318

Table 4.9 Comparasion with Hoek - Diederichs (Rock Type – 2)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range (Hoek - Diederichs)
Rock Type - 2	Alternation of Shale - Sandstone - Claystone	311 - 318	150 – 250 (Shales) 200 – 350 (Sandstones) 200 – 300 (Claystones)

The correlation range obtained as a result of studies with Hoek and Diederichs (2006) is similar.

Table 4.10 Comparasion with Other Studies (Rock Type – 2)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range
Rock Type – 2 (Alternation of shale – sandstone – claystone)	Claystone	311 - 318	141[a]
			276[b]
	Sandstone		372[c]
			119[d]
			303[e]
			236[f]

a: Malik&Rashid,1997 (number of data = 30)

b: Małkowski&Ostrowski,2017 (Carboniferous) (number of data = 81)

c: Bell&Lindsay,1999 (number of data = 27)

d: Malik&Rashid,1997 (number of data = 30)

e: Sabatakakisetal.,2008 (number of data = 36)

f: Małkowski&Ostrowski,2017 (Carboniferous) (number of data = 86)

The correlation range obtained as a result of studies with Hoek and Diederichs (2006) is similar. Since the number of samples in some studies is not larger, the correlation coefficients are different. When the relationship between the correlation coefficient and the depth is examined;

Table 4.11 Summary Table According to Depth (Rock Type – 2)

Depth Range	**MR Value (according to chart)**	**MR Value (according to arithmetic mean)**	**MR Value (according to geometric mean)**
0 – 100 meters	321.69 (R^2 = 0.9190)	329.44	331.15
100 – 200 meters	310.08 (R^2 = 0.9598)	313.35	311.04
200 – 300 meters	282.49 (R^2 = 0.9864)	284.06	283.41
All Depths	311.74 (R^2 = 0.9403)	317.33	317.63

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

As can be seen in Figure 4.38, the correlation value is different for some of the samples. There basically two sets of different correlations in this graph. When investigated deeply, there seems no specific difference between the samples in these two groups. They were taken from three boreholes along the route of the tunnels and there was no specific depth correlation among the samples.

Therefore, it was decided to separate these two sets to find the upper and lower bounds for the correlation between E and UCS for this specific rock type. The Figure 4.40 and Figure 4.42 are provided as useful examples of how the correlation coefficient may be in a wider range than anticipated. Figure 4.40 represents 20-15% of all samples, whereas Figure 4.42 represents the remaining 80-85%. As can be seen from these two figures, the range of the correlation coefficient has become wider, in the range of 289.38 to 496.04.

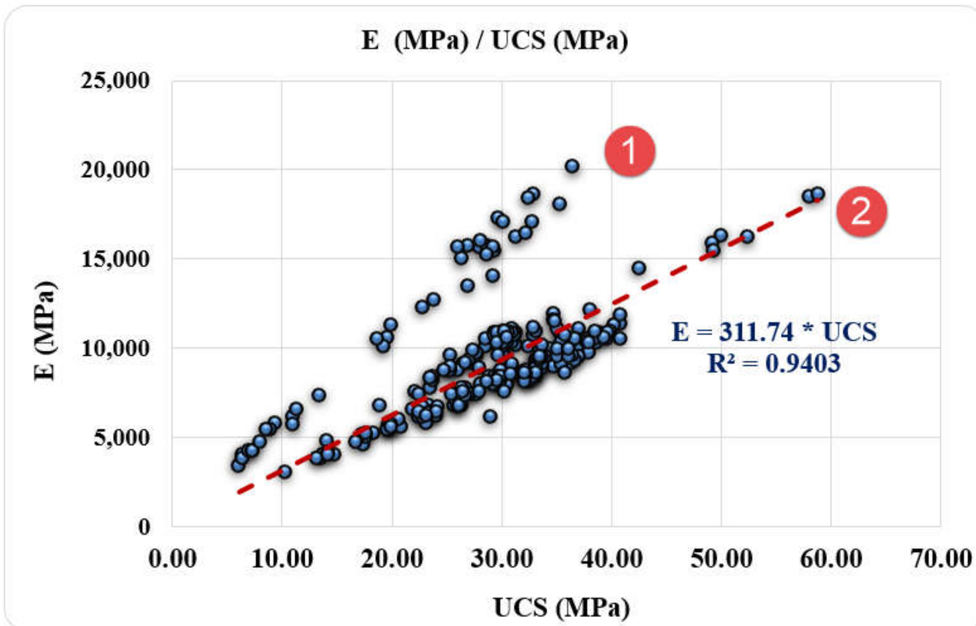


Figure 4.38 E (MPa) / UCS (MPa) Correlation for Two Groups (Rock Type – 2)

As can be seen from the box pictures (Figure 4.39, Figure 4.41) there is no significant difference in the physical conditions of the rocks.

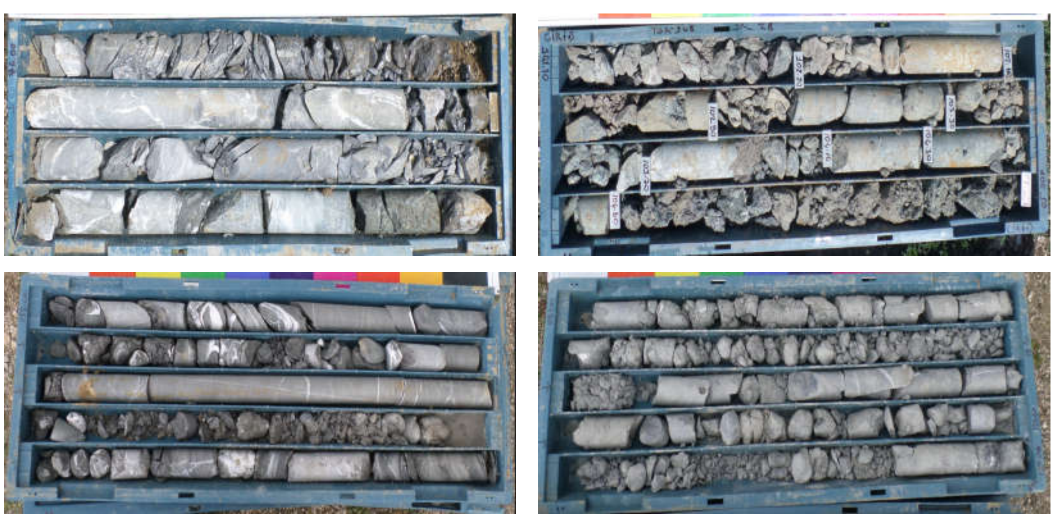


Figure 4.39 Core Sample Boxes (related to figure 4.40 graphic)

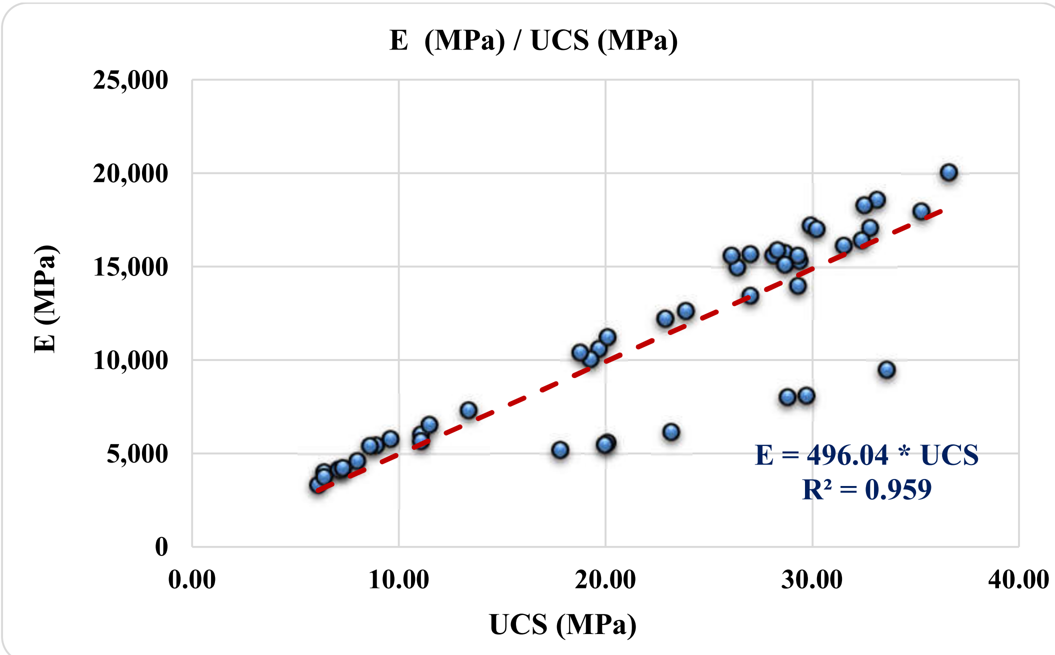


Figure 4.40 E (MPa) / UCS (MPa) Correlation (group - 1)

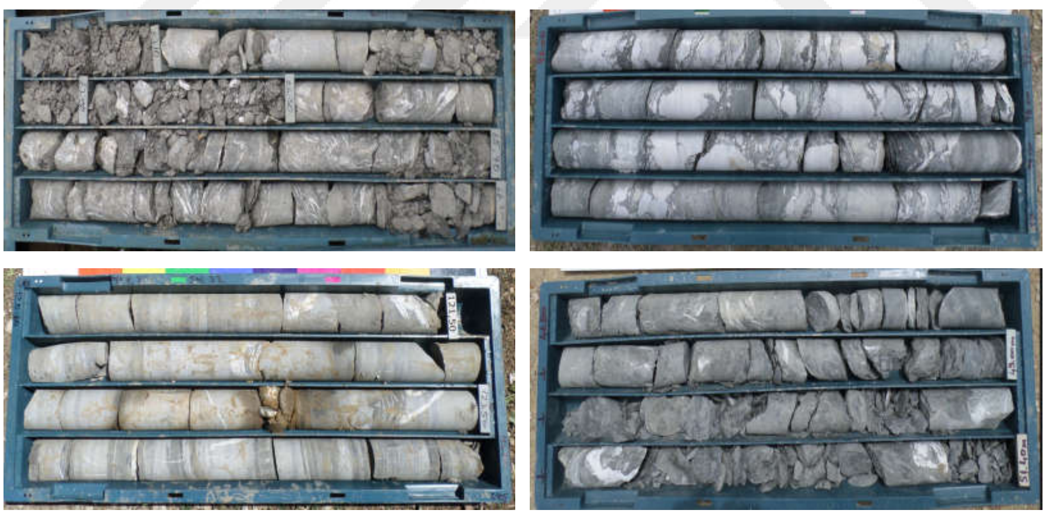


Figure 4.41 Core Sample Boxes (related to figure 4.42 graphic)

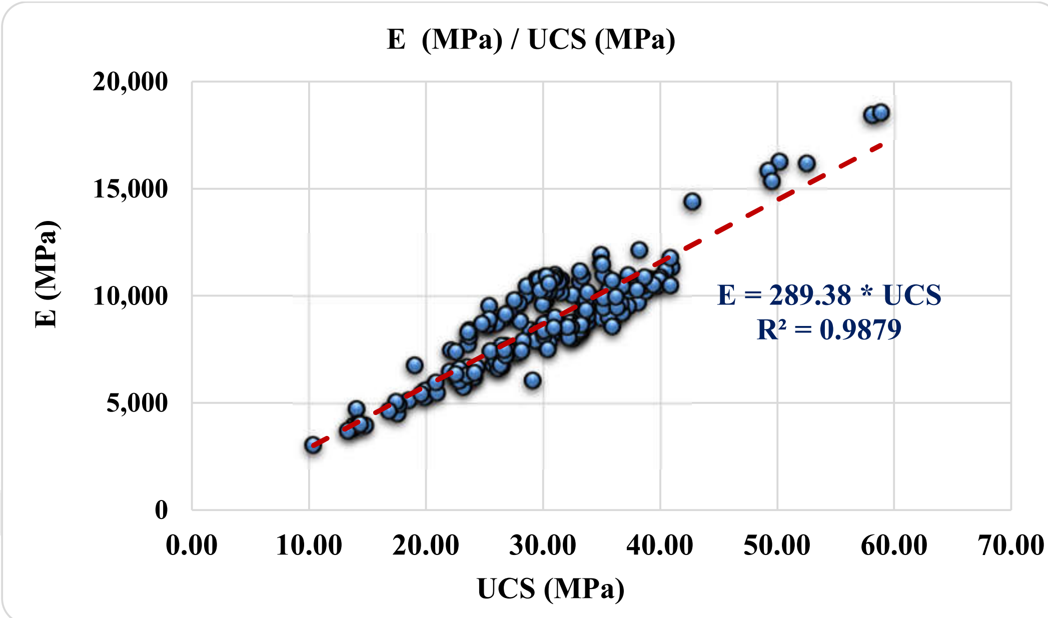


Figure 4.42 E (MPa) / UCS (MPa) Correlation (group - 2)

It can be accepted as an example that the correlation variation can show great changes with the rock ratios in the this rock type.

4.2.3. Correlation of PLI and UCS Values

Point load index test was applied to 287 samples. The UCS test was applied on 559 samples within the scope of the project.

When the PLI values of the samples are classified;

- Minimum PLI test value : 0.34 MPa
- Maximum PLI test value : 2.67 MPa

Quantity of observations within the specified interval;

- 0-0.5 MPa : 13 samples (% 4.5)
- 0.5-1MPa : 66 samples (% 23.0)
- 1-1.5 MPa : 64 samples (% 22.3)
- 1.5-2 MPa : 100 samples (% 34.8)
- 2-2.5 MPa : 42 samples (% 14.6)
- >2.5 MPa : 2 samples (% 0.7)
- Total samples : 287 samples

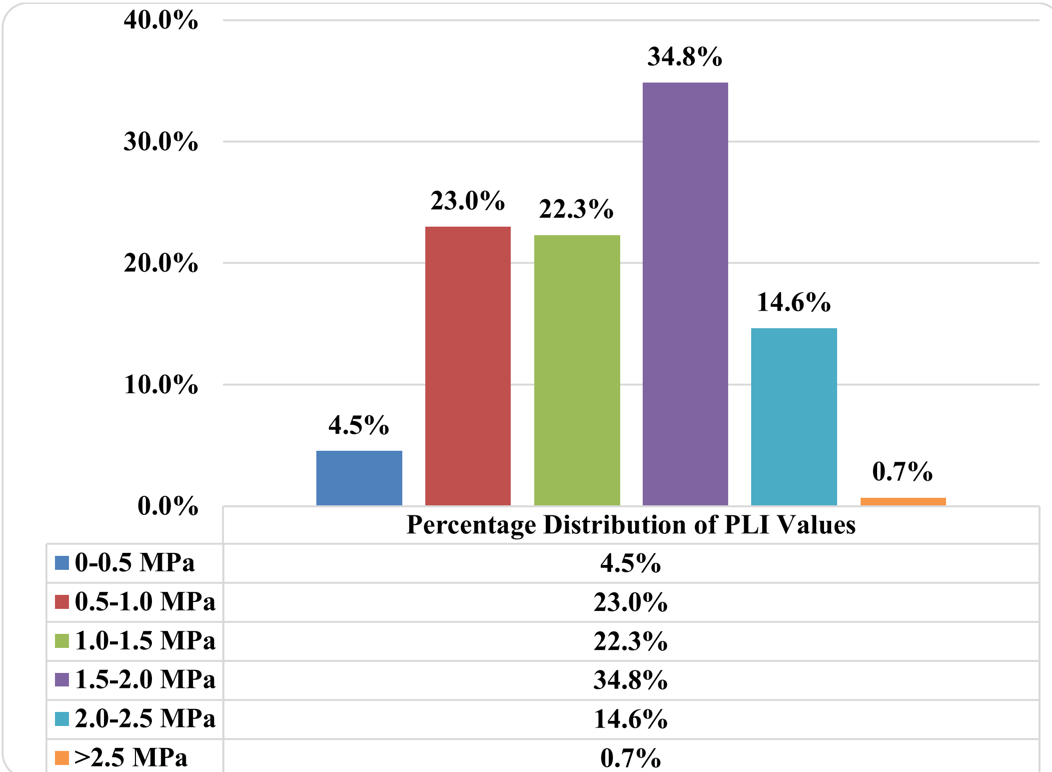


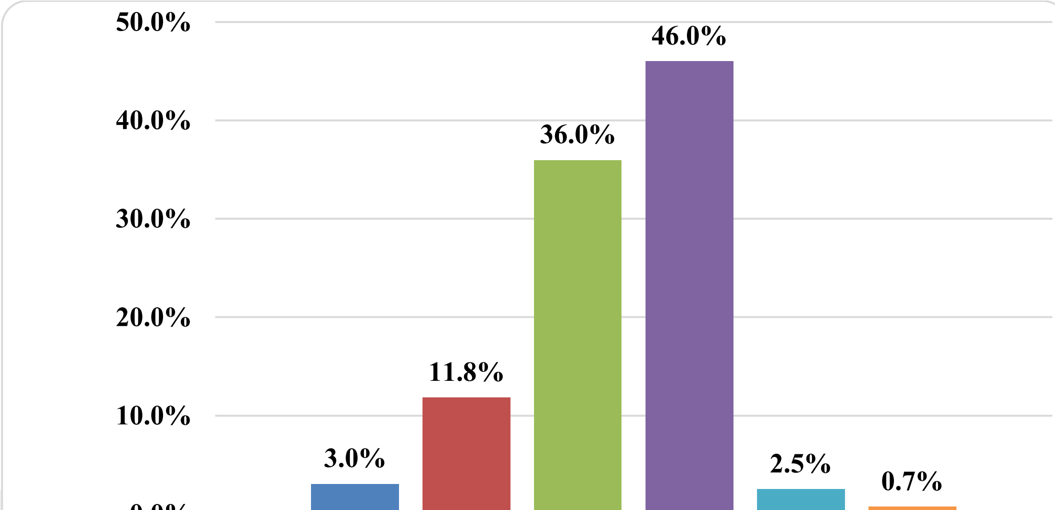
Figure 4.43 Percantage Distribution of PLI Values (Rock Type - 2)

When the UCS values of the samples are classified;

- Minimum UCS test value : 6.10 MPa
- Maximum UCS test value : 58.80 MPa

Quantity of observations within the specified interval;

- ➢ 0-10 MPa : 17 samples (% 3.0)
- ➢ 10-20 MPa : 66 samples (% 11.8)
- ➢ 20-30 MPa : 201 samples (% 36.0)
- ➢ 30-40 MPa : 257 samples (% 46.0)
- ➢ 40-50 MPa : 14 samples (% 2.5)
- ➢ >50 MPa : 4 samples (% 0.7)
- ➢ Total samples : 559 samples



	Percentage Distribution of UCS Values
0-10 MPa	3.0%
10-20 MPa	11.8%
20-30 MPa	36.0%
30-40 MPa	46.0%
40-50 MPa	2.5%
>50 MPa	0.7%

Figure 4.44 Percantage Distribution of UCS Values (Rock Type – 2)

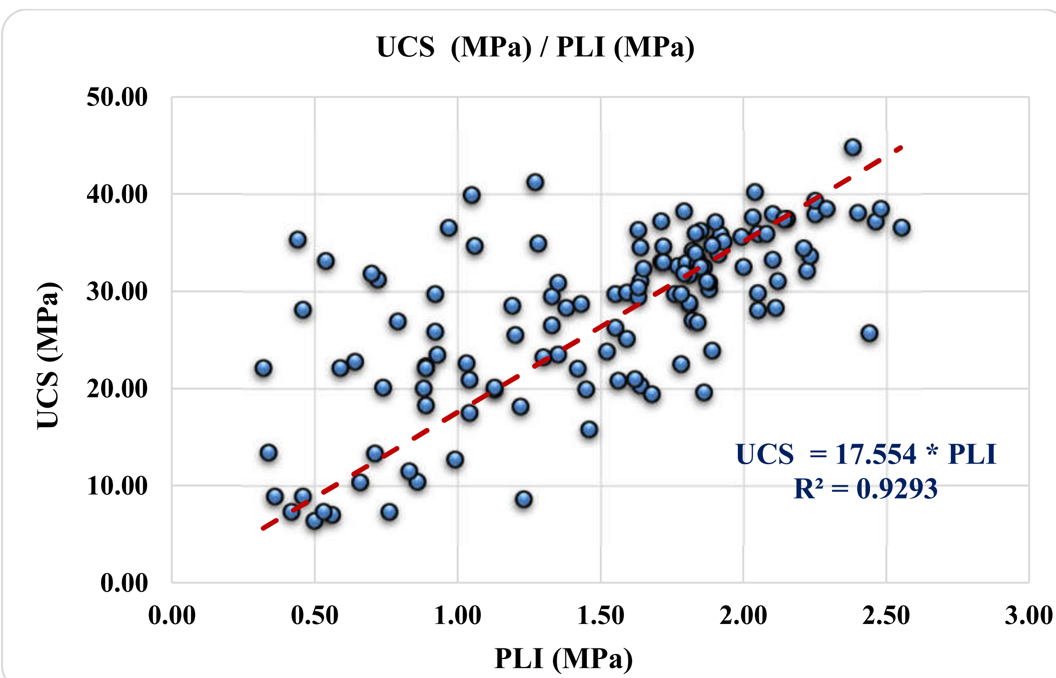


Figure 4.45 Chart of UCS (MPa) / PLI (MPa) Correlation (Rock Type – 2)

Arithmetic Mean of All UCS Results	:	28.81 MPa
Arithmetic Mean of All PLI Results	:	1.42 MPa
Ratio (UCS / PLI)	:	20.29
Geometric Mean of All UCS Results	:	27.37 MPa
Geometric Mean of All PLI Results	:	1.30 MPa
Ratio (UCS / PLI)	:	21.05

According to the above graphical and mathematical calculation results;
*Uniaxial Compressive Strength ~ 18 - 21 * PLI value*

Some of the samples were included for regression analysis and all of them were included for mathematical calculations. Because regression analysis requires UCS - PLI matches and this is not available for all depths.

