SUSTAINABLE MINING AND GEOINFORMATION

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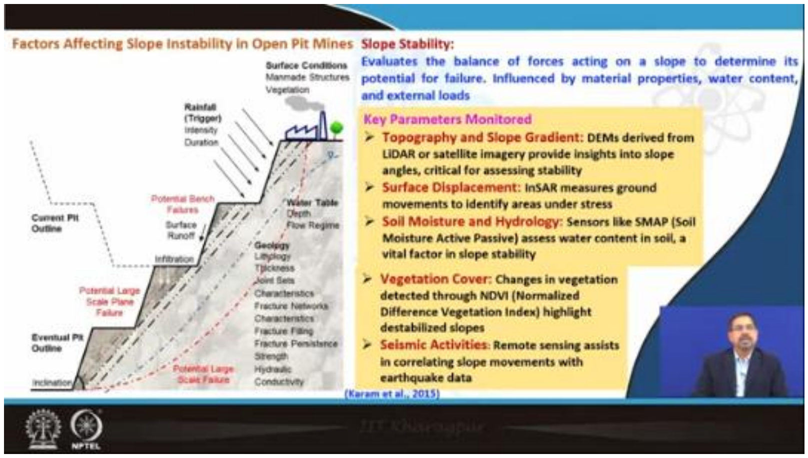
Week – 04

Lecture 17: Topographic & Slope Analysis

Welcome we will talk about topographic surveys and slope management in our lecture number 17. So, friends in the second week we have already discussed the technique of LiDAR the light detection and ranging principle as far as the geoinformation tools are concerned. Today's lecture on topographic survey and slope management. We will heavily discuss on the applications of LiDAR and photogrammetry principle as far as conducting topographic surveys. We will also see the slope stability analysis and management in open pit mines we'll also try to discuss about the multi-faceted approaches that are used to enhance the slope stability assessments and also helps in ensuring the regulatory compliance and thereby support proactive risk management

So, these are in a sense the utilities of topographic survey and slope analysis. And we will also take two case studies on mitigating landslides and slope failure in mining sector using geospatial monitoring approaches. So, let us understand the factors that affect the slope instability as far as a kind of open pit mine is concerned. On the left-hand side, this particular picture or the depiction talks about the factors that leads to slope level instability. You can see the slope conditions, man-made structures including vegetation are there.

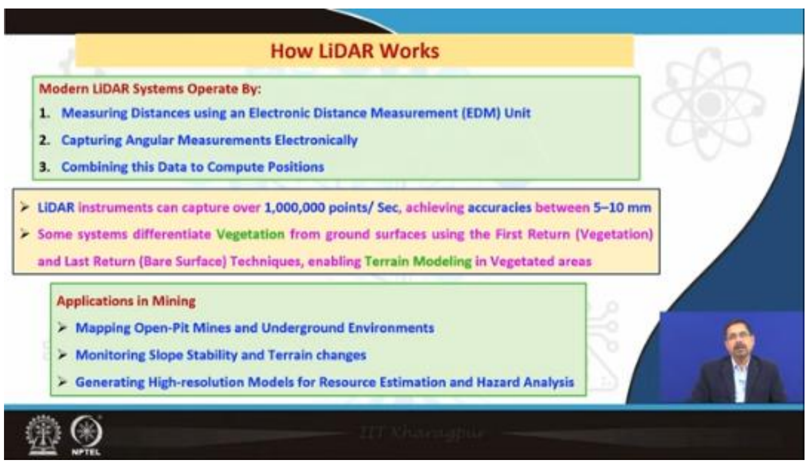


And little lower to that, you see the first factor is the rainfall. So, the triggering factor rainfall triggers and this kind of slope instability and the kind of duration and intensity of the rainfall contributes to the slope instability. second the potential bench failure because when there are rain you have runoff so surface runoff is again what you say country means affects the are affected by the bench failures then you have potential and large-scale plane failure so these are the sources that trigger the slope instability and Slope stability evaluates or we say slope instability evaluates the balance of forces acting on a slope to determine its potential for failure, which is influenced by materials, the property of the material, the water content and the external loads.

