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Experimental Investigation of the Change of Elastic Moduli of Clastic Rocks under Nonlinear Loading

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ABSTRACT

This paper presents an experimental investigation on the nonlinear nature of the dynamic geomechanical characteristics of a clastic rock (sandstone). Rock samples of 7.5 mm in diameter and 15.6 mm in length were prepared. Rock properties were identified. Firstly, the limits of the rock linear elasticity zone were defined during quasistatic loading and uniaxial compressive strength determination at the Tinius Hounsfield rig. Secondly, the small experimental custom-built rig was designed to study the nonlinear nature of the Young's modulus in the zone of linear elasticity. At the rig the sample was stationary preloaded. The dynamic load was generated by a piezoelectric actuator powered with a signal generator. The displacement of rock sample surfaces was recorded by a laser sensor and an eddy current probe. The dynamic experiments were conducted at the load amplitude ranging from 50 to 250 N for each of frequencies of 25 Hz and 40 Hz. It was found that the dynamic Young's modulus increased with amplitude for all the frequencies studied. The newly developed experimental rig allows to investigate elastic moduli dispersion of rocks at the strain up to 10^{-3} under vibrations with frequency up to 40 Hz.

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NOMENCLATURE

d	Sample's diameter (m)	l_0	Sample's length at preloading (m)
d_0	Sample's diameter at preloading (m)	t	Time (s)
E	Young's modulus (GPa)	ε	Strain
E_{dyn}	Dynamic Young's modulus (GPa)	ε_{ax}	Axial strain
f	Frequency of the dynamic load (Hz)	ε_{rad}	Radial strain
F_{dyn}	Dynamic load (N)	ν	Poisson's ratio
F_{max}	Maximum load applied to a sample (N)	σ	Stress (MPa)
F_{min}	Minimum load applied to a sample (N)	$\sigma_{lim.low}$	Lower limit of the linear elasticity zone (MPa)
F_{st}	Preload value (N)	$\sigma_{lim.up}$	Upper limit of the linear elasticity zone (MPa)
l	Sample's length (m)	$\sigma_{UCS\ av.}$	Average uniaxial compressive strength (MPa)

1. INTRODUCTION

Elastic moduli of rocks are not constant and have nonlinear nature under the influence of the dynamic loading [1]. The phenomenon of the dispersion of elastic moduli under vibrations is considered while geotechnical engineering in such fields as mining [2], modelling the tunnels constructed in liquefiable soil rock [3], cutting and blasting [4, 5], construction in limestone sands [6], well drilling and completion [7] and reservoir engineering [8]. Experimental studies of clastic rocks elastic moduli dispersion can be differentiated in two groups in accordance with rock saturation during the investigation. In the first group, dynamic elastic moduli are studied on rocks saturated with a fluid (e.g., brine). A study of Opalinus clay in literature [9, 10] and Mancos

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shale by Szewczyk et al. [11], showed an increase in the Young’s modulus and a decrease in Poisson’s ratio with an increase in frequency of the dynamic loading from 1 to 100 Hz at the strain of 10^{-6}. Similar dispersion of the Young’s modulus was also reported in literature [12, 13] for Fontainebleau sandstone for frequency ranging from 1 to 100 Hz at the strain lower than 10^{-5}. An increase in Young’s modulus was also reported in literature [14] while studying the Berea sandstone in the range of frequencies from 1 to 100 Hz. A schematic nonlinear relation among clastic rock elastic moduli and load frequency is given by Batzle et al. [15]. A strong frequency and rate amplitude dependent elastic behavior over variety of sandstones was reported in literature [16]. Based on these and other works, a number of poroelastic mechanisms have been proposed and modelled on the nonlinear nature of the Young’s modulus while studying saturated rocks. Those models characterize in saturated porous media global inertia mechanisms [17], local mechanisms [18, 19], both global and local mechanisms [20] and other (see literature [21]).

