Mechanical characterization of unconventional shales – experimental challenges and solutions

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Abstract. Unconventional shale is commonly transversely isotropic with a vertical axis of symmetry (VTI). To fully characterize its elastic anisotropy using the traditional laboratory methods, three core plugs cut in three orientations are required: one parallel, one perpendicular, and one at 45° to the bedding. This poses the technical challenges: it is very difficult, if not impossible, to drill these oriented plugs with good quality due to the brittleness and weakness of unconventional shale. This paper introduces a technique to characterize the elastic anisotropy of a VIT medium from one horizontal plug only. The scarcity of shale samples often leads the multi-stage triaxial (MST) testing as the only laboratory option for determining the rock failure parameters. One major challenge of a MST test is to predict the imminent failure state of the sample and thereby prevent the failure of the sample from occurring at each loading stage except for last stage. Another technique, radial strain gradient method, is presented for predicting the imminent failure of a test sample, thus enabling more consistent and accurate determination of the failure criterion from a MST test.

1 Introduction

Unconventional shale is generally (not always) transversely isotropic with a vertical axis of symmetry (VTI), in which the vertical axis is usually aligned normal to the bedding. Characterizing the elastic behaviour of a VTI medium traditionally requires the measurement of five wave velocities on three plugs that are cut along three directions: perpendicular, parallel, and 45° to the bedding, respectively [1-4]. Due to the brittleness and weak planes associated with shale, it is practically very difficult to drill these plugs, especially in the vertical and 45° directions to the bedding. Most often than not, only horizontal plugs are available for characterizing the elastic anisotropy of shale formation. This challenge translates to the development of a laboratory technique for performing the velocity anisotropy analysis of a VTI medium from one horizontal plug only [5], which will be described in this paper.

Mohr-Coulomb failure criterion (hereafter referred to as only failure criterion for simplicity) of a rock sample is required in various engineering applications including borehole stability analysis and sand onset prediction. Its determination traditionally requires to perform either three single-stage triaxial (SST) testing on three samples, or one multi-stage triaxial (MST) testing on one sample at various confining pressures. Due to the limited availability of shale samples, MST testing is very often the only option used to determine the failure criterion of a sample.

In the MST test, one sample is compacted cyclically at three confining pressures or more. At each confining pressure (or stage), the sample is loaded axially until a pre-determined unloading criterion is reached. At this point, this stage test is stopped and unloaded. Then, the confining pressure increases to the next level and next stage test starts. This process is repeated until the last stage, where the sample is loaded to failure. By failure, it is defined here to be when the sample reaches at the peak stress at a given confining pressure.

One major challenge associated with the MST test is to determining precisely the unloading points that should be as close to the peak stress or failure as possible while at the same time preventing failure from occurring. Otherwise, the sample will break and the test could not continue to determine the failure criterion of the sample. Many methods have been proposed to approximate the unloading points for MST testing [6-10]. This paper illustrates by example the effectiveness of the radial strain gradient (RSG) method [11-12] for predicting the unloading points that enables more consistent and accurate determination of the failure criterion from a MST test.

2 Velocity anisotropy analysis

Unconventional shale is commonly considered as the vertical transverse isotropic media [13-15]. Velocity anisotropy analysis is required to perform to characterize the elastic anisotropy of unconventional shale, which is important for applications including seismic imaging, in-

