Slope failure susceptibility zonation using integrated remote sensing and GIS techniques: A case study over Jhingurdah open pit coal mine, Singrauli coalfield, India

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The susceptibility of slopes in open pit coal mines to various modes of failure (i.e., plane, wedge, circular and toppling failure) could be envisaged by virtue of processing and analysis of pertinent satellite data. The aim of the present study was to integrate thematic maps generated using remote sensing image processing techniques, in order to finally produce slope failure hazard zonation maps in and around Singrauli coalfield, India. The various failure-inducing factors, variables and parameters can be extracted from different satellite data and imageries. The data acquired by different sensors such as TM, ETM+, etc., of LANDSAT series and CARTOSAT of ISRO Bhuvan was used in this study. All these data were subsequently used to create different thematic maps such as slope map, lithological map, land use/land cover map, principal component analysis map, digital elevation model (DEM), etc. An advanced analysis for extraction of lineament attributes was also undertaken.

Keywords. Slope failure; remote sensing; open pit coal mine; slope stability.

1. Introduction

Increasing coal mining to meet the energy demands often forces the operators to accommodate both the highwall slope and overburden dumps. This largely emanates from the fact that there is inadequate availability of land and space for creating more hospitable conditions for mining. These steep slopes of substantial height then succumb to various failure modes following certain failure paths. The failure of these slopes are aspects of various foundations such as slope, height, type of lithology, geological discontinuities, seismicity, etc. Of all the geological factors influencing the stability of rock slopes, there is little doubt that joints, bedding planes, faults, shear zones and intersections of such structures, are the most significant ones (Ghobadi

1994). Conditions such as presence of geological structures, incompetent rock strata, sparse vegetation, etc., makes slope failure inevitable.

In view of the above, hazard assessment was necessary to identify area with degree of hazard, which well serves for land-use planning (Arnous *et al.* 2007, 2010). Nonetheless, slope failure susceptibility investigation is usually difficult and computationally intensive as well as extensive. Alternatively, for efficient mitigation and management of disasters, RS and GIS are very effective tools helping in monitoring, assessment, identifying gaps and recommendation of appropriate strategies (Arnous 2011). It gives a regional and integrated perspective of inter-relations between various land features (Dehnavi *et al.* 2010). Remote sensing can detect features such as subsurface faults,

Figure 1. Location map of Jhingurdah, Singrauli coalfield.

fractures, etc., otherwise unseen on the surface, map them accurately and offer interpretations based on their form, distribution and their inter-relation with respect to each other (Kokalj and Ostir 2007). High resolution data together with advanced image processing techniques, has enlarged the potential of remote sensing in mapping geological features with better accuracy (Drury 1987; Rawashdeh *et al.* 2006).

Remote sensing techniques thereby act as a tool in the extrapolation, approximation and assessment of natural hazards. Moreover, many studies have envisaged RS and GIS tools for predicting the probable slope failure sites (Jade and Sarkar 1993; Kumar *et al.* 1993; Pandey *et al.* 2008).

The Singrauli coalfield, covering an area of 2200 km², is located mainly in the Singrauli District of Madhya Pradesh, except an area of 80 km² in the east falling in the Sonebhadra District of Uttar Pradesh. Singrauli town is 768 km from Bhopal, capital of the Madhya Pradesh. Singrauli shares its district boundary with Mirzapur and Sonebhadra districts of Uttar Pradesh on the north and north-east. It is enclosed on the south and south-east by Koriya and Surguja districts of Chhattisgarh and on the west by Rewa and Sidhi districts of Madhya Pradesh (figure 1).

Singrauli coalfield and surrounding regions comprise of two distinct morphological units – plateau region and the plain below. Mining blocks are largely situated in the plateau region. The plains below are drained by Rihand river and its tributaries including northern boundary being drained by Gopad river system (Das *et al.* 2007). The Singrauli coalfield area is situated in the plateau region on the undulating fertile plains and the area is dominated by cluster of low hills. Singrauli coalfield is located at a greater elevation as compared to those of Talchir Formation. The coalfield is bounded on south, east and west by scarp faces of rock formations belonging to Barakar formation. The northern side is bounded by rocks of Archaean formation that limits the rocks of Barakar formation (CMPDI 2005). The Lower Proterozoic rock formation in this region forms a series of east–west trending ridges which is prominent all along the northern boundary of the coalfield. Singrauli has a step-like scarp faces towards south, and representing different stages of peneplanation (Arnous *et al.* 2010). The different platforms are of remnant type resulting from erosion of sedimentary strata of varying resistance. The Jhingurdah open pit coal mine constitutes the northeastern part of the coalfield.