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

Table 4.12 Sample Depth Range for C Values (Rock Type - 2)

Depth Range	C Value (according to arithmetic mean)	C Value (according to geometric mean)
0 – 100 meters	19.63	19.99
100 – 200 meters	20.20	21.24
200 – 300 meters	20.61	21.54
All Depths	20.29	21.05

Correlations in the academic literature for this rock type are listed below.

*Mohamad et al. (2015) : UCS = 12.291 * PLI + 5.892 (mixed)*

*Kohno and Maeda (2012) : UCS=16.40 * PLI (mixed)*

*Singh et al (2012) : UCS=14.4 * PLI*

*Sabatakakis et al. (2008) : UCS = 25.3 * PLI (sedimentary rocks)*

*Akram and Bakar (2007) : UCS = 22.792 * PLI + 13.295 (sedimentary rocks)*

*Kahraman and Alper (2006) : UCS = 17.91 * PLI + 7.93 (limestones)*

Tsiambaos and Sabatakakis (2004): $UCS=7.3 * PLI^{1.71}$ *(sedimentary rocks)*

*Sulukcu and Ulusay (2001) : UCS=15.3 * PLI (mixed)*

*Rusnak and Mark (1999) : UCS=21.8 * PLI (shales)*

*Brautigam et al. (1998) : UCS = 20.4 * PLI (sedimentary rocks)*

*O'Rourke (1988) : UCS = 30 * PLI (sedimentary rocks)*

*Das (1985) : UCS=12.6 * PLI (shales)*

*ISRM (1985) : UCS = 20 - 25 * PLI (all rocks)*

*Gunsallus and Kulhawy (1984): UCS = 16.5 * PLI + 51 (sedimentary rocks)*

Read et al. (1980) : UCS = 20 PLI (sedimentary rocks)*

*Hassani et al (1980) : UCS = 29 * PLI (sedimentary rocks)*

*Broch and Franklin (1972) : UCS = 23.7 * PLI (various rock types)*

In Figure 4.46, UCS values are calculated with the assumption of PLI = 1 MPa.

As can be seen from Figure 4.46, significant differences emerge between the correlations. Similar to previous case, geotechnical engineers have to be careful when using correlation coefficients. In order to minimize the error, it is recommended to evaluate with more than one correlation.

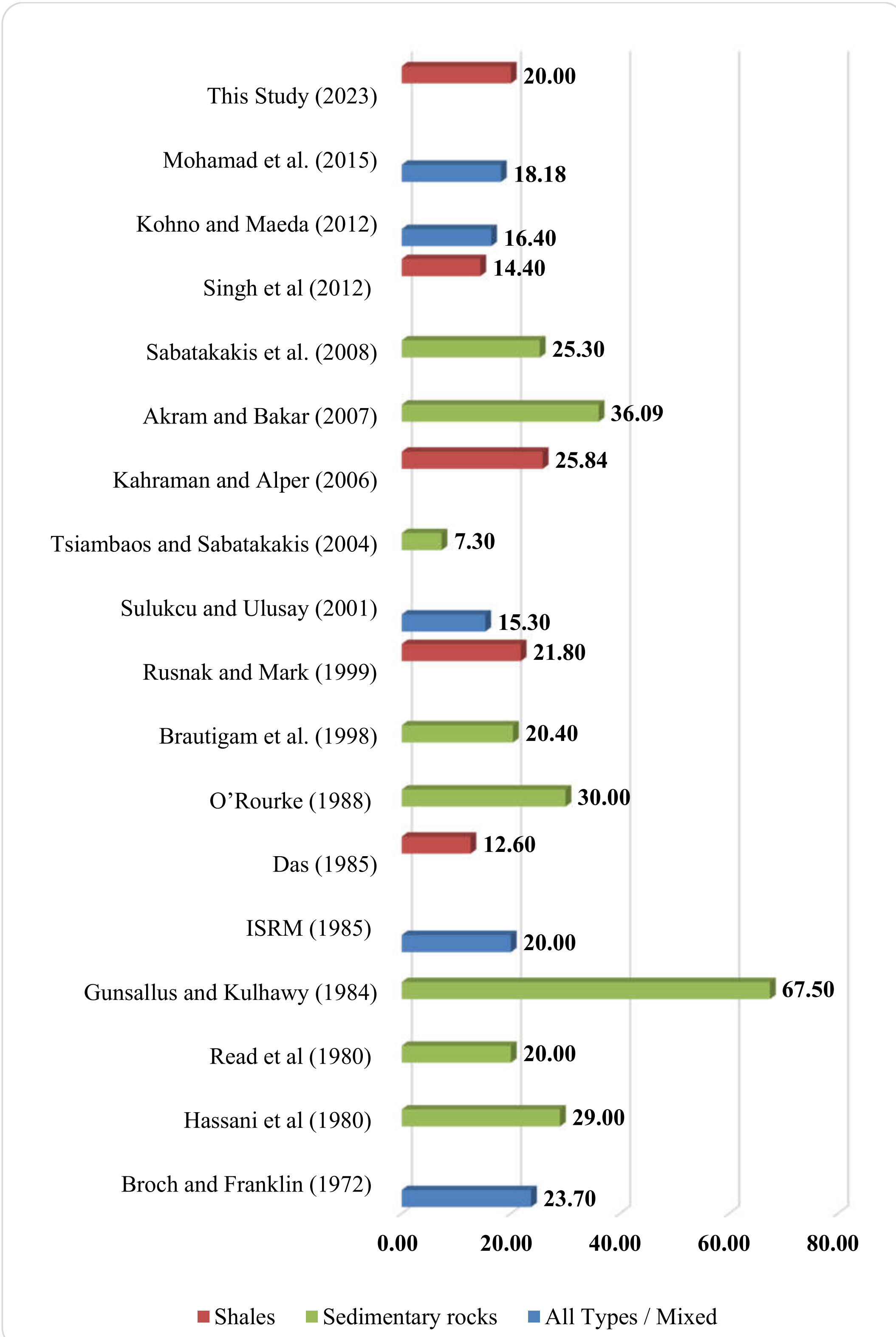


Figure 4.46 Comparison of Some Studies from Literatures for PLI / UCS (For PLI = 1 MPa)

4.3. Rock Type - 3 (Andesite)

In this section, correlation studies related to andesites are presented. The samples were taken from the Konya in the Central Anatolia region. The working area is marked on the map below (Figure 4.47).

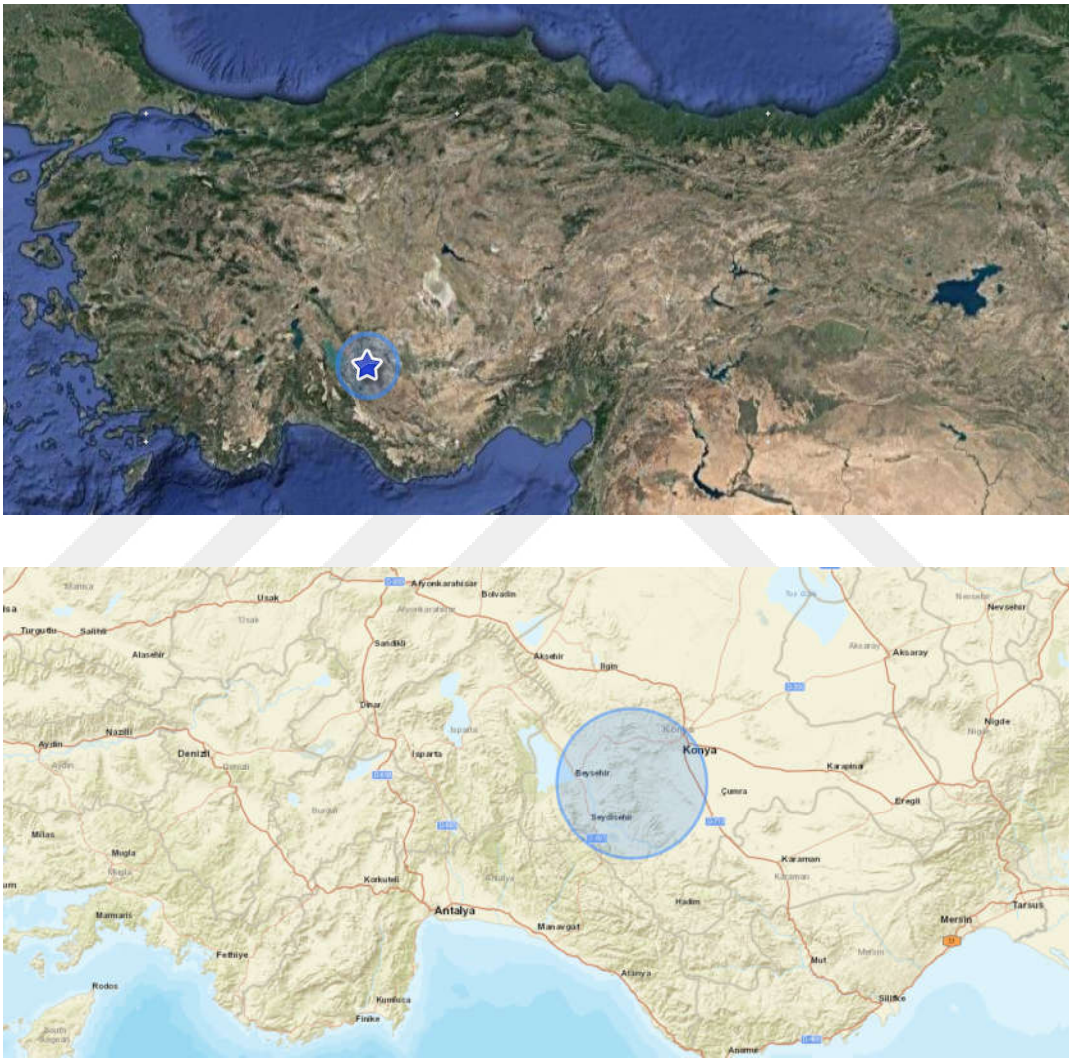


Figure 4.47 Location of Samples (Rock Type – 3)

As indicated in the geological maps below (Figure 4.48 and Figure 4.49), the presence of andesite is evident in the general formation of the region.

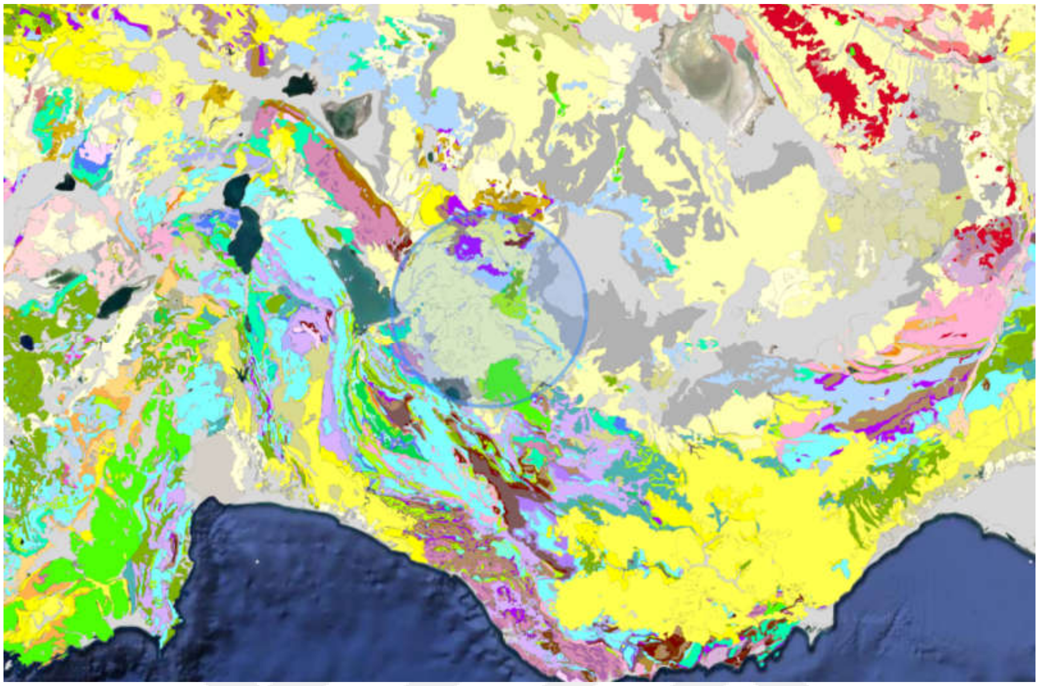


Figure 4.48 Formation Information (from MTA website)

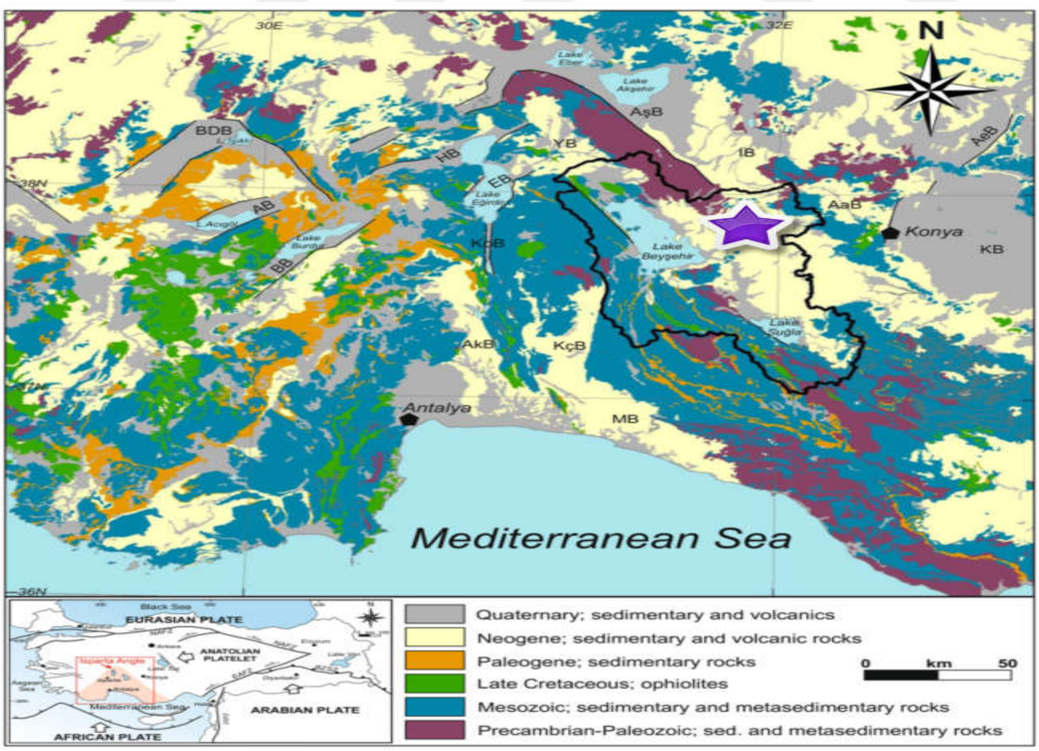


Figure 4.49 Geological Position of the Beyşehir-Sugla Basin in the Isparta Angle, Thick Black Line (Geological Map is Derived From MTA, 2002)

Some core sample box pictures of these rock samples are presented in Figure 4.50.

Figure 4.50 Core Sample Boxes (Rock Type - 3)

4.3.1. Depth of Samples

Similar to the previous ones, the effect of sample depth on correlations will also be studied for this rock type also. The graphs (Figure 4.51, Figure 4.52 and Figure 4.53) below show the percentage distribution of the depth ranges of the samples.

Table 4.13 Number of Samples Summary Table (Rock Type - 3)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 3	Andesite	340	134	155	155

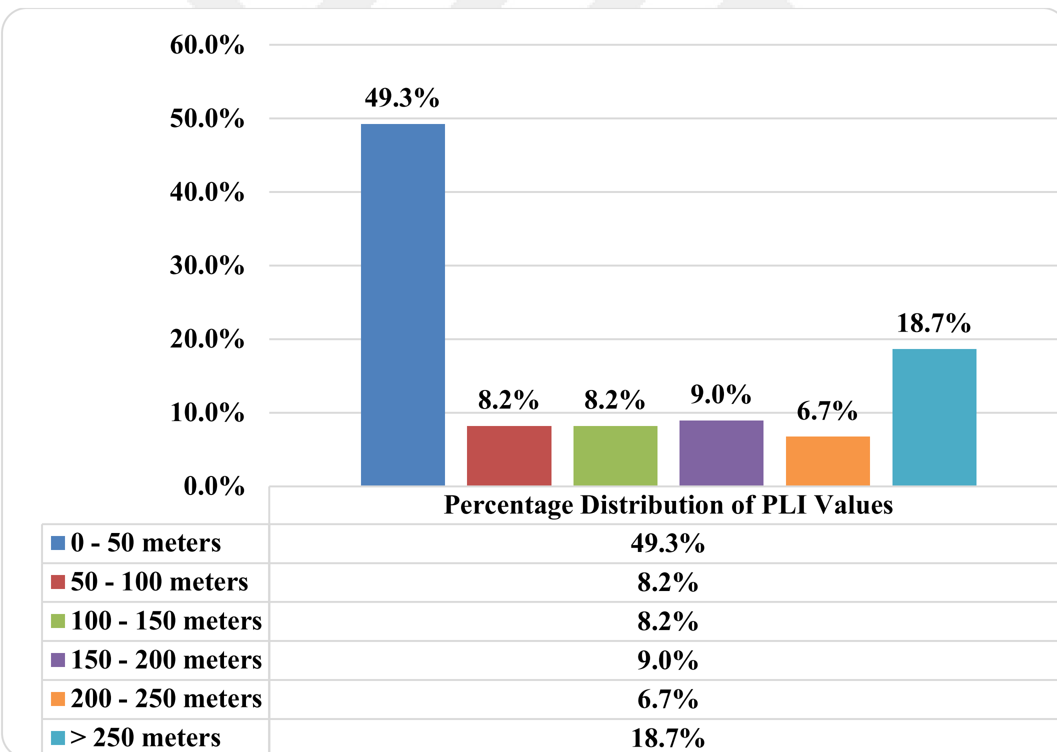
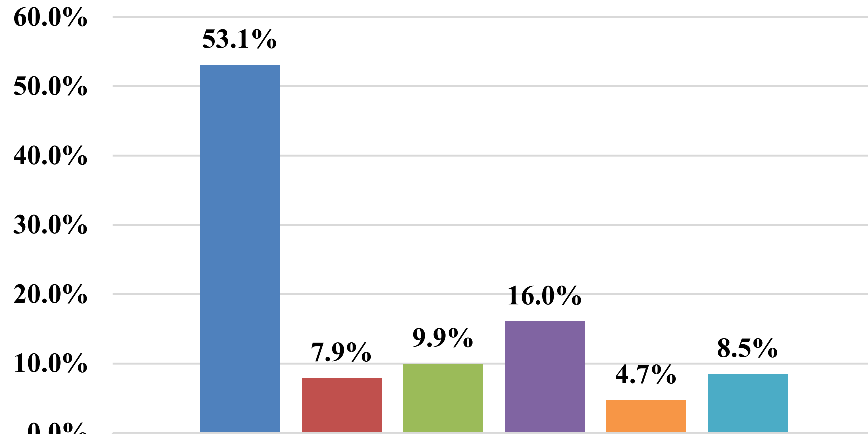
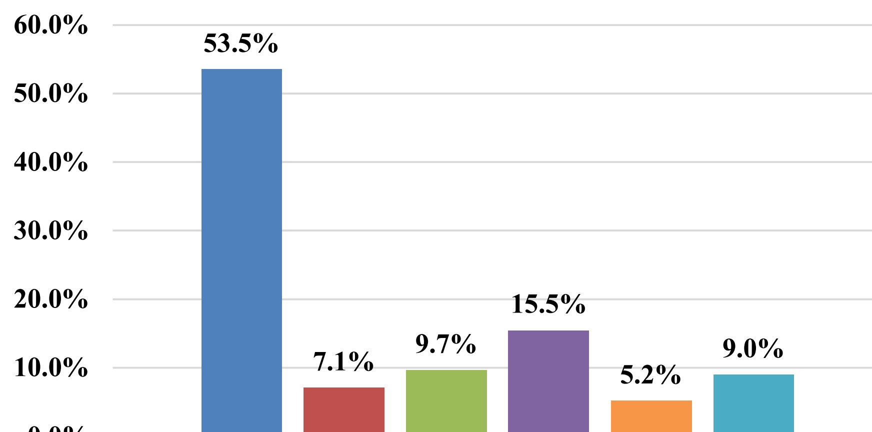


Figure 4.51 Percentage Distribution of PLI Values by Depth (Rock Type - 3)



	Percentage Distribution of UCS Values
0 - 50 meters	53.1%
50 - 100 meters	7.9%
100 - 150 meters	9.9%
150 - 200 meters	16.0%
200 - 250 meters	4.7%
> 250 meters	8.5%

Figure 4.52 Percentage Distribution of UCS Values by Depth (Rock Type – 3)



	Percentage Distribution of E Values
0 - 50 meters	53.5%
50 -100 meters	7.1%
100 - 150 meters	9.7%
150 - 200 meters	15.5%
200 - 250 meters	5.2%
> 250 meters	9.0%

Figure 4.53 Percentage Distribution of E Values by Depth (Rock Type – 3)