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situ stress estimation, and hydraulic fracturing design. The elastic anisotropy of a VTI medium is generally characterized by five independent constants (C_{11}, C_{33}, C_{44}, C_{66}, C_{13}), which are defined as

$$C_{11} = \rho(V_{PH})^2 \quad (1)$$

$$C_{33} = \rho(V_{PV})^2 \quad (2)$$

$$C_{44} = \rho(V_{SV})^2 \quad (3)$$

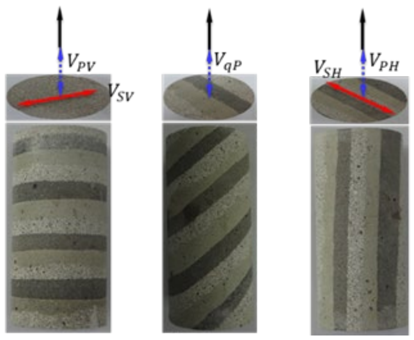
$$C_{66} = \rho(V_{SH})^2 \quad (4)$$

$$C_{13} = -C_{44} + \sqrt{4\rho^2\left(V_{qP}\right)^4 - 2\rho\left(V_{qP}\right)^2 A + B} \quad (5)$$

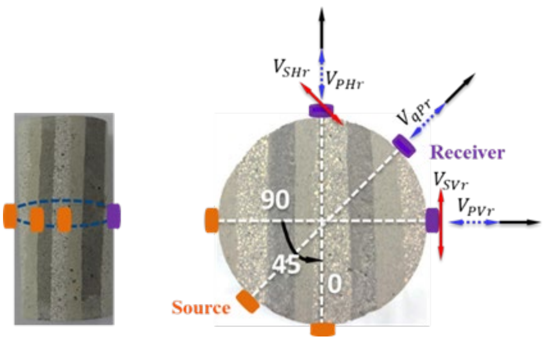
$$A = C_{11} + C_{33} + 2C_{44}$$

$$B = (C_{11}+C_{44})(C_{33} + C_{44})$$

Where ρ is the bulk density of the sample, V_{PV} and V_{SV} are compressional and shear wave velocities propagating perpendicular to the bedding plane (Figure 1a), V_{PH} and V_{SH} are compressional and shear wave velocities travelling parallel to the bedding plane, and V_{qP} is the quasi-compressional wave propagating along the 45º relative to the bedding. Note that the shear wave (V_{SH}) polarizes parallel along the bedding.



(a) Three-plugs method



(b) One horizontal plug method

Fig. 1. Schematic diagram illustrating two methods of performing velocity anisotropy analysis of the VTI media: (a) traditional three-plugs method, and (b) one horizontal plug method. The wave propagation direction is denoted by the single arrow, while the polarization direction is given by double arrow. The dash line double arrow shows the compressional wave polarization direction, and the solid line double arrow represents the shear wave polarization direction.

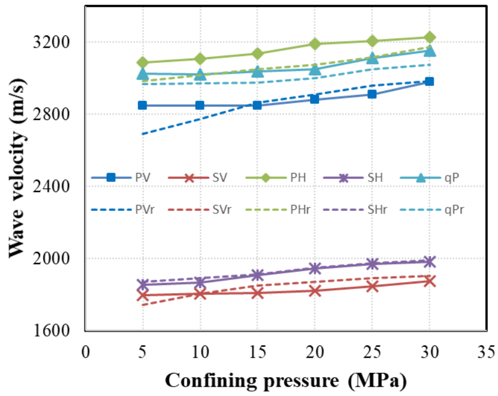
To determine the five elastic constants, the traditional three-plug method requires measuring five wave velocities (V_{PV}, V_{SV}, V_{qP}, V_{PH}, V_{SH}) on three core plugs drilled along the perpendicular, 45º, and parallel to the bedding (Fig. 1a). During the test, one set of planar transducers (sources and receivers) is installed axially on the two ends of the plug. V_{PV} and V_{SV} are measured from the vertical plug (left) testing, V_{qP} from the 45º plug (middle), V_{PH} and V_{SH} from the horizontal plug (right), separately. It is worth mentioning that V_{PH} and V_{SH} are the velocities of wave traveling along the fastest horizontal layer, while V_{PV}, V_{SV} and $V_{qP}$are the average velocities of wave traveling across all layers.

For unconventional shale, due to its brittleness and weak planes, very often only horizontal plugs of good quality are available for the testing, rendering it impossible to apply the traditional three-plugs method for performing the velocity anisotropy analysis. This practical challenge translates to the development of one-horizontal plug technique.

