SUSTAINABLE MINING AND GEOINFORMATION

Prof. Mukunda Dev Behera

Centre for Ocean, River, Atmosphere and Land Sciences (CORAL)

Indian Institute of Technology Kharagpur

Week – 02

Lecture 08: 3-Dimentional Terrain Modeling

 Welcome. Let us discuss 3D Terrain Modeling in Mining. This is the 8th lecture. In this lecture, we will discuss the importance of 3D Terrain Modeling and the options we have to generate 3D models.

From the various geo-information sources. So, coming to the concepts we will cover: the various techniques for creating 3D terrain models using photogrammetry and LiDAR. 3D visualization, which is another important aspect, is needed to visualize them in three dimensions. So, 3D visualization for mining planning and geotechnical analysis, and we will also take a case study that uses 3D models for resource estimation and visualizing mining development. So, let us explore 3D terrain models in mining.

As you can see on the right-hand side, a three-dimensional depiction of topography or terrain. A 3D terrain model represents the surface features of an area, capturing changes in elevation, topography, and landscape structures. Friends, on the upper right-hand side of the picture, you can visualize that the red color indicates higher elevation than the blue area. This means the terrain is represented in three dimensions, as we perceive or see in the real world. So, generating or visualizing a three-dimensional surface in a two-dimensional space.

So, we need to do some modeling, which falls under the 3D terrain modeling. And we need to do it, and it has a lot of application requirements as far as the mining industry is concerned. It enables visualization, analysis, and measurement of the terrain in three-dimensional mode, which is really critical for complex environmental systems like various mining sites. So, what are the tools we have? The tools and technology we have to generate these kinds of 3D models could be or are photogrammetry, the LiDAR—we already have discussed a few things in our LiDAR class.

The geographic information system—we will also see how, based on the TIN, triangulated area network, we also see this, we generate these three-dimensional models. And also, the virtual reality or VR and augmented reality or AR. So, these are the four broad tools and techniques we have to come out with three-dimensional models. Understanding the digital elevation model (DEM)—so, friends, a DEM generally represents land surface elevation across an area, typically a raster grid where each pixel represents the average elevation of that area. If an elevation model is represented in terms of a grid, in terms of a raster grid, The midpoint or each pixel represents the average elevation of that area.

Now, on the lower right, we can see a grayscale depiction that very well talks about or demonstrates the digital elevation model in grayscale. So, the types of DEM—sometimes we come out with two terminologies in terms of surface and terrain. So, this necessarily differentiates the other earth features which are present over the earth's surface apart from the terrain. So, basically, the terrain model is minus the surface features which are present over the earth, such as the tree canopy or a construction or a house or an industrial area. So, if you include the surface, including the forest areas or the green space, you call it the DSM, digital surface model.

Otherwise, the raw or bare terrain model, if considered, is the digital terrain model. So, methods of generating DEM, as we discussed, include photogrammetry, LiDAR scans, and satellite imagery for large-scale DEM generation. For example, SRTM-DEM—the Shuttle Radar Topography Mission, which flew in the early 2000s—was when the first digital elevation model was created and generated. Using the radar datasets, the ASTER DEM and the CartoDEM—Carto comes from the term CartoSat, which is an Indian satellite (we have CartoSat-1 and 2)—they offer what you might call data at 2.5-meter resolution but in a kind of synchronization mode, which helps use photogrammetry techniques to produce a DEM, also regarded or named as CartoDEM.

So, it is generated or has been generated from Indian satellites. Now, let us look at the term TIN for 3D terrain modeling. A TIN is a 3D surface representation constructed by connecting a set of irregularly spaced points into non-overlapping triangles. Friends, if you look at the image shown there, the points are connected in terms of triangles. Three sides are connected, and at each corner—each meeting point—you have a point.

So, that means this is a representation of a triangular irregular network. The three-dimensional surface representation is constructed by connecting a set of irregularly spaced points. All these points are not regularly spaced because they represent the terrain, the non-uniform variation as far as the points are concerned. So, irregularly spaced points form non-overlapping triangles. The triangles are non-overlapping.

