Dynamic Deformation Modulus of Weak Rock Measured from Laboratory and Field Tests

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Abstract:-

This paper compares the dynamic deformation modulus of weak rock measured from laboratory and field tests which were carried out as part of the site investigation works for a major project, west of Iraq. The objective of the survey was to obtain the compressional (Vp) and shear (Vs) seismic wave velocities for computation of dynamic properties of the rock material (shear modulus, Young's modulus, and Poisson's ratio) interposed between the investigated boreholes. Laboratory ultrasonic velocity tests were conducted on unconfined core rock specimens using TICO ultrasonic velocity equipment. Field measurements comprised seismic geophysical methods including crosshole technique were used to determine the (Vp) and (Vs). In addition, empirical relationships were used for estimating the unit weight of rock mass employing the results of the seismic wave velocities. The dynamic insitu stiffness measurements were determined and compared with the laboratory values from the ultrasonic tests for estimating rock mass stiffness from the seismic wave velocities.

Keywords: Weak Rock, shear modulus, Young's modulus, Poisson's ratio, ultrasonic velocity, crosshole.

1. Introduction

There is an increasing requirement for geophysical surveys carried out during geotechnical investigations to provide direct information about rock quality or other geotechnical parameters, [2]. A range of seismic tests have been developed commercially including the seismic cone penetration test (SCPT), crosshole and down-hole shear wave velocity measurement, and the surface wave (Rayleigh Wave) methods of SASW (spectral analysis of surface waves) that uses a hammer as the seismic source and CSW (continuous surface wave) that uses a frequency controlled vibrator as the seismic source. The field seismic methods can be divided into borehole methods and surface methods; [6].

The seismic crosshole method provides the designer within formation pertinent to the seismic wave velocities of the materials. This data may be used as input into static/dynamic analyses, as a means for computing shear modulus, Young’s modulus, and Poisson’s ratio, or simply for the determination of anomalies that might exist between boreholes, [2]. In the laboratory; small strain stiffness can be measured using local measurements of axial strains either with Hall Effect local strain measurement or LVDT based devices, [6]. Ultrasonic pulse velocity tests can be carried out on rock core specimens using ultrasonic velocity equipment. Similar method to those described in ASTM [2] and BS [3] for measurement of ultrasonic pulse velocity in concrete was adopted for rock core specimens, [1], [9].

This work represents the results of laboratory ultrasonic velocity tests and seismic borehole logging for shear wave velocities which were carried out as part of the site investigation works for a major project in the west of Iraq. The objective of the survey was to obtain the compressional and shear seismic wave velocities the (Vp) and (Vs) of the shallow subsurface for computation of dynamic properties of the rock material interposed between the investigated boreholes. The dynamic insitu stiffness measurements were compared with the laboratory values obtained from ultrasonic pulse testing method.

2. Laboratory and Field Work

2.1 Basic Properties and Classification Tests

Series of laboratory tests were conducted to determine the basic and classification properties of the rock material. Classification tests were performed first and then unit weight and specific gravity of rock determination. Geomechanics classification of rock was carried out to determine the Rock Quality Designation (RQD) of core samples. It should be mentioned that the testing program performed in this paper carried out in accordance with ASTM standards.

2.2 Ultrasonic Pulse Testing

Ultrasonic pulse velocity tests were carried out on weak rock core specimens using TICO ultrasonic velocity equipment (Plate 1). Similar method to those described in ASTM C 597 and BS 1881-203 for measurement of ultrasonic pulse velocity in concrete were adopted. These tests were conducted to determine the pulse compressional wave velocity the (Vp) and subsequently the elastic modulus of the material at zero confining pressures. The rock specimens were mounted between the transmitter and receiver transducer holders as shown in Plate. 1.

Plate 1. Ultrasonic velocity equipment

2.3 Crosshole Studies

In this study, the shear and compressional wave velocity versus depth profile (1.0 m logging interval) was determined using the crosshole seismic method. These measurements can be used to obtain dynamic soil properties (shear modulus, Young’s modulus, and Poisson’s ratio).

