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Main aspects of constructing snow foundations for the new buildings of the Russian Vostok Station, East Antarctica

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Abstract. The present buildings of the Russian station Vostok (East Antarctica) began to operate in 1963 and have been under snow for many years. In connection with the extensive plans to study the subglacial Lake Vostok, it was decided to build a new wintering complex. Since there is a thick snow-firn layer in the construction area, the building of the complex requires solid foundations measuring 200×120 m. It was decided to build them by means of layer-by-layer snow compaction. Based on the approximate weight of the complex of 2 500 tons, its operation time of about 30 years, and the estimated pressure of the station supports on the snow cover of 100 kPa, the foundations slab must have a density of at least 550 kg/m³, and the hardness of the coating of more than 0.5 MPa. In developing the methodology of constructing the slab for the new wintering complex, the method of layer-by-layer snow compaction was taken as the basis, developed for the construction of airfields on deep snow and suitable for taking heavy aircraft on wheeled landing gear. Experimental snow compaction was carried out using various caterpillar tracks, after which stamp tests of snow surfaces with different initial snow characteristics were performed. The bearing capacity of the foundations was assessed by calculating the vertical mechanical stresses on their lower surface, which are formed by the pressure of the station supports. The strength characteristics of the snow were assessed by direct measurements using the Brinell method and with the help of a mechanical press based on the samples taken and a penetrometer. Ultimately, the density of the snow layers in the upper part of the foundations reached 650 kg/m³. In addition to the base layer, 9 additional layers were formed. The first eight were formed in the summer of 2019/20, and the last one in January 2022. The total thickness of the foundations exceeded 3 metres. Upon their construction, the average surface excess relative to the natural snow cover was 210 cm. Based on the rate of snow accumulation, as well as the subsidence of the station supports and foundations into the snow mass, the foundations surface will equal the level of natural snow cover in approximately 30 years.

Keywords: Vostok Station, new wintering buildings, snow compaction technique

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Introduction

During the Second Comprehensive Antarctic Expedition, the domestic inland Vostok Station was opened near the South Geomagnetic Pole on December 16, 1957. In addition to many multidisciplinary, primarily glaciological research programmes, core drilling began in 1970 [1]. After the discovery of a unique natural phenomenon — the subglacial Lake Vostok [2, 3] — studying this Antarctic area became especially important and relevant. Russia undertook systematic research with the great advantage of having a wintering station and annual logistic traverse. The main emphasis was on remote geophysical work, which included the seismic-reflection method and radio-echo sounding. The results made it possible to identify the features of the glacier structure, subglacial relief, and depth structure of the Vostok Lake area, as well as to measure the water layer thickness [4–6]. The penetration into Lake Vostok on February 5, 2012 [7] was the greatest event in the study of Antarctica and allowed the investigation of the body of water by direct methods, i.e., a direct study of the lake water [8, 9], with the study of the bottom sediments in sight. A general overview of the studies performed and planned is given in our paper, this issue [10].

The current Vostok Station housing complex has been under a layer of snow up to 6 metres thick for many years. These buildings were constructed between January and June 1963 [11]. The materials used for the construction are in a gradually deteriorating condition. The station operates all the year round, including winter, when access is virtually impossible. However, with the forthcoming intensification of research work, which is planned following Measure No. 21, “Comprehensive studies of the subglacial Lake Vostok and paleoclimate of the Earth in the area of the Russian Antarctic Vostok Station”, “Action Plan for implementing the Strategy for Development of Activities of the Russian Federation in the Antarctic until 2030”, approved by the Russian Government on June 30, 2021, No. 1767-r, the lack of modern living and laboratory facilities becomes evident. Therefore, it was decided to build a new wintering complex (NWC) at the Vostok Station, which will be close to the buildings of the currently operating station and eventually replace it (Fig. 1).

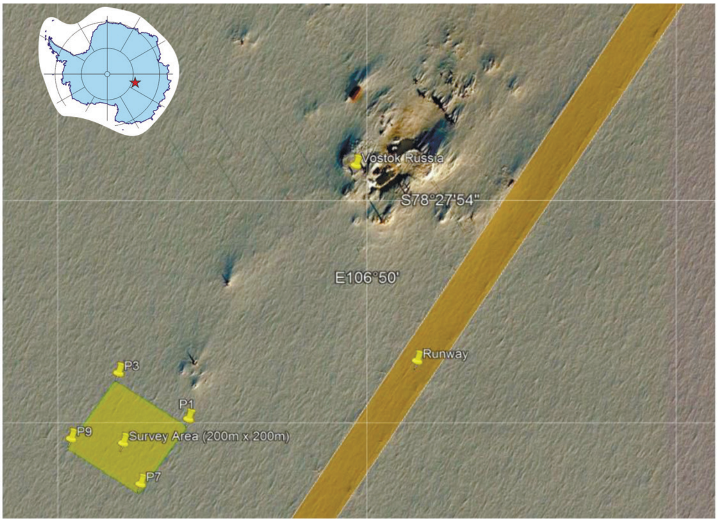

Fig. 1. Location of the new buildings of the Vostok Station [12]

Рис. 1. Схема расположения новых корпусов станции Восток [12]

