J. Ind. Geophys. Union (July 2015)
v.19, no.3, pp:270-281

Geological and Geotechnical Characterisation Using Geophysical Logs – An Example from Adriyala Longwall Project of Singareni Collieries, Telangana, India

M. Shanmukha Rao[1] and G. Uday Bhaskar*[2]

[1]Superintending Geophysicist, Exploration Division, SCCL, Kothagudem, ms_rao_gp@yahoo.com
[2] DGM (Geophysics), Exploration Division, SCCL, Kothagudem, uday_bhaskar_g@yahoo.com
*Corresponding Author: uday_bhaskar_g@yahoo.com

ABSTRACT

The studies conducted at Adriyala longwall block of Singareni Collieries Company Limited (SCCL) in the state of Telangana, India conclude that geophysical logs comprising electrical, density, neutron, caliper, Full Waveform Sonic (FWS) and acoustic image probes can provide reliable geological and geotechnical models required for longwall mining. The basic lithological details, sedimentary features and associated geotechnical risks are interpreted using these logs. The P wave velocities obtained from sonic logs are correlated with the lab determined strength parameters such as uniaxial compressive strength (UCS), Tensile Strength (TS) and Young's Modulus. The empirical equations provided a means to construct UCS map of interburden strata of coal seams from sonic data which optimised depending on available core data. The Geophysical Strata Rating (GSR) similar to Coal Mines Roof Rating (CMRR) and Rock Mass Rating (RMR) has also been applied to assess the competency of interburden strata right at the exploration stage itself. The insitu stress directions and master cleats orientation are determined from the acoustic image logs. UCS and GSR maps prepared from geological and geophysical inputs provided an effective means to analyse the competency of immediate overburden of 23m to 28m (SS-80) of Seam-I, which is considered for longwall mining.

Seam-I was deposited in stable conditions resulting in uniform thickness of 6m of coal including that of 0.40m thick dirt band in the middle. Weak bed in the middle of Seam-I and intertonguing of clay of 1.20m thickness with sandstone along the immediate roof influence working sections and roof support system. Sandstones comprising the overburden strata of coal are very thick massive beds whose UCS and GSR ranges of 6MPa to 8MPa and 30% to 45% classify them as low strength and fair rocks respectively. These massive beds also contain thin to thick beds of good (45% to 60% GSR) and very good (60% to 80% GSR) rocks along with poor rocks having GSR of 15% to 30% at places. Very thick massive beds can create conditions of heavy periodic weighting during longwall extraction while the thin beds contained by it can act as separation planes and reduce the effective thickness of sandstone that could otherwise contribute to periodic weighting. GSR provides both petrophysical and geotechnical models where as the UCS maps provide details of intact strength only.

Back analysis of behaviour of strata will validate and refine developing predictive models and appropriate strata control strategies to be applied at Adriyala and other mines and also for multiseam extraction.

INTRODUCTION

Longwall mining depends on good understanding of mode and mechanism of subsidence (goafing) of strata during the extraction of coals. Green and Ward (2002) remarked that subsidence takes place in different forms at three different depth ranges during the longwall mining. The zone-1, lying immediately above the seam collapses as broken rock into the mining void and eventually fills up the free space through bulking. The height of zone-1 is generally taken as nine times the mined thickness but can be less in stronger strata. The various beds of zone-1 cantilever into the free space and are subject to unrestrained release under gravitational loading, with detachment occurring along planes of weakness. The presence of defined weak planes would thus appear to determine the goafing behavior of zone-1. The goafing behavior would also depend on combinations of several factors such as bed thickness, strength homogeneity, and presence of strong and weak beds and the juxtaposition of beds of contrasting character. Hanson et al. (2005) concluded that detailed geological and geotechnical studies of zone-1 form the first step towards understanding the caving/goafing mechanism and designing suitable roof support and strata management systems. The strata of middle zone-2 are not broken up but tend to incur physical dislocation with induced fractures or bed separation. The height of zone-2 is usually taken as 30 times the mined height. The strata of upper zone-3, lying above zone-2 tend to subside as an intact block without damage. The goafing behavior is different in each of these zones and different predictive parameters would apply in each case. The uniaxial compressive strength (UCS) is considered an important means to define the strength of rocks and roof support systems.

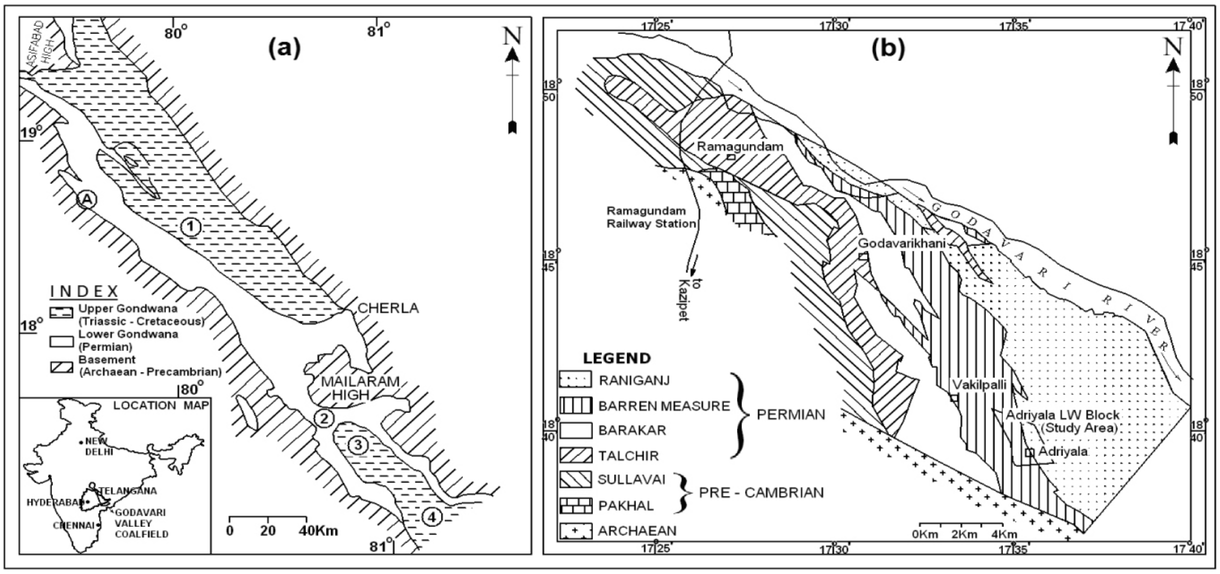

Figure 1. (a) Pranhita-Godavari Valley and its Sub-Basins. (1) Godavari Sub-Basin, (2) Kothagudem Sub-Basin, (3) Chintalpudi Sub-Basin and (4) Krishna-Godavari Sub-Basin and (A) Ramagundam Coalbelt (b) Ramagundam Coalbelt and Adriyala Longwall Project.