Jhingurdah is a crescent shaped sub-basin, with the northern boundary truncating along boundary fault against the adjacent metamorphics. The entire sub-basin has a centripetal dip with strike from east to west varying from NE–SW to NW–SE. The coal seams occur as a synclinal deposit with a northerly dip (Joshi and Guha 1963). The coal-bearing sediments are separated from the adjacent metamorphics by an E–W trending boundary fault (figure 2). The boundary fault runs parallel to the Son–Narmada lineament and might be an offshoot of the same. The general trend of the faults traversing the pit area are ENE–WSW to NE–SW and WNW–ESE to E–W (Chaudhuri *et al.* 2000).

The coal bearing Raniganj formation sediments (primarily sandstone) have been separated from the adjacent metamorphics, in the northern extremity of the pit by E–W trending aforesaid boundary fault having a southerly throw (Tripathi *et al.* 1972). It was also observed that there were development of several detachment faults also parallel to the slope azimuth of the major boundary fault in the pit area. N–S trending detachment faults having a westerly throw are located to the north of central part of the pit. These might have caused a displacement of the boundary fault,

Figure 2. The boundary fault along the northern periphery of Jhingurdah open pit coal mine separating the sedimentary formations from the adjacent metamorphic rocks.

thereby shifting the contact of the sandstones belonging to Raniganj formation and the pink quartzite (metamorphics). The central part of the pit is also traversed by other offshoot parallel and sub-parallel faults having a trend of E–W with northerly throw of 60–90 m and those trending NE–SW with an easterly throw of 10 m (Tripathi *et al.* 1972). The trend of the faults traversing the western part of the pit are E–W, NE–SW and ENE–WSW. These faults truncate against the boundary fault, with the throw varying in between 25 and 85 m in different sections of the pit (Tripathi *et al.* 1972). Highwall slopes in the mine pit are thereby prone to different failure modes by virtue of rock formations in some of the sections being completely faulted as a consequence of aforesaid faulting. Other than these, the entire pit area is traversed by several other faults of smaller scale truncating against each other.

Mining operations in Jhingurdah open pit coal mine, Singrauli coalfield are confronted with serious slope failure problems. Jhingurdah open pit coal mine was experiencing movements of highwall benches without any major slide since July 2000. Since then, this phenomenon was still continuing with development of minor cracks. But, again from January 2009 onwards, fractures were observed on the highwall benches in the eastern part of the pit, with horizontal movement of 4–5 cm per day and vertical movement to the tune of 3–4 mm per day. Some of the common highwall slope instability manifestations observed were plane, wedge and toppling failure in case of rock mass whereas

circular failure in case of clay and highly jointed rock mass. Henceforth, accordingly a potential highwall slope failure susceptibility zonation was done using multi-layered spatial information.

The main data used in this study mostly comprised of Landsat 7 satellite images acquired from National Aeronautics and Space Administration (NASA) Landsat archive <http://landsat.gsfc.nasa.gov/data>. The same was also obtained from the Earth Resources Observation and Science (EROS) Centre of USGS by using the Global Visualization Viewer (GLOVIS) <http://glovis.usgs.gov>. Elevation data was obtained from Indian Space Research Organization (ISRO), Indian Earth Observation Visualization (Bhuvan), National Remote Sensing Centre, NRSC (CARTOSAT Data) <http://bhuvan3.nrsc.gov.in/applications/bhuvanstore.php> website.

2. Methodology

A hazard zonation technique was used in this study to demarcate regions and areas of potential slope failure within the mining areas as well as adjoining areas governed by geological, atmospheric, geomorphological and anthropological parameters.

This study involved identifying and mapping of lineaments, analysis of their trend and density. A discrimination of lithology, derivation of elevation, aspect, and slope were done for further processing, analysis and integration. Land use/land cover data of the area were also integrated for generation of

slope failure hazard zonation maps. Satellite data obtained for this study from various websites were geo-referenced to the Universal Transverse Mercator (UTM) coordinate system, using zone 44 North based on topographic map. These satellite imagery and data were processed, enhanced and evaluated. The topographic features of the study area and the adjoining regions were studied by means of digital elevation model (DEM) created from CARTOSAT digital elevation data obtained from ISRO, Bhuvan website (ISRO 2011). Finally, in this study the potential slope failure zones within the study area was demarcated and mapped. Different techniques were undertaken for the aforesaid study included (i) layerstacking, (ii) classification (generation of land use/land cover maps), (iii) generation of false colour composites (band combinations and ratioing), (iv) generation of shaded relief and digital elevation models, and (v) lineament extraction and generation of density maps, buffer maps, rose diagrams.

