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EXPERIENCE OF USING NON-SPECIALIZED UNMANNED AERIAL VEHICLES FOR AERIAL SURVEYS IN THE STUDIES OF EXOGENOUS GEOLOGICAL PROCESSES

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Abstract: The article reviews the experience of aerial surveys using a quadcopter DJI Inspire 1 PRO (unmanned aerial vehicle, UAV) for solving problems of engineering geodynamics. It describes the application of photogrammetry to estimate quantitative parameters of the studied objects, the experience of using UAVs to study flood processes in the Tunka valley (Russia) and erosion structures in the Ulaanbaatar agglomeration (Mongolia). The first UAV-acquired data on debris flow alluvial fans and elementary drainage basins of erosion structures are presented. The ranges of UAV flight heights were 100–150 m and 1–30 m for local and detailed aerial photography surveys, respectively. Local surveys covered relatively large objects – debris flow alluvial fans and drainage basins. Detailed aerial photography aimed to investigate the granulometric compositions of debris flow deposits and to construct transverse profiles of erosion structures. Processed aerial photos provided a basis for a schematic map showing the distribution of accumulated debris flow deposits. The granulometric compositions of coarse fractions in the debris flow deposits were determined. Based on the survey results, 3D models of the fragments of the erosion structures and their cross-sections were constructed.

Key words: unmanned aerial vehicle (UAV); engineering geodynamics; photogrammetry; debris flow; erosion; Tunka Ridge; Ulaanbaatar

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Решение тематических задач при изучении экзогенных геологических процессов с применением неспециализированных беспилотных комплексов для аэрофотосъемки

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Аннотация: В статье рассмотрен опыт применения комплекса для аэрофотосъемки на базе мультироторного беспилотного летательного аппарата (БПЛА) при решении различных задач в области инженерной геодинамики, в частности, для получения количественных показателей исследуемых объектов с использованием фотограмметрического метода. Рассматривается опыт использования БПЛА при исследовании селевых процессов в предгорьях Тункинских гольцов (Россия) и эрозионных форм в пределах Улан-Баторской агломерации (Монголия). Представлены первые результаты исследований конусов выноса селевых бассейнов и элементарных водосборных бассейнов эрозионных форм. Для изучения вышеперечисленных процессов была выполнена разномасштабная аэрофотосъемка – локальная и детальная, с использованием БПЛА. Локальная аэрофотосъемка, высота полета 100–150 м, применялась при изучении относительно крупных объектов – конусов выноса, локальных водосборных бассейнов. Детальная аэрофотосъемка, высота полета 1–30 м, использовалась как для получения данных гранулометрического состава селевых отложений, так и для построения поперечных профилей эрозионных форм. По результатам проведенной работы составлена схема распределения аккумулятивных селевых отложений, определен гранулометрический состав крупной фракции селевых отложений. На основе созданных по результатам аэрофотосъемки трехмерных моделей фрагментов эрозионных форм построены поперечные профили этих форм.

Ключевые слова: беспилотный летательный аппарат (БПЛА); инженерная геодинамика; фотограмметрия; сель; эрозия; Тункинские гольцы; Улан-Батор

1. Introduction

The use of photography to prepare topographic maps was extensively investigated by Aime Laussedat, a French topographer. In 1852, he prepared several maps using photographs taken from balloons. In 1858, the first aerial photography session using balloons was carried out Gaspard-Félix Tournachon, a French photographer known by the pseudonym Nadar [*Krasnopevtsev, 2008*]. Since the mid-19th century, the use of photography to determine the shapes, sizes and spatial positions of objects has been continuously improved, and now contributes to various fields of human activity. Photogrammetry – a reliable method for remote exploration of the Earth surface on the basis of measurements from photographs – has progressed and developed dramatically since 1960s when space imagery was introduced in geological, geomorphological, topographic and other studies [*Gonin, 1980*]. Aerial photo geodetic surveys are widely used for investigating new territories, discovery and development of mineral deposits, reconnaissance studies prior to design and construction of roads, highways and other industrial facilities, as well as for monitoring hazardous natural and technogenic processes. Modern methods of airborne geodesy can provide extensive topographic information and high resolution images for various fields of science and industry [*Deineko, 1968*].

In East Siberia, aerial photo geodetic methods were used in the studies of exogenous geological processes, including monitoring of abrasion-accumulation processes on the shores of Lake Baikal and artificial water reservoirs [*Rogozin, Trzhtsinsky, 1993*] and surveys of ice accumulation sites [*Pisarsky, Rogozin, 1975*] and debris flows [*Agafonov, Rogozin, 1987*].

It should be noted that airborne geodesy has its shortcoming: high cost of photo shooting, relatively low efficiency, and time-consuming acquisition of data. Furthermore, aero geodesic flights are technically limited by shooting heights, and, as a consequence, the range of scales and details in photos is reduced. Another shortcoming is relatively low efficiency and, correspondingly, high labour costs of selection of aerial images and their interpretation.

