15 Apr 2004, 1:00pm - 2:45pm

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

CONSTRUCTION OF FILLED HILL FOR DOWNHILL SKI RACING COMPLEX IN MOSCOW

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ABSTRACT

In 1997-2002 large scope soil excavations for construction of Business Center 'Moscow-City', Third Highway Circle and other large structures with deep foundations were carried out in Moscow. The soil excavated out of 180,000.00 m^3 pits was dumped on a disposal site originally designed as a temporary soil storage site in the Southwestern suburbs of Moscow. Snow, ice and clots of frozen soil were left untouched and piling was effected over the frozen surface. This spoil heap was a mass of exceedingly wet sandy clay heterogeneous as to composition and density with low strength and deformation properties, including crushed concrete and bricks and tended to land sliding and self-compaction deformations.

Erection of the hill can be divided into four stages, judging by differences in physic-mechanical properties of soils down the depth of the embankment (Fig. 1).

Upon fulfillment of the 2nd stage of excavation (Fig. 1 'b') at the end of the year 2001 the absolute mark of the top of the slope has reached 222 m, with the natural relief surface mid-mark making 177-178 m prior to heap excavation, and a heap height from its cone base has made 45 m. At the same time it was decided to use that hill as a standing ski-racing complex with a ski-jump.

At the stage 'b' (Fig. 1) prospectors have made studies of physic-mechanical properties of the entire mass of fill-up soils and natural lower stratum as well by well-boring and static probing of soils for the ski-racing complex project design.

Natural lower stratum (layers 2,3,6,7,9, Fig. 1) has physic-mechanical properties as follows:

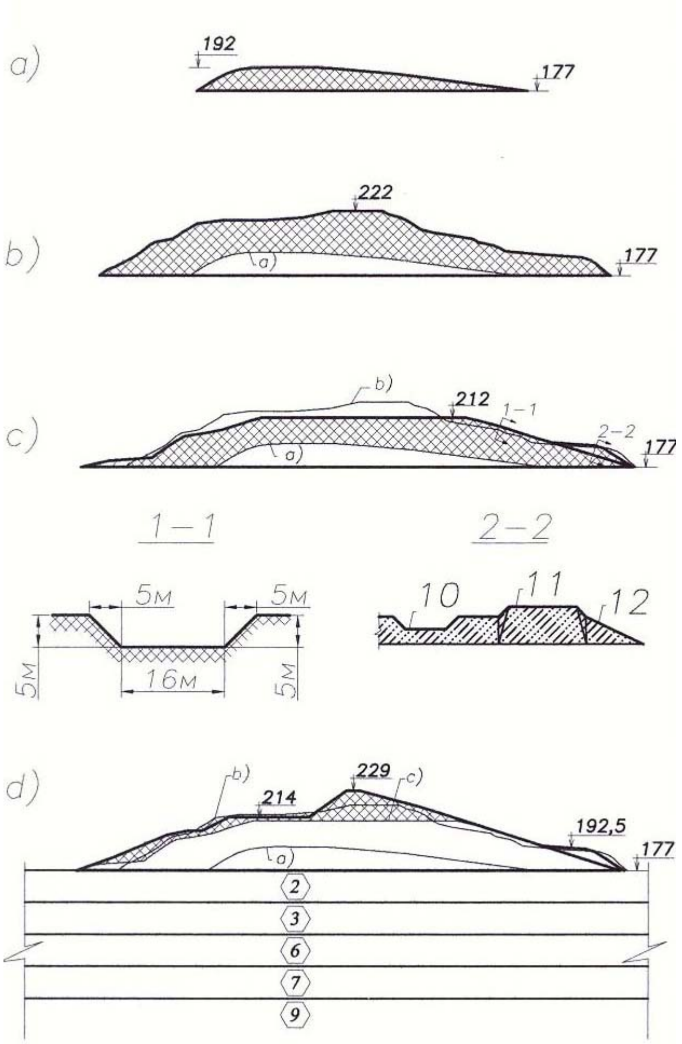
layer 2 – low-pliant loams, layer thickness H=1.6 m, module of deformation E=12 MPa, angle of internal friction φ=16^0, specific adhesion c=25 kPa, soil density ρ =19 kN/м^3;
layer 3 - low-pliant loamy soils with sand bands, H=3.1 m, E=14 MPa, φ=17^0, c=37 kPa, ρ =19.7 kN/м^3;
layer 6 - low-pliant loamy soils with sand bands and gravel, H=3.6 m, E=20 MPa, φ=18^0, c=36 kPa, ρ =20 kN/м^3;
layer 7 - stratified low-pliant ferriferous, H=2.5 m, E=12 MPa, φ=15^0, c=40 kPa, ρ =19 kN/м^3;
layer 9 - low-pliant loamy soils with sand lens, gravel and pebble, H=43.8 m, E=45 MPa, φ=18^0, c=42 kPa, ρ =21 kN/м^3.

