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RECOMMENDATIONS FOR THERMAL CONSOLIDATION OF WEAK CLAYEY SOILS

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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The present recommendations are intended for surveyors, designers, and production workers, responsible for pre-construction consolidation of foundations, composed of weak water saturated clay and mud soil, and for their compression by reduced static loads with simultaneous heating to some optimum temperature in the range from 323-353° K (50-80° C).

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RECOMMENDATIONS FOR THERMAL CONSOLIDATION OF WEAK CLAYEY SOILS
(RTM 31.3006-75)

USSR Naval Ministry, Moscow
1975

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Recommendations on Thermal Consolidation of Weak Clayey Soils	RTM 31.3006-75 First Edition

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Effective from July 1, 1975
for experimental use.

The present recommendations are intended for surveyors, designers, and production workers, responsible for pre-construction consolidation of foundations, composed of weak water-saturated clay and mud soil, and for their compression by reduced static loads (see 1.6) with simultaneous heating to some optimum temperature in the range from 323-353°K (50-80°C).

The recommendations do not apply to compaction of soils in underwater locations.

1. General Views

1.1. Thermal consolidation is the generally accepted term to describe a method of compacting weak water-saturated soil by increasing its temperature, so that physical and chemical processes occur between the neutral particles of soil and water which cause weakening of the structural bonds, an increase in permeability, and compaction of the soil with much less force than at natural temperatures.

1.2. For heating the soil, it is recommended that the most advantageous method is that in which an alternating electric current is passed through the soil by means of a system of metal electrodes sunk vertically in the ground.

1.3. Compaction of the soil by the recommended method includes the following operations: imposition of a load on the soil massif; sinking a system of electrodes; heating the soil; withdrawing the electrodes, and removing the load following natural cooling of the massif. Use of this method allows vertical drainage of the soil by sand or cardboard drains. The massif can be stressed either before or after the electrodes have been inserted.

In some cases it is possible to employ thermal consolidation of the soil without any additional stress being imposed, using only the action of the natural weight of the soil. The possibility of using this version of the method can be established on the basis of special field tests.

1.4. Thermal consolidation, as a method of preconstruction compaction of foundations for ports and other facilities, is used for clay and mud soil which is saturated with water and can be tightly compressed, and which has a specific electrical resistance $\rho < 30$ ohms per meter, a porosity coefficient $\varepsilon >$ > 1.0, and a filtration coefficient $K_f < 10^{-9}$ m/sec.

It is most advantageous to employ thermal consolidation under the following conditions:

a) the limiting thickness of the layer to be compacted must be no more than 7-8 meters;

b) a significant initial filtration gradient which governs the low efficiency of consolidation of the soil in the usual manner (without heating);

c) a shortage of material to use for applying a stressing load;

d) the presence of cheap electrical energy from State power systems.

1.5. It is forbidden to use thermal consolidation in the event when structures on natural foundations are located near the area to be heated. A distance of more than 20 meters from the edge of the area to the foundation of an existing structure is assumed to be safe.

1.6. The advisability of using thermal consolidation is governed by the technical and economic comparison of different versions, taking into account the specific conditions. In order to obtain raw data, laboratory compression tests can be carried out using the two-curve method: at natural temperature and with heating (Figure 1).

In Figure 1, the upper curve was obtained for soil at natural temperature ("cold"), and the lower one for heated soil ("hot").

Given the coefficient of porosity, which is to be obtained as a result of compaction, the required heating intensity needed for compaction is determined in the "cold" (σ_0) and "hot" (σ_r) state.

Taking into account the fact that $\sigma_r < \sigma_0$ for linearly stressed structures, we obtain the following value for the reduction in the volume of the stressing pile (per linear meter of length of the structure) with a transition to the thermal consolidation method:

$$\Delta V = \frac{h_0^2 - h_r^2}{a} + b(h_0 - h_r), \qquad (1)$$

where $h_0 = \sigma_0/\gamma_{lim}$ - the height of the file used for stressing at normal temperature, meters;

$h_r = \sigma_r/\gamma_{lim}$ - ditto, with thermal consolidation, meters;

γ_{lim} - bulk weight of loading material, MH/m^3;

b - width of massif to be consolidated, meters;

a - slope of the curve of the pile (tangent of the slope angle).

1.7. With a large volume of soil to be compacted final refinement of the thermal consolidation parameters (temperature to which the soil is to be heated, intensity and duration of the stress) it is advantageous to perform a field test on the construction site.

1.8. The costs of electrical energy for thermal consolidation of the soil are determined by heat engineering calculations (see 3.1-3.16) taking into account the specific conditions. They are approximately 110 to 220 megajoules/m^3 (30-60 kWh/m^3).

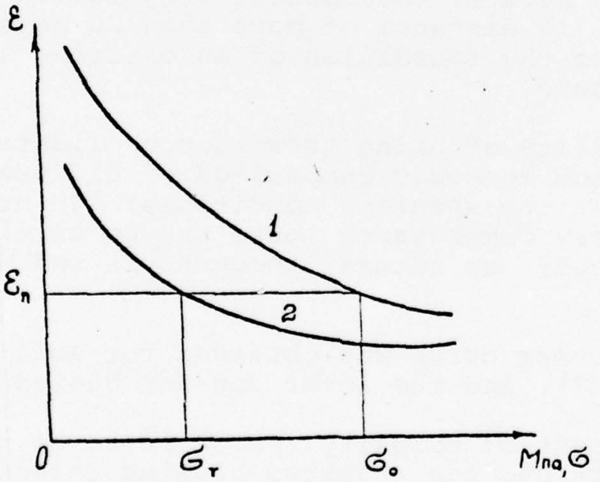


Figure 1. Curves for Compression Tests of Soil.
1. At natural temperature
2. With heating

2. Study of Soils for Designing a Thermal Consolidation Project

2.1. The study of the composition and content, preceding the development of a project, is basically similar to the operations which precede the consolidation of clay and silt foundations by ordinary mechanical compression with vertical sand or cardboard drains. The results of the studies will be presented in the form of the following data:

2.1.1. Geological sections and plan of the area on a scale of 1:200 indicating the position of prospecting and engineering excavations to determine the level and direction of flow of ground water.

2.1.2. Ordinary characteristics of composition, state, and properties of the soil to be compacted, performed in accordance with the applicable All-Union State Standards.

2.1.3. Specific characteristics of the soil, determined at normal 293°K (t = + 20°C) and at elevated temperatures, i.e., at the calculated temperature to which the soil is to be heated as follows: specific electrical resistance, coefficients of filtration in the calculated range for the porosity coefficient, deformation modulus (coefficient of compaction), heat capacity, thermal conductivity, and temperature conductivity.

2.1.4. Temperature of the soil prior to heating or the mean annual temperature of the air or soil on the basis of data from the nearest meteorological station;

2.1.5. Preliminary information and characteristics are supplied by exploratory and engineering drilling, laboratory tests, field tests and observations, researching reference and archival sources.

The method of determining the compressibility of the soil in the heated state is given in Appendix 2.