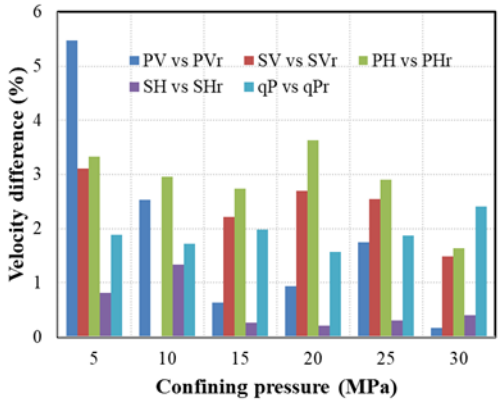
Figure 1b illustrates the one horizontal plug method for measuring the required five wave velocities required in the velocity anisotropy analysis [5]. Three sets of curved planar transducers (sources and receivers) are installed radially around the perimeter of the sample. The first set is along the direction perpendicular to the bedding, the second set along the 45º direction to the bedding, and the third one parallel to the bedding. This setup enables to measure the five wave velocities, similar to the traditional three-plugs method. Alternatively, one set of transducers can be used to measure the five velocities, in which the relative position of the sample bedding to the transducers needs to be adjusted to align with the perpendicular, parallel, and 45° to the bedding.

Figure 2 compares the corresponding velocity measurements between the one-horizontal plug approach and traditional three-plug method on the synthetic samples of Fig. 1. Velocities labelling with a subscript r are the measurements from the horizontal plug only. Wave velocity measurements were performed at room temperature and various confining pressures of 5, 10, 15, 20, 25, and 30 MPa. Considering the uncertainty of the first arrival time pick, the measured wave velocities from one horizontal plug method match very well with those from the traditional three-plug method. The difference between these two techniques are mostly less than 3%, demonstrating that the one-horizontal plug approach can be used to characterize the elastic anisotropy of the transversely isotropic unconventional shale when the traditional three-plug method is not applicable

Unconventional shales are not always transversely isotropic with a vertical axis of symmetry [16], where one horizontal plug technique is not applicable. One practical challenge associated with both one- and three-plug approaches is to identify and mark the orientation of beddings within the sample. In practice, the high-resolution medical computed tomography (CT) imaging technique is first applied to detect the orientation of the layers within the whole core samples, from which the vertical, horizontal and 45-degree plugs are drilled carefully. For the horizontal plug, the micro-CT imaging technique is further used to mark the orientation of the layers for the velocity measurements. Other techniques such as 3D magnetic anisotropy [17] could also be employed to identify the structure of the anisotropic samples.



(a)



(b)

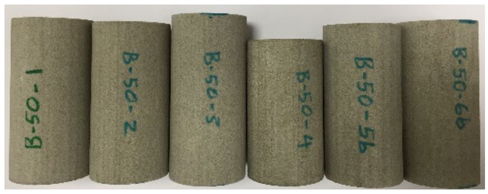
Fig. 2. (a) Comparison of velocity measurements between the traditional three-plug method (solid curves) and one horizontal plug approach (dash curves); and (b) Velocity difference (%) between these two methods, which is calculated as $|V_3 - V_1|/V_3 \times 100\%$ for each corresponding velocity measurement. V_3 and V_1 denote the corresponding velocities from the 3-plug and 1-plug methods.

Note that one horizontal plug technique is not developed to replace the traditional three-plug approach, but provides an alternative method for characterizing the elastic anisotropy of a VTI medium when three plugs of specific orientations are not available. Discrepancy could be expected, due to the property heterogeneity of each layer. In the horizontal velocity measurement of V_{PH} and V_{SH}, they are the velocities of wave traveling along the fastest layer within the covered area. Due to the limitation of the design, the planar transducer covers more layers than the curved one because of its larger size. Therefore, the fastest layer could be different along the axial direction (three-plug approach) and the radial direction (one-horizontal plug method).

