this changes salt conditions of the soil and ensures a water content near to the optimum moisture content. To increase adhesion as well, sodium salts of organic acids may be added to the bitumen.

Available experience shows that for stabilization with cut-back bitumen and tar various types of sandy loam, silty and clayey loam soils with a plasticity index below 17, may successfully be used in the central zone of the European part of the USSR. Carbonate varieties of soils and humus soils are used with a plasticity index up to 25. Soils of excessive plasticity are improved with bitumen or tar only after adding leaning additives of sand or sand-gravel material.

Soil stabilization with cut-back bitumen and coal tar in regions with excessive precipitation and comparatively cold climatic conditions is not as efficient and besides there are also technological difficulties, caused by excessive soil moisture content. In these conditions only sandy loam and light loamy soils with a plasticity index not over 12 are efficiently stabilized with bitumen.

Furforal aniline, naphtha soap and other surface-active reagents are also used for soil stabilization. When these materials are being considered, it is necessary to take into account the mineralogical constitution of the clayey part of the soil to ensure maximum ionic sorption, which lowers the surface energy of the soil and develops forces of ionic bond. An example may be the hydrophobic strengthening of non-carbonate acid loamy soil by its treatment with small quantities of furfurol aniline (1-2 per cent). Soils stabilized with synthetic furfurol aniline resins may be used successfully as bases of road pavements, as water-insulation, and as stronger layers.

When the amount of the reagent is increased, the rise of strength is regular up to a certain optimum value after which the soil strength drops, this being connected with the cohesion of the reagent, which is frequently less than its adhesion. In saturated condition the variation of strength of hydrophobized soil is of the same character, but with somewhat lower ultimate strength values *(Fig. 4)*.

Stabilization of Settling and Weak Clayey Soils by Thermal Treatment

I. M. Litvinov

Settling loess soils are very abundant in many countries and especially in the Soviet Union where they cover vast areas. Numerous cases of excessive differential settlement occur on these soils, often followed by collapse of various buildings and other structures owing to the high compressibility of such soils when wetted under applied load. This has already brought about great damage and will do so in the future, for an immense number of large buildings and structures have already been erected on settling soils and the rate of important construction on such soils is steadily increasing.

Different methods of loess soil stabilization have been suggested by a number of investigators. These methods, however, do not ensure the degree of consolidation required, or otherwise involve too much cost and labor.

The Southern Research Institute for Industrial Construction (Academy of Construction and Architecture, Ukrainian SSR) has developed different methods for the thermal consolidation of loess soils *(Fig. 2)*.

Thermal treatment of loess and other soils can be accomplished by two methods.

The first method, attributed to N. A. Ostashev, consists in blowing hot air under pressure into the soil through heat-proof pipes and bore holes, the air having been heated to a temperature of 600-800° C in special stationary or movable furnaces. This method has been found not to be sufficiently effective, hence it is not used in construction work.

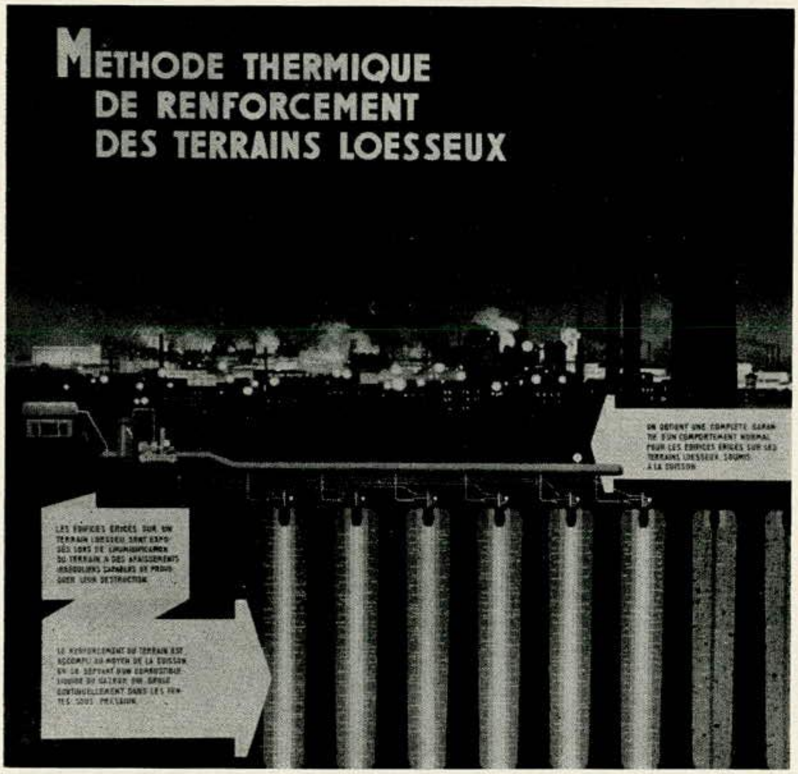

FIGURE 1
Thermal consolidation of soils. Photograph taken for the Brussels International Exhibition, 1958.

The second method, as offered by the author, has found wide application on building sites. It involves burning various fuels in the soil being treated, the process of combustion taking place in sealed bore holes with control of the temperature and chemical composition of the combustion products *(Fig. 3)*.

Heating of the soil to a temperature high enough to cause the necessary changes in the soil characteristics is achieved mainly by infiltration of the compressed heated air or of the incandescent products of combustion through the pores in the soil.

This method, which has been successfully applied in practical construction work, involves less complicated equipment and less labor while being more effective and economical than the first method, all of which facilitates and extends the range of its application.

In this paper the author describes the basic requirements which must be met in using the second method of thermal stabilization *(Fig. 4)* applicable to settling loess and other soils of porous structure.

By using the thermal method of consolidation the settling properties of loess soils can be entirely eliminated to a depth of 10 to 15 meters below the footing base, while the load bearing capacity of these soils is greatly increased *(Fig. 5)*.

From the engineering and economical standpoint deep thermal treatment of soils should be recommended:

(a) To consolidate loess soils in the foundations of important residential and industrial buildings, as well as other engineering and special types of structures to be erected, which do not allow differential settlement.

(b) To eliminate the possibility of failures of various existing buildings and structures due to excessive differential settlement.

(c) To prevent landslides and many other causes of failures.

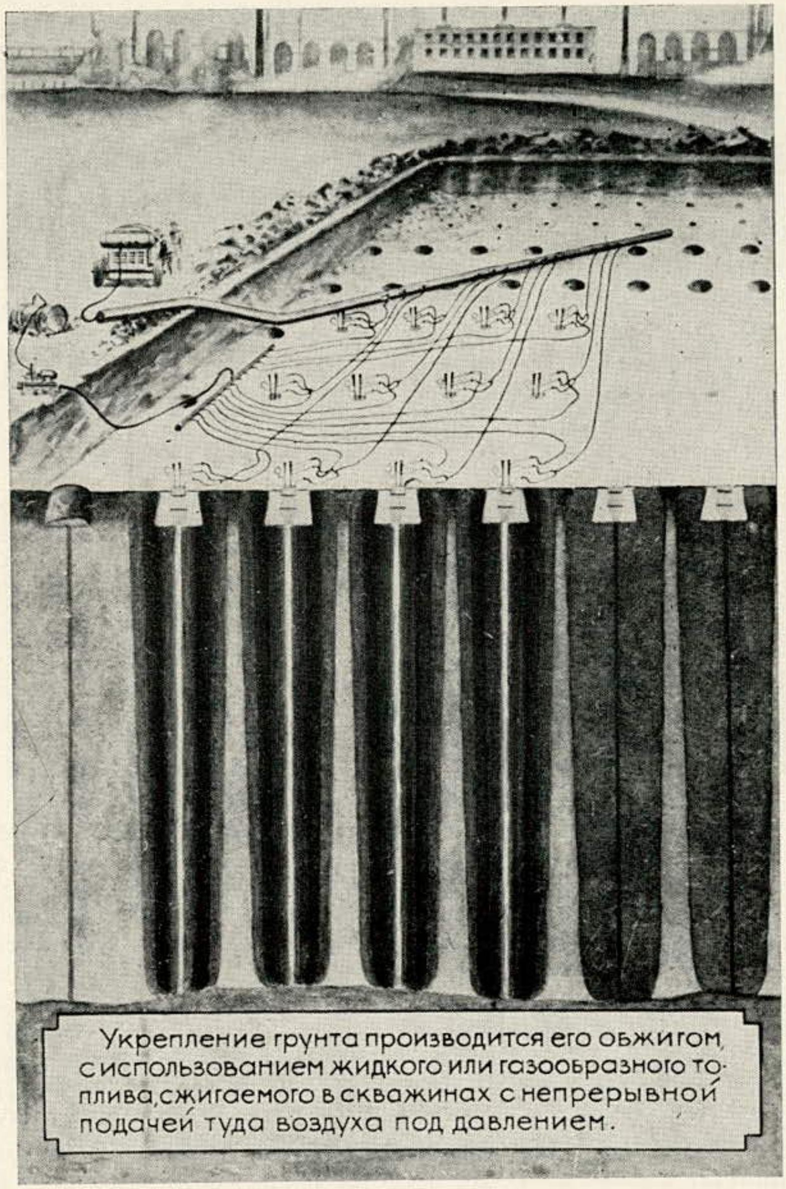

FIGURE 2
General scheme of the procedure for thermal treatment of soils.

Apart from thermal processing, the second method also enables thermo-chemical treatment of soils by means of the hot gaseous products of combustion to which special chemicals are added, if necessary. As a result of the joint effect of the incandescent gases and chemicals introduced before, during, and after thermal processing, thermal, thermo-chemical or combined consolidation of various soils is made possible *(Fig. 6)*.