The standard crosshole seismic test was carried out in four test points in accordance to ASTM D 4428. At each test point, two boreholes were drilled with 4.0 m apart and on a line. The depth of the drilling was more than 15.0 m in order to get the required 15.0 m depth. The boreholes were cased with PVC casing pipes with completely closed bottom end to prevent sediments getting inside while lowering the casing. The annular space outside the PVC pipes was grouted with cement grout up to the top of the borehole. The test was carried out in a borehole filled with water and caped at the top with proper caps. A borehole source capable was inserted in one of the boreholes to generate shear and compressional waves, and a three component triaxial geophone receivers were placed in the other borehole to measure the arrival of the seismic wave. The inter-borehole distance is divided by the travel time at each depth to calculate the wave velocity. The travel times for both seismic waves were measured by the seismograph as a single seismic record, see Fig. 1.

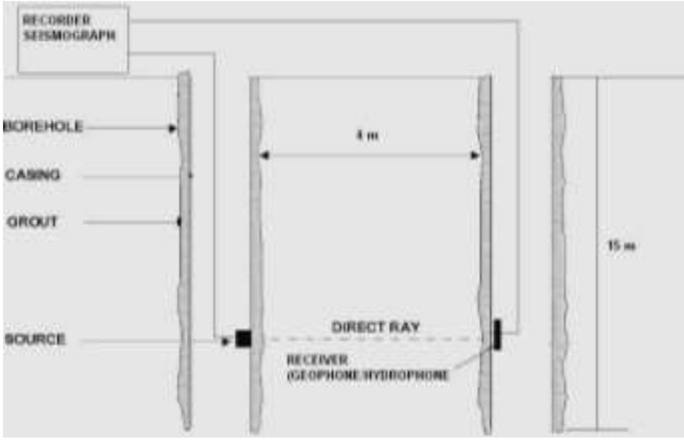


Fig 1. Crosshole seismic test method

3. Results and Discussions

3.1 Basic Properties and Classification

Based on the results of basic properties and classification tests, it was found that the predominant major profile of the investigated site consists of Limestone with different secondary constituent such as dolomite, clay, marl, shell, chalk and sand. For the rock core specimen test results the RQD varied from (10 to 21), thus the investigated rock can be described as (very poor) quality according to ASTM D 6032-96. Bulk unit weights of tested specimens were ranged from (17.49 to 23.25) kN/m^3 with an average value of 19.76 kN/m^3, while the results of specific gravity tests indicate that the values of apparent specific gravity are ranged from (2.52 to 2.62).

3.2 Ultrasonic Pulse Testing Results

3.2.1 Pulse-Propagation Velocity

The velocity of ultrasonic waves covering the length of the specimens can be calculated by measuring the time between sending and receiving waves. The propagation velocity of the compression waves, Vp was calculated as follow, [9]:

$$Vp = Lp / Tp \qquad (1)$$

Where Vp is the pulse-propagation velocity (compression wave) (m/s), Lp= pulse-travel distance, (Compression wave) in meter, and Tp = effective pulse-travel time, (compression wave) in second. According to the test results obtained from ultrasonic pulse velocity, the value of Vp was calculated and ranged from (1445-1995) m/s with an average value of 1765 m/s. The average value of Vp for dolomite limestone is 1787 m/s, while the value for crystalline limestone is 1995 m/s. The lower value of Vp is 1445 m/s obtained for limestone specimen with secondary constituent of shell as shown in Figs. 2 and 3.