3 Mohr-Coulomb failure analysis

Mohr-Coulomb failure analysis is performed to determine the failure parameters (the cohesion strength and internal friction angle) and the unconfined compressive strength (UCS) of a rock sample, which are important for judging if the sample will fail when subjecting to an external stress. This section applies a recently developed quantitative method of predicting precisely the unloading points during a multi-stage triaxial (MST) test for enhancing the accuracy of the failure criterion determination [11-12]. For validation and comparison, the single-stage triaxial (SST) tests were also conducted on Berea sandstone outcrops (Figure 3).

(a) Berea sandstone outcrops



(b) Plugs cut from outcrops above.

Fig. 3. (a) Berea sandstone outcrop of ~50 mD permeability selected for conducting SST and MST tests. Different colours were due to light. (b) Plugs cut from outcrops above. B50-1, -2, -3, and -4 are cut from the bottom outcrop, and B50-5b and -6b from top one.

3.1 Radial strain gradient method

The radial strain gradient (RSG) method was developed to determine quantitatively and consistently the unloading point for enhancing the MST testing [11-12]. During a test, the rate of change of radial strain is observed to be much more sensitive to failure than that of axial strain as the sample approaches the peak stress. Figure 4 illustrates the variation of deviatoric stress, axial strain, and radial strain with the time during the SST testing on sample B50-1 under the confining pressure of 591 psi. The peak stress is defined as the maximum deviatoric stress, while MVS and ZVS are the maximum and zero volumetric strains, respectively. Axial strain is defined as the positive in compression, and radial strain is negative in tension. In Fig. 4, the radial strain is plotted as its absolute values for comparison of the axial strain.

Radial strain gradient (RSG) is defined as a function of the rate of change of radial strain with the time,

$$RSG = \tan^{-1}\left(C \cdot \frac{\Delta\varepsilon_r}{\Delta t}\right) \quad (6)$$

where $\Delta\varepsilon_r = \varepsilon_{r,t_2} - \varepsilon_{r,t_1}$ is the change of radial strain (dimensionless) within the change time (second) of $\Delta t = t_2 - t_1$. The constant $C = 1.0 \times 10^6$ seconds is set to ensure the RSG value varying in the range of 0 ~ -90.

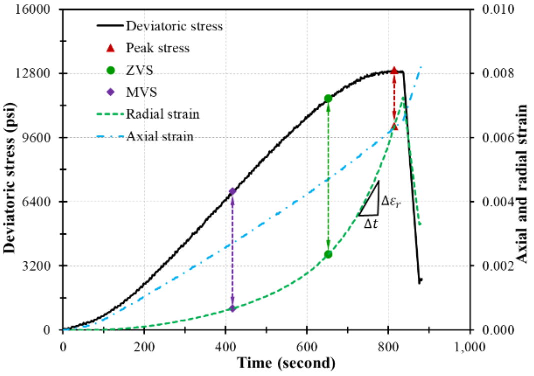


Fig. 4. Variation of deviatoric stress, axial strain, and radial strain with time during the SST testing on sample B50-1 under the confining pressure of 591 psi. MVS is the maximum volumetric strain, while ZVS is the zero volumetric strain.

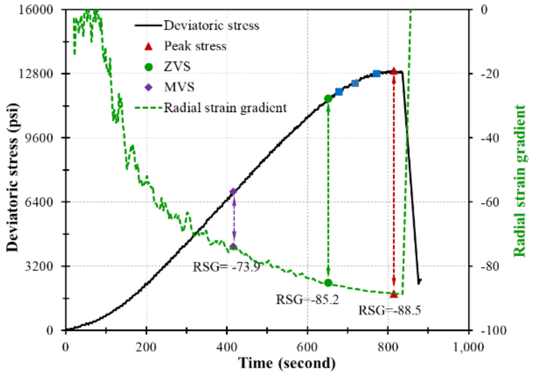


Fig. 5. Variation of radial strain gradient with the time during the SST testing of sample B50-1.

