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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

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COMPLEX PROCESSING OF EARTH REMOTE SENSING DATA FOR PREDICTION OF LANDSLIDE PROCESSES ON ROADS IN MOUNTAIN AREA

Abstract. Today, the economic development of mountain territories leads to the fact that mountain ecosystems are undergoing significant changes in land use. Highways in mountainous areas are practically the only transport routes. Their construction and other facilities lead to a sharp increase in man-made loads on the natural environment and to an increase in the danger of its significant negative change. Based on the above, engineering-geological studies of exogenous processes are now becoming increasingly important. Landslide processes are the most common and at the same time the most complex, lengthy and multifactorial, causing significant material damage.

The study of the mechanisms of landslide processes with the involvement of modern satellite technologies is part of a global project funded by the Ministry of Education and Science of the Republic of Kazakhstan on the topic «Design of an intelligent system to forecast landslides' processes and their influence on the roads' technical and operational characteristics». Within the framework of this project, new knowledge will be gained in the theory of forecasting the occurrence of landslide processes and their impact on the technical and economic indicators of highways, which undoubtedly has applied significance and contributes to the widespread introduction of intelligent systems for forecasting and making industry decisions.

This project is especially relevant for the road industry of Kazakhstan, as

issues related to the destruction of roads under the influence of natural disasters, such as landslides, remain poorly understood. Therefore, the purpose of the study is to survey the landslide slope in the area of the «Almaty-Cosmostation» highway and identify the causes of the destruction of the highway for the development of recommendations. This site was chosen due to the extreme danger associated with the possible closure of the river flowing through the gorges along the road under study due to a landslide slope. This can lead to a change in the riverbed, the formation of a strong water flow, which will create a danger to the population, will lead to significant material damage.

Key words: Remote sensing, geodynamic processes, earth surface displacements, road diagnostics.

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ТАУЛЫ ЖЕРЛЕРДЕГІ АВТОМОБИЛЬ ЖОЛДАРЫНДА КӨШКІН ПРОЦЕСТЕРІН БОЛЖАУ ҮШІН ЖЕРДІ ҚАШЫҚТЫҚТАН ЗОНДТАУ ДЕРЕКТЕРІН КЕШЕНДІ ӨҢДЕУ

Аннотация. Бүгінде таулы аумақтардың экономикалық дамуы тау экожүйелерінің жерді пайдалануда айтарлықтай өзгерістерге ұшырауына әкеледі. Таулы аумақтардағы автомобиль жолдары іс жүзінде жалғыз көлік жолы болып табылады. Оларды және басқа объектілерді салу табиғи ортаға техногендік жүктемелердің күрт өсуіне және оның айтарлықтай теріс өзгеру қаупінің өсуіне әкеледі. Жоғарыда айтылғандарға сүйене отырып, қазіргі уақытта экзогендік процестерді инженерлік-геологиялық зерттеу маңызды бола түсуде. Көшкін процестері ең көп таралған және сонымен бірге ең күрделі, ұзақ және көп факторлы, айтарлықтай материалдық шығын әкеледі.

Заманауи спутниктік технологияларды тарта отырып, сырғыма процестерінің пайда болу тетіктерін зерделеу «сырғыма процестерін болжамдаудың зияткерлік жүйесін әзірлеу және олардың таулы жерлердегі автомобиль жолдарының техникалық-пайдалану сипаттамаларына әсері» тақырыбында ҚР БҒМ қаржыландыратын жаһандық жобаның бір бөлігі.

Осы жоба шеңберінде көшкін процестерінің пайда болуын болжау және олардың автомобиль жолдарының техникалық-экономикалық көрсеткіштеріне әсері теориясында жаңа білім алынады, бұл сөзсіз қолданбалы мәнге ие және салалық шешімдерді болжау және қабылдау үшін зияткерлік жүйелерді кеңінен енгізуге ықпал етеді.