2.2. Exploratory drilling.

2.2.1. Exploratory drilling determines the depth of occurrence of the foot and top of the formation to be compacted, the depth of occurrence and stable level of underground water.

2.2.2. The number of exploratory shafts is governed by the purpose, level of capital investment, and dimensions of the structures to be built, as well as by the geological structure of the area.

Some approximate figures for the number of exploratory shafts for geological purposes of average complexity are presented in Table 2.1.

TABLE 2.1.

No.	Characteristics of massif to be compacted	No. of shafts
1	Massif measuring no more than 20-25 m in the plan	1-2 shafts per massif
2	Linearly extended massif up to 20 m wide	1 shaft for 20-25 running meters
3	Massif measuring more than 20-25 m	1 shaft for 400-600 m^2 of area of massif

2.2.3. During exploratory drilling, samples are collected from the shafts at 0.5-1.0 m intervals for laboratory analyses and especially to determine the natural moisture and specific electrical conductivity of the soil which is to be compacted and whose structure has been disturbed.

2.3. Engineering drilling or pitting.

2.3.1. Work is carried out to collect soil samples for laboratory tests. For this purpose, shafts are drilled with a diameter of at least 150 mm with a special nose piece which makes it possible to collect soil samples with minimal disruption of its natural composition.

2.3.2. The collected samples (cores) are wrapped in gauze to preserve their natural moisture and carefully coated with paraffin. The minimum dimensions for the samples are as follows: a cube 15 x 15 x 15 cm (pitting), cylinder with $d = 15$ and $\ell = 15$ cm (drilling). When marking the samples, the top and bottom are clearly indicated.

2.3.3. As a minimum, one engineering shaft must be drilled. If it is possible to dig a pit, collection of core samples for laboratory research should preferentially be carried out in the pit rather than in the shafts.

2.4. Field tests.

2.4.1. Specific electrical resistance of the soil is determined as follows:

a) in a state of disturbed composition - in rectangular trays with a cross section of 3 x 3 cm and a length of 9 cm, at normal and elevated temperatures (see Appendix 1.B);

b) in a state of natural occurrence - by sounding (see Appendix 1.A), at the original of the soil massif.

2.4.2. One of the shafts is specially bored using a casing string closed at the bottom for measuring the original temperature of the massif. The dimensions of the shaft and the method of measuring the temperature are given in Section 7.6.

2.4.3. Before heating, special engineering shafts are used to determine the resistance of the soil with a vane. These determinations must always be accompanied by a collection of soil samples to determine moisture.

2.5. Laboratory tests.

2.5.1. Laboratory tests assume the following:

a) the generation of a list of soil characteristics which make it possible to classify them by types according to SNiPOM;

b) to produce nomenclature characteristics, providing technical and economic data on the soil to be compacted.

2.5.2. Determination of the composition, condition, and properties in the form of special characteristics:

a) granulometric composition;

b) limits of plasticity;

c) specific density of the skeleton of the soil, Δ kg/cm^3;

d) specific density of the soil, γ kg/m^3;

e) moisture by weight, W_0;

f) degree of moisture σ_0;

g) content of water-soluble salts on the basis of data from water extracts;

h) porosity coefficient ε or porosity n;

i) content of organic impurities;

j) chemical analysis of ground water.

The above soil characteristics are determined in accordance with the existing standard documentation established or approved by Gosstroy USSR.

2.5.3. The characteristics for determining the advisability of using thermal consolidation and designing the project;

a) the dependence of the specific electrical conductivity and calculated range of temperature variation;

b) compression curve of the soil at a temperature corresponding to the natural state;

c) compression curve for the soil at the temperature to which heating is proposed to be carried out (323-353°K, i.e., 50-80°C).

Method of determining the applied characteristics is given in Appendix 2.

2.6. Analysis of the data.

2.6.1. All of the data obtained as a result of research and investigation are subjected to statistical analysis and organized into a report which must contain the following:

a) an introduction, presenting the problems and the scope of the work to be carried out;

b) the geological and hydrogeological characteristics of the area to be developed;

c) the climatic characteristics, presenting the mean yearly air temperature and if possible the temperature of the surface of the area;

d) detailed lithological cross sections of the area with the characteristics of the ground water and the subterranean water in the area;

e) results of measurement of soil temperature with depth at various points in the area;

f) characteristics of the composition, state, and properties of the soil;

g) materials from special studies of thermal consolidation;

h) results on the advisability of using thermal consolidation;

2.6..2. The report should also have the following:

a) a plan of the area on a scale of 1:200, showing the contours of buildings, test bores, and indications of geological profiles;

b) cross sections of excavations, showing the coordinates and the depth markings;

c) a relief plan on a scale of 1:200, showing the isohypses of the roof and floor of the stratum to be compacted;

d) engineering and geological profiles of the area on a scale of 1:200 in the horizontal and 1:100 in the vertical;

e) tables and graphs of the actual measurements of temperature;

f) field measurements of the specific electrical resistances of the soil.

3. Energy Calculations for Heating the Soil

3.1. Energy calculations are used to determine the required power, regime, and duration of heating, as well as the consumption of electrical energy.

3.2. Calculations are performed on the basis of the characteristics of the soil determined under field and laboratory conditions. In the absence of information on the characteristics of the soil in the area, the preliminary calculations must be carried out on the basis of data from the literature.

3.3. The layout of the electrodes in the area is planned in several versions, with the optimum one being selected later, i.e., the one which satisfies the requirements, uses standard equipment, is economical, etc.

3.4. In doing this preliminary work, it is important to consider the distances between the electrodes, the radii of the electrodes, the voltage, and other variable parameters. When there are ready-made metal parts available to be used in construction such as rails, channel, angle iron, stamped and bent profiles, etc., preference must be given to those elements which have the largest values for radius r_0.

3.5. One dimension which is of considerable importance in these energy computations is the radius of the electrode r_0: if the electrodes are pipes, the calculation will use the outside radius if the cross section of the electrode is complex in form, the calculated radius will be determined by the formula:

$$r_0 = P/2\pi, \tag{2}$$

where P is the length of a thread stretched across the electrode, meters.

3.6. With an orthogonal system or installation, the electrical resistance between two rows of electrodes will be calculated using the formula:

$$R_p = \frac{\rho\left(\frac{b}{a} + \frac{1}{2}\ln\frac{a}{2\pi r_0}\right)}{Nl}, \tag{3}$$

where ρ is the specific electrical resistance of the soil, ohms/m;

a is the distance between the electrodes in a row, m;

b is the distance between rows of electrodes, m;

ℓ is the length of the working part (not covered by protected varnish), m;

N is the number of electrodes in the row.

3.7. If there are several rows in the system for heating, the phase resistance is calculated using the formula:

$$\frac{1}{R} = \frac{1}{R_{p_1}} + \frac{1}{R_{p_2}} + \dots + \frac{1}{R_{p(n)}}, \qquad (4)$$

where R_{p_1} is the resistance between rows, calculated using formula (2). 1,2 . . . n is the number of rows in phase.