So, using the geo-information tools, we can very well monitor this slope instability, the topographical gradient, and the changes in the topography. So, topography and slope gradient digital elevation models derived from LiDAR or other satellite-based techniques or satellite imagery provide insights into slope angle, which is critical for assessing slope stability. Then, surface displacement. In the last class, the 16th class, we discussed the utility of SAR interferometry, which helps in measuring ground movement to identify areas. So, here, these areas can be attributed to different stresses, different drivers, including soil moisture and hydrology.

So, sensors like SMAP, Soil Moisture Active Passive, assess the water content in soil, a vital factor that gives an indication about slope stability. Vegetation cover—the change in vegetation cover—is well detected by various optical satellite-derived vegetation indices such as NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), GVI (Greenness Vegetation Index), and so on. So, these kinds of vegetation indices very well capture any changes as far as the vegetation is concerned. So, changes in vegetation, or you could say deforestation, lead to or have a direct relationship with slope instability because the rain or precipitation falls directly on the ground, on the soil, bypassing the vegetation layer if it is not there. And another one is seismic activity.

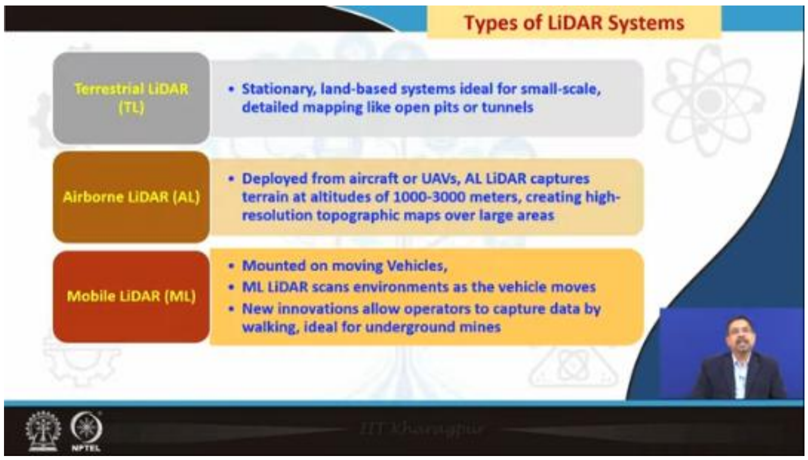
Yes, remote sensing satellite-based images assist in correlating slope movement with earthquake data. So, Karam et al. in 2015 provided this particular narration as far as slope stability or instability is concerned. Now, let's move on to the working principle of LiDAR. Yes, we know that modern LiDAR systems operate by measuring distances using an electronic distance measurement unit called EDM. And these LiDAR systems capture angular measurements electronically and also combine these data to compute positions, locations, including X, Y, and Z, particularly elevation, which is more important.



The LiDAR instruments can capture over 1,000,000 points per second. That is why we call it huge data or point cloud data. So, if these LiDAR systems or instruments capture over 1,000,000 points per second, they are bound to achieve very high accuracy. The accuracy level ranges between 5 to 10 millimeters. Such high precision.

Some systems differentiate vegetation from the ground surface using the first and last return, where the first return may come from vegetation on the ground, and the last return may come from bare ground or the base of the vegetation. This technique helps in terrain modeling over vegetation areas. In the mining sector, this helps in mapping applications. Open-pit mines and also the underground environment. Different types of LiDAR systems exist, and they can be suitably used for mapping open-pit mines and underground environments.

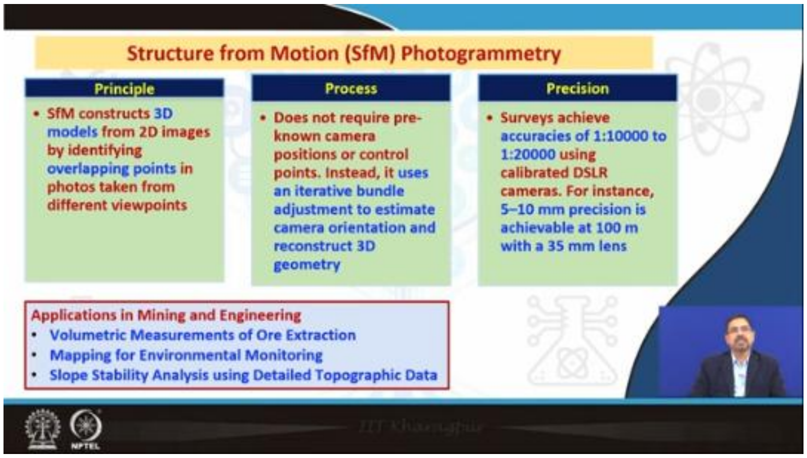
This LiDAR-based information helps monitor slope stability as well as changes in topography or terrain. LiDAR systems help generate high-resolution models useful for resource estimation, particularly stockpiling, and various hazard analyses, where applicable. Now, let us revisit the types of LiDAR systems. We understand that they can be categorized into three types. The TLS, or terrestrial LiDAR scanning, is mostly a stationary device mounted on a tripod and is land-based.