Due to simple temperature control during soil firing (by blowing in different amounts of air per 1 kg of liquid or solid fuel or per 1 m^3 of gaseous fuel) in a wide range of temperatures (up to 200° C), the second method can be adopted not only for a uniform consolidation of large volumes of loess soil at temperatures between 300° and 1,000° C, but for other structural purposes

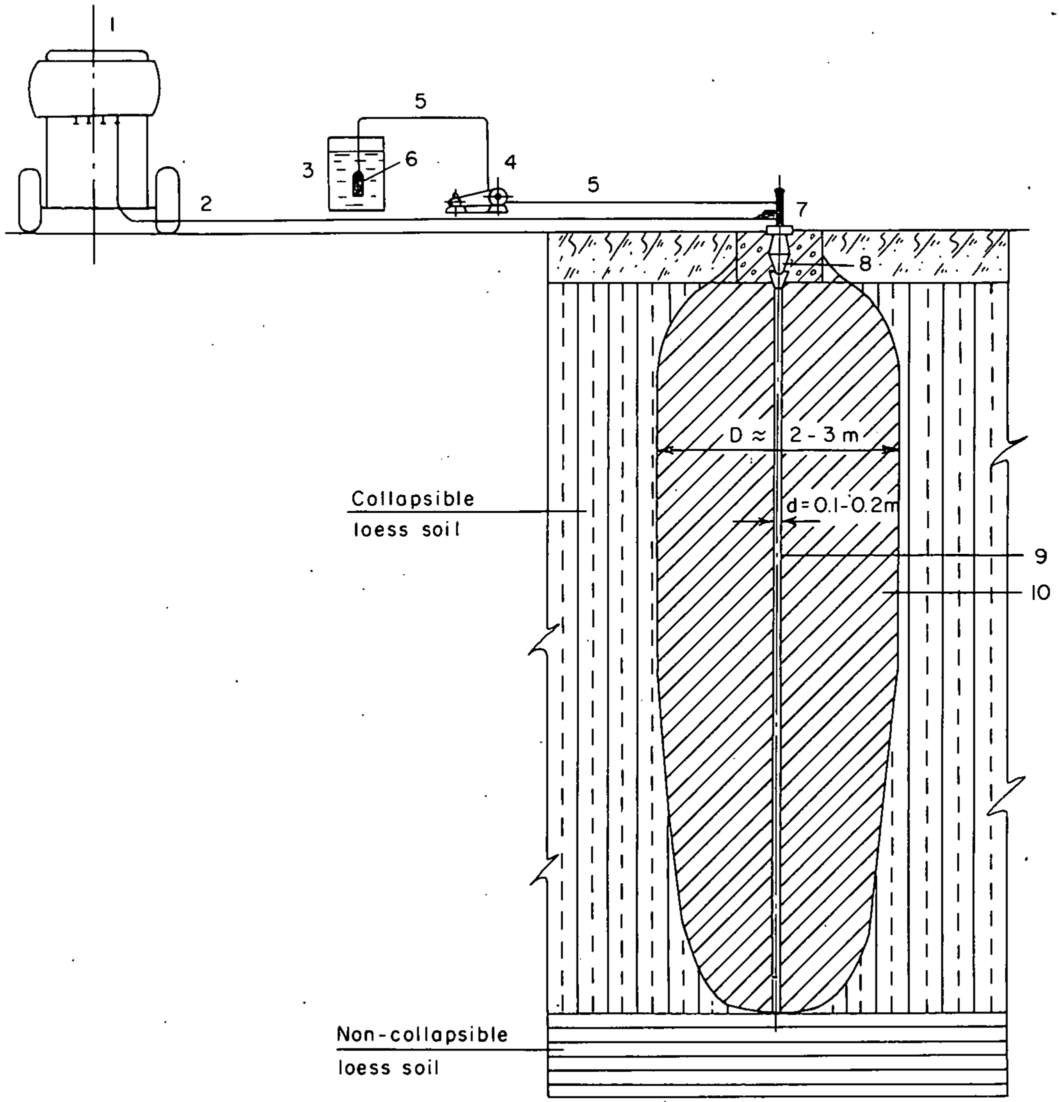

FIGURE 3

Diagram of installation for thermic stabilization of collapsible loess soils by the second method. 1. Compressor; 2. pipeline for cold air; 3. container for liquid fuel; 4. pump for supplying fuel under pressure into the bore hole; 5. fuel pipe line; 6. filters; 7. nozzle; 8. cover with combustion chamber; 9. bore hole; 10. zone of thermic stabilization of soil.

as well, when higher temperatures are required causing melting of the ground.

To facilitate the penetration of the incandescent air into the soil, the pressure of the hot gases should be maintained above that of the atmosphere by pumping cold air into the bore holes. Raising the excess pressure greatly increases the effectiveness of thermal treatment and improves the technical and economical characteristics.

The temperature of the products of combustion must not exceed fusion temperature of the soil to be consolidated; this is easily ensured by regulating the amount of cold air supplied. The amount of fuel required per unit of time (kg per hour for solid and liquid fuel or m^3 per hour for gaseous fuel) is determined in accordance with the permeability of the soil.

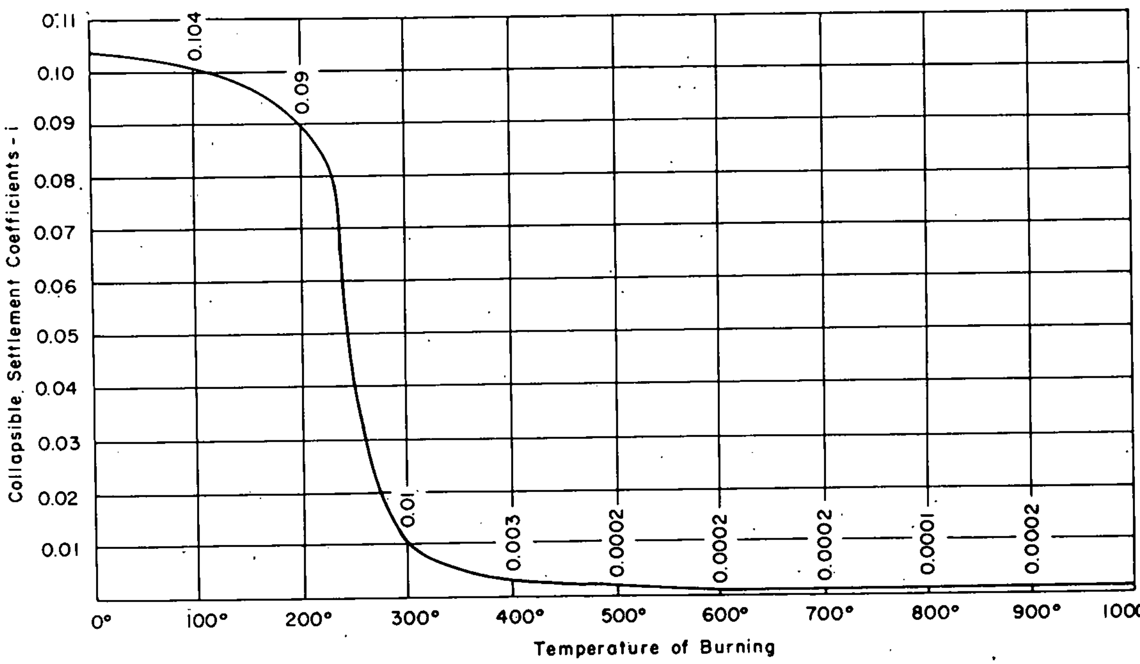

FIGURE 4
Variation of the collapsible settlement coefficients of loess soils as a function of the temperature of burning.

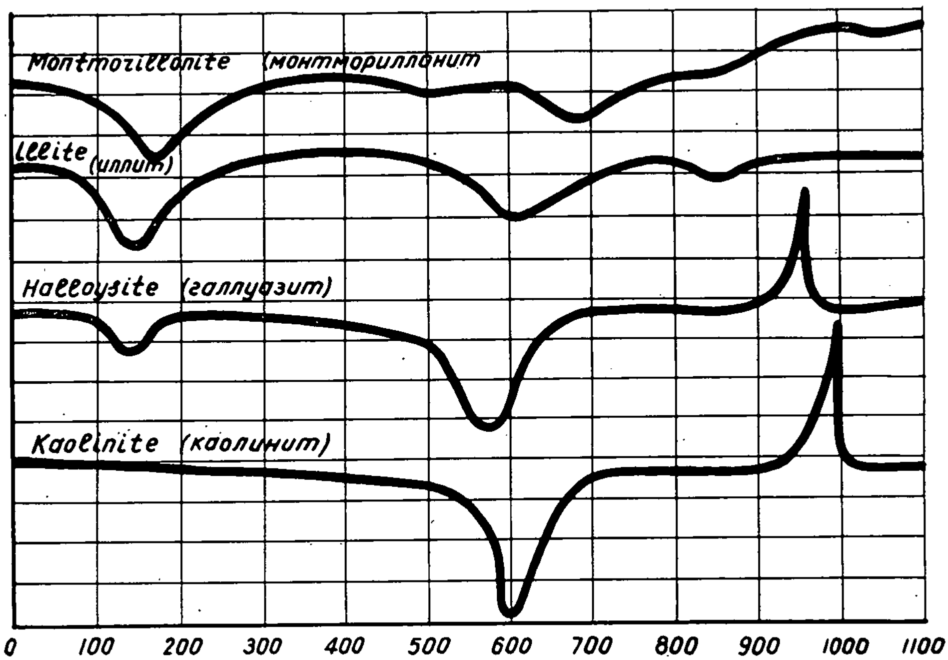

FIGURE 5
Differential thermal diagrams for the four basic constituents of clay.