3.8. The power of the electrical system for supplying three-phase current, ensuring heating of the soil in the area where the rows are connected together, is calculated using the formula:

$$P = 3 \cdot 10^{-3} \frac{U}{R_{min}}, \qquad (5)$$

where U is the difference in potential between phases;

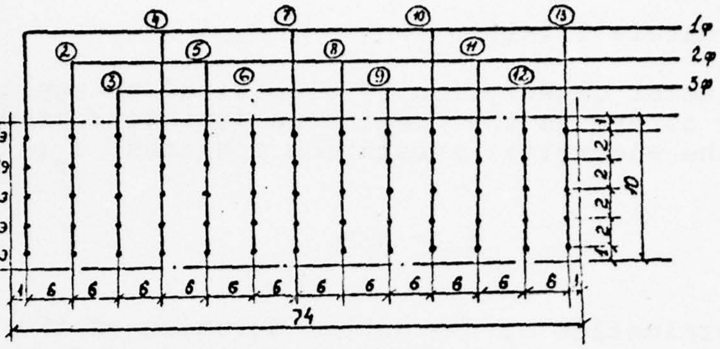
R_{min} is the smallest of three resistances determined by formulas (3) and (4) in ohms.

3.9. The rows of electrodes are arranged either along or across the area. When three-phase current is used, they are connected in a triangle (Figure 2). The number of rows must be a multiple of three plus one (3 + 1). If the substation power is insufficient to allow simultaneous heating of all the area, heating can be carried out in smaller sections, regulating the electrical resistance by reducing the number (N) of electrodes operating simultaneously.

3.10. The smallest number of electrodes that can be connected together may be three (one for each phase), and the phase resistance can be calculated by using the formula:

$$R = \rho \frac{\ln \frac{b}{r_0}}{\pi \ell}, \qquad (6)$$

where b is the distance between electrodes.



Symbols

———·——— - boundary of the area
• - electrode
⑩ - ordinal number of row
2э - ordinal number of electrode in the row

Figure 2. Diagram of Connection of Electrodes.

3.11. Inhomogeneity of electrical fields creates non-uniform heating of the soil as a function of time; the soil heats up rapidly near the electrodes and slowly between the electrodes.

The temperature of the massif can be evened out by periodically disconnecting the current while heating the soil at the electrode to 363°K (90°C).

3.12. It is categorically forbidden to raise the temperature of the soil near the electrodes to the boiling point of water, since copious amounts of steam which are formed will loosen up the soil and inhibit consolidation.

3.13. An approximate idea of the amount of energy consumed in heating the entire massif can be obtained from the following formula:

$$W = V \cdot C(T_n - T_0)\ \xi, \qquad (9)$$

where W is the energy consumption in joules;

V is the volume of the massif to be heated, m^3;

C is the volume thermal capacity, joules/m^3;

T_n and T_0 are the planned and initial soil temperatures, °K;

ξ is the coefficient expressing thermal losses. This coefficient is a function of the volume of the massif and the length of time it is heated.

ξ = approximately 1.1-1.3.

3.14. The total consumption of electrical energy and the calculated power determine the continuous (uninterrupted) time during which the electrical substation operates, τ_r:

$$\tau_r = W/P \tag{10}$$

3.15. Determination of the actual duration of the time during which the soil is heated τ_f can be determined from τ_r, taking into account the periods during which the electrical current is switched off and the following empirical formula can be used for this purpose:

$$\tau_f = L\tau_r \tag{11}$$

4. Thermophysical Computations for Cooling of the Soil

4.1. The length of time required for the heated soil to cool down is a naturally developing process. It governs the preparation time for the foundation, and therefore the time when construction can begin.

4.2. The duration of the cooling process is governed by the dimensions of the heated massif, engineering and geological conditions, thermophysical properties of the soil, and the difference in temperature between the heated and unheated massif.

4.3. Soil temperature prior to heating T_0 is assumed constant, corresponding approximately to the mean annual air temperature.

4.4. Calculation of the temperature of the center of the cooling massif as a function of time in the simplest cast can be carried out for a hypothetical parallelepiped: it has a thickness 2A corresponding to the thickness of the entire massif to be heated, including the superjacent layer, and has a width of 2B and length 2C, corresponding to the distances between the extreme electrodes plus 2.0 meters (one meter on each side). These calculations are performed using the dimensionless parameter F_0

$$F_0 = a\tau/L^2, \tag{12}$$

where a is the coefficient of temperature conductivity, m^2/sec;

τ is the cooling time, sec;

L is the linear parameter, m.

Depending on the direction in which the heat spreads, we calculate the number F_0. In accordance with the dimensions of the cooling massif, in formula (12) we can use the following as the linear parameter: for the vertical L = A, for the horizontal L = B and L and C.

4.5. The coefficient of temperature conductivity is taken from a handbook or calculated using the formula

$$a = \lambda / C, \tag{13}$$

where λ is the coefficient of thermal conductivity for very moist soil equal to 1.80 joules/m/sec/degree;

C is the volume heat capacity of the soil, joules/m^3/degree.

4.6. When no data are available, the specific heat capacity of water-saturated soil can be calculated with sufficient accuracy using the coefficient of porosity of the soil prior to compaction - ε_0 using the formula:

$$C = 4{,}2 \cdot 10^6 \frac{0{,}2 + \varepsilon_0}{1 + \varepsilon_0} \tag{14}$$

4.7. Substituting the original data in formula (12) and given the time τ, we can calculate the number F_0 for given moments in time.

4.8. Then, using F , we can use Table 4.2 to find the relative temperatures θ each direction:

$$\theta = \frac{T - T_0}{T_c - T_0} \tag{15}$$

Here T, T_0 and T_c are the temperature of the soil at moment in time τ before heating and at the time heating stops, respectively.

4.9. Having used Table 4.2. to determine the relative temperatures for three directions θ_Λ, θ_b, and θ_c, we can use formula (16) to calculate the relative temperature of the center of the massif:

$$\theta = \theta_\Lambda \cdot \Theta_b \cdot \theta_c \tag{16}$$

If the heated area is very long, i.e., C >> B,

$$\theta_c = 1.000$$

TABLE 4.2. RELATIVE TEMPERATURES VERSUS NUMBERS FOR CENTER OF COOLING MASSIF

F_o	Θ_1	Θ_{bc}	F_o	Θ_a	Θ_{bc}
I	2	3	I	2	3
0,04	0,999	I,000	0,76	0,I96	0,582
0,06	0,992	0,996	0,80	0,I77	0,57I
0,08	0,975	0,988	0,84	0,I60	0,559
0,I0	0,949	0,976	0,88	0,I45	0,547
0,I2	0,9I8	0,960	0,92	0,I32	0,54I
0,I4	0,882	0,94I	0,96	0,II9	0,528
0,I6	0,846	0,923	I,00	0,I08	0,522
0,I8	0,809	0,905	I,04	0,098	0,5I0
0,20	0,772	0,886	I,08	0,089	0,504
0,22	0,744	0,869	I,I2	0,080	0,497
0,24	0,7I6	0,850	I,I6	0,073	0,49I
0,26	0,669	0,835	I,20	0,066	0,478
0,28	0,637	0,820	I,24	0,060	0,47I
0,30	0,609	0,803	I,28	0,054	0,465
0,32	0,578	0,789	I,32	0,049	0,458
0,34	0,550	0,774	I,36	0,044	0,45I
0,36	0,524	0,762	I,40	0,040	0,445
0,38	0,499	0,749	I,44	0,037	0,438
0,40	0,475	0,737	I,48	0,033	0,436
0,44	0,430	0,7I5	I,52	0,030	0,43I
0,48	0,390	0,692	I,56	0,027	0,424
0,52	0,353	0,673	I,60	0,025	0,4I4
0,56	0,320	0,657	I,76	0,0I7	0,404
0,60	0,290	0,637	2,00	0,009	0,383
0,64	0,263	0,62I			
0,68	0,238	0,6I0			
0,72	0,2I6	0,594			