Molinda and Mark (1994) and Mark and Molinda (2005) however concluded that rocks of contrasting geological nature can still have similar UCS and one would need to consider several geological and geotechnical aspects to define the overall competency and strength of rocks to make underground mining more safe and productive. They introduced the concept of Coal Mines Roof Rating (CMRR), which is similar to Rock Mass Rating (RMR) of Bieniawski (1989) to an extent. CMRR/RMR studies are now routinely conducted in underground mines and on core samples obtained from exploratory boreholes. Mark and Molinda (2003) and Calleja (2006 and 2008) used sonic logs to estimate UCS to compute CMRR from core samples of exploratory wells. Frith and Colwell (2008) described the importance of geotechnical data during various stages of longwall mining. In India the RMR or CMRR studies are usually carried out in underground mines but not so at the exploration stage. The UCS and/ or Rock Quality Designation (RQD) are used to assess the competency of rocks at the exploration stage. Hatherly et al. (2001) remarked that conventional methods of laboratory testing of cores are usually prone to sampling problems and misrepresentation of actual conditions insitu. The cost of coring and rock testing makes it impractical to drill enough geotechnical holes to sample the full range of variability present within the rock mass. Hatherly et al. (2008) used density, natural gamma and sonic logs to define the competency of rocks in terms of Geophysical Strata Rating (GSR) similar to CMRR/RMR. CMRR and GSR generally deliver values between 10 and 100 depending on overall quality of the strata. GSR can be determined at exploration stage thereby enabling its evaluation during mining. Hatherly et al. (2009) also concluded that GSR formulation and Q-value scheme developed by Barton (2002 and 2006) are similar to each other. Hatherly et al. (2009) demonstrated that GSR evaluates the competency of overburden strata of coals in a manner better than UCS models alone. Colwell and Frith (2006) also concluded that UCS might not be a good indicator of roof stability in all the areas of longwall mining. Medhurst et al. (2014) classified the rocks on the basis of GSR and went on to establish the interrelationship between GSR characterisation, longwall monitoring analysis and caving behaviour.

The layout of longwall panels also requires information of major and minor principal horizontal stress directions, magnitude, the predominant joint and cleat orientation, and geological structures because poor panel layouts lead to gate end stress concentrations, roof falls and loss of production (Hanson et al., 2005). The acoustic scanner image logging (Borehole Televiewer) enables measuring the directions of horizontal stress by identifying the breakout of borehole walls and orientation of cleats, joints and bedding planes. Borehole breakouts form as a result of the interaction of stresses induced by drilling and the existing stress regime of the country rock. Small brittle fractures occur in the borehole around a rotating bit along the minimum horizontal stress direction because of the unequal horizontal stress regime in the formation. Borehole breakouts provide greater number of measurements, both at different depths and spatial distribution, than other techniques such as overcoring or hydraulic fracturing (MacGregor et al., 2003). The standard suite of geophysical logs, along with sonic and acoustic logs provide all the basic inputs to plan the longwall panels and mines. Pell et al. (2014) also used sonic and acoustic logs to establish the geotechnical characters, stress and joint pattern of coalfields of New South Wales and Queensland, Australia.

The present paper has considered all these aspects and applied geophysical logs to assess the caving zone (zone-1) along one of the proposed longwall panels of Adriyala block of Singareni Collieries Company Limited (SCCL) located in the state of Telangana, India.

GEOLOGICAL SETTINGS

SCCL carries out exploration and extraction of coal deposits of Pranhita Godavari Valley, which is a major NNW-SSE trending belt on the pre-Cambrian platform extending over 470 km in strike length from Eluru on the east coast of Andhra Pradesh in the SE through the state of Telangana in the central parts up to Boregaon of Maharashtra in the NW (Fig. 1a). It is a 'Crevice' type of platform rift zone containing 4,000 m to 5,000 m fluviatile sediments of Early

Table 1. Generalised Lithostratigraphy of Pranhita-Godavari Valley

Age	Group	Formation	General Lithology	Thickness (m)
Holocene		Recent	Alluvial sands and clays ………………Unconformity……………	25+
Upper Cretaceous		Deccan Trap	Basaltic flows ………………Unconformity………………	65
Upper Jurassic to Lower Cretaceous	UPPER GONDWANA	Chikiala/ Gangapur	Brownish red & yellow to buff ferruginous sandstone with conglomerates & a few clay beds. …………………Unconformity……………	300
Lower to Early part of Middle Jurassic		Kota	Pale brown sandstones with red clays with a few thin persistent limestone bands and local carbonaceous matter. …………………Unconformity……	675
Middle to Upper Triassic		Maleri	Alternate sandstone and clay beds. Lime Pellet rocks, coarse, buff sandstones with clay galls.(Dharmaram and Maleri) Coarse-grained sandstone with clay galls and a few biozene clay intercalations (Bhimaram) and soft red mudstone with calcareous bands (Yerrapalli biozone)	1000
Lower Triassic		Kamthi	Coarse-grained, ferruginous, sandstone with clay clasts and pebbles and subordinate violet cherty siltstones and pebble beds.	500
Upper Permian	LOWER GONDWANA	Raniganj	Alternating sequence of medium grained white to greenish grey white sandstone and buff to greenish grey clays. Medium to coarse-grained greyish white calcareous sandstone with a few coal seams	1000
Middle Permian		Barren Measure	Medium to coarse-grained greyish white feldspathic sandstone with subordinate variegated clays & micaceous siltstone.	450
Upper part of Lower Permian		Barakar	Upper Member: Coarse-grained white sandstone with subordinate shales & coal seams.	
			Lower Member: Coarse-grained sandstone with lenses of conglomerates, subordinate shales/clays and few thin bands of coal.	300
Lower Permian		Talchir	Fine grained, sandstones splintery green clays / shales chocolate coloured clays, pebbles beds and tillite. ………………Unconformity……………	350
Upper Pre-Cambrian		Sullavai	Medium to coarse-grained white to brick red sandstones, at places quartzitic and mottled shales.	545
Lower Pre-Cambrian		Pakhal	Greyish white to buff colored shales and phyillites. ……………………Unconformity…………	3335
Archaean		-	Granites, banded gneisses hornblende gneisses, quartz magnetite, schist, biotite schist, quartz and pegmatite veins.	