According to studies during the 1st stage 'a' (heap core) soils of relatively high density (16.0-16.5 kN/м^3) and wetness (W=0.22, φ=18^o, C=18 kPa, E= 12 MPa) are evident.

During the stage 'b' (Fig. 1), when the heap was erected to the mark 222 m, the heap composition was extremely heterogeneous.

Results of lab and field investigations of the made grounds by static probing within basic part of the heap say that strength properties are closely related with type and composition of the made grounds. Accordingly, the angle of internal friction is increasing and specific adhesion is decreasing with the growth of soil particles.

It should be noted that the surface layers of the slope appeared to be the 'weakest' part of the heap. In most cases, they were dumped onto the slope without compaction and are characterized by increased porosity and wetness and the lowest readings of density and deformation indexes for soils. Because of that landsliding processes developed at the steep slopes under breaking points occurred by increase of wetness of the filled loamy soils at the rainy autumn time or in spring under defrosting of snow bands and frozen soils. Extra loads due to increase of the heap height, dynamic impacts from the heavy soil compressors and loaded trucks have all contributed to landsliding progress.



a) Heap core (1997-2001)

b) Chaotically raised embankment (2001-2002)

c) 1st Turn initial complex (15.08.2002-1.01.2003)

d) 1st Turn of embankment erection (1.01.2003-1.06.2003)

2,3,6,7,9 - natural lower stratum

10 – Half-pipe for snowboarding bottom side

11 – Big-air Jump-ski for freestyle

12 – Thrust berm prism

Fig.1. Stages of heap erection.

At the second stage of excavation (Fig. 1, stage ‘b’) an enormous mass of heterogeneous made grounds was delivered (over 800,000.00 m³), thus causing the heap to be considered as a complicated engineering structure. Later, when the decision to provide ski-, snowboard and free-style ski-jump routes was made, working on the downhill ski-racing design was started. Prior to design works, some attempts were taken in 2000-2001 to shape the slope down from the mark 222 m. These attempts have caused landslides, massive removal of over-wetted soils down to the heap bottom. Under that circumstances new approach from the point of stage-by-stage erection of the heap became evident**.**

A number of landslides has happened during the works in 2000-2001, mostly at the northeastern slope of the heap, just before shaping of the ski-racing routes, Half-pipe and Big-air. Direction of landsliding progress is shown at the Fig. 2. The way landslides developed and their mass is the evidence of the presence of ‘sacks’ of over-wetted soils at the upper part of the slope, which have formed a landslide (Fig. 2, Pos. 5). Evidence of such soils at the northeastern slope of the heap is caused by filling in wintertime, high content of ice and snow in made grounds and lower stratum melting in spring and lack of isolation at the slope due to its northern orientation, etc.

Taking these facts into consideration it was decided to settle the hill in few stages. At the first stage (so called ‘first turn initial complex’, as by our definition, stage ‘c’ – Fig. 1) the following work stages were presumed:

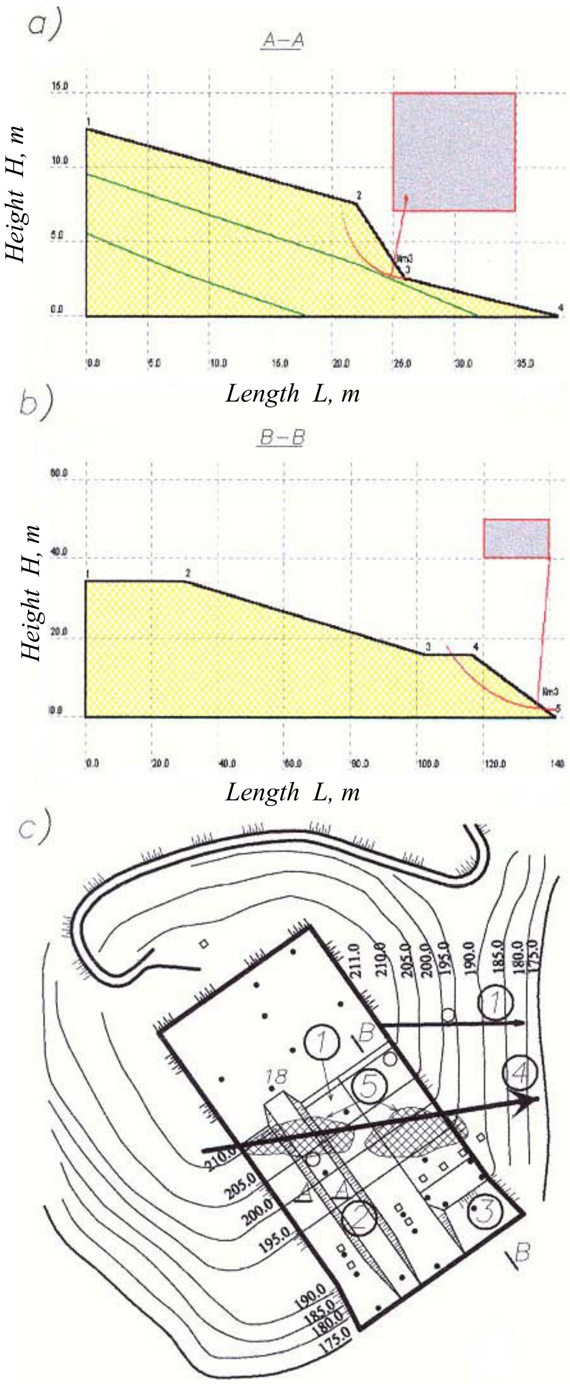
- hill top cutting off for 10-12 m to the absolute marks 212-210 m and removal of the excavated soil to slopes, generally, at the northern and northeastern downhill (see Fig. 1);
- erection of the Big-air ski-jump for free-style and 100 meters long Half-pipe for snowboarding at the northeastern downhill (see Fig. 1, stage ‘c’, Section 1-1 and 2-2) with putting them into service even in current winter season of 2002-2003.

Final works of the 1st stage of the construction (stage ‘d’, Fig. 1) were to begin immediately after commission of the first turn initial complex (stage ‘c’), including:

- declination of western and southern side slopes to established gradients 1:2.5;
- development of the heap height to the mark 229 m, i.e. exceeding of the former heap height for 7 m (at the stage ‘b’, Fig. 1), with thorough increase of the ski-racing route and Half-pipe for snowboarding to 150 m.

Designers were supplied with instructions on safe downhill values and providing of excavation on slopes within ranks of first turn initial complex (stage ‘d’, Fig. 1) based on physic-mechanical features of soils analysis and estimations of slopes stability provided. Safe downhills shall not exceed 1:2.5, and excavation principles recommended shall provide minimization of the technological costs for delivery, filling and compaction of soils and self-compacting sediments and elimination of landslides on slopes.

It is necessary to mention that works at the stage ‘c’ (Fig. 1) were provided up-tempo and were finished between August and December 2002. Over 600,000.00 m³ of soil were delivered, filled and compacted. In September-October 2002 intense landsliding processes nullified all efforts of constructors at the most complicate northwestern section of the heap during this period of intensive works**.**

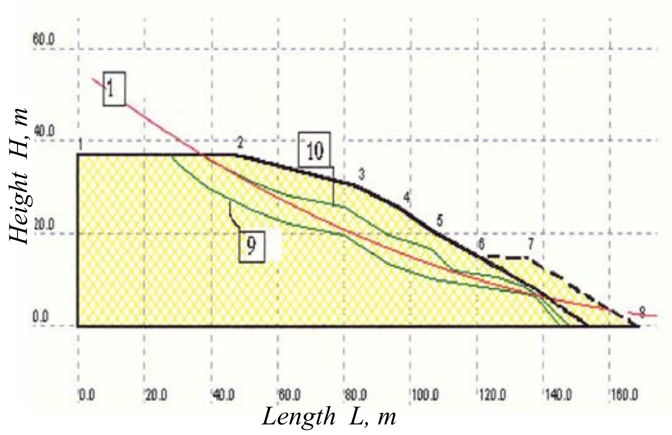


(a), (b) – sections for calculation of stability for Half-pipe and Big-air Jump-ski sides respectively, (c) diagram of the designed ski-racing routes (1), Half-pipe (2) for snowboarding, (3) Jump-ski for Big-air, samples boring points - ◊, test holes - O, surface survey marks - ●
●18 – mark for that settlement extrapolation is made, (4) landslide development direction, (5) Over-wetted ground area

Fig. 2. Sections & diagram.