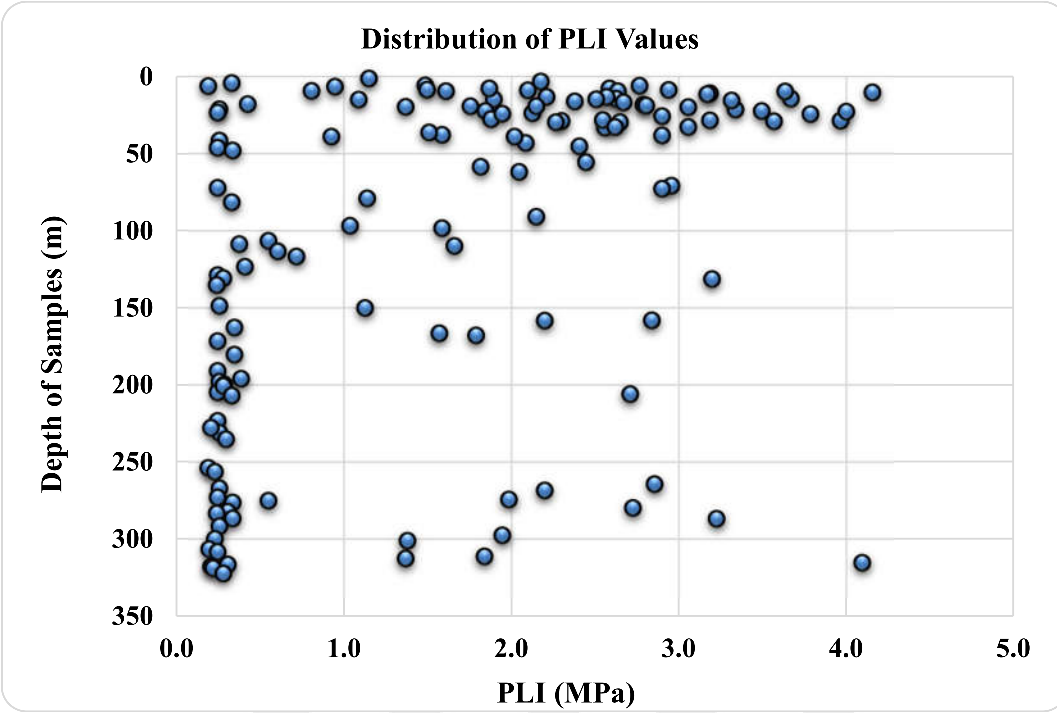


Figure 4.54 Distribution of PLI Values by Depth (Rock Type - 3)

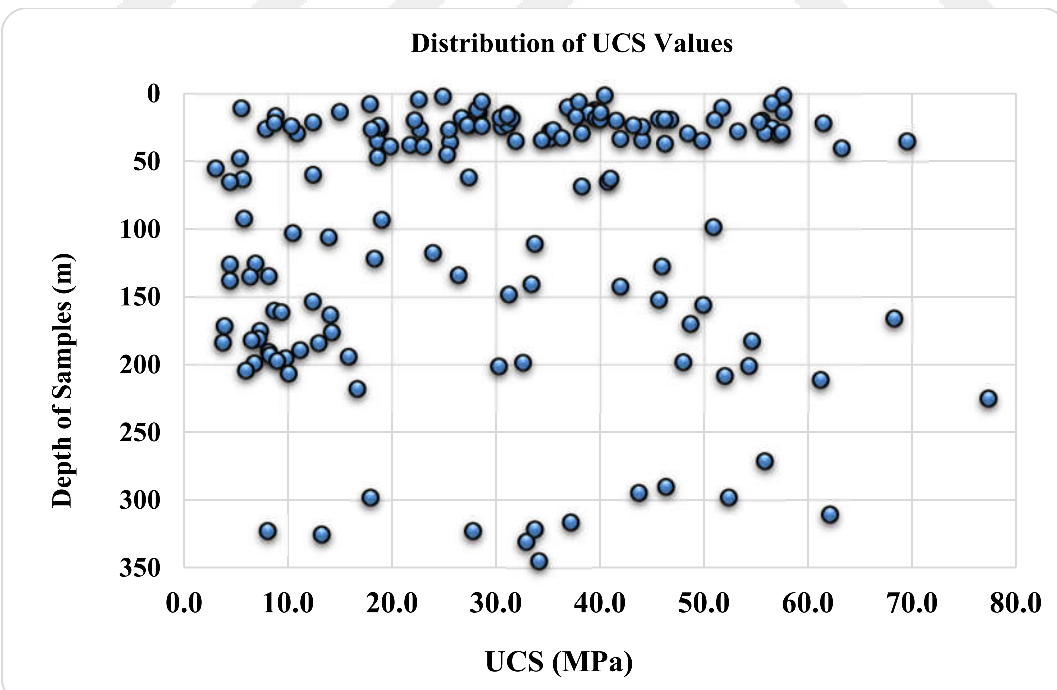


Figure 4.55 Distribution of UCS Values by Depth (Rock Type – 3)

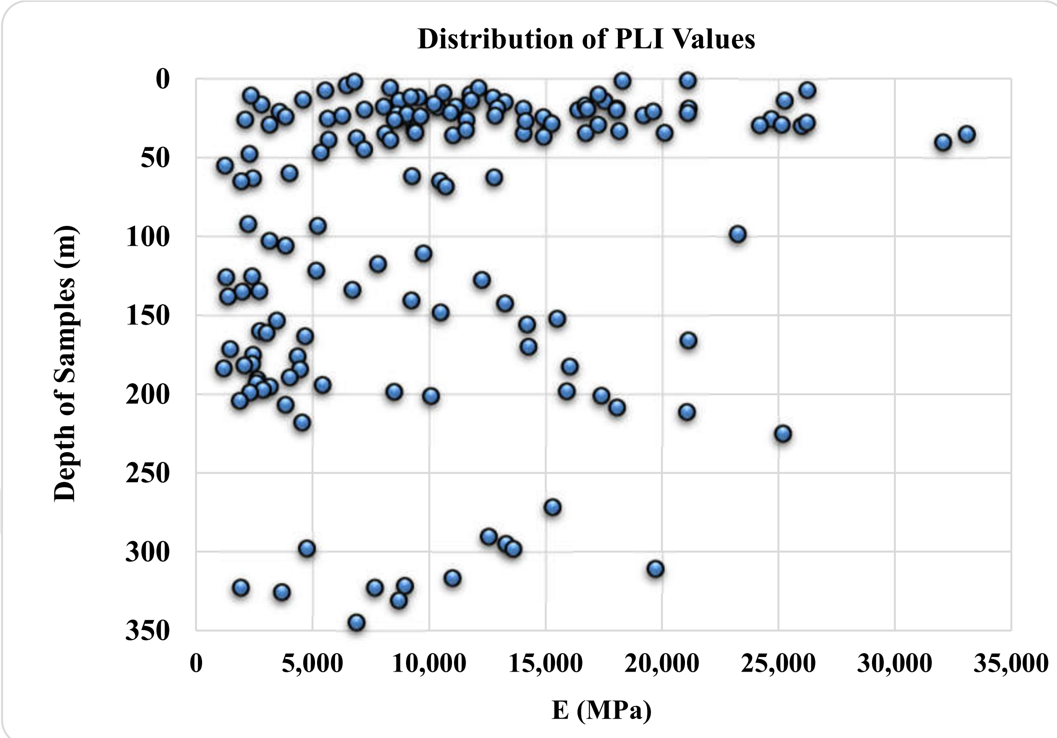


Figure 4.56 Distribution of E Values by Depth (Rock Type – 3)

4.3.2. Correlation of UCS and E Values

Uniaxial compression test was applied on 155 samples. In these tests, the modulus of elasticity values were also measured. In this section, individual UCS tests were not taken into account for correlation study.

The distribution of the uniaxial compressive strength values are given proportionally. There are samples with different strengths at different rates.

Table 4.14 Field Estimates of Uniaxial Compressive Strength and Point Load Index (Hoek and Marinos – 2001)

Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown [2]
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results.

According to Table 4.14, the majority of the samples are considered "Medium strong - weak" among this database.

When the UCS values of the samples are classified;

- Minimum UCS test value : 3.10 MPa
- Maximum UCS test value : 77.40 MPa

Quantity of observations within the specified interval;

- 0-10 MPa : 28 samples (% 18.1)
- 10-20 MPa : 26 samples (% 16.8)
- 20-30 MPa : 21 samples (% 13.5)
- 30-40 MPa : 32 samples (% 20.6)
- 40-50 MPa : 23 samples (% 14.8)
- 50-60 MPa : 18 samples (% 11.6)
- > 60 MPa : 7 samples (% 4.5)
- Total samples : 155 samples

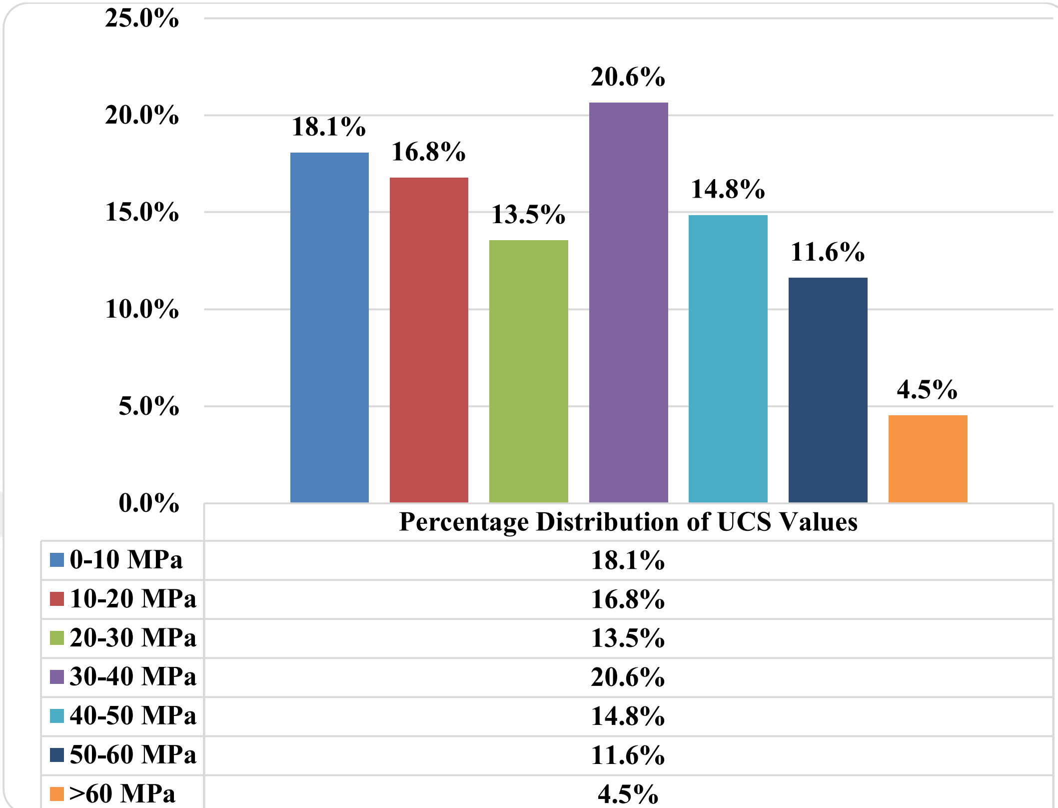


Figure 4.57 Percantage Distribution of UCS Values (Rock Type - 3)

When the E values of the samples are classified;

- Minimum E test value : 1.170 MPa
- Maximum E test value : 33.080 MPa

Quantity of observations within the specified interval;

- 0.000 – 5.000 MPa : 43 samples (% 27.7)
- 5.000 – 10.000 MPa : 38 samples (% 24.5)
- 10.000 – 15.000 MPa : 34 samples (% 21.9)
- 15.000 – 20.000 MPa : 23 samples (% 14.8)
- 20.000 – 25.000 MPa : 9 samples (% 5.8)
- 25.000 – 30.000 MPa : 6 samples (% 3.9)
- > 30.000 MPa : 2 samples (% 1.3)
- Total samples : 155 samples

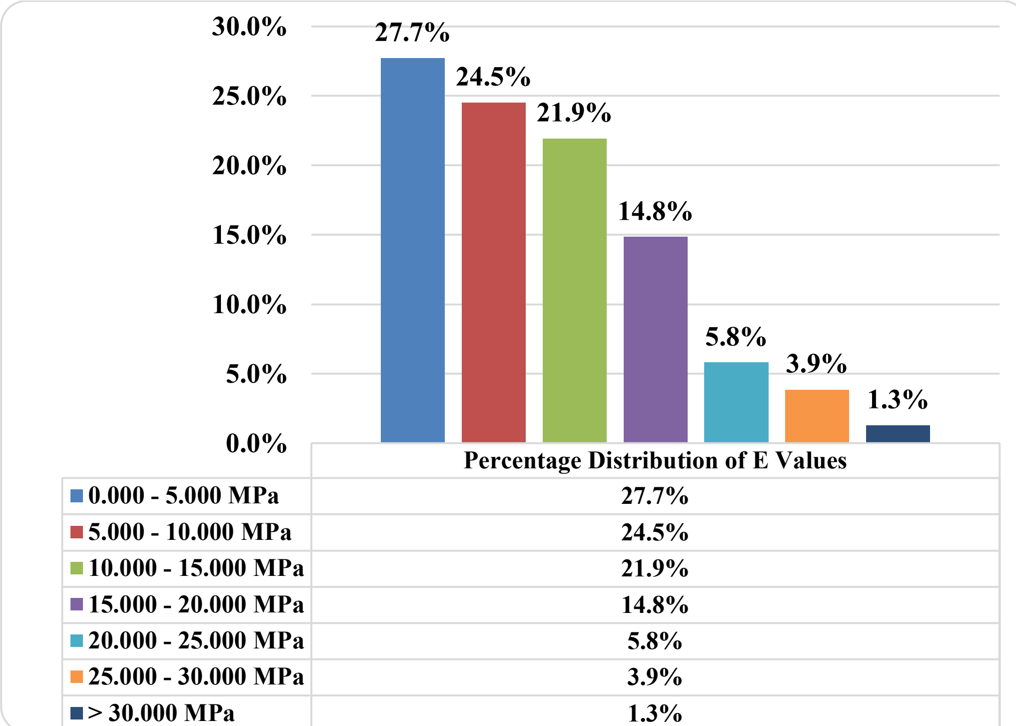


Figure 4.58 Percantage Distribution of UCS Values (Rock Type - 3)

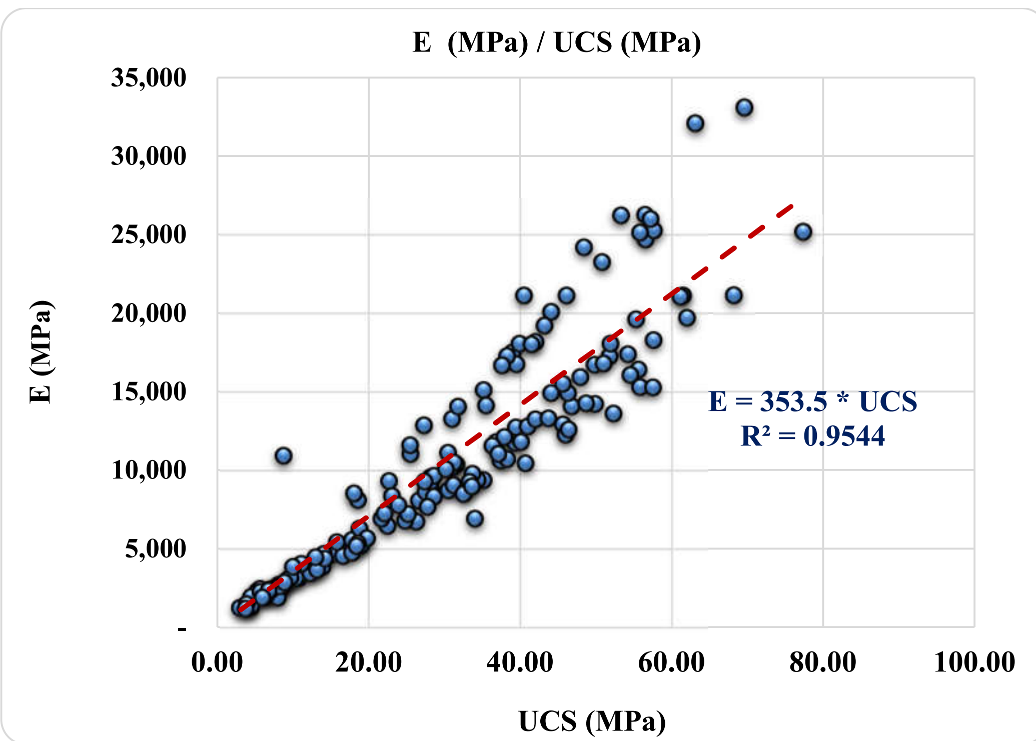


Figure 4.59 Chart of E (MPa) / UCS (MPa) Correlation (Rock Type - 3)

Arithmetic Mean of All E Results	:	10628.52 MPa
Arithmetic Mean of All UCS Results (MPa)	:	30.48 MPa
Ratio (E / UCS)	:	348.70

Geometric Mean of All E Results (MPa)	:	8098.99 MPa
Geometric Mean of All UCS Results (MPa)	:	24.06 MPa
Ratio (E / UCS)	:	336.64

According to the graphical and mathematical calculation results;
Modulus of elasticity value = 336 - 354 x UCS value
MR (modulus ratio) ~ 336 – 354

Table 4.15 Comparasion with Hoek - Diederichs (Rock Type – 3)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range (Hoek - Diederichs)
Rock Type - 3	Andesite	336 - 354	300 - 500

The correlation range obtained as a result of studies with Hoek and Diederichs (2006) is similar.

When the relationship between the correlation coefficient and the depth is examined;

Table 4.16 Summary Table According to Depth (Rock Type – 3)

Depth Range	MR Value (according to chart)	MR Value (according to arithmetic mean)	MR Value (according to geometric mean)
0 – 100 meters	379.89 (R^2 = 0.9567)	373.24	360.66
100 – 200 meters	301.74 (R^2 = 0.9936)	304.27	310.03
200 – 300 meters	298.71 (R^2 = 0.9853)	294.07	287.56
All Depths	353.50 (R^2 = 0.9544)	348.70	336.64

It is understood that the correlation coefficients for all depths are close to the literature. The fact that the number of samples is less for some depths causes different correlation values.

4.3.3. Correlation of PLI and UCS Values

Point load index test was applied to 134 samples. The UCS test was applied on 340 samples within the scope of the project.

