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Simulation of ash dump embankment stability

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Abstract
Ash and slag materials are removed from boiler rooms of CHP "Combined Heat and Power Plant" (Teploelektrotsentral') by hydraulic transport and disposed in ash dumps. These are specially organized areas encircled by protective dams depending on the relief either along the entire perimeter or only in certain low-lying areas. The dams of hydraulic structures must provide stability to the whole structure against the following factors: shear; stability of slopes against sliding; filtration resistance of a dam body soils; reliable slope protection against possible failure due to atmospheric precipitation; as well as against wave action of water (within a settling pond); sufficient excess of dam crest over water level of a pond, etc. The study focuse on the design of ash and slag dump embankment (for storage of the ash and slag removed from the boiler rooms of Karaganda CHP by hydraulic transport). Ash dump design requires a broad range of problems to be solved. These include determination of location, design features and type of embankment, area of the basin and volume of the stored waste, strength of the embankment structures, etc. In order to assess the condition of the ash dump design, the stability of the facility embankment slopes for different combinations of loads, the conditions of possible watering of the dams, the presence of "geomembrane", and pore pressure need to be analysed. A software program based on the finite element method allows simulation of ground (soil) conditions based on the strength and strain characteristics of the dam body filling soils and the base soils. Safety factors of the outer (downstream) slopes of hydraulic structures is determined taking into account the category and design of a structure, type of base (foundation), criticality of the design process stage, and other factors on the basis of conditions that ensure the prevention of the onset of limit states. The most critical and characteristic cross-sections across the perimeter of the ash dump embankment were selected for the computations, based on the analysis of the designed hydraulic structure base lithological composition. According to the computations performed, the outer slopes of the embankment at the paths of wells No. 373-19, No. 381-19, characteristic of almost the entire length of the embankment, are stable for different combinations of loads.

Keywords
Karaganda CHP, ash dump, embankment, structure, slopes, stability, simulation, soil, finite element method, load, factor of safety, drawdown curve, head gradient

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Моделирование устойчивости ограждающих сооружений золоотвала

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Аннотация
Складирование золошлаковых материалов, удаляемых из котельных помещений ТЭЦ «Теплоэлектроцентраль» при помощи гидротранспорта, производится в золоотвалы: специально организованные участки местности, по границам которых, в зависимости от рельефа, возводятся ограждающие дамбы либо по всему периметру золоотвала, либо только на отдельных пониженных участках. Ограждающие дамбы гидротехнических сооружений должны обладать устойчивостью всего сооружения на сдвиг; устойчивостью откосов на оползание; фильтрационной прочностью грунта тела сооружения; надежностью защиты откосов от возможных разрушений в результате действия атмосферных осадков, а так-

же от волнового воздействия воды (в пределах отстойного пруда); достаточным превышением гребня дамбы над уровнем воды пруда и т.д. Основное внимание в исследовании сконцентрировано на вопросах проектирования ограждающих сооружений золошлаковых материалов, удаляемых из котельных помещений Карагандинской ТЭЦ при помощи гидротранспорта. При проектировании золоотвала решаются многие задачи, в том числе определяются местоположение, конструктивные особенности и тип ограждающих сооружений, площадь зеркала и объем складируемых хвостов, прочность сооружений ограждающих дамб и т.д. С целью оценки состояния проектируемого золоотвала выполнен анализ устойчивости откосов ограждающей дамбы для различных сочетаний нагрузок, условий возможной обводненности дамбы, наличия «геомембраны» и порового давления. Расчетная программа, основанная на методе конечных элементов, позволяет моделировать состояние массива в соответствии с прочностными и деформационными характеристиками насыпных грунтов тела дамбы и грунтов пород основания. Коэффициент устойчивости внешних откосов гидротехнических сооружений определяется с учетом класса и конструкции сооружения, типа основания, ответственности расчетного технологического этапа и других факторов исходя из условий, обеспечивающих предупреждение наступления предельных состояний. На основании анализа геологического строения основания проектируемого гидротехнического сооружения выбраны наиболее ответственные и характерные поперечные расчетные сечения по периметру ограждающих дамб золоотвала. Согласно выполненным расчетам внешние откосы дамбы по линиям скважин № 373-19, № 381-19, которые являются характерными практически по всей длине ограждающей дамбы, являются устойчивыми для разных сочетаний нагрузок.

Ключевые слова
Карагандинская ТЭЦ, золоотвал, дамба, конструкция, откосы, устойчивость, моделирование, грунт, метод конечных элементов, нагрузка, коэффициент запаса, кривая депрессии, градиент напора

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Introduction

Hydraulic structures have a number of features, so they differ significantly from other engineering structures. Their size, layout, types of individual elements significantly depend on local conditions: topography, hydrogeological conditions, geological structure (lithological composition) of a base, etc.

The dams of hydraulic structures must provide stability to the whole structure against the following factors: shear; stability of slopes against sliding; filtration resistance of a dam body soils; reliable slope protection against possible failure due to atmospheric precipitation; as well as against wave action of water (within a settling pond); sufficient excess of dam crest over water level of a pond, etc. [1].