Not only impartial high wetness of soils constituting that section of downhill and nearly mean less to compaction but also high ratios of soil delivery to the upper part of slope shall be considered the cause of landslides. In order to specify over-wetted soil areas the radiometric method (NIIOSP 2002) was used to investigate landsliding progress profile (Fig. 2), well-boring and dynamic probing were provided. Soil samples from wells were additionally tested in laboratories. Hence reasons and possible landslide development areas at the northeastern slope during the progress of the first turn initial complex were figured out and landslide-preventing solution (making of thrust berm prism at the bottom of the northeastern slope) was proposed (Fig. 3). Alternative ways to strengthen and reinforce landsliding northeastern slope were also considered and declined due to necessity to complete works in under time.

The thrust berm prism (Fig. 3) is conformed in accordance with estimation made by means of the software complex 'MAESTRO-K' using the method of round-cylinder slickensides based on algorithms of Alexandrov and Rusinov (Alexandrov et al. 1999). Estimated values of soils at the landslide downhill were taken equal to $\varphi_1= 14^o$, $c_1= 5$ kPa, for compacted berm soils - $\varphi_1= 18^o$, $c_1=18$ kPa, with stability coefficient for the northeastern slope reinforced by thrust berm prism equal to 1.15, as by laboratory research of soils.



1- Round-cylinder curve of slickenside;

9,10 – Separate soil layers margins.

Line 2-6 – Slope profile, 6-8 – shape of thrust berm prism

Fig. 3. Estimated diagram for stability of the northeastern slope with erection of the thrust berm prism (stroked line).

In addition, Half-pipe for snowboarding and Big-air ski-jump for free-style were erected at the slope (see Fig. 1 'c', Pos. 2,3 Fig. 2). Inclination of the side slopes of the said erections is forcedly exceeding, due to sport standards, maximum limits for made grounds. Estimated stability for the ski-jump is provided at the stability ratio 1.1 but the stability of the Half-pipe sides is insufficient. Deliberately supposing temporary slight local landsliding of the said erections and inevitability of the further slope improvement works it was decided to put the into service in current season of 2002-2003 with prior 0.5 m granite gravel filling alongside entire Half-pipe. Further on (spring – summer 2003) it is suggested to provide various schemes of Half-pipe and Big-air ski-jump slopes improvement in favor of stability.

Thus during the 3rd stage of construction of the downhill ski-racing complex it became alike those given at the Fig. 1, pos. ‘c’. Upon expiration of one month after completion of works at the first stage of construction (stage ‘c’) stage ‘d’ was initiated to provide declination of southern and southwestern slopes and development of the heap height to the mark 229 m (see Fig. 1).

Test technological sampling during the progress of works on construction of the initial complex of the 1st turn of downhill ski-racing (stage ‘c’) has shown that the density of soils framework has made 16-17 kN/m³ at the compaction ratio equal to 0.88-0.92 in the removed mass of soils (Fig. 1) with the thickness equal to 3-5 m. Non-compacted, non-recycled, mellow, over-wetted, tending to self-compaction settlement made grounds have left below compacted soils. At that process of self-compaction settlement has to be intensified due to recommencement of load at the central part of the heap by adding of 17-meters-heigh embankment (see Fig. 1, stage ‘d’). Beside embankment erected at the stage ‘d’ is capable for self-compaction by itself.

Realizing proximity and some convention of the principles accepted we have tried to estimate the final ratio of self-compaction of the heap assuming the phasic character of its erection.

Estimation of the final settlement of the heap consisting of soils heterogeneous by density and wetness is quite difficult.

It was supposed that self-compacting settlements at each of the previous three stages of erection had been completely realized and soils have found higher mechanical properties as result of self-compaction. Quantitative assessment of successive increase of soil deformation module, angle of internal friction and specific adhesion was based on the estimation of the heap strained-deformed status (SDS) at stages ‘a’, ‘c’ and ‘d’ of finite-element method by means of software complex “LIRA” (NIIASS 1995-2002) for the linear two-dimensional model. Here growth of soils density (decrease of porosity at the expense of self-compacting settlement with taking side expansion of soils into consideration) improves their mechanical properties, estimated to a first approximation by SNIP 2.02.01-83* (SNIP 1983) charts of standard values of deformation modules, specific adhesion and angle of internal friction depending on porosity ratio and types of soils. Tabulated points of SNIP were presented in graphic form for convenience and mechanical properties of soils were correlated at further stages of erection by taking into account the previous files on their compaction.