Бұл жоба Қазақстанның автожол саласы үшін ерекше өзекті, өйткені көшкін сияқты табиғи стихиялық құбылыстардың әсерінен жолдардың қирауына байланысты мәселелер аз зерттелген. Сондықтан зерттеудің мақсаты «Алматы-Космостанция» автомобиль жолы ауданындағы көшкін бөктерін зерттеу және ұсынымдар әзірлеу үшін автомобиль жолының бұзылу себептерін анықтау. Бұл учаске көшкін беткейінің салдарынан зерттелетін жол бойындағы шатқалдар арқылы ағып жатқан өзеннің ықтимал бөгелуіне байланысты төтенше қауіпке байланысты таңдалды. Өзен арнасының өзгеруі күшті су ағынының пайда болуына әкелуі мүмкін, бұл халыққа қауіп төндіреді және айтарлықтай материалдық шығындарға әкеледі.

Түйін сөздер: Қашықтықтан зондтау, геодинамикалық процестер, Жер бетінің жылжуы, автомобиль жолдарының диагностикасы.

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КОМПЛЕКСНАЯ ОБРАБОТКА ДАННЫХ ДИСТАНЦИОННОГО ЗОНДИРОВАНИЯ ЗЕМЛИ ДЛЯ ПРОГНОЗИРОВАНИЯ ОПОЛЗНЕВЫХ ПРОЦЕССОВ НА АВТОМОБИЛЬНЫХ ДОРОГАХ В ГОРНОЙ МЕСТНОСТИ

Аннотация. На сегодняшний день хозяйственное освоение горных территорий приводит к тому, что горные экосистемы претерпевают значительные изменения в землепользовании. Автомобильные дороги на горных территориях являются практически единственными транспортными путями. Их строительство и других объектов приводит к резкому возрастанию техногенных нагрузок на природную среду и к росту опасности её существенного негативного изменения. Исходя из

вышесказанного, в настоящее время все большее значение приобретают инженерно-геологические исследования экзогенных процессов. Оползневые процессы являются самыми распространенными и в то же время наиболее сложными, длительными и многофакторными, принося значительный материальный ущерб.

Изучение механизмов возникновения оползневых процессов с привлечением современных спутниковых технологий является частью глобального проекта, финансируемого МОН РК на тему «Разработка интеллектуальной системы прогнозирования оползневых процессов и их влияния на технико-эксплуатационные характеристики автомобильных дорог в горной местности». В рамках данного проекта будут получены новые знания в теории прогноза возникновения оползневых процессов и их влияния на технико-экономические показатели автомобильных дорог, что, несомненно, имеет прикладное значение и способствует широкому внедрению интеллектуальных систем для прогнозирования и принятия отраслевых решений.

Этот проект особенно актуален для автодорожной отрасли Казахстана, так как вопросы, связанные с разрушением дорог под воздействием природных стихийных явлений, таких как оползни, остаются малоизученными. Поэтому целью исследования является обследование оползневого склона в районе автомобильной дороги «Алматы-Космостанция» и выявление причин разрушения автомобильной дороги для разработки рекомендаций. Данный участок был выбран ввиду чрезвычайной опасности, связанной с возможным перекрытием реки, протекающей по ущельям вдоль исследуемой дороги из-за оползневого склона. Это может привести к изменению русла реки, образованию сильного водного потока, что создаст опасность для населения, приведет к значительному материальному ущербу.

Ключевые слова: дистанционное зондирование, геодинамические процессы, смещения земной поверхности, диагностика автомобильных дорог.

Introduction. Currently, space survey and remote monitoring technologies are actively used throughout the world in land use planning, both for general tasks (Abdelaziz et al., 2020) and for planning urban areas (Anderssohn et al., 2008:8). This makes it possible to significantly reduce the work time of specialists and optimize the work as much as possible at the planning stage of various states and local level works (Chang et al., 2019).

Mapping landslides along highways is a necessary condition for making optimal technical decisions when designing and maintaining roads, taking

into account the likely areas of slope destruction (Cees et al., 2008:19). Over the past two decades, studies on predicting the risk of landslides have been conducted all over the world (Dou et al., 2020:17).

Meanwhile, the causes of landslide processes, first of all, are the impact of various natural processes developing on the slopes (De Rouffignac et al., 1995:14). Taking into account the impact of natural factors and processes on the highway is one of the fundamental principles in the design of the highway both as a transport structure and as an engineering structure (Elias et al., 2020). In many ways, the importance of this principle is well known and is explained, first of all, by the closest connection of the road with the geological environment and all those deeply natural processes that occur in it and on its surface (Kirschbaum et al., 2018:18).

