GIS Based Spatial Modelling of Snow Avalanche Hazard along the North-South Alternative Road

Ismailov, N.,[1]* Chymyrov, A.,[1] Bekturov, A.[2] and Karagulov, A.[3]
[1]Geodesy and Geoinformatics Department, Razzakov Kyrgyz State Technical University, Kyrgyzstan
E-mail: nursultan.ismailov@kstu.kg, chymyrov@kstu.kg
[2]Service of Land Resources under Ministry of Agriculture of Kyrgyz Republic
E-mail: adilet.bekturov@gmail.com
[3]State enterprise Project-research institute Kyrgyzdortransproekt
E-mail: karagulov1982@mail.ru
Corresponding Author

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Abstract
This study aims to investigate the potential of TanDEM-X DEM and geoinformation technology for mapping and assessing avalanche hazard along the North-South alternative road. This new 433kilometer long transportation corridor connects the northern part (from the Balykchy city) with the southern part (to the Jalal-Abad city) of Kyrgyzstan, separated by the Fergana Mountain range. The North-South road under construction should become an strategic automobile route between two parts of the country, an alternative to the existing Bishkek-Osh road, which passes through high mountainous regions. The existing road is subject to congestion and closures in natural emergencies, in cases of territorial disputes of neighbor countries, and affected economic development of the country. The road construction in the high mountainous areas requires a detailed study of all types of natural and man-made hazards and risk assessment. There are many road sections under potential hazards of avalanches, landslides and rock falls. Research and mapping of all types of natural hazards requires the use of modern engineering survey technologies, remote sensing data, geographic information systems and field research. Digital Elevation Models and Digital Surface Models have many advantages providing detailed information about the terrain's topography, which is essential for assessing avalanche hazard and risk. The TanDEM-X DEM gives detailed topographic information, including elevation, surface slope, aspect, and curvature used to identify potential avalanche release areas for assessing avalanche risk and implementing mitigation measures.

Keywords: Avalanche, DEM, GIS, Remote Sensing, TanDEM-X

1. Introduction

Kyrgyzstan, a mountainous country in Central Asia, is susceptible to various natural hazards, and avalanches are one of the significant hazards in the region. Snow avalanches annually cause significant damage to transport infrastructure, communication and power lines, in agriculture and forestry in the Kyrgyz Republic. In total, more than 30 thousand avalanche centers can be identified, but about a thousand of them pose a threat to the life and activities of people, which shows the poor development of the mountainous regions of the country [1]. Here are some key points regarding avalanche hazards in Kyrgyzstan:

- Steep and rugged terrains of the Tien Shan and Pamir-Alai mountains are conducive to avalanches, especially during the winter and early spring when there is heavy snowfall.
- Human activities such as winter tourism, skiing, and mountaineering in the mountainous regions of Kyrgyzstan pose a risk of triggering avalanches.
- Kyrgyzstan authorities work to monitor and predict avalanche conditions to mitigate risks, which includes providing avalanche forecasts and closing off areas when avalanche danger is high.
- Kyrgyzstan has dedicated search and rescue teams to respond to avalanche incidents. If an avalanche occurs, it's crucial to report it immediately to local authorities so that rescue efforts can be initiated.

It can be noted that snow avalanches occur in the mountainous regions of the Kyrgyz Republic almost all year round; the avalanche period in the mountains of the Western Tien Shan lasts 3-4 months, in the Central Tien Shan up to 11-12 months, depending on the altitude and climatic features of the area [2]. The existing automobile road that connects Bishkek and Osh cities in Kyrgyzstan is a significant transportation route in the country is known as the "Osh-Bishkek road". It plays a crucial role in connecting the southern and northern parts of Kyrgyzstan and covers a distance of approximately 600 kilometers. This road traverses some of the most beautiful and mountainous terrain in Kyrgyzstan and offers stunning views of the Tien Shan mountain ranges, making it a popular route for tourists. The road can be challenging due to its mountainous terrain and weather conditions. It passes through high-altitude areas where snow and ice are common during the winter months [2] [3] and [4].