Finally, the relative temperatures are converted into absolute temperatures using the formula

$$T = (T_c - T_0)\theta + T_c \qquad (17)$$

5. Equipment, Materials, and Apparatus

5.1. In order to carry out the work involved in thermal consolidation of clayey and muddy foundations, it is necessary to have the following materials, equipment and apparatus available:

A. Materials and parts

a) Metal electrodes;

b) Cables;

d) Settling markers, pipes.

B. Equipment, apparatus and instruments:

a) Devices for sinking and withdrawing the electrodes;

b) Transformer substations (6/0.4 or 6/0.23) with actuating and protective devices, electrical measuring instruments;

c) Thermometers;

d) Devices for geodedic measurement;

e) Equipment for drilling shafts and investigating soil samples.

5.2. Any steel shape can be used to make the electrodes (rails, angles, channel, etc.) and they can also be punched or curved shapes.

Due to the fact that electrodes are not subjected to corrosion during thermal consolidation using alternating current, in other words they are not used up (can be reused several times), it is recommended to use special thin-walled shapes with well developed lateral surfaces. The working part of the lateral surface of an electrode, in other words the surface within the limits of the layer to be heated, must be able to transmit electrical current to the soil at a density of no more than 100-120 amperes/m^2.

The head of the electrode must be provided with devices (a) for rapid connection to an assembly for sinking and extracting it; (b) for attaching power cables or buses.

5.3. As the power cables, it is recommended that multistrand power cables be used, types APRGDO or PRGDO. The cross section of the cable is determined as a function of the estimated current in the phase following appropriate testing of the cables during heating.

When the cables are strung in the air, it is permissible to use bare steel and aluminum wire, Type "AS". However, this kind of wire, as well as steel strip, can be used for jumpers between the individual electrodes within the limits of the massif being heated.

5.4. Levelling (sinking) markers are recommended of the screw type (interval markers designed by NIIOSP).

5.5. Any type of pile driving equipment can be used to sink the electrodes, primarily the type which is mounted on tracks or rubber tires. It is preferable to use assemblies that have high frequency vibrating equipment to drive the piles, or "vibrohammers" (see Table 5.3).

The choice of a standard size of vibrating pile driver (virbohammer), depending on the dimensions of the electrode and the sinking conditions, is carried out on the basis of existing standard documents and modified on the basis of results of tests carried out at the site.

5.6. The power for the electrical components involved in the thermal consolidation is supplied from any transformer substation (KPTM) of an appropriate power, with a voltage of 6/04 kV or 5/023 kV, used for construction. When it is necessary to use reduced voltage, an additional stepdown transformer (0.4/0.23 kW or 0.23/0.13 kW) is attached to the low side of the KTPN (the characteristics of a recommended power supply are listed in Appendix No. 4).

6. Composition of the Project

6.1. The project involving preparation of the foundation by the thermal consolidation method is developed as follows:

a) A report prepared in accordance with Section 2.7;

b) Technical data on construction equipment;

c) The planned construction;

d) Electrical engineering and thermophysical computations, carried out in accordance with Section 3.4.

6.2. The project must include the following:

a) Plan on a scale of 1:200 showing the number of electrodes, monitoring temperatures shafts, piezometers, levelling markers, reference points and other equipment;

b) Electrical engineering computations, determining the values of the phase resistances, the manner in which the electrodes are to be connected, required power and duration of heating of the area;

c) List of electrodes, indicating the length of the insulated part and the type of insulating coating;

d) The volume of the required load, calculated for compacting the soil without thermal consolidation and with thermal consolidation;

TABLE 5.3. TECHNICAL CHARACTERISTICS OF VIBROHAMMERS.

Parameters	Brand of vibrohammer				
	S-833	S-402A	S-834	S-835	BM-7U
Total power of electric motors, kW	2.2	6	11	14	14
Number of electric motors	2	2	2	2	2
Number of blows of hammer per minute	705	480	480	483	1450
Energy of each blow, kgs/m	16	50	120	165	62
Static moment of disbalances, kgs/m	54	220	536	500	322
Disturbing force, kgs	1100	2250	5000	11250	7000
Mass of vibrohammer with driving cap, kg	150	1000	1100	1100	1400
Including shock section, kg	100	280	650	700	670
Dimensions:					
Length, mm	380	725	850	1360	1150
Width, mm	590	705	750	1800	1050
Height, mm	970	1040	1450	1030	1100

e) A calendar graph describing the work involved in heating the area;

f) A calendar chart of the natural process of cooling of the heated area;

7. Preparatory Work

7.1. Composition of preparatory work:*

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* In the event of combination of thermal consolidation with vertical drainage, it is necessary to use "Recommendations on Compaction of Weak Soil by Temporary Stressing in Rows, Using Sandy and Paper Drains" (Gosstroy USSR, N. M. Gersevanov NIIOSP).

a) Planning the territory and laying out the grid of electrodes;

b) Preparation, insulation, and sinking of the electrodes;

c) Assembly of the electrical system;

d) Installation and levelling of the settling markers;

e) Construction of temperature shafts;

f) Erecting a barrier around the area and putting up warning signs (see the section "Safety Requirements").

7.2. The territory is smoothed in the usual fashion (using bulldozers, scraper, etc.) with an accuracy which will ensure that pile drivers and other equipment of the designated type can move around within the area to be compacted.

7.3. The total length of the electrodes ℓ is determined by the following relationship:

$$\ell = h_y + h_n + 0.5, \qquad (18)$$

where h_y is the thickness of the layer to be compacted, m

h_n is the thickness of the superjacent layer, m (in the case where the electrodes are sunk after the load has been applied, the height of the loading pile is included).

If the specific electrical resistance of the soil in the superjacent layer exceeds the specific electrical resistance of the layer to be compacted by less than a factor of 10, some of the electrodes which are within the limits of the superjacent layer are coated with an electrically insulating compound (for example, one layer of bituminous varnish) before being sunk.

7.4. Installation of the electrical system includes the following: laying the supply cables (from the substation to the massif to be heated) and the distributing cables (within the limits of the massif to be heated).

If the substation is used for thermal consolidation of several areas simultaneously (or if other energy consumers are connected to it), a panel with safety-starting equipment and meters is mounted within the limits of the supply cables and services each individual section (acceptor) of thermal consolidation.