Multi-data integration, weight and rank calculation was primarily used to combine the characteristics of different slope failure causative and/or influencing datasets into one. Accordingly, a weighted overlay classification of different input rasters generated in this study, i.e., slope, aspect, elevation, lineaments and land use/land cover was carried out. Thus, the resulting map obtained as output had all the attributes of the different aforesaid inputs. In this overlay analysis, layers from both surface as well as proximity analysis were included. This approach was then used to rank of the different causative factors (inputs) by suitability and risk factor and then added, to produce an overall ranking for each cell. The different input layers were also assigned relative importance to create a weighted ranking. The ranks in an input layer were multiplied with that of the weight value of different classes identified within the layer before being summed up with other input layers. Same process was repeated for rest of the input layers and corresponding classes. Further, details of this analysis, ranking and weightage allocation has been elaborated in section 5. Future significance and scope of such work may be foreseen as its predictive value in similar mining regions. The detailed flow chart presenting the methodology employed to acquire the desired final output is shown in figure 3.

Spatial database such as classification, subsequent land use/land cover and false colour composites of the study area were generated using TM

satellite data. The elevation data was extracted and analyzed from CARTOSAT data for spatial data base generation. These were further processed and analyzed in order to obtain slope failure hazard zonation maps.

3. Results

3.1 Slope map

The different derived slope attributes were elevation, slope and aspect. Through the slope analysis in ArcGIS 10.1, the gradient of slope from each cell of the raster layers representing the study area and adjoining areas were identified. Slope map represents the rate of maximum change of z-value from each cell and hence is very essential for determination of slope parameters. The slope angle distribution has been grouped into five classes for Jhingurdah open pit coal mine, Singrauli coalfield as shown in figure 4. Highest slope failures were observed in the field within classes between 50 and 78°, whereas lowest within classes between 12° and 38–49°.

3.2 Aspect map

The aspect analysis was done through the aspect utility of the surface function to derive the aspect (the direction the highwall slopes were facing) from the raster surfaces of the study area. Aspect gave the slope direction, by identifying the downslope direction of the maximum rate of change in value of a cell (processing cell/centre cell) with respect to that of each neighbouring cell. Thus, the values in the output raster gave the compass direction that the highwall slopes faces in the open pit mine as well as adjoining areas. This is measured clockwise in degrees from 0 to 360° due north and is shown in figure 5. During generation of the output raster (aspect map of the study area), the level areas with no downslope direction in the mine were allotted a value of -1. Accordingly, the aspect of the slopes (figure 5) of Jhingurdah open pit coal mine, Singrauli coalfield were obtained in positive degrees measured clockwise from north. Certain cells within the raster layer with no inherent data in them were analysed by assigning them as centre cell, followed by calculation of aspect.

In Jhingurdah open pit coal mine, Singrauli coalfield, slope failure densities are minimum for north, north-east, north-west, east and south-east

Figure 3. Methodology adopted in this study for slope failure hazard zonation.

facing slopes as compared to that of south and south-west facing slopes. West facing slopes too are vulnerable to slope failure. The susceptible slopes in this region were mostly located in south-western quadrant. Accordingly, on the basis of directions, entire region has been categorized into high risk (south and west), medium risk (south-west and north-east) and low risk (north, east, south-east and north-west).

3.3 Elevation map

The elevation map (figures 6 and 7) was developed using ArcGIS 10.1, by virtue of classification and processing of the Cartosat elevation data obtained from ISRO Bhuvan's data services. These maps were used for studying the correlation between

heights and slope failures, thereby aiding in determining the potential failure zones.

The slopes at height range of 341–571 m within the study area were observed to be most susceptible to failure. These slopes were also characterized with steeper slope angles. The susceptibility of these slopes to failure was further enhanced due to combined effect of soft strata constituting them and the associated mining practice. Also, the regions having heights within the range of 273–340 m showed some proneness to failure, if and only if guided by any type of disturbed geological discontinuity traversing the rock formations constituting the slopes of the area and region. The other areas of the region with heights ranging from 137 to 272 m were comparatively stable. The rate of erosion in these areas were also guided by the heights of the slopes in the region.