Land-based systems are ideal for small-scale detailed mapping, such as open pits or tunnels. As far as airborne LiDAR is concerned, it needs to be mounted on a platform that is airborne. So, it has to be either an aircraft or a kind of UAV (unmanned aerial vehicle). This airborne LiDAR captures terrain at altitudes varying based on the platform where it is mounted. It may go up to 1 kilometer to 3 kilometers, depending on the elevation or the altitude of the system or the mounting platform.

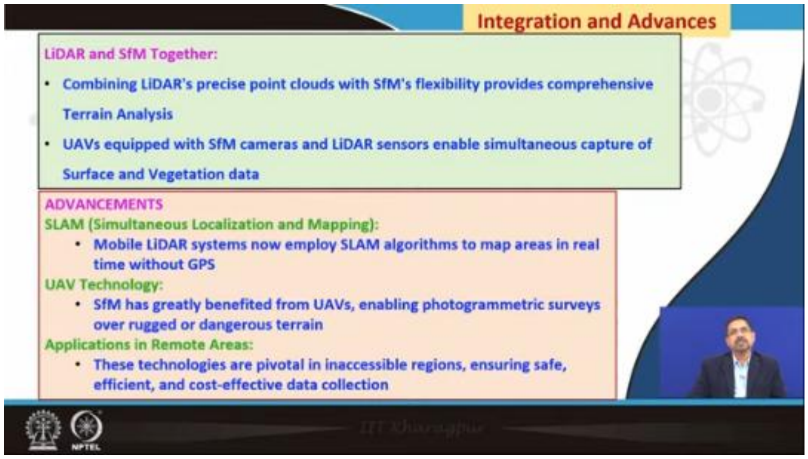
Thereby, it creates high-resolution topographic maps but over a larger area compared to the previous one we discussed, which is the terrestrial LiDAR scanner. Now, the third one we have also studied is the mobile LiDAR. As the name indicates, it could be mounted on a moving platform or a mobile or moving vehicle. This moving vehicle or mobile LiDAR scans the environment as the vehicle or the platform moves. In a sense, this is a new innovation that allows operators to capture data by walking, which is ideal for underground monitoring in mining activities.

Based on the systems, we classify LiDAR into three types: terrestrial, airborne, and mobile. Now, an interesting terminology called SFM, and its expansion is structure from motion photogrammetry. Let us understand this particular term as far as the principle of SFM or structure from motion photogrammetry is concerned. The SFM constructs three-dimensional models from two-dimensional images by identifying overlapping points in photos taken from different viewpoints. Furthermore, as far as the processing is concerned, SFM photogrammetry does not require pre-known camera positions or control points.



Whereas, it uses iterative bundle adjustment to estimate camera orientation and reconstruct 3D geometry. So, that means it saves a lot of time and effort as far as the ground-based locations of the points, meaning the collection of the points, is concerned. Let us have a look at the precision. So, SFM photogrammetry-based surveys achieve very high accuracy. So, accuracy is of 1:10000 to 1:20000 using calibrated differential SLR cameras.

So, these SLR cameras can be very well used for this SFM photogrammetry. So, such as 5 to 10 millimeter precision is achievable at 100 meters with a 30 millimeter lens. So, the applications in terms of the mining sector are concerned with volumetric measurement of ore extraction or stockpile mapping, as well as environmental mapping, as far as the environment and its monitoring are concerned. Steep slope stability can be analyzed using detailed topographic maps that can come from any of these platforms. So, now, talking about the integration and the different advancements as far as LiDAR and SFM together.

