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ESTIMATION OF UNIAXIAL COMPRESSIVE STRENGTH OF COAL MEASURES OF PRANHITA-GODAVARI VALLEY, INDIA USING SONIC LOGS

Makesh Shanmukha Rao¹, Gudlavalleti Uday Bhaskar² and Shivakumar Karekal³

ABSTRACT: The Singareni Collieries Company Limited (SCCL) carries out exploration and exploitation of coal deposits of Early Permian Barakar Formation in the 350km long NNW-SSE trending Pranhita Godavari Valley located in the state of Telangana, India. Empirical studies undertaken by SCCL established an exponential relationship between Vp obtained from sonic logs and UCS determined on core samples of sandstones of from all parts of Godavari Valley. Polynomial and exponential relationships are also established between Vp and Tensile Strength (TS) and Vp and Young's Modulus (E) respectively. The empirical relationships can give a major opportunity to understand the implications of regional and local geological and geotechnical conditions on planning and managing various types of mines.

INTRODUCTION

The uniaxial unconfined compressive strength (UCS) is an important mechanical property of the rock mass having several implications in planning and designing both underground and opencast coal mines. UCS is usually determined on core samples obtained from exploratory boreholes and tested either in the field or preferably in the laboratory. McNally (1987 and 1990) has the unique distinction of establishing empirical relationships between compressional wave velocity (Vp) obtained from sonic logs and UCS determined on core samples collected from various coal mines in Australia. These studies paved the way towards generating a continuous strength profile of the interburden strata between coal seams using Vp-UCS relationships. Turvey and Hanna (1998) highlighted the importance of UCS predicted from Vp logs to evaluate the immediate roof and floor conditions of longwall mines to determine roof bolting requirements. These studies help improve productivity in difficult geomining conditions and evaluating blasting requirements and rippability in open cast mines. Studies by Payne and Ward (2002), Payne (2008) carried out at Crinum mine; Australia delineated roof strata into geomechanical units along the main gate sections which helped define mining conditions and roof support requirements. Hatherly *et al.*, (2001, 2004), Gordon (2002), Hoelle (2004) and Stam *et al.*, (2012) extended the studies to various coalfields of Australia. Hatherly (2013) reviewed the Vp-UCS empirical studies made by several workers in Australia and USA and concluded that site specific empirical estimates of Vp-UCS are established all over Australia and extensively used in all types of coal mining. Butel *et al.*, (2014) have further improved Vp-UCS correlations at Hunter Valley, Australia. Pell *et al.*, (2014) have extended the Vp-UCS empirical studies to the coalfields of New South Wales and Queensland, Australia. Vp derived UCS contour maps can be created for use in a number of important mine planning and design applications. The Vp obtained from sonic logs are therefore a very important and even a key component of roof control in underground coal mines of Australia. The experiences and benefits gained by the Australian coal mining industry clearly document a great need to extend sonic logging to other coal basins of the world to make mining safer and more productive.

FIELD STUDIES

A similar uptake of geophysical logging was made by Singareni Collieries Company Limited (SCCL) a state owned public sector carrying out detail exploration and extraction of coals of Early Permian Barakar Formation of Godavari Valley located in the state of Telangana, India (Figure 1).

SCCL introduced tri-receiver Full Waveform Sonic (FWS) logging in 2007 to obtain the complete geotechnical spectrum of the interburden strata of coals and complement the testing of core samples

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and laboratory studies. SCCL has so far carried out sonic logging in about 600 closely spaced boreholes of various exploration blocks of Godavari Valley. UCS and TS determined on core samples of 10 boreholes and YM determined on core samples of four boreholes were empirically related to V_p obtained from sonic logs.

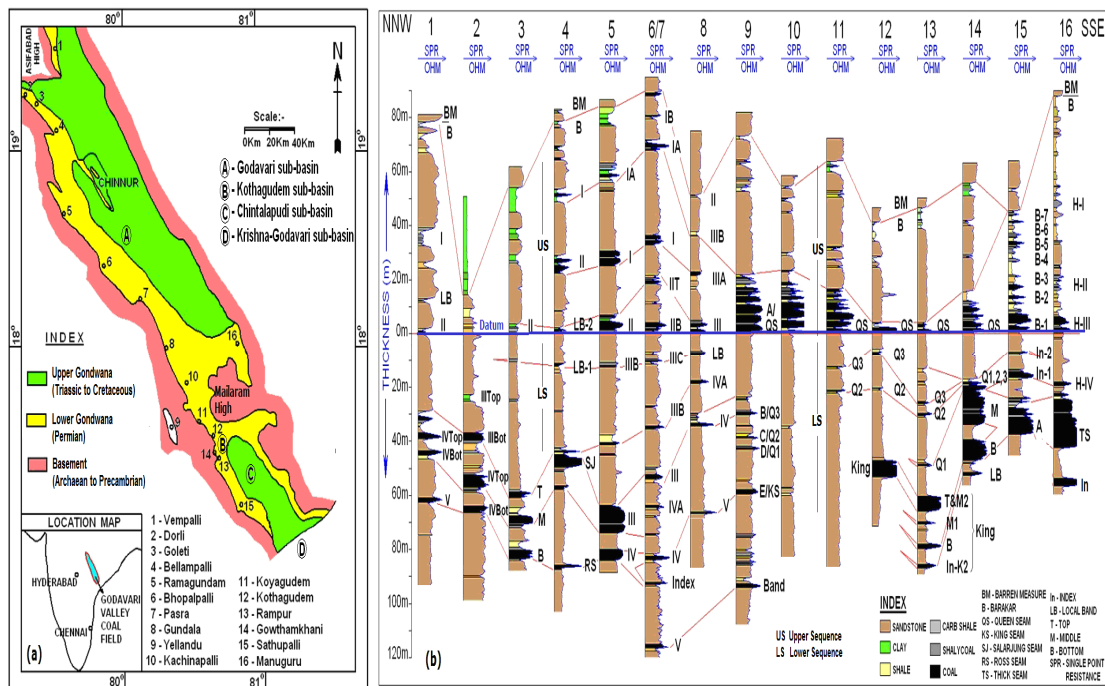


Figure 1: (a) Outline of Pranhita-Godavari Valley, (b) Nomenclature and Correlation of Coals. Queen Seam (QS) is the datum of section (locations in Figure 1, modified after Uday Bhaskar *et al.*, 2002 and 2011)