The network is created by triangulating points, typically selected to best represent significant terrain features such as ridges, valleys, and slopes. So, friends, then what is the advantage of this TIN? So, these triangulated irregular network advantages are adaptive in terms of resolution, very precise as far as irregular terrain representation is concerned, and very efficient in data storage because they are vector-based. The representation and the calculation of the slope and aspects generated from this TIN are very precise, and they offer a lot of flexibility in terms of modeling. So, these are the five very important advantages of this triangular irregular network.

So now, let us understand the difference between the digital elevation model and the triangular irregular network. So, as far as the data structure is concerned, DEMs are represented by grids of cells or pixels. So, these are the raster-based representations. Whereas, TINs are triangular irregular networks, which are vector-based representations, as we just saw. So, they are a network of connected triangles represented in terms of vectors.

Difference Between DEM and TIN

Feature	DEM	TIN
Data Structure	Raster (grid of cells/pixels)	Vector (network of connected triangles)
Surface Representation	Continuous grid representing elevation	Irregular network of Triangles formed from points
Resolution	Uniform (all cells have the same size)	Variable (Denser Triangles in complex areas, sparse in flat)
Data Requirement	Requires dense elevation data	Requires fewer points, selectively placed
Application	Broad-scale Terrain Modelling, analysis over large areas	Detailed surface Modelling, Suitable for irregular terrain
Typical Uses	Mineral Pile-up, erosion studies, large-scale mapping	Slope stability, Site-specific analysis

DEM is often used for General Terrain Analysis, while TIN is Preferred for Precise Modeling in Specific Areas

As far as the surface representation is concerned, DEM offers or gives a kind of continuous grid that represents the elevation. In contrast, for the triangular irregular network, it is the triangles that are formed from points. As we saw, the triangles are non-overlapping and are connected through different points. So, an irregular network of triangles is formed from the points. And let us talk about the difference between DEM and TIN as far as the resolution is concerned.

In terms of DEM, the resolution is uniform. That means uniform for all cells. All the grid of cells or pixels have the same size as it is expected for a raster-based representation. Whereas in form of a tin, TIN, it is variable. It is not uniform like raster.

It is variable. So that means it is expected that the denser triangles in complex areas whereas very sparse triangles over flat terrains. So if it is complex areas, you will have more of the triangles whereas for less complex or the flat terrains, we will have very less triangles. As far as the data requirement is concerned the DEM requires very dense elevation data sets whereas the TIN requires few points selectively very selectively placed. And in terms of the applications the DEM have broad scale terrain molding application and the analysis it helps in analyzing over larger areas.

Whereas TIN have detailed surface modelling and suitable for irregular terrain though it is also suitable for over larger areas as well. So, typical uses DEM use in terms of the mining industry could be for mineral pile up and best analysis, erosion studies, large scale mapping. Whereas, as far as the TIN is concerned specifically they could be applied or used in terms of the very precise slope stability calculation and site specific analysis but to be honest all these five different types of applications are valid for both uh in the mining sector so the simple difference is DEM is often used for general terrain analysis while TIN

is preferred for a very precise modeling in specific areas That is the way we use and give little bit of preference in terms of using DEM over TIN or vice versa.