Design solutions for embankment erection

Ash and slag materials are removed from boiler rooms of CHP “Combined Heat and Power Plant” (Teploelektrotsentral’) by hydraulic transport and disposed in ash dumps. These are specially organized areas encircled by protective dams depending on the relief either along the entire perimeter or only in certain low-lying areas.

According to a detailed design for the construction of the 1st section of the Karaganda CHP ash dump, crest height was taken at 534.6 m, with a crest width of 8.0 m. According to design projections, the maximum filling level of the ash dump basin can reach 533.1 m. The design height of the dam on the inside of the basin is 12 m with the dam slope ratio $m = 1 : 4$. The dam height on the outer side varies depending on the terrain with the dam slope ratio $m = 1 : 2.5$.

According to the findings of a geotechnical survey performed by “GeolProject and K” LLP in 2019 (in accordance with GOST 25100–2011 and GOST 20522–2012), the sequence of drilled rocks includes sediments of Upper Devonian Famennian stage (D3fm), eluvial sediments of Upper Devonian Famennian stage (el(D3fm)), Neogene (*N*) and Quaternary (*Q*) sediments, covered with topsoil and recent man-made sediments.

The Upper Devonian Famennian (D3fm) rocks are represented by rocky and semi-rocky sandstones. The Upper Devonian Famennian (el(D3fm)) rock eluvium is represented by a weathering crust: rubbly soil, rubbly and landwaste soil with sandy loam aggregate, rubbly and landwaste soil with loamy aggregate.

Based on the analysis of the spatial variability of particular indicators of soil properties and taking into account the features of the geological structure and lithological composition, three layers were identified in the sequence: 1st layer, topsoil; 2nd layer, clay alluvium (silt); 3rd layer, filled soil t(qiv). According to the degree of water permeability, 7 layers of geotechnical units (GTUs) can be determined: 1st GTU, loam; 2nd GTU, sandy loam; 3rd GTU, clay; 4th GTU, rubble-landwaste soil eld3fm; 5th GTU, landwaste soil eld3fm; 6th GTU, rubble soil eld3fm; 7th GTU, rock (sandstone) d3fm.

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Hydrogeological conditions of the study area

According to drilling data, groundwater was intersected at a depth of 2.00–5.5 m. The elevations of standing-water levels are at 519.05–524.87 m. Under natural conditions, the level of groundwater is subject to seasonal fluctuations. The minimum standing-water level is observed in March, the maximum in early May.

The groundwater is fed by infiltration of precipitation, and, in the spring, by meltwater and floodwater. The recharge area is the area of the aquifer.

The amplitude of the level fluctuations in the study area is 1.0–1.5 m. In some years of high precipitation, the amplitude can reach 2.0–3.0 m.

The standard depths of freezing according to SP RK 5.01-102-2013 "Foundations of buildings and structures" are as follows: loam and clay, 1.41 m; sandy loam and dusty sand, 1.72 m; coarse and medium gravelly sands, 1.84 m; coarsely clastic soils, 2.09 m. The average depth of "0°C" penetration into the soils is 1.77 m.

The strength and strain characteristics of soils were established in studies conducted by Azimut Geology LLP, a chemical analysis laboratory in Karaganda.

In order to reduce filtration through the dam (embankment) body, the dam design provides for laying a geomembrane as a watertight barrier, covering the upstream slope of the dam and the bottom of the ash dump basin.

The dam detailed design provides for dewatering of the ash dump area, water diversion, and leveling the basin bottom to the elevation of 522.6 m. In this case, it is planned initially to remove the fertile soil layer, silts, and upper soil layers to the design elevation, in accordance with the requirements of SP RK 3.04-103–2014 "Bases of Hydraulic Structures".

Depending on the terrain and the soil lithology, different soil layers will be removed: from loam to clay deposits [2, 3].

The project envisages filling the body of the dam with the soils removed during leveling. This is compliant with the requirements of SP RK 3.04-105–2014 "Dams made of soil materials", which include loamy-sand and loamy soils. Analysis of the findings of the geotechnical survey performed by "GeolProject and K" LLP in 2019 shows that the most suitable are the Quaternary (*Q*) sediments represented by brown loam and sandy loam[1].

Based on the report "Geotechnical survey for design of ash dump of Karaganda CHP", the characteristics of soils to be used in the construction of the embankment body, are given below.

The strength and strain characteristics for the 1st GTU layer, loam, were determined at natural moisture. The particular values of the strength properties of the loam at natural moisture, as well as those of density were subjected to statistical processing (according to the requirements of GOST 20522–2012). The resulting values[2] are shown in Table 1.

Table 1

Strength and strain characteristics of layers

Parameter	Angle of internal friction, degrees	Specific cohesion, MPa	Soil density, g/cm^3
1st GTU, loam	22.39	0.060	2.02
2nd GTU, sandy loam	17.24	0.013	1.97

The strain moduli according to laboratory tests at natural moisture vary from 6.17 to 13.96 MPa, with an average value of 8.23 MPa.