The main difficulty is that the Vostok Station is located in central Antarctica. This region, according to the classification of glaciers [13], is a zone of dry snow with a snow-firn thickness of about 100 m [14] and a total glacier thickness of more than 3 700 m [5]. The density of the surface snow layer averages 350 kg/m³ [15, 16]. The thickness of the snow-firn strata at the construction site is also significant, due to which, at the stage of the NWC Vostok project development, the question arose of constructing preliminary foundations. In choosing the material, various options were considered, including construction from frozen ice through layer-by-layer pouring of water and from reinforced concrete structures. All of these methods were rejected as they required enormous resources. In the end, it was decided to build the foundations of the station from compacted snow [12] since this method was thought to be the most reliable and economical, especially considering the difficulties of transporting materials and equipment to central Antarctica. Similar stations — Amundsen-Scott (USA) and Concordia (Italy-France) are built on compacted snow. Based on the authors' knowledge, this will be the first attempt to construct such special foundations for a capital structure in Antarctica.

This work aims not only to communicate to the scientific community the main aspects of the construction of the NWC Vostok foundations, but also to present the results of experimental tests and characteristics of the snow cover and foundations for possible use in the future.

Methodology for the construction of the NWC Vostok foundations

In developing the methodology for building the NWC Vostok foundations slab (FS), the layer-by-layer snow compaction method developed for constructing airfields on deep snow, suitable for taking heavy aircraft with wheeled landing gear, was taken as the basis [17]. It is used to build snow-ice runways with a density of snow-firn material over 600 kg/m³ and a hardness of more than 1 MPa. The technique of building such runways was adapted for coastal Antarctic stations, where the surface temperature of the snow during the warm period is close to the phase transition temperature. However, the snow surface temperature in the Vostok Station area does not exceed –25 °C, even in the summer months. During the 2006–2008 field seasons, experimental and methodological work was carried out to determine the possibility of compacting the cold snow to create an airfield suitable for taking wheeled aircraft. The work was carried out in the area of the existing airfield, which can only take aircraft with ski landing gear. Experimental snow compaction was carried out using the tracks of different tractors, followed by stamping tests of snow surfaces with different initial snow characteristics. The results obtained [18] formed the basis for developing a technique for constructing the NWC foundations. In particular, dependencies of the snow density on the impact on the snow cover were obtained. They are shown in Fig. 2. The uniaxial compression strength of the snow was measured using a mechanical press. A total of 50 plate load tests were conducted. The hardness of the compacted snow was measured with a penetrometer with a fracture energy of 8.5 J [17]. Its strength was measured on cylindrical specimens 9 cm in diameter and 16 cm long on a hydraulic press with a dynamic range of 0.2 to 1.5 MPa. The press was calibrated with a precision DOSM-3-1 dynamometer with a dynamic range from 0.1 to 10 kN. A total of 300 measurements were made on the samples. Their accuracy is estimated to be no worse than 2 %. Fig. 2 shows the averaged data for different initial snow characteristics.

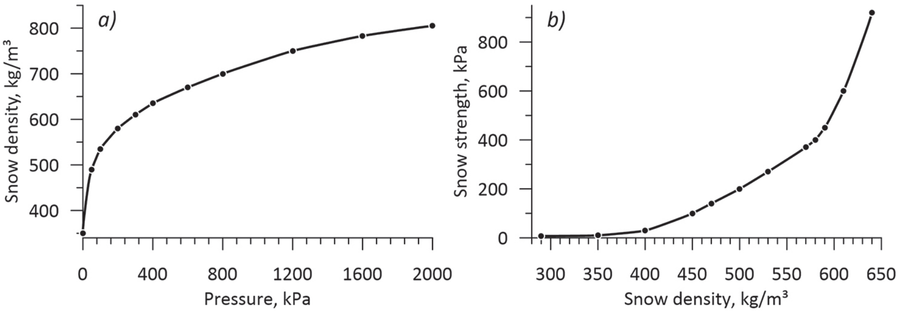

Fig. 2. Dependencies of the density of the compressed snow on the pressure (*a*) and the snow strength on density (*b*)

Рис. 2. Зависимости плотности образующегося снега от оказанного на него давления (*a*) и прочности снега от его плотности (*b*)

The density of the natural snow cover was measured using the VS-43 weight snow meter, and the density of the compacted snow was measured using samples obtained from the core samples. The density variation of the natural snow cover did not exceed 10 %.

Fig. 3 shows the dependence of the depth of impact on the snow cover of the applied stamp pressure P for different snow densities ρ and its hardness σ, obtained as a result of the plate load tests. The depth of impact refers to the depth of the snow layer in which the physical and mechanical characteristics of the snow changed after the mechanical impact. The experiments were carried out on the snow airfield of the Vostok Station, designed for planes with ski landing gear, where the snow is of varying densities. The impact depth was measured for compacting devices, and the impact time on the snow cover was several tens of seconds. The experiments aimed to examine the possibility of compacting cold snow to a certain density and, consequently, strength.