Now let us talk about the techniques available for creating 3D terrain models, the three-dimensional terrain models, based on two different methods. As we know, these are the DEM (Digital Elevation Model) based methods and the Triangulated Irregular Network based methods. So, as far as the DEM-based methods, where the representation is by raster, it has potential in terms of hill shadow analysis, vertical profiling, and perspective view. When we talk about hill shadow, we consider the sun direction and sun azimuth as far as the hill shading analysis is concerned. The perspective view is also very well done using the DEM-based methods. As far as the TIN (Triangular Irregular Network) based methods, we go for contouring, and then break lines are generated in this TIN kind of model.
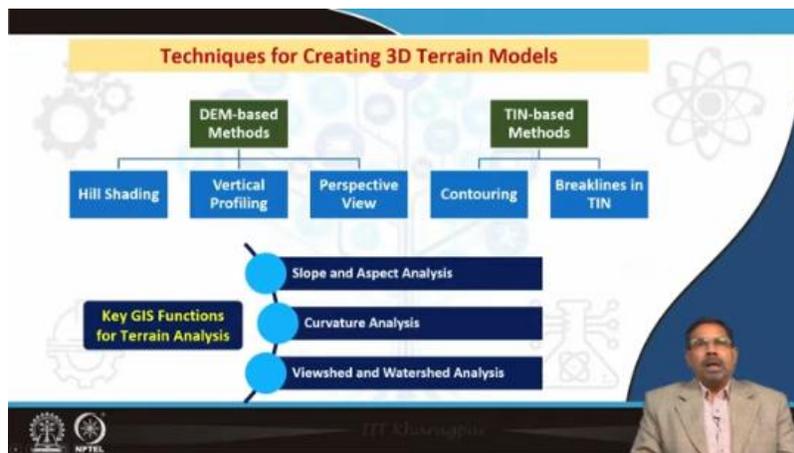
The key GIS functions for terrain analysis are slope and aspect analysis. We very often use this for slope and aspect analysis. Also for curvature analysis. Also for watershed, you could say hydrological analysis, or viewshed—meaning when you go as a tourist, you see from which point you can get a good view or the maximum view of the terrain, or a beautiful view of the terrain, keeping the sun angle and viewing angle into consideration. These are some of the key GIS functions, and they also have similar implications in the mining sector.

Now, coming to the 3D visualization for mine planning and geotechnical analysis. Let us talk about slope and aspect analysis and surface curvature. In terms of slope and aspect, slope measures the rate of elevation change. It is essential for geotechnical analysis to determine stable slopes for excavation and to evaluate the potential for landslides. As far as aspect is concerned, it refers to the direction the slope faces, and therefore it is crucial for assessing sunlight exposure, which impacts erosion and vegetation growth.

3D Visualization for Mine Planning and Geotechnical Analysis

❖ Slope and Aspect Analysis:
➢ Slope: Measures the rate of elevation change. It is essential for geotechnical analysis to determine stable slopes for excavation and for evaluating the potential for landslides.
➢ Aspect: Refers to the direction a slope faces and is crucial for assessing sunlight exposure, which impacts erosion and vegetation growth.

❖ Surface Curvature
➢ Curvature Analysis: Determines if a surface is concave or convex, which helps identify areas where water might pool or where material might accumulate. It's important in erosion analysis and in estimating the stability of a Terrain

Let us talk about the third one, which is the surface curvature. The curvature analysis determines whether a surface is concave or convex. Thereby, it helps in identifying areas where water might pool or where materials might accumulate. This is important in terms of soil erosion analysis or in estimating slope stability in rough or complex terrain, which is mostly expected in mining environments. So, the photogrammetry techniques that are available for 3D terrain modeling.

Photogrammetry Techniques for 3D Terrain Modeling

Photogrammetry is an Image-Based Approach that relies on Overlapping Photographs to create 3D Models

- Stereoscopic Imagery: Photographs from different angles are used to create a stereoscopic effect, allowing the identification of depth in 3D models
- Ground Control Points (GCPs): Accurate GCPs are essential for georeferencing and scaling photogrammetric models. GCPs allow for more precise alignment of terrain features across images
- Image Matching and Processing: Digital photogrammetry uses algorithms to automatically match points across image pairs, thus generating dense point clouds or 3D meshes
- Structure from Motion (SfM): Series of 2D-Images taken from multiple angles. SfM algorithms calculate the Camera's position relative to the Object, then reconstruct the 3D structure, making it ideal for Areas where LiDAR may not be feasible

Aerial Photogrammetry uses Drones or Aircraft to capture images from above, ideal for large areas like Open-Pit mines

Terrestrial Photogrammetry uses Ground-based Cameras, better suited for detailed or localized studies

Photogrammetry is an image-based approach that relies on overlapping photographs to create 3D models. So, with respect to photogrammetry, let us understand these steps or processes. One is stereoscopic imagery. So, photographs taken from different angles use different angles of the same terrain. If the photograph is taken

from different angles of the same terrain. So, it can be front and aft mode, fore and aft mode, or at a different angle. So, if the photographs are taken in that way, they can be used to create a stereoscopic effect that allows the identification of the third dimension or the depth factor. The GCPs, or ground control points. The ground control points are accurate

because they are generated on the ground, and therefore they are essential for georeferencing and scaling these photogrammetric models.