The empirical equations thus developed were further successfully tested using the subsequently generated UCS and TS values of core samples of about forty boreholes from different coal exploratory blocks of Godavari Valley. Empirical relationships established between V_p from sonic logs and UCS, TS and YM provided bed-wise geotechnical characteristics of interburden strata. The procedures followed to derive the empirical equations to estimate geotechnical properties from V_p are discussed in the following pages.

SCCL uses a tri-receiver full waveform sonic probe made by M/s Robertson Geologging, UK to generate the elastic wave velocities. This probe consists of a piezoelectric transmitter operating at 23 kHz and firing at approximately 2ms intervals. Data is received at 4μs interval by the three receivers located 20 cm apart along the body of the logging tool. The distance between the first receiver and the transmitter is 60 cm. The probe records the full sonic wave-train at all receivers simultaneously. The source/receiver pair distance is sufficiently large to ensure that first arrivals are waves refracted along the borehole walls, rather than direct rays. A water or mud-filled (and uncased) hole is required to ensure adequate acoustic coupling. Two centralizers are used to ensure the vertical movement of the probe. Propagation of sonic waves through coal measures and determination of UCS are extensively reviewed by Oyler *et al.*, (2008), Stam *et al.*, (2012) and Butel *et al.*, (2014)

WellCAD software is used to interpret the sonic data. Data from three receivers are processed to pick up the arrival times of compressional (DTP), shear (DTS) and Stoneley (DTSTN) waves through velocity/semblance analysis which are shown as dark and thick black stripes in Figure 2.

Arrival times are converted into the respective V_p , V_s and V_{stn} wave velocities, which are in turn compared with acoustic mean amplitude (AMA), single point resistance (SPR), neutron (NEUT), density (DENS), natural gamma (NGAM), short normal resistivity (SNR), self potential (SP), caliper (CALP) logs. Such an approach improves the reliability of depth estimates and geological interpretation of geophysical logs. The compressional wave velocities (V_p) obtained from the tri-receiver full waveform sonic probe (FWS) is used to empirically estimate UCS and TS of sandstones. Figure 2 also shows the comparison between geotechnical properties estimated from V_p logs and those determined on core

samples at laboratories. UCS_VP, TS_VP and YM_VP are the uniaxial compressive strength, tensile strength and Young's Modulus estimated from Vp logs respectively. UCS_SCC, TS_SCC are UCS and TS determined on core samples at SCCL laboratory respectively. UCS_CMRI and YM_CMRI are UCS and YM determined on core samples at the Central Institute of Mining and Fuel Research of India, Dhanbad, India.