In the second group, the studies are performed on dry rocks. It was exhibited in literature [22] that with an increase of frequency from 1 to 100 Hz for samples with a strain range between 10^{-8} and 10^{-6}, the Young’s modulus and Poisson’s ratio of Donnybrook sandstone are nearly constant, i.e. no dispersion of the Young’s modulus is observed. Earlier, it was reported in literature [23] that Young’s moduli of Navajo sandstone, Spergen limestone and Oklahoma granite do not depend on frequency of the dynamic loading at the strain of 10^{-7} in the frequency range from 4 to 400 Hz. Similarly, studies conducted by Winkler [24] on vacuum dry sandstones Massilon, Berea and Boise at frequencies up to 0.1 MHz did not reveal any relationship between attenuation and frequency at small strain, which is also relevant for man-made rocks with no intergranular cement. However, the phenomenon of dispersion of elastic moduli in dry clastic rocks is still exists and can be captured by hysteresis loop on the strain–stress diagram as shown in literature [16]. Manifestation of dispersion in dry clastic rocks is accompanied by the phenomenon when the dynamic Young’s modulus exceeds the static one which is directly related to a strain rate and a loading path [25, 26]. There is a number of models designed to describe the nature of dynamic elastic characteristics observed under high strain by, for example, inertial approach (see literature [27]). Nevertheless, the mechanism of the dynamic dispersion of elastic moduli under vibrations is still open for research.

Since the standard loading rigs allow us to perform linear loading of rocks at frequency ranging from 0.1 to 2 Hz and strain up to 10^{-3} [26-28], it is practically not possible to use such the rigs to study the effect of nonlinear dynamic loads (vibrations) on rocks. As is shown in literature [4, 29] studying of the dynamic elastic characteristics of rocks at high strain is limited by the complexity of experiments and data processing. It is possible to study the effect of nonlinear dynamic loads on rocks in the range of seismic frequencies from 1 to 100 Hz at the strain of $10^{-8}..10^{-6}$ using custom-built experimental set-ups, described in literature [10, 12, 15, 30-32]. Recently, Borgomano et al. [33] have built the experimental apparatus able to measure the dynamic rock elastic characteristics at frequencies up to 1 kHz and strain up to 10^{-5}. However, considering that during mining (e.g., well drilling and perforation [34]) the rocks experience much higher strain ($\geq 10^{-2}$) the capacity expansion of existing rigs is required. Studying of the effect of significant dynamic loads up to 10^{1}-10^{4} is possible using the Kolsky-Hopkinson bar machines [35, 36], but those machines do not allow to create cyclic (harmonic) loads on rock samples. Therefore, to study the elastic moduli under high strain nonlinear dynamic loads new experimental techniques are necessary. The aim of this paper is to study the nonlinear nature of the dynamic elastic moduli of a dry clastic rock being in the zone of the linear elasticity using a small custom-built experimental rig.

The paper is organized as follows. In Section 2, the experimental methodology, details on samples preparation procedure, quasistatic and nonlinear dynamic experiments are described. The obtained experimental results and its discussion are given in Section 3, followed by the conclusion in Section 4.

2. MATERIALS AND METHODS

2. 1. Description of Rock Samples

A clastic Permian age rock (sandstone) was used for this study. The properties of the rock are given in Table 1 and Figure 1. Each sample was 7.5 mm in diameter *d* and 15.6 mm in length *l*. The samples were prepared in accordance with industrial standards [37, 38].

TABLE 1. Properties of the studied rock

Property	Value	Study rig
Porosity, fr. units	11.7	Helium porosimeter PHI-220
Gas permeability, μm^2	0.353	Benchtop Permeability Sistem BPS-805
Pore size, mm	0.02-0.24	Microfocus X-ray tomography rig, Nikon Metrology XT H 225
Pore distribution	uniform	
Fracturing	no	
X-ray density composition	nonuniform (0.05 mm high-density inclusions)	

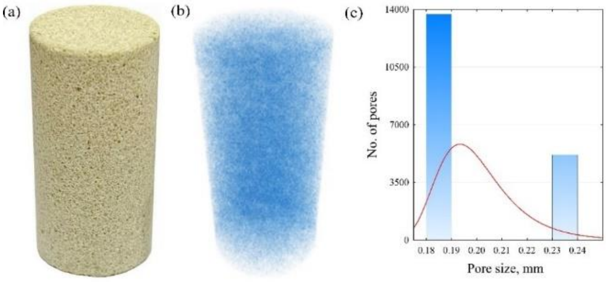

Figure 1. Characteristics of the prepared samples: (a) a photograph depicting a sandstone sample; (b) a sample's pore space model; (c) a diagram for pore distribution

Using diamond drill bits Tacklife AHS02C the samples were cored form rock blocks with water flush, then cut, washed and dried. In total there were 18 samples prepared. For both quasistatic tests and dynamic experiments there were 9 samples used in order to ensure reliable results.