Factors determining landslides on highways can be divided into 2 groups (Krutskikh et al., 2018:9):

• Potential – geology, relief and seismic hazard of the area, characteristics of groundwater;

• Provoking – climate, weather conditions, erosion of streams, human development and vibrations from the movement of cars (Yesilnacar et al., 2005:15).

The multifactorial nature of the occurrence of landslides determines the use of an integrated approach when calculating the risk of dangerous situations. Within the framework of the project funded by the Ministry of Education and Science of the Republic of Kazakhstan on the topic “Development of an intelligent system for predicting landslide processes and their impact on the technical and operational characteristics of highways in mountainous areas”, an intelligent system will be developed designed to make decisions to ensure the quality of the roadway with the use of complexing of space sensing data, technical and operational characteristics of the highway obtained in as a result of diagnostics using a road laboratory, methods of geo-radar sensing, climatic data from weather reports. An important aspect of this study is to clarify the key variables that cause landslides. Therefore, it is necessary to select more objective data for cross-analysis in accordance with the overall potential and initiating factors before an objective generalized conclusion can be made.

Almaty is one of the major cities of Kazakhstan, where mountain highways pass, which are often destroyed by landslides, mudflows caused by sudden changes in weather conditions. Therefore, a section of the earthquake-prone mountain road to the Big Almaty Lake (BAL) was taken as an object of research.

Research Material and methods. There are a number of parameters that can be used to describe the structural condition of roads obtained by processing satellite data:

• Vertical displacements of the Earth's surface based on SAR interferometry data;

• Morphometric analysis of DEM;

• Characteristics of vegetation and soil cover;

• Snow cover.

• Development of a map of vertical displacements of the Earth's surface based on SAR interferometry data of the mountain highway to the Big Almaty Lake.

Observation of movements of the Earth's surface when monitoring the condition of highways is a priority task.

Since a road with a length of 26 km (Fig. 1) was investigated, an area processing of measurements was chosen, this is not only economically profitable, but also productive, due to the uniform coverage of the studied area. The methods of SAR interferometry have long established themselves as a reliable tool for monitoring the displacements of the Earth's surface for any tasks related to the monitoring of technical objects. Methods of multi-pass interferometry, in the presence of an initial data volume of more than 30 images and with the smallest time base, make it possible to obtain displacements of the observed surface with millimeter accuracy.

Input data. 75 archival images of the Sentinel-1 satellite for the period 2017-2021 were used to assess the geodynamic state of the highway territory and develop an appropriate map. After analyzing the archival optical images, the snow period of this territory was determined, this lasts from November to April. This is done due to the low coherence of the images of the Sentinel-1 satellite in the conditions of a mountain cluster; therefore winter images were excluded from the calculations.

Since this processing takes place in mountainous terrain, two images processing in ascending and descending orbits were carried out for a complete overview of the highway.

Specifics of Sentinel-1 data processing on the territory of the BAL. The processing of radar images is reduced to calculating the phase difference of the reflected signal from the same object for repeated shooting dates and its subsequent transformation into a change in elevation. The phase difference is calculated by creating interferograms – the result of pixel-by-pixel multiplication of two images with further conversion to the amplitude of the displacements, implemented in the ENVI-SARscape software package (Harris Geospatial Solutions, USA).