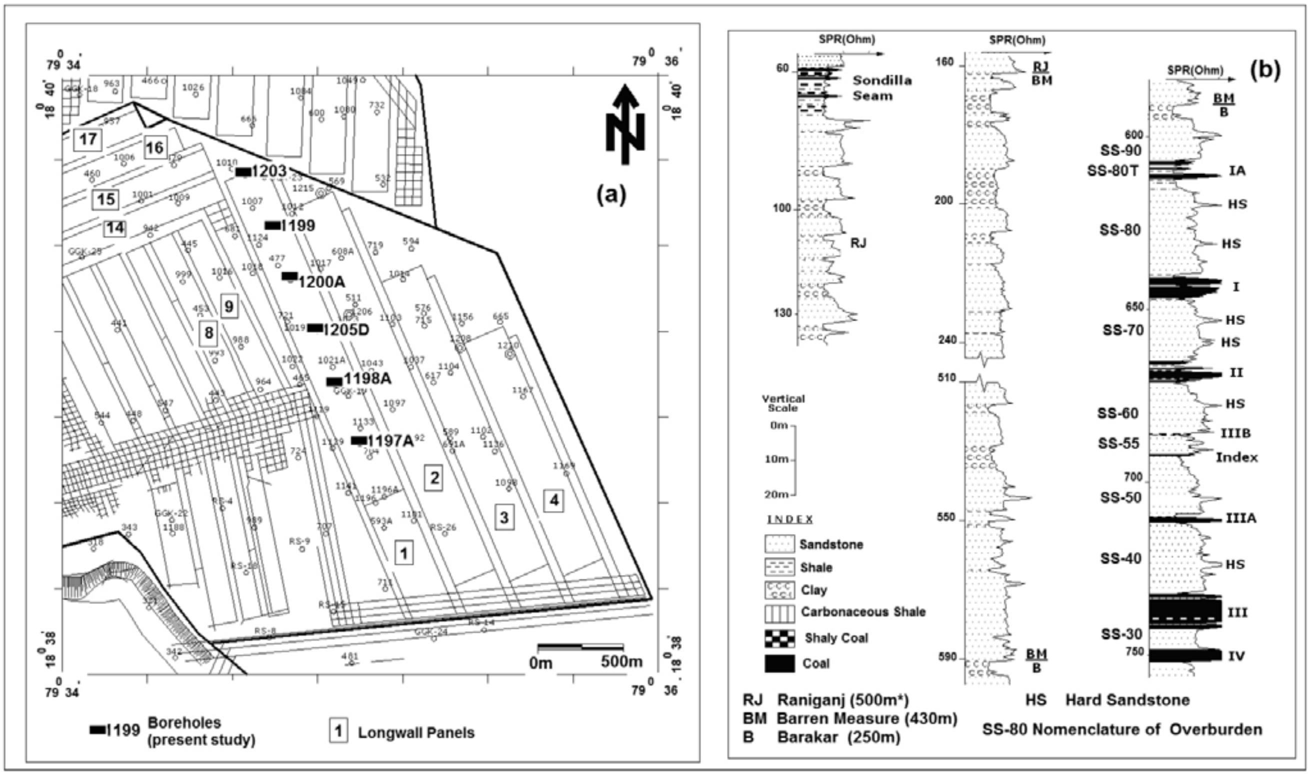

Figure 2. (a) Location Map of boreholes and longwall panels, Adriyala longwall project, (b) Permian Lithostratigraphic Succession of Adriyala Longwall Project constructed using Single Point Resistance Logs.

Permian to Early Cretaceous and is considered the largest single Gondwana basin belt in India. Based on geological and geophysical data the valley is divided into four sub-basins from north to south as Godavari, Kothagudem, Chintalpudi and Krishna-Godavari (Ramana Murty and Parthasarathy, 1988). Table-1 describes the generalised stratigraphy of the valley. The Early Permian Barakar Formation contains seven to ten correlatable coals of 1m to 22m thickness and the Late Permian Raniganj Formation contains intercalated carbonaceous horizons. Uday Bhaskar et al. (2002 and 2011) established the regional extent and correlation of coals from one sub-basin to the other of the valley.

The Adriyala longwall project lies in the southern part of Ramagundam coalbelt, located on the western margin of Godavari sub-basin of Pranhita Godavari Valley (Figs 1 and 2). The Adriyala longwall project is bounded between latitudes 18º38′ and 18º40′ and between longitudes 79º34′ and 79º36′ spanning an area of 4.635 sq km extending over a strike length of 2.75 km (Fig. 2a). Longwall panels of 2.60 km length are being planned in Adriyala block to produce 2mt of coal per annum from the top section of 6m thick coal locally known as Seam-I (Fig.2b). The immediate overburden strata of Seam-I is around 23m to 28m thick mostly containing medium grain to coarse grained sandstones and is called SS-80.

The Adriyala longwall project is mostly covered by soil followed by Middle Permian Barren Measures over most of the area and Late Permian Raniganj Formation along the dip side. The Adriyala block contains seven regionally persistent coal seams locally known as IV, III, IIIA, IIIB, II, I and IA in ascending order within the Upper Barakar Formation of 160 m thickness (Fig. 2b). The Seam-II and Seam-IA are further resolved into bottom and top sections. The Index band lying below Seam-IIIB has a tendency of laterally grading to surrounding sandstones in several parts of the block. The Barakar comprises white to greyish white, coarse to medium grained feldspathic sandstones interbedded with shale and coal horizons. The Barakar is overlain by ~430m of Barren Measure sediments made up of green to greenish grey, coarse to very coarse grained feldspathic and kaolinised sandstones intercalated with shales and variegated clays. The Raniganj Formation consists of medium to coarse grained greyish-white sandstones, clays and 16m thick intercalated carbonaceous horizon locally known as Sondilla Seam.

The general trend of the coal measures is north-northwest (NNW) to south-southeast (SSE) direction with slight swings at places with northeasterly dips. The gradient of the coal seams in the northern part of the block is 1 in 6 to 1 in 6.8 and flattens in the central part to 1 in 8 then the gradient gradually becoming steeper in the southern part.

METHOD AND RESULTS

Geophysical Logs

Extensive drilling followed by geophysical logging established geological and geotechnical characters of the interburden strata of Early Permian coals of Barakar Formation of Adriyala block. The geophysical logs of six boreholes located along the proposed longwall panel are considered for the present study (Fig. 2a). The geophysical logging was carried out by deploying the geophysical logging equipment of Ms Robertson Geologging, Deganby, UK whose probes are called SPRN, GLDS, HRAT and TRSS. The SPRN probe contains single point resistance (SPR), short normal resistivity (SNR), self potential (SP), single detector of neutron and ^{241}Am-Be radioactive source of 37GBq strength. The GLDS probe contains far and near density detectors to compute bulk density (DENS), natural gamma (NGAM), focussed resistivity (FRES) and caliper (CALP) and ^{137}Cs of 3.70GBq strength is the radioactivity source. The HRAT is the high resolution acoustic televiewer imaging probe and TRSS is the tri-receiver monopole full waveform sonic probe. The interpretation of geophysical logs was carried out using the standard procedures and the various modules of WellCad software. The interpretation of geophysical logs was also reviewed and correlated with the available core data. Figs 3 and 4 show the basis of geophysical log interpretation. and electrosequential analysis of overburden strata of Seam-I considered for longwall mining. Hatherly et al. (2008) provided the guidelines to compute GSR from geophysical logs.

Coals are identified by high resistance/resistivity, low density of 1.40 to 1.70g/cc, low neutron and natural gamma values of about 50 cps and 30 to 50 cps respectively (Fig. 3). The P (Vp) and Stoneley (Vstn) wave velocities of coals are around 2300m/s and 1200m/s respectively. Coals and clays are characterised by the absence of propagation of shear wave (Vs). The Vp, Vs and Vstn of very coarse to medium grained grey-white sandstones are around 3000m/s to 3500m/s, 1500m/s to 1750m/s and 1200m/s to 1600m/s respectively and bulk density of 2.30g/cc to 2.50g/cc. Hard and strong sandstones marked 'HS' are characterised by high resistance/resistivity, neutron (400cps to 500cps), density of 2.65g/cc to 2.80g/cc and Vp of 4500m/s to 5500m/s. Fine grained sandstones, sandy shales, shales and clays show low neutron (50cps to 125 cps) and high gamma (200 cps to 300 cps) values and densities of 2.20g/cc to 2.50g/cc. Some of the clays and shales are prone to caving as observed from the increase in borehole diameter on caliper logs and are considered weak planes and marked 'WP' in Figs 3 and 4.