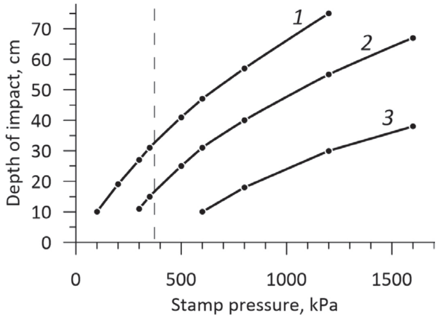

Fig. 3. Depth of impact on the snow depending on stamp pressure for various initial snow characteristics: *1* — ρ = 420 kg/m³, σ = 0.045 MPa; *2* — ρ = 500 kg/m³, σ = 0.2 MPa; *3* — ρ = 580 kg/m³, σ = 0.45 MPa.

The vertical dotted line shows the maximum possible pressure (P = 0.35 MPa) on the surface exerted by the sealing devices

Рис. 3. Глубина воздействия на снежный покров в зависимости от давления штампа для различных исходных характеристик снежного покрова: *1* — ρ = 420 кг/м³, σ = 0,045 МПа; *2* — ρ = 500 кг/м³, σ = 0,2 МПа; *3* — ρ = 580 кг/м³, σ = 0,45 МПа.

Вертикальной пунктирной линией показано максимальное возможное давление (P = 0,35 Мпа) на формируемую поверхность, оказываемое уплотняющим устройством, имеющимся в распоряжении строительного отряда

Based on the compactor capabilities, the maximum thickness of the snow layer to be compacted was selected. A mandatory condition was sealing the layer over the entire thickness, which means the thickness of the layer should not exceed the exposure depth. The FS snow layers were applied using the Kässbohrer Pisten Bully Polar 300 (Fig. 4*a*). After that, due to mixing the snow, its density increased from the initial value of 350 kg/m³ to 420 kg/m³. The main device to compact the FS snow layers was a compaction platform designed and built to create snow aerodromes suitable for heavy-wheeled aircraft. It received a patent for invention [19].

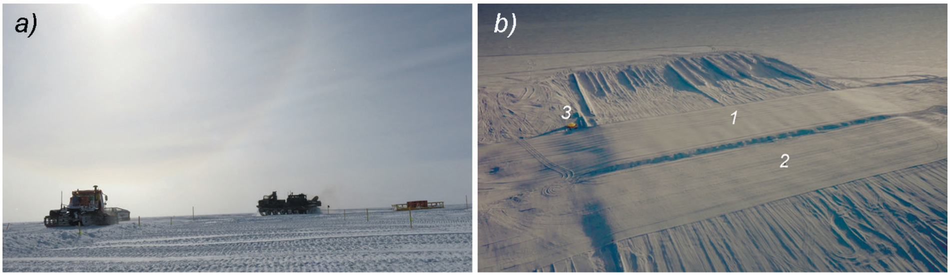

Fig. 4. Fragment of the foundations slab for the new buildings of the Vostok Station (a) and the top view (b).

The compaction of the snow layer by a special platform towed by a heavy artillery tractor is shown in the background of section a. In section b: 1 — the eastern part of the foundations (intended directly for the new buildings); 2 — the western part of the foundations; 3 — the temporary glaciological laboratory. The photos are by K.A. Ovchinnikov

Рис. 4. Фрагмент создания плиты фундамента НЗК Восток (a) и вид сверху на нее (b).

Уплотнение нанесенного снежного слоя специальной платформой, буксируемой артиллерийским тяжелым тягачом (АТТ), представлено на заднем плане секции а. На секции б: 1 — восточная часть ПФ размером 200×60×3 м (предназначена непосредственно для расположения модулей НЗК); 2 — западная часть ПФ, размером 200×60×2 м (для дополнительной инфраструктуры НЗК); 3 — временная гляциологическая лаборатория. Фото К.А. Овчинникова

Foundations slab construction technology and main results

The horizontal dimensions of the FS were determined by the design dimensions of the NWC, as well as the accompanying infrastructure (fuel storage, etc.). In addition, we considered the possibility of working on it with construction equipment on the entire perimeter of the NWC under construction. The horizontal dimensions of the FS were 200×120 m. The FS thickness was calculated based on the main functions of the foundations: to withstand the load from the plant supports and to ensure a higher position of the NWC relative to the surrounding natural snow cover over a long period (about 30 years). Several factors cause the gradual deepening of the NWC over time: (1) natural snow accumulation in the area, which is about 7.2 cm/year [15, 16]; (2) sinking of the station supports into the FS body, due to the compression creep of the snow material under prolonged exposure to mechanical stress and (3) sinking of the FS into the underlying snow cover, also due to compression deformation of the snow under prolonged mechanical impacts of the total weight of the FS and NWC.