2. 2. Methodology of Nonlinear Loading

Since the elastic moduli, and the dynamic ones in particular, have to be studied in the state when a rock experiences elastic deformation (the Young's modulus can be determined as $E = \sigma/\varepsilon_l$) the limits of the linear elasticity zone should be defined prior to the dynamic experiments. In order to obtain the repeatable dependencies of elastic moduli the experiments on nonlinear dynamic loading were performed on 9 samples (Figure 2).

Elastic limits of the studied clastic rock were defined during quasistatic loading of prepared samples at the Tinius Hounsfield rig. Quasistatic loading was performed at the loading rate of displacement plate of 0.05 mm/min. As a result, the standard diagram of loading–displacement was obtained for all the samples tested which comprised compaction, elastic deformations, irreversible deformations and fracture. Figure 3 shows the limits of the linear elasticity zone equal to $\sigma_{lim.low} = 10.2$ MPa and $\sigma_{lim.up} = 31.7$ MPa defined as average values of limits of the linear section according to literature [39].

After the elasticity zone being determined in order to study the nonlinear behaviour of elastic moduli under dynamic loads at the strain up to 10-3 the small experimental rig was built. In the rig (see Figure 4) the rock sample was installed at a load table, below which load sensor Kistler 9027C was mounted. There was a piezoelectric actuator Extrema Model 250µ located on top of the sample through the metal dist. Above the actuator there was a static load ensuring sample's preloaded (compacted) state. The actuator was powered with a signal generator Manual MOS-01 able to set the amplitude and frequency of the actuator operation and produce axial-stress oscillations.

During the dynamic experiment the sample was experiencing stationary load F_{st} equal to 700 N and periodic dynamic load F_{dyn} the amplitude of which was varied between 50 N and 250 N at two frequencies f such as 25 Hz to 40 Hz. At stationary load F_{st} the sample's length was equal to l_0 and sample's diameter was equal to d_0 (see Figure 5). The largest $F_{max}=F_{st}+F_{dyn.max}$ and the smallest $F_{min}=F_{st}-F_{dyn.min}$ load applied to a sample corresponded to maximum distance between the sensors and samples top and side surfaces (see Figure 4) and consequently the sample's strain. The radial displacement

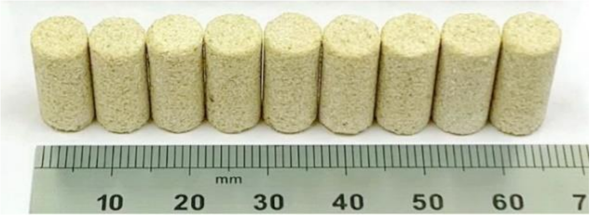

Figure 2. Prepared nine samples of a clastic rock

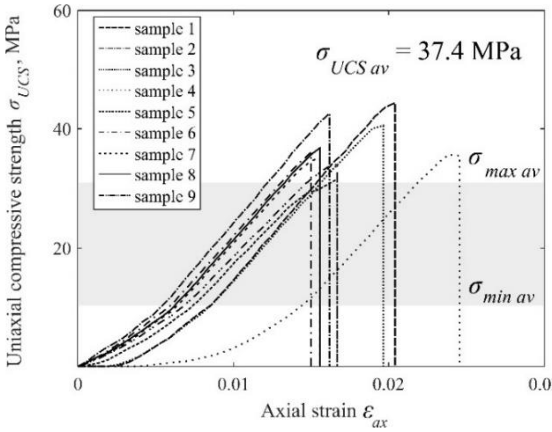

Figure 3. The zone of linear elasticity determined during UCS tests of nine samples