Figure 5 displays the variation of radial strain gradient with the time for the SST test of sample B50-1. The radial strain gradient decreases monotonically and approaches to a horizontal asymptote of $RSG = -90$ as the sample is compressed close to the failure. It observes clearly that each value of RSG is correlated to the corresponding stress state on the deviatoric stress-time curve, indicating that RSG can be used to quantitatively predict the unloading point that should be as close to the peak stress or failure.

3.2 Comparison of unloading criteria

In theory, the unloading point should be selected at the stress state that approaches very closely the peak stress but still prevents the failure of the sample from occurring [9, 19, 20]. This poses a practical challenge because the peak stress of a sample is never known in advance. Many criteria have been proposed to approximate the unloading point, which for example include the zero volumetric strain [6], zero tangent modulus, maximum secant modulus [18], maximum volumetric strain [7, 8], radial strain reference line [10], and radial strain gradient [11].

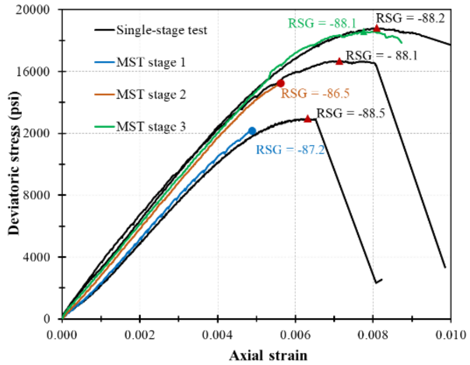


Fig. 6. Comparison of deviatoric stress-axial strain curves between the SST and MST tests. The deviatoric stress is defined as the axial stress minus the confining pressure. The filled circle denotes the unloading point, and the filled triangle is at the peak stress.

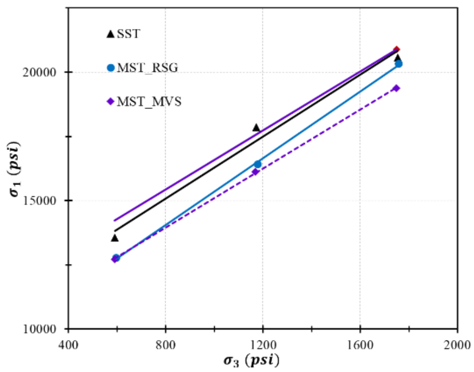


Fig. 7. Comparison of the failure envelopes determined from the SST testing (black line), the MST testing using the RSG (blue line) and MVS (solid purple line) unloading criteria. The dash purple line is the original non-failure line from the MST test using the MVS unloading criterion, which is shifted to derive the final failure line based on the sample peak stress (red diamond).

Figure 6 displays the stress-strain curves obtained from the SST and MST testing on Berea sandstone samples. Three SST tests were first performed to determine the RSG value at the peak stress, which is used to determine the unloading points for the MST test. All three SST samples fail almost at the same RSG of -88.2, from which the unloading points in the MST test are conservatively pre-selected at the RSG of -87. The actual RSG values at the unloading points of the first two stage are -87.2 and -86.5, respectively. The MST sample fails at the RSG of -88.1.

The stress-strain curves from the MST test match very well with those form the SST tests. Figure 7 compare Mohr-Coulomb failure envelopes derived from the test results in the major (σ_1) and minor (σ_3) principal stress space, where σ_1 is the axial stress and σ_3 is the confining pressure. The failure envelope from the MST test using the RSG unloading criterion generally approximate the one from SST test. For comparison, another MST test using the MVS unloading criterion was also conducted, whose non-failure envelope is shown as the purple dash line. Its final failure envelope was obtained from the shift based on the peak stress of the last failure stage.