At the initial stage of construction, after selecting the FS location, the natural snow cover was compacted by heavy artillery tractor (HAT) caterpillars, with their pressure on the snow at about 45 kPa. Compaction was carried out on the entire site of the prospective FS. As a result, the snow surface lowered by about 50 cm relative to the surrounding terrain, and the density of the snow surface of the site to a depth of 40 cm increased from 350 kg/m³ to 470 ± 20 kg/m³. Below 40 cm, the density of the snow changed insignificantly. Thus, a basic FS layer was created. Further, the snow layers applied to the foundations site were compacted by HAT tracks and the compacting platform. When the snow layers were applied, geodetic control of their thickness and horizontality was carried out. The ground control of the marks was carried out by a Trimble R10-2 GNSS receiver (Trimble Inc., USA) in real time over a 10×15 m network. The height mark was taken on the calculation of +30 cm from the average height of the previous compacted layer. The snow layers were applied with the Kässbohrer Pisten Bully Polar 300 (PB-300). In one trip, it could take up to 4 m³ of snow, which was evenly distributed at the FS construction site. Snow was taken from the surrounding area at 50 to 150 m from the construction site. One transporter PB-300 took 7 days to apply a snow layer of 30 cm thickness on the entire area of 200×120 m. The work was carried out only during the daytime because the air temperature dropped below –30 °C at night, which was unacceptable for the operation of the blade's hydraulic system. In general, according to the NWC design, the foundations surface was to consist of two sites located at different levels. The western part of the 200×60 m FS is one metre lower than the eastern part of the same size FS (Fig. 4). Given the dispersion of vertical stresses with depth under the station supports, the lower FS layers were not compacted as thoroughly as the upper ones. The lower FS layers were compacted once, at most twice, unlike the upper layers, which were compacted repeatedly.

The FS surface in the first construction phase was divided into two equal parts measuring 200×60 m to save time and for more efficient use of the technology. On one of the FS sites, the compacted snow layer was applied and on the other already compacted layer, another snow layer was applied. Fig. 4*a* shows a photo of the snow layer compaction section with a platform weighing 9 tons, towed by a HAT with simultaneous application of the next snow layer by the conveyor blade on the other half of the FS.

In the second phase of construction, after the FS reached a thickness of two metres, the application of snow layers and their subsequent compaction was carried out only on the eastern half of the FS. All the foundations work was done during the two summer field seasons of 2019/20 and 2021/22. No work was performed during the 2020/21 season for technical reasons.

During the work, the maximum pressure exerted by the compaction platform on the snow surface was 0.35 MPa. As follows from Fig. 3, the maximum depth of impact on the snow cover at a snow density of 420 kg/m³ is 30 cm. Based on this value, the maximum thickness of the applied snow layer was selected, which should not be exceeded. It took 10 to 12 hours for the HAT caterpillars to compact the newly applied snow layer over the entire FS area once. It took at least 14 hours to compact the snow layer with a platform towed by an PB-300 transporter over the entire FS area. In compacting, the speed of the towed device should not exceed 5 km/hour because any increase above this speed may destroy the snow cover [20], i. e., the compacted snow may be thrown out from under the skids of the compacting platform. Eventually, the density of the snow layers in the upper part of the FS reached 650 kg/m³ to a depth of 2.5 m. In addition to the base layer, 9 layers were formed. The first eight were formed in the summer of 2019/20, and the last one in January 2022. The total thickness of the FS, including the base layer, under the NWC modules exceeded 3 m.

A temporary glaciological laboratory was organized near the construction site to obtain the main characteristics of the resulting FS snow material. The density and uniaxial compressive strength were measured using cores taken from the FS body. The hardness of FS snow layers was measured using a penetrometer directly on the FS. Fig. 5 shows the averaged vertical distribution of the density and the uniaxial compressive strength of the snow material inside the FS body on its eastern part, which is intended directly for the location of the Vostok Station modules.

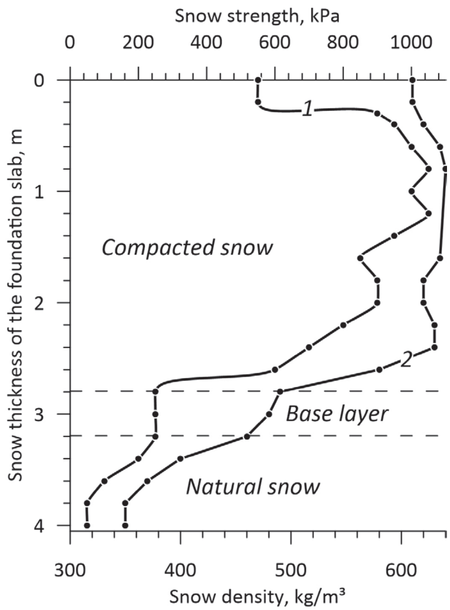

Fig. 5. Density and strength distribution of the compacted snow in the eastern part of the foundation slab.

1 — strength of the compacted snow layer for uniaxial compression, *2* — snow density

Рис. 5. Распределение плотности и прочности снежного материала в восточной части плиты фундамента НЗК.

1 — прочность снежного покрова на одноосное сжатие, *2* — плотность снега

The measurement data presented in Fig. 5 were obtained from cores sampled at the FS in early February 2022. The uppermost ninth layer, formed in January 2022, has much less strength due to the short time that has passed since its formation. The strength of the compacted snow layer increases gradually over a long period, which is due to the slow process of diffusion sintering of the compacted snow granules [21]. In constructing the FS, an experiment was conducted to measure changes in the strength of the compacted snow layer over time. At the western FS site, where no additional layers were applied after the completion of the first phase of construction, the hardness of the compacted snow layer was measured daily with a penetrometer. The density of the layer investigated increased immediately after compaction and reached 640 kg/m³, and the hardness actually initially decreased. Fig. 6 shows the change in the hardness of the compacted layer over time. Measurements were taken daily for 15 days in January 2020. Further measurements were not carried out because the seasonal work at the Vostok Station finished. In the following year, no work was carried out in the Vostok Station area for technical reasons. After two years, the work resumed and the measurement of the hardness of the FS was carried out

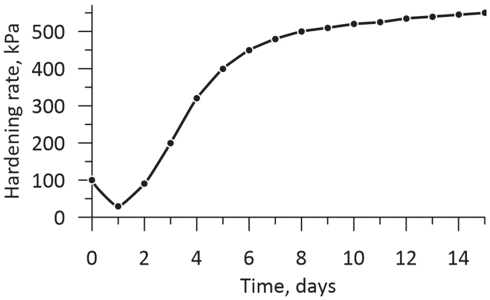

Fig. 6. The hardening rate of the compacted snow.

