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IDENTIFYING THE MAIN FEATURES OF LANDSLIDE MOVEMENT AND DEVELOPING THE BASIC MECHANISMS

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The results of studies of the mechanisms and main features of the movement of fast and extended clayey and other landslides are presented. Landslides are said to cause about 1,000 deaths and $4 billion losses of property each year. However, at least 90% of all landslide losses could have been avoided if the problem had been recognized in advance. At present, as a result of a preliminary statistical analysis, results have been obtained that generally explain the occurrence of the onset of landslides. On their basis, three mechanisms were explained that cause the movement of the geomass of landslides: under the influence of gravitational forces, fluidization and lubrication of the landslide bed along the base of the main guides. However, additional research has found that those gravitational forces do not ensure the movement of significant geomasses over long distances. The third mechanism we have identified is the participation of nanoparticles of the lower layer of the moving landslide as natural nano-bearings. Halloysite nanoparticles have been studied, which are nanotubes (having a length of 0,5...2 μm and an outer diameter of about 200 *nm*, with a lumen diameter of 10...15 *nm*), in which sheets of aluminosilicate are coiled into a spiral. Typically, the shells of such hallusite pipes include 15...20 layers. In addition, halloysites, depending on the conditions of crystallization and geological structure, may have another morphology (such as, for example, spheroidal or disk), which also plays the role of nano-bearings that contribute to the movement of the landslide geomass.

Keywords: landslides, movement mechanisms, gravity, geochemical transformation of underlying rock.

Introduction. Landslides cause about 1,000 deaths and $4 billion losses of property every year. At the same time, at least 90% of landslide losses could have been avoided if this problem was recognized in advance. Therefore, there is a very urgent need to assess the risk of landslides at different spatial scales.

At present, as a result of a preliminary statistical analysis, the following results have been obtained, explaining the onset of the movement of landslides [1]:

1. More than 90% of dangerous landslide slopes have a slope of more than 20^0. In this case, landslides occur mainly on mountainous or hilly slopes, with a slope of 20^0 to 35^0.

2. Landslides mainly occur in mountainous areas with elevations less than 1200 *m* (Fig. 1). For example, in the Chechen Republic, landslides are typical for mountain slopes belonging to the foothills with absolute heights from 350 to 800 *m* [2].

Fig. 1. Landslide about 5 km long and up to 1 km wide from the slope of Mount Guzeripl (Adygea, 2012)

3. In addition, landslides occur mainly on mountain slopes with a slope length of 200 to 400 *m*.

4. The number of landslides on the mountain slopes in the northern direction is 2 times higher than on the slopes in other directions. Thus, in the Chechen Republic, it was found that slopes with northeastern (16,08%), northern (15,44%) and northwestern (14,59%) exposures are subjected to landslide processes most of all [2]. One of the possible explanations for this can be less solar illumination and, accordingly, less evaporation of moisture, leading to greater wetting of the northern slopes.

5. The number of landslides on mountain slopes with a distance to a geological fault of less than 0,5 *km* is 2 times higher than on slopes of other categories.

6. The number of landslides on mountain slopes with a distance of less than 5 *km* from a stream is 3 times higher than on the slopes of other categories.

7. No clear relationship has yet been established between landslides and a specific catchment area.

8. There is no clear relationship between the occurrence of landslides and the existing lithology. Although it has already been established by field studies that the most common type of landslide has a fracture surface [3] following a horizontal or

slightly inclined plane of weakening (such as a bedding plane or a weak layer in stratigraphy).

Research methods. Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), solid-state nuclear magnetic resonance (SSNMR), thermogravimetric analysis (TGA), and X-ray powder diffraction (XRD) have been used.

The main part. A landslide can begin with slow pre-fracture deformation and cracking of the surface soil on a steep slope. Then a shallow sliding stall develops. The landslide mass accelerates, disintegrates, enlarges due to entrainment and turns into a flow-like avalanche of rock fragments [3]. The avalanche enters the drainage channel, drags water and more saturated geomass with it, and turns into a seething stream of various debris. Upon entering the final stage of sedimentation, the landslide flow ("tongue") ejects the largest fractions of rocks and continues in the form of a sediment-saturated flow.