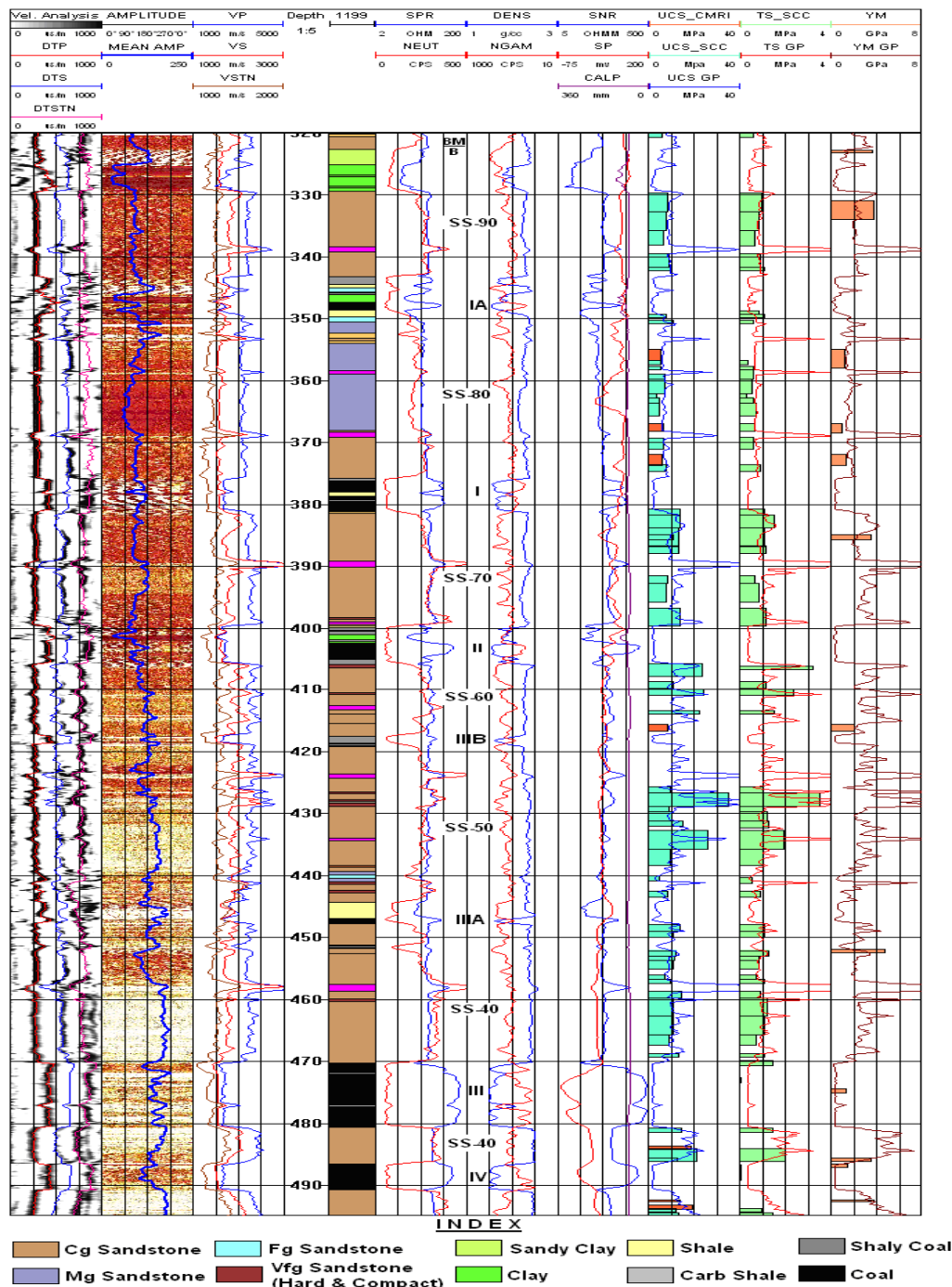


Figure 2: Interpretation of Lithologies and Geotechnical properties of Barakar Formation using Geophysical Logs, Borehole RG-1199, Adriyala Longwall Block, Ramagundam area

The empirical studies relating Vp of sonic logs and laboratory determined geotechnical properties were initiated using the data of Adriyala longwall block, Ramagundam (Figure 3). The coal-bearing Barakar Formation of Adriyala longwall block shown in Figure 2 is about 170m thick and contains seven correlatable coals. The Seam-II resolves the Barakar into lower and upper sequences. The lower sequence is mostly made up of well sorted, compact fine to coarse grained quartzose sandstones with cement. The Vp of sandstones of lower sequence is around 3750 m/s to 4000 m/s. The grey to greyish

white sandstones of upper sequence is mostly very coarse to pebbly, porous and friable whose Vp varies from 3000m/s to 3500 m/s. SS-80 and SS-30 constituting the overburden of Seam-IA and Seam-IV respectively have minimum and maximum Vp of 3000m/s and 4000 m/s respectively. The interburden strata of coals also contain 1m to 2 m thick very fine grained sandstones which are very hard, compact and silicified whose Vp varies from 4500 m/s to 6500 m/s. The determination of UCS of these sandstones is difficult because they are usually fractured and not intact.

McNally (1990) and Oyler *et al.*, (2008) concluded that the correlation of Vp of sonic logs and UCS determined on core samples depends on how well the depths and thicknesses obtained from core and geophysical logs tally with each other. They framed broad guidelines and procedures to improve the correlation between Vp and core data which are followed in the present study. Sonic data is initially correlated with geophysical logs followed by core data (Figure 2). The determination of UCS and TS on core samples was carried out by SCCL at its own laboratories. UCS and YM are also determined at Central Institute of Mines and Fuel Research of India (CIMFRI). Vp values were selected from homogenous zones of thickness greater than twice the sonic tool receiver spacing. The core samples falling close to the Vp values were selected for laboratory testing. The average of three test values of UCS, TS and YM were considered.

GEOLOGICAL SETTING

The Pranhita-Godavari Valley is a major north-northwest-south-southeast trending belt on the Precambrian platform extending over 470km in strike length from Eluru on the east coast of Andhra Pradesh in the southeast of India through the State of Telangana in the central parts to Boregaon of Maharashtra in the northwest (Figure 1). It is the largest single Gondwana basin belt of 'Crevice' type of platform rift zone containing 4,000 m to 5,000 m fluviatile sediments of Early Permian to Early Cretaceous (Ramana Murty and Parthasarathy, 1988). The major southeast part of the valley lying in the States of Telangana and Andhra Pradesh, India is called the Pranhita-Godavari Valley and the northwest part falling in the State of Maharashtra is called the Wardha Valley. The Godavari Valley having a strike length of 350km covers an area of about 17,000sq. km whose stratigraphic succession is provided by King (1881), Raja Rao (1982), Raiverman *et al.*, (1985), Ramana Murty and Madhusudan Rao (1996) and Lakshminarayana (1996). Based on geological and geophysical data the valley is divided into four sub-basins from north to south as Godavari, Kothagudem, Chintalpudi located in Telangana and Krishna-Godavari located in Andhra Pradesh (Raja Rao, 1982; Ramana Murty and Parthasarathy, 1988) (Fig. 1a). 'Mailaram High' disposed transverse (northeast-southwest) and located in the southcentral parts of the valley is a major tectonised zone of basement rocks of Middle/Upper Proterozoic Pakhal and older gneissose group and was uplifted during the Early Jurassic (Lakshminarayana, 1996). Asifabad High' is another such tectonised zone located in the northcentral parts of the valley.

In this valley, the potential coal deposits occur essentially in the Early Permian Barakar Formation and partly in the Late Permian Lower Kamthi/Raniganj Formation. These are separated by 100 m to 500 m thick non coal-bearing strata of the Barren Measure Formation mostly made up of medium to coarse grained sandstone and shales/clay. The Barakar is resting conformably over the Talchir Formation along the western margin of the valley and at a few places on the eastern margin. Structural disturbances resulted in the occurrence of Barakar in different pockets or coalbelts/coalfields. The Barakar of 250-300 m thickness is divisible into the Lower and Upper Members. The 70 m to 120 m thick Lower Member (Basal Barakar) is devoid of coal seams and consists of medium to coarse grained sandstones with lenses of conglomerates and a few shale bands. The Upper Member (coal bearing) has a maximum thickness of 200m and exhibits a cyclic repetition of sandstone, shale and coal seams (Ramana Murty and Madhusudan Rao, 1996). Workable coal seams of two metres to 30 m thickness vary in number from two to eight and on an average three to four seams occur in the sub-basins.