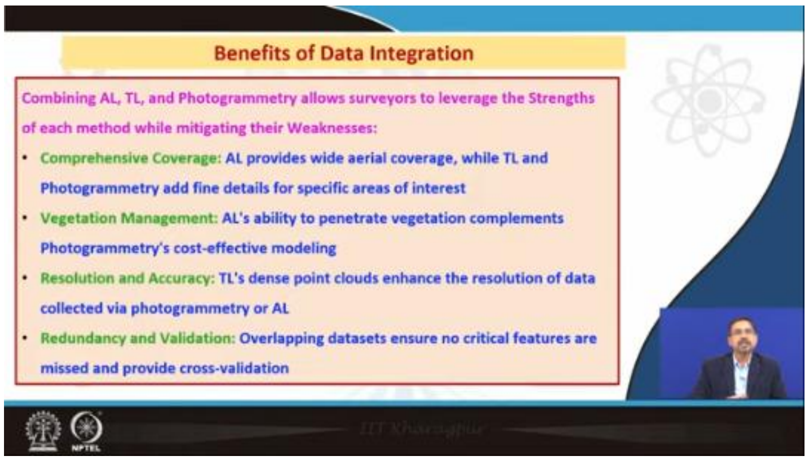


So, combining LiDAR's precise point clouds or data clouds with SFM offers flexibility in terms of very comprehensive terrain analysis. So, one is coming from your high differential SLR camera, and then you merge or combine this data with the very high-precision or large number of point data clouds so that you get a very comprehensive analysis of the terrain. And the UAVs equipped with SFM cameras and LiDAR sensors, both mounted on UAVs, enable simultaneous, or tandem, capture of surface and vegetation areas. So, that is why the integration of SFM and LiDAR sensors provides very comprehensive data analysis. So, the different advancements—let us understand the first one: SLAM.

So, SLAM stands for simultaneous localization and mapping. So, the mobile LiDAR systems employ SLAM algorithms to map areas in real time without GPS. So, when we are taking a lot of this data from the mobile LiDAR platform, we need to do it without GPS because, in underground mining, collecting location points using GPS is nearly difficult—almost impossible—due to satellite visibility and other issues. So, this SLAM method helps in mapping areas in real time without relying on data points from GNSS or GPS-based surveys. Coming to the second one: the UAV technology.

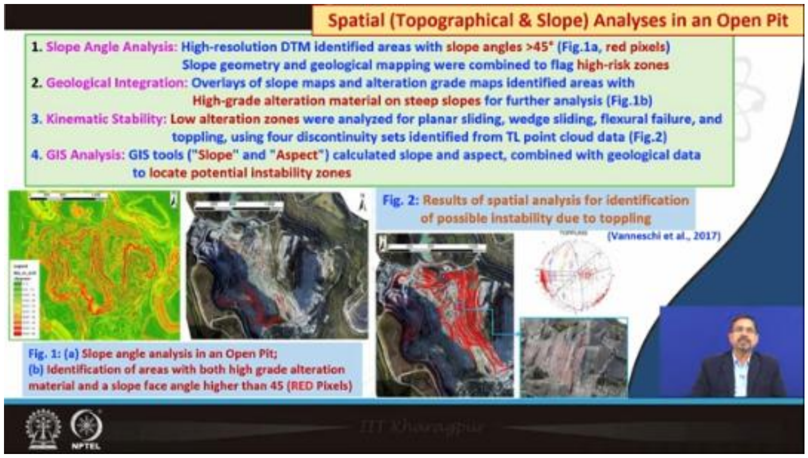
Yes, SFM has greatly benefited from UAVs, enabling photogrammetric surveys over rugged or dangerous terrain. You just mount it on a UAV, with the sensors—either the SLR or the LiDAR cameras—and then you get a lot of data from the UAV platform. Then, applications in remote areas. Yes, these technologies are pivotal in inaccessible regions, such as very complex terrain or terrain you cannot traverse. So, they ensure a safe, efficient, and very cost-effective way of data collection.