Figure 4. Slope map of Singrauli coalfield.

Figure 5. Aspect map of Singrauli coalfield.

A statistical correlation of the elevation of the slopes with that of the corresponding failures as recorded in the field was also carried out. It was observed that both these variables are positively correlated with the correlation coefficient being 0.96.

3.4 Map generation for feature discrimination

A discrimination of different features within the mine pit as well as adjoining areas was undertaken in this study. The various image processing techniques applied for the preparation of refined maps

Figure 6. DEM of Singrauli coalfield area.

Figure 7. Elevation map of Singrauli coalfield.

included principal component analysis (PCA), false colour composites, band ratioing and band combination.

3.4.1 Band ratioing

Through this technique, different rock units existing in the area were highlighted by virtue of their strong absorption or reflection of radiation in certain bands depending upon the mineral content of the different rock units. Different ratios applied in this work on the Landsat TM data and imagery were 3/1, 5/7, 5/4, 2/1 and 4/2. Different

lithological strips or strata were discriminated, by virtue of their different levels of reflectance at band ratio of 5/4 and 4/2. Ferrous minerals bearing formations, within the pit showed high reflectance at band ratio of 4/2. On the other hand, exposed coal seams and mine water bodies were characterized with low reflectance value in the same band ratio (figure 8).

3.4.2 Band combination

The Landsat TM data and imagery that was used in this work comprised of seven bands each of which

Figure 8. Singrauli coalfield at band ratio 4/2, with Fe bearing soil and rock showing high reflectance and exposed coal seams and mine water bodies showing low reflectance value.

Table 1. Different band combinations employed on satellite imageries of Jhingurdah open pit coal mine, Singrauli coal-field.

Sl. no.	Combination no.	R (red)	G (green)	B (blue)
1	I	7	5	1
	II	2	3	1
	III	2	4	1
	IV	2	4	5

were combined in various diverse combination in order to extract more information from the images. The various band combinations employed in this work on the satellite imageries are tabulated in table 1.

A band combination of R(7), G(5), and B(1) bands into a colour composite provided the best results among the other attempted band combinations in this study. The broad features discriminated in the area (figure 9) are: (a) mine water bodies, (b) Fe bearing rock overlying the Barakar formations within the pits, (c) overburden waste rock dump material, (d) exposed coal seams within the operative mining corridors, (e) sparsely and densely vegetated areas, and (f) water bodies.

Two classes of water bodies were identified within the mining areas, producing black colour in the output raster in the band combination 7, 5 and 1 (i.e., Band 7 = red, Band 5 = green and Band

1 = blue). First one being mine water sumps in areas of active mining and the second one being abandoned pits filled with water. A third class of water body, i.e., those outside the mining areas produced blue colour, as manifested in the output raster by Govind Ballabh Pant Sagar reservoir, located in the eastern side of the pit. The sedimentary rocks pertaining to Barakar Formation were perceived as red strips owing to their high reflectance in the above mentioned band combination. The highest reflectance values in this aforesaid band were obtained for the heterogeneous mixture of blasted and fragmented spoil heaps of soil and rocks. These spoil dump heaps comprises of sandstone, shale, carbonaceous shale and shale. These are excavated from surrounding layers of coal seams, and are accommodated both inside the quarry and outside the quarry as internal and external dump respectively.

3.4.3 Lithological map of the pit areas

Lithological map of the pit area was compiled from (a) the geological map of the study area (Choubey and Shankaranarayana 1990), (b) geological quadrangle map, Sihawal quadrangle Madhya Pradesh–Uttar Pradesh, Geological Survey of India, based on Survey of India map No. 63L, Government of India, 1983, and (c) from the discriminated lithological entities in the processed Landsat imageries of the study areas. Finally, the lithological entities

Figure 9. False colour composite (FCC) map of Singrauli coalfield with band combination R(7), G(5) and B(1) showing different features in and around the study area.

Figure 10. Lithological map of Singrauli coalfield.

were classified into nine different groups as shown in figure 10.