The layer of the 2nd GTU, sandy loam, is characterized by the physical parameters given in Table 1.

All types of soils are suitable for the formation of the main body of an earth-fill embankment [1] except for the following:

1) containing incompletely decomposed organic matter (plant residues) in an amount greater than 5% by mass or fully decomposed substances in an amorphous state in an amount greater than 8% by mass[3];

2) containing water-soluble inclusions in the form of chloride and sulfate-chloride salts in an amount exceeding 5% by mass or sulfate salts in an amount exceeding 2% by mass. However, such soils may be placed in that part of the dam which is not exposed to seepage water.

The design provides for a single-layer barrier with one impervious element in the form of a polymer sheet (geomembrane) with a protective layer over it. It is planned to lay the geomembrane on the upstream slope of the dam and the bottom of the ash dump basin.

The single-layer barrier includes:

– an underlying layer of soil;

– an impervious element, which is a polymer sheet composed of flexible web products;

– a protective layer of soil.

[1] Report "Geotechnical survey for design of ash dump of Karaganda CHP", performed by "GeolProject and K" LLP in 2019.

Program of geotechnical survey performed by "GeolProject and K" LLP in 2019.

[2] Ibid.

[3] MSP (Interstate Building Rules) 3.04-101-2005 Determination of basic design hydrological characteristics.

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In order to prevent mechanical impacts on the protective layer of soil (wave, ice, etc.), this layer on the dam slopes will be provided with additional protection, rock fill[4] [2].

Also in order to assess the stability of the slopes of the designed ash dump, the computations were undertaken of embankment stability for the different combinations of the degree of loading, the conditions of the dam possible watering, the presence of "geomembrane", and pore pressure.

Simulation of the designed structure stability

A detailed study of all factors affecting the process of displacement of rocks in an earthfill embankment is required, in order to justify the parameters of stable slopes of an embankment. It is of key importance to select a computation method which will meet the specific geotechnical and geological conditions and physical and mechanical properties of the rocks composing the body of dams and their bases. The computations should use methods which satisfy the equilibrium conditions of the wedge of failure and its elements in the limit state and take into account the stress state of a structure and its base.

A software program based on the finite element method allowing simulating ground conditions in accordance with the strength and strain characteristics of a dam body filling soils and a base soils was used to assess the stability of the ash dump dam (embankment) slopes. Phase2 applications automatically compare the stresses with the strength properties of soils and certain procedures were used to ensure that the stress pattern matches the equilibrium conditions and the specified properties of the soils.

The advantage of the finite element method [4] lies in its potential to investigate areas of any configuration and take into account different soil properties, each of which is unique in its boundary conditions and medium characteristics. It also provides for the possibility of arbitrary discretization of the investigated area, i.e. it is possible to thicken the finite element network in expected places of high gradients of investigated parameters.

The simulation of stability of the designed structure was carried out on the basis of the findings obtained on the basis of the analysis of topography, hydrogeological conditions, lithological composition of the base, physical and mechanical characteristics of soils and wastes of the ash dump. The simulation also took into account the geotechnical survey data, the category of the structure, and operating conditions [3–5]. For each soil (ground) layer, its own physical and mechanical properties, density, bulk density, modulus of elasticity, and other parameters required to solve the problem, were prescribed.

Studies of the base soils, on which the designed dams are to be erected along the embankment perimeter were conducted in accordance with the report "Geotechnical survey for design of ash dump of Karaganda CHP"[5]. Four sections of different length with similar operating conditions in terms of hydrogeological conditions, lithological composition of the base, and a number of other factors were united into the computation zones.

The first section, 2.5 km long, according to the materials of the report is described by wells 374-19, 347-19, 346-19, 375-19, 345-19, 376-19, 377-19, 343-19, 378-19, 379-19, 341-19, 380-19, 340-19, 381-19, 339-19, 382-19, 338-19, 383-19, 385-19, which penetrated the following soil layers:

– clay alluvium and a 0.4–0.5 m thick topsoil;

– brown hard water-saturated loam 1.8 to 14.9 m thick;

– mottled or grayish-green hard water-saturated clay 8.0 to 10.9 m thick.

The second section, 0.75 km long, is similar to the previous one and described by well 328-19, intersecting hard sandy loam of brown and gray color with low degree of water saturation, up to 15.0 m thick; and wells 384-19, 330-19, 385-19, 327-19, 337-19, 326-19, intersecting the following soil lithologies:

– brown hard water-saturated loam 2.4 to 15 m thick;

– brown hard sandy loam of medium water saturation degree, 2.2 to 2.5 m thick;

– rock represented by gray massive sandstone of medium water saturation degree, 2.6 to 7.9 m thick.

The third section 300 m long, described by wells 324-19, 366-19 and 332-19, requires special attention. In terms of lithology, this section base is mainly presented by brown or red-colored hard water-saturated clay. The thickness varies from 5.5 to 8.5 m, and loam of low thickness (1.5–1.8 m). A gray hard loam 7.0 to 21 m thick occurs below this layer.