So, the benefits of this data integration—combining airborne LiDAR, terrestrial LiDAR, and SFM-based photogrammetry—allow the surveyor or user to leverage the strengths of each method. Without mitigating their weaknesses, it is based on a hybrid principle: you derive synergy by taking the best of them. In a sense, we get comprehensive coverage—the airborne LiDAR provides wide aerial coverage, while the terrestrial LiDAR scanner and SFM photogrammetry add finer details for specific areas of interest. So, if we combine them, we get very comprehensive coverage of the area as far as the data is concerned. Then, coming to vegetation management: the airborne LiDAR's ability to penetrate vegetation helps complement photogrammetry, particularly SFM-based photogrammetry, in reducing costs. So, airborne gives you data over a very broad region.



Whereas the SFM-based photogrammetry gives you data over a small region but very high-precision data. So perhaps we do not need a lot of data as far as the vegetation is concerned, but perhaps as far as the other regions—subsidence, topographic features—are concerned, we only need the SFM photogrammetry-based data. So that is how we see a kind of very selective scanning where we need it, and there we put our maximum energy or effort and the best suitable platform. Coming to resolution and accuracy, yes, the terrestrial LiDAR scanners' dense data cloud or the point data clouds enhance the resolution of data which is collected via photogrammetry or the aerial LiDAR platform. And coming to the last one, as far as redundancy and validation are concerned, yes, overlapping datasets ensure no critical features are missed and provide cross-validation. If you have more than one set of data, then the other set of data sometimes becomes useful for validating the results of the other set.

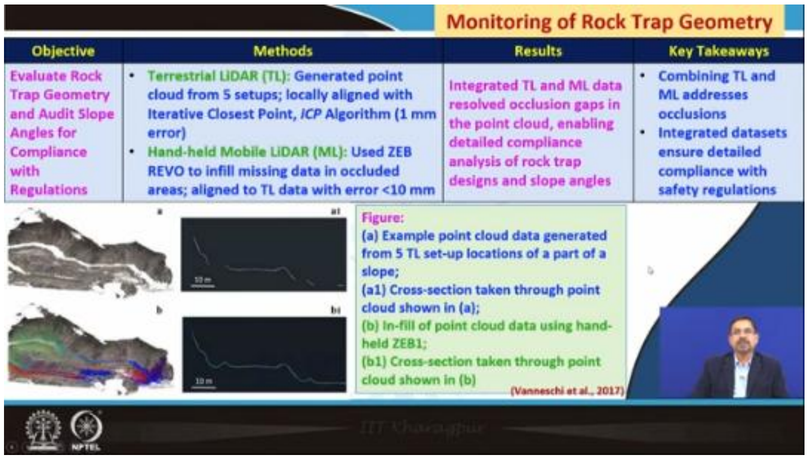
It goes or becomes useful for validating the results of the other set. So, one and other datasets are also sometimes used for cross-validation. So, that is also an important way in terms of our method to validate each other's output coming from different sensors. So, let us understand the spatial analysis in an open-pit mine. So, what happens in terms of the topographical and slope analysis, slope-based spatial analysis?



So, we can see that the slope angle analysis, geological integration, kinematic stability, and finally GIS analysis are possible—these are the different ways to do the spatial analysis in open-pit mines. So, high-resolution DTM—what you say, digital terrain models—identifies areas with slope angles greater than 45 degrees. So, down below, the lower left we can see the slope angle in terms of figure A, has been given. These particular diagrams have been taken from Vanneschi et al., published in 2017. So, the lower left talks about or demonstrates the slope angle in an open pit, and the middle one—the second one—talks about the identification of areas with both high-grade alteration material and a slope face angle higher than 45. Which is shown in terms of the red pixels—so, this itself gives a very clear idea in terms of the angle or the slope coming from slope angle and the areas where alteration has happened.

On the lower right, we can see the results of spatial analysis for the identification of possible instability due to any kind of toppling phenomena. So, slope angle, high-resolution DTM identified areas with slope angles greater than 45 degrees. And slope geometry and geological mapping were combined to flag the high-risk zones. Geological integration and overlaying of the slope maps and alteration grade maps helped in identifying areas with high-grade alteration material on steep slopes. This can be used for any further or future analysis along with other variables.