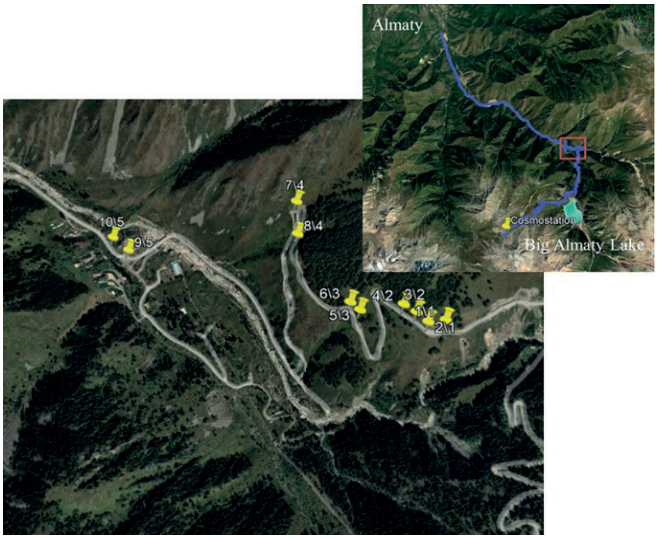


Figure 1. Overview drawing of the highway to the Big Almaty Lake (the blue line is the length of the road under study, the red square is the test site, the yellow dots are places with pronounced defects on the road)

As a result of using a set of interferograms for different shooting dates, it is possible to track the dynamics of vertical displacements of points on the earth's surface, that is, to build a map of displacements or the velocity of vertical displacements over the time period under study.

To analyze multi-pass chains of interferometric radar images, two modifications of radar interferometry are implemented in SARscape: Small Baselines Series Interferometry (SBas) and Persistent Scatterer Interferometry (PS). To solve the problem of the project, a modification of PS was used, due to the fact that the road is a good signal reflector (Zhantayev et al., 2017:4).

The PS modification is characterized by the accuracy of estimating displacements of 2-4 mm per year. For a guaranteed successful processing result, it is necessary to take a series of at least 25-30 images of the same territory for different dates taken in the same shooting geometry (Saf'yanov et al., 2014:5).

During processing, the program automatically selects the main image, on which the remaining images of the interferometric chain are recorded with an accuracy of 1/100 pixel. Next, the program builds interferograms for each pair of images.

Then the program determines the points – persistent scatterers of the radar signal. Several thresholds are used to select points: the amplitude correlation threshold, the coherence threshold, the spatial standard deviation of the displacements of the first iteration, etc. After the persistent scatterers are

determined, the procedure for estimating phase differences and multi-time phase sweep is performed for them. It is in the phase difference of each image that the magnitude of the displacements for the period between the shooting of these images is recorded.

Thus, for each of the selected points, the chronology of the phase change in time is restored, which is then mathematically recalculated into displacements in millimeters. Additionally, a special filter is used during the processing to remove the possible influence of the atmosphere on the interferometric phase.

The result of processing is a vector file of points, in the attributes of which are written:

- displacements as of each shooting date;
- average annual displacement rate;
- total amount of displacement;
- coherence;
- height above the ellipsoid WGS-84.

Characteristics of vertical displacements maps. As a result of interferometric processing by the PS method for the period 04.2017-05.2021, an interpolated map of the amplitude of vertical displacements of points of the Earth's surface to the territory of the studied area was created and corresponding graphs of vertical displacements characterizing individual areas of the territory of interest were constructed (Fig. 2).

Figure 2 shows several graphs of vertical displacements, indicating that slow but steady subsidence occurs in sections 4 and 5 during the observed period with amplitude of up to 30 and 20 mm. And in areas 1, 2, 3, elevations are observed, which reach up to 20 mm on the 3rd area, and up to 10 mm on the 1st and 2nd in 5 years.

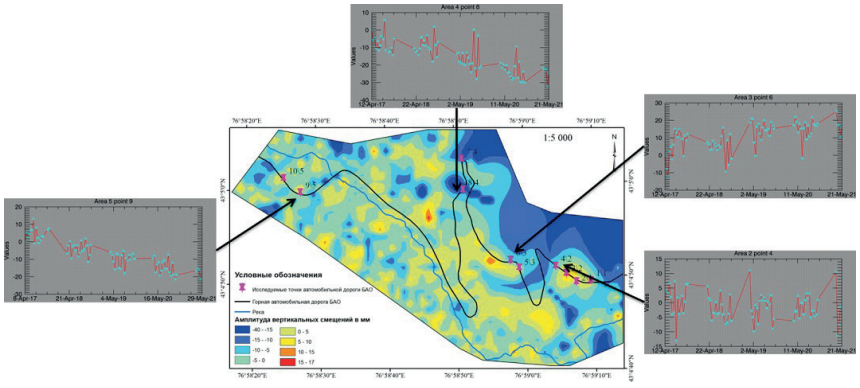


Figure 2. Map of the distribution of the values of the amplitudes of vertical displacements in mm of the points of the Earth's surface on the last date of the survey

Morphometric analysis of DEM. The nature, scale and intensity of natural exogenous slope processes affecting the highway depend to a very significant extent on the characteristics of the territory through which the road passes. In this regard, the mountain relief is of particular importance, the consequences of geodynamic processes often turn out to be such that these processes are called “dangerous”.