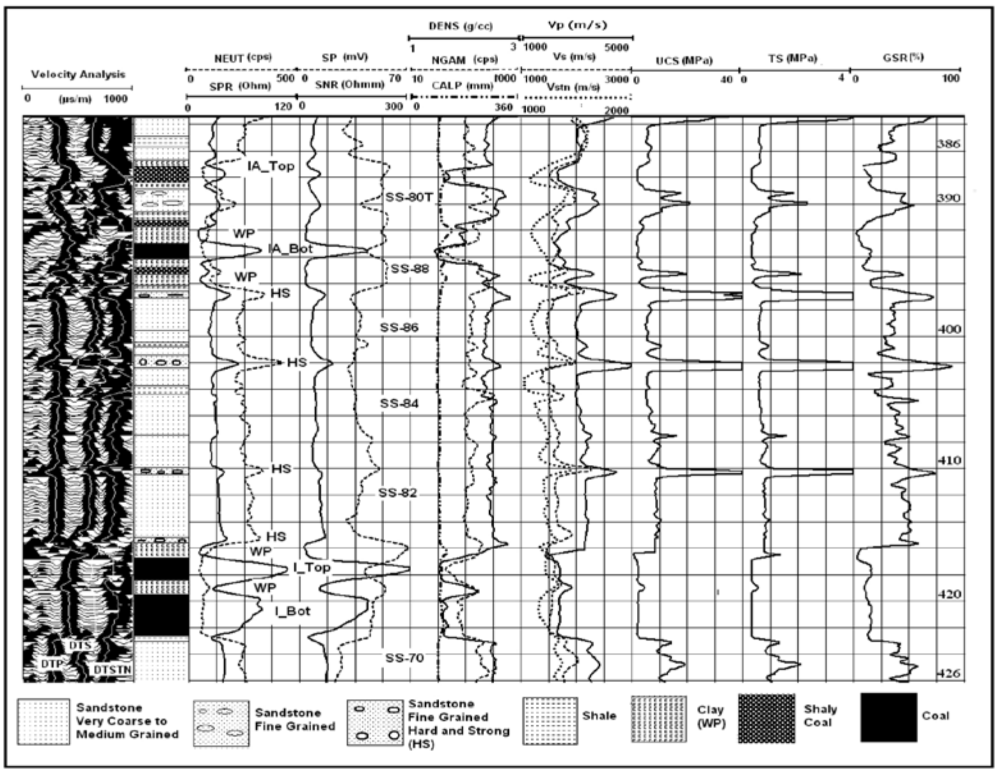

Figure 3. Interpretation of basic lithological details and strength parameters using geophysical logs, Borehole 1197A (location in Fig.2a).

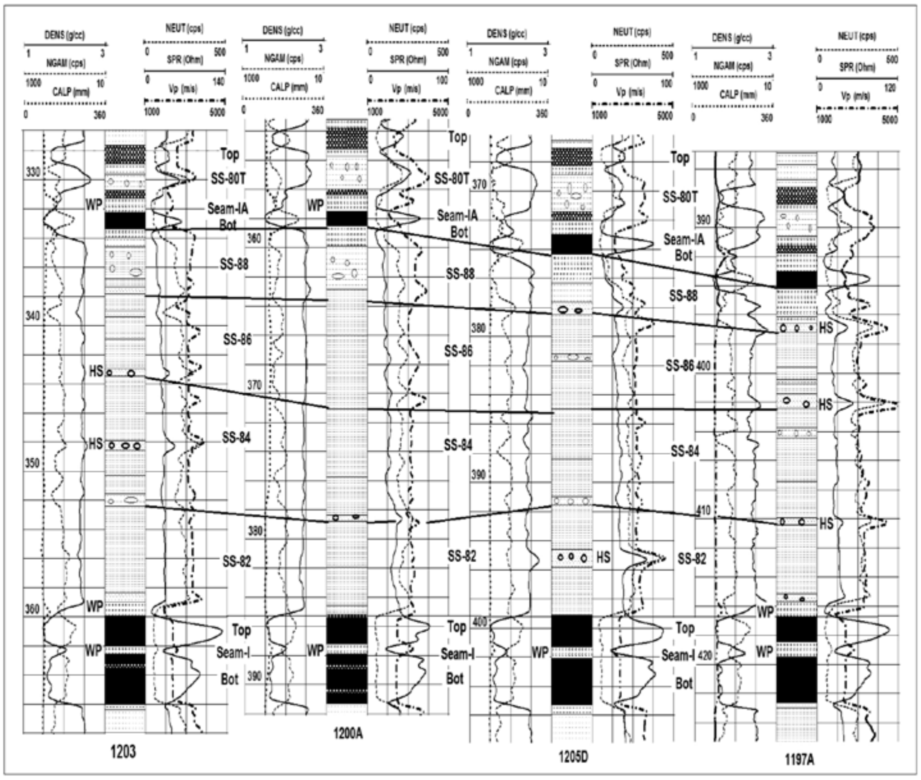

Figure 4. Correlation of coals, SS-70, SS-82, SS-84, SS-86, SS-88 and SS-80T using geophysical logs. Lithology index in Fig 3. See text for explanation of numbers.

Estimation of Rock Strength from Sonic Logs

The sonic logging being a function of rock elasticity enables empirically estimating strength parameters by correlating P wave velocities (Vp) with lab determined strength parameters such as Uniaxial Compressive (UCS) and Tensile (TS) strengths of sandstones. McNally (1987 and 1990) was the first to estimate coal measures rock strength using sonic and neutron logs of Australian coalfields. Hatherly et al. (2001 and 2004), Gordon (2002), Payne and Ward (2002), Hoelle (2004), Calleja (2006), Stam et al. (2012) and Butel et al. (2014) carried out similar studies in various coalfields of Australia. Mark and Molinda (2003) and Oyler et al. (2008) use sonic data to estimate UCS in some coalfields of USA. Hatherly (2013) concluded that site specific empirical estimates of Vp-UCS are established all over Australia and in some parts of USA. In Australia, the sonic logs are used in all types of mining methods.

In the present study, P wave velocities (Vp) obtained from sonic logs are correlated with the laboratory determined strength parameters such as uniaxial compressive strength (UCS), Tensile Strength (TS) and Young's Modulus. The equations are as follows

$$UCS=0.0798\ e^{0.0014Vp} \qquad \text{----------- (1)}$$
($R^2=0.72$)

$$TS = 8.7749E\text{-}13Vp^4 - 9.9760E\text{-}09\ Vp^3 + 4.2466E\text{-}05\ Vp^2 - 0.0798\ Vp + 55.9746 \qquad \text{--------- (2)}$$
($R^2=0.59$)

$$YM = 0.0069e^{0.0017\ Vp} \qquad \text{---------- (3)}$$
($R^2=0.73$)

Where UCS is uniaxial compressive strength in MPa,
TS is Tensile Strength in MPa
YM is Young's Modulus in GPa
Vp is P wave velocity in m/s

The above equations are applicable only to the sandstones. One would need to establish similar relationships for other sediments. These studies also indicate that UCS of Permian sandstones of Godavari Valley are less strong than those of Permian and Cretaceous sandstones of Australia and USA respectively for a given range of Vp.