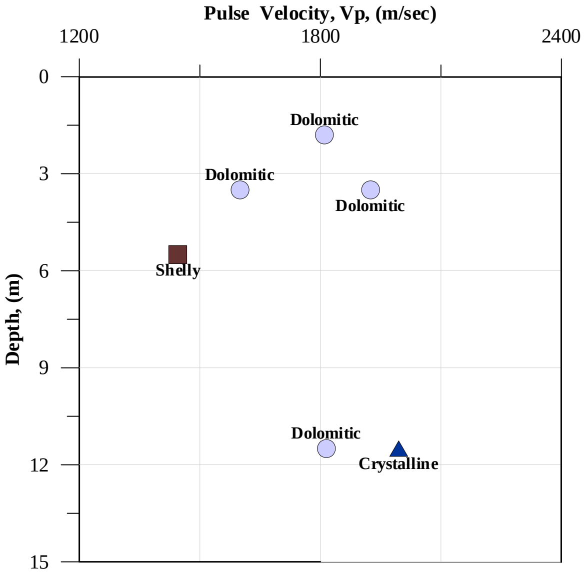


Fig 2. Ultrasonic Pulse Velocity with Depth

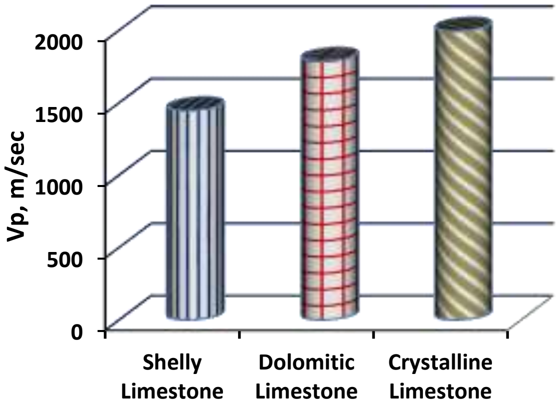


Fig 3. Variation of Vp with Rock Classification

3.2.2 Elasticity Parameters

Several parameters of elasticity such as constraint modulus of elasticity (Ec), dynamic modulus of elasticity

(Young's modulus, Ed) may be obtained easily from the ultrasonic velocity (Vp). The constraint modulus, Ec, is related to Vp by the following expression, [1];

$$Ec = \rho\, Vp^2 \qquad (2)$$

$$\rho = \gamma / g \qquad (3)$$

From the theory of elasticity, it is known that the Young's modulus of elasticity (E) is related to the constraint modulus (Ec) by the following expressions:

$$Ed = Ec\,(1 + \upsilon)\,(1 - 2\,\upsilon) / (1 - \upsilon) \qquad (4)$$

The Ec and Ed values are calculated based on laboratory and geophysical test results of the density (ρ) and Poisson's ratio (υ) for each rock formation as shown in Table 1.

Table 1. Dynamic Modulus from Ultrasonic Velocity

Rock Classification	Average Vp, m/s	Ec, MPa	Ed , MPa
Shelly Limestone	1445	4206	3388
Dolomitic Limestone	1787	6618	5308
Crystalline Limestone	1995	7096	5286
Average Values			
Limestone with different secondary constituent	1742	5973	4661

3.2.3 Estimation of Unit Weight Using Vp

When density data is unavailable, Gardner's relationship [5] is commonly used to estimate density from Vp:

$$\rho = 0.23\, Vp^{0.25} \qquad (5)$$

where:
ρ = bulk density in gm/cm ^{3}
Vp = P-wave velocity in ft/s

This empirical relationship is based on field and laboratory measurements of saturated sedimentary rocks from a wide variety of basins and depths. The relationship is essentially an average of the fits for sandstone, shale, and carbonates.

On the other hand, [10] stated that if the seismic P-wave velocities of subsoil layers are measured, the unit weight γ may be determined, in kN/m3 units, from anyone of the two following empirical expressions:

$$\gamma = 3.2\, Vp^{1/4} \qquad (6)$$

$$\gamma = \gamma_0 + 0.002\, Vp \qquad (7)$$

where
γ_0= the reference unit weight values in kN/m^3 given as follows:
γ_0 =18 for mudstone, limestone, claystone, conglomerate, etc.
γ_0 = 20 for cracked sandstone, tuff, graywacke, schist, etc,
γ_0 = 24 for hard rocks.
Vp = P-wave velocity in m/s,

The validity of these expressions verified on the basis of laboratory testing of presented in this paper as shown in Fig. 4.