Recently, with the development of modern cameras and computer technologies, unmanned aerial vehicles

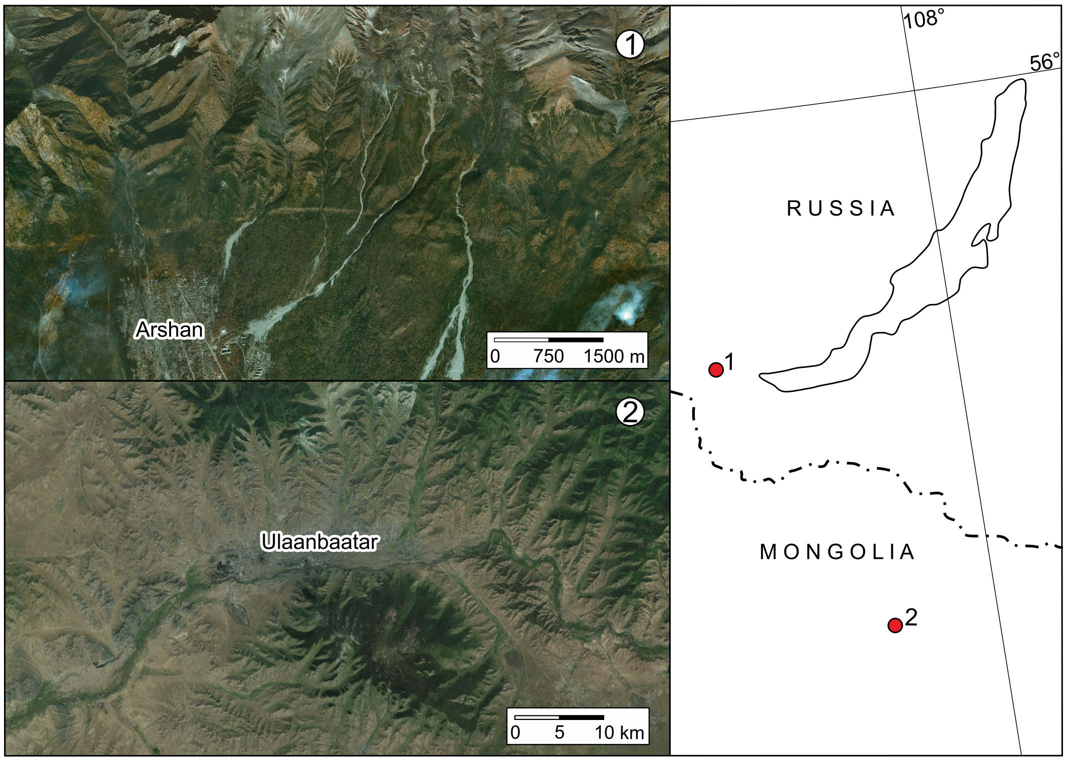

Fig. 1. UAV surveyed sites for studying the exogenous geological processes. 1 – debris flows; 2 – erosion structures.

Рис. 1. Участки проведения работ с использованием БПЛА при изучении экзогенных геологических процессов. 1 – сели; 2 – эрозия.

(UAVs) have successfully replaced manned vehicles in surveys of the ground surface [*Caron et al., 2014; Colomina, Molina, 2014; Gomez, Purdie, 2016; Giordan et al., 2017*].

In comparison to manned aerial vehicles, UAV advantages are better availability, easy use, lower costs of equipment and operations, high mobility and efficient data acquisition, processing and updating. For example, UAVs can rapidly provide information on consequences of a large-scale hazardous natural or technogenic event, and changes in time and space can be assessed through the use of UAVs in a more effective way [*Giordan et al., 2017*].

In addition to assistance in solving aero-geodetic problems, UAVs present various advantages for geophysical studies [*Caron et al., 2014; Firsov et al., 2015; Parshin et al., 2018*]. The UAV ability to fly at low altitudes and capture high resolution images provides for more detailed aerial surveys. High resolution images are useful for detailed monitoring and mapping of local sites and 3D simulation.

Although UAVs have been relatively recently in use for scientific purposes, the range of problems investigated with the use of UAVs is increasing and covers a variety of natural processes: fires [*Gerasimov et al., 2014; González-Jorge et al., 2017*], floods [*Feng et al., 2015; Popescu et al., 2017; Izumida et al., 2017*], landslides and karsts [*Luo et al., 2019; Fan et al., 2017; Comert et al., 2019; Karantanellis et al., 2019; Pellicani et al., 2019; Valkaniotis et al., 2018; Lazzari, Piccarreta, 2018*], debris flows [*Adams et al., 2016; Imaizumi et al., 2019; Liu et al., 2015; Hänsel et al., 2018*], rock collapse [*Buill et al., 2016; Coe et al., 2016*], volcanoes [*Nagatani et al., 2018*], glaciers monitoring [*Buri et al., 2016; Benoit et al., 2019; Immerzeel et al., 2014*], etc.

In this paper, we present the results of photogrammetry surveys carried out using UAVs to study exogenous geological processes in East Siberia (Russia) and Mongolia, specifically on the Tunka Ridge sites (debris flows) and in the vicinity of Ulaanbaatar (erosional processes) (Fig. 1).

These sites have been in focus of research for several years, and the major geological factors and the dynamics of processes were reported in [*Kozyreva et al., 2014a, 2014b, 2016; Kadetova et al., 2016a, 2016b; Rybchenko et al., 2018*]. Quantitative data on the processes under study were obtained by various methods, including tachometry surveys, ground photogrammetry and direct field measurements. A decision to use UAVs in field surveys of the existing facilities was taken to collect new data for comparison to the previously consolidated databases.