Avalanches are most common during the winter season when snow accumulates in the high-altitude regions through which the Osh-Bishkek road passes. Travelers who plan to use this road during the winter months should be well prepared and take safety precautions. This includes having appropriate winter driving equipment, such as snow chains and winter tires, and being aware of avalanche safety measures. The existing Osh-Bishkek road is often closed during the winter season when snowfall is heavy and the risk of avalanches is high. These closures are necessary to prevent accidents and to ensure the safety of travelers. Road closures may also occur during the winter for road maintenance and snow clearing and lost of the strategic communication between the South and North parts of the country is indeed a significant factor and the Kyrgyz authorities weigh the economic losses due to closures against the risks and costs of maintaining the road in hazardous conditions [5] and [6]. The new North-South alternative road construction has been started in 2014 in order to provide an alternative route to enhance the reliability, safety and accessibility of two geographically divided parts of the country. The total length of the alternative North-South alternative road is 433 km. The project involves the construction of roads according to the parameters of the technical category 2 and divided into three phases to be completed in 2024:

- Phase-I, 154 km long, runs along the route Kyzyl-Zhyldyz - Aral (km 183-195), Kazarman
- Jalal-Abad (291-433 km) and includes the construction of a tunnel through the Kok-Art pass, length 3,890 km.
- Phase-II, 96 km long, runs along the Aral - Kazarman route (km 195-291). The construction of the 1 076 m and 396 bridges are planned in this road section (Figure 1).
- Phase-III, 183 km long, runs along the route Balykchy - Kyzyl-Zhyldyz (km 0-183) [3].

The construction of such a complex infrastructure project requires a detailed study of all types of natural and man-made hazards and risk calculations. Most of the route passes through high mountain areas with great dangers of avalanches, landslides and rock falls. Research and mapping of all types of natural hazards requires the use of modern engineering survey technologies, remote sensing data, geographic information systems and field research.

Figure 1: 396 m long bridge of the North-South alternative road

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2. Materials and Methods

When assessing avalanche danger on roads, forecasting conditions is carried out through modeling geomorphological, meteorological conditions for the formation of snow avalanches, their genetic types, identifying avalanche catchment areas, calculating dynamic parameters and describing the avalanche regime. The North-South alternative road goes through the Tian Shan Mountain range in Central Asia, one of the largest and highest mountain ranges in the world. Tian Shan mountains were formed as a result of the collision between the Indian and Eurasian tectonic plates, leading to the uplift of the region and the creation of this massive mountain range (Figure 2). The main natural hazards, difficult conditions and exogenous geological processes along the North-South Road corridor are:

1. Avalanche-prone areas are located mainly in the 317-334 km and 338-356 km sections.
2. Landslide-hazardous areas are in the section at 361-363 km.
3. The road passes highlands, where the intensity and duration of precipitation, the watershed areas are large, and in many areas need measures to protect against mudflows.
4. Many sections of the road lie in the highlands and designers and builders were forced to go along steep mountain slopes with large volumes and high slopes of excavations that create risk of rockfalls and landslides.

The North-South road construction in areas prone to avalanches requires comprehensive avalanche studies and mitigation measures to ensure the safety and functionality of the road (Figure 3). Before constructing a road in avalanche-prone areas, a thorough site assessment is essential. This includes evaluating the local topography, snow accumulation patterns, existing avalanche paths, and the potential for avalanches to impact the proposed road route. The investigations in these areas are complicated with difficult access and remote sensing is a highly convenient and effective method for large-scale surveying and mapping in mountainous areas.

Avalanche hazard mapping involves identifying and mapping the specific areas where avalanches are likely to occur. This information is crucial for determining the road's alignment and for designing avalanche protection structures. Meteorological data and snowpack observations are used to create avalanche forecasts, which help in predicting when and where avalanches are likely to happen, allowing for proactive road management. Avalanche risk zones of the road are based on the assessment of avalanche hazards and are used to develop strategies for mitigation. Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) play a crucial role in avalanche modeling by providing detailed information about the terrain's topography, which is essential for assessing avalanche hazard and risk. They are to analyze the terrain's characteristics, such as slope angles, aspect, and curvature. Steep slopes are more prone to avalanches, and DEMs help identify these areas. Avalanche paths are often mapped using DEMs for identifying and delineating these paths on the topographic map to assess which areas are likely to be affected by avalanches [7] and [8].