Analysis of Seam-I and SS-80

The correlation of coals and associated overburden of coals is carried out using various geophysical logs by considering the floor of Seam-I as the datum. Fig 4 showing log responses of some of the boreholes clearly document that

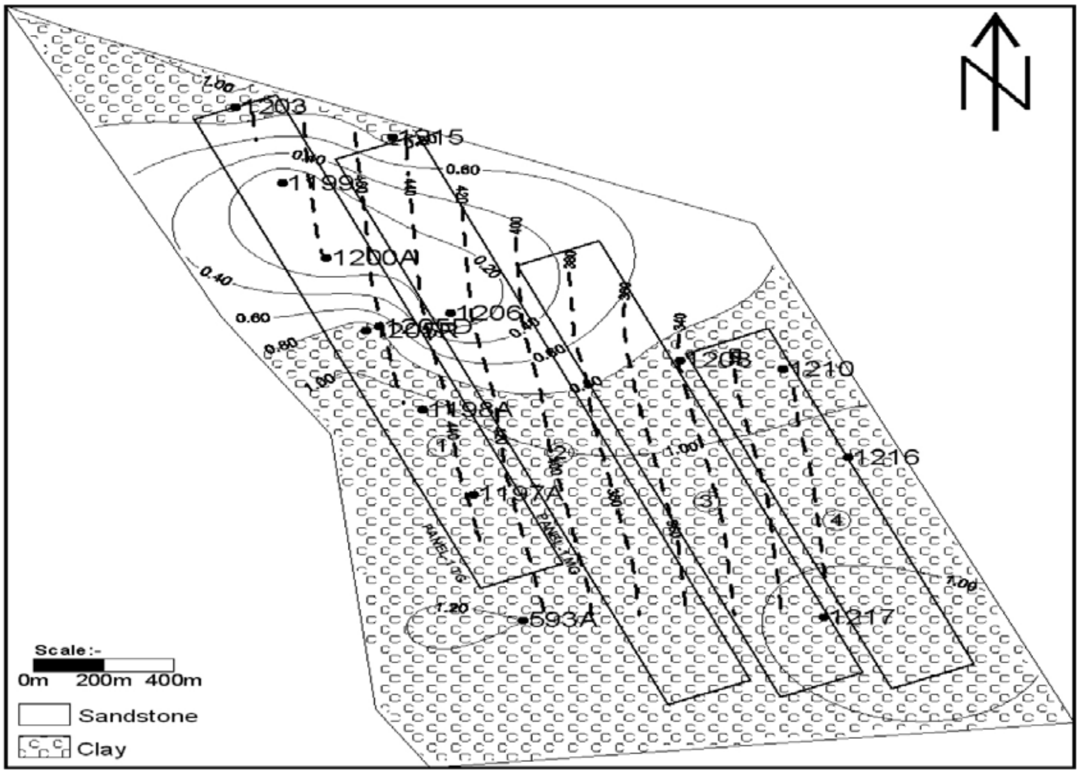

Figure 5. Thickness Map of Clay forming immediate roof of Seam-I along proposed longwall panels (black rectangles). Thick dashed lines are floor contours of Seam-I, whose depth increases from 350m to 600m from left to right. White colour in the northcentral parts indicates replacement of clay by sandstone.

SPR logs provide characteristic signatures of coals. The SPR and neutron logs show similar shapes and characters for various lithounits (except coal) and useful for correlation of interburden strata of coals. The logs indicate clay and sandstone form the immediate roof of Seam-I in different parts of the area. Fig 5 shows thickness contour map of clay forming the immediate roof of Seam-I indicates that clay is replaced by sandstone along the northcentral parts of the area.

The Seam-I, the targeted seam having a thickness of about six metres, contains a potential weak plane in the form of a dirt band along the middle parts (Figs.3 and 4). The dirt band of about 0.40m thickness is an interbedded sequence of thickly laminated to very thinly bedded carbonaceous shale, carbonaceous clay and clay and is prone to caving. The dirt band resolves Seam-I into bottom and top sections of 2.50m to 3.00m thickness respectively. The immediate roof (1.0m to 2.0m) of Seam-I indicates abutment of coarse grained sandstone with easy to cave clays on either side. The development of sandstone could be due to the palaeochannel washing out/eroding the previously deposited clay and depositing sandstone along the northcentral parts (Fig. 5). Hanson et al. (2005) concluded that intertonguing of rocks of contrasting strengths leads to differential compaction and fractures/joints along the contact planes which might pose geotechnical risks.

The geophysical logs reveal that SS-80 of 23m to 28m can be broadly resolved into succession of four sequences of sandstones separated by fine to medium grained sandstones, siltstones and hard and strong fine to very fine grained sandstones 'HS' (Figs. 3 and 4). These one metre to two metres thick 'HS' beds are lensoids which laterally grade to surrounding sandstones. They reappear at different stratigraphic levels and are not geologically continuous. SS-80 is classified into SS-82 at the base; SS-84, SS-86 in the middle and SS-88 at the top forming the floor rocks of Seam-IA. The thicknesses of SS-82, SS-84, SS-86 and SS-88 range from 8m to 10m, 9m to 11m, 4m to 6m and 0m to 6m respectively. The clay bed of 0.60m to 1.00m thickness constituting the immediate floor of Seam-IA Bottom is considered the upper boundary of SS-88. SS-88 of 6m thickness thins out towards SSE of the panel-1. As such SS-80 containing four sequences at NNW contains only three sequences and is devoid of SS-88. SS-80 having a maximum thickness of 28m at NNW decreases to 20m at SSE. These sequences dominated by coarse to very coarse grained sandstones display variations in compaction as observed from increase in neutron and Vp values towards SSE. They also condense towards SSE which is observed by

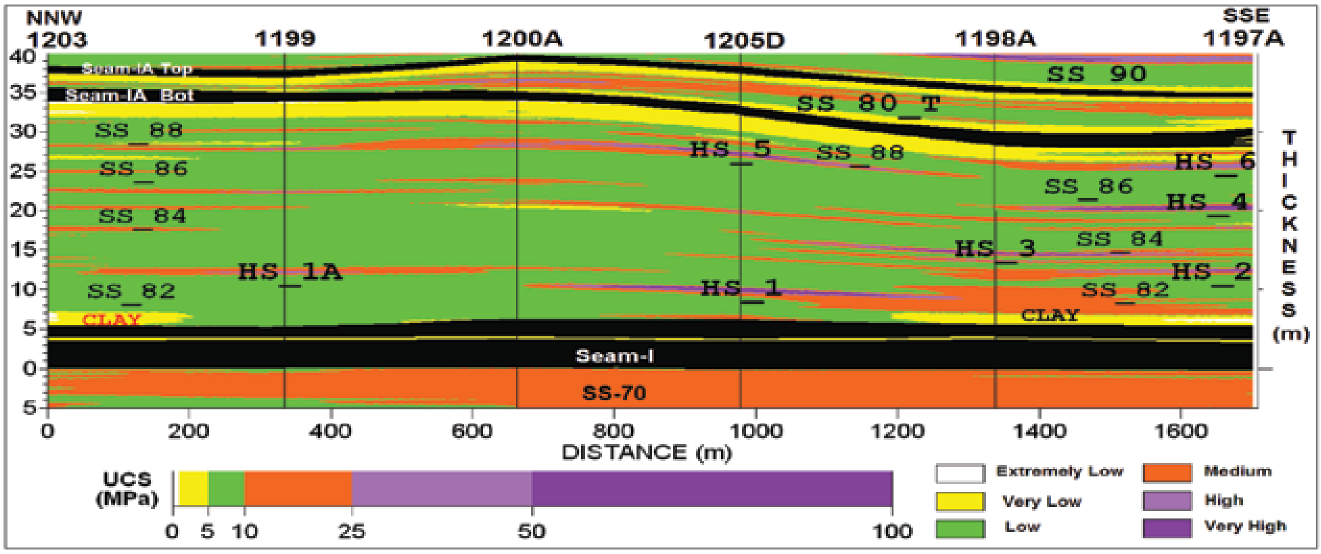

Figure 6. UCS Map of Overburden Strata of Seam-I.

decrease in thickness from NNW to SSE. The sequences of SS-82, SS-84, SS-86 and SS-88 also contain one or two lensoids of 'HS' beds at different stratigraphic levels. 'HS' beds prominent in the SSE laterally grade to fine to medium grain sandstones in the NNW (Fig. 4). The intertonguing/ lateral gradation of HS' beds with the surrounding rocks is one of the characteristic features of these sandstones. These features might as well be considered potential planes of delamination and separation.