And as far as kinematic stability is concerned, low alteration zones were analyzed for planar sliding, wedge sliding, flexural failure, and toppling using four discontinuity sets identified from the terrestrial laser scanner data cloud points, which is shown in the lower right figures. So finally, the GIS tool that includes or corroborates the slope and aspect and combines it with other geological data to locate the potential instability zones. So, this study has been done by Vanneschi et al. and published in 2017. Now, from the same study, let us see the monitoring of the rock trap geometry. So, the objective is to evaluate the rock trap geometry and audit the slope angles for compliance with any kind of rules or regulations that prevail.



And the methodology used is the terrestrial LiDAR data (TLS) that generates a lot of data clouds from five different setups locally aligned with the ICP (iterative closest point) algorithm, which gives an error of up to one millimeter. And another dataset comes from the handheld mobile LiDAR (ML) using ZEB REVO. So, that is the specification to fulfill missing data in any of these areas coming from the TLS. So, this has an error that is less than 10 millimeters. Now the results: when this TL and ML—that means the data coming from the terrestrial LiDAR and the data coming from the handheld mobile LiDAR—are combined, this data resolves the occlusion gaps in the point clouds.

Thereby, it enables detailed, comprehensive, and compliance analysis of the rock trap designs and the slope angles. So, the key takeaways in terms of combining data generated using terrestrial LiDAR—the LiDAR data coming from the terrestrial LiDAR scanner and the mobile LiDAR platform—this addresses the occlusions. So, integrated datasets ensure detailed compliance with safety regulations. So, this is very important as far as monitoring the rock trap geometry is concerned. Also, monitoring the slope regression and the material deposition in an open pit.

This study here lets us understand how to analyze the slope regression and the material deposition using multi-temporal datasets. The methods used can be the LiDAR data clouds coming from the airborne platform. And this data was compared with CloudCompare—meaning the CloudCompare software was used to identify the 3D differences in the volume. And this helped in conducting a kind of cross-sectional analysis of the slope profile.

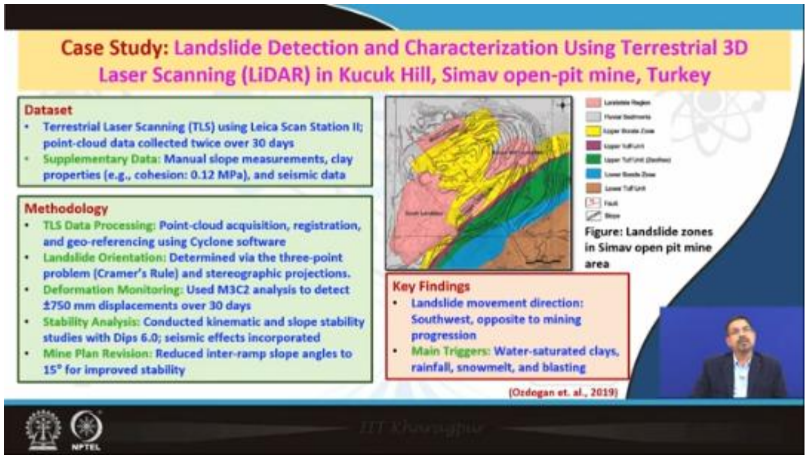
It helped in identifying areas of instability. Instability as far as the loss in volume is concerned and as far as the deposition—that means gain in volume—is concerned. So, that we are getting in a three-dimensional array in a volumetric way. So, this helps in providing insights into slope changes over time. So, the key takeaway in terms of airborne LiDAR data is that it is effective for large-scale analysis as far as volumetric changes are concerned—both loss and gain.

tools like cloud compare software helps in bringing out a 3d differential visualization so this can be very well seen from the diagram the depiction given on the lower left look at the lower left where the material deposition and the slope along the slope has been very well shown in terms of the red color and in a three-dimensional visualization. 2D cross sectional on the red circle area of area is shown and white line refers to the 2011 DTM and red line refers to the 2015 DTM. So, they both of them go together, but you can very well see the marginal difference the shift which is because of the what you say material deposition can be seen or can be separated. Now let us talk about the two case studies.

First one is the slow failure susceptibility zonation using integrated remote sensing and GIS techniques over Jhingurdah open pit coal mine singularly coal field in India. So, here two datasets particular satellite data optical Landsat TM ETM and the digital elevation model has come from the come from the CARTOSAT using digital photogrammetry technique. The thematic layers derived out of this at the slope aspect elevation lithology and land use land cover. The methodology that have been used are the pre-processing steps have been followed, mapping has been followed and particularly the integration using weighted overlay classification ranked factor was followed. And the output is a slow failure hazard map has been generated that highlights different risk zones as has been shown in the upper right-hand side figure.