3.5 Lineament mapping – lineament extraction and analysis

Lineaments are frequently observed in remote sensing imagery as combinations of stream patterns or topographic alignments. Linears are naturally/culturally occurring features observed in remote sensing imagery, which are delineated based on distinct patterns of adjacent features with various combinations of linear patterns, tonal changes or tonal variation (Pal *et al.* 2006, 2007a, b; Narayan *et al.* 2017). They are seen in remotely sensed images as a simple or composite linear feature on the surface (Pal *et al.* 2006). The

lineaments have often been observed to be surface expressions of sub-surface faults (Sabins 2007). Henceforth, it was prudent to carry out a mapping and analysis of the lineaments traversing the area.

The procedure followed here for the extraction, analysis and elucidation of lineaments in the study area involved the steps similar to that suggested by Rahiman and Pettinga (2008) and were accomplished in three phases: (i) The first phase involved digitization and analysis of lineaments (grid-wise) using multiple satellite imageries and shaded DEM relief maps of the grids, at a scale of 1:155083, (ii) in the second phase, all the lineaments from all the grids covering the entire study area were extracted and analyzed from various colour composites including both true colour composites as

well as false colour composites and shaded relief DEM's illuminated from north and, (iii) in third phase, lineaments were extracted and analyzed with its impact on the stability of the slopes of the region point of view.

3.6 Lineament extraction

Nine diverse processed as well as unprocessed satellite images were employed in this work for identification and digitization of lineaments in and around the study area. Different scales of the processed images as per the requirement was used in the mapping of lineaments. The minimum length of lineament mapped was of 0.076 km and the maximum that of 5.35 km, and as a result inclusion of lineaments of these dimensions, covered almost all the lineaments of the study areas. No association of any major geological structure, geomorphological unit or any other was found with traced and digitized lineaments of lengths less than 0.5 km. On the other hand lineaments with lengths of 0.6, 2.2 and 2.3 km were the best indicators of faults, fractures and associated slided areas within the pits as well as in the adjoining areas.

The inclusive set of processed images generated and used for lineament identification, digitization and representation includes figures 11, 12 and table 2.

Amongst all the composite images generated principal component and shaded relief DEMs were two of the images that overall provided the most conspicuous and distinct view of the lineaments in the area, to be analysed and digitized. The trends revealed by the digitized lineaments, showed close association with the faults mapped in the study areas which in turn again were found closely associated with the various failures of slopes within the mine pit as well as in the adjoining area.

Attribute table tool was used to create and store the various classes of information associated with the digitized lineaments such as length, category, etc. Jhingurdah open pit coal mine, Singrauli coalfield area mainly comprised of structural lineaments with selected geomorphic lineaments, which were categorized on the basis of drainage pattern, tonal variation as well as other traces used for mapping. The lineaments in the study area were selected and digitized, only if their straight, non-curved length was more than a pre-determined fixed length in the region. Some specific curvy linear lineaments were also established on the western flank of Jhingurdah open pit coal mine, Singrauli

coalfield, which were digitized by the use of a number of straight line segments.

3.7 Lineament analysis

The lineament analysis in this work is mainly based on the length of the lineaments, i.e., maximum, median, average length of the lineaments and standard deviation of the length (table 3). The total count of lineaments in the study area affecting the stability of the slopes of the region has also been accounted in this work. All these analyses were done by importing the geo-database into Microsoft Excel worksheet (MS-Office).

Again, rose diagrams (figure 13) were made in order to illustrate the orientation of the lineaments. These diagrams were generated for further comprehensive analysis of manually extracted lineaments common in both principal component Landsat colour composite red (PC1), green (PC2), blue (PC3) and false colour composite red (7), green (4), blue (2). GeoRose 0.5.1, a geological rose diagram program was used to create the rose diagrams. In this case, with lineaments digitized, the primary trend was E–W, and the secondary trend NW–SE.

The identified lineaments have vector mean value of 268 with circular variance 0.75 and circular standard deviation 96. The number of lineaments identified in the south of the boundary fault (separating the coal bearing sedimentary rock formations from the adjacent metamorphics) is 46, which have a vector mean value of 209 with circular variance 0.90 and circular standard deviation 125. On the other hand, the number of lineaments identified in the north of the boundary fault is 13, which have a vector mean value of 284 with circular variance 0.01 and circular standard deviation 11. In accordance with the study carried out by Pal *et al.* (2006), it was observed in this study too that the lineaments to the south of the boundary fault have greater circular variance as well as greater circular standard deviation than those of lineaments to the north of the boundary fault. This indicates that the sedimentary rocks within the pit area south of boundary fault have relatively undergone several phases of structural deformation than the metamorphic rocks adjacent to the north of the boundary fault.

