Mapping of faults in underground mine by Sub Surface Profiling technology

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ABSTRACT: Underground mines often experience roof collapse due to the presence of faults. While major faults are identified during exploration, many a time smaller faults remain unidentified. Underground mine approaching such unidentified faults may result in sudden roof fall and groundwater ingress. To resolve the issue, we utilized GPR based Sub-Surface Profiling technology that is capable of capturing fault related deformation features as anomalies. Results of SSP scanning and its interpretation from an underground coal mine in India is presented. Signatures from SSP are found useful in mapping fracture frequency, identifying fault core and damage zone, and helped assessing the degree of cataclasis. Regular SSP scanning helped predicting the rock conditions in advancing galleries and facilitated to adopt appropriate roof and water management strategy beforehand. Considering the usefulness of the technology, it may be adopted in underground mines globally, particularly where fault related deformation pose challenge to roof management.

Keywords: Underground-mine, fault, roof-collapse, Sub Surface Profiling, roof-management.

1 INTRODUCTION

Brittle faults and fault zone rocks demand particular attention during design and development of underground mines, owing to its adverse impact on the stability of the excavations. Brittle faults are common features of the upper crust, that generally shows complex structures resulting from brittle fracture mechanics. “Fault rocks” (Sibson 1977), form because of localized strain within a fault zone (Brodie et al. 2007). Despite the tremendous importance of faults in rock engineering projects, its identification, engineering geological and mechanical characterization are not well practiced (Riedmüller et al. 2001). Complex structures associated with fault zones and the disturbed weak rocks induce substantial heterogeneity to the rockmass. It is established that faults and fault rocks have highest impact on the rock mass behavior.

Identifying faults and associated deformation zones is crucial, particularly from underground mining perspective. This paper discusses the use of Sub Surface Profiling (SSP) technique for identification and characterization of rocks associated with brittle fault zones and presents a case study of fault zones intersected in an underground coal mine. The instrument was found useful to recognize subsurface fault zone rocks in advancing drives and galleries. It is also suggested how the new tool may be utilized to enhance safety in operating underground mine.

2 UNDERGROUND MINING IN FAULT AFFECTED ZONES

2.1 Fault core and damage zones

Recent research indicates that brittle fault zones are characterized by a highly strained and extensively deformed central or core zone flanked by relatively less-deformed damage-zones (Figure 1). The core zone accommodates majority of displacement and thereby is more intensely deformed, resulting in mechanical anisotropy to the rockmass (Caine et al. 1996; Wibberley et al. 2008; Bastesen & Rotevatn 2012; Choi et al. 2016 and Torabi et al. 2020). Experimental data indicates a gradual decrease in strength and elastic modulus and an increase in relative ductility and permeability from damage zone to core zone (Chester & Logan 1986). Presence of cataclasites, fault gouge, and breccia in the fault core zone results in sudden and uncontrolled roof collapse in an underground mine. Water inrush is often experienced as fault zones usually act as zones of concentrated groundwater flow. Hoek (1999) discussed the importance of early detection of faults during an underground operation and emphasized the requirement of specialized support system as soon a fault zone is encountered. However, early detection of a fault zone is difficult during an underground operation. Probe hole or cover hole provide some indications, however, are found time and cost intensive.

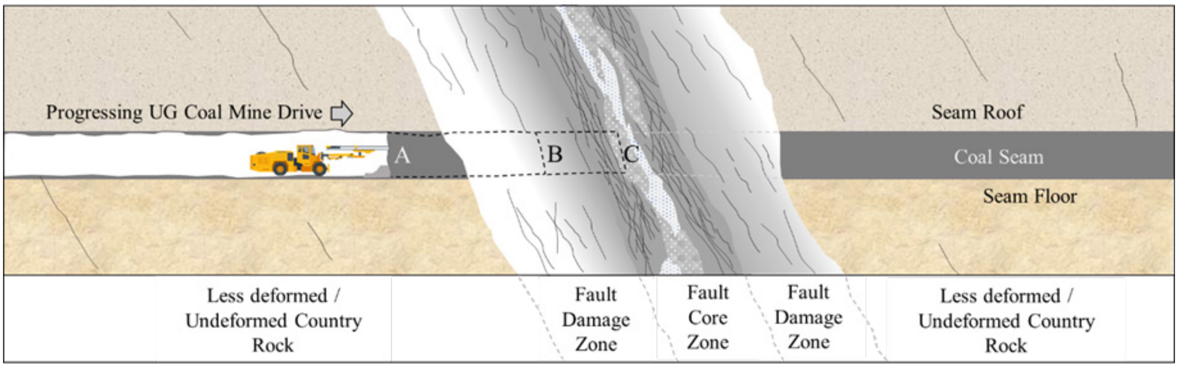

Figure 1. Schematic diagram showing disposition of fault core and damage zones. An underground mine drive is shown progressing towards a fault that currently passes through the undeformed country rock (location A). With further progress the drive will enter the fault damage zone (location B) and finally it will encounter the fault core zone (location C).