The Seam-IA Bottom and IA Top which are almost coalesced at the NNW diverge towards SSE due to the development of SS-80T made up of stacked rocks of clays, shales, sandy shales, fine grain and medium to coarse grain grey sandstone attaining maximum thickness of about 5m at the SSW, along which SS-88 of 6m thickness thins out. Thus, the thinning and wedging of SS-88 from NNW to SSE is compensated by the development of SS-80T along left to right end of the panel. The splitting of Seam-IA and thinning of bed SS-88 roll down the Seam-IA Bottom towards the SSE of the panel. Accordingly, the Seam-I rolls down from one end to the other end of the panel.

The present studies confined to a single longwall panel may document lateral variations but not the sub-environments of the fluvial system producing them. Sedimentary environments producing these latero-vertical variations can be better understood by studying the spatial distribution of these sequences in the entire block.

The linear distribution of these beds along with their UCS and GSR values along panel-1 are shown in Figs 6 and 7 respectively. These maps can provide some inputs to establish the interrelationship between UCS and GSR characterisation, longwall monitoring analysis and caving behaviour as being done by Hatherly et al. (2009) and Medhurst et al. (2014) in Australia.

Geotechnical Maps

Green and Ward (2002) remarked that thick massive beds in the overburden can create conditions of heavy periodic weighting during longwall extraction while thin beds can act as separation planes. These thin beds may promote caving and thereby reduce the effective thickness of sandstone that could otherwise contribute to periodic weighting. Goafing behavior in the intermediate and upper caving zones (above approximately 23m) cannot be predicted solely on the basis of weak partings and is governed by a combination of factors, including bed thickness, strength homogeneity, and the juxtaposition of beds of contrasting character. Venkataramaiah (2008) observed that strong beds produced weighting of different magnitudes at the face in the active caving zones in some longwall panels of Godavari Valley. UCS and GSR maps are constructed by considering the floor of Seam-I as the datum to provide these details of bedding surfaces/planes contained by the sandstones of SS-80 resolved into SS-82, SS-84, SS-86 and SS-88 and to depict the strength and competency of rocks (Figs. 6 and 7). The maps are constructed by gridding log data using 'GeoInterp' software developed by Peter Hatherly of Coalbed Geosciences, Sydney, Australia and Binzhong Zhou of CSIRO, Brisbane, Australia. 'GeoInterp' has the unique feature of considering as many as 10 controlling surfaces to create grid files. 'Surfer' software is used to contour these grid files.

SS-80 is mostly made up of sandstones having UCS of 6MPa to 8MPa, which are classified as low (5MPa to 10 MPa) strength rocks as per the classification proposed by Larkin and Green (2012) of Australia (Fig. 6). ISRM1979 classifies these sandstones having UCS of 5MPa to 25 MPa as low strength rocks (Bieniawski, 1984). GSR of

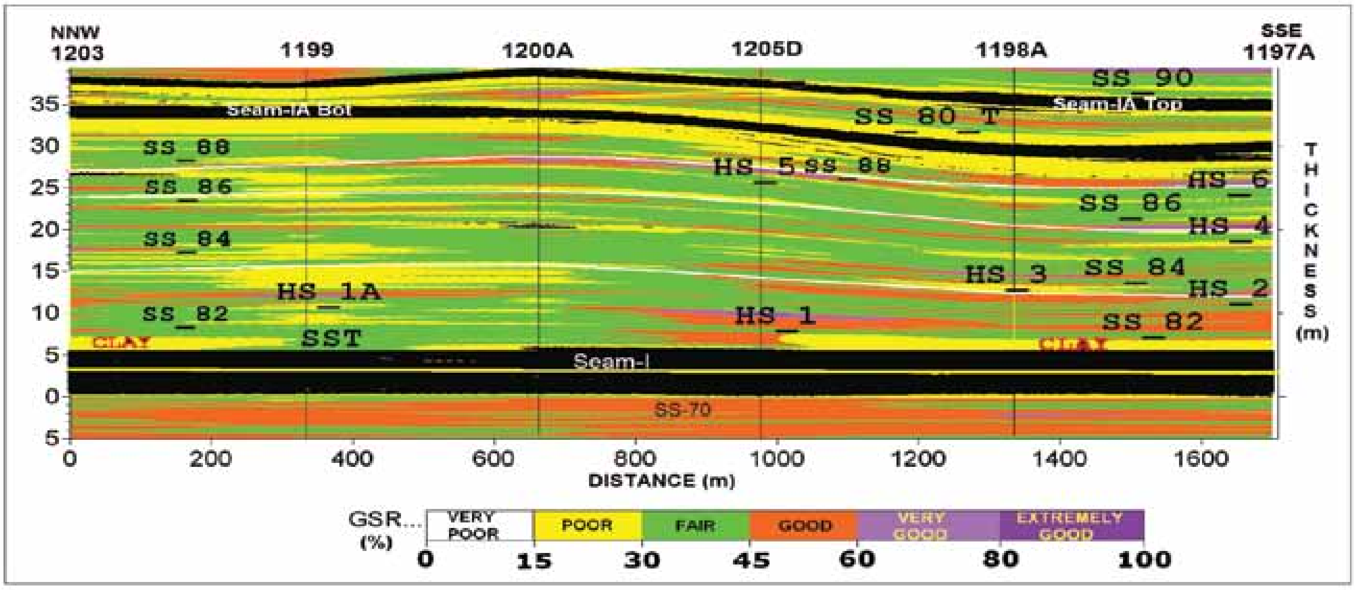

Figure 7. GSR Map of Overburden Strata of Seam-I.

these sandstones show a general range of 30% to 45%, that classifies them as fair rocks (Medhurst et al., 2014) (Fig. 7). These very thickly bedded sandstones in the NNW laterally grade to lensoids of poor rocks whose GSR is 15% to 30% at places. Lensoids of thickly bedded rocks of 0.50m to 1m thickness having GSR of 45% to 60% and are classified as good rocks that separate these fair rocks of SS-82, SS-84, SS-86 and SS-88. These fair rocks are more massive at the NNW and condense and transform into inter-beds of fair (30% to 45% GSR) and good (45% to 60% GSR) rocks towards the SSE. SS-82 and SS-84 are more inter-bedded than SS-86 and SS-88 at SSE. UCS maps also display a similar change where the rocks have higher UCS values of 8 MPa to 12 MPa at SSE against 6 MPa to 8 MPa at NNW. The low strength rocks grade close to medium strength rocks whose range is 10 MPa to 25 MPa (Larkin and Green, 2012). Very fine to fine grained hard and strong sandstones, 'HS', are rocks of moderate strength (25MPa to 50 MPa). Some of these beds are also medium strength (50MPa to 100 MPa) rocks. These finer clastic sediments separating the various sequences at places are rocks of very low strength whose UCS ranges from 3MPa to 5MPs. Along the NNW parts of the section, fair rocks (30% to 45% GSR) are mostly separated by thin beds of good rocks of GSR of 45% to 60%. This NNW area is almost devoid of very good rocks of GSR of 60% to 80%. Thin beds of very good rocks of GSR 60% to 80% separate the sequences of SS-80 along the SSE parts of the panel. Fig 7 also documents that the good rocks separating the sequences of SS-80 roll down towards SSE and transform into very good rocks. Intertonguing of these strong rocks with low strength rocks on one hand and lateral gradation of very low strength rocks with surrounding low strength rocks and stacking of beds of varying strengths induce differential compaction and development of potential zones of delamination and planes of separation. UCS and GSR maps also indicate SS-80 having maximum thickness and more massive at the NNW rolls down and become more interbedded towards SSE. The thick massive beds in the overburden can create conditions of heavy periodic weighting during longwall extraction while the thin beds can act as separation planes and reduce the effective thickness of sandstone that could otherwise contribute to periodic weighting.