So, GCPs are useful to have a control as the name is ground control point. They have a control as far as the ground point is concerned, ground reference is concerned. So, GCPs allows for more precise alignment of terrain features across images. The third step is image matching and processing. Digital photogrammetry uses algorithms to automatically match the points across image pairs, thus generating dense points clouds or 3D mesh.

So in this step what happens there has to be overlapping areas. Overlapping areas that mean the same area when has been visualized from two different angles. okay so these place these points they are automatically matched across the image pairs and that is how it enables generation of dense points or clouds which helps in creating the 3D mesh the structure of motion or SFM The structure from motion series of this is the series of 2D images taken from multiple angles. So, SFM algorithm calculates the camera's position relative to the object and then construct the 3D structure.

That is how it makes it ideal for areas where LiDAR or LiDAR may not be feasible or many other technologies or mode of capturing the image is not possible. So aerial photography sometimes we use from drones or aircrafts or the terrestrial photogrammetry uses ground based cameras that are better suited for detailed or localized studies. Friends, the photogrammetry technique can be applied to aerial photographs or the photographs which are taken using the terrestrial cameras. But both of them have different applications in mining sector including open pit mines and many localized applications or studies. We also discussed about this LiDAR for 3D terrain modeling.

LiDAR is a laser-based remote sensing technique that creates highly accurate three-dimensional point clouds of terrain surfaces. So, we know LiDAR scanning sends laser pulses. The time taken for these pulses to return is used to calculate the distance. So, thereby it results in a high-resolution point cloud, which we call a data cloud or data points. LiDAR data is commonly processed into the creation or generation of digital elevation models.

Further, they can be classified into DSM (digital surface model) or DTM (digital terrain model), which excludes surface or earth features based on inclusion or exclusion criteria. So, the filtering algorithm involves many advanced filtering techniques. These are used to separate ground points from non-ground points. That is how, or thereby, it allows for accurate modeling of bare earth terrain, which we discuss or need in terms of the digital elevation model. Let us talk about data processing and accuracy.

LiDAR typically achieves greater accuracy in vertical measurements, often within centimeters. It is less dependent on light conditions. We know it is independent of light because it falls under active remote sensing. That means it uses its own source of data, which is the laser pulses, to create this. So, applications of 3D terrain modeling in mining could be many.

So let us try to understand or divide them as far as photogrammetry and LiDAR based inputs are concerned. As far as photogrammetry based application is concerned, 3D terrain modeling is concerned, the mining industry we use it for surveying open pit mines which gives accurate monitoring of pit walls, stability, stockpile volumes and waste dumps, the mine planning and design. And also volume estimation. Photogrammetry based 3D terrain modeling helps in volume estimation so that we can know how much stockpiling is there. If it is calculated perfectly then it helps in reconciliation with production data.