3.3 Application of radial strain gradient

This section demonstrates the applicability and usefulness of the RSG unloading criterion in the MST testing. Two types of rock samples were selected to conduct unconfined compression test, SST and MST tests: unconventional shale and tight sands.

The maximum volumetric strain (MVS) criterion was proposed to determine the unloading point in the MST testing [7, 8]. However, it is not always applicable, especially for brittle rocks [12]. Unconventional shale is usually very brittle and weak, making it very difficult to drill enough plugs for mechanical characterization. In the example given here, only one horizontal and two vertical plugs were successfully drilled from one-foot whole core of unconventional shale.

Unconfined compression test was first conducted on one vertical shale plug to obtain the RSG value at the peak stress. Figure 8 shows its volumetric strain continuously increase until the vertical shale plug failed suddenly. In this type of rock, the MVS criterion is not applicable. The plug fails at the RSG of about -86.8, from which the unloading points for the MST test are conservatively selected at the RSG of -75 for the other vertical plug.

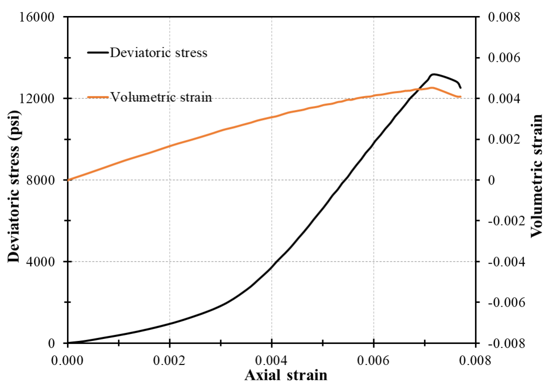


Fig. 8. Example showing the volumetric strain increases continuously till the sudden failure of one vertical shale plug during the unconfined compression test.

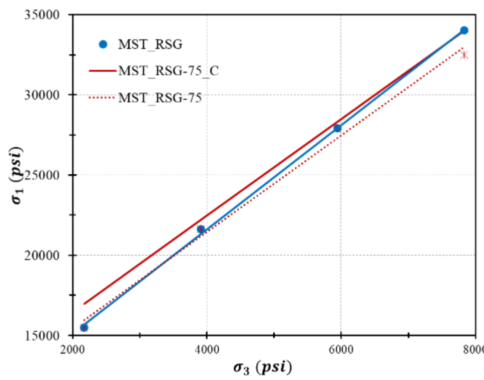


Fig. 9. Failure envelope of the vertical plug derived from the MST test using the RSG of -75 as the unloading points.

Figure 9 gives the failure envelop (blue line) of the other vertical shale plug from the MST testing using the RSG value of -75 as the unloading points. The actual values at the unloading points of the first three stages are -72.4, -75.0, -74.7, respectively. The RSG value at the peak stress of the last stage is -80.5 only, lower than that from the unconfined compression test, -86.8. Similar to the MVS criterion, the RSG method can also construct the non-failure envelop (red dot line) using the axial stress at the RSG of -75 from the last stage, and then shift to obtain the failure envelope (red solid line) based on the peak stress of the last stage. The difference between two derived failure envelopes are negligible.

The second sample is to illustrate the effectiveness of the RSG unloading criterion in the MST test by comparing with the SST test result on tight sand samples. Four plugs are drilled very closely within one block of outcrop rock, in which three are used to conduct the SST tests and one for the MST test under different confining pressures. Figure 10 compares the failure envelopes derived from the SST tests (black line) and MST test (blue line). The red solid failure envelope is shifted from the non-failure envelope (red dot line) from the same MST test result. Generally, these envelopes approximate each other well, indicating the effectiveness of the RSG criterion for enhancing the MST test. The RSG values at the peak stress of three SST tests are -88.7, -87.8, and -87.4, respectively. The unloading points were selected at the RSG of -80.0 for the first two stages of MST test. The RSG value is -87.2 when the MST sample fails at the last stage, very close to those of three SST test samples.