When the PLI values of the samples are classified;

- Minimum PLI test value : 0.20 MPa
- Maximum PLI test value : 4.16 MPa

Quantity of observations within the specified interval;

- 0-0.5 MPa : 44 samples (% 32.8)
- 0.5-1MPa : 7 samples (% 5.2)
- 1-1.5 MPa : 10 samples (% 7.5)
- 1.5-2 MPa : 17 samples (% 12.7)
- 2-2.5 MPa : 16 samples (% 11.9)
- 2.5-3 MPa : 22 samples (% 16.4)

- >3.0 MPa : 18 samples (% 13.4)
- Total samples : 134 samples

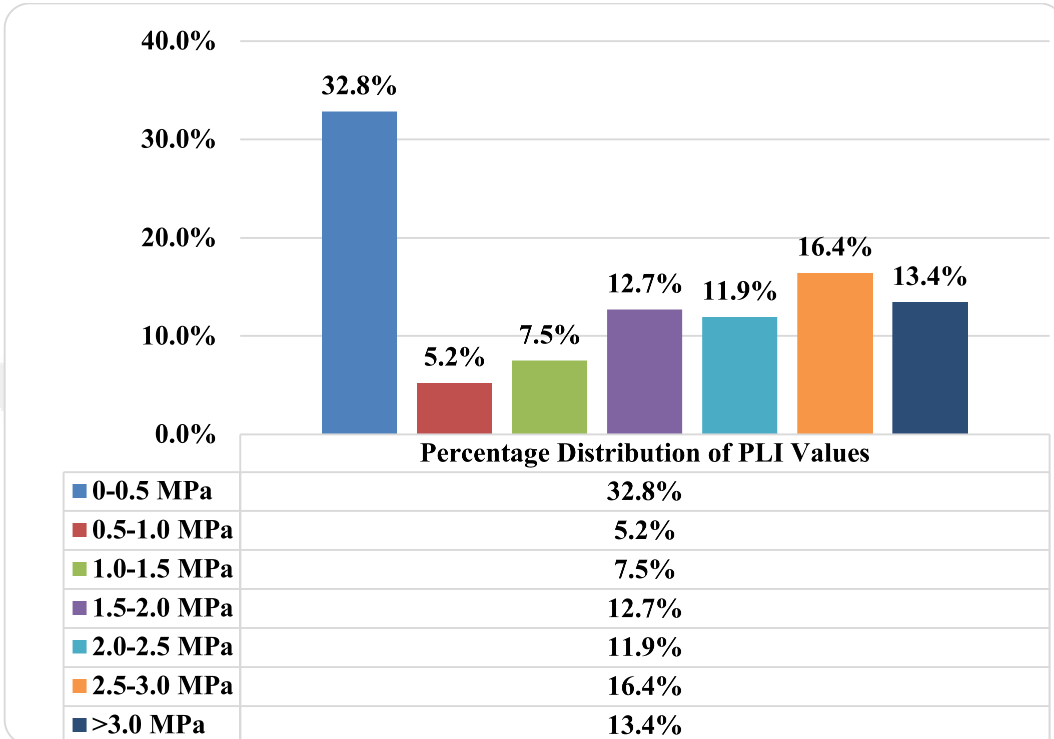


Figure 4.60 Percantage Distribution of PLI Values (Rock Type - 3)

When the UCS values of the samples are classified;

- Minimum UCS test value : 2.50 MPa
- Maximum UCS test value : 69.60 MPa

Quantity of observations within the specified interval;

- 0-10 MPa : 86 samples (% 25.3)
- 10-20 MPa : 56 samples (% 16.5)
- 20-30 MPa : 52 samples (% 15.3)
- 30-40 MPa : 55 samples (% 16.2)
- 40-50 MPa : 40 samples (% 11.8)
- 50-60 MPa : 35 samples (% 10.3)
- >60 MPa : 16 samples (% 4.7)
- Total samples : 340 samples

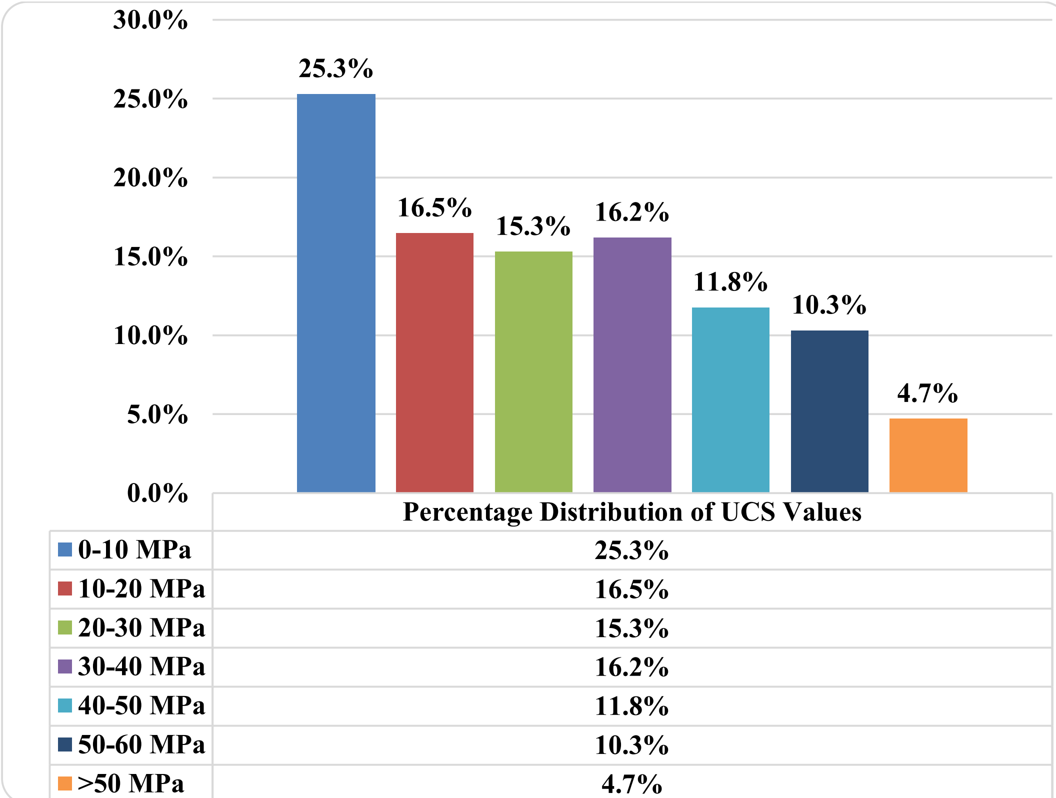


Figure 4.61 Percantage Distribution of UCS Values (Rock Type - 3)

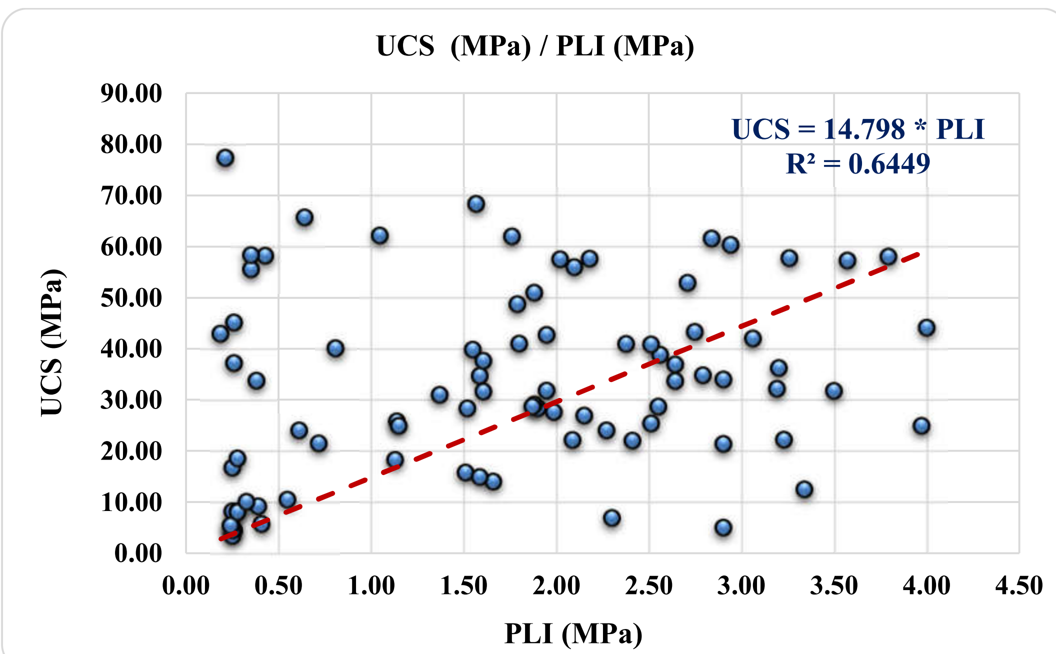


Figure 4.62 Chart of UCS (MPa) / PLI (MPa) Correlation (Rock Type – 3)

Arithmetic Mean of All UCS Results : 27.43 MPa
Arithmetic Mean of All PLI Results : 1.63 MPa
Ratio (UCS / PLI) : 16.82

Geometric Mean of All UCS Results : 20.03 MPa
Geometric Mean of All PLI Results : 1.08 MPa
Ratio (UCS / PLI) : 18.55

According to the above graphical and mathematical calculation results;
*Uniaxial Compressive Strength ~ 15 - 18 * PLI value*

Some of the samples were included for regression analysis and all of them were included for mathematical calculations. Because regression analysis requires UCS - PLI matches and this is not available for all depths.

When the relationship between the correlation coefficient and the depth is examined;

Table 4.17 Sample Depth Range for C Values (Rock Type – 3)

Sample Depth Range	C Value (according to arithmetic mean)	C Value (according to geometric mean)
0 – 100 meters	14.58	14.07
100 – 200 meters	20.82	22.02
200 – 300 meters	32.99	43.93
All Depths	16.82	18.55

It is understood that the correlation coefficients for all depths are close to the literature. The fact that the number of samples is less for some depths causes different correlation values. It has been determined that the value in the range of 200-300 meters is not realistic. There are only 23 samples in this range.

Correlations in the literature for this rock type are listed below.

*Mohamad et al. (2015) : UCS = 12.291 * PLI + 5.892 (mixed)*
*Kallu and Roghanchi (2015) : UCS = 90.14 * PLI* $^{0.92}$ *(igneous rocks)*
*Kohno and Maeda (2012) : UCS = 16.40 * PLI (mixed types)*
*Kahraman and Gunaydin (2009): UCS = 8.2 * PLI + 36.43 (igneous rocks)*
*Basu and Aydin (2006) : UCS = 18 * PLI (igneous rocks)*
*Quane and Russel (2003) : UCS = 24.4 * PLI (strong rocks)*
*Sulukcu and Ulusay (2001) : UCS = 15.3 * PLI (mixed types)*
*Tugrul and Zarif (1999) : UCS = 15.25 * PLI (igneous rocks - granites)*
*Brautigam et al. (1998) : UCS = 14.2 * PLI (igneous rocks)*
*Chau and Wong (1996) : UCS= 12.5 * PLI (granites, tuffs)*
*Ghosh and Srivastava (1991): UCS = 16 * PLI (granites)*
*ISRM (1985) : UCS = 20 - 25 * PLI (all rocks)*
*Lumb (1983) : UCS = 22 * PLI (igneous rocks - granites)*
*Broch and Franklin (1972) : UCS = 23.7 * PLI (various rock types)*

In Figure 4.63, UCS values are calculated with the assumption of PLI = 1 MPa.

As can be seen from Figure 4.63, significant differences emerge between the correlations. Similar to previous case, geotechnical engineers have to be careful when using correlation coefficients. In order to minimize the error, it is recommended to evaluate with more than one correlation.

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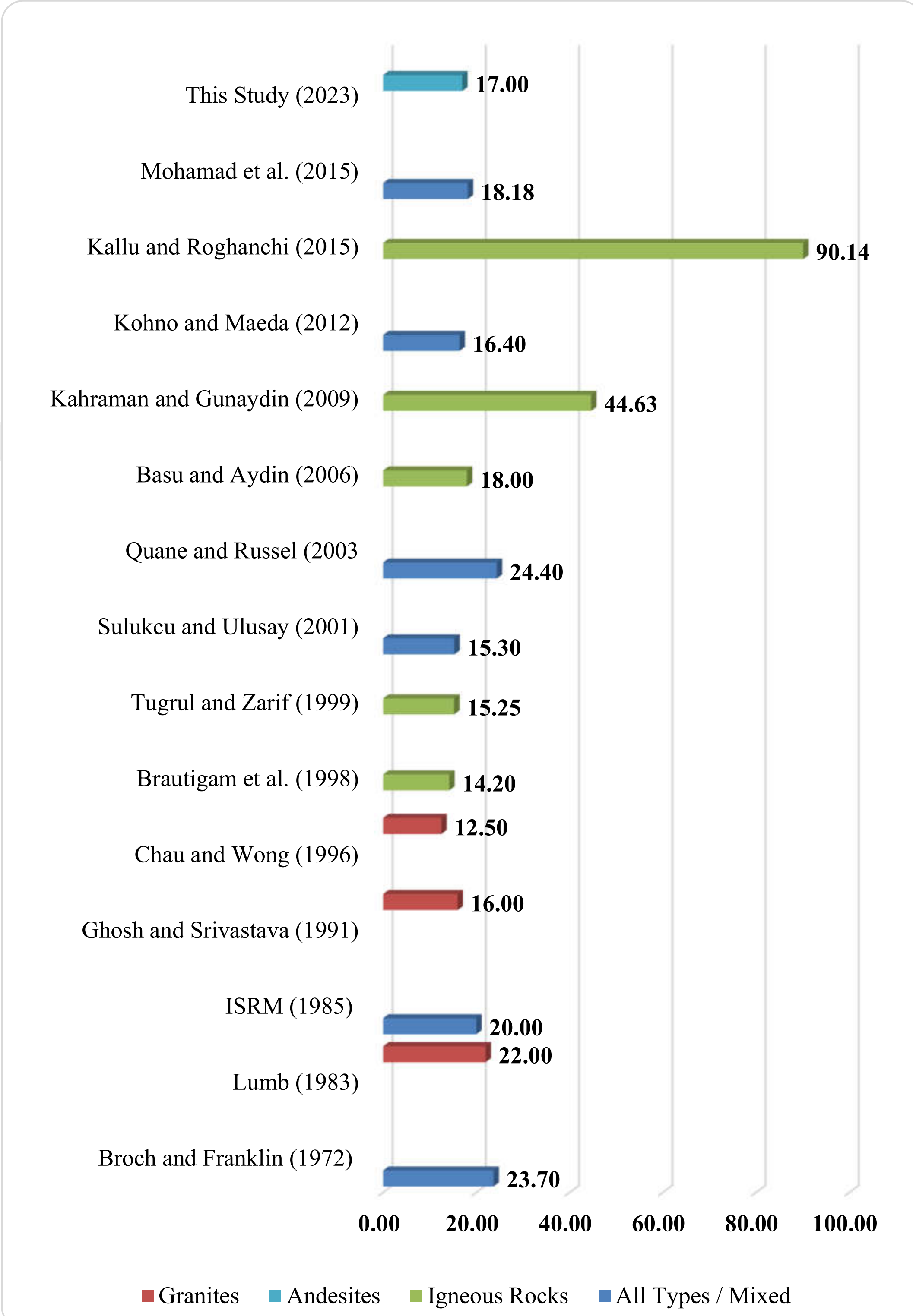


Figure 4.63 Comparison of Some Studies from Literatures for PLI / UCS (For PLI = 1 MPa)

4.4. Rock Type - 4 (Granite – Granodiorite)

In this section, correlation studies related to granite and granodiorite are presented. The samples were taken from Giresun-Yaglidere-Alucra-Sebinkarahisar in the Eastern Black Sea region. The working area is marked on the map below (Figure 4.64).

Figure 4.64 Location of Samples (Rock Type – 4)

As indicated in the geological maps below (Figure 4.65 and Figure 4.66), the presence of granite and granodiorite is evident in the general formation of the region.

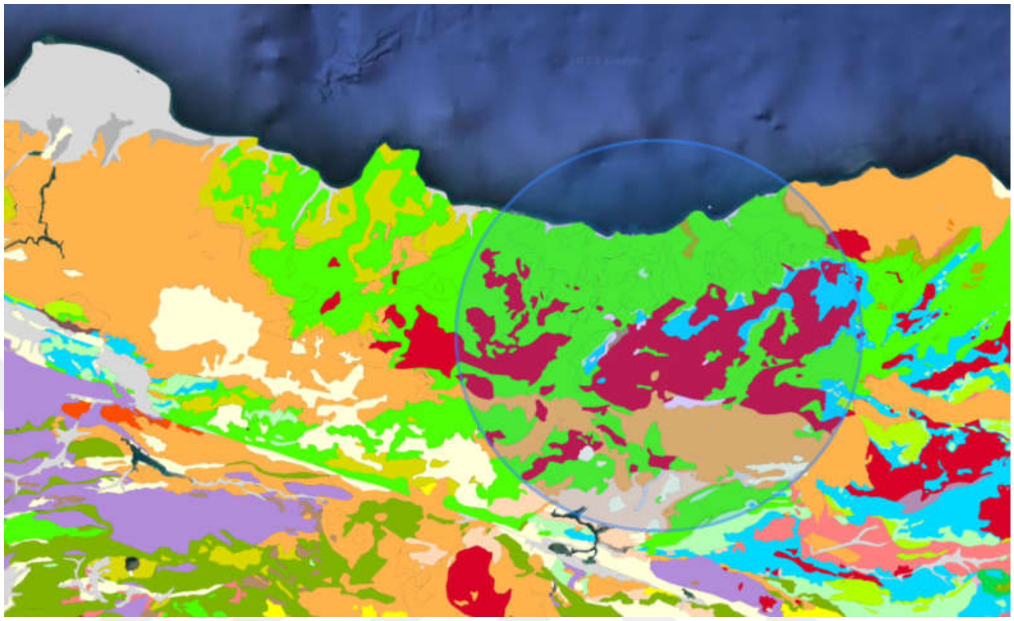


Figure 4.65 Formation Information (from MTA website)

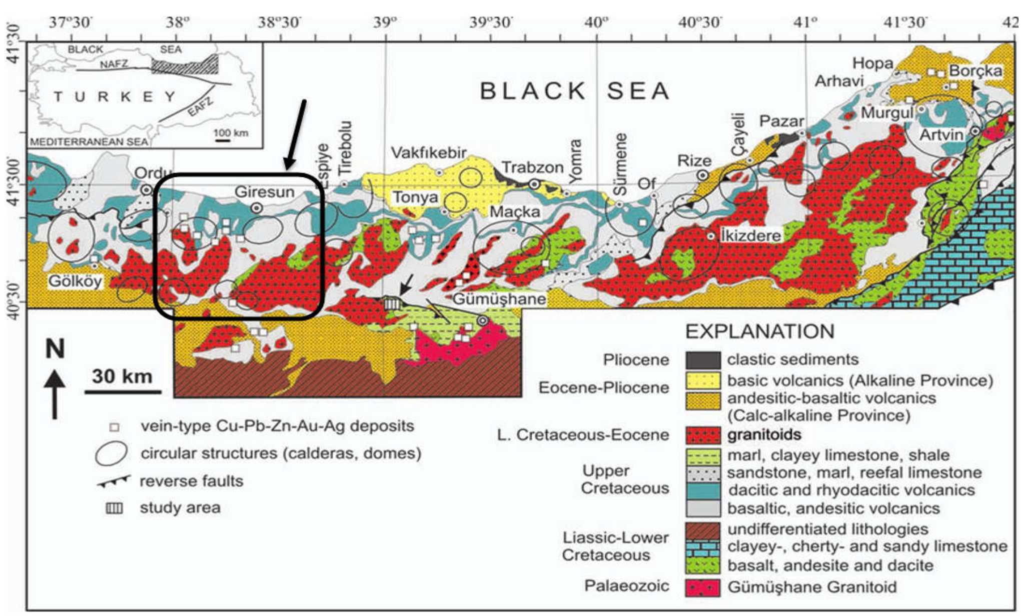


Figure 4.66 Simplified Geological Map of the Eastern Pontides (Modified After Guven 1993)

Some core sample box pictures of these rock samples are given in Figure 4.67 below.

Figure 4.67 Core Sample Boxes (Rock Type - 4)

4.4.1. Depth of Samples

Within the scope of the thesis, it is also aimed to examine the effect of sample depth on correlations as mentioned before. The graphs (Figure 4.68, Figure 4.69 and Figure 4.70) below show the percentage distribution of the depth ranges of the samples.

With the increase of the cover depth; It is determined that the weathering degree of the rock and the PLT test percentage are decreased.

Table 4.18 Number of Samples Summary Table (Rock Type – 4)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 4	Granite, Granodiorite	233	125	113	113

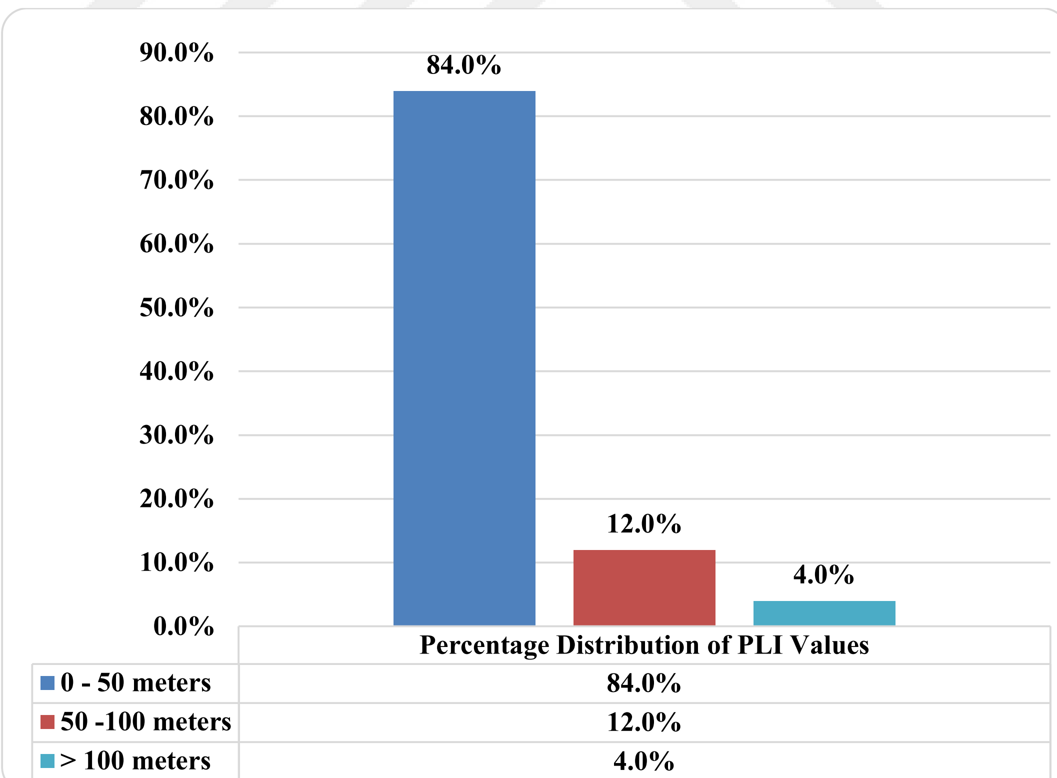


Figure 4.68 Percentage Distribution of PLI Values by Depth (Rock Type – 4)