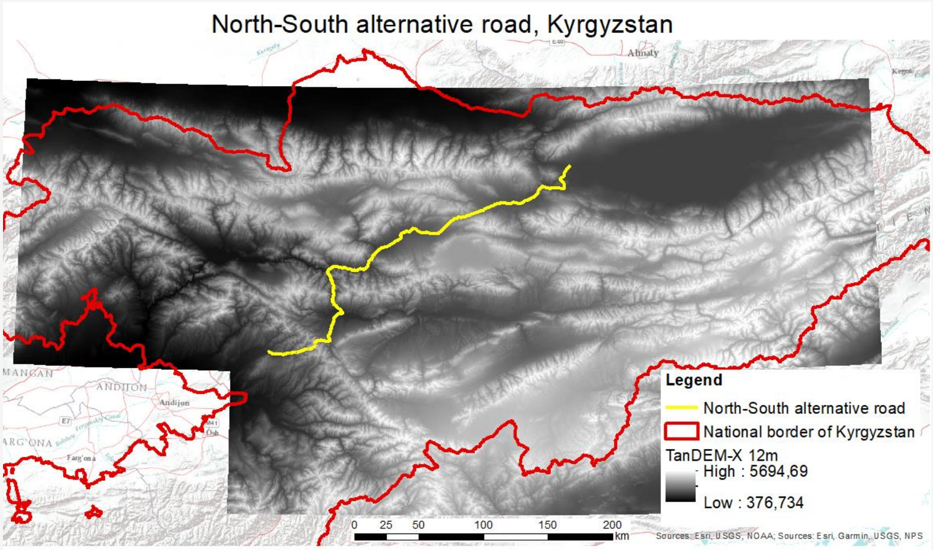

Figure 2: The North-South alternative road and TanDEM-X DEM

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Figure 3: Avalanche prone section of the North-South alternative road
(Courtesy of the Ministry of Transport and Communications of the Kyrgyz Republic)

DEMs provide information about the distribution of snow on the terrain. By combining DEM data with snowpack data, it's possible to identify areas with a high potential for avalanche release due to snow accumulation. DEMs assist in identifying areas where avalanches are likely to originate to assess the risk and determine suitable locations for protective measures such as snow sheds and avalanche barriers. Nowadays, available open global DEMs and DSMs are often used, mainly based on stereoscopic and radar space imagery data [9] and [10]. These include ALOS (Advanced Land Observation Satellite), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), SRTM (Shuttle Radar Topography Mission) satellite systems, GTOPO30, GMTED2010, SPOT DEM, NextMap World 30, World 3D Topographic Data, WorldDEM and other models [11] and [12].

TanDEM-X DEM (TerraSAR-X add on daily for the Digital Elevation Measurement), acquired in the frame of the common effort of German Aerospace Center (DLR) and AIRBUS Defense and Space mission between 2010 and 2015 with a spatial resolution of 0.4 arcseconds (12 m at the equator) has unprecedented geometric resolution, precision and accuracy as a global DEM product and often used for detailed morphological studies in hydrological and geological studies. The goal is achieved by exploiting the interferometric capabilities of the two twin SAR satellites TerraSAR-X and TanDEM-X, which fly in a close orbit formation, acting as an X-band single-pass interferometer.

Many researches demonstrate that the high horizontal and vertical accuracies of the TanDEM-X DEM, coupled with its dense pixel grid, provide a considerable improvement in space-borne remote sensing for a wide range of applications [13] and [14].

TanDEM-X DEM resulted in three types of data with resolutions of 12, 30 and 90 m, respectively [15] [16] and [17]. The 12 m resolution TanDEM-X DEM based on a mosaic of scenes from TanDEM-X imagery with less than 10 m absolute vertical accuracy provided by the German Aerospace Center (DLR) is used in this research [18]. The study area is located in the road section 320-350 km from the Balykchy city in the Issyk-Kul Province to the Djalal-Abad Province in the south of Kyrgyzstan. When using Earth Observation data, quality control of georeferencing of images plays a particularly important role [19]. To assess the horizontal accuracy of the modeled river networks and basins, topographic maps at a scale of 1: 100,000 were used in this work. The graphical accuracy of the horizontal position of these maps is up to 10 m, which allows their use as a source of verification of the TanDEM-X data. Processing of spatial data was carried out using the ArcGIS Pro-software in the projected coordinate system WGS_1984_UTM_Zone_43 (EPSG:32643). The geodetic (Pulkovo_1942 - EPSG:4284) and projected (Pulkovo_1942_GK_ Zone_13-EPSG:28413) coordinate systems of 1942 or SK-42 were also used, which is due to the use of topographic maps of the USSR at a scale of 1:100,000.