Rao *et al.*, (1989, 1992 & 1996) applied single point resistance and gamma logs to identify and correlate coal seams of Godavari Valley and detect geological faults within the sedimentary strata. Rao *et al.*, (1996), Uday Bhaskar (2006) and Uday Bhaskar *et al.*, (2002 & 2011) resolved the Upper Barakar into Lower and Upper sequences and established regional extent and correlation of coals from one sub-basin to the other of the valley (Figure 1b). The lower set of coals coalesce at selective portions of the valley to form major composite seams locally known as combined Ross-Salarjung-IIIa, combined IV-III-IIIa and Thick Seam and King Seam at Belampalli, Ramagundam, Manuguru and Kothagudem respectively. The top set of coals is locally by different names including Seam-II, LB, I, IA. These coals exist as independent entities in northern parts of Godavari sub-basin and coalesce at the southern parts of Godavari where the seam is referred to as Queen Seam (QS) and extends further south into Kothagudem and Chintalpudi sub-basins (Uday Bhaskar *et al.*, 2011).

UNIAXIAL COMPRESSIVE STRENGTH (UCS)

Uniaxial Compressive strength (UCS) of an intact rock sample is the amount of compressive force per unit area in a single direction required to induce failure (Figure 3). It is obtained by dividing the compressive load at failure by the cross sectional area of the sample. UCS measurements were carried out as per IS norms IS: 9143-1979 by Central Institute of Mining and Fuel Research of India (CMFRI) and also by SCCL. According to the norms the length to diameter ratio of the intact cylindrical rock sample was maintained two and compressed parallel to the longitudinal axis. The UCS of the specimen in dry condition was calculated by dividing the maximum load by original cross-sectional area. Young's Modulus of the sample was also measured simultaneously during UCS tests.

$$\text{UCS (MPa)} = P/A$$

where, P is Compressive Load at Failure (kN) and A is cross sectional area (mm) of the rock sample.

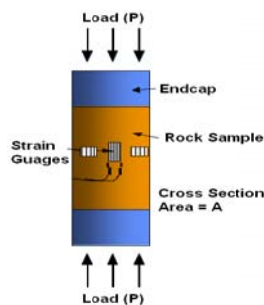


Figure 3: Schematic diagram showing test setup for measuring UCS

Empirical studies initiated with 58 data samples from four boreholes drilled at the Adriyala mine produced an exponential strength relationship which is shown in Figure 4a.

$$\text{UCS}_{\text{ADR}} = 0.0429e^{0.0016V_p} \quad R^2 = 0.82 \quad (1)$$

where UCS is in MPa and V_p in m/s.

Equation (1) was developed during the year 2007.

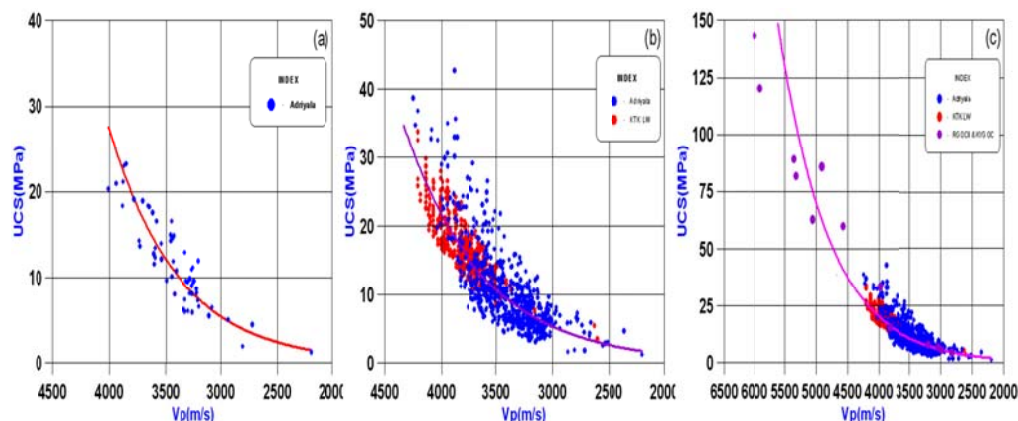


Figure 4: Exponential Curve showing the relation between log determined V_p and laboratory determined UCS values of (a) Adriyala mine of Ramagundam (b) Adriyala of Ramagundam and Kakatiyakhani longwall block of Bhopalpalli (c) Adriyala, Kakatiyakhani and high strength sandstones of Opencast-II of Ramagundam and Koyagudem blocks

Equation (1) when applied to the Adriyala boreholes produced UCS values similar to laboratory determined UCS values for V_p of 3000 m/s to 4000 m/s however log derived UCS values are very greater than the laboratory determined UCS values for V_p of 4000 m/s to 6000 m/s (see circles in Figure 5). It was therefore concluded that the empirical relationship could be improved by considering the V_p -UCS data of wider range of test data from various mining blocks.