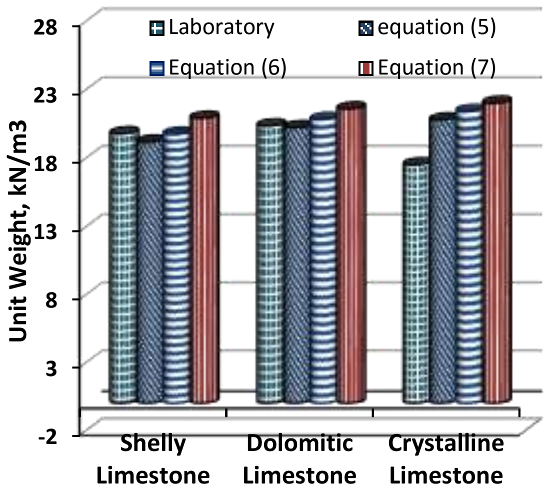


Fig 4. Comparison of empirical and experimental Unit weight Values

It can note that the unit weights of Shelly and Dolomitic Limestone calculated by eqs. (5) and (6) are in good with those determined in the laboratory. A correction factor is necessary for the unit weights of limestone calculated by these equations. Thus, a correction factor of about 1.05 and 0.93, for eqs (5) and (6) respectively, can be adopted in this research. As a conclusion, if insitu measured P-wave velocities are available in the absence of core samples or laboratory testing, the empirical expression shown in eqs. (5) and (6) with the adopted correction factor provides a reliable first approximation for the unit weights of rock.

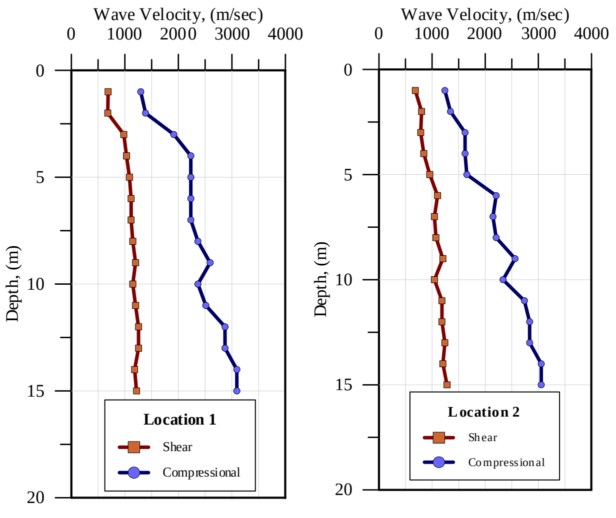
3.3Crosshole Measurements

3.3.1 Shear and Compressional Wave Velocities

Fig. 5 shows the variation of shear and compressional wave velocities (Vs and Vp) determined from field measurements in the form of velocity profiles. It is seen that, in general both the Vs and Vp are considerably not different from one location to another. Furthermore, both Vs and Vp increase with depth showing clearly the transition from the layer to layer.

It is also seen in Fig. 5 that both the Vs and Vp for every depth interval considerably not different from one location to another.

The variation of Vs and Vp between investigated points is given in Fig. 6. It may be seen that there is a considerable difference in measured values from BHs 1 to 4. It is calculated that the average ratio of change in Vs value to average shear wave velocity (ΔVs/V's) from BHs 1 to 4 is hearty equal to 1. In view of the subsurface geotechnical investigation the drop in Vs and Vp values at shallow depth may be explained in terms of gradual change of formation from weathered limestone to limestone with different secondary constituent such as dolomite and shell along the axis of investigated boreholes.



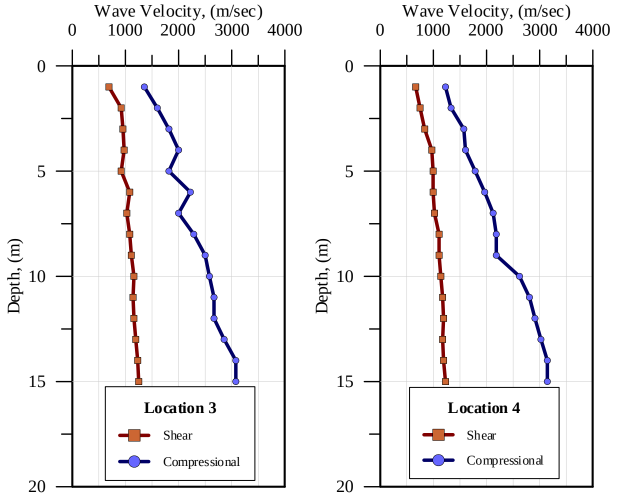


Fig. 5 The Variation of Vs and Vp for each Borehole

For the whole investigation, wave velocities range from (666 to 1228) m/sec to (1228 to 3144) m/sec for shear and compressional respectively. This range of velocities is indicative of different stiffness of rock. However, within each respective overburden in the rock, the range of both shear and compressional wave velocities is much narrower (Figs. 5 and 6). The lower values in the shear wave velocities for the whole investigation were observed at a shallow depth. The shear wave velocities were observed to be as low as 660 m/s within a depth of 0.0 m to 2.5m from the ground surface. It may be seen that this weak zone is the closer to the surface for the whole investigation, and reached to greater depths about 3.0m below the surface.