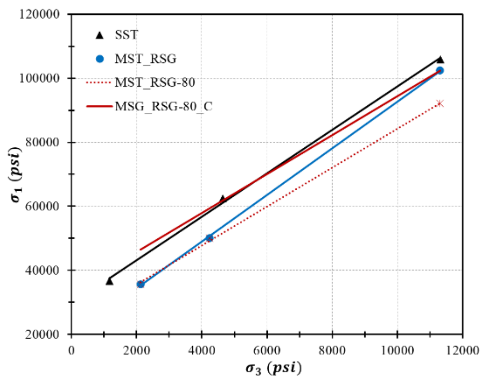


Fig. 10. Comparison of failure envelopes constructed from three SST tests (black line) and the MST test using the RSG criterion (blue line) on the first type of tight sand samples. The red line is the failure envelop derived from the same data set of MST test using the approach similar to the MVS method.

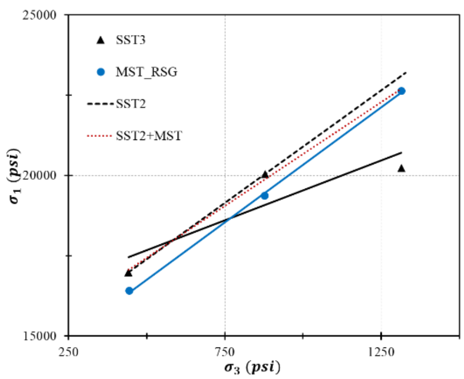


Fig. 11. Illustration of the importance of the MST test (blue line) when the SST tests fail (black line) to determine the failure envelope of the second types of tight sand samples. The black dash line is the envelope from the first two SST samples, while the red dot line is from the first two samples plus the last stage result of the MST test sample.

The MST test is very useful when the samples are limited or the SST tests fail to obtain a good failure envelope. Figure 11 illustrates a case in which the MST test but not the SST test is able to determine successfully the failure envelope. Four plugs from another type of tight sand are available for mechanical characterization. Three SST tests were originally planned and conducted to obtain the failure envelope. Results are denoted by three triangles in Fig. 11, in which a good approximation of failure envelope could not be obtained (black line). This results in the decision of performing a MST test on the remaining plug.

The unloading point for the MST test was selected at the RSG value of -86, which is based on results of three SST samples. All of them failed at the RSG of about -87.7, irrespective of the applied confining pressures. The failure envelope from the MST test (blue line) matches very well with the one from the first two SST tests (black dash line), which indicates that the third SST sample may be different in structure with other two samples. For comparison, results from the first two SST samples and the last stage of the MST sample were also used to derive the failure envelope (red dot line), which approximates well with ones of SST2 and MST_RSG.

4 Conclusions

Conventional lab techniques are difficult to apply directly for the mechanical characterization of unconventional core because of the scarcity and the anisotropy of samples. This study briefly reviewed the challenges of traditional methods including velocity anisotropy analysis and Mohr-Coulomb failure analysis for unconventional shale lab measurements, and introduced the recently developed techniques to overcome these challenges.

Application of traditional three-plug approach of velocity anisotropy analysis may be limited in unconventional shale because of the unavailability of the vertical and 45° shale plugs. The one-horizontal plug method provides an option to characterize the elastic anisotropy of unconventional shale. Results from this new technique are in good agreement with the traditional three-plugs method, confirming the feasibility and applicability of the one-horizontal plug technique in velocity anisotropy analysis.

The multi-stage triaxial test is most possibly the only option to perform the Mohr-Coulomb failure analysis when the number of test samples is limited. One key challenge in the MST is to determine precisely the unloading points. Previous unloading criteria may not always be applicable, especially for brittle rocks. The development of radial strain gradient technique enables determine quantitatively and consistently the unloading point for the MST test for any type of rocks. Results demonstrated the effectiveness and applicability of this new unloading criterion for the MST test.