No.	Characteristics of Soil Samples	Coefficient of Collapsible Settlement under $p = 3$ kg/cm²	Compression Modulus under $p = 3$ kg/cm²		Magnitude of Shear Load in kg/cm² under:						Angle of Internal Friction ϕ (°)		Coeff. of Internal Friction f		Cohesion c kg/cm²	
					$p =$ 1 kg/cm²		$p =$ 2 kg/cm²		$p =$ 3 kg/cm²							
			Dry	Sat.	Dry	Sat.	Dry	Sat.	Dry	Sat.	Dry	Sat.	Dry	Sat.	Dry	Sat.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	City of Zaporozhye, Block No. 84 (1957)															
1	Before burning	0.1030	56.6	148.4	0.60	0.36	0.98	0.70	1.60	1.20	21	19	0.38	0.34	0.22	0.22
	At 300 to 500 C	0.0067	12.9	13.5	3.80	2.40	—	—	5.50	4.00	40	39	0.85	0.80	2.95	1.47
	At 500 to 700 C	0.0005	10.5	11.2	—	—	—	—	—	—	—	—	—	—	—	—
	At 700 to 900 C	0.0002	9.6	9.5	4.3	2.50	5.30	—	5.90	4.50	40	44	0.85	0.98	3.50	1.60
	City of Dniepropetrovsk, Firehouse Depot (1957)															
2	Before burning	0.0650	90.0	160.0	0.80	0.30	1.20	0.70	1.80	1.00	27	19	0.50	0.35	0.30	0.05
	At 300 to 500 C	0.0003	24.0	24.2	2.50	2.30	3.30	3.00	4.20	3.70	40	35	0.85	0.70	1.65	1.60
	At 500 to 700 C	0.0002	13.5	13.6	—	—	—	—	—	—	—	—	—	—	—	—
	At 700 to 900 C	0.0000	12.8	12.8	5.00	4.80	5.80	5.60	6.80	6.60	42	42	0.90	0.90	4.10	3.90
	City of Bagley, Coke Chemical Plant (1957)															
3	Before burning	0.0500	90.0	162.5	0.70	0.40	1.10	0.70	1.60	1.00	24	17	0.45	0.30	0.25	0.10
	At 300 to 500 C	0.0008	23.0	23.8	2.40	2.20	3.30	2.90	4.10	3.70	40	37	0.85	0.75	1.55	1.45
	At 500 to 700 C	0.0001	12.5	12.6	—	—	—	—	—	—	—	—	—	—	—	—
	At 700 to 900 C	0.0000	12.0	12.0	4.50	4.00	5.70	5.30	7.00	6.30	51	49	1.25	1.15	3.25	2.85
	City of Nikopol, Southern Pipe Plant (1958)															
4	Before burning	0.0590	90.2	149.2	—	—	—	—	—	—	—	—	—	—	—	—
	At 300 C	0.0175	30.2	47.7	—	—	—	—	—	—	—	—	—	—	—	—
	At 600 C	0.0044	24.0	28.4	—	—	—	—	—	—	—	—	—	—	—	—
	At 900 C	0.0008	15.1	15.9	—	—	—	—	—	—	—	—	—	—	—	—
	City of Upper-Dneprovsk, Starch Plant (1958)															
5	Before burning	0.1340	26.0	160.0	—	—	—	—	—	—	—	—	—	—	—	—
	At 300 C	0.0227	12.1	34.8	—	—	—	—	—	—	—	—	—	—	—	—
	At 600 C	0.0060	10.4	16.3	—	—	—	—	—	—	—	—	—	—	—	—
	At 900 C	0.0027	9.2	11.3	—	—	—	—	—	—	—	—	—	—	—	—

Note: The color of the soil before burning was pale yellow; at 300 C, yellow-pink; at 300 to 500 and 600 C, pink, at 700 to 900, red.

FIGURE 6

Variation of the most indicative physico-mechanical properties of collapsible loess soils under the action thereon of different temperatures.

In this second method, the use of gaseous fuel is especially effective, since starting the firing of the bore holes is greatly simplified, the walls of the bore hole, and thus the soil layers, are more evenly heated, temperature control in the bore hole is improved, better conditions are created to prevent partial fusion of the walls of the bore hole, which is not permissible, and the total cost of thermal treatment is considerably lowered. The cost of gaseous fuel, as shown by information from the site, is but a small part (about 3 per cent) of the total cost of the thermal treatment of soil, about 70 per cent of the total cost involving air and boring expenses (*Figs. 7, 8*).

The burning of the fuel, gaseous, liquid or solid, is done in the mouth of the bore hole or directly in the soil mass itself. The mouth of the bore holes above are tightly closed by special shutters and an excess pressure of the hot gases, 0.25 to 0.50 atm, is permanently kept above atmospheric pressure. There being no outlet, the incandescent gaseous products of combustion infiltrate through the pores in the ground and heat the soil mass to the temperature required.

If air sources of sufficient power are available ensuring an excess pressure of 0.25 to 0.50 atm, the thermal treatment of large volumes of ground can be carried out simultaneously.

The heat transfer from the hot gases in the bore hole to the soil mass is achieved in

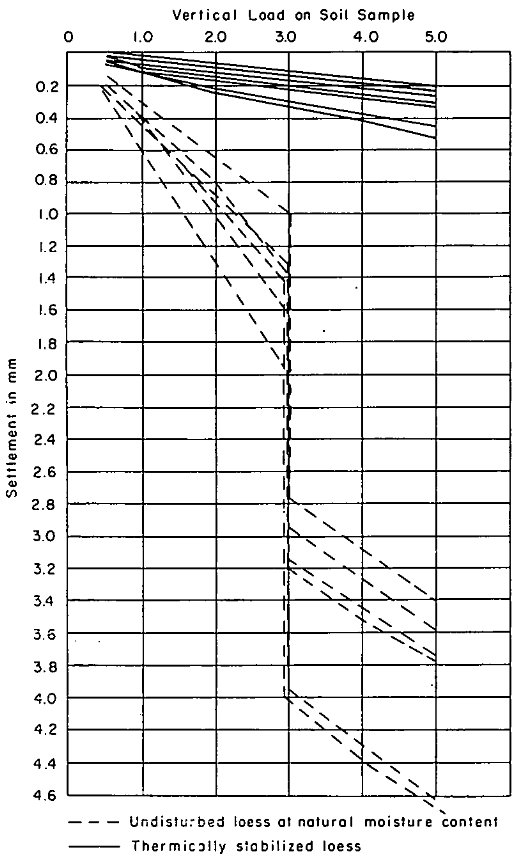

FIGURE 7

Composite results of compression tests of loess samples before and after thermal treatment.

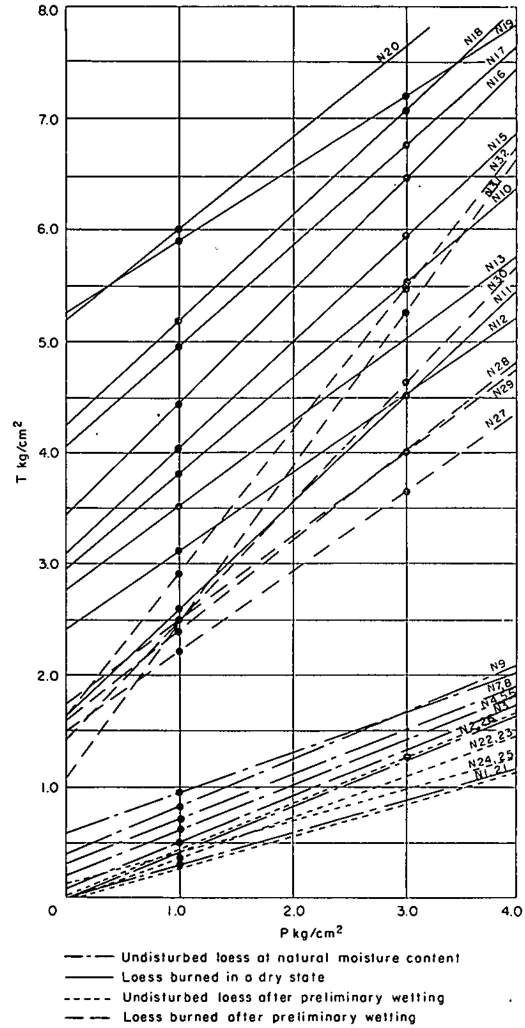

FIGURE 8

Composite results of shear tests of undisturbed loess (at natural moisture content and after preliminary wetting) and of thermically stabilized loess (dry and after preliminary wetting).

two ways: mainly by filtration of the air and incandescent gaseous products of combustion through the pores of the soil to be consolidated, and by direct transmission of heat due to temperature difference and the contact between the heat source and the surface of the soil.

Settling loess soils when subjected to thermal treatment greatly change their physico-mechanical properties, viz.:

(a) Ability to settle and to be wetted are entirely eliminated.

(b) Cohesion, compressive and shear strengths are greatly increased.

(c) Settlement under an applied load when the ground is wet immediately ceases.

(d) Color changes from natural pale yellow to various shades of red.