It has been established that the main driving factor in almost all known landslides is the force of gravity acting on a section of a dangerous slope that is out of balance. Therefore, initially, the mechanism of movement of the geomass of a landslide on a mountain slope was taken as a basis only under the influence of gravitational forces.

But further studies have shown that gravitational forces do not ensure the movement of such volumes of geomass and over such distances. Thus, the Bayraman landslide in Papua New Guinea (volume 180 million m^3) from porous karst tertiary limestone (biosparite), destabilized by an earthquake of magnitude 7.1 on a sliding surface inclined only a few degrees towards the river gorge, moved a distance of more than 2 *km* along an almost horizontal slope [3]. Here, the porous material of the landslide was crushed (it was found that the body of the landslide contained less than 10% boulders), which, during its destruction, created excessive pore pressure in the basal shear band.

Another example is in China caused by the occurrence of a huge Daguangbao landslide in 2008 (Fig. 2), under the influence of an earthquake with a magnitude of 8,2 points, an earthquake with a magnitude of 8,2 points, as a result of which more than 1 km^3 of stones and various debris were moved. This geomaterial quickly rushed down the mountainside, over a distance of more than 4 *km* [4] and its area was 7,2 km^2.

Many researchers have made great efforts to understand how and why such very large landslide geomasses (like Daguangbao, for example) can travel quite a considerable distance.

In the course of the static-theoretical studies carried out, it was found that, firstly, the run-out distance of a landslide directly depends on the geometric parameters of the slope of occurrence and is proportional to its area and volume (Fig. 3).

a) b)

Fig. 2. Daguangbao Landslide, China (a) and Frank Slide, Southern Alberta, Canada. The horizontal length of the avalanche path is 3 km, the volume is 36 million m^3 *(b) [3, 4]*

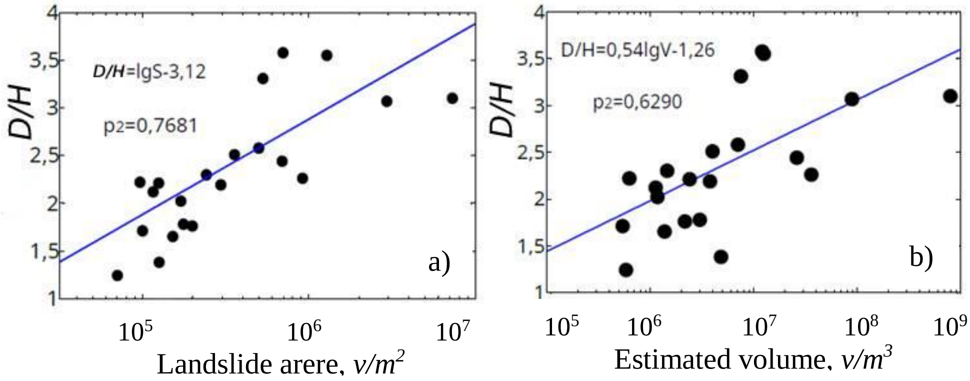


Fig. 3. Dependence of the normalized run-out distance on (a) the area of the landslide and (b) the volume of the landslide [1]

A subsequent review of all existing models of landslide geomass movement allows to single out four main categories [1]:

- volumetric fluidization and hydrodynamic flow of landslide debris (mudflow type);
- geomass loss mechanisms combined with normal frictional sliding;
- special forms of lubrication of the landslide bed along the base of the guides (this mechanism assumes that the bulk of the landslide geomaterial moves along a thin layer of strongly “agitated” particles).

Thus, the researchers found that the resulting friction between the sliding geomaterial and the stable rock of the Daguangbao landslide bed heated (the so-called "frictional heating", which increases with the initial rate of geomass descent, but decreases with the increase in the thickness of the shear zone) a dynamically recrystallized layer of thickness ~0,1 *mm* to more than $850^{0}C$, which is enough for the decomposition of dolomite to begin [4]. And this ensured the evaporation of carbon dioxide from the dolomite rock, which helped to further reduce the existing friction value (the friction coefficient was $\mu \approx 0{,}05$). At the same time, high temperatures and pressures inside the Daguangbao landslide caused recrystallization of the moving rocks. This created a viscous layer that helped to lubricate the slide bed of this landslide. These two mechanisms, working together, allowed the Daguangbao landslide to reach a displacement speed of about 60 *m/s*.