The fourth section, up to 3.7 km long, is the most solid base for the ash dump dams and is penetrated

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[4] SP RK 3.04-105-2014 "Dams made of soil materials".
SP RK 3.04-101-2013 "Hydralic structures".
SNiP RK 3.04-40-2006 "Loads and impacts (wave, ice and from ships) on hydraulic structures".
SP RK 3.04-103-2014 "Foundations of hydraulic structures".
SP RK 2.03-30-2017 "Construction in seismic areas of the RK".
SNiP RK 3.02-05-2010 "Automated system for monitoring of buildings and structures".

[5] Report "Geotechnical survey for design of ash dump of Karaganda CHP", performed by "GeolProject and K" LLP in 2019.

by wells 323-19, 373-19 and up to well 350-19. The section is characterized by the following lithologies:

– brown hard water-saturated loam 1.7 to 15 m thick;

– rubbly hard water saturated soil with loamy and sandy loam aggregate from 1.5 to 10.4 m thick;

– rock and semi-rocky soil represented by gray massive sandstone of medium water saturation from 1.0 to 11.0 m thick.

The stability of a filling dam is strongly influenced by its base watering due to rising groundwater table[6]. This leads to a deterioration of the strength characteristics of base rocks and a decrease in their strength. Thus, the various combinations of the degree of watering of a dam and its base need to be considered when modeling [1, 2, 6, 7].

Based on the analysis of the designed hydraulic structure base lithology, the most critical and characteristic cross-sections across the perimeter of the ash dump embankment were selected.

The criterion for dam slope stability is the compliance (for the most dangerous wedges of failure) with inequality [3]:

$$\gamma_{fc} F(\gamma_f) \le \frac{\gamma_c}{\gamma_n} R\left(\frac{1}{\gamma_g}\right),$$

where γ_{fc} is load combination factor; F is design value of generalized force impact, determined taking into account the load safety factor γ_f (f is resultant active forces or moments of these forces relative to the shear surface axis, which depends on the slope stability computation method); γ_c is condition load effect factor; γ_n is facility responsibility factor; R is design value of the generalized bearing capability of a "building – base" system, defined taking into account the safety factor for a soil γ_g, i.e. generalized design value of the ultimate shearing resistance forces along the surface in question.

When searching for a dangerous shear surface, a FoS dependence can be used

$$n_з = \frac{R}{F} \ge \frac{\gamma_n \gamma_{fc}}{\gamma_c}.$$

For hydraulic structures of the II category of importance [2, 8, 9], to which the designed structure belongs, factor of safety (FoS) is equal to:

1) with a special combination of loads during operation:

$$n_з = \frac{\gamma_n \gamma_{fc}}{\gamma_c} = \frac{1,2 \cdot 0,95}{1,0} = 1,14;$$

2) at the main combination of loads during operation:

$$n_з = \frac{\gamma_n \gamma_{fc}}{\gamma_c} = \frac{1,2 \cdot 1,0}{1,0} = 1,2.$$

In order to study the stability of the designed dams and the correctness of the decisions made, simulation of altered characteristics of the designed embankment in various conditions of operation was performed. This was based on the provisions of regulatory documents (SNiP RK 3.04-40-2006 "Loadings and impacts (wave, ice and from ships) on hydraulic structures")[7].

The following computations were performed in the course of the simulation:

1) hydrostatic pressure at maximum filling without a dam watering;

2) hydrodynamic head at minimum filling with a watered dam;

3) pore pressure at maximum filling without a dam watering;

4) pore pressure at minimum filling with a watered dam;

5) hydraulic pressure gradient at full filling of the ash dump basin;

6) hydraulic pressure gradient in the initial period of operation;

7) volumetric moisture at full filling of the ash dump basin;

8) volumetric moisture in the initial period of operation;

9) computations of the embankment inner slope stability for different combinations of the embankment watering degree;

10) computation of the stability of the embankment outer slope.

This paper presents the findings of inner slope stability computations for the most characteristic cross-section at well 373-19 for various combinations of dam watering. It also takes into account the presence/absence of "geomembrane", and pore pressure values, as well as the complicated part of the embankment next to well 324-19. The computations were performed using the "Phase2" computer program for different combinations of loads: filled soils with standard strength characteristics, compaction factor of 1.75, ash dump basin filling for the initial period of 0.4 m, and up to the level of 533.1 m. The slurry composition by content was 1/10-1/14. The characteristic cross-sections were compiled based on the lithological units found in the wells closest to the cross-sec-

[6] SP RK 3.04-103-2014 "Foundations of hydraulic structures"

[7] SNiP RK 3.04-40-2006 "Loads and impacts (wave, ice and from ships) on hydraulic structures".

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tions[8]. The physical and mechanical characteristics of soils were taken according to the research of soils in wells drilled along the perimeter of the territory, allocated for the ash dump. The computations showed that factor of safety (FoS) of the inner slope of the dam at the cross-section passing through well No. 373-19 without watering (the inner slope is reinforced with geomembrane and rock fill) is 1.718, and, with dam watering, 1.064.