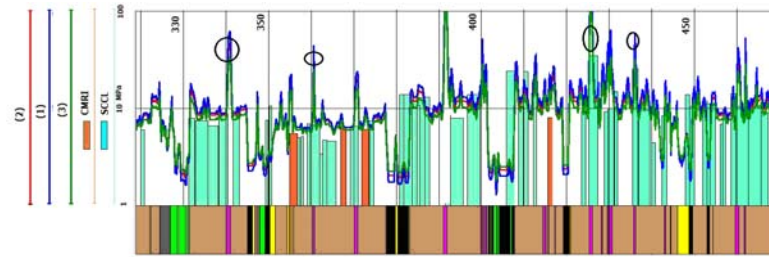


Figure 5: Comparison of Laboratory determined UCS and UCS obtained by different equations (1), (2) and (3), Borehole RG-1199 (Index in Figure 2)

Studies continued by considering 1005 data points of Kakatiyakhani and Adriyala longwall blocks of Bhopalpalli and Ramagundam areas mines respectively (Figure 4b). This combined data set produced the exponential relationship:

$$\text{UCS_ADTK} = 0.0798e^{0.0014Vp} \quad R^2 = 0.72 \quad (2)$$

where UCS is in MPa and Vp in m/s.

Equation (2) was developed in the year 2010 (Figure 3b).

Equation (1) and (2) when tested produced UCS values similar to laboratory determined UCS values for Vp of 3000 m/s to 4000 m/s (Figure 5). Equation (2) is close to the laboratory determined UCS values for Vp of 4000 m/s to 6000 m/s but the UCS was still greater than laboratory determined UCS values overall. Studies were continued by generating some more data of Vp of 4000 m/s to 6000 m/s from the Opencast-II of Ramagundam and Koyagudem mining blocks to produce the following exponential relationship:

$$\text{UCS_ALL} = 0.1401e^{0.0012Vp} \quad R^2 = 0.73 \quad (3)$$

where UCS is in MPa and Vp in m/s.

Equation (3) as shown in Figure 3c was developed during 2012.

Equation (3) incorporating Vp up to 6000 m/s fits quite well with the laboratory data and performs better than (1) and (2) at Vp range of 4000 m/s to 6000m/s. Results thus reflect that the wide range of data increases the accuracy of cross correlation studies. Equation (3) is good enough to predict the UCS values of various exploratory blocks of SCCL.

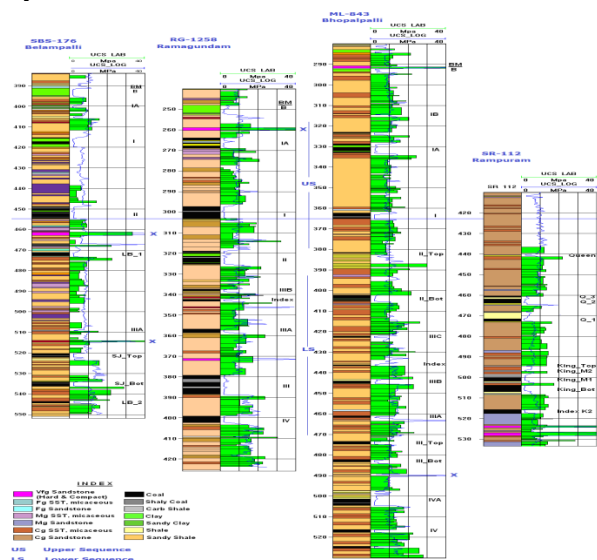


Figure 6: Comparison of Vp derived and Laboratory determined UCS values of various blocks

Figure 6 displays the UCS profile derived using equation (3) and laboratory determined UCS values of various exploratory blocks. It is concluded that the data from geophysics and laboratory tally very well with each other.

Figure 6 indicates a broad consistency in the UCS values of sandstones from one block to another of the various Godavari sub-basins. The UCS of sandstones of the upper sequence (US) are around 10 MPa and those of the lower sequence (LS) are 10 MPa to 30 MPa. 'X' in Figure 6 are very fine grained sandstones silicified whose UCS ranges from 40 MPa to 100 MPa. The Figure can not depict their true values because the upper limit is scaled to 40 MPa.

The fractures in sandstones would have a tendency of holding more water due to which Vp decreases. Accordingly, the Vp derived UCS values will be less than the UCS determined on dry samples as observed in the case of borehole SR 112 of Rampur block shown in Figure 6. In this case the laboratory determined UCS is around 10 MPa to 15 MPa against the Vp derived UCS of around 6 MPa around the depths of 470 m to 490 m of SR112. UCS determined on dry core samples would be greater than the UCS of sandstones saturated at insitu conditions. Figure 7 shows the core samples of fractured sandstones at depths of 487m. The impact of fracturing on UCS values is also well depicted in the UCS map shown in Figure 8.