But besides those considered, there are other mechanisms for the rapid movement of the geomass of landslides. An example of powerful fast landslides that occurred as a result of earthquakes is the Gissar earthquake in Tajikistan, which occurred on January 23, 1989, which caused great damage to this republic and took the lives of 274 people [5-8].

The prerequisites for the occurrence of this destructive very fast landslide were that by the end of January 1989, in the thickness of the soil of a high clay hill, at the foot of which the village Sharor was located, quite a lot of moisture had accumulated [5-8]. And after the first vibrations of the earth's crust, which occurred under the influence of an earthquake, the top of this hill moved and a huge (several meters high and 2 *km* wide) mass of mud and damp clay, quickly picking up speed, rushed to its foot, completely destroying the village Sharor.

The village of Okuli-Bolo, located at some distance from this clay hill, was somewhat more fortunate [5-8]. A landslide of semi-liquid clay that fell down while approaching this settlement had already significantly slowed down, i.e. it was not so catastrophic. However, 67 people died here, and a landslide destroyed most of the dwellings.

The result of the natural disaster, which covered an area of over 2100 km^2, was as follows [5-8]: 274 people died, dozens of people were injured and hospitalized, almost 3000 households were destroyed, about 2 *km* of the highway were completely destroyed, thousands of livestock were killed, and degradation occurred. Large areas of adjacent agricultural land were destroyed.

The range of geomaterials prone to liquefaction is much broader than current conventional experience suggests. Therefore, such rapid landslides are observed in different parts of the world. For example, the Attachee landslide near Fort St. John (British Columbia, Canada) occurred in May 1973 in a series of overconsolidated, insensitive clays and silts and transferred 7 million m^3 of this geomaterial over a distance of more than 1 *km* at an average slope angle of 7,7° in less than 1 *min*, crossing the floodplain of the river Pis and raising a displacement wave 15 *m* high on its opposite bank. It is obvious that the plastic nature of a part of the geomaterial during movement has changed significantly as a result of cracking and softening (following the initial instability).

As a result, one of the greatest risks of natural disasters in the world are fast clay landslides (Fig. 4), the mechanism of action of which is based on the manifestation of the physico-chemical properties of the so-called "fast" clays. "Fast" clay is found mainly in Norway and Sweden, but is also found in parts of Finland, Russia, Canada, and Alaska.