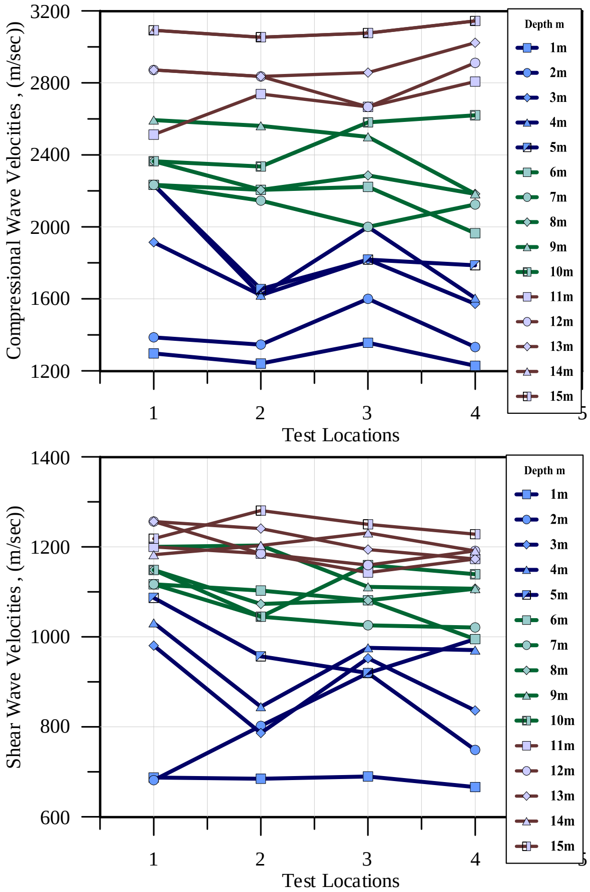


Fig. 6 The Variation of Vs and Vp between Investigated Points

3.3.2. Dynamic Deformation Modulus

It is possible to obtain an estimate of the dynamic deformation modulus of rock mass from empirical relationships with the wave velocities. The constraint modulus of elasticity (Ec); dynamic modulus of elasticity (Young's modulus Ed); shear modulus (G) as well as the Poisson's ratio (υ) were calculated using the recorded Vs and Vp at each depth with their related densities. The natural bulk densities values were calculated and deduced from Vp values using the expression eq. 6 down to a depth of 15 meters. The related familiar equations (listed below) were used for elastic modulus calculations, [10]; [8]; [7]:

$$G = \rho V^2 s \qquad (8)$$

$$Ec = \rho V^2 p \qquad (9)$$

$$Ed = 2(1 + \upsilon)\, G \qquad (10)$$

$$\upsilon = (V^2 p - 2 V^2 s) / 2(V^2 p - V^2 s) \qquad (11)$$

Where:

V_p is the propagation velocity of the compressional waves

V_s is the propagation velocity of the shear waves

ρ is the bulk density of the material

υ is Poisson's Ratio

G is the Shear Modulus

Ec is the constraint modulus of elasticity

Ed is the dynamic modulus of elasticity

The results of the calculations are provided in Figs. 7 and 8. These figures show graphs of dynamic modulus (shear, Young and constraint), Poisson’s ratio and unit weight versus depth. These figures show that highest Young’s and shear moduli are associated with limestone layers at a depth of (7 to 15.0) m. The values in these layers are as high as (3 and 7) GPa for shear modulus and Young’s modulus, respectively. For rock at shallow, values decrease abruptly to values as low as (1 to 2) GPa, indicating weaker rock units that will be deformed easily when subjected to high stress and strain conditions prevailing during mining.