Laboratory techniques introduced in this paper enable obtain the complete set of mechanical properties from limited number of shale samples, which will considerably simplify the lab measurements, lower testing cost and time and save precious core plugs for other applications.,

References

1. T.-W. Lo, K.B. Coyner, M.N. Toksoz, Earth Resources Laboratory Industry Consortia Annual Report, 1985-16, Massachusetts Institute of Technology (1985).
2. P. Armstrong, B. Chmela, K. Dodds, C. Esmersoy, B, Hornby, S. Leaney, H. Lynn, Oilfield Review, **6(4)**, 36-47 (1994).
3. R.C.K. Wong, D.R. Schmitt, D. Collis, R. Gautam, Journal of Geophysics and Engineering, **5**, 103-117. (2008).
4. M. Yenugu, Geohorizons, **15**, 15-22 (2010).
5. G. Jin, H. González-Pérez, G. Agrawal, A.Z. Ali, M.R. Khodja, SPE-170839-MS presented at the SPE Annual Technical Conference and Exhibition held in Amsterdam, The Netherlands (2014).
6. A.M. Crawford, D.A. Wylie, ARMA-0133 presented at the 28th US Symposium on Rock Mechanics (USRMS) held in Tucson, Arizona, USA (1987).
7. A. Pagoulatos, MS thesis, University of Oklahoma (2004).
8. D.T. Tran, A. Pagoulatos, C.H. Sondergeld, N.N. Canh, J.-C. Roegiers, ARMA 10-263 presented at the 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT (2010).
9. H. Youn, F. Tonon, 2010, International Journal of Rock Mechanics & Mining Sciences, **47(4)**, 678-684 (2010).
10. H. González-Pérez, S.A., Syed, G. Jin, A.A. Al Dhamen, SPE-177631-MS presented at the Abu Dhabi International Petroleum Exhibition and Conference held in Abu Dhabi, UAE (2015).
11. S.A. Syed, G. Jin, A.A. Al Dhamen, B. Saad, SPWLA-2018-FFF presented at the SPWLA 59th Annual Logging Symposium held in London, UK (2018).
12. G. Jin, S.A. Syed A.A. Al Dhamen, B. Saad, M.G. Hussain, G. Chinea, A. Nair, E. Alshaqaiti, ARMA18-1163 presented at the 52nd US Rock Mechanics and Geomechanics Symposium held in Seattle, Washington, USA (2018).
13. J.-X. Deng, G. Shi, R.-X. Liu, J. Yu, Chinese Journal of Geophysics, **47(5)**, 972-979 (2004).
14. M. Frydmann, IBP2304_10 presented at the Rio Oil & Gas Expo and Conference held in Rio de Janeiro (2010).
15. N. Banik, M. Egan, SPE-150269-MS presented at the SPE Middle East Unconventional Gas Conference and Exhibition held in Abu Dhabi, UAE (2012).
16. V.T. Ebufegha, Potter, D.K., SCA2017-095 presented at the 2017 International Symposium of the Society of Core Analysts held in Vienna, Austria (2017).
17. V.T. Ebufegha, Potter, D.K., SCA2014-011 presented at the 2014 International Symposium of the

Society of Core Analysts held in Avignon, France (2014).

18. A. Taheri, K. Tani, ISRM-ARMS5-2008-058 presented at the ISRM International Symposium - 5th Asian Rock Mechanics Symposium, Tehran, Iran (2008).
19. M.M. Kim, H.Y. Ko, Geotechnical Testing Journal, **2 (2)**, 98-105 (1979).
20. K. Kovári, A. Tisa, H.H. Einstein, J.A. Franklin, International Journal of Rock Mechanics and Mining Sciences, **20 (6)**, 285–290 (1983).