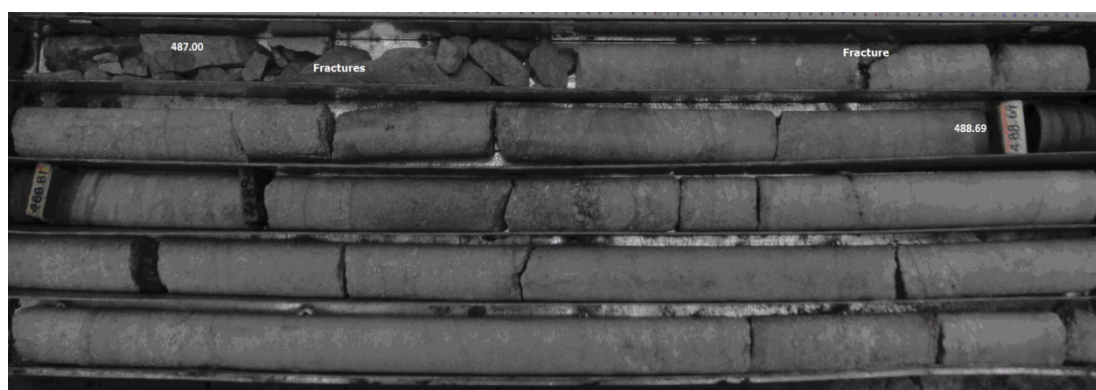


Figure 7: Sandstones fractured around 487m depth, Borehole SR 112, Rampur Block

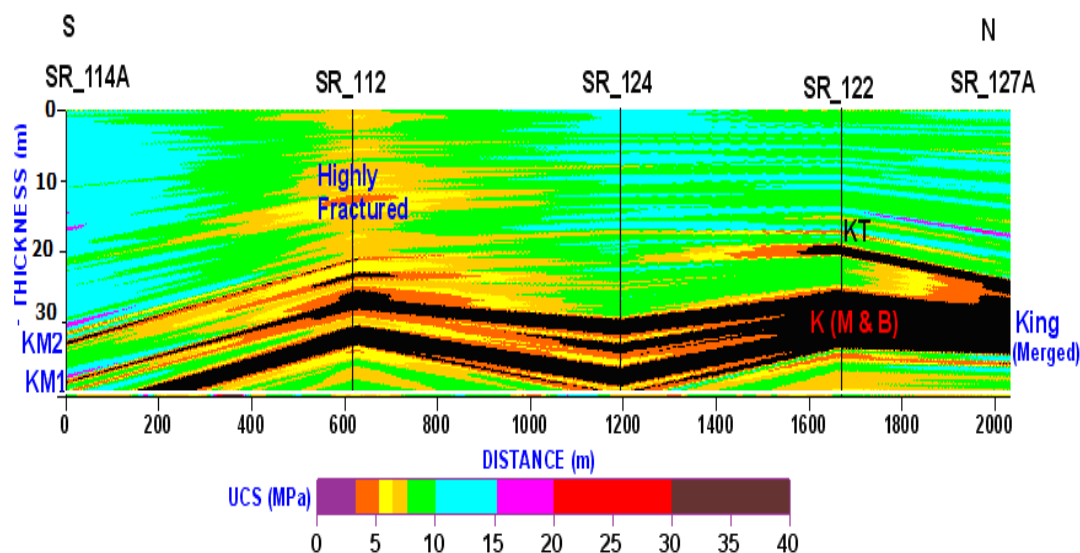


Figure 8: UCS map of overburden strata of King Seam, Rampuram Block. '0' is the datum

Figure 8 displays the UCS map of overburden strata of the King Seam of Rampuram block including the impact of fracturing on UCS values. Overburden strata of King Seam have an UCS of 10 MPa to 15 MPa which is reduced to 5 MPa to 7.5 MPa at SR-112, and it is concluded that this is due to the saturation of fractured sandstones with water (Figure 7). Vp logs document such sensitive structural features influencing the strength of rocks whereas the UCS determined on dry core samples might not record the

impact of insitu conditions. Differences between the laboratory determined and Vp derived UCS can therefore be visualised as differences in laboratory and insitu conditions.

Figures 9 and 10 enable classification of the Permian sequences based on the UCS values. The Middle Permian Barren Measure having a thickness of 200 m to 250 m is resolved into Upper and Lower sequences dominated by UCS values of 3 MPa to 5 MPa and 5 MPa to 10 MPa respectively. Early Permian coal-bearing Barakar Formation of 200 m thickness is also resolved into Upper and Lower sequences dominated by UCS values of 5 MPa to 15 MPa and 15 MPa to 20 MPa respectively. Sandstones of Barren Measure are poorly sorted, less compact and less cemented and friable than the sandstones of the Barakar. Sandstones of the Barren Measure are also more kaolinised and are prone to weathering into clay bearing rocks which seem to influence UCS values. Competency of Permian sequences increases in the descending order. Figure 8 also indicates regional consistency and near parallelism of the various beds making up the Permian sequences. UCS maps can be very useful to plan and manage the opencast mines.

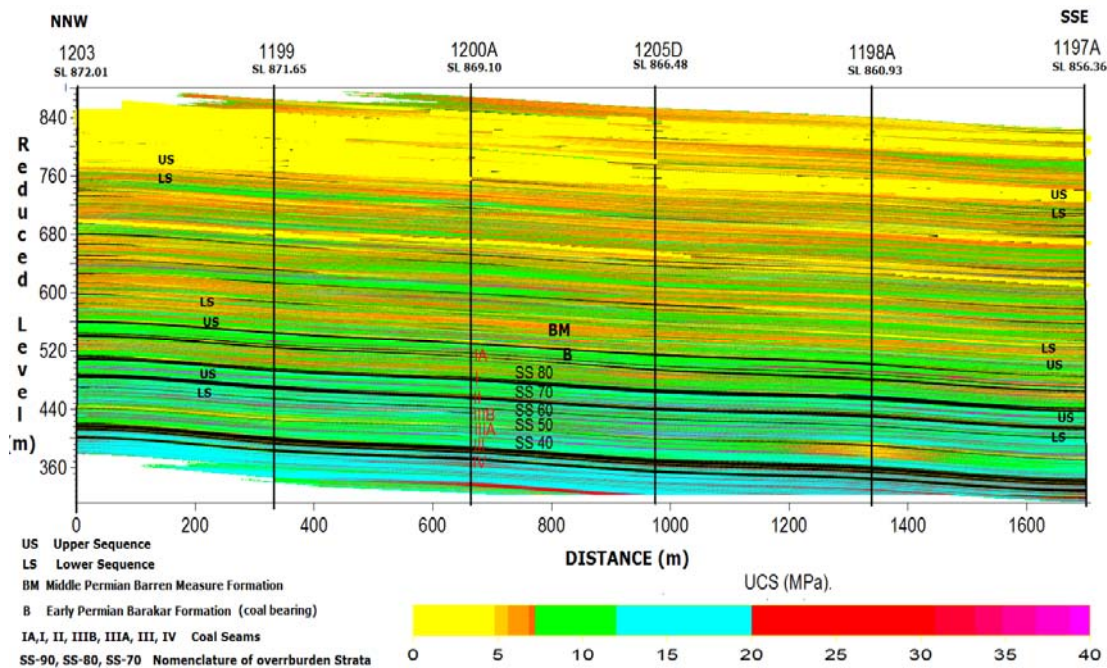


Figure 9: Vp derived UCS Map of Permian Sequences of Adriyala Longwall block, Ramagundam