This article aims to review the experience of using UAVs in order to acquire quantitative and qualitative data on the origin and development of exogenous geological processes.

2. Data acquisition and processing

2.1. Data acquisition

A quadcopter DJI Inspire 1 PRO was used to study the exogenous geological processes on the above-mentioned sites (Fig. 2 and specifications in Table 1). This UAV is a professional aerial filmmaking and photography platform (https://www.dji.com/ru/inspire-1-pro-and-raw?site=brandsite&from=landing_page). Featuring an onboard camera Zenmuse 5X, it shoots aerial photos with a maximum resolution of 4608×3456 pixels. Its retractable landing gear pulls up out of view, giving the built-in camera an unobstructed 360-degree view of the area below.

The UAV positioning is activated automatically when the aircraft is launched. Maximum service flight height is 500 m. Maximum service ceiling above sea level is 4500 m. The flight distance is about 1000 m, including the return to the start position before the built-in battery is depleted to a point that may affect the safe return of the aircraft. Remote control radius in open space is 2000 m.

Piloting and operating the UAV is simple. Preparing the aircraft for work takes several minutes. Flight control and configuration is performed via DJI Go software that changes shooting settings and flight parameters, controls the UAV status and reports problems, if any, during take-off and/or flight. In addition to manual mode, the DJI Go software allows shooting in automatic mode along a selected path and at a given height, and timing of automatic photography can be set as required.

Reliable control of the quadcopter flight heights relative to the ground surface is ensured by the built-in ultrasonic sensor, barometer, GPS and visual positioning sensor. It should be noted that in case of shooting in automatic mode, the UAV is moving, its body is in a tilted position, and the camera is thus slightly away from the nadir point. For this reason, we carried out shooting in manual mode after the UAV was stopped and leveled to the horizontal position.

Depending on the objectives for studying the exogenous geological processes, aerial photos are needed with different degrees of detail of the objects under study. The use of UAV allows changing the degree of detail by changing the flight height and, accordingly, the image scale (Table 2). Local and detailed aerial photography surveys are schematically illustrated in Fig. 3. For a local survey of quite large objects (in our study, debris flow alluvial fans and elementary catchments), the flight height is 100–150 m, and the area covered by

Fig. 2. Unmanned aerial vehicle DJI Inspire 1 PRO (debris flow alluvial fan, Tunka Ridge).

Рис. 2. Беспилотный летательный аппарат DJI Inspire 1 PRO (конус выноса селевого потока, предгорье Тункинских гольцов).

aerial photography is about 1.0 km^2. Due to the short duration of flights, an aerial photography session to photo a large object is carried out in several cycles. The UAV zigzag flight path goes along the surveyed element from its uppermost to the lowest point (or vice versa). Shooting in manual mode yields images overlapping by

Table 1. **DJI Inspire 1 PRO specification (http://www.dji.com)**

Таблица 1. **Технические характеристики БПЛА DJI Inspire 1 PRO (http://www.dji.com)**

Characteristics	Values
Dimensions (W x H x D)	451 mm × 438 mm × 316 mm
Max speed	18 m/s
Max flight height	2500 m
Service flight height	500 m
Max flight time	18 minutes
Max takeoff weight	3500 g
Operating temperature	–10 °C to +40 °C
Max wind speed resistance	10 m/s
Hovering accuracy (P Mode)	Vertical: ±0.5 m Horizontal: ±2.5 m
Camera ZENMUSE X5	
Effective pixels	16 M
Max resolution	4608×3456
Focal length	f=15 mm

Table 2. **Specifications of local and detailed surveys**

Таблица 2. **Характеристика детальных и локальных работ**

Parameters	Surveys	
	Local	Detailed
Flight height, m	100–150	1–30
Accuracy	1–5 %	0.7–1.0 %
Image scale	From 1:650	1:10 – 1:200
Resolution of orthophotomap	From 2.99 cm/pixel	From 0.74 mm/pixel
Resolution of height map	From 2.77 cm/pixel	From 1.49 mm/pixel
Surveyed objects	Elementary catchments, avalanche and debris flow alluvial fan	Erosion structures, debris flow transit zones, debris flow deposits
Max area of objects	1 km²	500 m²

70 % along the route and 50 % between the routes, as required for generating a mosaicked orthophotomap. The camera is positioned at the nadir point.

Detailed shooting at 1–30 m heights yields larger scale images with higher resolution (Table 2). In our study, such images were taken to study the erosion structures and analyse the granulometric compositions of the debris flow deposits. The surveyed areas ranged from 30 m² to 500 m².

For investigating the granulometric compositions of the debris flow deposits, the requirements were as follows: 1–30 m heights; the camera positioned at the nadir point; true vertical photos. The UAV flights were arranged across the main directions of the debris flow movements along several transverse profiles in different parts of the debris flow alluvial fan, from one edge of the fan to the other. Such a flight path ensures obtaining an objective picture of the particle-size distribution along the profile on different morphological elements of the debris flow deposits, including the edges, debris fans and erosion incisions.

To determine the accuracy of shooting, a geodetic rod was laid at the profile section. When processing the orthomosaic, the software compared the actual length of the geodetic rod to its measured size, and possible measurement errors were determined.