Borehole Breakouts and Stress Directions

The breakouts indicate that the minor horizontal stress is aligned along N110º -120º and is perpendicular to the major/principal horizontal stress component (N24±14º) determined by hydrofracturing. These are shown in Fig 8b.

Fig 8b indicates that the major horizontal stress ($S_{H\,max}$ (1)) aligned along N24º±14º and cleats (2) along N30º to N40º are close to each other. Most of the geological faults (3) trend in N110º -150º to N290º -330º direction and close to N110º -120º, along which the minor horizontal stress ($S_{H\,min}$ (4)) is aligned. NNW-SSE is the geological strike direction of Adriyala longwall project. Longwall panels (5) are aligned N148º to N328º so as to trend oblique to major and minor horizontal stress directions to avoid roof falls and concentration of stress at gate ends.

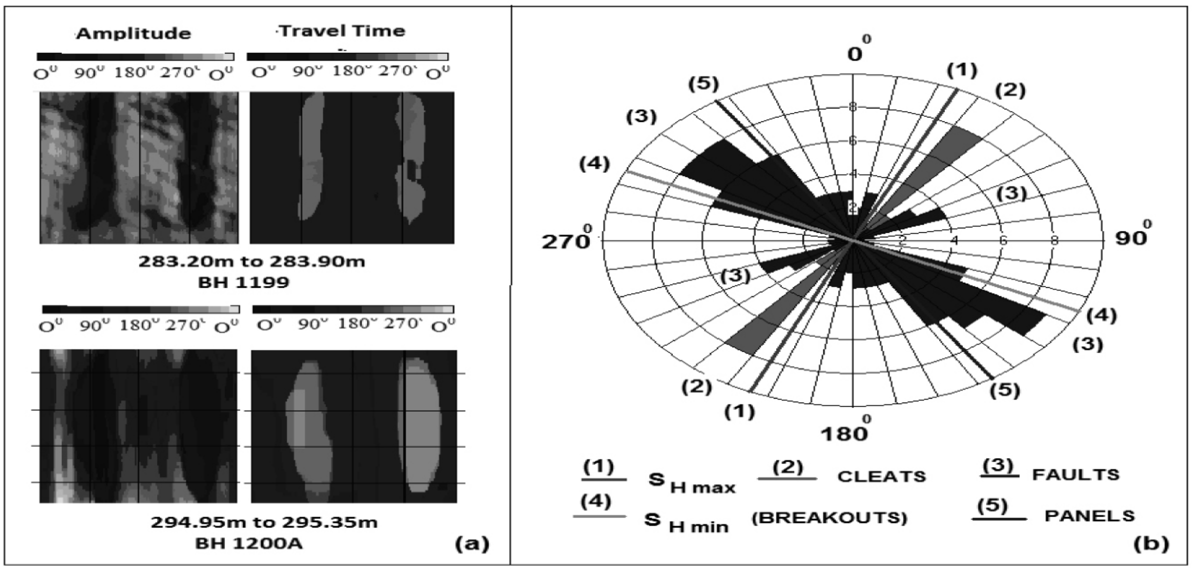

Figure 8. (a) Borehole Breakouts observed on Acoustic Amplitude and Travel Time images, (b) Orientation of Stress, Geological Faults, Cleats and Longwall Panels

SUMMARY AND CONCLUSIONS

Ramesh Kumar et al. (2011) concluded that the majority of downtimes and failures of longwall mining in India were due to severe ground control problems and selecting inadequate capacity and type of powered roof support systems. Geo-mining conditions should be understood well in advance to choose the appropriate powered roof support system. The present study therefore makes a critical conclusion that geophysical logs can play an invaluable role in providing a good understanding of geological and geotechnical environment of overburden strata of coal towards successful longwall mining in India. These inputs obtained from geophysical studies can help the uptake of numerical modelling to establish the interrelationship between UCS and GSR characterisation, longwall monitoring analysis and caving behaviour as is being done by Hatherly et al. (2009) and Medhurst et al. (2014) in Australia.

The Seam-I was deposited in stable conditions resulting in uniform thickness of coals including that of 0.40m thick dirt band in the middle. Weak bed in the middle of Seam-I and intertonguing of clay of 1.20m thickness with sandstone along the immediate roof influence working sections and roof support system. Development of these sandstones is possible by the palaeochannel washing out/eroding the previously deposited clay and depositing sandstone along the northcentral parts of the panel. A near uniform thickness of SS-82, 84 and SS-86 speaks of uniform subsidence and fluvial channel maintaining similar course during these episodes. On the other, the attenuation of SS-88 and SS-80T in opposite directions of SSE and NNW respectively are the manifestations of channel avulsion and differential subsidence through time and space. Splitting of Seam-IA into two distinct sections along SSE is another good example of channel avulsion. Mapping of spatial distribution of lithofacies of SS-80 and SS-80T can further define the geometry of fluvial system and help tracing the associated geotechnical risks as was carried out by Horne et al. (1978) in Appalachian region.

The sandstones of SS-80 are very thick massive beds whose UCS and GSR ranges of 6MPa to 8MPa and 30% to 45% classify them as low strength and fair rocks respectively. These massive beds also contain thin to thick beds of good (45% to 60% GSR) and very good (60% to 80% GSR) rocks. Some of them are also poor rocks having GSR of 15% to 30%. These studies also observe that GSR provides both petrophysical and geotechnical models unlike the conventional UCS maps, which speak only of intact strength. Hatherly et al. (2009) made similar conclusions in Australia. The very thick massive beds in the overburden can create conditions of heavy periodic weighting during longwall extraction while the thin beds contained by it can act as separation planes and reduce the effective thickness of sandstone that could otherwise contribute to periodic weighting. The stratigraphic placements of these beds brought out by the UCS and GSR maps help predicting the zones of separation and delaminations.

It is also true that exploration data can help visualising the mining conditions to a large extent but cannot depict the ground realities of longwall mining. These exploratory models should therefore be validated during mining by mapping bed separations and taking up appropriate modelling studies at appropriate times. Back analysis of behaviour of strata will allow developing predictive models and appropriate strata control strategies to be applied at Adriyala and other mines and also for multiseam extraction.

ACKNOWLEDGMENTS

Authors are thankful to the management of Singareni Collieries Company Limited for according permission to publish the paper. Authors are also grateful to Rao Balusu, Binzhong Zhou and Deepak Adhikary of CSIRO and Renate Sliwa, former CSIRO for their encouragement. Special thanks to Peter Hatherly of Coalbed Geoscience, Australia for his valuable comments and suggestions. They also thank the reviewer's for their suggestions to improve the paper. The opinions expressed in this paper are personal to the authors and do not represent the management of their company.

REFERENCES

Barton, N., 2002, Some new Q-value correlations to assist in site characterisation and tunnel design. Int. J. Rock. Mech. Min. Sci. v.39-2, pp:185–216.

Barton,N., 2006, Rock quality, seismic velocity, attenuation and anisotropy. Taylor and Francis: London and Netherlands.

Bieniawski, Z. T., 1984. Rock Mechanics Design in Mining and Tunnelling,. Balkema, Rotterdam, v.272

Bieniawski, Z. T., 1989, Engineering Rock Mass Classifications, Wiley, New York.