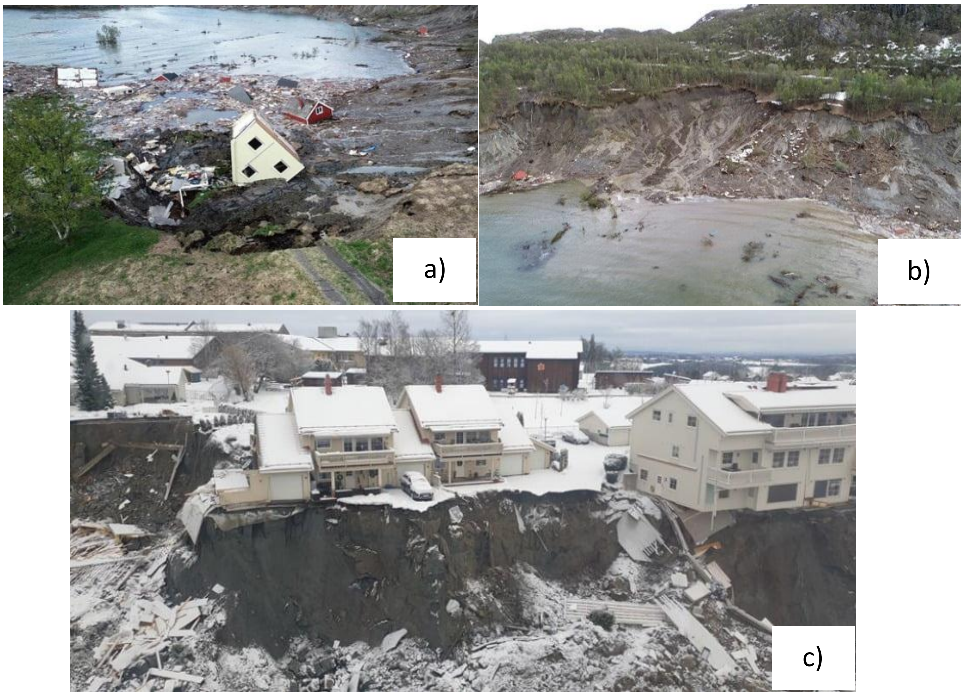


Fig. 4. Fast clay landslides: a - in Norway; b - in Kroknes near Alta; c - in Gerdrum (2020) [9]

Typically, clays become plastic when wet due to the molecular film of water surrounding the clay particles. Fast Clay (also known in Canada as Leda Clay and Champlain Sea Clay) is one of several highly environmentally sensitive glacier-marine clays. “Fast” clay (known in Norwegian as kvikkleire) refers to a special type of clay that, when overloaded, can break down and liquefy at high speed [5].

Shear failure in cohesive materials prefers curved rotating or composite sliding surfaces [3]. If slip occurs, it is probably controlled by the weakest layer or fracture tilted at an angle greater than the friction angle (taking into account the pore pressure and volume forces of the earthquake).

It is also necessary to take into account the fact that fast clay is initially deposited in the marine environment, then the particles of clay minerals (due to the presence of permanent negative charges and charges that depend on pH on their surface) are always negatively charged. Due to the need to maintain electrical neutrality and zero balance of electrical charges, these negative electrical charges are always compensated by the positive charges of cations (such as Na+) adsorbed on the surface of the fast clay or present in it [3]. In this case, exchangeable cations are present in the interlayers of clay minerals and on the outer basal planes of clay plates. The cations also compensate for the negative charges at the edges of such clay particles caused by the protolysis of the silanol and aluminol groups (charges dependent on the pH of the environment). Besides, plates of such clay are always surrounded by a double electric layer (EDL) or a double diffuse layer (DDL), the thickness of which, as a rule, depends on the salinity value of the formed water of the given geomaterial. Under saline conditions (at a fairly high ionic strength), these layers shrink and are further destroyed. This process greatly facilitates the aggregation of the clay platelets, which flocculate and stick together into a more stable structure of aggregates. Once marine deposits of clay are brought to land and are no longer exposed to salt water, rainwater slowly seeps into the poorly compacted clay layer and the excess NaCl present in such clay begins to diffuse. As a result, the electrical layers become less compressed and begin to expand. This leads to a stronger electrostatic repulsion between the negatively charged clay plates, which are much easier to disperse and form stable suspensions in water (peptization phenomenon). This effect leads to a significant destabilization of the structure of clay aggregates. Such clay becomes so unstable that when its mass is subjected to sufficient stress, the behavior of this geomaterial can change dramatically from that of a granular material to that of an aqueous fluid.

As a result, with insufficient mechanical compaction of the clay layer and under shear stress, a weaker compression of the DEL by salts in mobile clay leads to the repulsion of clay particles and their rearrangement into a weaker and more unstable structure. It should be noted that the fast clay quickly regains its original strength upon repeated addition of salt (providing compression of the DEL), which allows the particles of such clay to regain a high degree of adhesion to each other.

Using an X-ray diffractometer, samples of fast clays from large landslides in Nepal [10] were studied to determine the role of clay minerals in the occurrence of such landslides. X-ray diffraction analysis revealed illite, chlorite, and kaolinite (as the main clay minerals in the underlying geomass of landslides). A comparison of landslide activity and types of clay minerals shows that landslides with litter containing illite as a dominant component are more active than landslides with little or no illite in combination with chlorite and kaolinite.

The third mechanism of rapid movement of the geomass of landslides, proposed by us, is associated with clay nanoparticles and, above all, halloysite, which act as an effective lubricant on sliding surfaces.