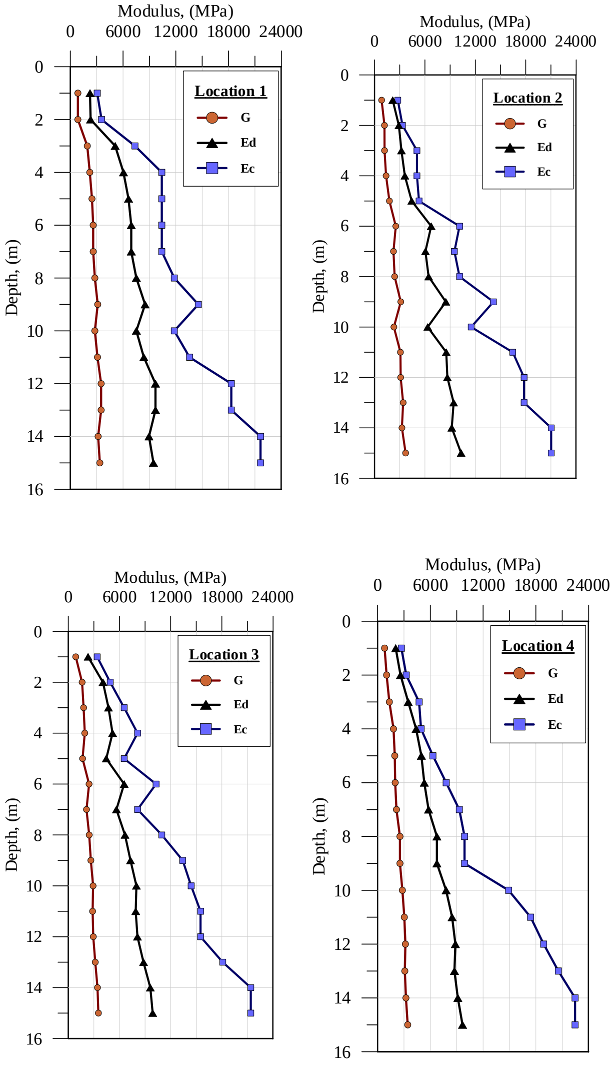
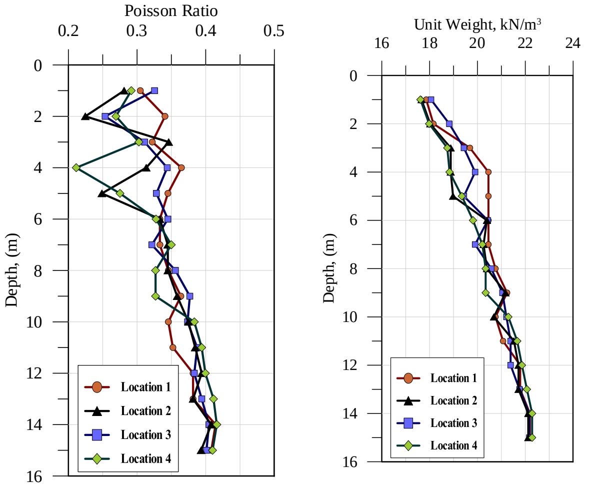


Fig. 7 The Variation of G, Ed and Ec with depth

However, the crosshole tests show shear modulus (G) values (<1000) MPa for the top two meters. For depths from (2.0 to 7.0) meters the shear modulus values range from (1000 to 2000) MPa. For depths (7.0 to 15.0) m the value of (2000 to 3700) MPa can be seen.



(a) (b)

Fig. 8 The Variation of (a) Poisson Ratio with depth, (b) Unit Weight with depth

3.4 Comparison of Field and Laboratory Measurements

Fig 9. presents and compares the dynamic modulus from field and laboratory measurements. The intact small strain dynamic Young's modulus at zero confinement was attained from the ultrasonic pulse velocity tests. The seismic geophysical crosshole survey was carried out to obtain the dynamic modulus of the insitu rock mass. In general, the stiffness results from the laboratory and field measurements compare relatively well. The stiffness results from ultrasonic velocity test results were underestimated the stiffness of the tested rock material. This result, however, expected, because the strain perturbation produced by the passage of shear waves are very small, the dynamic shear modulus represents an upper-bound estimate of the mass stiffness of the ground, [4]. In addition, the insitu rock mass stiffness should be lower than intact values due to the presence of joints and other defects in the overall rock mass. However, the general agreement between the different methods could be due to compensating effect arising from disturbance during sampling, strain level, overburden pressure and joint structure among others. In addition, the agreement between the field and laboratory tests depends on the material type and complexity of the geological structure.