Relatively wide range of researches of deformation and embankment stability was provided for ground hydraulic works where high reliability of the object is necessary (Fadeev et al. 1982, Fedorovsky 1985, Goldin et al. 2001, Maslov 1977, Tertsagi et al. 1958, Zaretsky 1988, Zenkevich 1975).

Adequately research of high embankments is made by Tertsagi and Peck (Tertsagi et al. 1958). It is mentioned that embankment stays stable with the standard slope 1:1.5. Settlement up to 8% of the height is observed under insufficient compaction of layers during the filling. Filling with soils of the proper wetness and rolling decrease settlement and terms of stabilization of self-compaction settlements.

If the soil has insufficient adhesion and low angle of internal friction at filling then development of landslides in the embankment itself is possible. At that probably ‘surface’ landslides are more likely, by Maslov classification (Maslov 1977).

Since the 70-s design of important ground engineering structures was designed with taking into consideration their insufficient adhesion stained-deformed status (SDS). Calculations of structures by finite-element method (FEM) has been widespread (Fadeev et al. 1982, Zaretsky 1988, Zenkevich 1975).

Special non-linear models assuming specific soil deformations are used for calculations of soil solids**.** In 1985, Fedorovsky has provided a detailed report about these models (Fedorovsky 1985). Non-linear models assuming ‘loaded surfaces’ by condition of Drucker-Praeger (Zenkevich 1975) had been spread wide enough and we used them in present calculations.

Universal software programs for example ANSYS, etc. may consider non-linear work by condition of Drucker-Praeger for bi- and tri-dimensional elements. The worth of universal programs is friendly interface and ability to deal with big problems.

Alteration of the loaded status of soil in poured dams upon interaction of embankment with more solid core is figured out by calculation (Goldin et al. 2001). Further comparison with readings of observations shows sufficient adequacy of the calculated soil models.

Bi-dimensional loading diagram including embankment and lower stratums (Fig. 4) was taken for elastic-pliant model ‘ANSYS’ for insufficient adhesion stained-deformed status (SDS) calculation. Calculation was made for three consecutively effected stages of filling. Non-linear progress was assumed by condition of Drucker-Praeger.

Loading diagram ‘ANSYS’ and calculation results for de-formed status of heap at different stages of erection are given at Fig. 4 together with removal marks for each section. The real shape of soil surface settlement of the natural lower stratum is given for comparison. The last one was defined as difference between the height of the given profile before the erection of embankment (by geodetic survey of the future heap, 1999) and after (upon completion of embankment test holes were drilled to figure out the top of land soils below embankment at the height mark 222 m, stage ‘b’ Fig. 1). Comparison of estimated ‘ANSYS’ values and the real surface removal of the natural lower stratum reveals their similarity proving accuracy of soil properties and loading diagrams accepted. Limits of the present lecture are not favorable for presenting the complete analysis of the loaded status of the heap therefore we contented ourselves with comparison of just selected data on its deformations (Fig. 4 ‘c’).

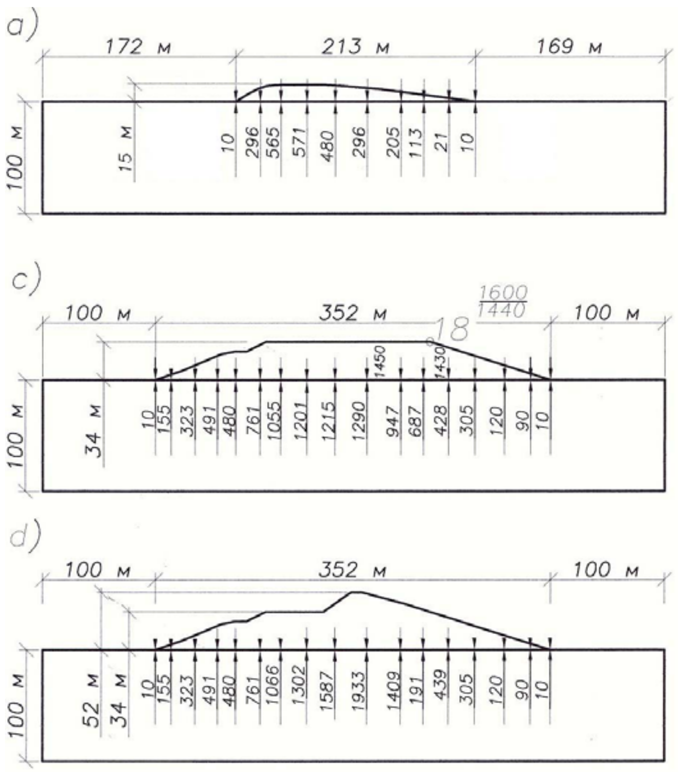


Fig. 4. General settlement calculation data (mm) for the heap bottom at different stages of loading (‘a’, ‘c’, ‘d’ below the bottom bordering line) in comparison with real (also see Fig. 1) settlement (‘c’, above the same bordering line).