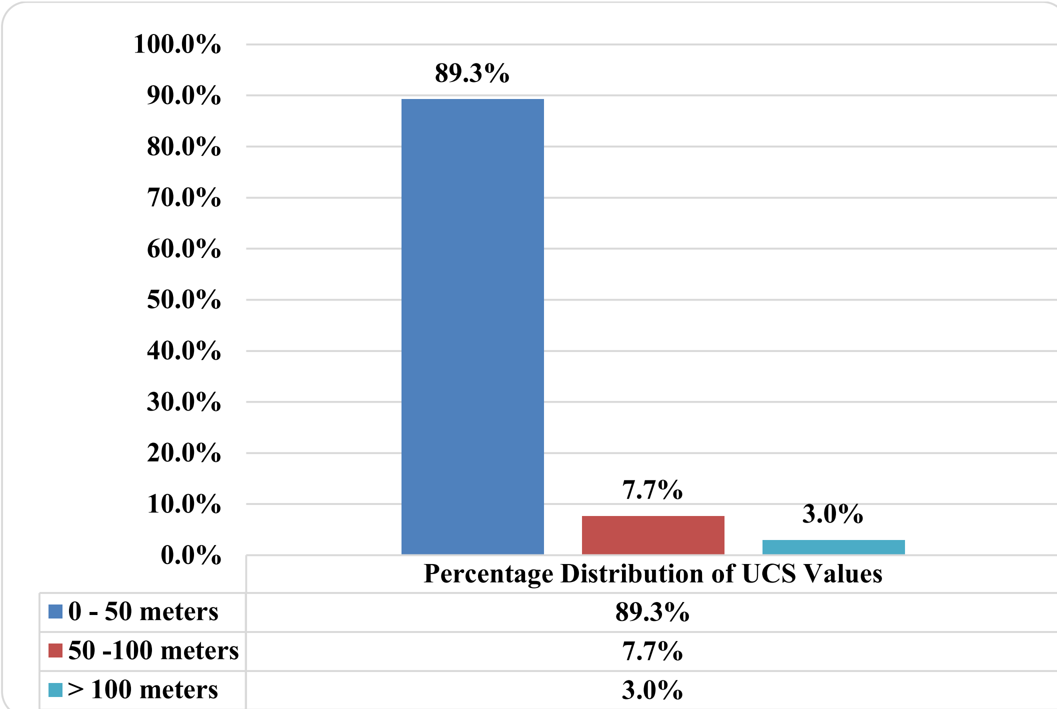


Figure 4.69 Percentage Distribution of UCS Values by Depth (Rock Type – 4)

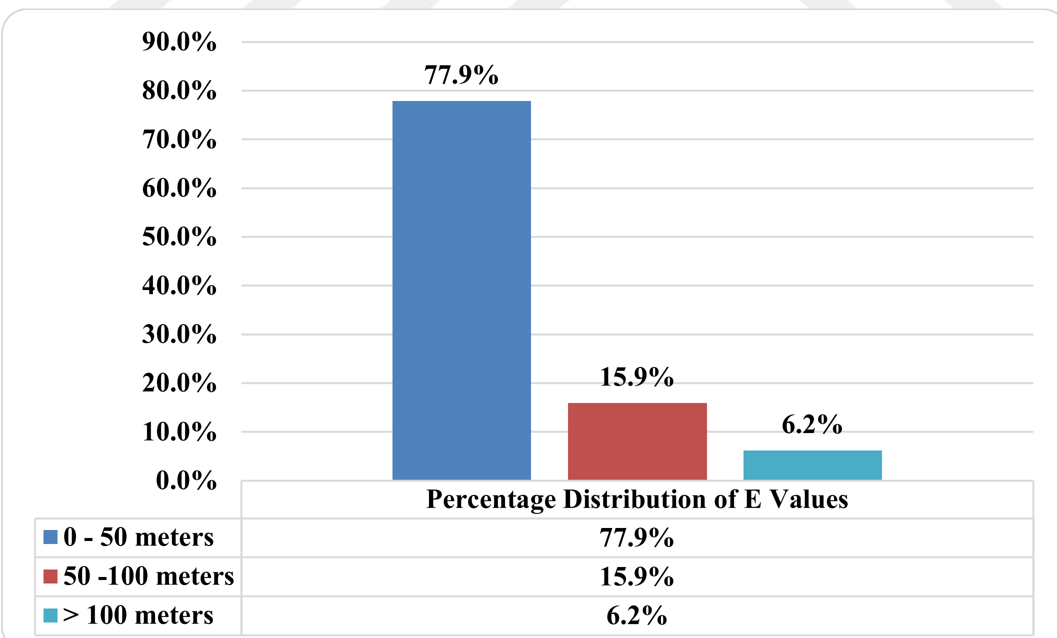


Figure 4.70 Percentage Distribution of E Values by Depth (Rock Type – 4)

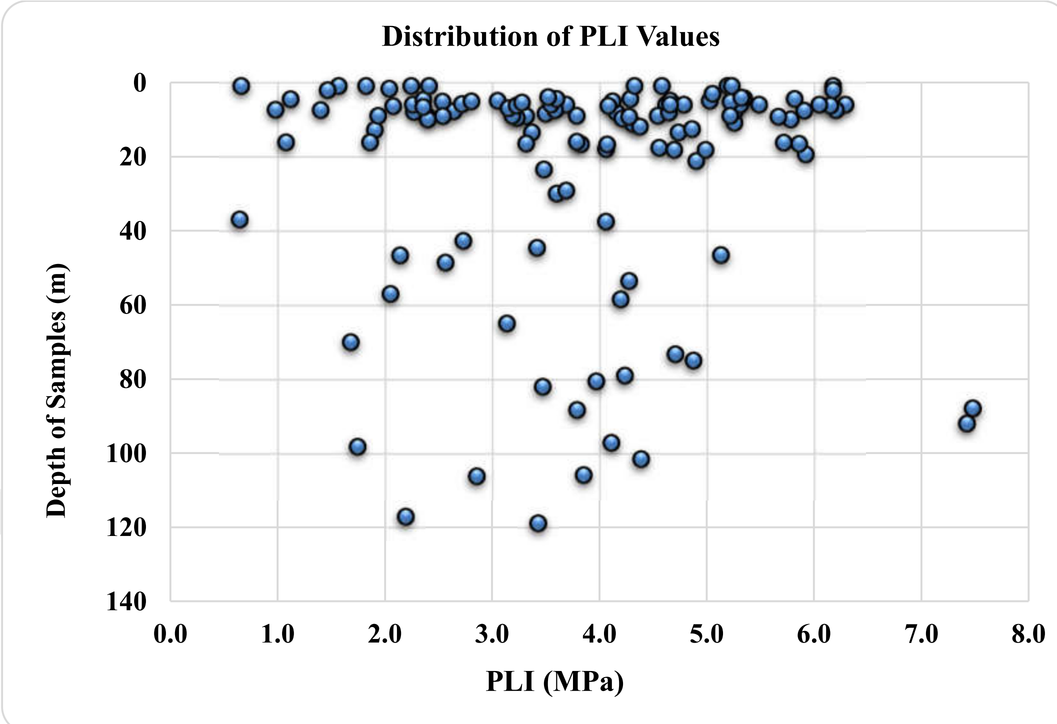


Figure 4.71 Distribution of PLI Values by Depth (Rock Type – 4)

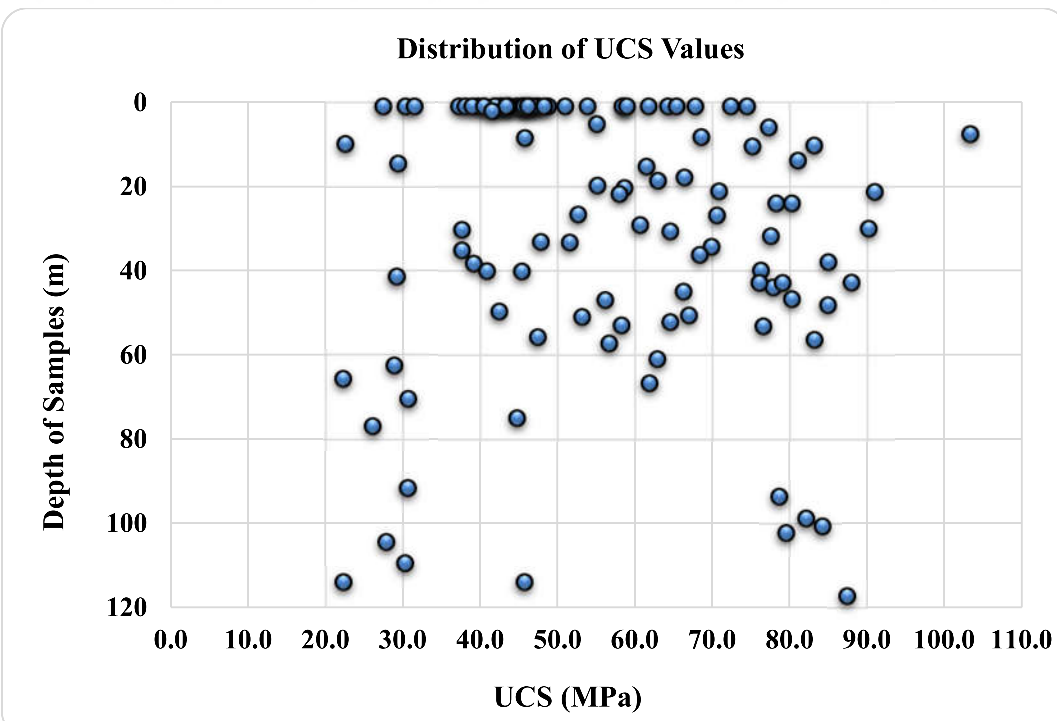


Figure 4.72 Distribution of UCS Values by Depth (Rock Type – 4)

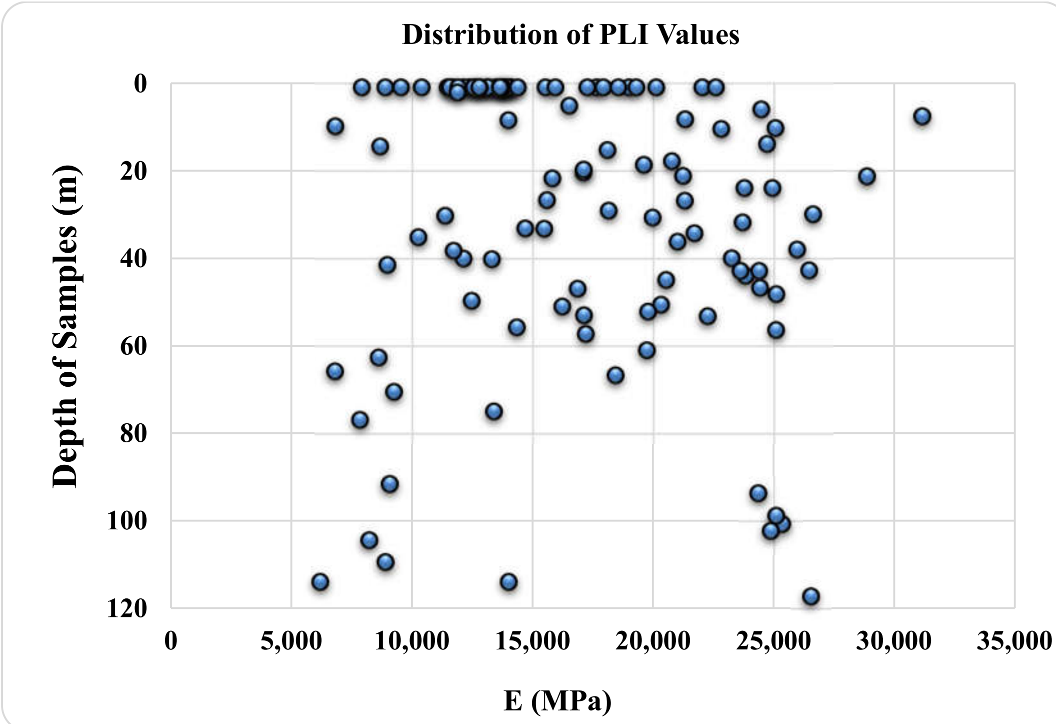


Figure 4.73 Distribution of E Values by Depth (Rock Type – 4)

4.4.2. Correlation of UCS and E Values

Uniaxial compression test was applied on 113 samples. In these tests, the modulus of elasticity values were also measured. In this section, individual UCS tests were not taken into account for correlation study.

The distribution of the uniaxial compressive strength values are given proportionally. Approximately 69.0 % of the total sample has compressive strength between 40-80 MPa. There are samples with strengths different from the average at low and different rates.

Table 4.19 Field Estimates of Uniaxial Compressive Strength and Point Load Index (Hoek and Marinos – 2001)

Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown [2]
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results.

According to Table 4.19, the majority of the samples are considered "Strong – medium strong" among this database.

When the UCS values of the samples are classified;

- Minimum UCS test value : 22.30 MPa
- Maximum UCS test value : 103.30 MPa

Quantity of observations within the specified interval;

- 20-40 MPa : 21 samples (% 18.6)
- 40-60 MPa : 46 samples (% 40.7)
- 60-80 MPa : 32 samples (% 28.3)
- 80-100 MPa : 13 samples (% 11.5)
- >100 MPa : 1 sample (% 0.9)
- Total samples : 113 samples

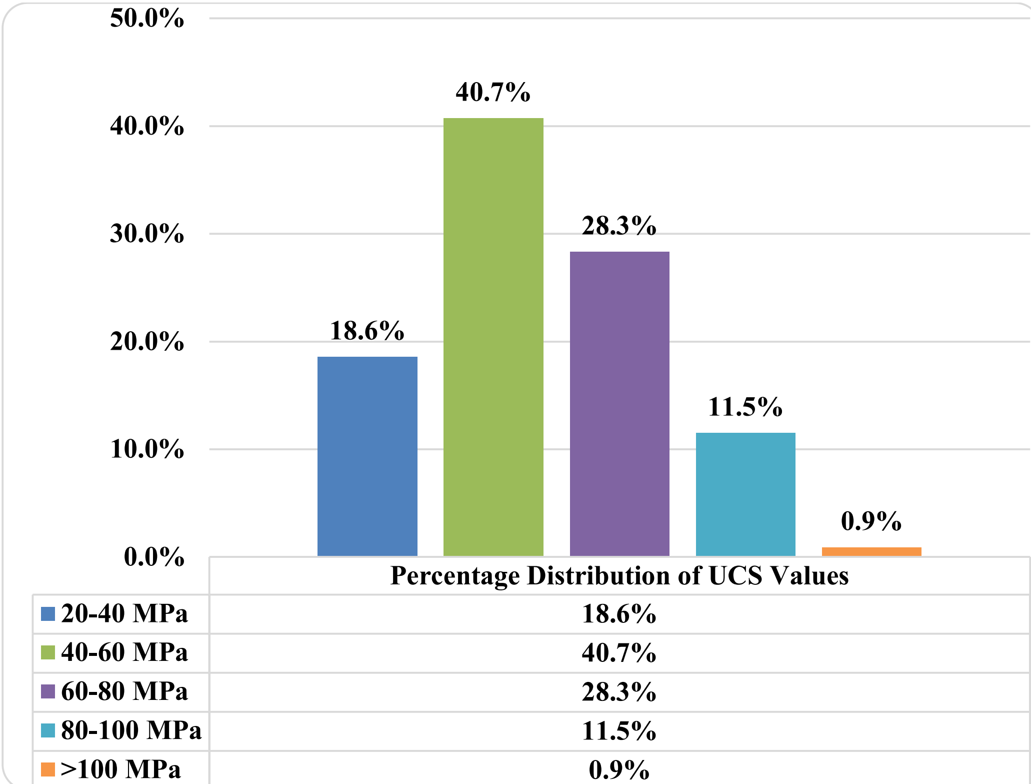


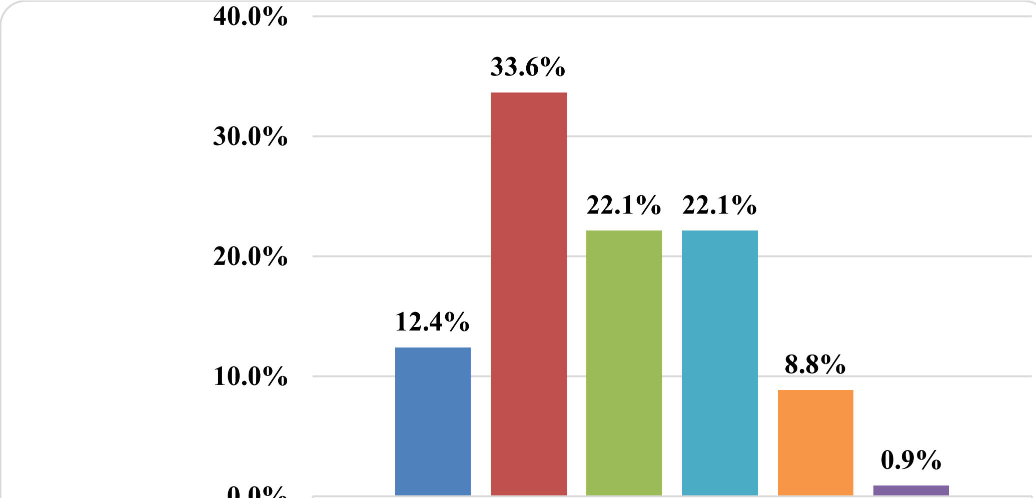
Figure 4.74 Percantage Distribution of UCS Values (Rock Type - 4)

When the E values of the samples are classified;

- Minimum E test value : 6.220 MPa
- Maximum E test value : 31.160 MPa

Quantity of observations within the specified interval;

- ➢ 5.000 – 10.000 MPa : 14 samples (% 12.4)
- ➢ 10.000 – 15.000 MPa : 38 samples (% 33.6)
- ➢ 15.000 – 20.000 MPa : 25 samples (% 22.1)
- ➢ 20.000 – 25.000 MPa : 25 samples (% 22.1)
- ➢ 25.000 – 30.000 MPa : 10 samples (% 8.8)
- ➢ > 30.000 MPa : 1 sample (% 0.9)
- ➢ Total samples : 113 samples



	Percentage Distribution of E Values
5.000 - 10.000 MPa	12.4%
10.000 - 15.000 MPa	33.6%
15.000 - 20.000 MPa	22.1%
20.000 - 25.000 MPa	22.1%
25.000 - 30.000 MPa	8.8%
>30.000 MPa	0.9%

Figure 4.75 Percantage Distribution of UCS Values (Rock Type - 4)

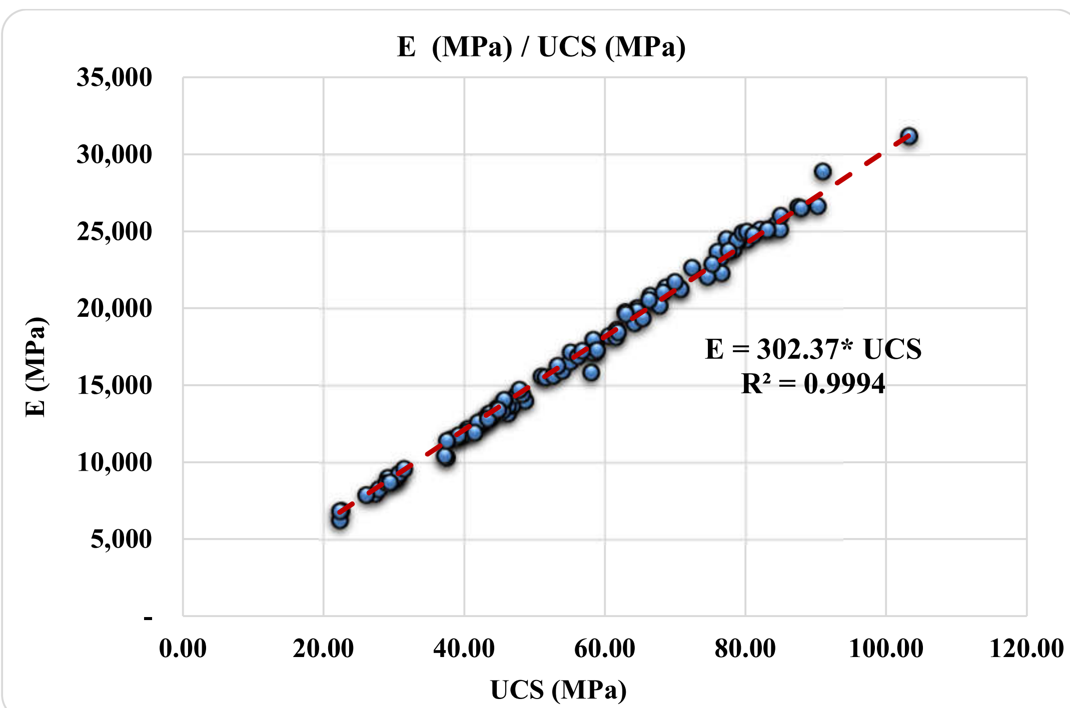


Figure 4.76 Chart of E (MPa) / UCS (MPa) Correlation (Rock Type - 4)

Arithmetic Mean of All E Results	:	16879.02 MPa
Arithmetic Mean of All UCS Results (MPa)	:	55.99 MPa
Ratio (E / UCS)	:	301.48

Geometric Mean of All E Results (MPa)	:	15858.15 MPa
Geometric Mean of All UCS Results (MPa)	:	52.80 MPa
Ratio (E / UCS)	:	300.32

According to the graphical and mathematical calculation results;
Modulus of elasticity value = 300 - 303 x UCS value
MR (modulus ratio) ~ 300 – 303

Table 4.20 Comparasion with Hoek - Diederichs (Rock Type – 4)

Type Number	**Rock Type**	**MR Value Range (this study)**	**MR Value Range (Hoek - Diederichs)**
Rock Type - 5	Granite / Granodiorite	300 - 303	300 - 500
	Andesite		300 - 550
	Basalt		250 - 450
	Dacite		350 - 450
	Ryholite		300 - 500

The correlation range obtained as a result of studies with Hoek and Diederichs (2006) is similar. Rock type - 4 is also in contact with andesite, basalt, dacite and ryhloite layers in some sections.

When the relationship between the correlation coefficient and the depth is examined;

Table 4.21 Summary Table According to Depth (Rock Type – 4)

Depth Range	MR Value (according to chart)	MR Value (according to arithmetic mean)	MR Value (according to geometric mean)
0 – 50 meters	302.14 (R^2 = 0.9993)	301.19	300.06
50 – 100 meters	302.74 (R^2 = 0.9996)	302.52	302.19
100 – 114 meters	304.37 (R^2 = 0.8953)	302.53	298.77
All Depths	302.37 (R^2 = 0.9994)	301.48	300.32

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

4.4.3. Correlation of PLI and UCS Values

Point load index test was applied to 125 samples. The UCS test was applied on 233 samples within the scope of the project.