Relief is one of the main factors in the differentiation of landscapes. Currently, due to the development of digital technologies and the wide availability of remote sensing data, a detailed assessment of the relief as a landscape-forming factor has become possible (Robbins et al., 2016:13). The use of DEM has greatly simplified the morphometric analysis of the relief (Piriev, 1986:120). It is the relief and its parameters that are recognized as the most important in the selection of landscapes (Richards et al., 2007:24). Obtaining morphometric information about the shape and structure of the relief surface serves as an initial procedure that precedes a meaningful study of genetic, dynamic, temporal (i.e. general geomorphological) aspects of the functioning of the relief (Mikhailov, 2015:8).

Input data. As initial data for GIS analysis of morphometric indicators of the relief of the studied region, the materials of the ALOS PALASAR satellite survey were used. This DEM has a grid with a cell size of 12.5×12.5 and a kind of raster file in which the pixel value is the height above sea level at a given point. The mathematical basis of the data is the reference ellipsoid WGS-84 and the projection GCS WGS 1984.

Processing methodology. Morphometric analysis of the relief of the BAL mountain highway was performed on the basis of the DEM using GIS technologies. Based on the processing performed, the following parameters were obtained: dissection index, aspect, slope, solar radiation, TWI.

To process DEM data, we used the ArcGIS software package (ESRI, Inc., USA).

Dissection index. This indicator expresses the ratio of relative relief (in this case, vertical dissection) to absolute relief (maximum relief indicators) (formula 1). DI – the dissection index, Z_{max} и Z_{min} – maximum and minimum elevation values:

$$DI = \frac{Z_{max} - Z_{min}}{Z_{max}} \qquad (1)$$

The index is an important indicator of the nature and magnitude of the dissection of the surface, i.e. it shows the nature of vertical dissection. A high index value indicates active mountain formation; a low value corresponds to stable areas. The value changes from zero (complete absence of dissection) to one (vertical rock). Within the study area, this indicator varies from 0.002 to 0.03 (Fig. 3).