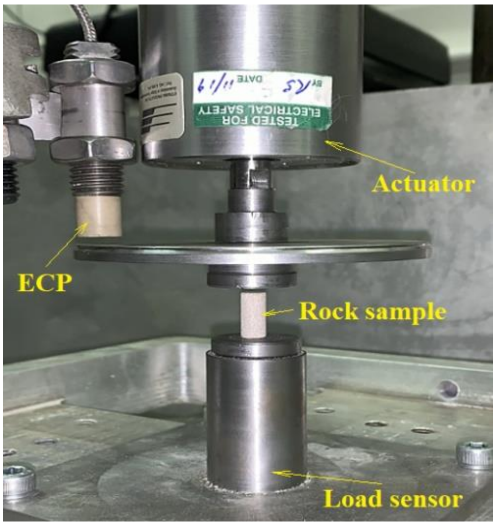

Figure 4. A clastic rock sample at the small experimental rig

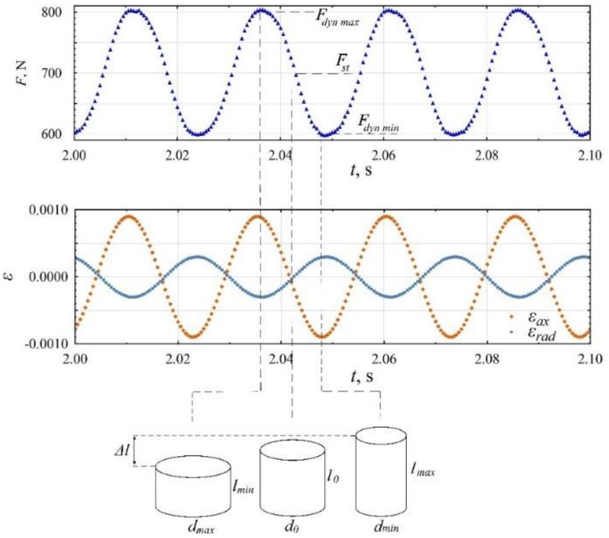

Figure 5. An example of the dynamic loading experiment at frequency of 40 Hz and dynamic load amplitude of 100 N characterizing sample' deformation

of the sample's side surface was recorded by Micro-epsilon. The axial displacement was recorded by an eddy current probe (ECP).

The data form the sensors went to a PC. After the signals of three sensors were acquired and processed in LabView and Matlab the data then was used to calculate the dynamic Young's modulus and Poisson's ratio by using the Equations (1) and (2):

$$E_{dyn} = \frac{\Delta\sigma}{\varepsilon_{ax}} \quad \Delta\sigma = \frac{F_{max}-F_{min}}{S} \quad \varepsilon_{ax} = \frac{l_{max}-l_{min}}{l} \tag{1}$$

$$\nu = \frac{\varepsilon_{rad}}{\varepsilon_{ax}} \quad \varepsilon_{rad} = \frac{d_{max}-d_{min}}{d} \tag{2}$$

3. RESULTS AND DISCUSSIONS

It was obtained during experiments that the elastic moduli of the clastic rock change under dynamic loading depending on frequency and amplitude of the load. Figure 6*a* demonstrates that at frequency of *f = 25Hz* the Poisson's ratio *ν* increases from 0.4 to 0.58 when dynamic load F_{dyn} on piezoelectric actuator is increased from 100 N to 250 N. At the same time the dynamic Young's modulus E_{dyn} increases up to 2.57 GPa (see Figure 6*c*). It is also noted that if frequency of dynamic loading is increased up to 40 Hz the Poisson's ratio *ν* increases from 0.52 to 0.6 (see Figure 6*b*), while the dynamic Young's modulus E_{dyn} increases up to 3.0 GPa (see Figure 6*c*). With an increase in the amplitude of dynamic load from 100 N to 250 N the value of E_{dyn} increased from 0.75 GPa to 0.86 GPa. After normalization the strain cycles (shown on Figures 6a and 6b) narrowed to the dashed lines.

The dispersion of the dynamic Young's modulus (see Figures 6*c* and 6*d*) corresponds to the varying in a loading cycle rock density. This fact may lead to a perception of rock hardening and softening under vibration. Another possible explanation for the phenomenon of rock elastic