In order to reduce energy losses in the supply cables, it is desirable to have the substation located as close as possible to the place where thermal consolidation is being carried out, but no closer than 5 m from the working electrodes.

7.5. The number of levelling markers is determined as a function of the class of capital investment of the equipment being used and the geological structure of the area. Roughly speaking, there is one marker for each 100-150 m^2 of area of massif to be compacted. The method of levelling and the type of measuring device must ensure that the measurement error is no more than 0.5 cm.

7.6. The temperature shafts are intended to monitor the heating of the massif. They are fitted with casing strings closed at the bottom, with thermometers of different types lowered into them, for example, electrical thermometers, semiconductor thermometers, etc. The inside diameter of the string b_H must ensure that the thermometer of the appropriate type can be lowered and raised inside. The recommended value is db_H = 25-30 mm. The material of which these casing strings are composed must ensure that the shape will remain stable at temperature up to 373°K (100°C). The temperature shafts must be located both in the middle of the massif to be heated and around its edges at the rate of one shaft for every 100-150 m^2 of area.

The temperature shafts ensure measurement of the temperature in the middle of the thickness of the layer to be heated. Moreover, at some points in the massif shortened and elongated shafts are placed in order to measure the temperature in the upper and lower boundaries of the layer which is heated.

8. Basic and Auxiliary Work

8.1. Composition of basic and auxiliary work:

a) Heating of the soil massif;

b) Removal of the cables and extraction of the electrodes;

c) Piling of the load-applying pile (see Section 1.3.);

d) Observation of temperature and settling;

e) Removal of the load;

f) Sounding the compacted massif.

8.2. The soil is heated after preparatory work is complete, and constitutes a separate event.

8.3. When sufficient power is available in the electrical system, the massif to be compacted can be heated by simultaneously connecting all the electrodes in a "triangular" system.

8.4. When limited power is available in the electrical system, the number of electrodes which can be connected simultaneously to each phase is determined by computation (see Section 3) and is confirmed by a sample run. The sample run makes it possible to limit the non-uniformity of the load on the phases to the available limits.

Note: The permissible non-uniformity of the load on the phases ("distortion") is determined taking into account the specific conditions of operation of the main power supply used for construction.

8.5. To limit the power requirements, which increase as a result of lowering the ohmic resistance of the soil when heated, a gradual decrease in the number of operating electrodes is effected, taking into account the specific conditions at the site.

8.6. The process of heating the soil is recorded in a log, of which an approximate form is provided in Appendix 3.

8.7. In order to even out the heating after reaching the necessary temperature of the soil, the latter is kept in a conditionally isothermal state by periodic applications of the current.

8.8. The electrodes are withdrawn using cranes on tracks or rubber tires. In view of the low mechanical strength of the soil to be heated, as a rule, there is no need to use special pile extractors of a vibrating or other type.

The lifting capacity of the cranes P_k is determined by sample extractions; in general, we can use the following value:

$$P_k = P_a + (3\text{-}4)W_{bok}, \qquad (19)$$

Where P_a is the weight of the electrode in tons;

W_{bok} is the lateral surface of the electrode, m^2.

When the superjacent layer is less than 3 m thick, the shifting of cranes and other machines within the limits of the heated massif must be restricted to special weight-distributing grids.

8.9. Observation of the temperature of the soil during the heating period is carried out once every 24 hours during the time of conditional isothermal maintenance, in accordance with the schedule for turning on and turning off the electricity, and during the period of natural cooling, once every 10-30 days.

8.10. The application and removal of the load-producing pile is carried out in the usual manner taking into account the comments listed in Section 8.9.

Before the pile is put in place, rods and pipes associated with the settling markers are installed, as well as the casing strings for the temperature shafts.

9. Safety Requirements

9.1. Thermal consolidation consists of a number of processes and operations which pose increased danger to the operating personnel. Hence, it is important that only those individuals who have undergone special training and course of instruction be admitted to the site.

9.2. When preparing for and actually carrying out the work involved in heating the soil, it is important to observe rules relating to safety techniques in conjunction with the construction work, the application of electrical energy for heating during construction, when servicing the electrical equipment at the industrial enterprises, and also in the drilling and general construction work.

9.3. It is especially dangerous to work in the area when heating is actually going on. Therefore, before the electrical current is switched on, all of the personnel must be thoroughly trained in rules pertaining to safety procedures.

9.4. When the electrodes are being sunk, no one must be located beneath the vibrating pile driver. Any electrode supports may be present must be handled with tongs or similar devices. When using electrical vibrating pile drivers, their housings must be grounded.

9.5. The area in which the electrical heating work is being carried, including the transformer substation and the service buildings must have appropriate protection, keeping out any people or animals who might accidentally enter. Every 3-4 m around the perimeter, signs warning of the danger must be posted such as for example "Stop!", "Lethal", etc.

A night, the area must be illuminated with flood lights or individual bulbs set up around the perimeter.

During heating, the attendant personnel carrying out the work must wear appropriate dielectric protective clothing: rubber boots, rubber gloves, rubber mats and tools with insulated handles.

All of the these protective measures must be labelled showing the date they were last used and the voltage for which they are approved.

9.6. Any access to the electrodes, temperature shafts, levelling markers, and other objects located directly in the area which is being heated should be possible only when electrical current throughout the area has been switched off.

9.7. The high-voltage side (6 kV) should be switched on and off only by the electrician on duty at the substation, in conjunction with the personnel at the area. It is forbidden for the personnel at the area to turn on the high-voltage side of the transformer.

9.8. All of the electrical equipment with the distribution grid must be located in a dry place beneath a roof, with a wooden floor covered by a rubber mat.

9.9. The knife switches used to turn the power on and off must be operated when wearing rubber footwear and rubber gloves. Current measurements in the power cables and at the electrodes must be made only when wearing rubber footwear and gloves.

9.10. The electrical supply cables must be enclosed in protective pipes. In each phase, fuses must be installed in the transformer building which are designed for the maximum permissible current.

9.11. In electrical assembly work, it is necessary to provide a device for protective grounding of the transformers, the neutral, and distributor grids. The knife switches and other types of switches in the distributor network must be provided with protective covers and handles provided with reliable insulation.

9.12. Heating at 380 V must be carried out only with a grounded neutral. It is important to keep in mind that when the zero lead breaks, the elements connected to it spontaneously are charged with 380 V. For this reason, it is not recommended to connect knife switches, other types of switches, fuses or the like to the zero wire.

9.13. When working on vibrating pile drivers, transformer substations or the like, it is important to be guided by the safety requirements set forth in a specified order.

Appendix 1

METHODS OF DETERMINING SPECIFIC ELECTRICAL RESISTANCES OF THE SOIL

A. Field Part

The basis for this method is the measurement of the resistance of the soil in a radial field of high-frequency alternating current, created between two sunken electrodes.

For this purpose, several measuring electrode pairs are mounted in the area, using exploratory shafts drilled earlier. The number of pairs, their locations in the area, and the depth to which they have been driven are determined in accordance with the program, but there must be at least two.