When the PLI values of the samples are classified;

- Minimum PLI test value : 0.64 MPa
- Maximum PLI test value : 7.48 MPa

Quantity of observations within the specified interval;

- 0-1 MPa : 3 samples (% 2.4)
- 1-2 MPa : 11 samples (% 8.8)
- 2-3 MPa : 21 samples (% 16.8)
- 3-4 MPa : 29 samples (% 23.2)
- 4-5 MPa : 32 samples (% 25.6)

- ➢ 5-6 MPa : 21 samples (% 16.8)
- ➢ >6 MPa : 8 samples (% 6.4)
- ➢ Total samples : 125 samples

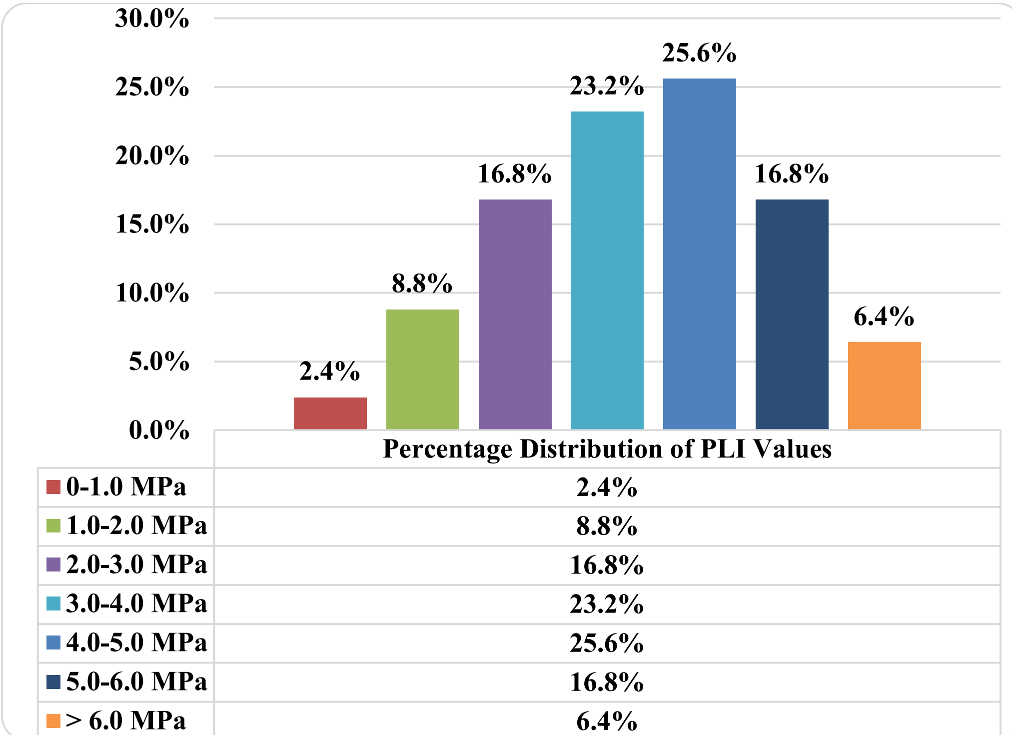


Figure 4.77 Percantage Distribution of PLI Values (Rock Type - 4)

When the UCS values of the samples are classified;

- Minimum UCS test value : 13.50 MPa
- Maximum UCS test value : 103.30 MPa

Quantity of observations within the specified interval;

- ➢ 10-20 MPa : 8 samples (% 3.4)
- ➢ 20-40 MPa : 63 samples (% 27.0)
- ➢ 40-60 MPa : 97 samples (% 41.6)
- ➢ 60-80 MPa : 50 samples (% 21.5)
- ➢ 80-100 MPa : 14 samples (% 6.0)
- ➢ >100 MPa : 1 sample (% 0.4)
- ➢ Total samples : 233 samples

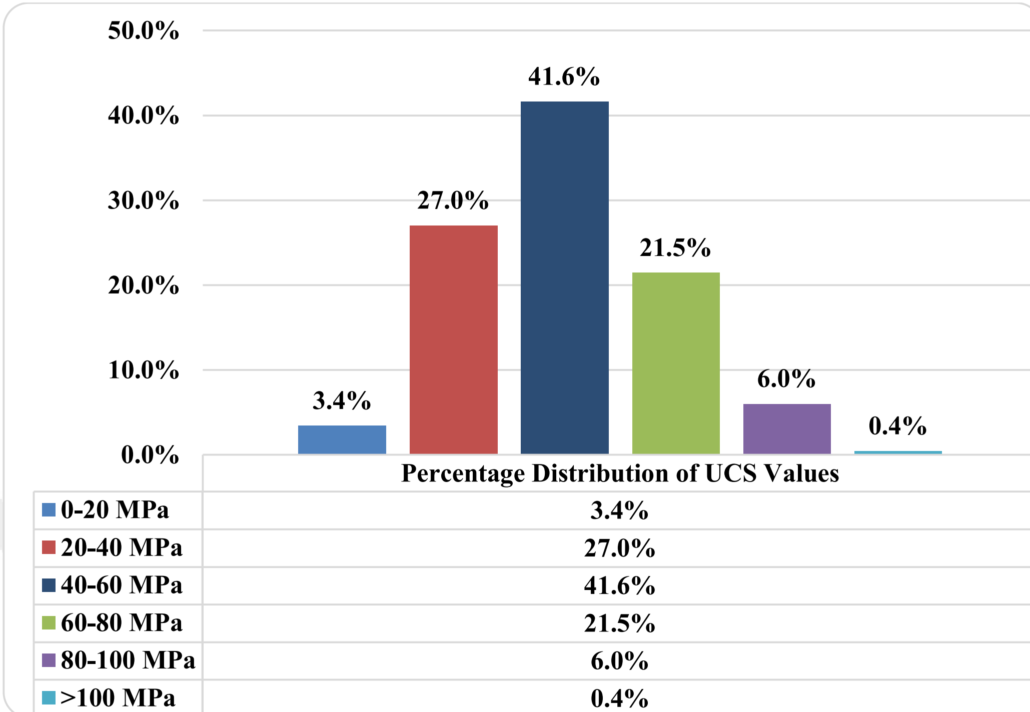


Figure 4.78 Percantage Distribution of UCS Values (Rock Type - 4)

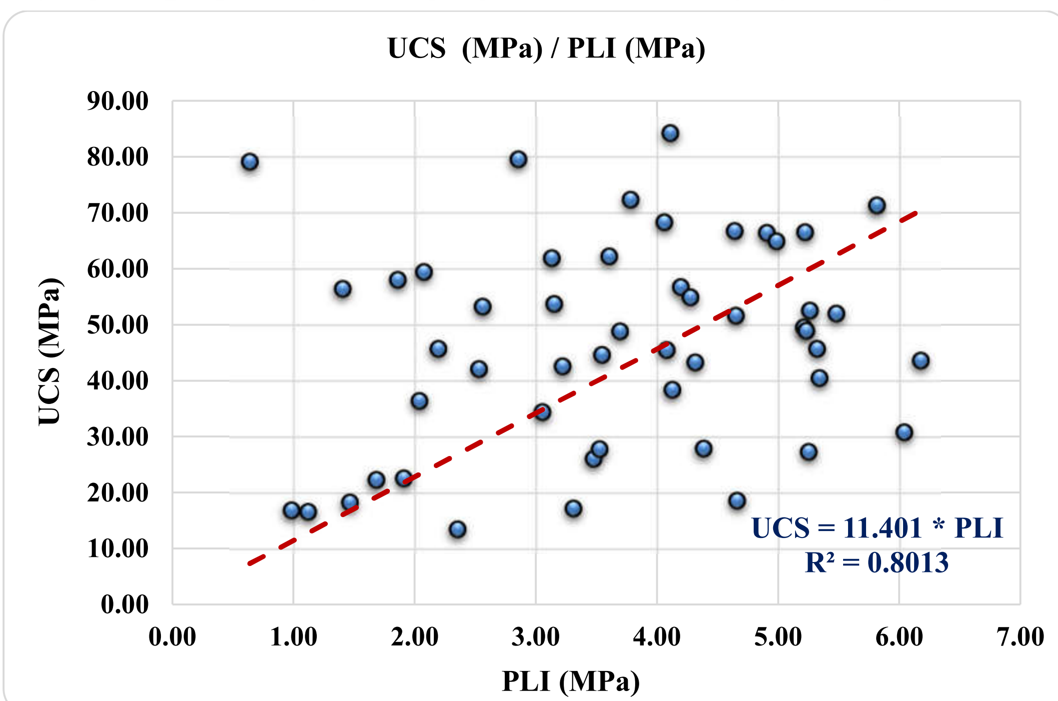


Figure 4.79 Chart of UCS (MPa) / PLI (MPa) Correlation (Rock Type – 4)

Arithmetic Mean of All UCS Results : 49.76 MPa
Arithmetic Mean of All PLI Results : 3.84 MPa
Ratio (UCS / PLI) : 12.96

Geometric Mean of All UCS Results : 46.21 MPa
Geometric Mean of All PLI Results : 3.50 MPa
Ratio (UCS / PLI) : 13.19

According to the above graphical and mathematical calculation results;
*Uniaxial Compressive Strength ~ 12 - 13 * PLI value*

Some of the samples were included for regression analysis and all of them were included for mathematical calculations. Because regression analysis requires UCS - PLI matches and this is not available for all depths.

When the relationship between the correlation coefficient and the depth is examined;

Table 4.22 Sample Depth Range for C Values (Rock Type – 4)

Depth Range	C Value (according to arithmetic mean)	C Value (according to geometric mean)
0 – 50 meters	12.86	13.17
50 – 100 meters	13.31	13.43
100 – 114 meters	16.14	14.47
All Depths	12.96	13.19

The fact that the number of samples is less for some depths causes different correlation values. It is understood that the depth does not have generally remarkable effect on the correlation coefficients.

Correlations in the academic literature for this rock type are listed below.

Sharo ve Al Tahawa (2019)	:	UCS = 23.52 * PLI (basalts)
Endait and Juneja (2015)	:	UCS = 24 * PLI (basalts-dry)
Endait and Juneja (2015)	:	UCS = 18 * PLI (basalts-saturated)
Kallu and Roghanchi (2015)	:	UCS =90.14 * PLI $^{0.92}$ (igneous rocks)
Kohno and Maeda (2012)	:	UCS = 16.40 * PLI (mixed types)
Kahraman and Gunaydin (2009)	:	UCS = 8.2 * PLI + 36.43 (igneous rocks)
Basu and Aydin (2006)	:	UCS = 18 * PLI (igneous rocks)
Sulukcu and Ulusay (2001)	:	UCS =15.3 * PLI (mixed types)
Tugrul and Zarif (1999)	:	UCS = 15.25 * PLI (igneous rocks - granites)
Brautigam et al. (1998)	:	UCS = 14.2 * PLI (igneous rocks)
Chau and Wong (1996)	:	UCS = 12.5 * PLI (granites, tuffs)
Ghosh and Srivastava (1991)	:	UCS = 16 * PLI (granites)
Brook (1985)	:	UCS = 22 * PLI (granites, limestones)
Brook (1985)	:	UCS = 20 * PLI (basalts)
ISRM (1985)	:	UCS = 20 - 25 * PLI (all rocks)
Lumb (1983)	:	UCS = 22 * PLI (igneous rocks - granites)
Read et al. (1980)	:	UCS = 18 * PLI (basalts)
Broch and Franklin (1972)	:	UCS = 23.7 * PLI (various rock types)

In Figure 4.80, UCS values are calculated with the assumption of PLI = 1 MPa.

As can be seen from the graph, significant differences emerge between the correlations. Similar to previous case, geotechnical engineers have to be careful when using correlation coefficients. In order to minimize the error, it is recommended to evaluate with more than one correlation.

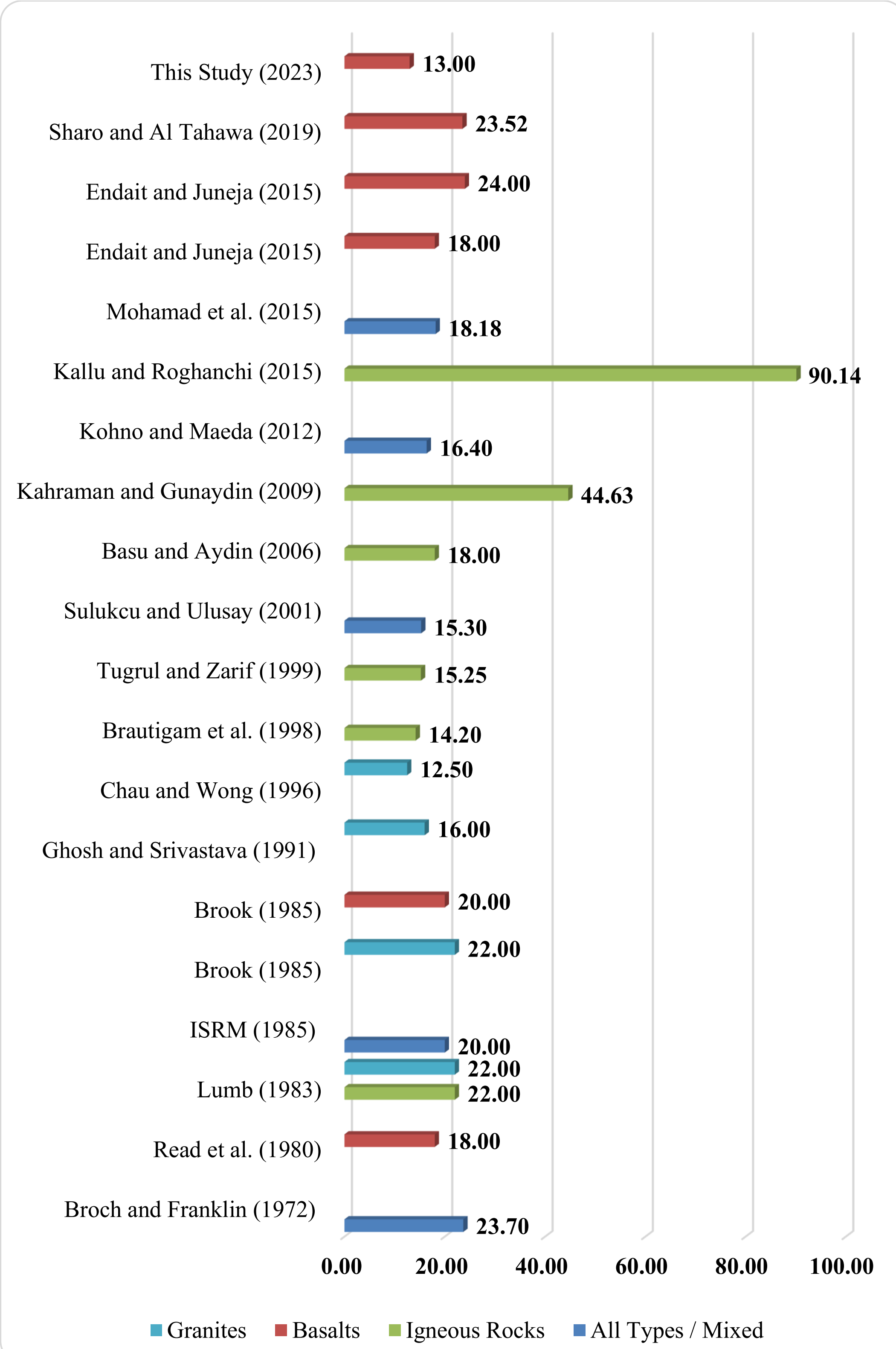


Figure 4.80 Comparison of Some Studies from Literatures for PLI / UCS
(For PLI = 1 MPa)

4.5. Rock Type - 5 (Claystone)

In this section, correlation studies related to claystones are presented. The samples were taken from the Trakya - Istanbul in the Marmara region. The working area is marked on the map below (Figure 4.81).

Figure 4.81 Location of Samples (Rock Type – 5)

As indicated in the geological maps (Figure 4.82, Figure 4.83 and Figure 4.84), the presence of claystone is evident in the general formation of the region.

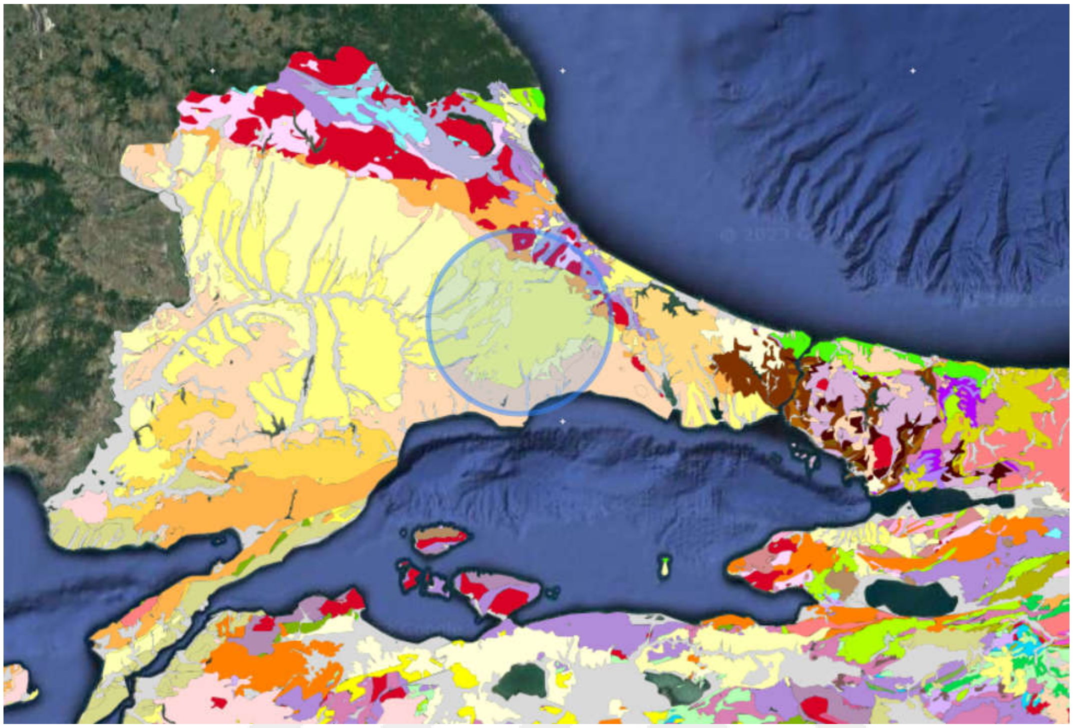


Figure 4.82 Formation Information (from MTA website)

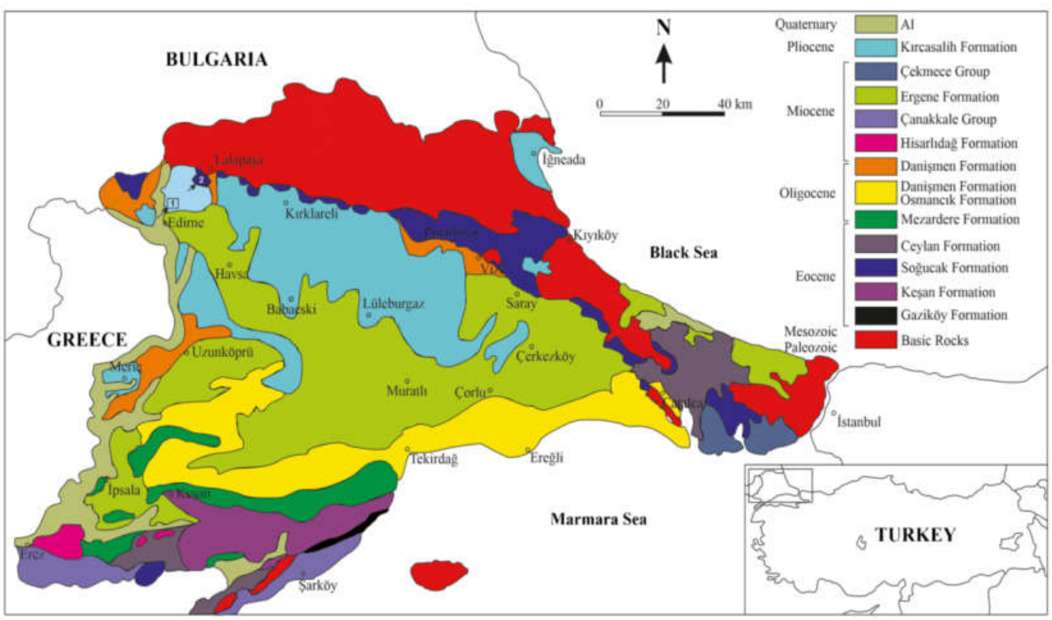


Figure 4.83 Geological Map of Thrace Region
(Complied from Kasar Et Al. 1983; Türkecan And Yurtsever 2002)

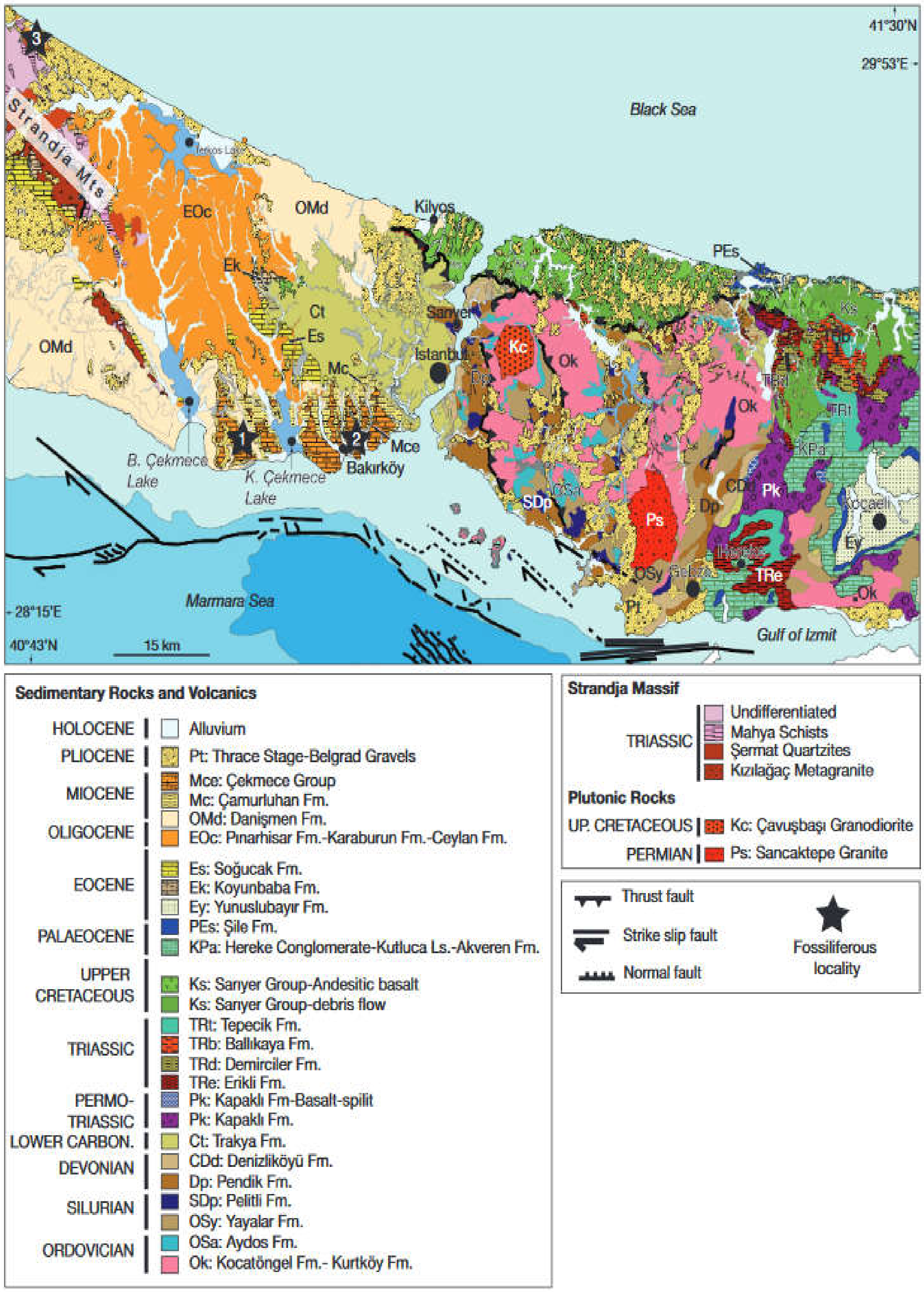


Figure 4.84 Geological Map of Istanbul and its Surroundings (Modified according to Türkecan & Yurtsever (2002) and Özgül (2011))

Some core sample box pictures of these rock samples are presented in Figure 4.85.