The category 2 North-South alternative road has been designed by the State Enterprise Design and Survey Institute "Kyrgyzdortransproekt". It is divided by the 3,890 meter long Kok-Art tunnel, which is under construction to be completed in 2024.

3. Results and Discussion

The TanDEM-X DEM is used for the terrain analysis to get detailed topographic information, including elevation, slope, aspect, and curvature. This data to is used to identify potential avalanche release areas (PRA) and to analyze terrain features that influence avalanche initiation and flow. These release zones are critical for assessing avalanche risk and implementing mitigation measures [5] and [20]. While the primary factors contributing to avalanche hazard are typically related to snowpack, terrain, and weather conditions, vegetation can play a role in modifying avalanche risk in several ways. The presence of trees, shrubs, and other vegetation can help anchor the snowpack to the ground, increasing its stability. Vegetation acts as a mechanical reinforcement, making it harder for the snowpack to slide downhill as an avalanche. This research focused on the slope calculation and avalanche mapping, the snow parameters, soil types and vegetation cover are not considered. The avalanche release area is an important parameter to be estimated for the avalanche hazard mapping procedure. The potential avalanche release areas are often difficult to determine, due to terrain inaccessibility in the upper areas of an avalanche track. Avalanche risk on a slope is a measure of the likelihood and potential consequences of an avalanche occurring on that particular slope. The slope's characteristics, including its steepness, aspect (the direction it faces), and shape, play a significant role in avalanche risk. Steep slopes, particularly those with angles between 30 and 45 degrees, are more prone to avalanches (Figure 4), the frequency of avalanches increases when the slope gradient exceeds 36° [21] [22] [23] and [24]. To obtain the individual avalanche prone areas, a watershead delineation method is applied. First, slopes are calculated for a central pixel and its eight neighbors. The flow direction, flow accumulation and stream ordering have been prepared using Hydrology Tool of the ArcGIS Pro. Individualized watersheds are obtained from flow accumulation values by identifying the most important flows and by attributing each pixel to one of these flows [25] and [26]. The avalanche release areas No. 1, 2, 3, 4 and 5 are selected as the most hazardous in 324-324 km section of the North-South road for the field studies and observations with delineated border lines are given in Figure 5. Detailed topographic information is crucial for optimizing the effectiveness of these measures. The TanDEM-X DEM based avalanche release areas and flow paths inform the design and placement of avalanche protection structures, such as barriers, deflectors, and tunnels.