The temperature of the hot gases which are formed in the bore hole due to the combustion of the fuel can be controlled by changing the amount of air blown into the bore hole. By increasing or decreasing this amount of air the temperature of the combustion gases is raised or lowered, respectively. The excess air blown into the bore hole does not participate in the chemical reaction of combustion but merely mixes with the products of combustion and lowers the temperature of the mixture, serving as an additional heat carrier transferring the heat through the pores of the ground.

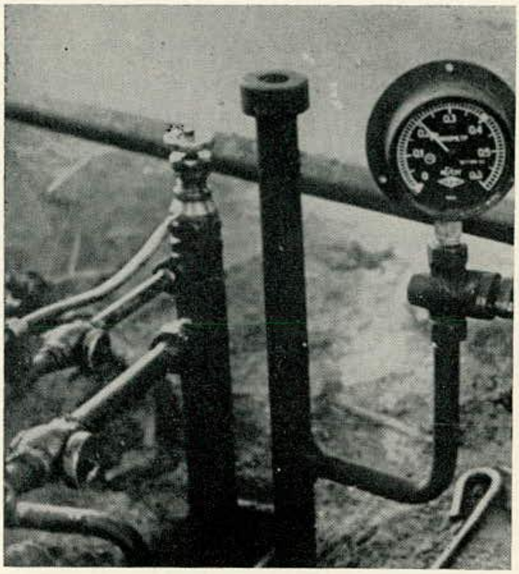

FIGURE 9
General view of the upper part of the bore hole being fired.

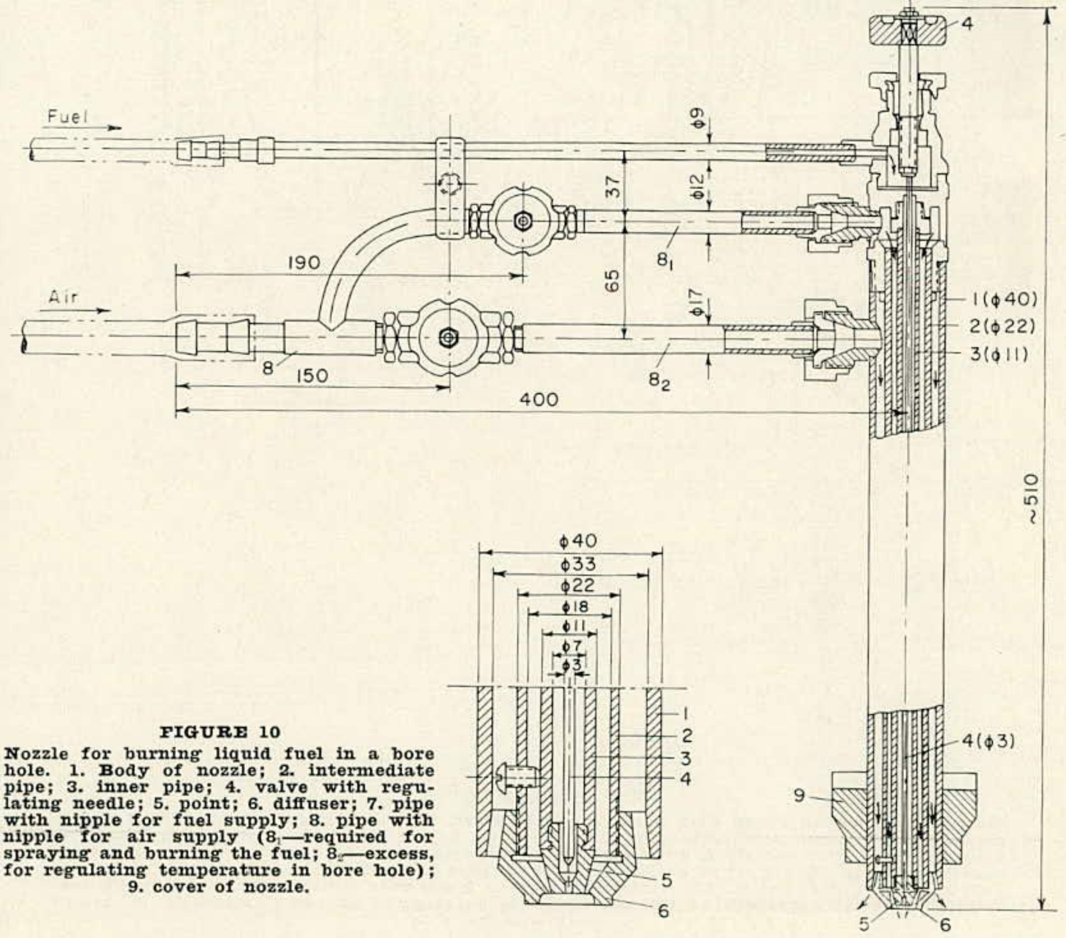

FIGURE 10
Nozzle for burning liquid fuel in a bore hole. 1. Body of nozzle; 2. intermediate pipe; 3. inner pipe; 4. valve with regulating needle; 5. point; 6. diffuser; 7. pipe with nipple for fuel supply; 8. pipe with nipple for air supply (8_1—required for spraying and burning the fuel; 8_2—excess, for regulating temperature in bore hole); 9. cover of nozzle.

The temperature of the gases in the bore hole (losses not taken into account) can be determined from the following equation:

$$t_r = \frac{Q_r}{(1.293\ V_B + 1) \cdot c_p}$$

in which

Q_r = the calorific value of the fuel;

V_B = the amount of air blown into the bore hole per 1 kg of fuel (m^3);

c_p = the average heat capacity of the products of combustion at constant pressure p (kg.-cal. per kg per deg) which is taken equal to 0.235 + 0.000019) t_r.

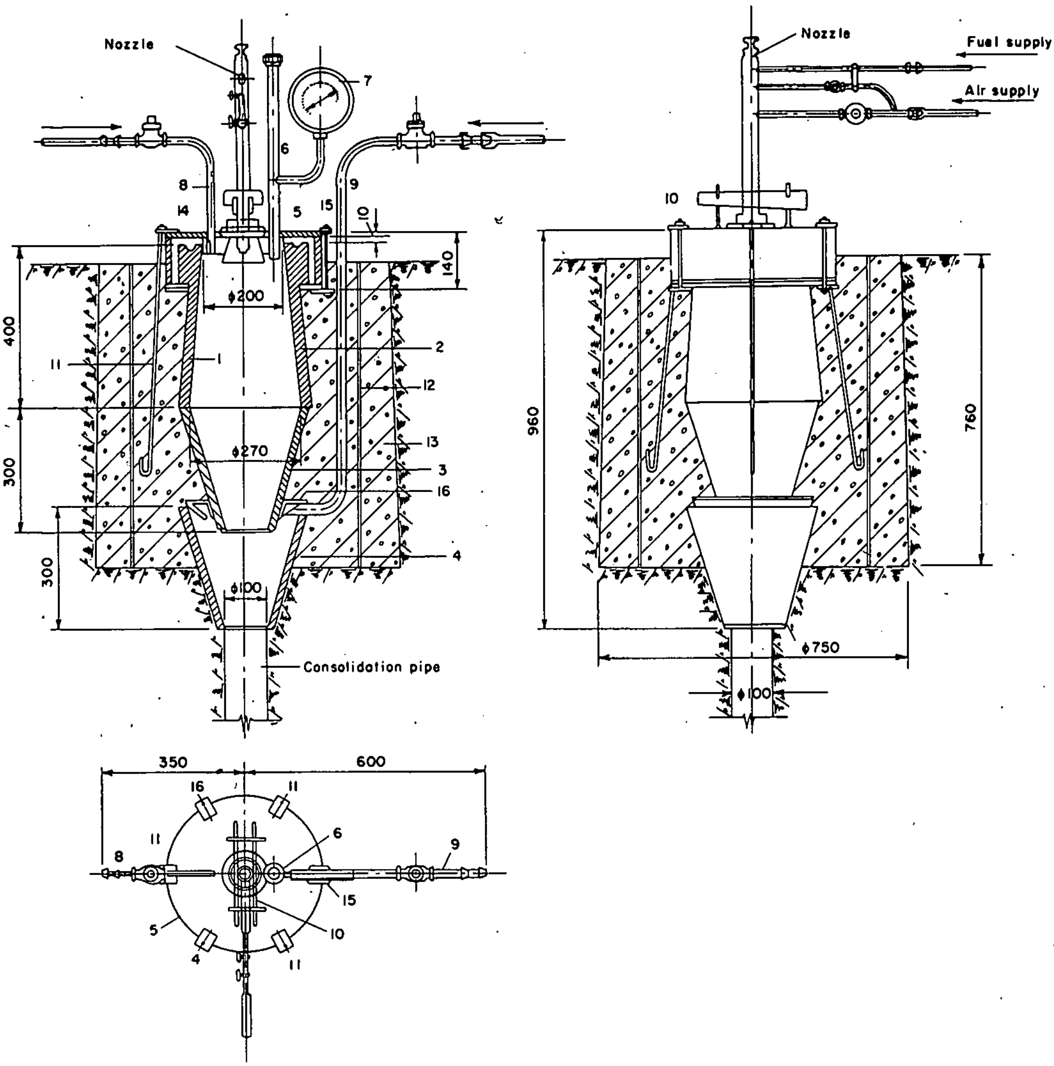

FIGURE 11

Hermetically sealed cover with combustion chamber. 1. Combustion chamber; 2, 3 and 4. ceramic cones lining combustion chamber; 5. metal lid; 6. observation pipe with branch to manometer; 7. manometer; 8. pipe for supply of excess air to upper part of combustion chamber; 9. pipe for supply of excess air to lower part of combustion chamber; 10. wedges to hold nozzle; 11. anchor ties; 12. reinforcing steel of 6-mm rods (total weight 3-4 kg); 13. concrete of red brick aggregate; 14. thermo-insulating packing; 15. fixation of metal lid; 16. hollow ring with lye.