Halloysite is a member of the kaolin aluminosilicate family, but while kaolinite nanoparticles are lamellar in shape, halloysite nanoparticles are nanotubes (having a length of 0,5...2 *µm* and an outer diameter of about 200 *nm*, with a lumen diameter of 10...15 *nm*), in which sheets of aluminosilicate are rolled into a spiral (Fig, 5). Typically, the shells of hallusite pipes include 15...20 layers.

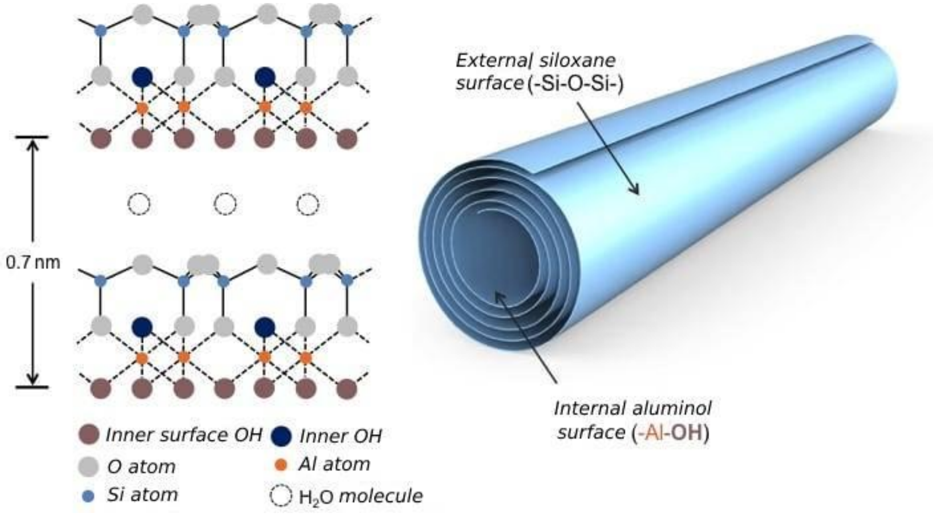
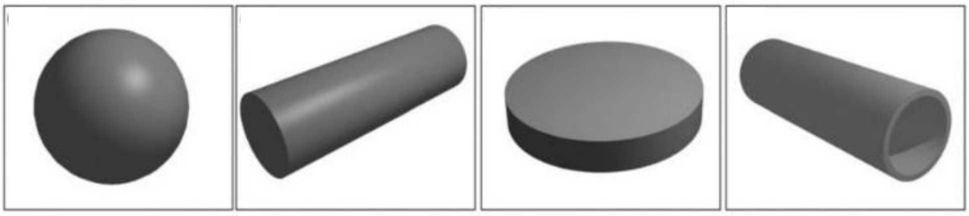


Fig. 5. Scheme of the structure of a halloysite nanotube [11]

In addition, halloysites, depending on the conditions of crystallization and geological structure [12], may also have a different morphology (such as, for example, spheroidal or disk – Fig. 6).



a) b) c) d)

Fig. 6. Geomorphology of clay nanoparticles: a -) a homogeneous sphere; b - homogeneous cylinder; c - homogeneous disk; d - hollow cylinder

In the course of research, it was found that halloysite nanotubes have rather unique physical (Table 1), chemical, and electrochemical properties.

Table 1

Physical parameters of hallusite nanotubes

Chemical formula	**$Al_2Si_2O_5(IS\ HE)_4nH_2O$**
Inner diameter	10…40 *nm*
External diameter	40…70 *nm*
Length	0,2…40 *µm*
Density	2,14…2,59 $g\ cm^{-3}$
Elastic modulus	Up to 600 *GPa*
Strength	N/A
Specific surface area	50...137 $m^2 \cdot G^{-one}$(compared to CNT 100...1000 and graphene up to 3630 $m^2 \cdot G^{-one}$)
Pore volume	1,25 mg^{-1}
pore space	14…46.8 %
Average pore size	7,97…10,02 *nm*
Crystal system	Monoclinic
Cell Options	*A* = 5,14 *Å*, b = 8,9 *Å*, c = 14,7 *Å*, β = 104°, a:b:c = =0,578:1:1.65, Z = 2 (monoclinic)