The average snow temperature during the measurement period was –32 °C.

Рис. 6. Результаты эксперимента по скорости затвердевания уплотненного снега.

Средняя температура снега за период измерений составила –32 °С

again in the same place with the same penetrometer. It was found that after two years the hardness of the compacted snow material almost doubled and reached 1 MPa. The hardness of the layer was measured once at 30 points evenly across the FS surface. The variation did not exceed 5 %.

Bearing capacity of the foundations slab

The FS bearing capacity was assessed by calculating the vertical mechanical stresses on its lower surface, formed by the pressure of the station supports. If the dissipation of the mechanical stresses on the lower surface of the FS does not exceed the carrying capacity of the natural snow cover on which it rests, then the FS bending deformation will not occur, and, as a consequence, its destruction will not follow. This calculation method is an upper estimate of the sufficient thickness of the FS to withstand the NWC load. The estimated pressure of the station supports on the snow cover is 100 kPa. The hardness of the snow material that makes up the FS must be at least higher than the pressure of the station supports. The dispersion of the vertical mechanical stresses in the FS body with depth will depend on the strength characteristics of the material forming the FS. They are shown in Fig. 5.

A rough estimation of the dissipation of the vertical mechanical stresses was made from the results of a plate load test on compacted snow [18]. A stamp with a different pressure impacted the pre-compacted snow cover with known mechanical characteristics. In this case, the depth of the impact on the snow cover studied was measured. In particular, at its density of 500 kg/m^3 and the corresponding uniaxial compressive strength of 0.2 MPa, a pressure of 0.8 MPa was exerted on the snow. The impact depth was 40 cm. This means that at a depth of 40 cm, the mechanical stress from the stamp fell to the strength of the snow cover studied and amounted to 0.2 MPa. Fig. 3 shows the dependencies of the impact depth on the applied stamp pressure for some snow cover characteristics. These tests were conducted between 2006 and 2008. The FS was stronger since the coating density was higher than in the stamp tests. By conducting about 50 experiments with different stamp pressures, a curve of mechanical stress dissipation with depth was obtained for certain snow cover characteristics. For example, Fig. 7 shows the vertical stress dispersion curve for a snow cover with a density of 500 kg/m^3 under the stamp at a surface pressure of 100 kPa.

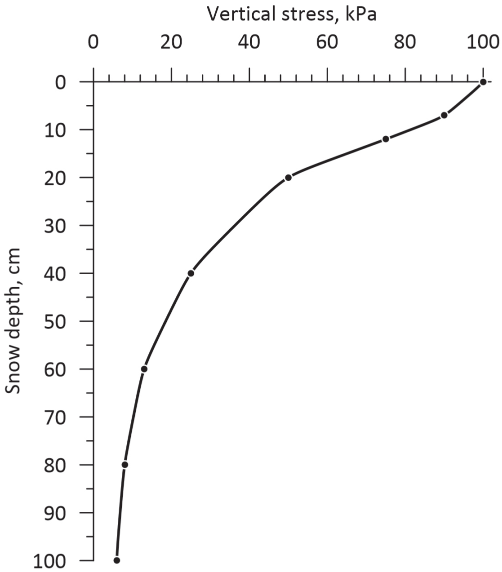

Fig. 7. Stress relaxation with depth for snow density of 500 kg/m³ based on the data collected in 2006–2008

Рис. 7. Ослабление вертикальных механических напряжений с глубиной для снежного покрова плотностью 500 кг/м³ по данным 2006–2008 гг.

The results of the experiments presented in Fig. 7 were obtained in 2006–2008 at the airfield of the Vostok Station, where there were snow layers of different densities and thicknesses. The values presented on the graph agree well with similar data on the dissipation of vertical stresses under the IL-76 landing gear, given in [17]. The greater the strength of the snow material investigated, the faster the vertical stresses under the stamp dissipate with depth. If one imagines an FS of infinite thickness, then at a certain depth, the vertical stresses from the station supports will reach their minimum value, equal to the ratio of the station's weight to the FS area, and will be 1 kPa for NWC Vostok. If the FS thickness is not less than the calculated depth where the vertical stresses will be less than the strength of the natural snow cover on which the FS rests, the latter is safe against collapse. The strength characteristics of the natural snow cover in the NWC construction area were evaluated by direct measurements using the Brinell method [22]. Fig. 8 shows a diagram of the experiment.