In Table 1 is given the approximate theoretical relationship between the amount of air blown into the bore hole per one kg of fuel and the temperature of the gases in the bore hole for liquid fuel (Diesel fuel):

TABLE 1

$\frac{V_B}{V_0}$ $\frac{m^3/kg}{m^3/kg}$	1	1.5	2	2.5	3	3.5
V_B m^3/kg	11.2	16.8	22.4	28	33.6	39.2
t_r degrees	2800°	1670°	1300°	1050°	896°	785°

The amount of air that is blown inside the bore hole (V_B) should be 2.5 to three times the minimum quantity which is required for complete fuel combustion.

The amount of air filtering through the walls of the bore hole into the ground is dependent on the gas permeability of the soil and on the pressure in the bore hole and should be determined experimentally by a blowing test. With loess soils of 8 to 20 per cent moisture content the quantity of air that is filtering into the ground is usually

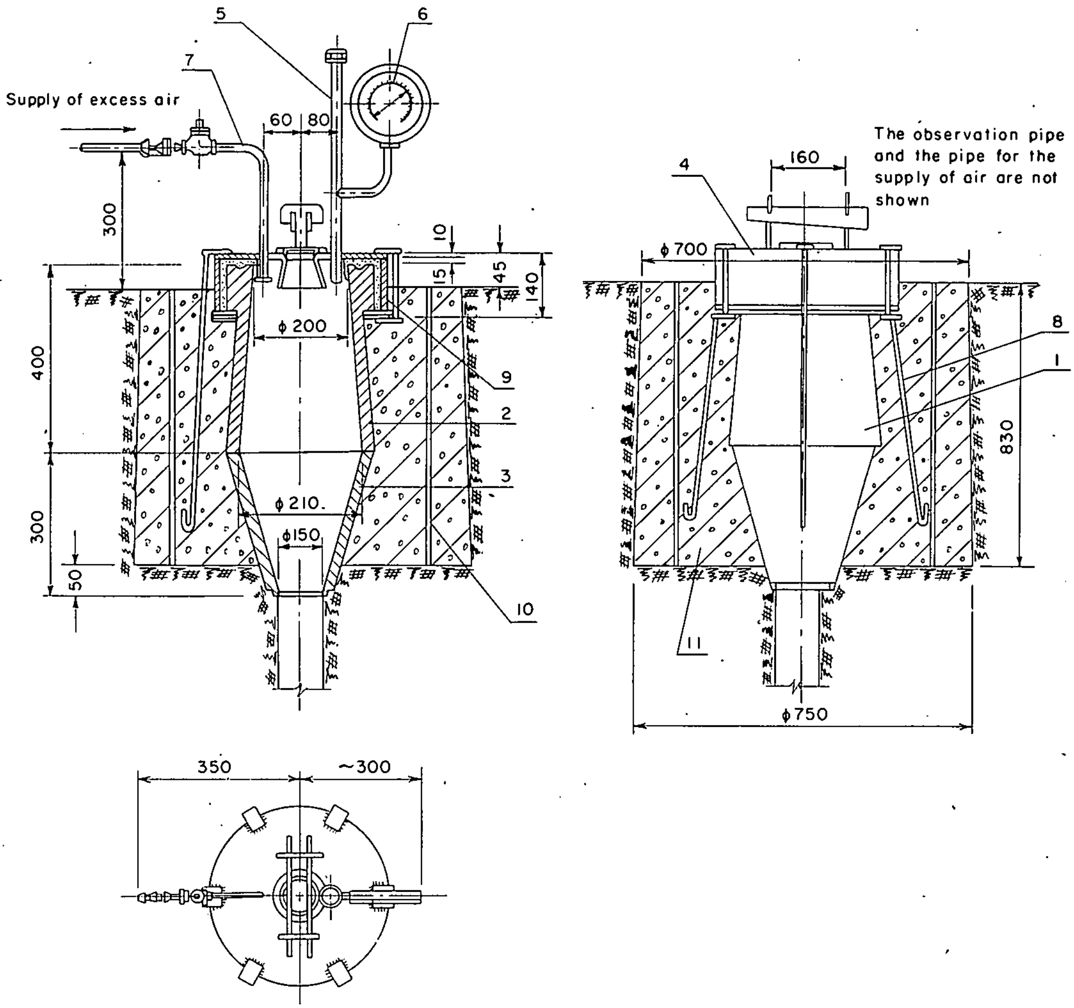

FIGURE 12

Hermetically sealed cover with combustion chamber for gas fuel. 1. Body of combustion chamber; 2 and 3. ceramic cones lining combustion chamber; 4. lid of body with wedge lock; 5. observation pipe with branch for manometer; 6. manometer; 7. pipe for supply of excess air; 8. anchor ties; 9. thermo-insulating packing; 10. steel reinforcing rods; 11. concrete of brick aggregates.

10 to 40 m^3/hr per 1 m bore hole depth *(Figs. 13, 14, 15)*.

The air quantity V_B that is necessary to provide for an optimum thermal treatment under conditions of complete fuel combustion and cooling of the combustion products (in m^3 per 1 kg of liquid fuel or 1 m^3 of gaseous fuel) is dependent on the temperature of the hot gases in the bore hole as determined from the formula above or from Table 1.

The quantity of fuel burned during one hour per 1 m run of the hole is determined from the caloric value of the fuel, gas per-

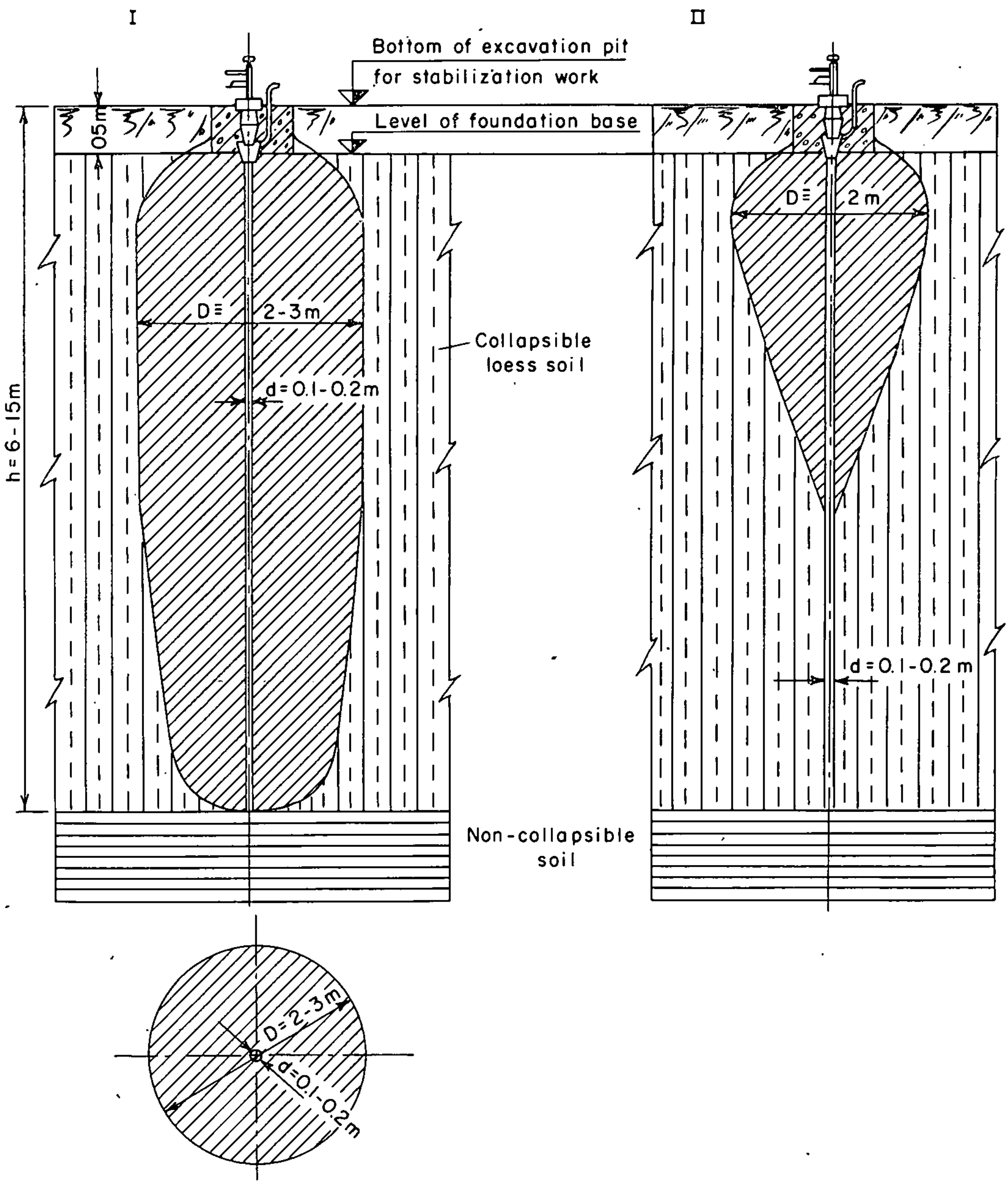

FIGURE 13

The spread of zones of thermic stabilization (strengthening) of soil around vertical bore holes. I. Under an excess pressure of 0.2-0.5 atm. in the bore hole. II. With no excess pressure in the bore hole.