2.2 Mapping of fault damage zone by SSP

Since fault core-zones are flanked by less-deformed damage zones, an underground mine excavation initially progresses through a damage zone (location B in Figure 1) before it encounters the fault core (location C in Figure 1). Since regular structural mapping in a progressing mine drive is difficult to implement, it is more practicable to map fault damage zone by some other quick and reliable method. To achieve this, we have used Sub Surface Profiling (SSP), a radar imaging technology to map fault related deformation features behind roof, floor, and sidewalls of an underground coal mine. The SSP technology is developed by Reutech Mining, South Africa. The fault damage zone rock, owing to its relatively less degree of deformation, generally do not pose poor roof rock issues. As a result, identification of deformation features associated with a fault damage zone may guide that a drive is approaching towards a fault core zone. From this perspective, SSP technology is found effective compared to conventional mapping methods practiced in underground mine.

3 SUB SURFACE PROFILING TECHNOLOGY

SSP is a hand-held, electromagnetic geophysical device, designed to map subsurface geological features, such as discontinuity planes and zones, around underground openings. Electromagnetic pluses reflected from deformed zones are represented as anomalies in the scan as the deformed zone possess unusual electrical properties compared to the undeformed host rock (Pienaar 2017). Based on the variation in geophysical character of the deformed rocks, the nature of reflection is found to be different in fault core, damage zone and undeformed country rock. Figure 2a & b shows the scanning principles and Figure 2c shows a typical SSP scan image obtained from the roof of an underground mine drive. Migration correction, a post-processing technique, is applied to estimate the true dip of inclined geological features.

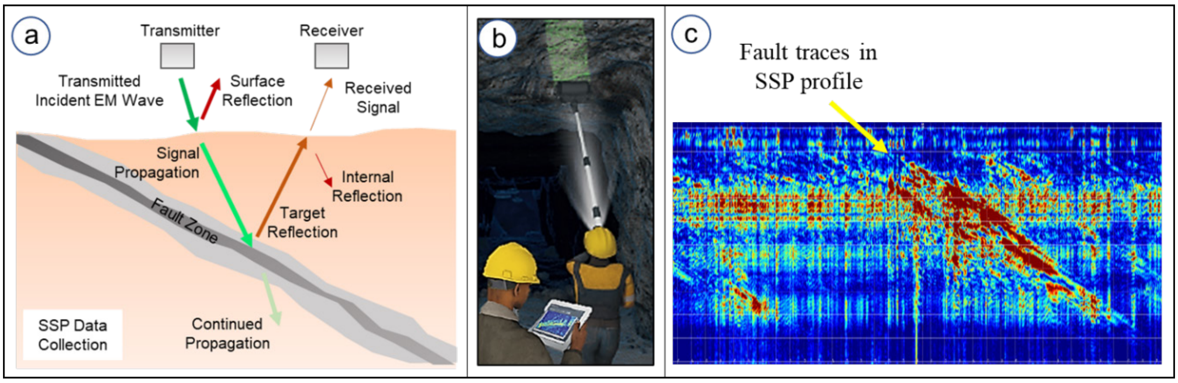

Figure 2. Sub Surface Profiling technology. (a) principles of imaging, (b) scanning of an underground mine roof (Pienaar 2017) (c) scan results that captured fault induced deformation features as anomalies.

4 SSP IMPLEMENTATION: CASE STUDY FROM AN UNDERGROUND COAL MINE

An underground coal mine in Central India was selected for SSP scanning. The mine adopts room and pillar method for underground development. The coal bearing stratigraphy is intersected by numerous faults, that strike E-W and W- ESE, and dip northerly at angles between 50º to 70º. Many of these faults were unidentified during the exploration programme. As a result, the progressing drives often encounter unknown fault core zones and experience collapse of the roof rock. To identify these fault zones beforehand, we undertook SSP scanning along the galleries and drives, preferably at high angle to the strike of the fault zones.