And also this is a low cost and very highly flexible information. then coming to lidar in mining so lidar based applications for 3d terrain modeling and their utility in mining it helps in detailed topographic mapping slope stability and geo hazard analysis also the vegetation penetration how much vegetation is present how much so when you talk about DTM and DSM these kind of things comes So, we know that how much vegetation is available and then environmental impact assessment and underground mapping. So, to comprehend the 3D terrain modeling applications in mining sector are mostly coming from the structural or the three-dimensional applications. The 3D visualization in mining planning, resource modeling and volume calculation, pit design and optimization, underground mine design.
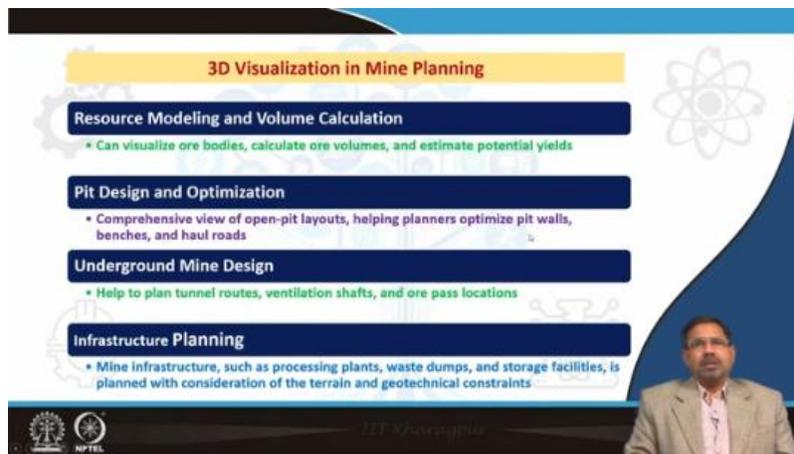
This helps to plan tunnel routes, ventilation shafts and overpass location. Some of this we will also take as examples. In terms of the pit design and optimization, it gives a comprehensive view of open pit layouts, thereby help the managers or the mining planners to optimize the pit walls, the benches and haul roads. As far as the resource modeling and volume calculation is concerned, this can visualize ore bodies, calculate the volume of ore present and thereby estimate the potential yield. So finally, it also has application as far as mining infrastructure planning is concerned.

So mine infrastructure such as processing plants, waste dumps, and storage facilities are planned with consideration of the terrain and the geotechnical constraints. So the moment you have a 3D visualization, which has come from a three-dimensional model, it helps in efficient planning. Mining infrastructure planning. The geotechnical analysis with 3D visualization broadly falls under slope stability analysis, subsurface analysis for tunnels and shafts, monitoring of mining subsidence, and rock mass characterization. The slope

stability analysis in the form of geotechnical analysis could be 3D terrain modeling with LiDAR data, identification of failure planes, and slope angle calculation.
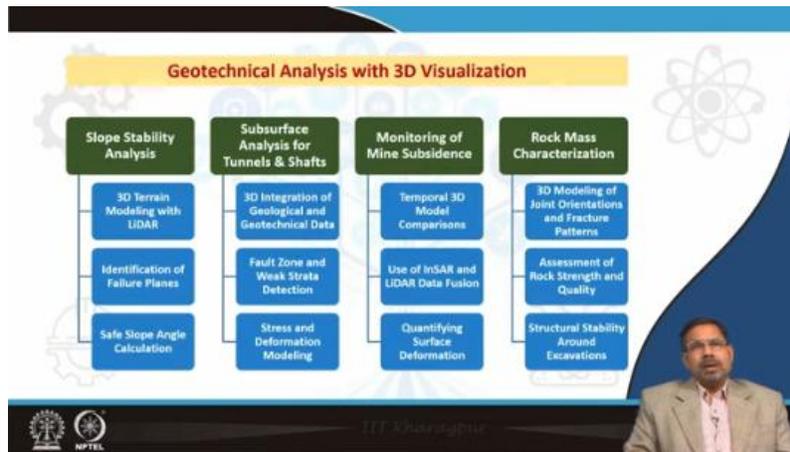
As far as the subsurface analysis for tunnels and shafts is concerned, 3D integration of geological and geotechnical data, fault zone and weak strata detection can be done, and stress and deformation modeling can also be done. Monitoring of mine subsidence includes temporal 3D model comparisons, use of InSAR and LiDAR data fusion, and quantifying surface deformation. And the fourth one, rock mass characterization, benefits from 3D visualization such as 3D modeling of joint orientations and fracture patterns, assessment of rock strength and quality, and structural stability around the excavations. Let us have a case study. Case study using 3D models for slope stability assessment and failure zone identification in mining operations.

Chand and Koner last year in 2023 did this study, which is selected as a case study. This study assesses the internal dump slope stability, identifies failure zones, and provides a cost-effective management framework to the managers. So as far as the data collection, 3D

model creation, slope stability analysis, and findings are concerned. Chand and Koner have used UAV-based photogrammetry images. The GCPs, ground-based control points.