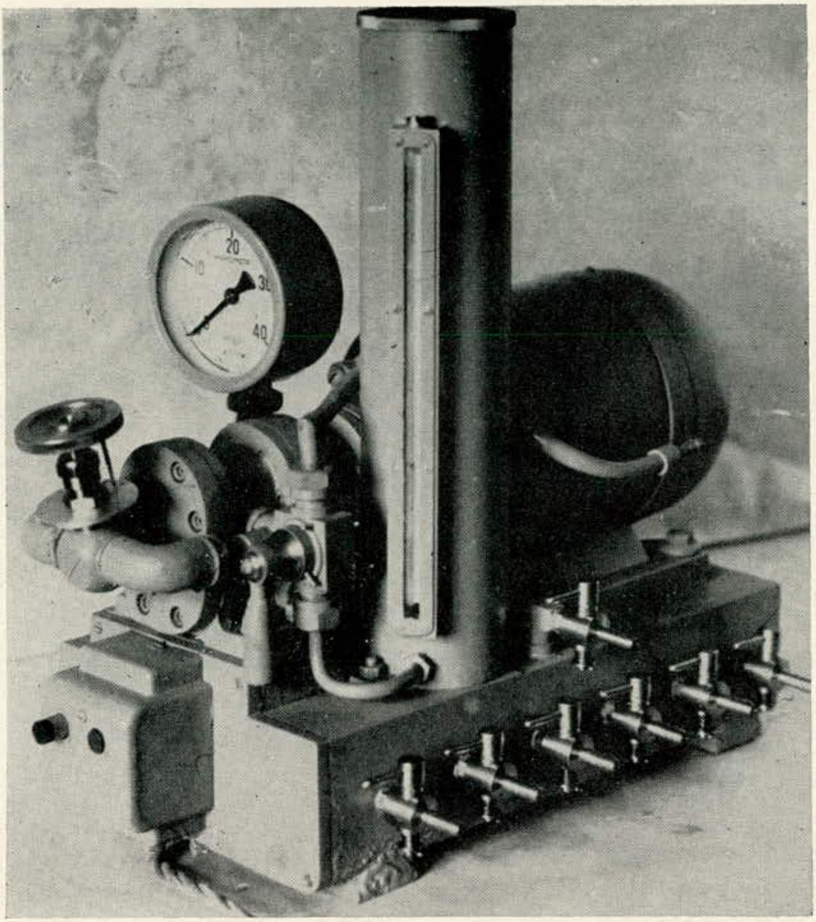

FIGURE 14
General view of equipment for pumping liquid fuel into 14 or more simultaneously fired bore holes.

meability, fusion temperature, moisture content and volume weight of the soil to be consolidated.

Increasing the quantity of fuel burned per unit time (1 hr) will raise the temperature of the hot gases above the calculated value and melting of the walls of the hole may take place; however, such a hole should be rejected and a new one drilled nearby.

The thermal treatment in one 15 to 20 cm dia. bore hole during a period of eight to 10 days will result in the formation of a consolidated zone of 1.5 to 2.5 m diameter and 8 to 10 m deep.

If the time duration of thermal treatment is increased, the consolidated zone around each hole will become larger (3 m diameter and 15 m depth or more, i.e., a volume of 100 m^3 and more of consolidated ground for one hole).

The thermal consolidation of soils is designed in one or several cycles with simultaneous thermal treatment of a corresponding number of bore holes in each cycle.

To increase the rate of processing the number of cycles should be as low as possible. Thus, in underpinning the foundation of various buildings or eliminating the consequences of failures due to local wetting of the soil, as well as in many other cases when the total number of fire bore holes varies from 6 to 30, the work of thermal treatment should be carried out in one or two cycles, i.e., during a period of 10 to 20 days *(Fig. 16)*.

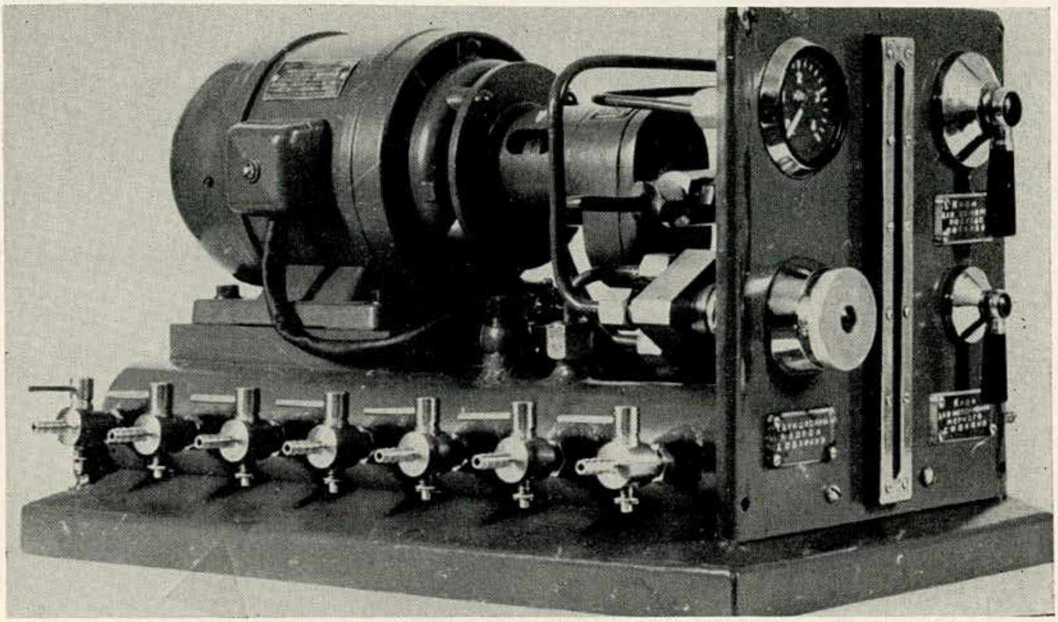

FIGURE 15
View of improved equipment with protective casing and automatic pressure regulation for pumping fuel into 15 to 30 simultaneously fired bore holes.

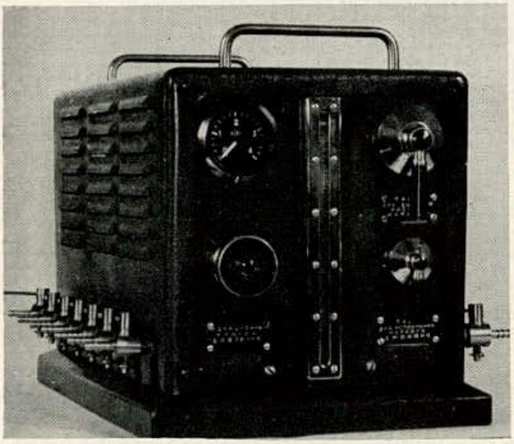

FIGURE 16
Simplified equipment for pumping fuel into six simultaneously fired bore holes.

The duration of each cycle of burning the calculated amount of fuel under the conditions assumed is about 10 days and may increase or decrease depending on the depth of the bore hole, the diameter of the consolidated zone and the output of the equipment for pumping air into the bore hole.

In applying the thermal method of consolidation, its economical and engineering advantages in the case under consideration should be taken into account. The application of this method is economically unjustifiable for underpinning the foundations of small and unimportant buildings and structures and when the thickness of the settling layer of soil is small *(Fig. 21)*.

In the course of thermal processing continuous control of the combustion process in the bore hole should be carried on by maintaining a temperature between 750 and 1000° C at pressures of 0.25 to 0.50 atm. The burning of the fuel can be observed through a special peep hole in the shutter.

The thermal treatment is considered complete when a calculated amount of fuel has been burnt inside the bore hole at a pressure not below 0.25 to 0.50 atm and when a proper amount of air has been pumped into the hole.

After firing has been completed and the ground inspected the bore holes are filled with soil and thoroughly rammed.

By applying the thermal method of consolidation a large number of damaged buildings and other structures have been saved from collapse and many have been

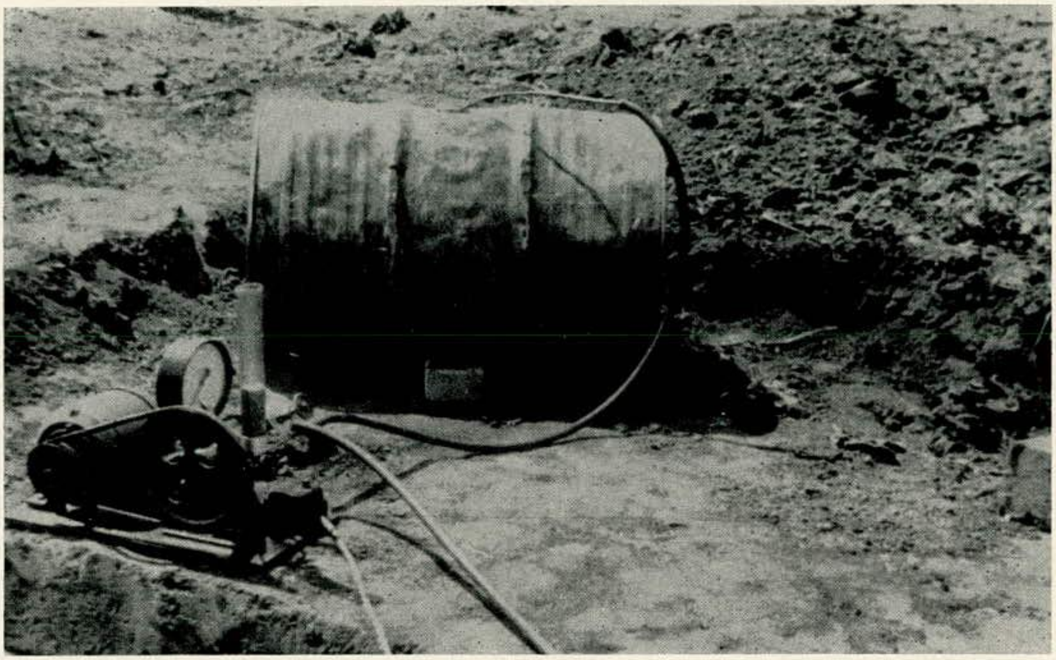

FIGURE 17
View of site during firing of bore holes by gaseous fuel (coke gas) at the Bagley Coke Chemical plant.