4.1 Mapping of the faults

A detailed fault mapping programme was undertaken before SSP scanning. The fault core zones were visually identified and mapped on the drive walls. These zones show signatures of intense deformation in the form of close-spaced fracturing, development of cataclasites and fault gauge at places. The thickness of the fault core zone ranges from a meter to about ten meters. Roof rock in the fault core zone is collapsed at many instances. In majority of the cases the fault zones are acting as conduits for groundwater flow and any failure along these zones show release of water into the galleries leading to water related mining hazards.

4.2 SSP Scanning, data analysis and interpretation

After physical mapping of faults and related deformation features, SSP scanning was undertaken along multiple sections, covering all the seams under operation. Long profile lines across the fault zone strike were used to assess signatures of faulting in the core and damage zones and the undeformed host rock in SSP scanning.

The result of SSP scanning across a fault zone is presented in figure 3a. Comparison of field mapping data and SSP scanline images indicate that the inclined surfaces with high reflectivity (marked as red bands and lines in the SSP profile, Figure 3a & b) represent fault related deformation zones. These zones on SSP profile show distinct orientation and are parallel to the dip of the fault core zones. The calculated dip of the faults from SSP profile is ~60° that agrees well with the underground mapping data and the regional structure of the area. In the process of interpretation of the SSP data, fracture traces were drawn on the SSP scans to assess geometry and fracture frequency (Figure 3b). The core and damage zone of the fault are well depicted in the SSP scan images. The core zone is marked by thick red bands representing intense fracturing (Figure 3a & b). The interpretation is validated with field mapping in the core zone of the fault. The thickness of the reflection bands decreases away from the core zone due to an increase in fracture spacing. Thin red bands represent these features away from the fault core zone (Figures 3b and c). Fault zone traces, derived from the SSP data, are shown in Figure 3c.