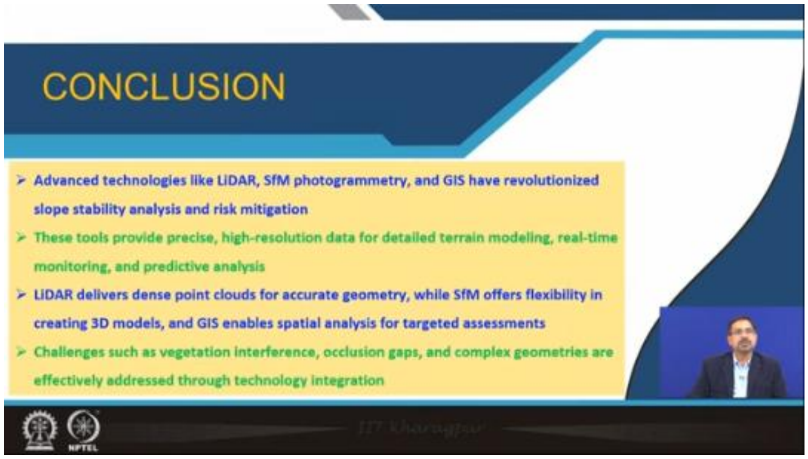
So, with different legends that vary between lowest risk number 1 to the highest risk that is 5 or V. So, the key findings high risk zones 10.57 percent areas that is accounting to 397 square kilometer that align with faults and steep slopes of the range between 40 to 80 degree gives a kind of 341 to 571 meter in terms of the high-risk zones. So moderate risk zones include overburden dumps and temporary mining. So, this way when you combine the optical data with the digital elevation data, you come out with different slow failure risk zones. So that helps us in terms of pre-planning, in terms of reforestation or avoiding any kind of safety or safety related issues.

Now, coming to another case study that talks about landslide detection and characterization using terrestrial three-dimensional laser scanning or LiDAR in Kucuk Hill, which is located in Turkey. Here, TLS data was used and supplemented with manual slope measurements, clay properties cohesion, and seismic data. The methodology followed involved TLS data processing in terms of point cloud acquisition and registration, as far as georeferencing is concerned. Then, the landslide orientation was determined via the three-point problem using Cramer's rule and stereographic projections. The deformation was monitored using M3C2 analysis to detect ±750 mm displacement over 30 days, and stability analysis was conducted using kinematic and slope stability studies with dips varying up to 6.0, while seismic effects were also incorporated.



Mine plan revisions reduced inter-ramp slope angles to 15 degrees for improved stability. Based on this study, the suggestion is to reduce the inter-ramp slope angle to 15 degrees to improve slope stability. The key findings: landslide movement direction was southwest, opposite to mining progression. The main triggers were water-saturated clay, and other drivers could also be identified. These could include rainfall, snowmelt, blasting, and water-saturated clays. Finally, on the upper right side, you can see a figure showing the landslide zones in the pit mine.

Different landslide zones were identified using terrestrial LiDAR scanner data. This was integrated with supplementary data using landslide orientation, deformation monitoring, and stability analysis. For more details, please refer to the publication by Ozdogan et al. in 2019. These are the references used to prepare these slides for our discussion. Finally, we conclude with these four points.



Advanced technologies like LiDAR, SFM photogrammetry, and GIS have revolutionized slope stability analysis and risk mitigation. These tools provide precise high-resolution data for detailed terrain modeling in real-time. Real-time modeling and future prediction are also possible if we imitate the pattern of change using any ML or AI-based techniques. LiDAR delivers dense point clouds for accurate geometry, while SFM offers flexibility in creating three-dimensional models. When combined, they perform well in terms of selective data processing.

Integrating data ensures a good analysis or highly accurate slope study. The challenges include vegetation interference, which must be negated, as well as gaps due to occlusion and complex geometries. Tough, undulating, or steep terrains pose challenges for slope analysis. Newer techniques address these challenges by integrating different data sources and applying high-end algorithms or emerging techniques. This is what we discussed in the 17th lecture. Thank you very much.