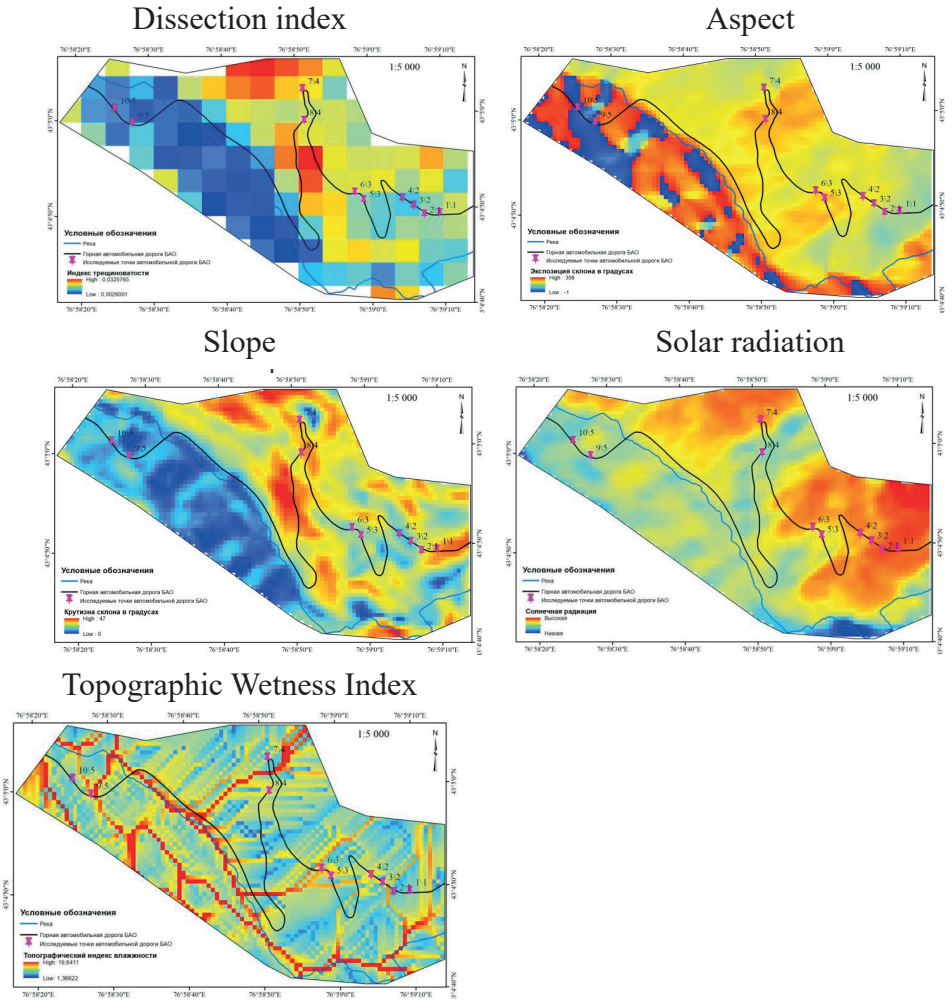


Figure 3. Results of morphometric analysis of DEM

Aspect and slope. One of the main morphometric indicators analyzed in this work are the slope angles and aspect. The calculation of the slope is necessary in the assessment of slope processes, in the calculations of soil erosion, land assessment, etc.

The aspect is one of the morphometric characteristics of the relief, characterizing the spatial orientation of the elementary slope. The orientation of slopes through the influence on erosion and denudation activity determines the morphological properties of the earth's surface. Aspect can be considered as the direction of the slope. The slope and aspect at any point of the raster DEM are calculated using adjacent cells in the window (sliding window method).

Solar radiation. Solar radiation analysis tools allow you to map and analyze

the effects of the sun by geographical area for specific time periods. This parameter reflects the amount of possible incoming solar radiation.

Topographic Wetness Index – displays the potential humidity of the catchment area and represents the natural logarithm of the ratio of the drainage area to the slope tangent. Large values of this index correspond to the accumulation of moisture, its increased content in the soil, which, in turn, affects other soil characteristics, microclimate, water balance, etc. This index is widely used to predict soil characteristics, to assess surface runoff, the degree of soil moisture and the movement of detrital material based on DEM. TWI makes it possible to assess the prerequisites for the development of waterlogged lands and take this factor into account when planning optimization measures (Fig. 3).

Characteristics of vegetation and soil cover. Among the factors influencing the occurrence of landslides, the condition of the earth's surface and vegetation cover are also of great importance. Since the vegetation cover retains precipitation, not only reducing the erosion of the earth's surface, but also improving the adhesion strength of root systems to stabilize the soil mass on the slopes. Based on the above, the analysis of the materials of the optical survey of the Landsat-8 satellite with a resolution of 30 meters was carried out in order to calculate the vegetation index.

To calculate the vegetation index, SAVI was taken – this is the vegetation index, which tries to minimize the effect of soil brightness by using the soil brightness correction coefficient. It is calculated by the following formula 2:

$$SAVI=((NIR-RED)/(NIR+Red+L))\times(1+L) \quad (2)$$

which:

NIR – pixel values from the near infrared channel;

Red – pixel values from the near red channel;

L – the value of covering green vegetation.