The images of erosion structures and construct transverse profiles were taken during the UAV flights at 1–30 m heights. Aerial photography combined shooting true vertical photos and oblique ones. The camera was positioned parallel to the surface to be photographed, i.e. at the nadir point to shoot the surfaces and bottoms of erosional structures, rotated to shoot the sides, and to the horizon to shoot the steeply dipping and vertical sides of the erosion structures.

Shooting was carried out along the reference profiles with markers placed at the edges of the reference network, so that they could be recognized on the construc-

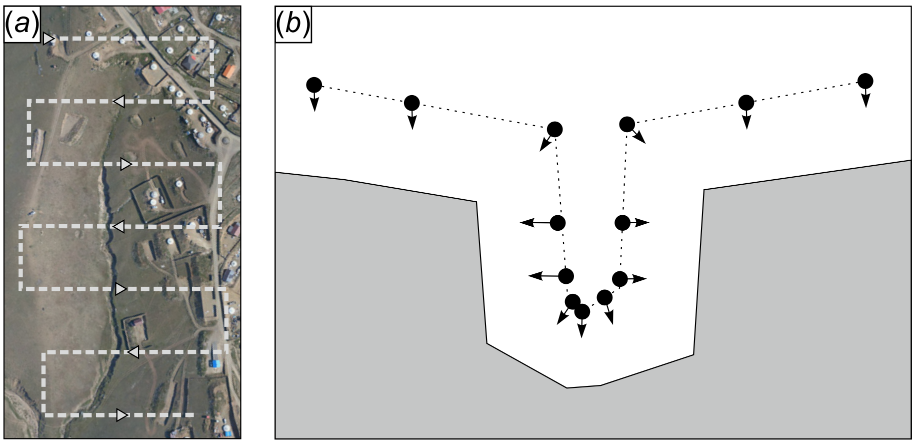

Fig. 3. Examples of UAV flight paths: (*a*) – local shooting of an elementary catchment basin; (*b*) – detailed shooting of the transverse profile of the erosion structure (arrows show positions of the camera during shooting).

Рис. 3. Траектория полета БПЛА при съемке: (*a*) – при локальной съемке элементарного водосборного бассейна; (*b*) – при детальной съемке поперечного профиля эрозионной формы (стрелки указывают положение камеры во время съемки).

ted models. To ensure the accuracy of shooting and eliminate possible errors, the distances between the markers and the main elements of the profiles (width and depth of an erosional structure) were double-checked by the laser range-finder measurements.

The aerial photography sessions detected some shortcomings in using the DJI Inspire 1 PRO in the field, mainly due to its short flight duration – after a flight of about 15–17 minutes, the battery is fully depleted, and charging takes about 2–3 hours. To ensure efficient battery replacement in the field, it is required to have either several charged batteries or a field facility to charge the batteries. The UAV sensitivity to weather conditions must also be mentioned – using the UAV is not recommended in case of low air temperature (below –10°C), rain and strong wind. This requirement puts a significant limit to the UAV use in the field conditions.

2.2. Data processing

Images taken by the UAV are processed by specialized software. We use AgiSoft Photoscan software (demo version) that automatically aligns images, builds point clouds, elevation maps and orthophotomaps, and creates 3D models of photoed objects. Parameters of each operation are adjustable, e.g. the accuracy of positioning and dense point clouds can be edited. Changes in the parameters are reflected in the quality of a model and an orthophotomap and change the speed of the operation accordingly. It should be noted that some operations last for more than 12 hours each.

Aerial images are visually checked to select good quality images and delete poor quality ones (out of focus, too dark, overexposed, etc.). Georeferencing and alignment of the selected images is done automatically by the AgiSoft PhotoScan software. The software automatically determines the tie points, creates a point cloud and edit it by deleting points that deviate from the surface of the object (the presence of such points adds noise to the point cloud and leads to a negative impact on constructing a 3D model). Based on the point cloud, the object heights are mapped. After this operation, it becomes possible to construct the orthophotomap and 3D models of the object under study. The AgiSoft Photoscan software allows exporting of the results to other file types for further processing and analysis by third-party software packages.

Orthophotomaps are used to determine the granulometric compositions of debris flow deposits – an orthophotomap is divided into squares, and particle-size distribution patterns are analysed within each square. Square dimensions are set with respect to the dominating sediment fraction: the smaller is the fraction, the smaller is the square. Positioning of the square along the profile is determined by the sediment sizes typical of the given profile. Typically, a square is located at the edge and middle parts of the debris flow deposit profile. The square should not cover areas with sediment fragments which size is not typical of the profile. Within the squares, contouring of each element of the granulometric compositions of the specified size is done in manual mode. After all the elements are identified, the MapInfo software is used in automatic mode to determine the precise dimensions of the particles and square areas comprised of such particles. Based on these detailed data, the sediments are sorted into groups by size. This method is used to analyse large fractions (0.09 m and larger). The granulometric composition of the aggregate is determined in laboratory conditions by standard methods.

The 3D models based on the aerial photography results are processed by software packages that can yield quantitative data from the analysed models. In our study, the Global Mapper 13 and Surfer 8 were used to construct transverse profiles of the erosional structures and yielded the quantitative data sets that are useful for monitoring the dynamics of these structure. Comparison of the heterochronous profiles allows obtaining information on the erosion activity due to more active erosion of the bottoms or sides of the studied structures. Models of elementary catchments can provide quantitative data required for calculations of surface runoff from melted snow and rainwater, which are needed for investigation and forecasting of the development of fluvial processes.