Figure 4.85 Core Sample Boxes (Rock Type - 5)

4.5.1. Depth of Samples

Within the scope of the thesis, it is also aimed to examine the effect of sample depth on correlations. The graphs (Figure 4.86 and Figure 4.87) show the percentage distribution of the depth ranges of the samples.

Table 4.23 Number of Samples Summary Table (Rock Type – 5)

Rock Type	Rock Type	UCS (total)	PLT	E	UCS (with E)
Rock Type - 5	Claystone	262	-	262	262

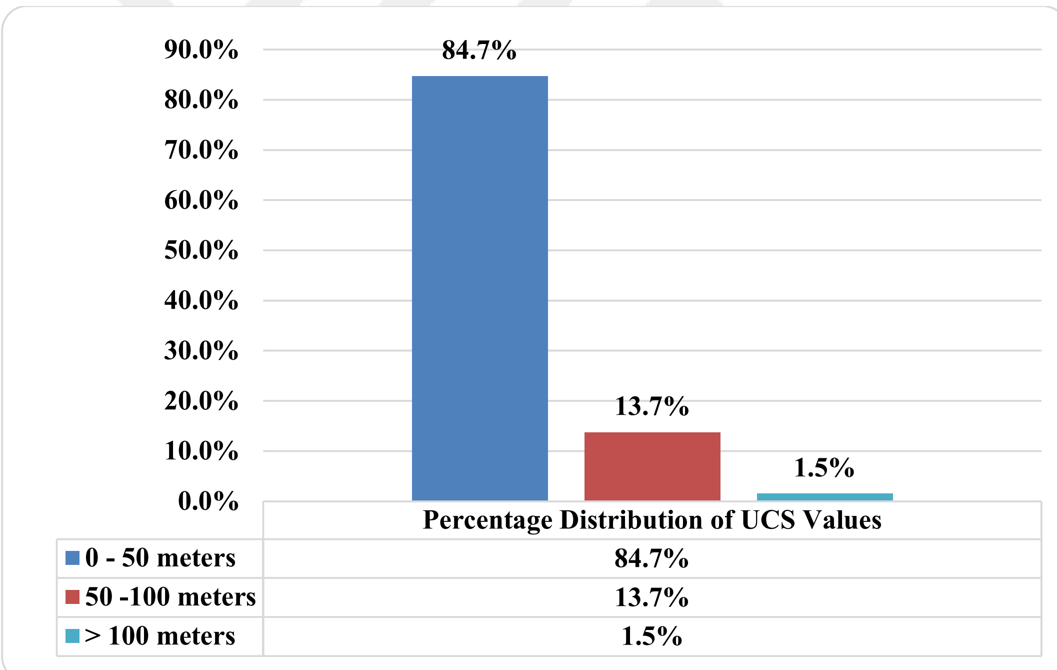


Figure 4.86 Percentage Distribution of UCS Values by Depth (Rock Type – 5)

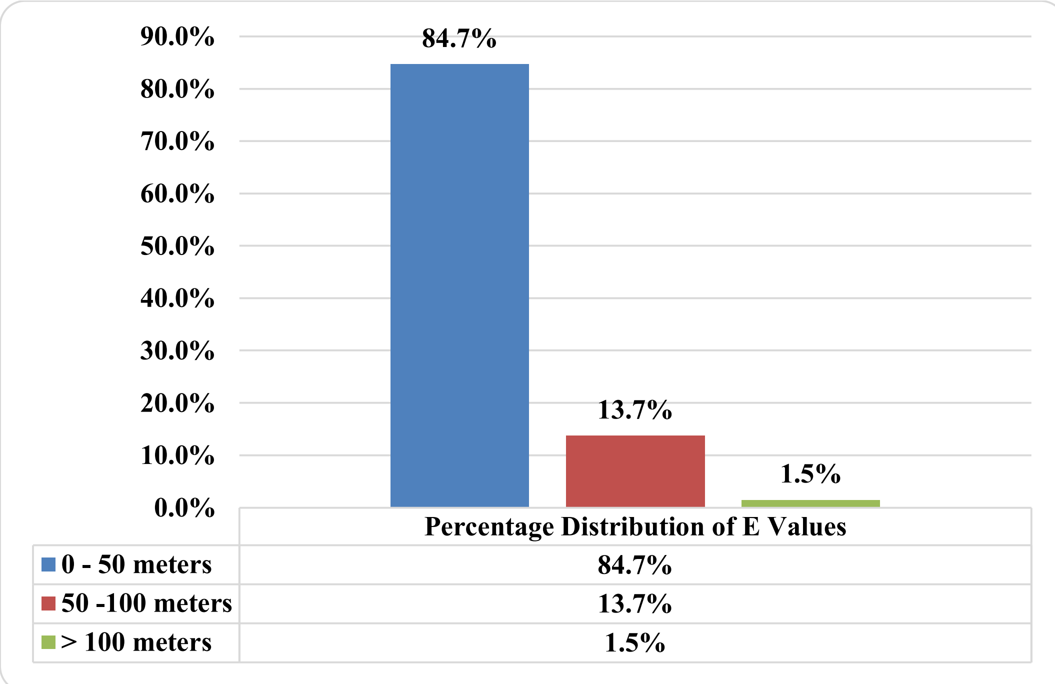


Figure 4.87 Percentage Distribution of E Values by Depth (Rock Type – 5)

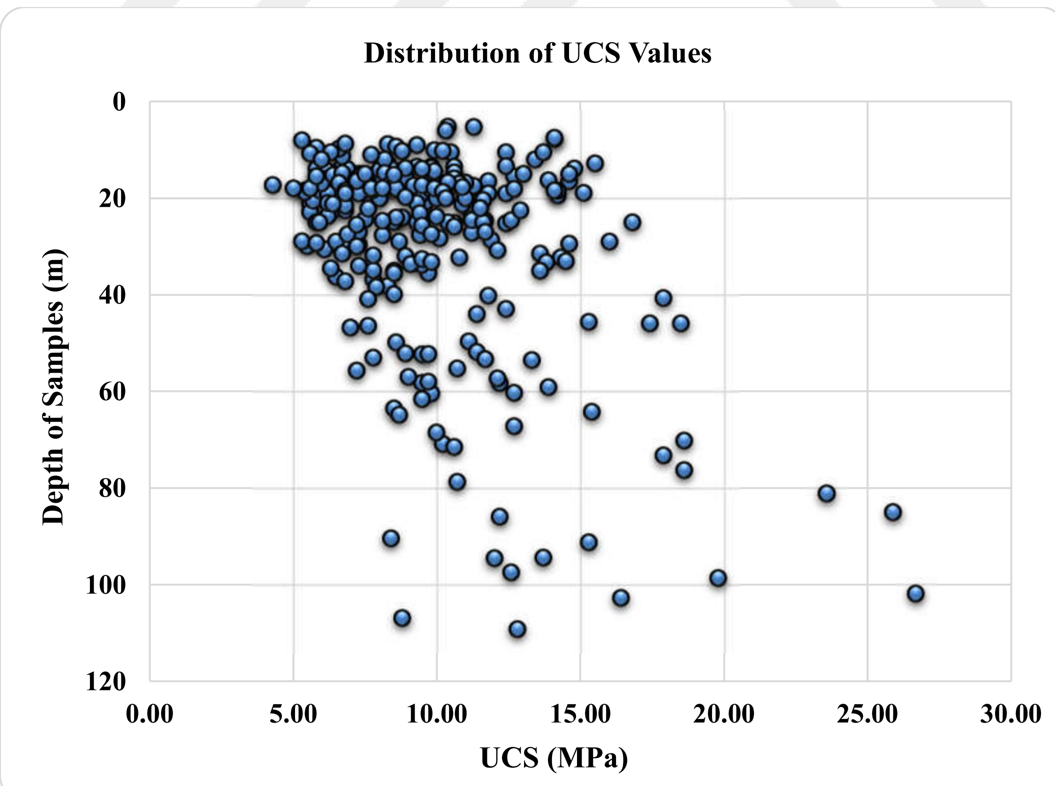


Figure 4.88 Distribution of UCS Values by Depth (Rock Type – 5)

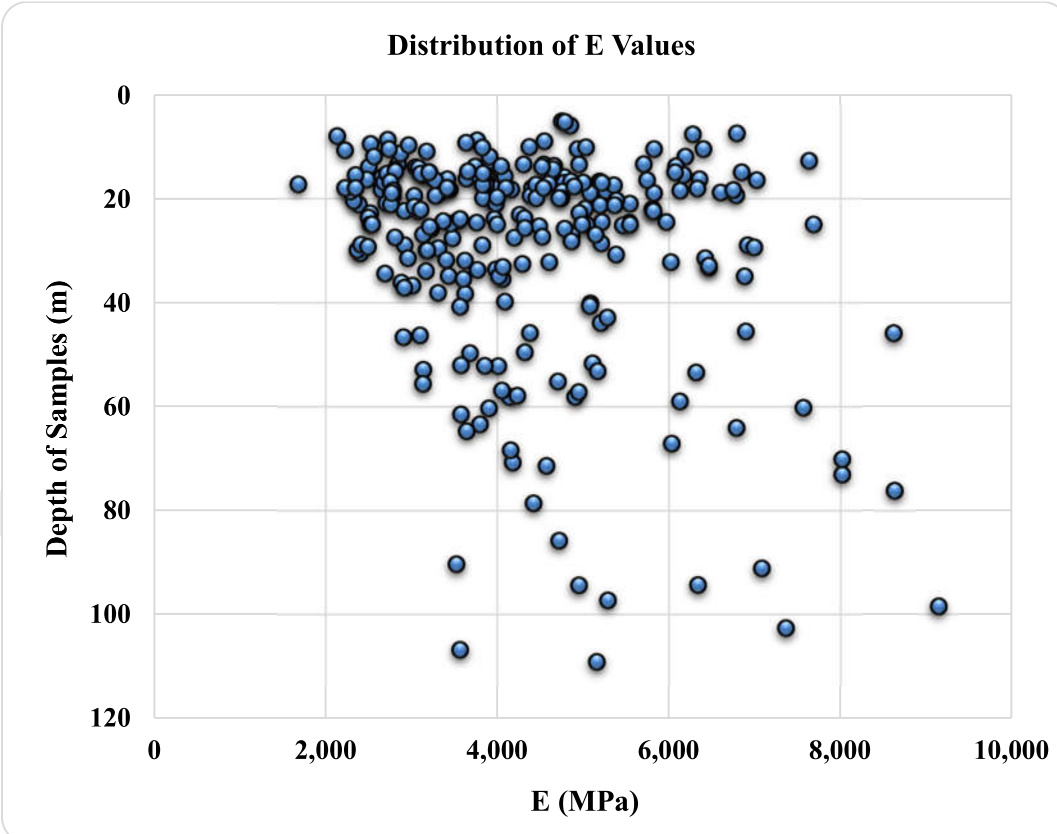


Figure 4.89 Distribution of E Values by Depth (Rock Type – 5)

4.5.2. Correlation of UCS and E Values

Uniaxial compression test was applied on 262 samples. In these tests, the modulus of elasticity values were also measured. In this section, individual UCS tests were not taken into account for correlation study.

The values of the uniaxial compressive strength values distribution are given proportionally. Approximately 93.0 % of the total sample has compressive strength between 5-15 MPa. There are samples with strengths different from the average at low rates.

According to Table 4.24, the majority of the samples are considered " Weak" among this database.

Table 4.24 Field Estimates of Uniaxial Compressive Strength and Point Load Index (Hoek and Marinos – 2001)

Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

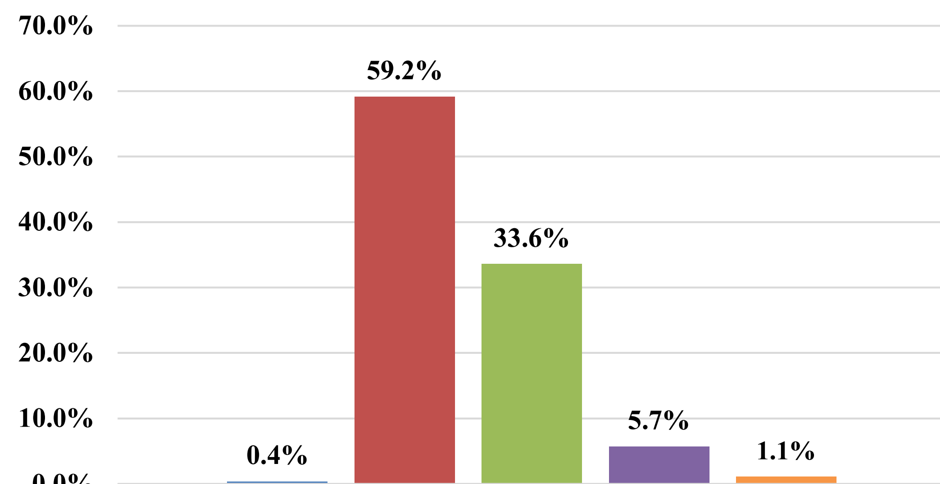
* Grade according to Brown [2]
** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results.

When the UCS values of the samples are classified;

- Minimum UCS test value : 4.30 MPa
- Maximum UCS test value : 26.70 MPa

Quantity of observations within the specified interval;

- 0-5 MPa : 1 sample (% 0.4)
- 5-10 MPa : 155 samples (% 59.2)
- 10-15 MPa : 88 samples (% 33.6)
- 15-20 MPa : 15 samples (% 5.7)
- >20 MPa : 3 samples (% 1.1)
- Total samples : 262 samples



	Percentage Distribution of UCS Values
0-5 MPa	0.4%
5-10 MPa	59.2%
10-15 MPa	33.6%
15-20 MPa	5.7%
>20 MPa	1.1%

Figure 4.90 Percantage Distribution of UCS Values (Rock Type - 5)

When the E values of the samples are classified;

- Minimum E test value : 1.679 MPa
- Maximum E test value : 12.255 MPa

Quantity of observations within the specified interval;

- 0.0 – 5.000 MPa : 187 samples (% 71.4)
- 5.000 – 10.000 MPa : 72 samples (% 27.5)
- > 10.000 MPa : 3 samples (% 1.1)
- Total samples : 262 samples

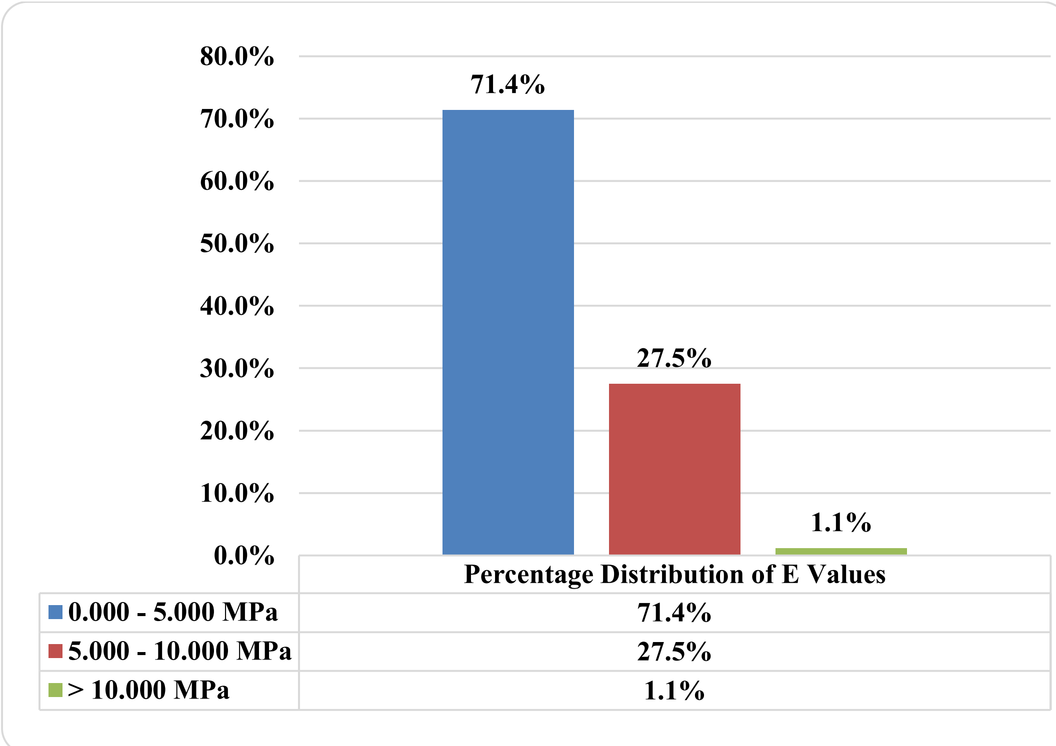


Figure 4.91 Percantage Distribution of E Values (Rock Type - 5)

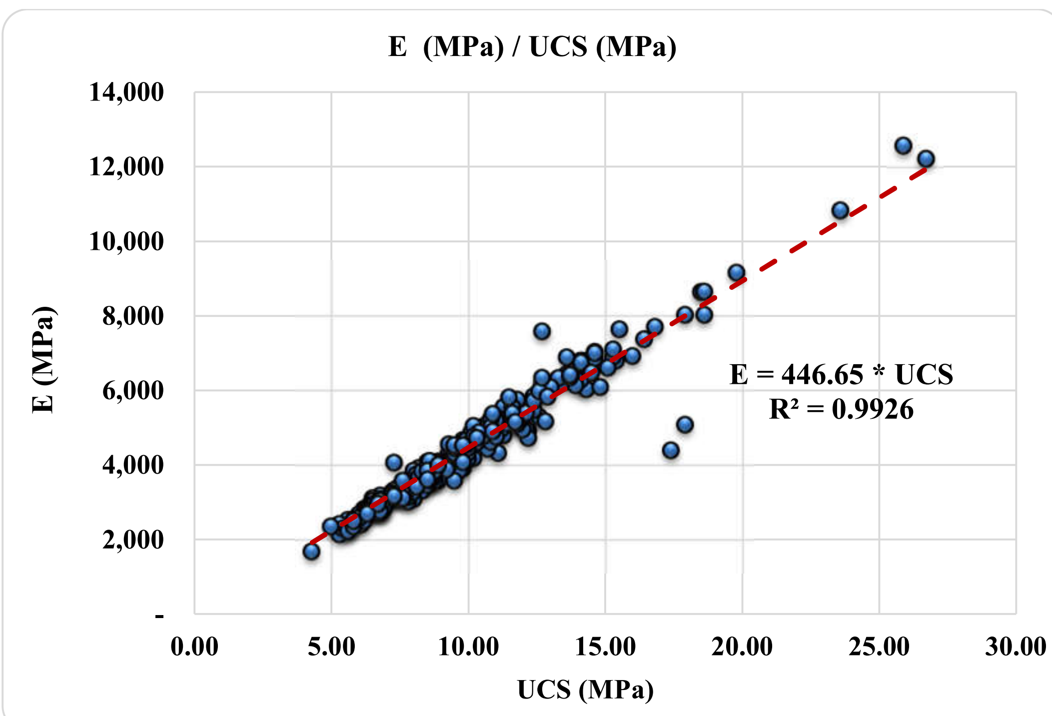


Figure 4.92 Chart of E (MPa) / UCS (MPa) Correlation (Rock Type - 5)

Arithmetic mean of all E results	:	4417.96 MPa
Arithmetic mean of all UCS results (MPa)	:	9.93 MPa
Ratio (E / UCS)	:	445.09

Geometric mean of all E results (MPa)	:	4164.31 MPa
Geometric mean of all UCS results (MPa)	:	9.42 MPa
Ratio (E / UCS)	:	441.89

According to the graphical and mathematical calculation results;
Modulus of elasticity value = 441 - 447 x UCS value
MR (modulus ratio) ~ 441 - 447

Table 4.25 Comparasion with Hoek - Diederichs (Rock Type – 5)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range (Hoek - Diederichs)
Rock Type - 5	Claystone	441 - 447	200 - 300

Table 4.26 Comparasion with Other Studies (Rock Type – 5)

Type Number	Rock Type	MR Value Range (this study)	MR Value Range
Rock Type – 5	Claystone	441 - 447	141[a]
	Claystone		276[b]

a: Malik&Rashid,1997 (number of data = 30)
b: Małkowski&Ostrowski,2017 (Carboniferous) (number of data = 81)

The correlation range obtained as a result of the studies conducted with Hoek and Diederichs (2006) differs. It is stated in different studies that the standard deviations are high in the correlations of low-strength rocks.