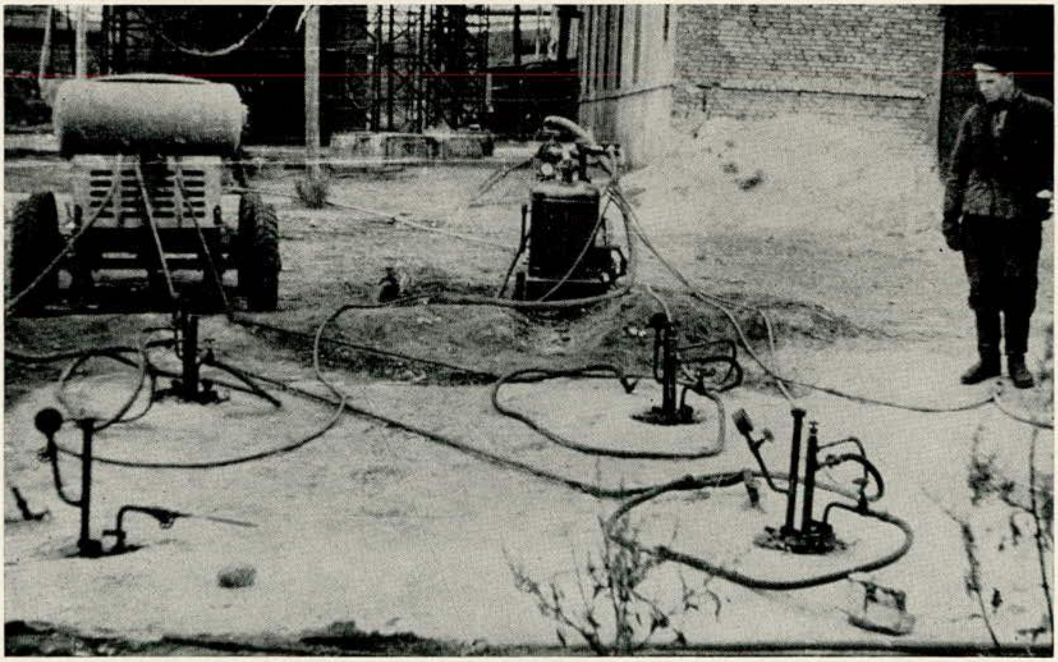

FIGURE 18
General view of site during thermal treatment of soil in a city block in Zaporozhye.

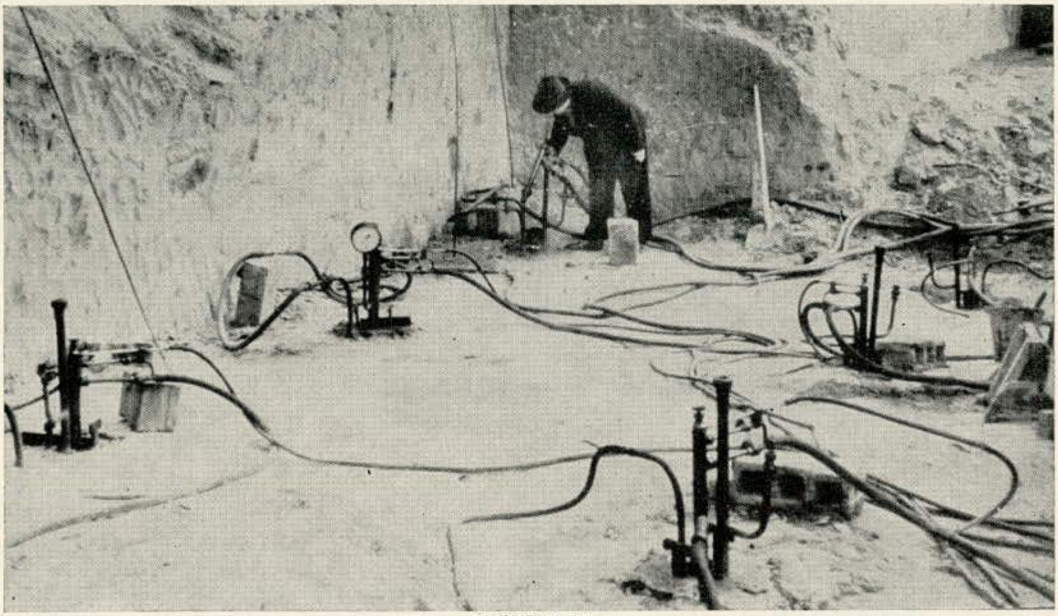

FIGURE 19
Example of the operation of equipment for 12 bore holes fired by liquid fuel.

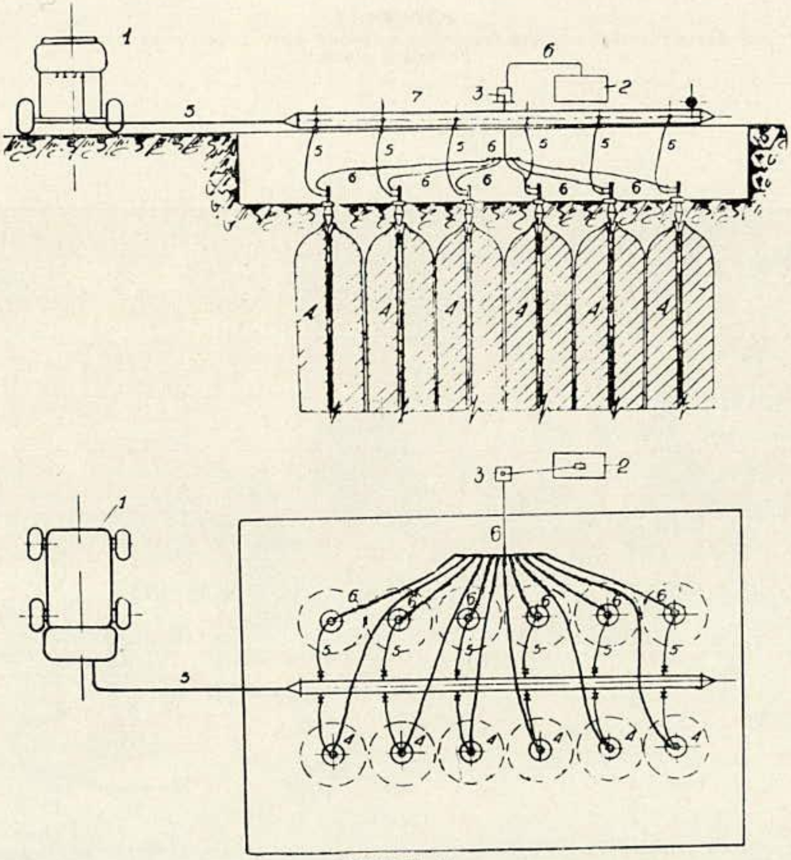

FIGURE 20
Diagram of equipment connections for the simultaneous burning of 12 bore holes by coke gas. 1. Air collector; 2. movable compressors; 3. overflow; 4. gas blower; 5. gas lines; 6. water line; 7. gas collector.

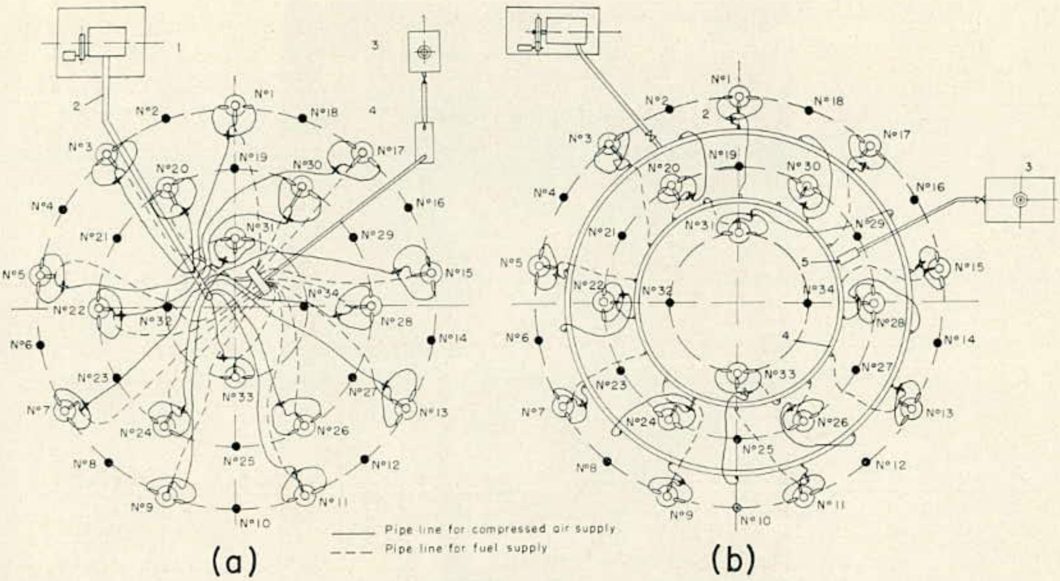

FIGURE 21
Diagram of equipment connections for simultaneously burning of 17 bore holes by liquid fuel. (a) First alternative (using benzo-resisting distribution hoses); 1. compressor; 2. receiver for compressed air; 3. overflow tank for solar oil; 4. fuel container. (b) Second alternative (partial replacement of benzo-resisting hoses by metal pipes); 1. compressor; 2. receiver for compressed air; 3. overflow tank for solar oil; 4. fuel receiver; 5. pump.