As the measuring electrodes, one can use gas pipe or other metal rods from the set of electrode equipment which is on hand, and the radius of the electrode is determined in accordance with formula (2). If the soil to be compacted is covered by soil which is not to be subjected to compaction, the upper part of the electrode is covered with insulating varnish. Total length of the electrode must correspond to that part of the soil which is to be compacted. Before sinking the working part of the electrode, it is carefully cleaned to remove any rust which may be present and the upper part is again covered with insulating varnish.

A diagram of the equipment associated with the electrode pair for determining the specific electrical resistance of the soil appear in Figure 3.

Measurement of the resistance of the electrode pair is accomplished using a resistance meter, Type MS-08.

When the latter is not available, one can use similar measuring devices of other types, for example the MS-07.

The measurements are carried out five or six times, using the arithmetic mean as the computational value.

The specific electrical resistance of the soil is calculated by the formula

$$\rho_{\text{м}} = \frac{R\pi l}{\ln\frac{b}{2}} \text{ ом м}, \qquad (20)$$

where R is the measured value of the resistance of the electrode pair in cm;

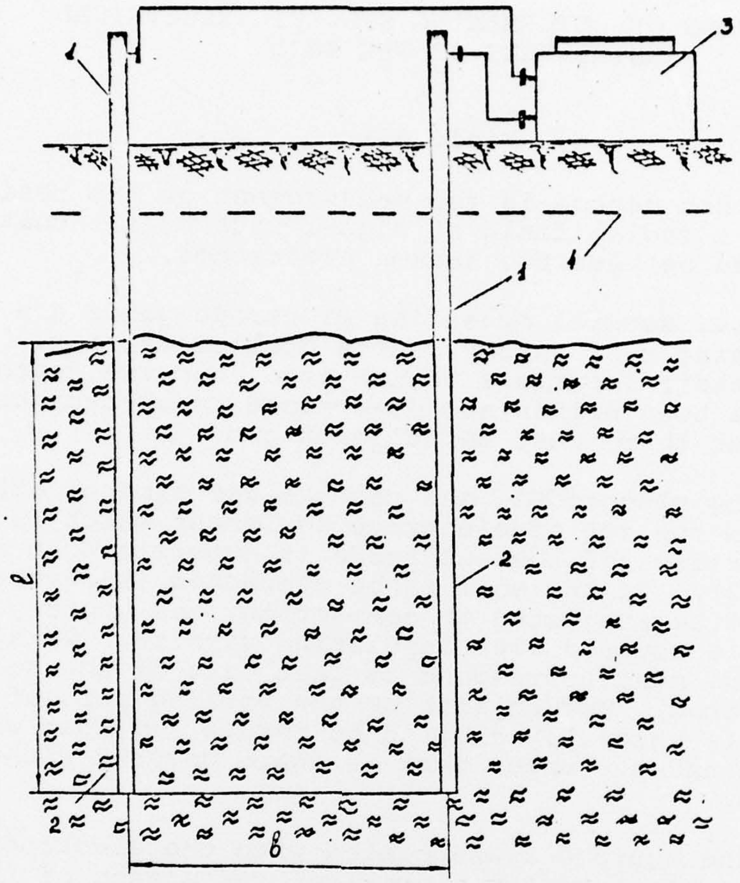

Figure 3. Diagram of Installation of Electrodes for Measuring Ohmic Resistance of Soil: 1, insulated part of electrodes; 2, working part of electrodes; 3, resistance measuring device; 4, ground water level.

l is the average length of the working part of the electrode, equal to the half-sum of the lengths of both electrodes, m;
b is the distance between electrodes, m;
R_0 is the calculated radius of the electrode, m.

The specific resistance thus determined is the weighted mean for the measured area.

The arithmetic mean value of the measurements for two areas in the site gives the weighted mean value for the entire massif of soil which is used in the calculations.

B. Laboratory Part

The measurement of the electrical resistance of the sample in the device is carried out on the basis of instructions supplied with measurement bridges, and are repeated three or four times.

The value of the specific resistance is calculated using the formula:

$$\rho = p\frac{F}{\ell}\ \text{ом}\cdot\text{м}, \tag{21}$$

where R is the resistance of the sample in ohms measured by the bridge;

F is the area of the cross section of the electrode, m^2;

ℓ is the length of the core in m.

The specific resistance of the soil thus determined is analyzed statistically as the average within the limits of each point at which a sample is collected and as an average for the entire volume of the massif to be compacted.

It is recommended that the following method be used, based upon the measurement of the electrical resistance of the soil in the volume of a regular geometrical shape and with known dimensions, using a bridge to measure the resistance of the conductors of ionic conductivity. For this purpose, plexiglas or another dielectric is used to make a rectangular box measuring 3 x 3 x 9 cm (Figure 4), with electrodes made of copper, brass, or stainless steel inserted in the ends and connected to terminals which are in turn linked to a resistance measuring device.

As the resistance measuring device, one can use any one of the Soviet-made bridges such as the Winston or the Kohlrausch with a telephone buzzer.

Before measuring the resistance, the surface of the electrodes is carefully wiped with alcohol, benzene or acetone to remove any contamination, which would prevent contact with the soil. Then the box is filled with soil and its surface is carefully smoothed. Then the container is connected to the resistance measurement bridge and placed in an ultrathermostat, with the resistance being measured at various temperatures.

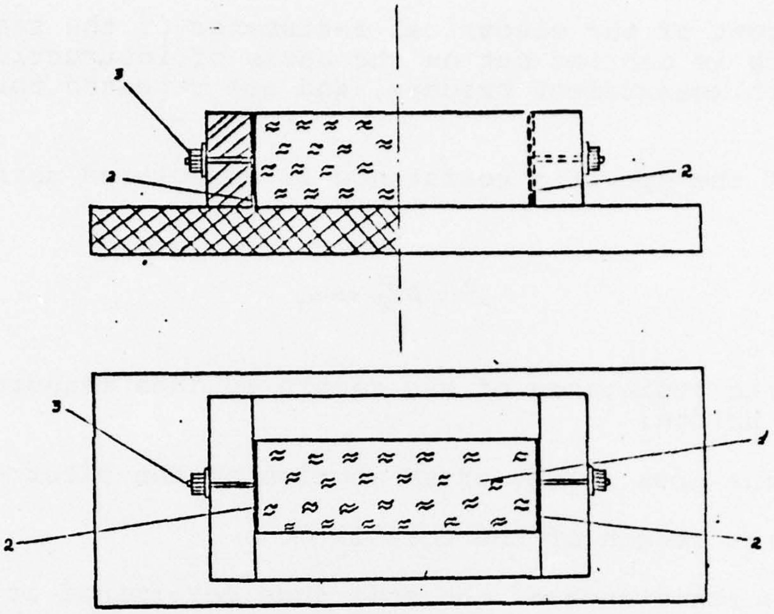

Figure 4. Container for Measuring Ohmic Resistance of Soil with Disrupted Structure. 1, soil; 2, electrode; 3, terminals for connecting measuring bridge.