3. Survey results

The UAV was used in the field surveys of the debris flows near the Arshan village (Tunka Ridge, Russia) and erosion processes in the Ulaanbaatar agglomeration (Mongolia). The survey results are presented below.

3.1. UAV in the study of debris flow processes

Our field surveys were focused on the debris flow that occurred near the Arshan village in the Tunka Ridge area in June 2014 and aimed to obtain quantitative data on this debris flow event. Its detailed descriptions are available in [*Makarov et al., 2014; Kadetova et al., 2016a, 2016b; Rybchenko et al., 2018*].

Debris flow composition, properties and dynamic characteristics (speed, flow rate, distribution of debris flow deposits, etc.) can be studied by a variety of methods, including tachymeter and leveling surveys, ground photogrammetry, etc.

Our research team carried out several field surveys near the Arshan village to study the entire debris flow area, take samples from the debris flow deposits, and investigate debris flow transit zones, rock failure locations and debris flow alluvial fans in detail. It should be noted that field surveys in the debris flow transit zones in the Tunka Ridge area are challenging – visual inspection of the transit zones is unsafe on the steep slopes due to potential rock collapse and landsliding. However, this particular part of the debris flow area contains traces of the debris flow path and its details are indicative of debris flow velocity, peak discharge, sources and accumulation history. Considering the local terrain conditions, the UAV was the most convenient tool for remote surveys of the transit zones. Having processed the aerial images taken by the UAV, we detected the morphological features of fresh debris flow transit zones, calculated their lengths, and selected the sites for more detailed surveying and transverse profiling. The survey database included quantitative parameters (dimensions, slope angles) of the sides and bottom of the transit zone, qualitative and quantitative compositions of the deposits inside the profile, including those at the sides of the transit zone. These data were used to analyse the debris flow material and reveal the sources of its solid components.

Using the orthophotomaps of the transit zones, it became possible to identify the bedrock outcrops, sites of intensive supply of the solid debris flow component, bending of the debris flow paths, narrow segments and other features of the debris flow channel that influenced the dynamic characteristics (debris flow velocity and peak discharge). Besides, debris flow wave splash sites and other accumulation structures were outlined. Thus, specific features of debris flow passage in the transition zone were clarified.

In studies of the debris flow process, analysis of the distribution of debris flow deposits in the accumulation zone is important for understanding the debris flow type and direction, estimating its velocity and peak discharge, and identifying its cycles within the spatial and temporal framework of one event. The above is required for properly justified identification of the most hazardous zones in debris flow basins, selection of optimal types of protective engineering structures and correct definition of their locations.

In large debris flow accumulation zones (in our case, 0.004 km^2 to 0.281 km^2), field surveys aimed at obtaining the data on the distribution of debris flow deposits are highly labour-intensive and time-consuming. Furthermore, it is challenging to consolidate the information covering an entire accumulation zone. Using UAVs for this purpose is the most efficient way. Aerial images and orthophotomaps can cover an entire accumulation zone and provide the information on the distribution of accumulated debris flow deposits (terraces, levees and debris flow alluvial fields). It thus becomes possible to identify the main and secondary debris flow channels and different time debris flow waves (Fig. 4).

Orthophotomaps of debris flow accumulation structures are used as a basis for constructing schematic maps of debris flow basins, which show the debris flow movement patterns in accumulation zones. Such maps are useful for planning debris flow protection activities and development of emergency plans against debris flow risk.

Rheological properties of a debris flow, such as density, viscosity, transportation capacity of the flow, can be estimated from the data on the granulometric composition (particle-size distribution) of the debris flow deposits coarse fraction. The presence of large boulders in debris flow deposits predetermines the debris flow density and concentration, as well as its peak discharge [*Johnson et al., 2012; Yong et al., 2013*].

Changes in the particle-size distribution pattern are indicative of the local features of debris flow movements. Particle-size segregation is crucial for transportation of particles and formation of morphological elements of debris flow alluvial fans, such as levees [*Gray, Kokelaar, 2010; Johnson et al., 2012*].

Based on the reconnaissance of the debris flow alluvial fans, we selected sites for UAV surveys to obtain quantitative data for granulometric composition analysis using orthophotomaps (Fig. 5).

3.2. UAVs in the study of erosion processes

The territory of Ulaanbaatar and surrounding settlements is located in the Tola (Tuul) river valley and the foothill areas. Its engineering and geotechnical setting is complicated due to the following: complex structural and tectonic features of the intermontane troughs and the neighbouring mountain frame; high seismicity of the neotectonic zone (to magnitude 8); diversity of geological rocks; the lithological composition of dispersed soils; significantly different air temperatures through the year; and increasing technogenic impacts on the geological environment. Furthermore, the geological environment is complicated by widespread involvement of this territory in fluvial processes, including floods, erosion and debris flow [*Kozyreva et al., 2014b; Gladkochub, 2017*].