The measurements were made by embedding spherical objects of two different diameters into the natural snow cover. The force applied to the objects and the size of the spherical indentation imprint were measured. The hardness of the snow layer tested was calculated using the Brinell formula [23]:

$$\sigma = \frac{P}{\pi D h},$$

where σ is the Brinell hardness of the snow cover, P is the impact force on the sphere, *D* is the sphere diameter, *h* is the sphere immersion depth in the snow cover. The minimum hardness of the natural snow cover, measured at 30 points by pressing a spherical object into the natural snow cover at the construction site, was 10 kPa. The measurement points

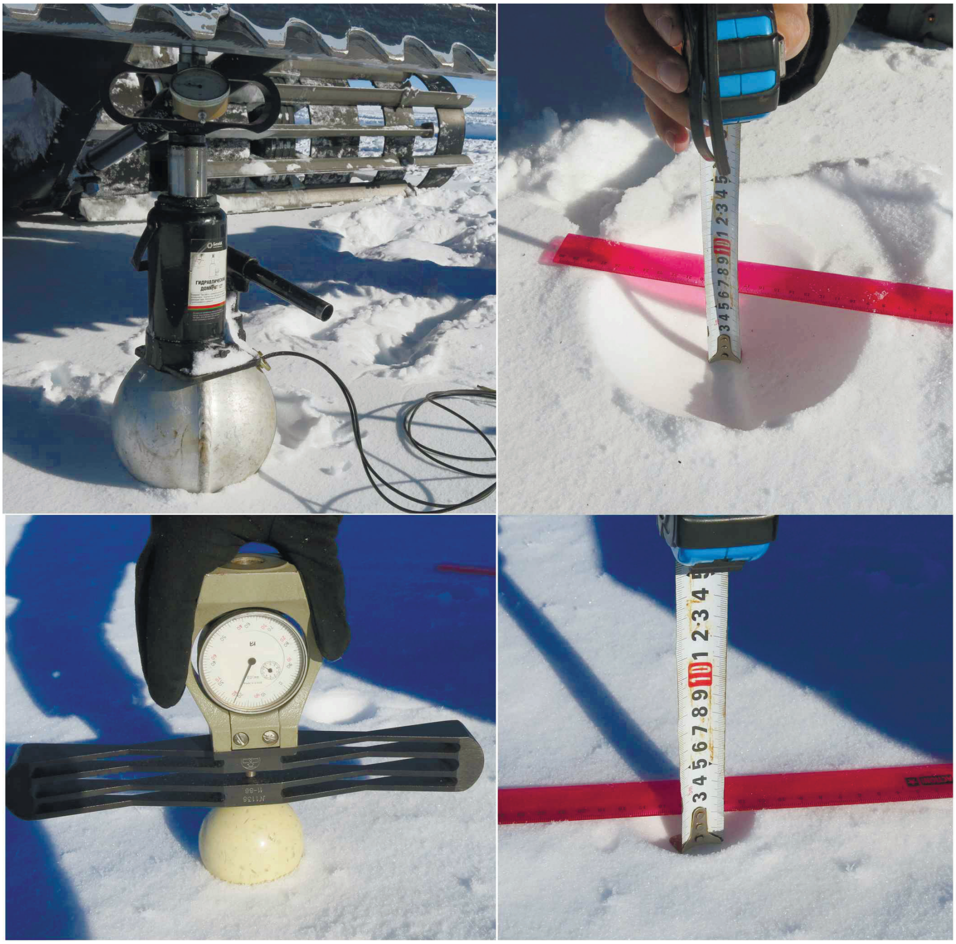

Fig. 8. Scheme of the experiment measuring the strength characteristics of natural snow cover by the Brinell method. The photos are by S.P. Polyakov

Рис. 8. Схема эксперимента по измерению прочностных характеристик естественного снежного покрова методом Бринелля. Фото С.П. Полякова

were chosen evenly. Previously, the density of snow on the surface was measured at 20 points evenly on the site using VS-43. The average value was 350 kg/m³, with no more than 10 % variation. This value was used to calculate the bearing capacity of the NWC FS. In general, the measurements were carried out according to the standard methodology.

As follows from Fig. 7, tenfold weakening of the mechanical stresses applied to the upper surface of the FS will occur at a depth of about 0.7 metres. Given that the initial pressure on the surface from the station supports is 100 kPa and considering the scale effect of the difference in the size of the test stamp and the station supports, the minimum FS sufficient thickness with a snow material density of 500 kg/m³ will be about one and a half metres. In the case under consideration, the density of the upper layers of the FS exceeded 600 kg/m³, and the FS thickness was more than 3 m. Thus, such an FS is certain to be sufficient to withstand the load of the NWC supports.

Creep of the snow material of the foundations slab under the impact of the NWC Vostok supports

One of the important processes that can lead to a decrease in the height of the NWC location relative to the surface of the surrounding natural snow cover is the plastic deformation of the FS snow material under the NWC supports. Calculations of the creep of snow material of different densities were carried out to assess the degree of influence of this process. The snow material begins to deform under the pressure of the NWC supports. The calculation of the deformation was carried out according to the relation

$$\tau = \eta_k \dot{\varepsilon}, \tag{1}$$

where τ is the mechanical stress in the snow (in the case considered, the pressure on the snow from the NWC supports), η_k is the compression viscosity factor of the FS snow material, $\dot{\varepsilon}$ — the rate of relative deformation.