Computations for the complicated embankment part near well 324-19 carried out, in order to assess the stability of the inner slopes of the embankment showed that FoS of the inner slope of the dam at well 324-19 without watering (with the inner slope strengthened by geomembrane and rock fill) is 1.672, and, with watering, 0.986. Fig. 1 shows the computation using the “Phase2” program of the embankment inner slope stability at characteristic cross-section 324-19 (near well 324-19) when the dam is watered.

The area allocated for the ash dump has difficult hydrogeological conditions, so resolving the problem of prior dewatering of the area and water diversion is paramount, in order to ensure the stability of erected structures. The simulation showsthat in order to ensure the stability of the inner and outer slopes when the dam is watered, pipe drainage needs to be installed.

The Phase2 program was used to calculate the stability of the outer slope of the selected sections. This takes into account the homogeneity of the soil mass, composed of filled soils (loam) with pipe drainage in place. Computation of the stability of the outer slope in cross-section no. 373-19 showed that FoS of the outer slope is 1.806, and for a special combination of loads at a seismic impact of 5 points (Fig. 2), 1.533.

[8] Report “Geotechnical survey for design of ash dump of Karaganda CHP”, performed by “GeolProject and K” LLP in 2019.

Program of geotechnical survey performed by “GeolProject and K” LLP in 2019.

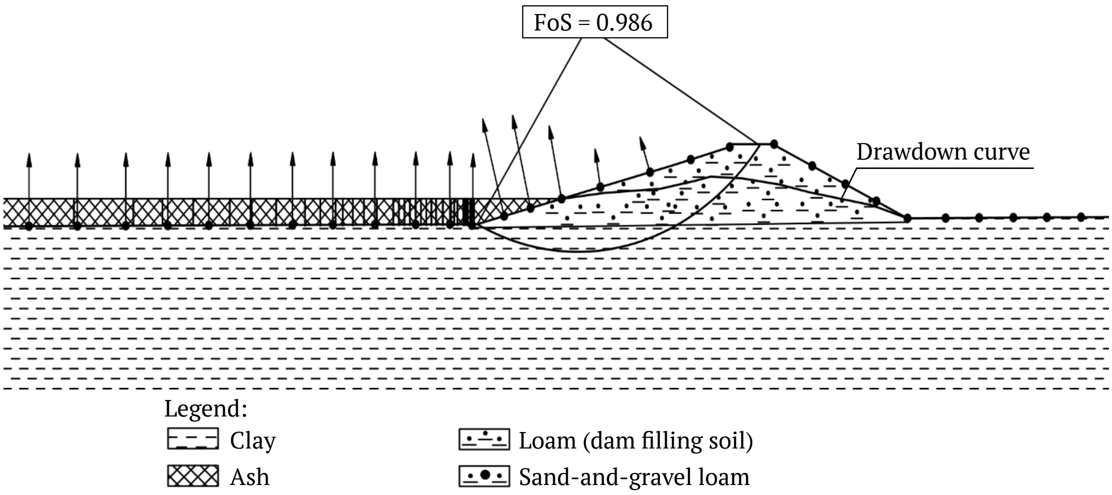

Fig. 1. Computations of embankment inner slope stability at characteristic cross-section 324-19 when the dam is watered

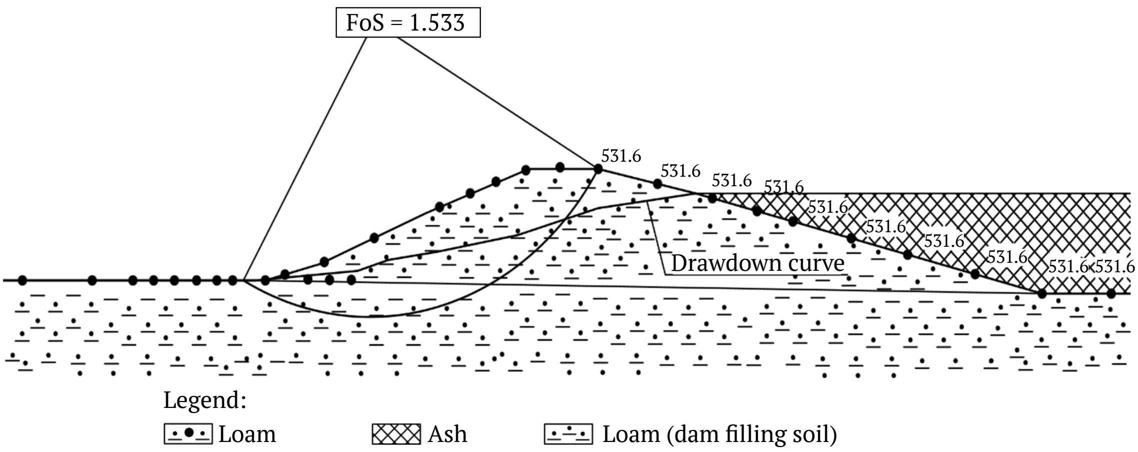

Fig. 2. Embankment outer slope stability computations for cross-section 373-19 at a special combination of loads

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The calculated position of the depression curve was determined by filtration computation using the FEM (finite element method). Filtration strength of soils, as well as that of impervious barriers, was estimated on the basis of the appropriate computations and experimental studies of soils at the head gradients acting in a structure. This also took into account the stress-strain state of the structure and its base, design features, construction methods, and operating conditions [6–9].