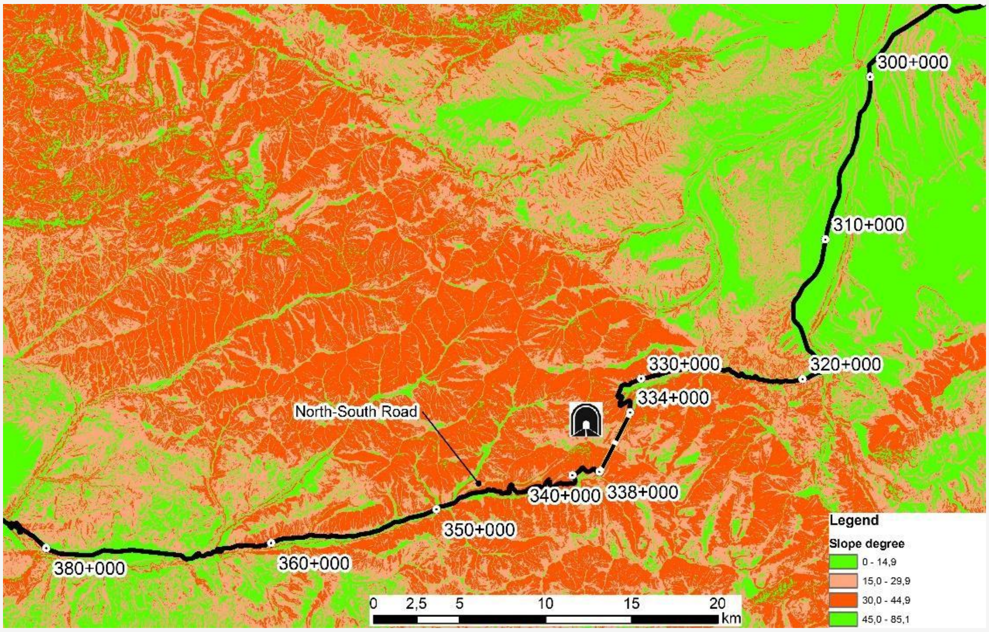

Figure 4: The slope map of the study area

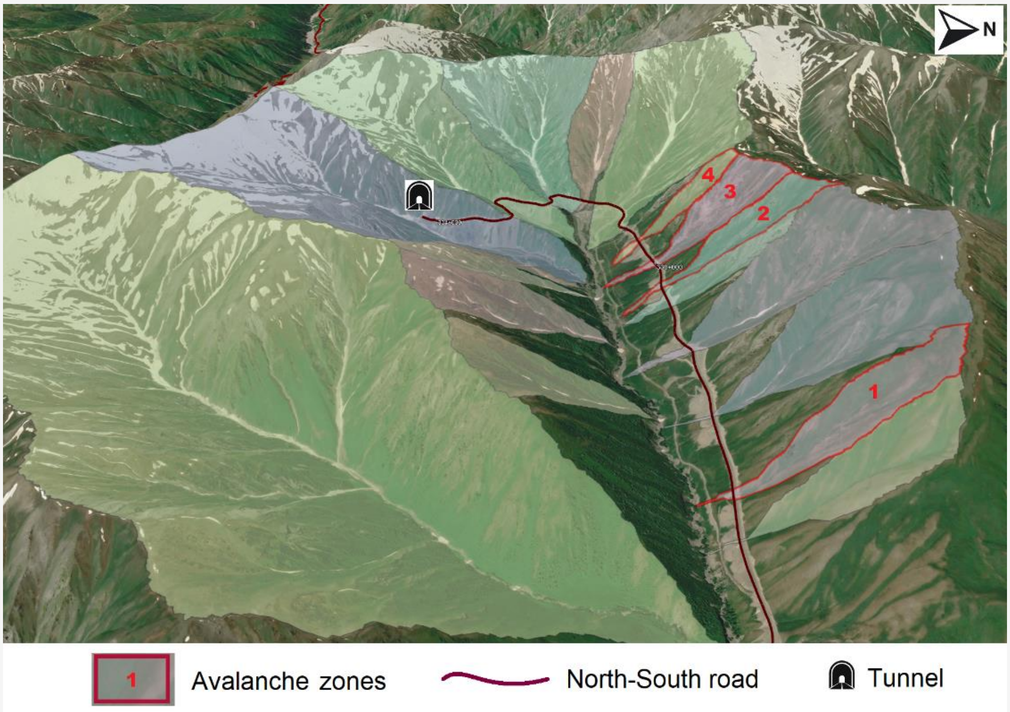

Figure 5: The delineated avalanche release areas No. 1, 2, 3 and 4 in 326-334 km section of the North-South alternative road

Installing avalanche forecasting and warning systems along the road can provide real-time information to road users and authorities. These systems can trigger road closures or safety measures when avalanche risks are high. Developing operational plans for road maintenance and safety during the winter season is crucial. These plans should specify the actions to be taken during avalanche events, including road closures and snow removal procedures. Educating the public and road users about avalanche risks and safety measures is important and timely providing information and signage about avalanche-prone areas can help prevent accidents.

4. Conclusion

The rapid development in Geographic information systems and Remote sensing cause these technologies have become the most powerful tools for spatial analysis and applications in the wide range of fields including natural hazard mapping and risk assessment. The study shows that 12 m resolution TanDEM-X DEM can be used for the river network modeling, surface slope and curvature calculation, watershed delineation to identify the most hazardous avalanche prone areas. The methodology used in this paper allows efficient and consistent geospatial data processing on TanDEM-X DEM of any size, where can be used into natural risk management.

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