Table 4.27 Summary Table According to Depth (Rock Type – 5)

Sample Depth Range	MR Value (according to chart)	MR Value (according to arithmetic mean)	MR Value (according to geometric mean)
0 – 50 meters	446.14 (R^2 = 0.9908)	446.64	443.95
50 – 109 meters	446.46 (R^2 = 0.9941)	440.54	433.89
All Depths	446.65 (R^2 = 0.9926)	445.09	441.89

With the change in the sample depth, there are significant changes in the mineralogical structure, rock mass characteristics, and physical conditions of the rock in natural conditions based on temperature. However, it is inferred that there is no significant change when only the statistics of the correlation coefficients are evaluated.

4.6. All Rock Types Correlations

Additional evaluations in accordance with the classification of rocks are included in this section. The rocks are divided into two groups as sedimentary and igneous.

Table 4.28 Summary Table According to Rock Classification

	Rock Type	**Rock Classification**	**Group Number**
Rock Type - 1	Limestone	Sedimentary Rock	Group – 1
Rock Type - 2	Alternation of Shale – Sandstone – Claystone	Sedimentary Rock	Group – 1
Rock Type - 3	Andesite	Igneous (Volcanic) Rock	Group – 2
Rock Type - 4	Granite, Granodiorite	Igneous (Volcanic) Rock	Group – 2
Rock Type - 5	Claystone	Sedimentary Rock	Group – 1

4.6.1. Group – 1 (Sedimentary Rocks)

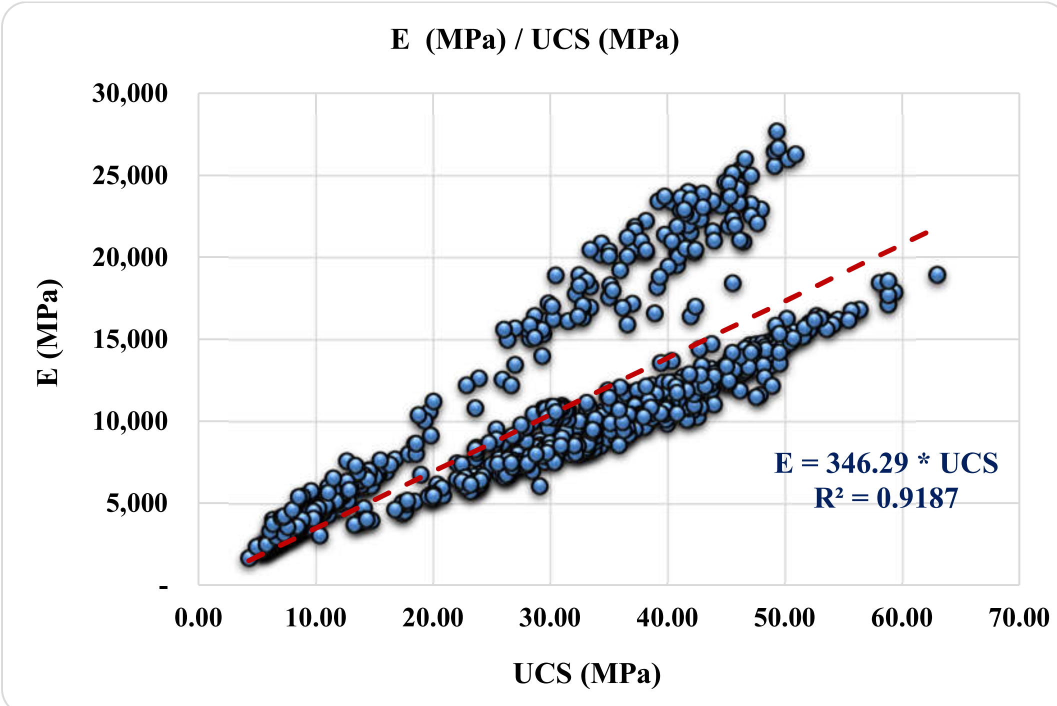


Figure 4.93 Chart of E (MPa) / UCS (MPa) Correlation (Sedimentary Rocks)

Arithmetic Mean of All E Results	:	10134.10 MPa
Arithmetic Mean of All UCS Results (MPa)	:	28.73 MPa
Ratio (E / UCS)	:	352.74

Geometric Mean of All E Results (MPa)	:	8578.03 MPa
Geometric Mean of All UCS Results (MPa)	:	23.87 MPa
Ratio (E / UCS)	:	359.19

According to the above graphical and mathematical calculation results;

Modulus of elasticity value = 346 - 360 x UCS value

MR (modulus ratio) ~ 346 – 360

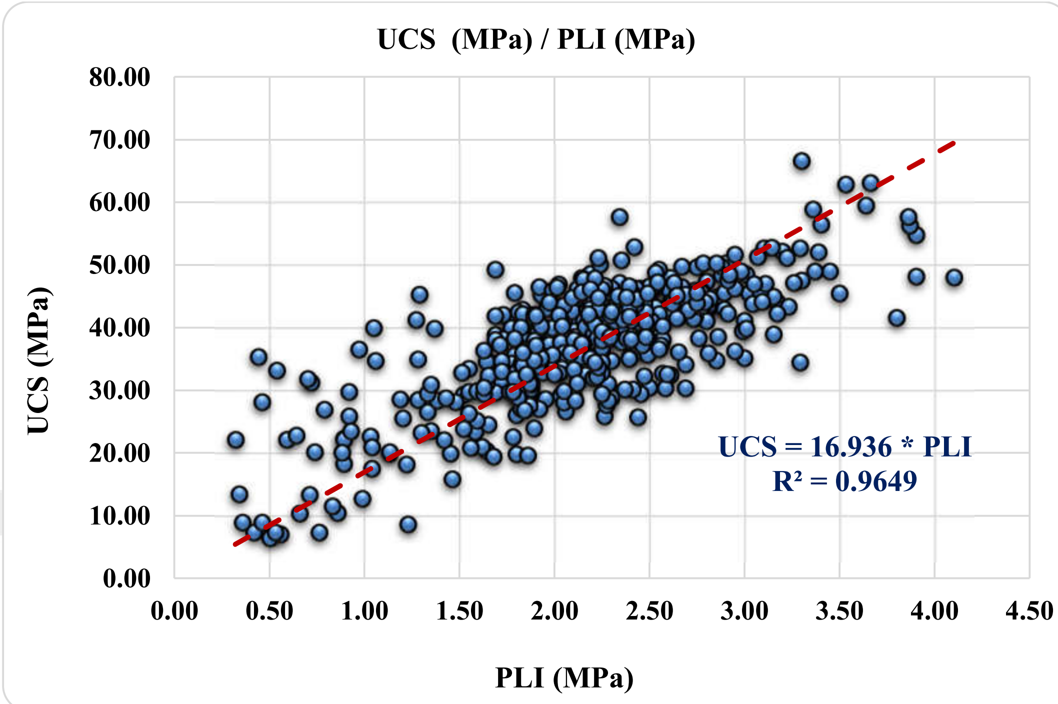


Figure 4.94 Chart of UCS (MPa) / PLI (MPa) Correlation (Sedimentary Rocks)

Arithmetic Mean of All UCS Results	:	37.58 MPa
Arithmetic Mean of All PLI Results	:	2.15 MPa
Ratio (UCS / PLI)	:	17.44

Geometric Mean of All UCS Results	:	35.96 MPa
Geometric Mean of All PLI Results	:	2.03 MPa
Ratio (UCS / PLI)	:	17.73

According to the mathematical calculation results;

*Uniaxial Compressive Strength ~ 17 - 18 * PLI value*

4.6.2. Group – 2 (Igneous Rocks)

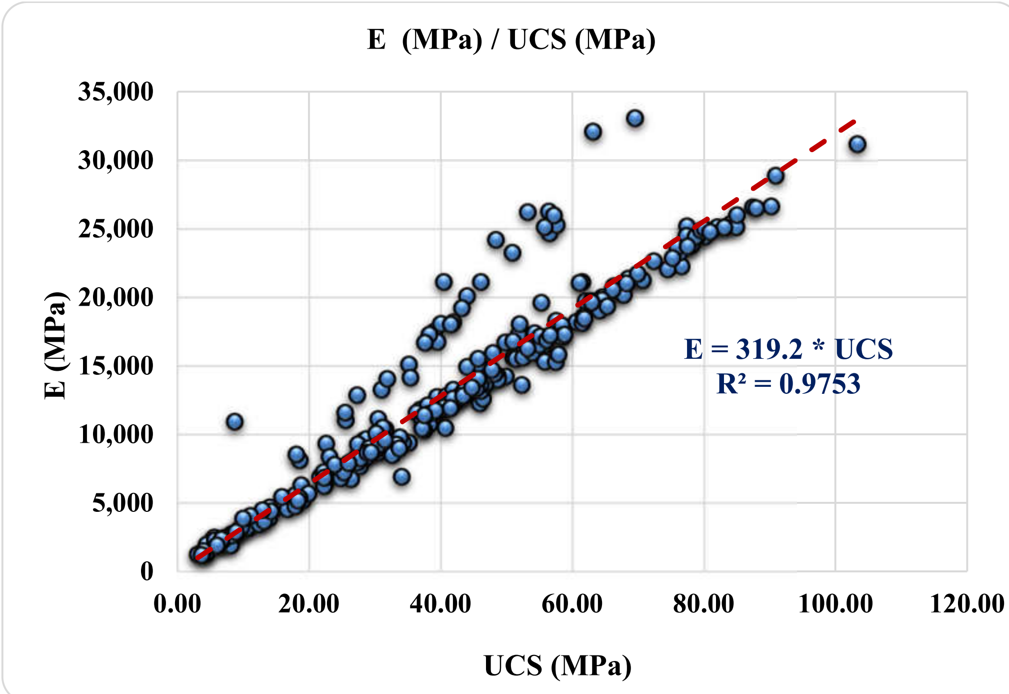


Figure 4.95 Chart of E (MPa) / UCS (MPa) Correlation (Igneous Rocks)

Arithmetic Mean of All E Results	:	13263.99 MPa
Arithmetic Mean of All UCS Results (MPa)	:	41.24 MPa
Ratio (E / UCS)	:	321.63

Geometric Mean of All E Results (MPa)	:	10751.65 MPa
Geometric Mean of All UCS Results (MPa)	:	33.51 MPa
Ratio (E / UCS)	:	320.82

According to the above graphical and mathematical calculation results;

Modulus of elasticity value = 320 – 322 x UCS value

MR (modulus ratio) ~ 320 – 322

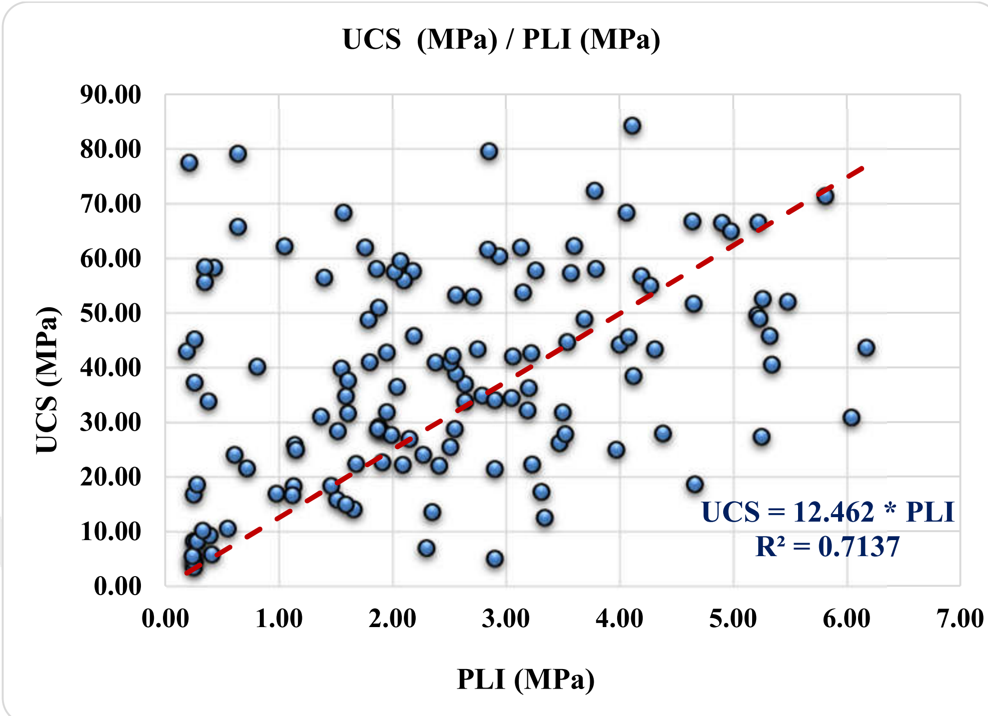


Figure 4.96 Chart of UCS (MPa) / PLI (MPa) Correlation (Igneous Rocks)

Arithmetic Mean of All UCS Results	:	38.01 MPa
Arithmetic Mean of All PLI Results	:	2.44 MPa
Ratio (UCS / PLI)	:	15.58

Geometric Mean of All UCS Results	:	31.49 MPa
Geometric Mean of All PLI Results	:	1.78 MPa
Ratio (UCS / PLI)	:	17.70

According to the mathematical calculation results;

*Uniaxial Compressive Strength ~ 13 - 18 * PLI value*

4.7. Summary of the Suggested Correlations

In the contents of these thesis, using a large amount of data points, correlation between i) E and UCS and ii) PLI and UCS values are investigated for five and four different rock types respectively. These values are in the similar ranges with the ones proposed in the literature. Summary tables of all correlation factors for different rock types are presented in Tables 4.29 and 4.30 as a summary.

Table 4.29 Summary of Studies (E - UCS Correlations)

Rock Type Number	Rock Type	Correlation Coefficients (MR Values)			Recommended MR values (for all studies)
		Arithmetic Mean	Geometric Mean	Chart Trendline	
Rock Type - 1	Limestone	354.95	340.05	354.50 (R^2 = 0.9150)	**~ 340 - 355**
Rock Type - 2	Alternation of Shale - Sandstone - Claystone	317.33	317.63	311.74 (R^2 = 0.9403)	**~ 311 - 318**
Rock Type - 3	Andesite	348.70	336.67	353.5 (R^2 = 0.9544)	**~ 336 - 354**
Rock Type - 4	Granite, Granodiorite	301.48	300.32	302.37 (R^2 = 0.9994)	**~ 300 -305**
Rock Type - 5	Claystone	445.09	441.89	446.65 (R^2 = 0.9926)	**~ 441 - 447**
Sedimentary Rocks		352.74	359.19	346.29 (R^2 = 0.9187)	**~ 346 - 360**
Igneous Rocks		321.63	320.82	319.2 (R^2 = 0.9753)	**~ 320 - 322**

Table 4.30 Summary of Studies (PLI - UCS Correlations)

Rock Type Number	**Rock Type**	**Correlation Coefficients (C Values)**			**Recommended C values (for all studies)**
		Arithmetic Mean	**Geometric Mean**	**Chart Trendline**	
Rock Type - 1	Limestone	18.01	18.15	16.873 (R^2 = 0.9715)	**~ 17 - 18**
Rock Type - 2	Alternation of Shale - Sandstone - Claystone	20.23	20.99	17.554 (R^2 = 0.9293)	**~ 18 - 21**
Rock Type - 3	Andesite	16.79	18.51	14.798 (R^2 = 0.6449)	**~ 15 - 18**
Rock Type - 4	Granite, Granodiorite	12.96	13.19	11.401 (R^2 = 0.8013)	**~ 12 - 13**
Sedimentary Rocks		17.44	17.73	16.936 (R^2 = 0.9649)	**~ 17 - 18**
Igneous Rocks		15.58	17.70	12.462 (R^2 = 0.7137)	**~ 13 - 18**

As can be seen from these tables, the MR values range in between 300 and 447 for different rock types. For the correlation between PLI and UCS, the range is 12 to 21. It was seen that, the depth of the samples has nearly no effect on both of the correlations, i.e.; between Young's Modulus – UCS and UCS – PLI in the samples of this study, similar to the literature.

4.8. Verification of the Correlation Coefficients

As mentioned above, there is a wide range in the correlations between the parameters in the literature. Similarly, although a large database has been used in this study, it was seen that there is still a confusion in the correlations even in the neighbouring boreholes among the same origin rocks (e.g. Figure 4.15). To verify the correlation coefficients proposed within this study, a different database which has not been used during the constitution was used. For this verification two sets of data, i) Limestone from Bursa & Bilecik, ii) Claystone from Burdur is used and presented below:

Limestones in Bursa & Bilecik: there were 30 samples of which UCS and E values were known. According to the samples, the arithmetic mean of UCS values of these samples were nearly 63 MPa and Young's Modulus have an arithmetic mean of nearly 25.700 MPa. Using the correlation coefficient in Table 4.29, a value between 340 – 355 should be used to obtain Young's Modulus. According to Hoek – Diederichs, this value is in the range of 400 to 600. Using the proposed value of this study, the Young's Modulus is obtained in the range of 21.420 MPa – 22.365 MPa. It can be said that the Young's Modulus values obtained from the laboratory tests and from the empirical coefficient proposed within this study are close to each other.

For the case of Claystones in Burdur, there are 70 UCS-E pairs in this data set. The average of UCS values is nearly 5.50 MPa and Young's Modulus is equal to 2.100 MPa. According to Table 4.28, the MR value is between 311 – 318. For Hoek – Diederichs, the value is between 200 and 300. Using the proposed equation of this study, the Young's Modulus is found to be nearly 1.700 MPa. We can say that these values are close to each other.

5. RESULTS AND RECOMMENDATIONS

Within the scope of this thesis, it is tried to propose correlations between UCS – E and PLI – UCS values for different rock types using a large amount of data. For this purpose, rock samples from five different locations of Turkiye, with different characteristic were obtained. These rocks are Limestone, Alternation of Shale – Sandstone – Claystone, Andesite, Granite – Granodiorite and Claystone. For the correlation between UCS and E, all samples have been used, whereas for the relation between PLI and UCS, 4 of them have been used as no data were available for Claystone for this samples. All soil investigation studies within the scope of this thesis have been approved by the responsible institutions and organizations and they were carried out in accordance with national and international standards at the laboratories with accreditation documents. In the correlation studies, laboratory test results, borehole logs, sample box pictures, etc. was checked and evaluated. The results of the studies are presented in the previous chapter. To summarize:

- The maximum depth of the samples is 350 meters.
- The correlation coefficient MR for all rock type is presented in Table 4.29.
- The correlation coefficient between PLI and UCS for all rock types are presented in Table 4.30.
- It was seen that, there is no remarkable effect of depth on the correlation coefficients.
- These equations are found to be consistent with the ones in the literature.
- Significant differences emerge between the correlations in both of the correlations.

However, it should be kept in mind that, although a large number of test results have been used, the data is still limited. It is understood that it is necessary to determine regional correlations rather than using a general correlation for a particular rock type and large number of samples are important for the correlation to give the closest results.
This article confirms that the real need to predict the physicomechanical properties of materials, especially at certain preliminary stages of engineering design, is not a substitute for testing, but rather these predictions serve as an extension and validation of some specific data.

Finally, it is recommended to use modulus of elasticity and uniaxial strength values obtained directly from the experiments. The correlation values with direct test results should be validated to some extent. As significant differences emerge between the correlations, geotechnical engineers have to be careful when using the correlation coefficients. In order to minimize the error and get more realistic values, it is recommended to;

- evaluate the natural state characteristics of the rock (e.g., degree of saturation)
- evaluate with more than one correlation,
- choose the ones with higher number of samples.

It is anticipated that the predictive power of the empirical formulas created with the mathematical and linear regression analyses will increase in the future with the addition of the various laboratory test findings to these databases. Furthermore, it is foreseen that the collected results will be useful in the future to be integrated into the regional statistical database.

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