Thus, there are natural tubular geomaterials with a number of physical and chemical features (such as a unique microspatial structure, a significant ratio of length and diameter, a large amount of clearance and wide distribution). It should be noted that due to the twisted structure, hallusite nanotubes exhibit different chemical properties between the inner (Al-OH) and outer (Si-O-Si) surfaces, i.e. chemically, the outer surface of these tubes has properties similar to SiO_2, while the inner core of the nanotube is associated with Al_2O_3 (Fig. 7). In particular, these two functional groups have different surface charges and pH. In addition, the lumen of the tubule of such a nanotube is positively charged with a pH of 8,5, while the outer shell is negatively charged with a pH of 1,5.

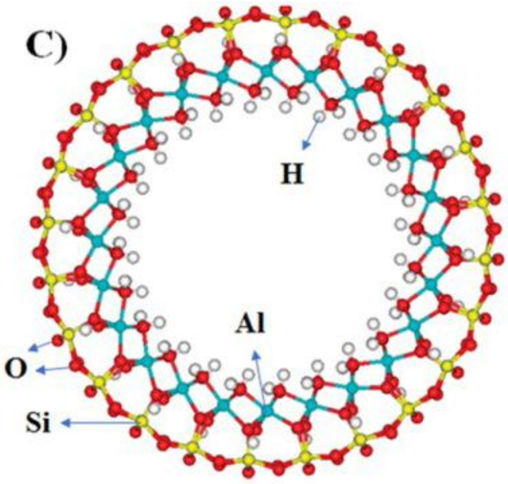


Fig. 7. Cross section of single-walled hallusite nanotubes [13]

The behavior of the charge (zeta potential) of halloysite particles can be described by the superposition of the predominantly negative (at pH = 6...7) surface potential of SiO_2 and a small contribution of the positive inner surface of Al_2O_3 (at pH = 2...7) [14]. In the future, their existing electric charge provides structuring of the arrangement of nanotubes.

It should be noted that the nanotubes of natural halloysite, as a rule, have a high water content due to the presence of single layers separated by water molecules, as well as metal particles (Fig. 8).

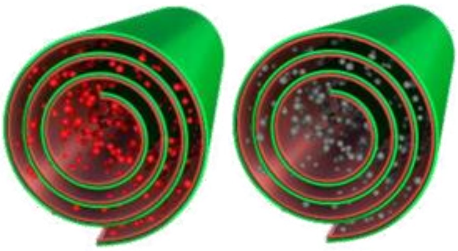


Fig. 8. Hallusite nanotubes with different magnetic content

In order for hallusite nanotubes to realize their maximum potential as natural bearings during the movement of the geomass of landslides, the random distribution of the orientation of nanotubes must be rebuilt, since their misalignment will create inefficient voltage transfer. And here, the structuring of the arrangement of nanotubes is possible under the influence of the local magnetic field that occurs during the movement of the geomass landslide.

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ՍՈՂԱՆՔՆԵՐԻ ԳԼԽԱՎՈՐ ԱՌԱՆՁՆԱՀԱՏԿՈՒԹՅՈՒՆՆԵՐԻ ԲԱՑԱՀԱՅՏՈՒՄԸ ԵՎ ՏԵՂԱՇԱՐԺՄԱՆ ԲԱԶԱՅԻՆ ՄԵԽԱՆԻԶՄՆԵՐԻ ՄՇԱԿՈՒՄԸ