Fig. 3 shows the depression curve and the calculated head gradient in the downstream (outer) slope of the embankment. According to filtration computation, the maximum design value of the effective head gradient in the downstream slope ranges from 0.523 to 0.360.

An outer slope strength analysis was performed in Phase2 for the weakest cross-section through well 324-19 with pipe drainage. The GLE/Morgenstern-Price method was used, taking into account the distribution of the main limit equilibrium with surcharged dam body. The method uses artificial loading as a basis, in order to identify weaknesses and possible failure points (Fig. 4). In this particular case, the weakest in terms of the stability factor is sector 3 on cross-section no. 324-19 (see Fig. 4).

During the analysis, a possible shear line for each sector is constructed separately. The computations show that the critical factor of safety at cross-section no. 324-19 is 1.026 (Fig. 5). This does not meet the requirements and criteria for the dam slope stability, which should be equal to 1.2.

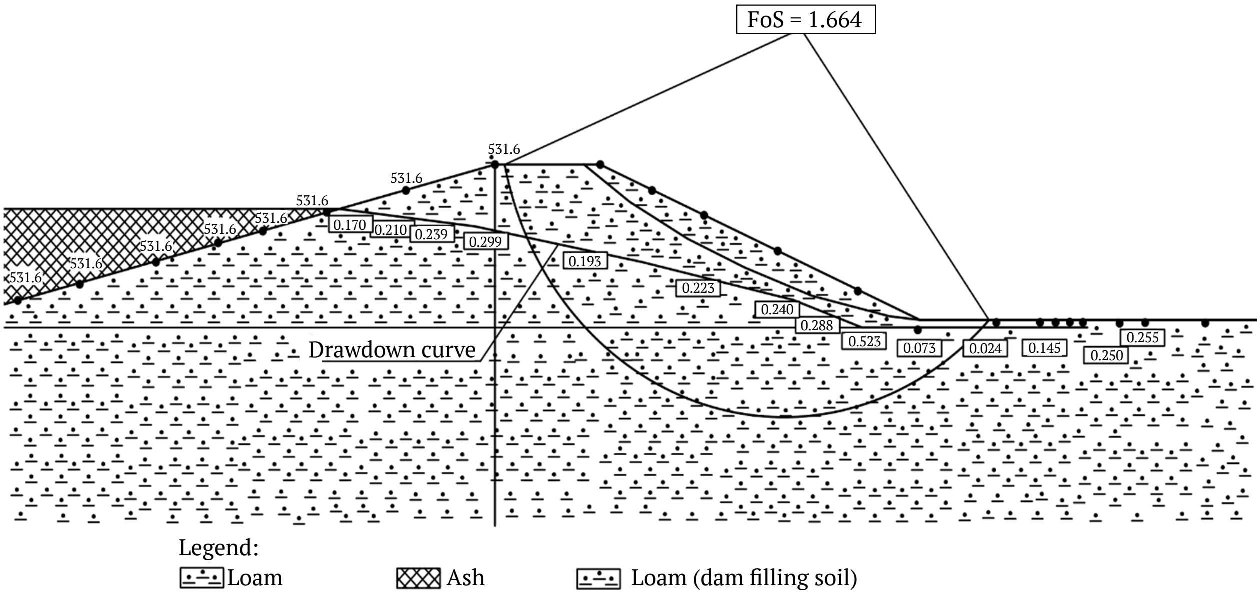

Fig. 3. Drawdown curve and head gradient readings

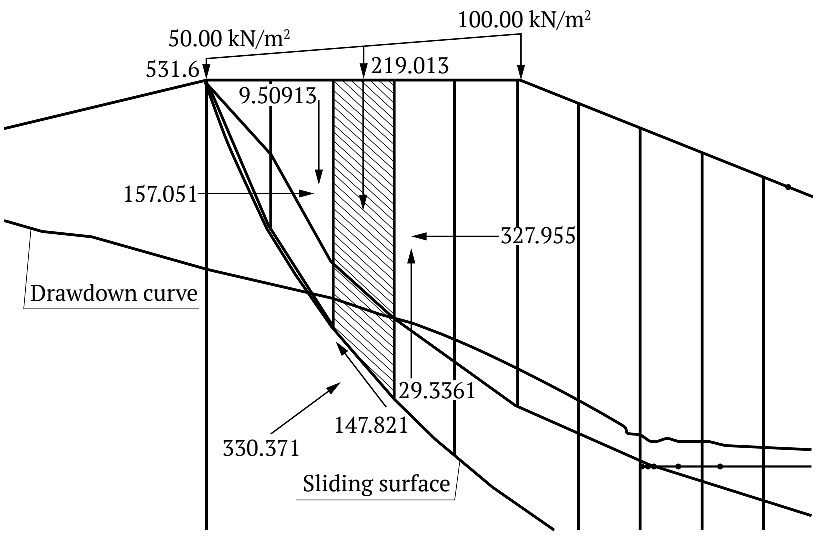

Fig. 4. Computation for cross-section no. 324-19 to identify weaknesses and possible failure points