Appendix 2

LABORATORY STUDIES OF THE INFLUENCE OF TEMPERATURE ON THE COMPRESSION CHARACTERISTICS OF MUD

The problem with which these experiments deal is the determination of the dependence of the coefficient of porosity of soil upon the pressure, at natural and set temperatures. For this purpose, a method was developed and a special device constructed which would make it possible to maintain a constant set temperature inside a device and to carry out compression tests of soil.

General appearance and design of this device are shown in Figure 5 and 6. The device is an odometer placed in a special thermally insulated housing, into which a circulating flow of heat conductor at a set temperature is supplied from an ultrathermostat (-10 or some other type).

As the heat conductor, we used distilled water whose temperature was automatically maintained at a fixed level with an accuracy of $\pm$ 0.1° in the range from 274-372°K (99°C). The dimensions of the odometer wheel were as follows: diameter 7.14 cm, height 2.00 cm, and area 40.0 cm^2. In order to eliminate drying out of the soil, located in the device, and to duplicate the conditions of a field experiment, the entire device should be filled with ground water from the area being investigated. To prevent corrosion, all the parts of the device which come in contact with the water or the soil must be made of glass, bronze, or stainless steel.

The heat-insulating covering and the connecting hoses are made ceramic cloth (Type VKR-150) or other ceramic material, which have high termal insulating and anti-corrosion properties.

The studies were conducted on soil with a disturbed or undisturbed structure. Due to the difficulty in keeping the soil in an undisturbed structural state, it was often necessary to perform soil tests on samples which had a disturbed structure by the following method:

a) Taking samples simultaneously from a single core or (when the structure was disturbed) from carefully mixed batches, soil was placed in the device whose moisture was approximately the same as that under natural conditions. As a control on the operation of the device, soil samples were selected for moisture;

b) The compressive load must be applied in stages: up to 50 pascals in 5-pascal steps (up to 0.5 kgs/cm^2 in 0.05-kgs/cm^2 steps) from 50 to 200 pascals in 25-pascal steps (from 0.5 kgs/cm^2, in 0.25-kgs/cm^2 steps);

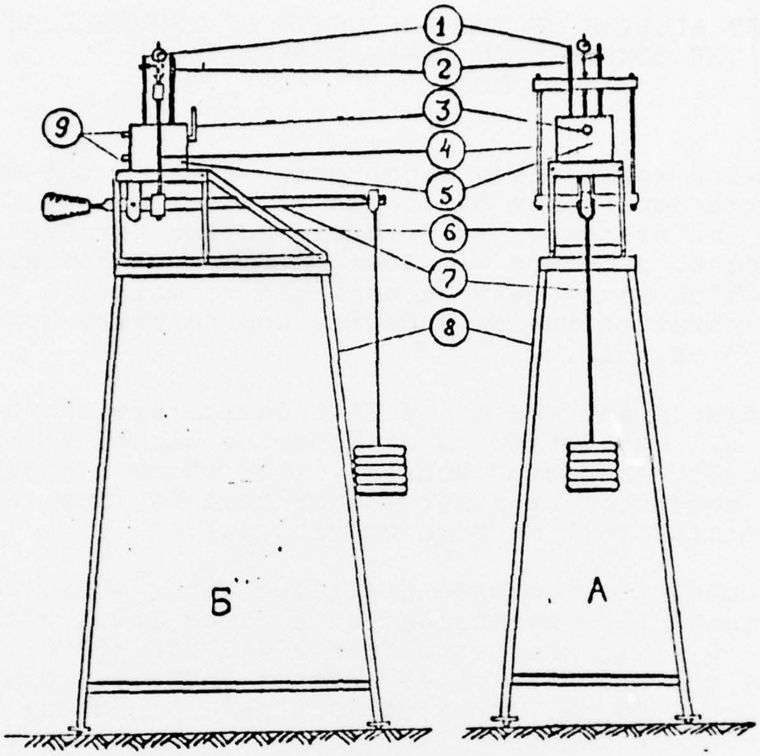

Figure 5. General View of Thermostatted Compression Device (A - front view, B - side view). 1, [illegible]; 2, thermometer; 3, water gauge glass; 4, connecting rods and cross arms; 5, odometer, thermostatted; 6, instrument stand; 7, lever with counterweight and weight; 8, frame of the device; 9, connector for hoses to thermostat.

c) With an extensive program, the experiments are carried out at constant temperatures both equal to those actually found in the field and higher temperatures, with intervals of 5, 10, 15, and 20° from 274 to 363°K. The reduced experiments can be limited by two isotherms: the natural one at 323 or 333°K.

d) In all of the experiments, after stabilizing the soil in the device, the stresses must be applied in sequential stages of 0.05 to 2.00 kgs/cm^2. When measuring the deformation of the sample, it is necessary to take into account the deformation of the device, for which purpose, prior to the start of the test, it is recommended that the device be calibrated for the anticipated tamperature ranges;

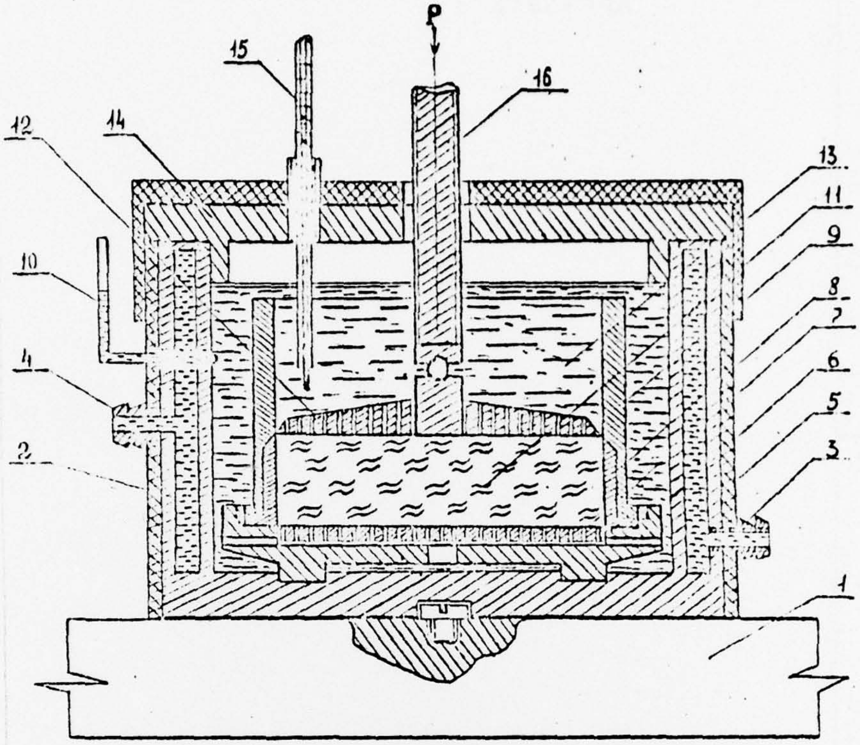

Figure 6. Odometer of Compression Device to be Thermostatted. 1, plate; 2, housing; 3, input connection for heat carrier; 4, output connector; 5, heat insulating jacket; 6, heat carrier; 7, perforated metal disk; 8, ring; 9, clip; 10, water gauge glass; 11, soil; 12, perforated piston; 13, water; 14, removable lid; 15, thermometer; 16, foot screw.

e) Duration of the observations at each load: for an extensive program, up to completion of total consolidation, shown at Point b, on the basis of a limited program, 24 hours, regardless of deformation;

f) The thermostats are disconnected after conditional consolidation (Point b) at the last load;

g) Upon reaching room temperature, the device is stressed in stages in the reverse order from Point d.