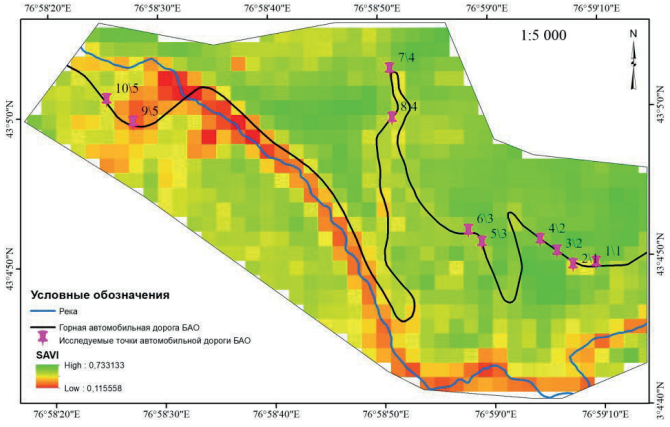


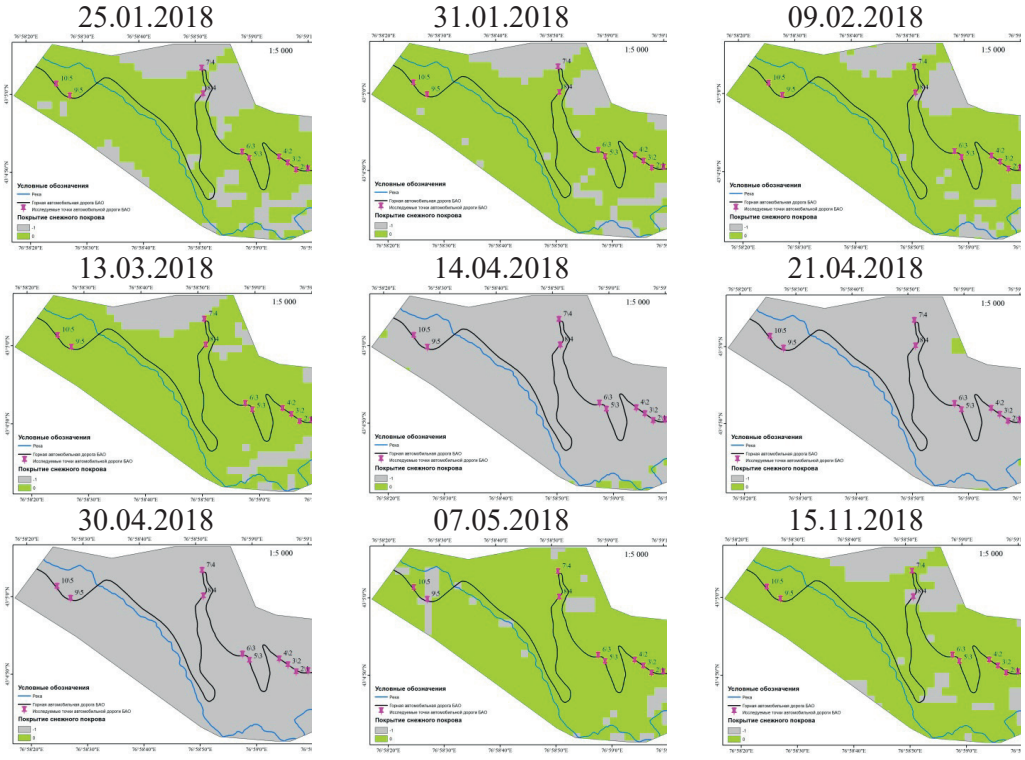
Figure 4. Map of the SAVI vegetation index

Results of processing optical images in order to identify the snow cover. It has already been mentioned above that precipitation has a direct relationship with the condition of the road surface. Therefore, the study of snow cover is an integral parameter for monitoring highways.

As the source material of remote sensing data, 50 cloudless Landsat images for the period from 2017 to 2021, taken during the snowy period, were used. All the necessary channels of the selected image were subjected to radiometric calibration and conversion of the brightness values DN to the reflectivity values of the underlying surface. To reduce the influence of the atmosphere and further compare different time data, atmospheric correction by the DOS method was applied. The normalized Snow Difference Index (NDSI) was used for identification:

$$\mathrm{NDSI} = \frac{\mathrm{Green} - \mathrm{Swir1}}{\mathrm{Green} + \mathrm{Swir1}} \qquad (3)$$

Based on the processed images, the snow period of this site was determined – from mid-November to early May. As an example of the processed array, it is presented for 2018 in Figure 5.