According to the computations performed, the structural concept for the erection of an embankment made of a homogeneous soil mass (loam) with a clay base and without a cutoff wall will not ensure the stability of a dam next to the cross-section through well No. 324-19.

In order to ensure embankment stability, pipe drainage and a cutoff wall in the base of the dam for reliable connection with the base were applied. The designed dam body made of heterogeneous soil mass (loam with admixtures of sandstone and gravel) was used. The structural cross-section of the design dam body is shown in Fig. 6.

Computations of the stability according to the second option of the dam design for the cross-section defined by wells 324-19, 366-19 and 332-19 300 m long with a clay base showed FoS = 1.664 for the main combination of loads, and FoS = 1.430 for a special combination of loads under seismic action.

Conclusions

The stability of the embankment and separating dams of a TSF is determined by a complex of geotechnical, hydrogeological, and anthropogenic factors. The following have the greatest influence: physical and mechanical characteristics of soils and tailings (wastes); the process of construction and operation of a structure; nature of its base; hydrodynamic, hydrostatic, seismic, and dynamic forces[9].

When designing embankment structures of dumps for ash and slag materials removed from boiler rooms of CHPs, many factors need to be established. These include: selection of the location of a dump and embankment; determination of the geological characteristics (lithology) of the embankment and dam bases; modeling the type and parameters of structures depending on the volume of waste

[9] MSP (Interstate Building Rules) 3.04-101-2005 Determination of basic design hydrological characteristics.

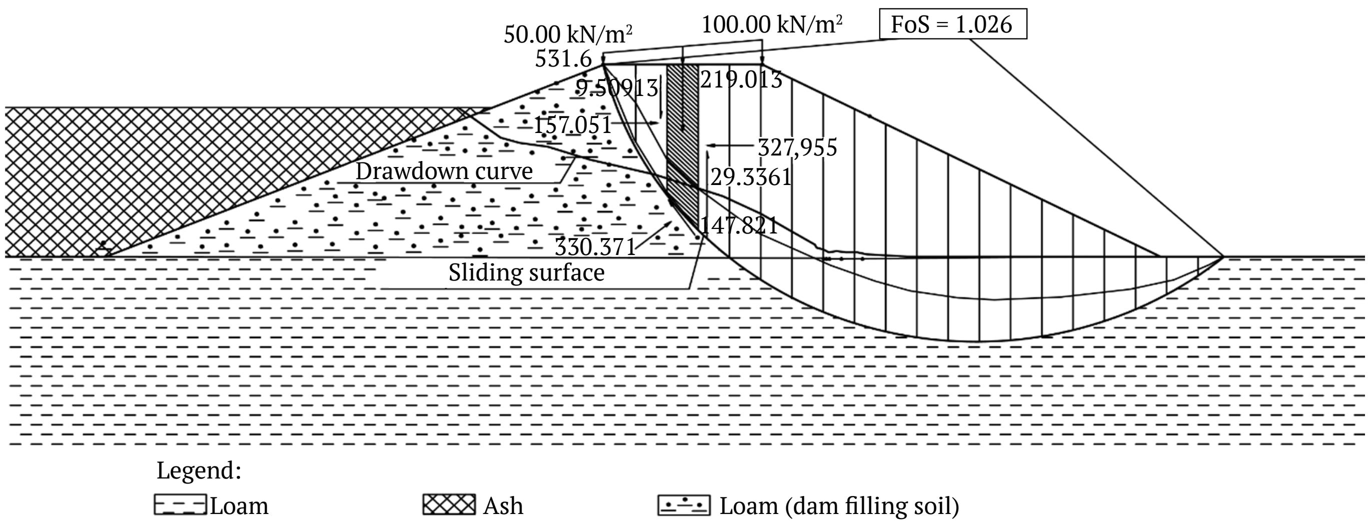

Fig. 5. Computation of outer slope stability for the weakest cross-section through well 324-19 with pipe drainage in place