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Ներկայացված են արագ և ծգված կավային ու այլ սողանքների տեղաշարժման հիմնական առանձնահատկությունների և մեխանիզմների ուսումնասիրությունների արդյունքները: Սողանքները տարեկան մոտավորապես 1000 մարդու մահվան և 4 միլիարդ ԱՄՆ դոլարի գույքի վնասի պատճառ են դառնում: Սակայն, միևնույն ժամանակ, սողանքներից առաջացած ամբողջ վնասի առնվազն 90%-ից կարելի է խուսափել, եթե դրանք նախապես բացահայտվեն: Մինչ այժմ ձեռք բերված տվյալները՝ որպես նախնական վիճակագրական վերլուծության արդյունք, ընդհանուր առմամբ բացատրում են սողանքների տեղաշարժման սկսվելը: Դրանց հիման վրա բացատրվել է երեք մեխանիզմ, որոնցով պայմանավորված են սողանքների երկրազանգվածի տեղաշարժը՝ գրավիտացիոն ուժերի ազդեցության տակ, գլխավոր ուղեկցողների հիմքի երկայնքով սողանքային հատակի հեղուկացումը և յուղումը: Այնուամենայնիվ, լրացուցիչ հետազոտությունները պարզել են, որ գրավիտացիոն ուժերը չեն ապահովում զգալի երկրազանգվածների տեղաշարժը մեծ հեռավորությունների վրա: Երրորդ մեխանիզմը, որը բացահայտվել է մեր կողմից, բնական նանո-առանցքակալների շարժվող սողանքի ստորին շերտի նանոմասնիկների մասնակցությունն է: Ուսումնասիրվել են հալուազիտի նանոմասնիկները, որոնք 0,5…2 *մկմ* երկարությամբ, մոտավորապես 200 *նմ* արտաքին տրամագիծով և 10…15 *նմ* լույսի տրամագծով նանոխողովակներ են, որոնցում ալյումինասիլիկատի թիթեղները պարուրվել են: Սովորաբար նման հալուազիտային խողովակների պատյանները ներառում են 15…20 շերտ: Բացի այդ, հալուազիտները, կախված բյուրեղացման պայմաններից և երկրաբանական կառուցվածքից, կարող են ունենալ այլ ձևաբանություն (օրինակ՝ գնդաձև կամ սկավառակաձև), որը նաև կատարում է նանո-առանցքակալների դեր, որն էլ նպաստում է սողանքային երկրազանգվածի շարժմանը:

Առանցքային բառեր. սողանքներ, տեղաշարժման մեխանիզմներ, գրավիտացիա, հիմնատակող ապարների երկրաքիմիական փոխակերպում:

ВЫЯВЛЕНИЕ ОСНОВНЫХ ОСОБЕННОСТЕЙ ПЕРЕДВИЖЕНИЯ ОПОЛЗНЕЙ И РАЗРАБОТКА БАЗОВЫХ МЕХАНИЗМОВ

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Представлены результаты исследований механизмов и основные особенности передвижения быстрых и протяженных глинистых и других оползней. Утверждается, что оползни ежегодно приводят к гибели около 1000 человек и потере имущества на сумму 4 млрд долл. США. Однако при этом, по крайней мере, 90% всех убытков от оползней можно было бы избежать, если эту проблему можно было распознать заранее. К настоящему времени в результате предварительно осуществленного статистического анализа получены результаты, в целом объясняющие возникновение начала движения оползней. На их основе объяснены три механизма, обуславливающие перемещение геомассы оползней: под влиянием сил гравитации, псевдоожижения и смазки ложа оползня вдоль основания главных направляющих. Однако в ходе дополнительных исследований было установлено, что силы гравитации не обеспечивают перемещение значительных геомасс на дальние расстояния. Третий выявленный нами механизм заключается в участии наночастиц нижнего слоя перемещающего оползня в качестве природных наноподшипников. Были исследованы наночастицы галлуазита, представляющие собой нанотрубки (имеющие длину 0,5…2 *мкм* и внешний диаметр - ~200 *нм* с диаметром просвета 10…15 *нм*), в которых листы алюмосиликата свернуты в спираль. Обычно оболочки таких галлуазитовых трубок включают 15…20 слоев. Кроме того, галлуазиты, в зависимости от условий кристаллизации и геологического строения, могут иметь и другую морфологию (такую, как, например, сфероидальная или дисковая), которая также играет роль наноподшипников, способствующих перемещению геомассы оползня.

Ключевые слова: оползни, механизмы передвижения, гравитация, геохимическая трансформация подстилающих пород.