Data pertaining to the mapped geological structures such as folds, faults, joints, fractures, etc., traversing the study area were compared to the digitized lineaments. Further analysis was carried out by creating multiple buffer zones (strips) (figure 14)

Figure 11. False colour composite – R(7), G(4) and B(2) of Singrauli coalfield with digitized lineaments.

Figure 12. Principal component Landsat colour composite – band combination R(PC1), G(PC2) and B(PC3) for Singrauli coalfield with digitized lineaments.

Table 2. *Generated satellite image composites and shaded relief DEMs.*

Landsat TM imagery
Single band (Band 5) raster data
True colour composite R(3), G(2), B(1)
False colour composite R(7), G(4), B(2)
Colour composite R(2), G(3), B(5)
Principal component R(1), G(2), B(3)
Cartosat imagery – DEM – shaded relief map
Sun illumination 30° (perpendicular to the prominent lineaments in the area)

covering the area of the lineaments (geological structures, specifically faults) at a distance of 0.5, 1 and 1.5 km. All the digitized lineaments were within each of these buffer zones and was highlighted. The orientation of most of the lineaments followed the general trend of E–W (east–west). However, some of the lineaments in the south-eastern parts were traced to have a trend of NW–SE. Lineaments of both these trends within the buffer zones was integrated in this study. The study area comprised of geological structures, of different scales and correspondingly the features around these structures generated were also of different scales. Nonetheless, the average feature size around the geological structure is of 3.6 km long and 3 km wide in the study area. Thus, this analysis provided specifics about lengths, total counts and orientation ranges supported by some of the mapped geological structures and other auxiliary data of the region. This analysis also aided in categorization of the buffer zones on the basis of lineament counts in a single buffer zone and their interaction with each other.

3.8 Land use/land cover map

The entire core area of Singrauli coalfield includes the area comprising of mine lease area. Therefore, to understand the land use/land cover of the contiguous areas of mining, it was also mapped. Core area of the Singrauli coalfield region showed dominance of deciduous forest cover (36%),

fallow land (21%), built-up active mining area (16%), agriculture cropland (12%), scrub land and scrub forest (13%) and built-up urban (1%). Rest of the remaining area under built-up rural, agriculture plantation, reservoir/lakes/ponds constituted 1% of the total core area.

4. Integration and analysis of thematic layers

The final objective of all the above image processing techniques was identification and extrapolation of potential zone of failures within the highwall slopes of Jhingurdah open pit coal mine as well as other open pits within the Singrauli coalfield. The maps generated through the processing of various satellite imagery and data was subsequently used for several reclassifications and in weighted overlays. This weighted overlay classification was achieved using the model builder function of geo-processing utility, in order to produce concluding absolute hazard maps relating and combining all the above mentioned and generated parameters of slope failure hazard zonation.

4.1 Ranking and weightage allocation

All the generated thematic maps were integrated in ArcGIS for analysis, i.e., deriving the aggregate score of weight rate and creation of the final hazard maps. The integration involved combination of various spatial data layers in different percentages as per their respective weightage. The input rasters in this work included lineaments, geology/lithology, slope, aspect, elevation and land use/land cover.

In the weighted overlay classification here, the different causative factors were assigned a numerical ranking on a 1–9 scale in order of their significance. The value class for each input raster was assigned a reclassified value on an evaluation scale of 0–9 on the basis of suitability, risk factor and preference, whereby 0 signifies minimum aptness and 9 signifies maximum aptness to failure. For example, in slope raster, suitability

Table 3. *Length statistics of lineaments digitized from Landsat imagery and Cartosat shaded relief DEM.*

Total count	Total length (m)	Average length (m)	Median length (m)	Maximum length (m)	Standard deviation
60	37500	625	489.5	2538	473.20

Figure 13. Rose diagram of lineaments extracted from Landsat TM (principal component image and false colour composite; R(7), G(4) and B(2)).

Figure 14. Buffer area map of lineaments located towards the northern periphery of Singrauli coalfield.

values are high with low risk factor for slopes with lesser overall slope angle ($0-40^\circ$) and low with high risk factor for slopes with higher overall

slope angles ($60-84^\circ$). In the aspect raster, suitability increases and the risk factor decreases with the orientation of the bedding planes forming the

Table 4. Ranking and weightage allocation of input thematic layers for weighted overlay classification/generation of potential slope failure hazard map.