The first study of the erosion processes in the Ulaanbaatar agglomeration was carried out in 2011. The geological environment was described and investigated [*Rybchenko et al., 2011*], and a monitoring network, including 10 sites, was established. On every site, there is a network of reference points for annual instrumental surveys and transverse profiling of erosional structures [*Kozyreva et al., 2014b*]. Every site has its certificate that includes the description of the lithological features and the size of the monitored catchment area. Monitoring of the dynamics of the erosional structures is carried out along 24 transverse profiles at the top, middle and bottom parts of the observed erosional

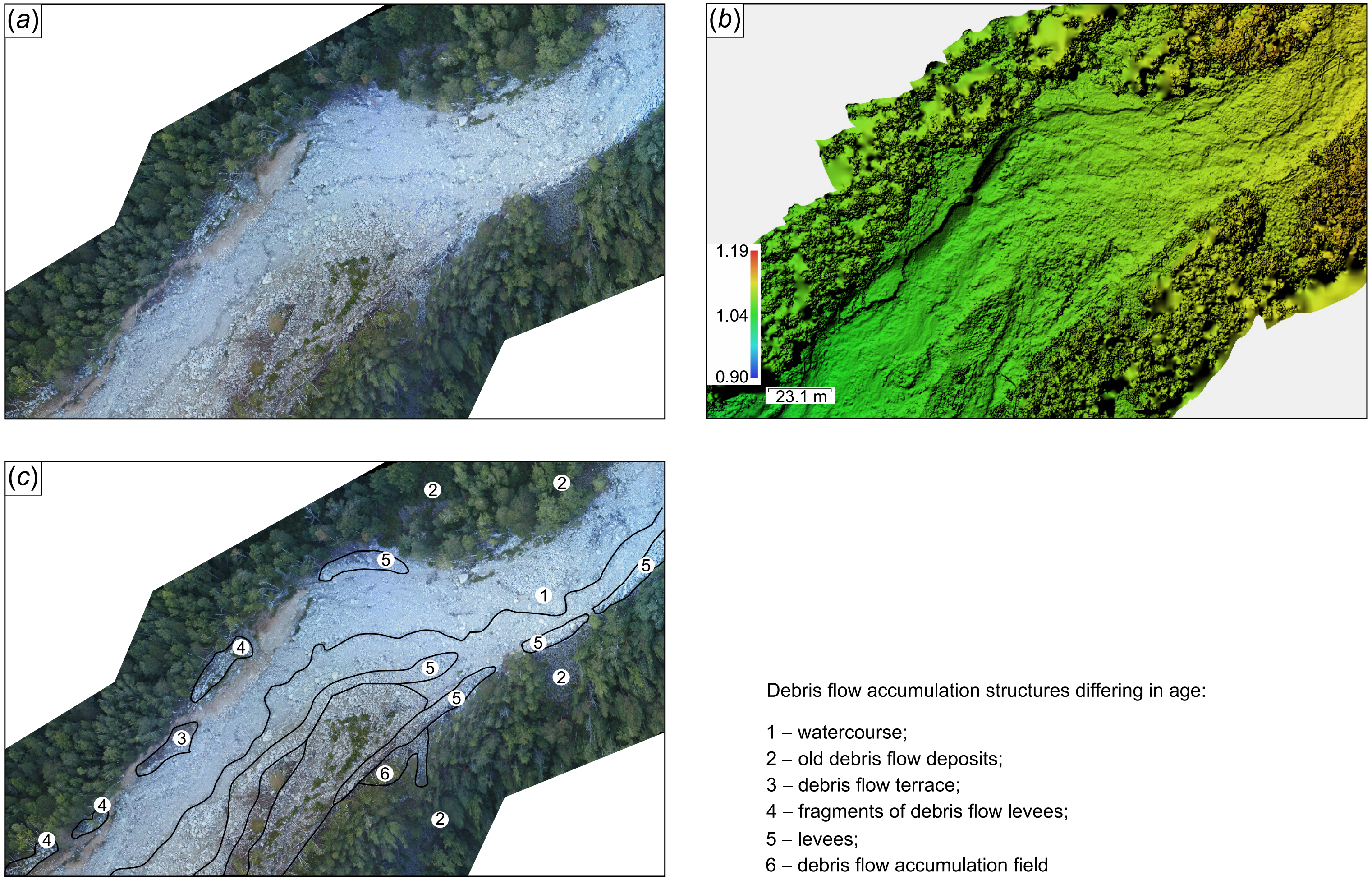

Fig. 4. Processed aerial images of a fragment of the debris flow alluvial fan: (*a*) – orthophotomap; (*b*) – 3D model; (*c*) – schematic map of debris flow accumulation structures.

Рис. 4. Результаты обработки аэрофотосъемки БПЛА (фрагмент селевого конуса выноса): (*a*) – ортофотоплан; (*b*) – трехмерная модель; (*c*) – схема селевых аккумулятивных форм.