So these UAV-based images have about 75% front and 65% side overlap so that the mesh can be created. Eight GCPs were set up and georeferenced using GNSS. They ensured eight GCPs were set up for each of the images or scenes. For three-dimensional model creation, Pix4D and CloudCompare—these two software tools—were used for generating dense point clouds, orthomosaics, digital elevation models, and digital terrain models. As far as geotechnical analysis is concerned, they collected samples tested in the lab for high-density 3D model creation.

Regarding slope stability analysis, the LEM (Limit Equilibrium Method) was adopted for calculating factors of safety across slices, whereas the FDM (Finite Difference Modeling) method was adopted for analyzing stress-strain, thereby validating the LEM. The findings of the Chand and Koner study identified the failure zone and found that key zones had lower safety factors. The seismic impact—that is, the safety factor under seismic load—decreased significantly, which emerged from this study in terms of dump slope stability and failure zone identification. Another case study discusses optimized 3D SAR imaging with drone trajectory studies.

Hence, we highlight the utility of three-dimensional SAR imaging, as presented by Dorzowicz and Samzengzi in 2022. In this study, they reduced flight time and energy consumption in drone-based 3D SAR imaging while maintaining high-resolution imaging quality. The methodology incl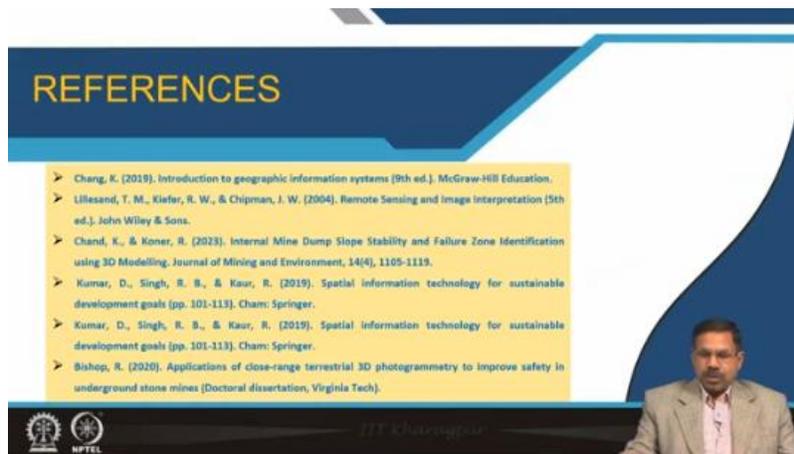uded trajectory optimization, algorithm parameter optimization, and a simulation approach. The data primarily used were SAR radar parameters. Trajectory constraints included maximum velocity and acceleration values tailored to the drone's motion and capabilities. The results showed reduced flight time, very

high-resolution data, improved efficiency, and better data storage. These are the references used for this particular lecture.

So, in terms of the conclusion, these are the five points we have discussed. Three-dimensional terrain modeling and visualization are essential in modern mining for planning, safety, and environmental management. Technologies like LiDAR, photogrammetry, and GIS accurately provide terrain models that help improve decision-making and management efficiency. This three-dimensional analysis helps in understanding slope stability, subsurface structures, volume calculation, and assessing risks to optimize mining or mining area layouts. All these tools, particularly 3D visualization and modeling tools, support the mining industry's focus on safety and sustainability, thereby helping achieve operational excellence and reduced environmental impacts.

So, friends, to conclude and summarize this study on three-dimensional modeling, we discussed the data sources for three-dimensional modeling, including SAR data, tandem

pairs for photogrammetry-related applications, LiDAR data, and GCPs or ground control points. As far as the technique is concerned, many software tools are involved in data processing. As far as the application is concerned, once we obtain the slope aspect and the three-dimensional model, we can proceed with volume calculation. Volume calculation is also related to weight or mass calculation. It helps in determining the amount of deposition in terms of ore or minerals, which relates to production and can also be linked to production efficiency, quantification, or the market.

So, three-dimensional models, satellite or geo-information-based three-dimensional model analysis, and visualization play a very important role and have applications in the mining industry. Thank you very much.