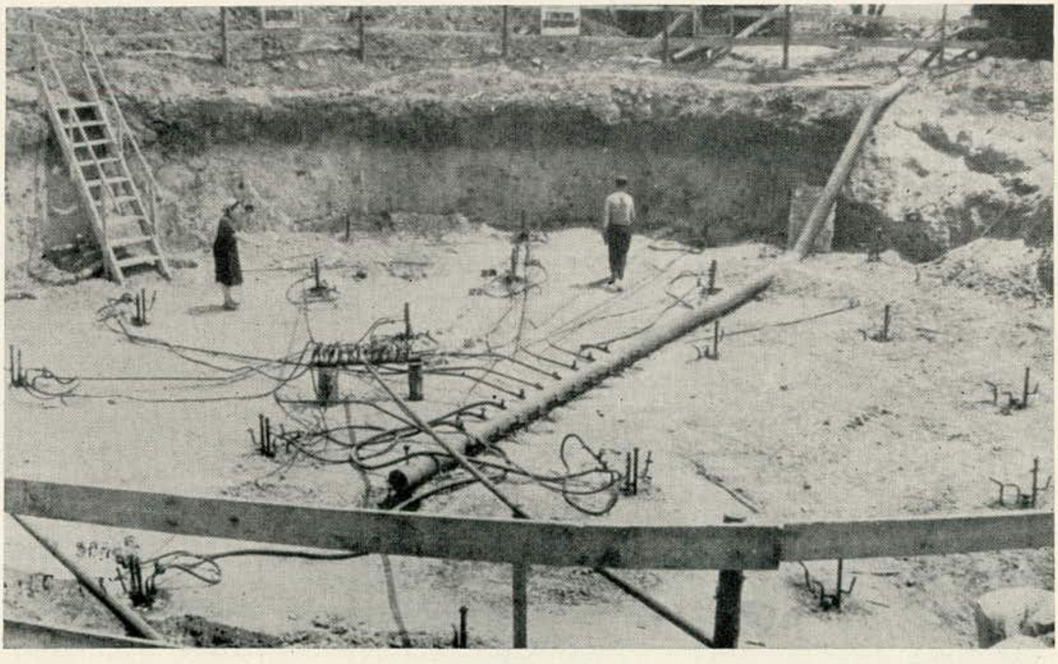

FIGURE 22
View of pit for 100-meter high chimney with foundation underpinned by thermal treatment. Bagley Coke Chemical plant.

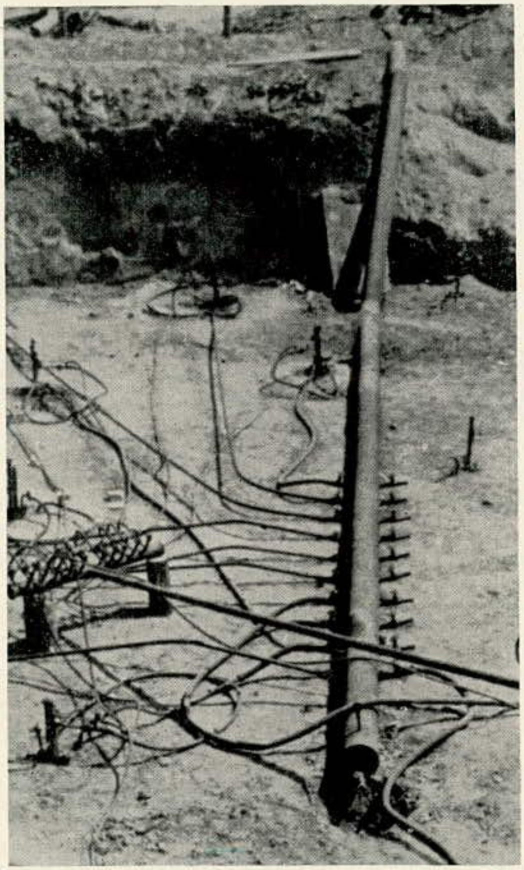

FIGURE 23
Same site with bore holes connected to air collector.

FIGURE 24
Foundations of this house in Zaporozhye were thermally underpinned (1955).

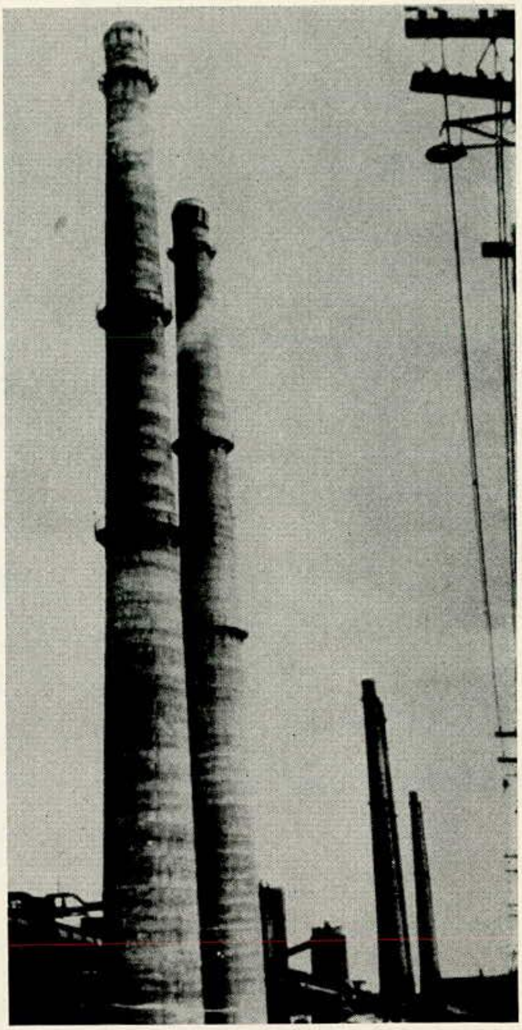

FIGURE 26
Foundations for these 100-meter chimneys in Dnieprodzerzhinsk were thermally underpinned.

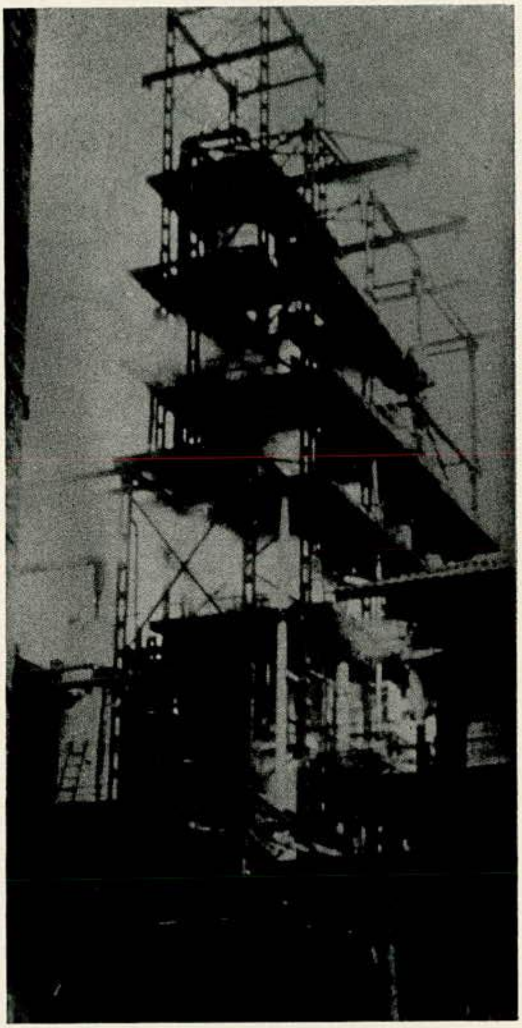

FIGURE 25
Ground beneath this structure was thermally treated (1957).

FIGURE 27
Foundations of this building in Zaporozhye showed no additional settlement when flooded with storm water.

erected on weak soils requiring treatment *(Figs. 24, 25, 26, 27)*.

The new method of loess soil consolidation has aroused great interest among the builders not only in the Soviet Union but in other countries as well.

At the Fourth International Congress on Soil Mechanics and Foundation Engineering in London in August 1957, the author made a report on the thermal treatment of settling loess soils, which was then published in the proceedings of this Congress and in a number of technical magazines in other countries.

Foundation Analysis for Machines with Dynamic Loads

ROMAN A. TOKAR, *Director,*
Institute of Foundations, Moscow

Since 1925, as a result of extensive development of large-scale industrial construction, systematic studies of the dynamics of machine foundations have been carried on in the USSR. These studies were conducted both by experimental and theoretical methods.

A characteristic feature of the experimental work was that it was performed, not in laboratories but directly on construction sites, and data thus obtained were checked by investigating numerous foundations at industrial plants in operation.

These data, combined with the results of fundamental research, enabled us to evolve sufficiently reliable and practical methods of foundation analysis for machines with dynamic loads.