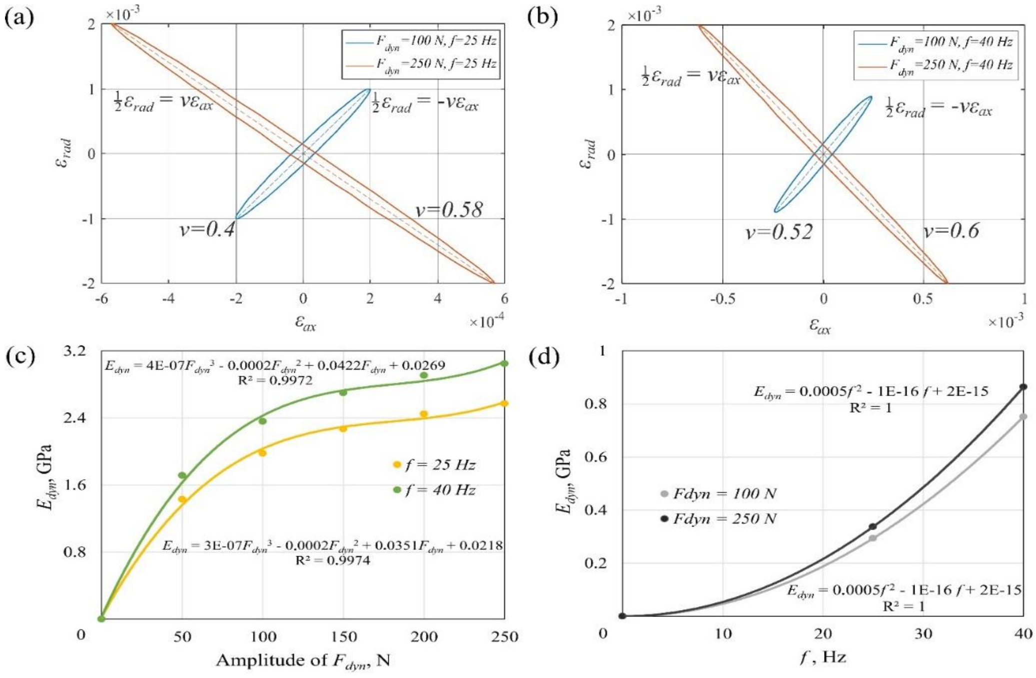

Figure 6. Dependance of strain and elastic moduli on dynamic loading parameters: (a) and (b) dependance of the sample's strain at frequency *f* of 25 Hz and 40 Hz; (c) and (d) dependance of the dynamic Young's modulus on frequency f of 25 Hz and 40 Hz and amplitude of dynamic load Fdyn of 100 N and 250 N

moduli dispersion under high strain vibrations can be inertial resistance of the rock to the dynamic load applied.

However, the experimental results represent a basis for further elastic moduli mathematical models' formulations. The phenomenon of dispersion of the dynamic elastic moduli under high strain vibrations has to be conceptualized, and further developed mathematical models needs to be verified.

4. CONCLUSION

In this work, we present the results of investigation of the nonlinear nature of clastic rock (sandstone) elastic moduli obtained during the series of experiments. The investigation was conducted in two phases. First, the limits of the zone of linear elasticity of samples of 7.5 mm in diameter were determined in quasistatic loading. Then, at the second stage, the experiments on dynamic loading were performed with help of a custom-built small experimental rig. During the course of dynamic loading experiments elastic properties were studied at two frequencies f such as 25 Hz and 40 Hz. At both these frequencies amplitude of nonstationary load varied from 50 N to 250 N. The nonlinear nature of the Poisson's ratio and the dynamic Young's modulus was revealed as a result of the study. The dispersion of elastic moduli values under dynamic loading was observed at each amplitude of the load for both frequencies at the strain up to 10^{-3}. The obtained results confirm the nonlinear nature of the dynamic elastic moduli of a clastic rock shown in the similar mentioned researches on dry rocks but at smaller strain. The newly developed experimental rig allows to investigate elastic moduli dispersion of rocks at the strain up to 10^{-3} under vibrations with frequency up to 40 Hz.

5. ACKNOWLEDGEMENTS

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Persian Abstract

چکیده

در این مقاله یک تحقیق تجربی در مورد ماهیت غیر خطی ویژگی های ژئومکانیکی دینامیکی یک سنگ آواری (ماسه سنگ) ارائه شده است. نمونه سنگهای قطر 7.5 و طول 6.6 میلی متر تهیه شد. خواص سنگ شناسایی شد. در مرحله اول ، محدوده منطقه کشش خطی سنگ در هنگام بارگذاری کوآیستاتیک و تعیین مقاومت فشاری تک محوری در دکل Tinius Hounsfield تعریف شد. در مرحله دوم ، دکل کوچک سفارشی ساخته شده برای آزمایش ماهیت غیرخطی مدول Young در منطقه کشش خطی طراحی شده است. در دکل نمونه از قبل ثابت مانده بود. بار دینامیکی توسط یک محرک پیزوالکتریک که از یک مولد سیگنال تغذیه می کند تولید شد. جابجایی سطوح نمونه سنگ توسط یک سنسور لیزر و یک پروب جریان گردابی ثبت شد. آزمایش های پویا در دامنه بار از 50 تا 250 N برای هر یک از فرکانس های 25 هرتز و 40 هرتز انجام شد. مشخص شد که مدول جوان پویا با دامنه برای تمام فرکانسهای مورد مطالعه افزایش می یابد. دکل آزمایشی تازه توسعه یافته امکان بررسی پراکندگی مدول الاستیک سنگها را در فشار تا 10–3 تحت ارتعاشات با فرکانس تا 40 هرتز فراهم می کند