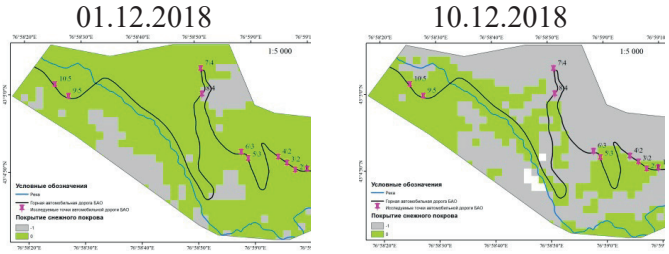


Figure 5. Example of snow cover for 2018
(Gray color – snow, green color – earth)

Result and discussion. The Almaty-Cosmostation highway was repaired in 2021. Visual assessment of the road surface at the beginning of the investigated section, i.e. from the city of Almaty in good condition without visible defects. As a test site for ground-based observations, the polygon indicated in Figure 1 was taken. 5 areas with more pronounced changes were allocated at this polygon.

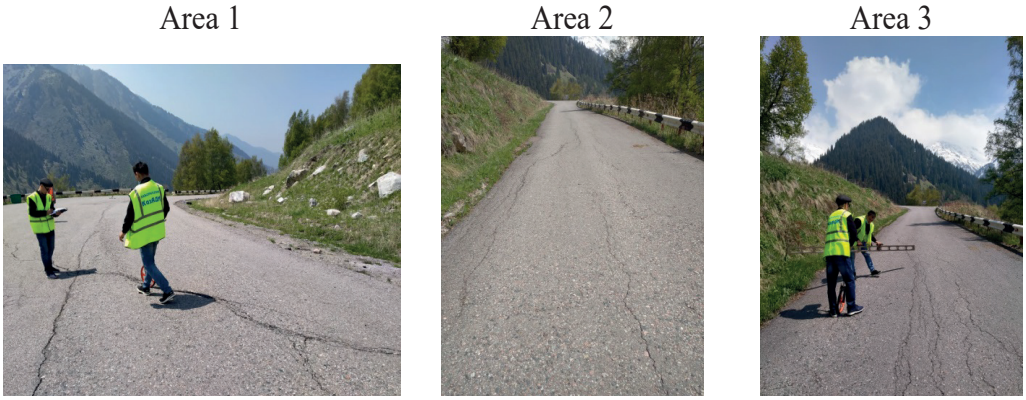


Figure 6. Longitudinal and transverse cracks formed on the surface of the automotive coating in areas 1-3

The comparison of space and ground data showed a qualitative correspondence. So in areas 1, 2, 3, according to radar interferometry data, elevations were recorded. Field work carried out by the road laboratory recorded axial and oblique deep cracks, as well as the effect of soil sliding is observed (Fig. 6). In area 4, the formation of transverse cracks has a different character (Zhantayev et al., 2021:9). This area is located on sharp turns and due to poor drainage from the road surface, the slope of the roadbed has been eroded (Fig. 7), which is confirmed by the results of interferometry in the form of subsidence (Fig. 2). The area is characterized by transverse cracks covering

the entire width of the roadway. Stable subsidence of the earth's surface was also recorded on area 5, which are reflected in the form of small pits on the surface of the highway (Fig. 8).

Figure 7. The formation of erosion of the slopes of the roadbed on area 4

Figure 8. Small cracks and pits that appeared on the surface of area 5

Conclusion. Analysis of archived and up-to-date radar data has shown that the use of the SAR interferometry method is an effective method for areal remote monitoring of mountain highways, despite the inaccessibility of this

territory. The processing results allowed us to identify areas with deformation processes that directly affect the condition of the road. For the next two years, it is planned to process a large array of up-to-date remote sensing data, for which recommendations will be offered.

The appearance of transverse and longitudinal cracks on the test site is not associated with the influence of dynamic load from moving vehicles, because starting from 13 km from the beginning of the study area; traffic is suspended due to construction work.

The presence of the above parameters allows us to take into account the nature of the development of negative natural processes. After analyzing the areal distribution of these parameters, the neural network after training will show how much each of them is of paramount importance.

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