Considering the one-dimensional case of only the vertical deformation of the FS under the action of the NWC supports, the formula for calculating the vertical deformation can be presented in the form:

$$\frac{dh}{dt} = \dot{\varepsilon} h,$$

where h is the thickness of the FS layer studied. Accordingly,

$$dh = \dot{\varepsilon} h \cdot dt. \tag{2}$$

The compression viscosity coefficient η_k was calculated using Bader's formula [19]:

$$\eta_k = \frac{a_\eta \rho_S}{\rho_I - \rho_S} exp\left(b_\eta \rho_S\right), \tag{3}$$

where ρ_I is the density of fresh ice, ρ_S is the snow density, a_η, and b_η are empirical coefficients. At the Berd station [24], unique experiments were conducted to measure the compression viscosity coefficient of snow of different densities at temperatures T = –28 °C, similar to the surface layer temperature of snow in the summer near the Vostok station. According to the experimental data obtained by Bader [20] at the Berd station, at temperature T = –28 °C: $\eta_k = 10^{11}$ Pa·s at ρ = 450 kg/m^3; $\eta_k = 10^{12}$ Pa·s at ρ = 500 kg/m^3; $\eta_k = 10^{13}$ Pa·s at ρ = 650 kg/m^3.

Given the relation (2), the compression deformation (creep) of the FS snow material under the NWC supports, ΔH, for the entire FS of thickness H for the time t_0 will be

$$\Delta H = \int_0^{t_0}\int_0^{H} \dot{\varepsilon} \cdot dh \cdot dt.$$

Substituting into it the value for the relative strain rate taken from (1), one can obtain:

$$\Delta H = \int_0^{t_0}\int_0^{H} \frac{\tau}{\eta_k} dh \cdot dt.$$

This formula was used to calculate the subsidence of the station supports for a given time period t_0 for different strength characteristics of the snow material of which the FS is composed.

The calculations were performed numerically with a depth step Δh = 5 cm and a time step Δt = 10 hours for an FS of thickness H = 3 m. The values of vertical mechanical stresses inside the FS, $\tau(h)$, were taken from experimentally obtained stamp test data for different snow characteristics. In particular, Fig. 6 shows the distribution of vertical stresses for a snow density of 500 kg/m³. The compression viscosity coefficient ηk values were calculated using Bader's formula (3). It depends on the snow density and its temperature and increases as the density increases as the snow material is compacted under the station supports. The compression viscosity coefficient also depends significantly on the snow temperature and increases as it decreases. In the calculations, a correction multiplier was introduced for the temperature of the snow layers inside the FS according to the relation [25]:

$$\eta_k = k\,exp\left(\frac{Q}{RT_0}\right), \quad (4)$$

where Q is the activation energy of snow; R is the gas constant; T_0 is the absolute temperature; k is a constant coefficient for a given snow type. The snow temperature in the calculations was set as the average monthly temperature of the upper snow layers in the area of the Vostok Station [15, 16].

Fig. 9 shows the results of calculations of the compression creep of the snow material under the station supports for different density characteristics of the snow material. If one substitutes the real distribution of snow density in the FS, shown in Fig. 5, the subsidence of the station supports in the FS body will be 12 cm, 28 cm, and 33 cm for 1 year, 10 years, and 30 years, respectively.

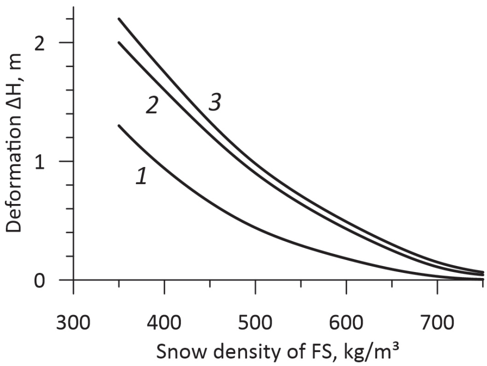

Fig. 9. Calculated compressive creep of the foundations under the station supports for various densities of the initial snow material for various periods

Рис. 9. Результаты расчетов компрессионной ползучести ПФ под опорами станции для различной плотности исходного снежного материала за различные периоды времени

Another process leading to the lowering of the Vostok NWC location is the compression deformation of the natural snow cover on which the station foundations rest. The total weight of the FS, on which the station rests (200×60×3 m), will be about 20 thousand tons. At the same time, the weight of the NWC itself is 2 500 tons. Thus, given the size of the FS, the pressure on the underlying snow layer from the FS side will be about 20 kPa. The deformation of the underlying snow layers was calculated according to the same scheme as the creep of the FS snow material under the station supports, presented above. As a result, for the initial density of the natural snow cover of 350 kg/m³, the FS decrease will be 9 cm in 1 year, 16 cm in 10 years, and 20 cm in 30 years.

Discussion of the results

During the whole period of FS construction, geodetic control of the excess of the FS surface relative to the surrounding natural snow cover was carried out. Thus, at the end of the 2019–2020 seasonal works, the excess of the FS surface position relative to the natural snow cover was 200 cm. The unevenness of the height of the FS surface itself did not exceed 10 cm. At the beginning of the 2021/22 construction season, geodetic measurements of the excess position of the FS surface were repeated. In fact, over 2 years, the average immersion of the FS into the snow strata was about 8 cm, which agrees well with the theoretical calculations presented above. A slightly overestimated result of the calculations of the FS immersion into the snow strata compared to the actual data can be explained by the increased density of the underlying snow layers, on which the FS rests after the first phase of construction in 2019/20. At the end of FS construction, the average excess of its surface relative to the natural snow cover was 210 cm.