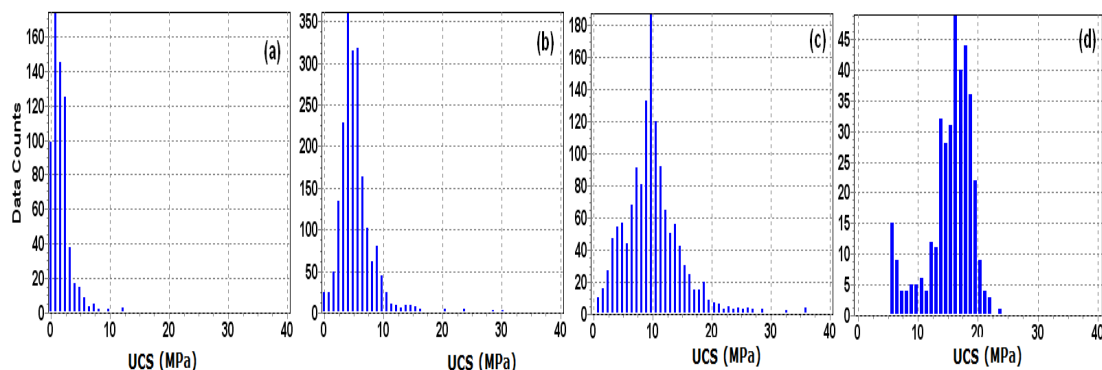


Figure 10: Classification of Permian Sequences on the basis of UCS values, Adriyala Longwall block, Ramagundam. (a) and (b) Upper and Lower sequences of Barren Measure. (c) and (d) Upper and Lower sequences of Barakar Formation

TENSILE STRENGTH (TS)

Tensile Strength is the maximum resistance offered by the rock to tensile loading. Due to practical difficulties tensile strength was determined by the indirect Brazilian method, wherein the cylindrical rock

sample was placed horizontally between the bearing flat platens of a testing machine and subjected to failure by compressional loading as shown (Figure 11). TS measurements were carried out as per IS norms IS: 10082-1981 by CMFRI and also by SCCL. According to the norms the length to diameter ratio of the intact cylindrical rock sample was maintained 0.5. Tensile Strength was calculated by the following formula.

$$TS \text{ (MPa)} = 0.636 \times P/Dt$$

Where, P is load at failure (kN), D is diameter (mm) of the rock sample and t is thickness (mm) of the rock sample.

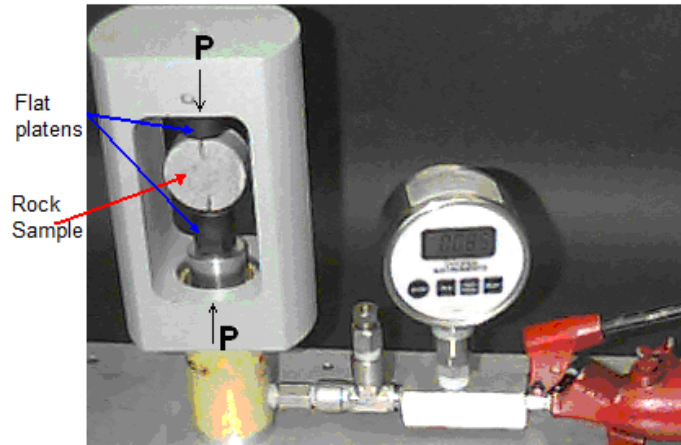


Figure 11: Testing setup for measuring Tensile Strength

Figure 12(a) shows the polynomial relation between V_p from sonic logs and laboratory determined Tensile Strength. The Figure 12(b) shows the linear relationship between laboratory determined TS and UCS. The respective equations are as follows. 762 data points are considered in the study.

$$TS = 9.1109E-007V_p^2 - 0.0047V_p + 6.2757 \quad R^2 = 0.76 \quad (4)$$

$$UCS = 9.5729 \times TS \quad R^2 = 0.95 \quad (5)$$

where TS and UCS are in MPa and V_p is in m/s.

Equations (4) and (5) give similar values of Tensile Strength.

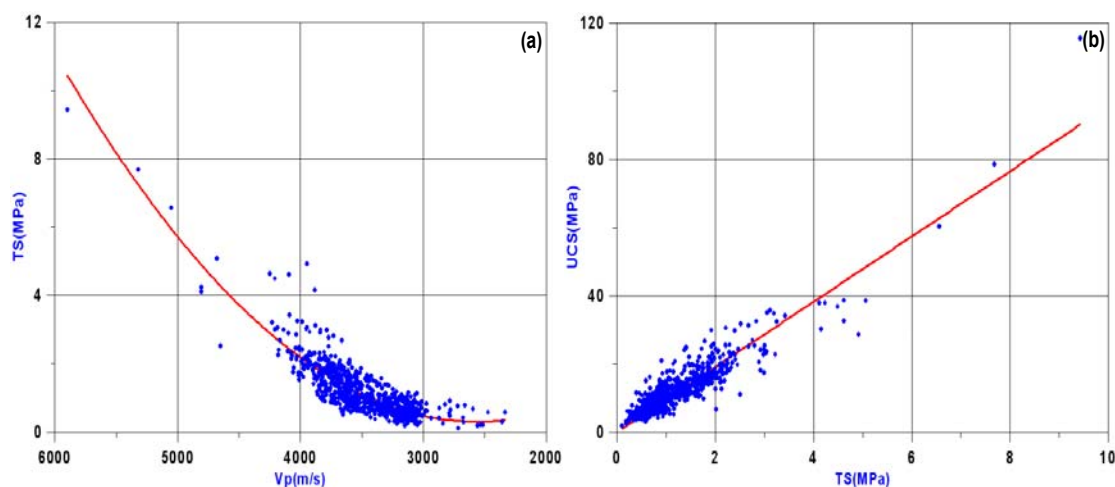


Figure 12: (a) Sonic P-wave Velocity (V_p) versus Laboratory determined TS of Sandstones. (b) Laboratory determined UCS versus Laboratory determined TS of sandstones

Figure 2 shows that the laboratory determined and V_p derived values of Tensile Strength tally very well with each other.