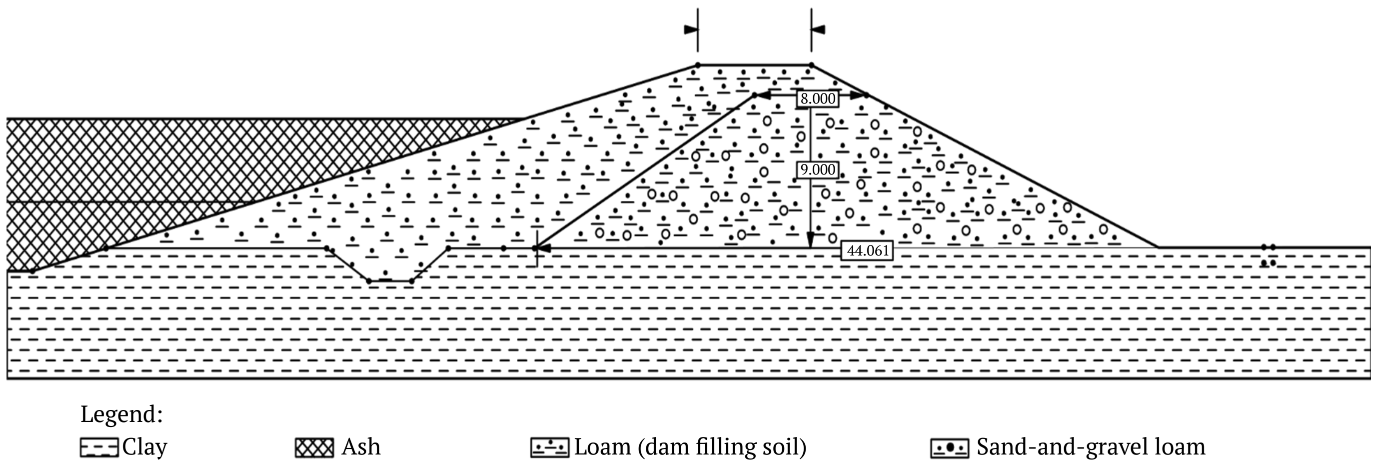

Fig. 6. Structural cross-section of the dam body with cutoff wall and pipe drainage

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disposed; determination of materials for the construction of an embankment body based on possible close location of a quarry as a source of building materials; determination of the structural features of an embankment body, which should ensure required strength of an erected facility.

1. When designing the embankment of ash dump No. 3 of Karaganda CHP-3, a software program based on the finite element method allowing for ground conditions to be simulated in accordance with the strength and strain characteristics of a dam body filling soils and a base soils, was used.

2. The computations were performed using the "Phase2" computer program for different combinations of loads for filled soils with standard strength characteristics and a compaction factor of 1.75, ash dump basin filling for the initial period of 0.4 m and up to the level of 533.1 m. The slurry composition by content was 1/10-1/14. The computations were made taking into account the homogeneity of the dam slope soil mass composed of bulk soils (loam) and pipe drainage in place at the base. The inner slope is reinforced with a geomembrane and a rockfill.

3. The simulation showed that the calculated values of the characteristic cross-sections exceeded the regulatory values of the stability factor for structures of category II, which are equal to 1.2 and 1.14, respectively, except for the section with a clay base. The stability of filling dams is practically ensured along the entire perimeter of the embankment except for the section with a clay base.

4. When modeling the 300 m long (approx) dam body section, the base of which consists of red-colored and brown hard water-saturated clay with thickness from 5.5 to 8.5 m and loam of small thickness (1.5–1.8 m), it should be considered that the stability of a filling dam is strongly affected by the watering of its base due to rising groundwater table[10]. This leads to a deterioration of the strength characteristics of the base soils and a decrease in their strength. Thus, when simulating, it becomes necessary to consider various combinations of the degree of watering of a dam and its base.

5. Computations of the stability of the dam built of homogeneous soil for the section with clay base in the worst conditions with maximum moisture of soils and minimum values of their strength characteristics showed that the condition of the dam slopes is close to the limit. The critical factor of safety at cross-section no. 324-19 is equal to 1,026, which does not meet the requirements and criteria for the dam slope stability.

Erection of an embankment made of homogeneous soil without additional structural elements to increase the structure strength can lead to violation of its integrity when the soil moisture and groundwater level increase.

6. In order to increase the strength of the embankment for the 300-m section with a clay base defined by wells 324-19, 366-19 and 332-19, the dam design, in addition to the built-in pipe drainage, provides for a cutoff wall in the base and a soil-fill toe (made of loam with sandstone and gravel admixtures), with the subsequent erection of the dam made of loam to the design parameters.

A structure option of the dam body at this specific section, developed on the basis of the simulation, provided a factor of safety values for the outer slope at well no. 324-19. This was FoS = 1.664 for the main combination of loads, and FoS = 1.430 for a special combination of loads under seismic action.

The ideal soil for the dam body construction is a soil, formed by large particles and clay-filled pores. Such a soil is characterized by a relatively high angle of internal friction, corresponding to a coarse-grained soil, and a low filtration coefficient, corresponding to a clay soil.

7. According to the filtration computations, the maximum calculated value of effective head gradient for well no. 324-19 will be 0.523; for well no. 373-19, 0.597; for well no. 381-19, 0.651; the regulatory value is not more than 1.3 [2, 6].

[10] SP RK 3.04-103-2014 "Bases of hydraulic structures".

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