Due to the severe climatic conditions in the area of the Vostok Station, only 2 months are suitable for work: December and January, when the air temperature rises to –30 °C. Nevertheless, with two PB-300s and one HAT, the entire 3 m thick snow base could be created in just one summer field season.

Yet, it should be noted that the performed analysis of experimental data and detailed numerical estimates do not take into account a possibility that the supports of the new station buildings could somewhat additionally sink not only due to the one-dimensional compression of the underlying snow-firn layer but also due to 3D deformational upward flow of snow and firn around the columns. Another submerging effect can be related to the fact that the new station area (~ 60×200 m^2) in both directions is comparable or even larger than the snow-firn layer thickness (~80–100 m) in the Vostok region. As a result, the load of the station, not being dissipated within the firn thickness, could lead to further increase in the total compression rate.

Conclusions

With the technical equipment available to the construction team that built the FS, namely: one HAT and one PB-300, the construction of the FS took 2 years. Each year the work was carried out only in the summer period from late November to early February. The main mechanism for lowering the height of the station location relative to the surrounding snow cover is natural snow accumulation on the surrounding NWC surface, which is about 7.3 cm/year [15, 16]. Accordingly, over 30 years, the height of the natural snow cover will increase by about 2 m relative to its original position. The total lowering of the lower part of the station supports relative to the surface of the natural snow cover, given the compression deformation of the FS under the station supports and the deformation of the natural snow cover on which the FS rests, will be about 240 cm in 30 years. Thus, it will take about 30 years for the height of the natural snow cover to reach the height of the bottom of the station supports. Consequently, the work performed has shown that the new buildings of the Vostok Station will last satisfactorily for at least thirty years and given that the height of the station piers themselves is 4 metres, the new buildings could last much longer.

Competing interests. The authors declare no conflict of interest.

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Основные аспекты строительства снежного фундамента для новых корпусов российской станции Восток, Восточная Антарктида

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Расширенный реферат

Имеющиеся на сегодняшний день корпуса российской станции Восток (Восточная Антарктида) начали эксплуатироваться в 1963 г. и уже многие годы находятся под снегом. В связи с обширными планами по изучению подледникового озера Восток было принято решение о возведении нового зимовочного комплекса. Поскольку в районе строительства имеется мощная снежно-фирновая толща, установка комплекса требует наличия твердого фундамента. Его размеры, исходя из конфигурации нового зимовочного комплекса, составляют 200×120 м. Строительство фундамента было решено осуществлять путем послойного уплотнения снега. Исходя из ориентировочного веса комплекса в 2500 тонн, времени его эксплуатации около 30 лет и предполагаемого давления опор станции на снежный покров в 100 кПа, плита фундамента должна иметь плотность не менее 550 кг/м³, твердость покрытия более 0,5 МПа. При создании метода ее формирования за основу была принята методика послойного уплотнения снега, разработанная для строительства снежных аэродромов на глубоком снегу, пригодных для приема тяжелых самолетов на колесном шасси. Экспериментальное уплотнение снега осуществлялось с помощью гусениц различных тягачей, после чего выполнялись штамповые испытания снежных поверхностей с различными исходными характеристиками снега. Оценка несущей способности фундамента осуществлялась методом расчета вертикальных механических напряжений на его нижней поверхности, образующихся от давления опор станции. Оценка прочностных характеристик снега производилась как прямыми измерениями по методу Бринелля, так и с помощью механического пресса по отобранным образцам и пенетрометром. В конечном итоге плотность снежных слоев в верхней части фундамента достигла 650 кг/м³. В общей сложности, помимо базового слоя, было сформировано еще 9 дополнительных слоев. Первые восемь — летом 2019/20 г., а последний — в январе 2022 г. Общая толщина фундамента превысила 3 метра. При нанесении снежных слоев осуществлялся геодезический контроль за их толщиной и горизонтальностью. Разброс неровности высоты самой поверхности фундамента не превышал 10 см. Для экономии времени и более эффективного использования техники его поверхность на первом этапе строительства делилась на две равные части размером 200×60 м. На одной из площадок фундамента проводилось уплотнение нанесенного снежного слоя, а на другой, уже уплотненной, наносился очередной снежный слой. По окончании его строительства среднее превышение поверхности относительно естественного снежного покрова составило 210 см. Исходя из скорости аккумуляции снега, а также погружения опор станции и фундамента в снежную толщу, поверхность нижней части опор станции сравняется с уровнем естественного снежного покрова примерно через 30 лет. Фактическое среднее погружение плиты фундамента за два года в снежную толщу составило около 8 см, что неплохо согласуется с теоретическими расчетами. Таким образом, новые корпуса станции Восток удовлетворительно просуществуют на протяжении по крайней мере тридцати лет, а с учетом того, что высоты самих ее опор составляют 4 метра, значительно дольше.

Ключевые слова: станция Восток, новый зимовочный комплекс, методика уплотнения снега

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