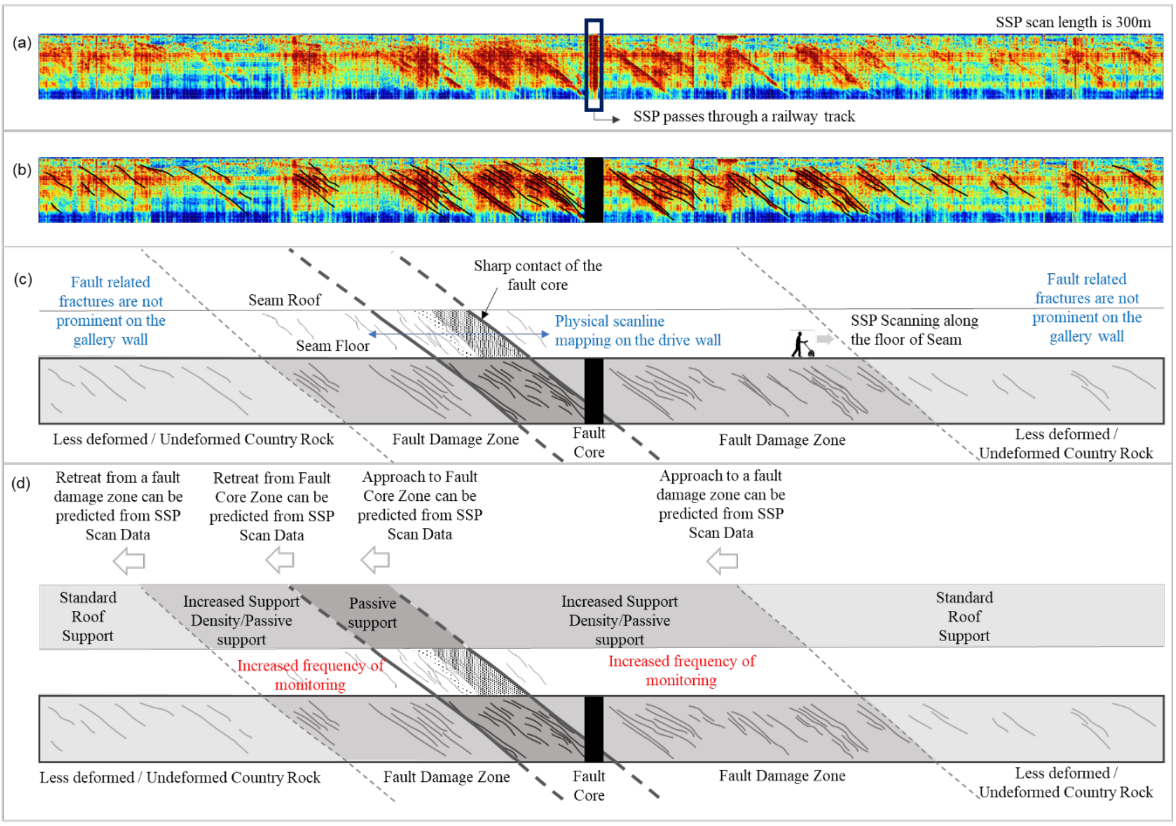

Figure 3. SSP Scanning and interpretation of data (a) and (b) SSP scanning results after correction (c) interpretation of structures from SSP data, (d) qualitative assessment of roof rock behavior, support, and monitoring requirement form the interpreted structures.

It may be noted that fracture frequency is significantly reduced in the damage zone in comparison to the core zone of the fault. This is in conformity with the conceptual model of fault zone anatomy. Figure 3c also shows that fault related deformation features diminish further away from the damage zone to the host rock free from fault induced fractures. The SSP scan images show clear distinction between fault core, damage zone and undeformed host rock (Figure 3c). Similar results were found in other SSP scans, where the fault core and damage zones were well picked up by the SSP scans.

SSP scanning programme indicates that the equipment is capable of capturing deformation features associated with faulting. The instrument provides results in real time, so decision making do not require post processing. Considering such advantages, SSP scanning was implemented in all development galleries at regular interval. This helped assessing if a development drive is approaching a fault zone. Adequate planning and precaution were arranged before a potential roof-fall or water inrush event. A standard operating procedure (SOP) for regular SSP scanning in an operating underground mine is presented in Figure 4.

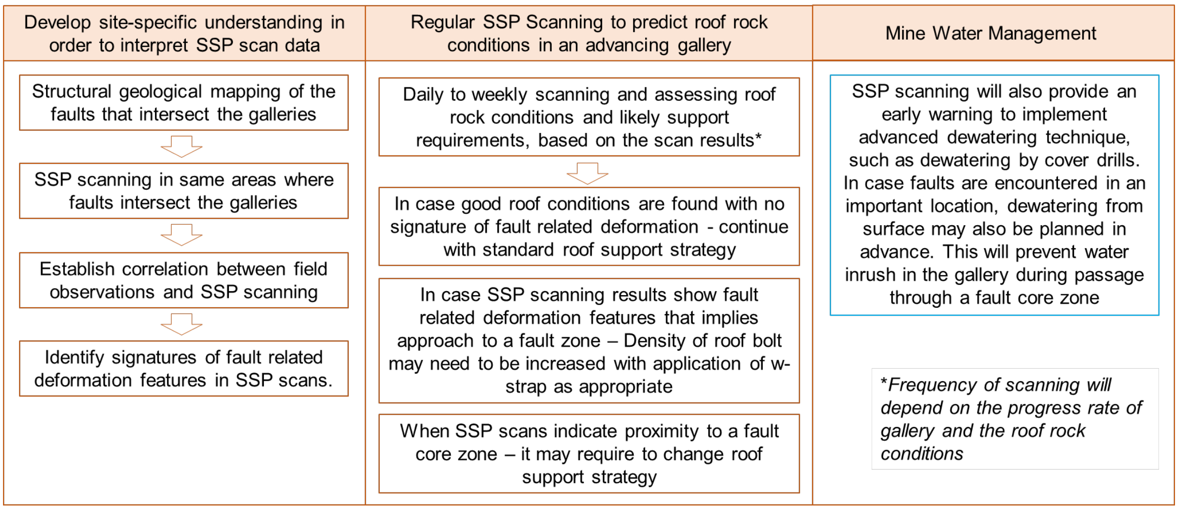

Figure 4. Recommended standard operating procedure for SSP Scanning in an operating underground mine.

4.3 *Qualitative prediction of roof-rock behavior and monitoring requirements*

It is noted that the mechanical behavior of roof rock is significantly different in fault core, damage zone and in the undeformed country rock. While Rock Mass Rating (RMR) and standard roof support principles are applicable in the undeformed country rock away from the fault zone, such support principles are not applicable for the fault core as well as in the damage zone rocks.