YOUNG'S MODULUS (E)

Young's modulus is the measure of change in strain parallel and normal to the direction of the applied stress. Measurement was conducted by applying load on the specimen continuously at a constant stress rate to a certain extent and then unloading in the same stress rate. The applied load and the resultant axial and circumferential strains or deformations were recorded through electronic load cell, LVDT's (Linear Variable Differential Transformer) and Data Logger connected with the computer during the investigation. Young's modulus was measured as detailed in Figure 13. This modulus was measured simultaneously with the UCS tests as per IS norms IS: 9221-1979 by Central Institute of Mining and Fuel Research of India.

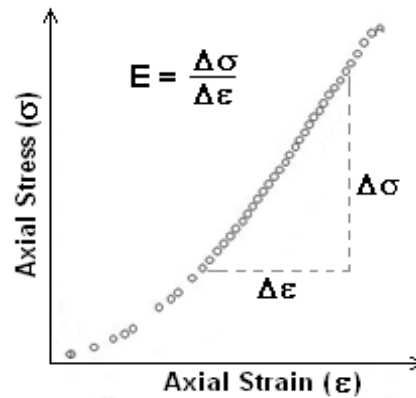


Figure 13: Determination of Young's Modulus (E) from stress and strain graph

Figure 14(a) shows the exponential relation between Vp from sonic logs and laboratory determined Young's Modulus under loading conditions. Figure 14(b) shows the linear relationship between laboratory determined Young's Modulus (E) and laboratory determined UCS values. 135 data points from Adriyala and Kakatiyakhani Longwall Block (Bhopalpalli) are considered. The respective equations are as follows:

$$E = 0.0069e^{0.0017V_p} \quad R^2 = 0.73 \quad (6)$$

$$E = 0.2442 * UCS + 0.0205 \quad R^2 = 0.79 \quad (7)$$

Where Young's Modulus (E) is in GPa, UCS is in MPa and Vp in m/s.

Equations (6) and (7) give similar values of Young's Modulus.

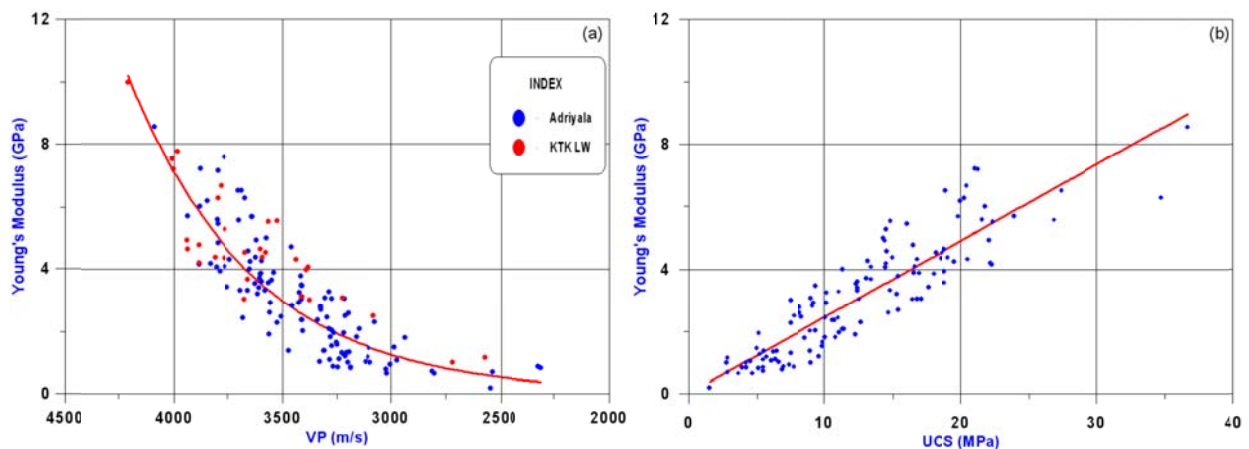


Figure 14: (a) P-wave velocity (Vp) versus Laboratory determined Young's Modulus (GPa). (b) Laboratory determined Young's Modulus (GPa) versus Laboratory determined UCS (MPa)

Figure 2 shows that the laboratory determined and Vp derived values of Young's Modulus tally very well with each other.

CONCLUSIONS

Uniaxial unconfined compressive strength (UCS) can now be empirically estimated from sonic geophysical logs and can be used in planning and designing both underground and opencast coal mines. It is found that the laboratory determination of UCS and TS being a regular affair offers a continuous scope to monitor and improve the relationships. A continuous down-hole profile of UCS is obtained from the Vp logs providing a visualisation of strata strength. Data from multiples boreholes can be modelled to provide a full UCS picture of the behaviour of the strata along strike and dip. Geological and geotechnical layering and the areas which have particular geotechnical significance are identified. These models provide better strata characterisation than that based on point-wise geotechnical testing of core samples. The generation of these models give a major opportunity for geological and geotechnical characterisation on local to regional scales to understand the implications of regional and local geological conditions on mine planning. Vp and UCS maps of interburden strata of coals bringing out the spatial distribution of weak and fissile horizons and the thick strong beds that can cause periodic weighting.

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