It has been found that the maximum compaction of mud is observed in the range from 313 to 333°K.

Appendix 3

LOG OF HEATING OF SOIL DURING THERMAL CONSOLIDATION.

Data	Time, hrs	Electrodes connected (diagram)	Regime			Power con-sumpiton, kWh	Temperature in shafts					Notes
	Increasing total since beginning of heating		Current intensity	Voltage	Power	Increasing total	1	2	3	4	5	

Appendix 4

ELECTRICAL EQUIPMENT AND DEVICES

Name and technical characteristics of electrical equipment	Type number in catalog	Manufacturer
1	2	3
1. Transformer Substation		
1.11. <u>Complex distributing system and points</u>		
Complex transformer substation KTPN 6/0.0-0.23 with transformer power of 630 kWh with 6-10 cabinets KN-2 2 each KN-3 2 each KN-4 2 each and bus bridge ℓ = 1600 mm		Khmel'nitskiy transformer substation factory
1.12. Complex distributing system for 6 kV, consisting of 18 chambers and bus bridge ℓ = 2400 mm	KSO-266	Glavelektromontazh plant, one set.
1.13. Distribution point with built-in switches	PR 9232	Khar'kov electromechanical factory

1.21. Cables for electric arc welder, GOST 6731-68

APRGDO - with aluminum wire and rubber sheath for insulation and protection;

PRGDO - ditto, with copper wire

TABLE FOR SELECTING CROSS SECTIONS OF WIRE.

Cross section of wire, mm^2	Current amperes*	Wholesale price in rubles for 1000 m	
		APRGDO	PRGDO
70	270/210	435	915
95	330/250	550	-

* Number in front of the slash mark - load for copper; after the slash mark - for aluminum cables.

Depending on the constant load for cables laid in the open with copper or aluminum current-conducting wires with rubber or PVC insulation for ambient temperatures of + 25°C and a permissible heating temperature of + 55°C.

1	2	3
1.31. Apparatus and instruments		
Switches	PVZ-10 VMG-10	
Transformer, current, type, class accuracy transformation coefficient	TPOL-10 1-800/5A	
Transformer voltage	NTIMI-6	
voltmeter, network	-	
ammeter network	-	
watt meter	-	
phase meter		
fuses	KDT/6	
fusible plugs		
stepdown transformer 0.4/0.23	TN 0.4/0.23	Kmel'nitskiy transformer substation factory

Appendix 5

AN EXAMPLE OF CALCULATION OF HEATING AND COOLING OF SOIL

It has been found that at depths from 2.0 to 6.0 meters, mud occurs whose coefficient of porosity is 1.35. This entire thickness is above water-bearing gravel. The ground water in the mud and sand have a common horizon at a depth of 1.0 m from the surface. The water temperature is 281°K (8°C) which corresponds to the average annual temperature of the air.

The dimensions of the area to be subjected to thermal consolidation is 74 x 10 m. With these dimensions, determined at 1.0 m from the edges, we find the following electrode positions: the distance between the electrodes in each row a = 2.0 m and between the rows, b = 6.0 m. The rows are arranged across the area (Figure 2).

Laboratory and field measurements of the specific electrical resistances have given a value of ρ = 3.80 ohms/m. As the electrodes it was decided to use old rails (R-33), for which P = 0.43 m. It was decided to insulate the upper part of the electrode for 2.00 m with black varnish. This gives a length of the operating part of the electrode of 3.0 m.

The effective radius of the electodes is:

$$r_{\circ} = \frac{0{,}43}{2.3{,}I4} = 0{,}068\ \text{м}$$

Then we calculate the resistance of one row of electrodes:

$$R_{p} = \frac{3{,}8\ (3 + \frac{I}{3{,}I4}\quad\frac{2}{2{,}3{,}I4{,}0{,}068})}{5{,}3} = 0{,}88\ (\text{ом})$$

When the rows are arranged crosswise, the number of electrodes in each row N = 5, and in each phase, four rows are connected in parallel. In accordance with formula (4) we have:

$$\frac{1}{R} = \frac{4}{0.88}\ ;\ R = 0.22\ \text{ohm}$$

Assuming that a transformer will be operating in the area with a potential difference between phases of 220 V, we will have the required power of:

$$R = 3\cdot10^{-3}\cdot\frac{220^2}{0.22} = 660\ \text{kW}.$$

Then we use formula (14) to calculate the thermal capacity of the soil:

$$S = 4.20 \cdot 10^6 \cdot \frac{0.2 + 1.35}{1 + 1.35} = 2.77 \cdot 10^6 \, \frac{\text{joules}}{\text{m}^3 \cdot \text{ degrees}}$$

The energy consumption required to heat the soil from the original temperature to the set temperature ($\Delta T = 60°$):

$$W = 424 \cdot 10^6 \text{ kilojoules} = 118 \cdot 10^3 \text{ kWh}$$

At the set power and full load on the system, continuous operation would require the following:

$$\tau_a = \frac{118.0 \cdot 10^3}{660} = 178.5 \text{ (hours)} = 7.4 \text{ (days)}$$

and the actual time of heating is approximately $\tau_\phi = 2\tau_e$ (11)
$\tau_r = 2 \cdot 7.4 \quad 15$ days

Calculating the cooling of the massifs is accomplished in accordance with Point 4. Assuming that the coefficient of temperature conductivity $a = 2.34 \cdot 10^{-3}$ m^2/hr, according to formula (12) for the given dimensions of the massif to be heated we will have

$$F_x = \tau \frac{2.34, 10^3}{37^2} = \tau \, 1,7.10^{-6}$$

$$F_y = \tau \frac{2.34 \, , \, 10^{-3}}{5^2} = \tau \, 93,6.10^{-6}$$

$$F_z = \tau \frac{2.34 \, . \, 10^{-3}}{3^2} = \tau \, 260.10^{-6}$$

Given the time r from Table 2 we determine the relative temperatures [illegible] in three directions and then use formula (16) to determine the relative temperature at the center of the area. According to formula (17), the relative temperature is converted to °C.

$$T = 52\theta + 8$$

The results of the calculation are listed in Table 4.

Summing up the heating and cooling times, we get the total duration of the preparation of the foundation -- about one year.

TABLE 4

r, days	θ_x	θ_y	θ_z	$\theta \cdot \theta_x \theta_y \theta_z$	T^0C
I0	I	0,999	0,992	0,99I	59,5
30	I	0,983	0,790	0,776	48,4
60	I	0,900	0,5II	0,460	3I,9
I80	I	0,475		0,08	I0,0
360	I	0,I70		0,009	8,I

TABLE OF CONTENTS