Geodetic surveys of heap removals provided at the 3rd and 4th stages of its erection (‘c’ and ‘d’) make it possible to compare final estimated and predicted data on settlement at some points on slope.

Unfortunately, geodetic surveys of heap removals are running not from the starting point of its erection but just from the height mark 212 m (stage ‘c’). Principles of prediction (extrapolation) of settlements based on incomplete surveys are available (Nichiporovich et al. 1961, Rudnitsky 1958). We have used reductive hyperbolic dependence for extrapolation of settlement progress by short-term survey data. Some marks were selected for analysis. Approximating curve is described by hyperbolic dependence for a single one (see Fig. 2, mark 18):

$$S_t = \frac{S_\infty \cdot t}{\alpha + t} \tag{1}$$

where S_t - settlement within survey period, cm;
S_∞ - final stabilized settlement;
α- rating determined by calculation, year;
t - time characterizing the survey period, year.

Extrapolation curve based upon short-term survey data is described by equation for mark 18:

$$S_t = \frac{144.92 \cdot t}{4.47 + t} \tag{2}$$

where 144.92 cm is a final proposed settlement, figured out by extrapolation from incomplete survey data;
4.47 is empiric ratio and the rest are the same than in equation (1). To make empiric dependence (2) more accurate further geodetic surveys are necessary.

Comparison of the estimated FEM ‘ANSYS’ of mark 18 removal (Fig. 4 ‘c’, mark 18, numerator) with the final settlement position of the same mark extrapolated by results of geodetic surveys according to (2) (Fig. 4 ‘c’, mark 18, denominator) reveals their similarity: 1600 and 1440 mm respectively.

RESUME

1. Filling of soils into heap as well as other earthwork structures provided in absence of thorough Works Design and non-compliance with the normative documents regulations referring to the said earthworks lead to formation of ‘adverse’ areas of ‘weak’ made grounds with low density, extreme wetness, decreased solidity and deformation properties of made grounds.

2. Evidence of such ‘adverse’ areas in solid soils, especially under following increase of wetness of dusty-loamy made grounds due to precipitation, melting of frozen soils, increase of loads due to subsequent fillings, dynamic loads from operating transport and soil compressors leads to development of local and generally surface landslides.

3. To prevent landslides under said conditions it is expedient: to decline selected unstable slopes, decrease heap height by moving a part of hilltop away, supply with the thrust berm prism made of well-compacted ground, provide further filling from the top to the bottom, make limits for additional loads at slopes, use special measures to improve slopes based on horizontal, vertical and inclined reinforcement of ‘weak’ made grounds in some cases, provide with in-situ piles, concrete piles, crushed rock piles, driven cast-in-place piles.

4. In spite of insufficiently organized filling and without compaction, in fact, solidity and deformation properties of

made grounds are in general high enough and close by values to natural grounds due to self-compaction hence varying in wide range. It makes it possible to use SNIP mechanic properties tabulated points depending on porosity ratio.

5. Deformation surveys made for surface of the heap have shown, as predicted, both vertical and horizontal removals and settlements, the last caused by self-compaction of made grounds under their own weight and compression of lower stratum from the weight of embankment.

6. Calculation principles of strained-deformed status (SDS) of the heap by FEM method "LIRA" (NIIASS 1995-2002) in elastic model used with further correction of mechanical properties of soils based on predicted decrease of soil porosity with attendance of SNIP tables (SNIP 1983) have demonstrated acceptable accuracy and make it possible to recommend for correction of mechanical properties of soils at phasic erection of embankments.

7. It is possible to apply FEM elastic/plastic properties programs together with above described principles of physic-mechanical properties of soils definition for calculations of loaded-deformed status of the heap.

8. Algorithm of taking into account of vicissitude of embankment erection applied has shown good accuracy and can be recommended for similar objects. It makes possible to provide well-grounded designs for lighting poles, ski lifts, etc.

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