Parameter	Ranks	Classes	Weight
Lineaments	8.5	Faults	7
Geology/lithology	9.3	Quartzite	4
		Sandstone	6
		Shale	5
		Coal	7
Slope	9.5	> 5°	1
		5–10°	3
		10–20°	6
		20–40°	8
		40–80°	9
Aspect	5	South facing (157.5–202.5)	9
		West facing (247.5–292.5)	6
		South-west facing (202.5–247.5)	6
		North-east facing (22.5–67.5)	5
		North facing (337.5–360)	5
		East facing (67.5–112.5)	3
		South-east facing (112.5–157.5)	2
Elevation	7	North-west facing (292.5–337.5)	1
		>30 m	1
		30–60 m	2
		60–150 m	2
		150–250 m	7
		250–300 m	8
Land use	7	<300 m	9
		Vegetated areas	1
		Water bodies	2
		Mine water bodies	7
		Exposed/excavated highwall slope face areas	8
		Overburden waste rock dump areas	9

Figure 15. Slope failure hazard risk map of Singrauli coalfield (integration of slope, aspect, elevation and land use/land cover data).

Figure 16. Slope failure hazard risk map of Singrauli coalfield (integration of lineament density).

highwall slopes (i.e., bedding planes dipping away from the pit). Classes that were not included in this analysis were allotted restricted values. For example, in land use/land cover, water bodies were allotted restricted value. The comprehensive allocation of ranking and weightage values of the input thematic layers are tabulated in table 4.

4.2 Slope failure hazard risk maps

The result of all the above-mentioned analysis techniques was the generation of slope failure hazard risk maps (figures 15 and 16). As per the hazard maps of the study area, it was found that the vulnerable zones cover 10.57% of the total area (397 km²). All the exceedingly vulnerable slopes in Singrauli coalfield are located all along the lineaments trending in the area and the associated faults traversing the highwall slopes of the Jhingurdah open pit coal mine located at northern periphery of the basin. Some failure susceptible slopes are also situated in the southwestern part of the study area along localized fractures passing through the slopes of the area. Apart from these, some of the man-made temporary slopes (dragline dumps) in the height range of 160–210 m were also demarcated as moderately susceptible to failure. Moderate hazard extents in the area also included slopes of overburden material of the active open pit coal mines of Singrauli coalfield other than Jhingurdah open

pit coal mine, dumped along the stream channels traversing the area.

5. Conclusion

The statistical analysis of the delineated lineaments based vector mean, circular standard deviation reveals that the lineaments to the south of the boundary fault have greater circular variance as well as greater circular standard deviation than those of lineaments to the north of the boundary fault. This study thereby reveals that the sedimentary rocks within the pit area south of boundary fault have relatively undergone several phases of structural deformation than the metamorphic rocks adjacent to the north of the boundary fault.

Further, present study highlights the significant contribution of remote sensing and GIS techniques in slope failure hazard zonation mapping. Six different parameters concerning slope failure in the area were identified which include lineaments, rock type, slope, aspect, elevation and land use depicting the area. Aforesaid causative factors were considered with proper ranks and weights on the basis of their significance, suitability, risk factor and preference. This analysis thereby directed towards generation of slope failure hazard maps and following specific potential risk zones were identified: (i) high risk zone areas comprising lineaments trending E–W, NW–SE and associated

faults encompassing the highwall slopes particularly in the northern periphery of the basin (Jhingurdah open pit coal mine), (ii) medium risk zone areas with highwall slopes constituted of soil and rocks such as shale, mudstone, etc., in the northern and north-eastern parts and (iii) low risk zone areas along localized water channels formed along the bedding planes and through the highwall slopes fed by aquifers as well as rain water.

The status of such vulnerable zones under slope failure hazard risk was found to be covered of 397 km², i.e., 10.57% of the study area. The weighted overlay technique used for this work led to infer the above slope failure hazard risk maps which is understood to be significant for its predictive value to the ongoing mining as well as future developments of mine planning in similar environment. The slope failure hazard risk maps highlight the risk zones of potential slope failures. This study has the capability of providing significant information about the slope situation without much field geological investigation of the slopes, drilling of rock cores from slopes and/or other such field investigation. Such maps generated may prove a likely platform to the mining agencies, operators and planners to better orient the mining practice accordingly and undertake desirable precautionary measures.

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