Butel, N., Hossack, A., and Kizil, M. S., 2014, Prediction of in situ rock strength using sonic velocity, 14th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy & Mine Managers Association of Australia, pp: 89-102.

Calleja, J., 2006, Rapid Rating Using Coal Mine Roof Rating to Provide Rapid Mine Roof Characterization from Exploration Drilling, in Aziz, N (ed), Coal: Coal Operators' Conference, pp:20-27, http://ro.uow.edu.au/coal/32

Calleja, J., 2008, CMRR-Practical limitations and solutions, in Aziz, N (ed), Underground Coal Operators' Conference, pp: 92-103.

Colwell, M. and Frith, R., 2006, Why Uniaxial Compressive Strength and Young's Modulus Are Commonly Poor Indicators of Roadway Roof Stability - Except in the Tailgate. Underground Coal Operators' Conference, http://ro.uow.edu.au/coal/33

Frith, R and Colwell, M., 2008, Geotechnical Design at a Mine Site Level–We Have No Choice, Underground Coal Operators' Conference, http://ro.uow.edu.au/coal/8

Gordon, N., 2002, The Development of Hazard Plans at Kestrel Mine, in Aziz, N (ed), Coal Operators' Conference, pp:159-168.

Green D R and Ward B., 2002, Determination of Goaf Delamination Horizons and Other Roof Geomechanical Features Using Downhole Acoustic Logs, ACARP Project C9003 Final Report.

Hanson, C., Thomas, D. and Gallagher, B., 2005, The Value of Early Geotechnical Assessment in Mine Planning, Underground Coal Operators Conference, pp:17-30, http://ro.uow.edu.au/coal/65.

Hatherly, P, Medhurst, T, Zhou, B and Guo, H., 2001, Geotechnical evaluation for mining – assessing rock mass conditions using geophysical logging, Final report, ACARP Project C8022b.

Hatherly, P., Sliwa, R. Turner, R. and Medhurst, T., 2004, Quantitative geophysical log interpretation for rock mass characterization. End of Grant Report, ACARP Project C11037.

Hatherly, P, Medhurst, T, and MacGregor, S., 2008, Geophysical Strata Rating, ACARP Project C15019.

Hatherly, P., Medhurst, T., Ye, G. and Payne, D., 2009, Geotechnical Evaluation of Roof Conditions at Crinum Mine Based on Geophysical Log Interpretation, Underground Coal Operators Conference, pp:16-22, http://ro.uow.edu.au/coal/67.

Hatherly, P., 2013, Overview on the application of geophysics in coal mining, International Journal of Coal Geology, http://dx.doi.org/10.1016/j.coal.2013.02.006

Hoelle, J., 2004, Exploration for Results: Moura Coal Mine, Underground Coal Operators' Conference. http://ro.uow.edu.au/coal/133.

Horne, J. C., Ferm, J. C., Caruccio, F. T. and Baganz, B. P., 1978, Depositional models in coal exploration and mine planning in Appalachian region, AAPG Bulletin, v.62, no. 12, pp:2379-2411.

Larkin, B. J. and Green, D. R., 2012, Borehole data standard for Australian coal industry (CoalLog Manual, version 1.1), ACARP Project C21003, pp:80-81.

MacGregor, S., 2003, Maximising In-Situ Stress Measurement Data from Borehole Breakout using Acoustic Scanner and Wireline Tools, ACARP Project C1009.

Mark, C. and Molinda, G. M., 2003, The Coal Mine Roof Rating in Mining Engineering Practice, Underground Coal Operators' Conference. pp:50-62, http://ro.uow.edu.au/coal/160

Mark. C. and Molinda G. M., 2005, The Coal Mine Roof Rating (CMRR)-a decade of experience, International Journal of Coal Geology, v.64, pp:85-103.

McNally, G.H., 1987, Estimation of coal measures rock strength using sonic and neutron logs, Geoexploration, v.24, no.4-5, pp:381–395.

McNally, G.H., 1990, The prediction of geotechnical rock properties from sonic and neutron logs, Exploration. Geophysics. v.21, pp:65–71.

Medhurst, T., Hatherly, P., and Hoyer, D., 2014, Investigation of the relationship between strata characteristics and longwall caving behaviour, 14th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy & Mine Managers Association of

Australia, pp:51-62.

Molinda, G.M. and Mark, C., 1994, Coal mine roof rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387

Oyler, D.C., Mark, C., Molinda, G., 2008, Correlation of sonic travel time to the uniaxial compressive strength of U.S. coal measure rocks. Proceedings of the 27th International Ground Control in Mining Conference, Morgantown, WV, pp:338–346.

Payne, D. A. and Ward, B., 2002, Strata Management in Weak Roof Conditions at Crinum Mine, Underground Coal Operators Conference, pp:22-43, http://ro.uow.edu.au/coal/203126-134.

Pell, S., Seedsman, R., and Straub, K., 2014, Geotechnical data from geophysical logs: stress, strength and joint patters in NSW and QLD coalfields, 14th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy & Mine Managers Association of Australia, pp:25-33.

Ramana Murty, B.V. and Parthasarathy, E.V.R., 1988, On the evolution of the Godavari Gondwana graben based on LANDSAT imagery interpretation, Journal of Geological Society of India, v.32, no.5., pp:417-425.

Ramesh Kumar, B., Siva Sankar, U. and Prasad, V. S. N., 2011, Selection of Powered Roof Supports-2-Leg Shields vis-à-vis 4-Leg Chock Shields, Proceedings of International Conference on Underground Space Technology, Bangalore, India p CM-05-1-20.

Stam, S., Guy, G., and Gordon., N., 2012, Back analysis of roof classification and roof support systems at Kestrel North, 12th Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, pp:42-51.

Uday Bhaskar, G., Srinivasa Rao, A., and Shanmukha Rao, M., 2002, Coal seams correlation and Permian Stratigraphy of Kothagudem and Godavari sub-basins of Pranhita-Godavari Valley-An example from geophysical logs, Journal of Indian Association of Sedimentologists, v.21, no. 1 and 2, pp:15-29.

Uday Bhaskar, G., Srinivasa Rao, A., G. V. S. Prasad, K. A. V. L. Prasad and Shanmukha Rao, M., 2011, Sondilla Seam and its implications on Permian stratigraphy of Pranhita Godavari Valley, Review based on geophysical logs, Proceedings of Proterozoic and Phanerozoic Evolutionary trends and Coal Exploration and Exploitation, Geological Survey of India and Singareni Collieries Company Limited, Kothagudem, India, Abstracts volume, pp:29-30.

Venkataramaiah, M. S., 2008, Studies on the influence of contact roof zone and worked out lower Seam on strata behavior in longwall panels in Godavari Valley Coalfields, India, Ph. D. Thesis, National Institute of Technology, Surathkal, India (Unpublished).

Mr. Makesh Shanmukha Rao passed out M. Sc (Tech) degree in Applied Geophysics from Andhra University in the year 1990. He is actively involved in geological and geotechnical studies of coal bearing strata using geophysical logs. He has established empricism between elastic and mechanical properties of overburden strata of coals and establishing stress directions from acoustic logs.

Dr. Gudlavalleti Uday Bhaskar obtained M.Sc (Tech) degree in Applied Geophysics from Andhra University in 1980 and Ph.D. from Indian School of Mines in 2001. He has solved several geological and stratigraphic complexities of Pranhita-Godavari Valley and now establishing coal seam-wise geomining conditions using geophysical logs.