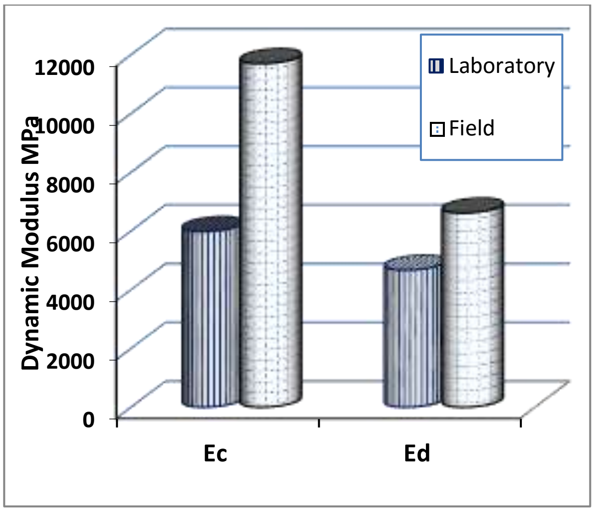


Fig. 9 Comparison of Laboratory and Field Values of Dynamic Modulus

4. Conclusions

On the basis of the content of the present paper, the following conclusions may be drawn:

1. In the laboratory; small strain stiffness of weak rock can be measured using local measurements of axial strains with direct transmission based devices. For very small strain measurements the TICO

Ultrasonic Instrument can be used.

2. In the field, seismic borehole method can be used for measuring the value of Gmax of weak rock from the west of Iraq.
3. The results from the laboratory measurements using the TICO Ultrasonic Instrument were lower than the seismic borehole method in weak rock. This is may be attributed to material disturbance during sampling.
4. Very useful information concerning the dynamic properties of the subsurface formation was provided from the crosshole testing program. This method was especially useful in detecting the weak zones in the form of low velocities, especially since it was not possible to obtain core samples in weak zones due to the fractured nature of the soil.
5. Shear and compressional wave velocities increase with depth showing clearly the transition from the low velocity and poor mechanical behavior in static loads to the locally weathered formations with high velocity and good mechanical behavior.

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Abbreviations

Ec	constraint modulus of elasticity
Ed	dynamic modulus of elasticity
Lp	pulse-travel distance in meter,
Tp	effective pulse-travel time
Vp	propagation velocity of the compressional waves
Vs	propagation velocity of the shear waves
γ_0	reference unit weight values
ρ	bulk density of the material
υ	Poisson's Ratio

معامل التشوه الديناميكي للصخر الضعيف مقاس من الاختبارات المعملية والميدانية

عباس جواد الطائي
أستاذ مساعد
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بغداد/ العراق

الخلاصة:-

تقارن هذه الدراسة معامل التشوه الديناميكي للصخر الضعيف المقاسة من الفحوصات المخبرية والميدانية التي أجريت كجزء من اعمال تحريات الموقع لاحد المشاريع الرئيسية في غرب العراق. الهدف من الدراسة هو الحصول على سرعة الموجة المنضغطة (Vp) وسرعة موجة القص (Vs) الزلزالية لحساب الخواص الديناميكية للمواد الصخرية (معامل القص، معامل يونغ، ونسبة بواسون) بين الحفر الاختبارية. تم أجراء الاختبارات المعملية للموجات فوق الصوتية على عينات الصخور غير المحصورة باستخدام جهاز TICO لتحديد سرعة الموجات فوق الصوتية. واستخدمت القياسات الميدانية للطرق الجيوفيزيائية السيزمية بما في ذلك تقنية crosshole لتحديد (Vp) و (Vs). بالإضافة إلى ذلك، تم استخدام العلاقات التجريبية لتقدير وحدة الوزن للكتل الصخرية باستخدام نتائج سرعات الموجة الزلزالية. وتم تحديد الصلابة الديناميكية من القياسات الحقلية ومقارنتها مع القيم المخبرية من فحص الموجات فوق الصوتية لتقدير صلابة الصخور من سرعات الموجة الزلزالية.