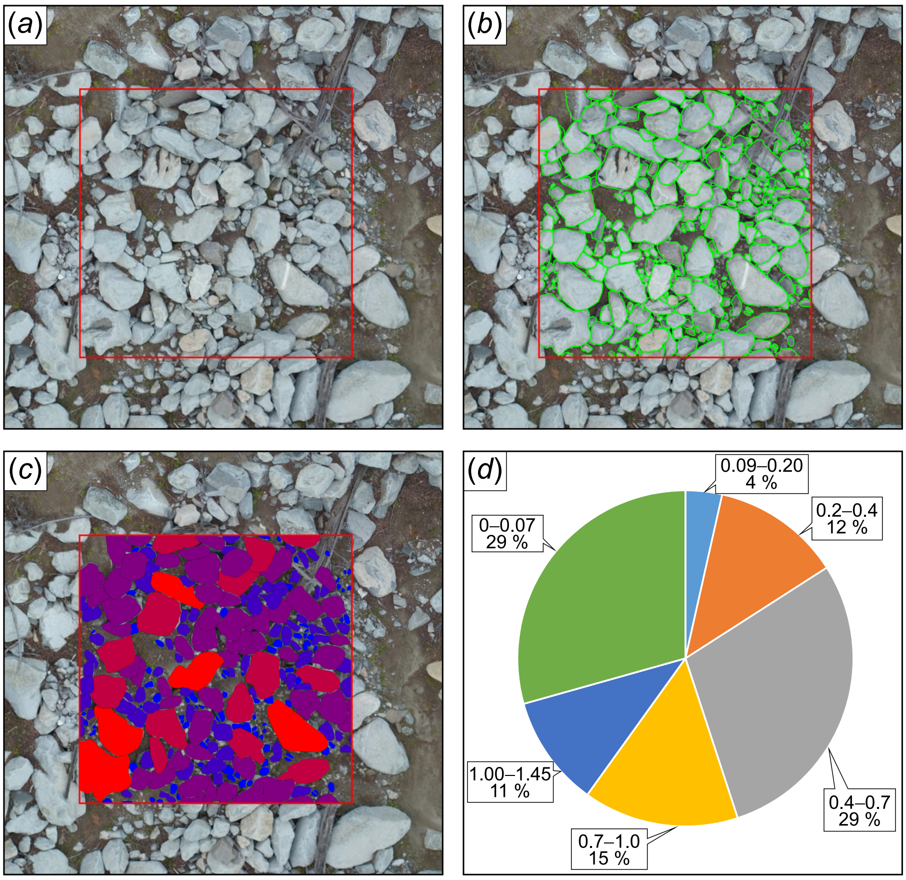

Fig. 5. Granulometric composition of debris flow deposits. Orthophotomap processing stages: (*a*) – selection of sites; (*b*) – definition of elements of the granulometric composition; (*c*) – sizing of rock elements; (*d*) – granulometric composition diagram.

Рис. 5. Результат детальных работ – определение гранулометрического состава селевых отложений. Этапы обработки ортофотоплана: (*a*) – выбор участка; (*b*) – обрисовка элементов гранулометрического состава; (*c*) – определение размеров обломков и их градация; (*d*) – гранулометрический состав отложений.

structures. The growth of tops of ravines is recorded separately.

In 2017, UAVs were introduced in the study of the erosion process in the Ulaanbaatar agglomeration. Local surveys covered elementary catchments, and detailed aerial photography aimed at erosion structures. Aerial images were used to construct orthophotomaps and 3D models of the catchment areas.

Using the models, morphometric parameters of the catchment area (square area, length, width, slope angle, and surface runoff direction) can be calculated. These parameters and the atmospheric precipitation values are the basis for hydrological calculations of water runoff volumes and velocities, which cause a more active development of the erosion process [*Gorshkov, 1979*]).

The knowledge of the dynamics of an erosional structure and the surface runoff volume allows correlating the dynamics with the quantity and intensity of precipitation, as well as considering various scenarios of fluvial processes depending on the forecasted atmospheric precipitation.

In addition to the 2017 instrumental survey of the transverse profiles of ravines, detailed aerial images were taken by the UAV and used to construct 3D models (Fig. 6).

The models provided the basis for transverse profiles of the surveyed erosional structures. Besides, 3D tile models make it possible to visually assess the geological section and distinguish various lithological layers, calculate their thicknesses, assess the degree of sorting of the material, and estimate sizes of coarse inclusions. Comparison of heterochronous models of the transverse profiles can give quantitative data on the dynamics of erosional structures and reveal the dominance of either bottom or side erosion in the periods under study.

4. Discussion

Our experience of using UAVs to study the exogenous geological processes, debris flows and erosional