- Intense fracturing, formation of cataclasites and gouge in the fault core reduces the integrity of the rock, and, as a result, some forms of specialized support system are required to be installed in the fault core zone. In case it is anticipated that an underground mine is progressing towards a fault core zone, it is important to design a support system, define sequence of excavation and keep planned support elements ready to deal with the anticipated conditions before the fault core zone is exposed to a significant extent. Depending upon the nature and extent of the fault and whether water is present, a variety of support systems and excavation sequences can be used. Hoek (1999) and Merwe & Madden (2010) discussed required support principles in detail.
- The fault damage zone experiences varied degree of fault induced deformation. A qualitative estimate of degree of damage may be assessed from the fracture frequency obtained from SSP scanning. The density of roof bolting and requirement of w-strap may be envisaged from the SSP scan data.
- Standard roof support principles may be adopted in the undeformed country rock free from fault induced deformation.

Frequency of roof monitoring should be increased in the fault damage zone, specifically close to the fault core, where the possibility of roof convergence is substantially high. Figure 3d presents interpreted SSP sections with qualitative comment on roof-support and monitoring requirements.

5 CONCLUSION AND RECOMMENDATIONS

1. This study indicates that SSP scanning is useful to capture fault induced deformation features in an operating underground mine.

2. Considering the uncertainties associated with fault disposition, it is recommended to undertake regular SSP scanning in all advancing mine galleries/drives.
3. The frequency of scanning should vary from daily to weekly, depending on the progress of mining and the nature of the ground.
4. Since the instrument provides real time scanning results, decisions related to roof management may be taken immediately.
5. A standard operating procedure is recommended for an operating mine.
6. A robust SSP database may help developing software tools based on machine learning (ML) and artificial intelligence (AI).

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REFERENCES

Bastesen, E., & Rotevatn, A. 2012. Evolution and structural style of relay zones in layered limestone–shale sequences: insights from the Hammam Faraun Fault Block, Suez rift, Egypt. *Journal of the Geological Society, London* 169, pp. 477–488. DOI: https://doi.org/10.1144/0016-76492011-100.

Brodie, K., Fettes, D. & Harte, B. 2007. Structural terms including fault rock terms. In: *Metamorphic rocks: A classification and glossary of terms*, D, Fettes. & J, Desmonds (eds), Cambridge, UK, 2007, pp. 24– 31. Cambridge University Press: The Edinburgh Building, Cambridge, UK.

Caine, J.S., Evans, J.P. & Forster, C.B. 1996. Fault zone architecture and permeability structure. *The Geological Society of America* 24, pp. 1025–1028, DOI: https://doi.org/10.1130/0091-7613(1996)024,1025:FZAAPS.2.3.CO;2

Chester, F.M & Logan, J.M. 1986. Implications for mechanical properties of brittle faults from observations of the Punchbowl fault zone, California. *Pure and Applied Geophysics* 124, pp. 79–106. DOI: https://doi.org/10.1007/BF00875720.

Choi, J.H., Edwards, P., Ko, K. & Kim, Y.S. 2016. Definition and classification of fault damage zones: a review and a new methodological approach. *Earth-Science Reviews* 152, pp. 70–87. DOI: https://doi.org/10.1016/j.earscirev.2015.11.006

Hoek, E. 1999. Support for very weak rock associated with faults and shear zones. *In: Proceedings of the Distinguished lecture for the opening of the International Symposium on Rock Support and Reinforcement Practice in Mining*, Kalgoorlie, Australia, March 14- March 19, 1999

Merwe, J.N. & Madden. B.J. 2017, Second Edition of Rock Engineering for Underground Coal Mining, *The Southern African Institute of Mining and Metallurgy*, Johannesburg, Republic of South Africa.

Pienaar, A. 2017. The Sub Surface Profiler: a giant leap for ground penetrating radar, Reutech Mining, Stellenbosch, South Africa.

Riedmüller, G., Brosch, F.J., Klima, K., Edmund W. & Medley, E.W. 2001. Engineering Geological Characterization of Brittle Faults and Classification of Fault Rocks. *FELSBAU* 19 (4), pp.13-19.

Sibson, R. H. 1977. Fault rocks and fault mechanisms. *Journal of the Geological Society* 133(3), pp. 191– 213. DOI: https://doi.org/10.1144/gsjgs.133.3.0191

Torabi, A., Ellingsen, S. S. T., Johannessen, U. M., Alaei, B., Rotevatn, A. & Chiarella, D. 2020. Fault zone architecture and its scaling laws: where does the damage zone start and stop? *Geological Society, London, Special Publications* 496, pp. 99–124.

Wibberley, C.A., Yielding, G. & Di Toro, G. 2008. Recent advances in the understanding of fault zone internal structure: a review. *Geological Society, London, Special Publications* 299, pp. 5–33. DOI: https://doi.org/10.1144/SP299.2