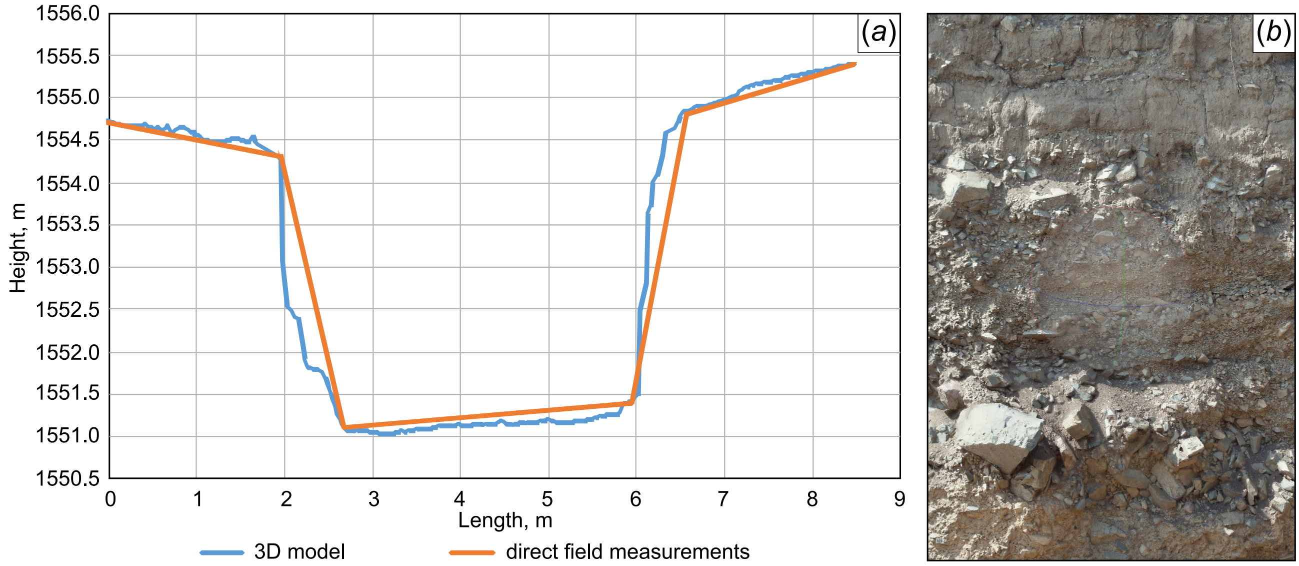

Fig. 6. Aerial image processing results for the erosional structure: (*a*) – transverse profiles based on the 3D model and direct measurements; (*b*) – fragment of the erosional structure's side.

Рис. 6. Результаты обработки аэрофотосъемки эрозионной формы: (*а*) – поперечный профиль формы по цифровой модели и по прямым измерениям; (*b*) – фрагмент борта эрозионной формы по тайловой модели.

structures, shows that aerial images taken by UAVs facilitate obtaining high quality quantitative information and considerably reduce time needed to perform similar tasks by traditional methods of field research, such as ground photogrammetry [*Rossi et al., 2018; Tziavou et al., 2018; Yu et al., 2017*]. New information of high quality can be received by processing orthophotomaps of the UAV surveyed objects.

In the studies of the erosion process, it is important to determine the granulometric composition of debris flow and sizes of the coarse fraction in the debris flow accumulation zones. Using the palette method and ground photogrammetry in field to calculate grain sizes and specify the composition of the coarse fraction is a rather labour-intensive and time-consuming process. In the previous field surveys, ground photogrammetry took us from 11 to 24 minutes to cover one 25 m^2 site, and three persons were involved in the work on each site.

Using UAVs for similar tasks, one person is enough to conduct aerial photography of an object and obtain images of adequate quality. An aerial photography session generally lasts for 10–15 minutes, and its duration depends on the lengths of profiles. The UAV survey is carried out along a profile, including three segments of 25 m^2 each. Preparation of the quadcopter for work takes 3–4 minutes. Its preparation for transportation is also 3–4 minutes.

Construction and comparison of heterochronous transverse profiles is widely applied in studies of the dynamics of erosion structures. Profiles are based on quantitative data collected by various measurement techniques, such as direct field survey, tacheometry, etc., each having its pros and cons. Aerial photography can provide more detailed and accurate quantitative data (compared to direct measurements) for constructing transverse profiles based on 3D models of erosion structures within the surveyed area. Direct field measurements are less precise due to errors caused by geometric deviations of measured lines from of the reference straight line.

Orthophotomaps are efficient tools for visual assessment of the scale of the surveyed process, e.g. debris flow development, which is challenging in case of using traditional labour-intensive field surveys. Orthophotomaps provide a variety of qualitative and quantitative data for studying the debris flow process and allow calculating morphometric parameters of debris flow elements. Using tacheometry to obtain such data would be a labour-intensive and time-consuming process.

5. Conclusion

For the studies of exogenous geological processes, UAVs can provide a variety of high quality images and quantitative data on the objects, considerably reduce the time of data collection and processing, compared to traditional methods. Surveys with UAVs provide the materials otherwise non-obtainable or requiring much effort to collect.

The UAV mobility and simple and fast data processing provide for higher efficiency of field surveys and deliver aerial photography results within a shorter time.

The use of UAVs at different heights allows obtaining images of different scales and ensure the degree of detail necessary for the study and imagery processing.

UAVs can be used for aerial photography surveys of difficult access environments, such as sites with complicated terrain, steep or vertical hill slopes, gorges, etc. Conventional field surveying is either impossible or associated with high safety risks on such sites, and the use of UAVs is an optimal solution for investigating these sites and expanding the survey coverage.

A shortcoming in using the DJI Inspire 1 PRO is a short duration of its flight before the built-in battery is fully depleted, which significantly reduces the range of the UAV use in both space and time. It should be noted that the accuracy of aerial images taken by this UAV is influenced by the lack of a real-time kinematics system. Nonetheless, the accuracy was sufficient for the tasks of our study. Another shortcoming is that the UAV flight duration may have to be reduced or cancelled in case of the air temperature below/above the allowable operating temperature range (–10 °C to 40 °C) or the wind stronger than 10 m/s (maximum wind speed resistance).

Given a wide range of UAVs, it should be noted that the conclusions in this article are based on the experience of using the DJI Inspire 1 PRO and may not be relevant for other UAV models.

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