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PILE FOUNDATIONS FROM THE THERMALLY REINFORCED WEAK SOILS

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U S S R

Collapsible 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 labour.

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

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

The first method, attributed to N.A.Ostachev, 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 not found to have been used in construction work.

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.1).

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.

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

This paper describes the basic requirements for designing and manufacturing of piles from thermally reinforced soils using the second method of thermal stabilization applicable to collepsible loess and other soils of similar porous structures.

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 is greatly increased.

From the engineering and economical standpoint the use of piles from thermally reinforced soils should be recommended for the following purpose:

(a) To consolidate loess soils in the foundations of important residential and industrial buildings, as well as other special types of structures, 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 similar other causes of failures.

Due to simple temperature control during soil firing (by blowing in different amounts of air per kg. of liquid or solid fuel or per cubic metre of gaseous fuel) in a wide range of temperatures (up to 2000°C), the second method can be adopted not only for manufacturing of the piles and a uniform consolidation of large volumes of loess soil at temperatures between 300° and 1,000°C, but for other structural purposes as well, when higher temperatures are required causing fusion of the soil.

To facilitate penetration of 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 is economical.

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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 supply of cold air. 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.

In this 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, partial fusion of the walls of the bore hole is prevented and the total cost of treatment is considerably reduced. 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 thermal treatment of soil, about 70 per cent of the total cost involving air and boring expenses.

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

If sufficient power is 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 mainly by filtration of the air and incandescent gaseous products of combustion through the pores of the soil and also by direct transmission of heat due to temperature difference between the heat source and the soil surface.

Loess soils, when subjected to thermal treatment, greatly change their following physico-mechanical properties:

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

(b) Cohesion, compressive and shear strengths are greatly increased (Fig.2)

(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.

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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. 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.

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

$$t_r = \frac{Q_r}{(1,293 . V_B + 1) . C_p}$$

in which

Q_r = the calorific value of the fuel;

V_B = the amount of air blown into the bore hole per 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 $0.235 + 0.000019 . t_r$.

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

Table 1

$\frac{V_B \quad m^3/kg}{V_o \quad m^3/kg}$	1	1.5	2	2.5	3	3.5
V_B m^3/kg	11.2	16.8	22.4	28.0	36.6	39.2
t_r degrees	2800°	1670°	1300°	1050°	896°	785°

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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 10 to 40 m^3/hr per metre bore hole depth.

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 kg of liquid fuel or 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 metre run of the hole is determined from the caloric value of the fuel, gas permeability, fusion temperature, moisture content and volume weight of the soil to be consolidated.

Increasing the quantity of fuel burned per hour will raise the temperature of the hot gases above the calculated value and fusion of the walls of the hole may take place. Such a hole should be rejected and a new one drilled nearby (Fig.4).

The thermal treatment in one 15 to 20 cm. dia. bore hole during a period of eight to ten days will result in the formation of a consolidated zone in shape of pile 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).

The setting up of the thermal reinforced piles is designed in one or several cycles with simultaneous thermal treatment of a corresponding number of bore holes in each cycle.

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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 piles produced 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.5).

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 designed diameter of the consolidated zone of the piles from the thermal reinforced soil and the capacity 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 not economically justifiable for underpinning the foundations of small and unimportant buildings and structures and when the thickness of the setting soil layer is small.

In the course of thermal processing, continuous control of the combustion process in the bore hole should be obtained 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 pile 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 throughly rammed.

By applying the thermal method of consolidation a large number of damaged buildings and other structures have been saved from collapse and have been erected on weak soils requiring treatment.

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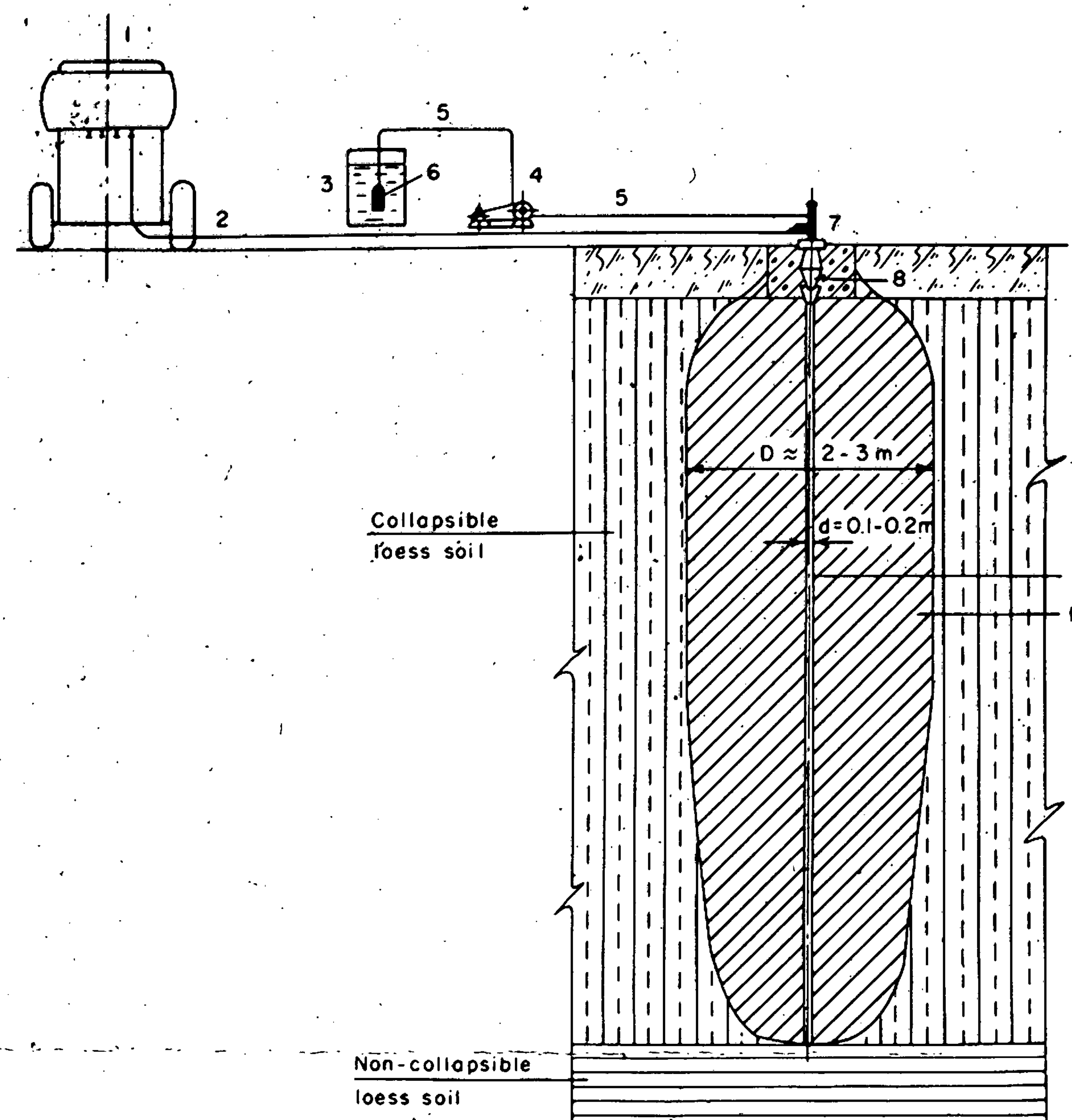

FIGURE 1

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.

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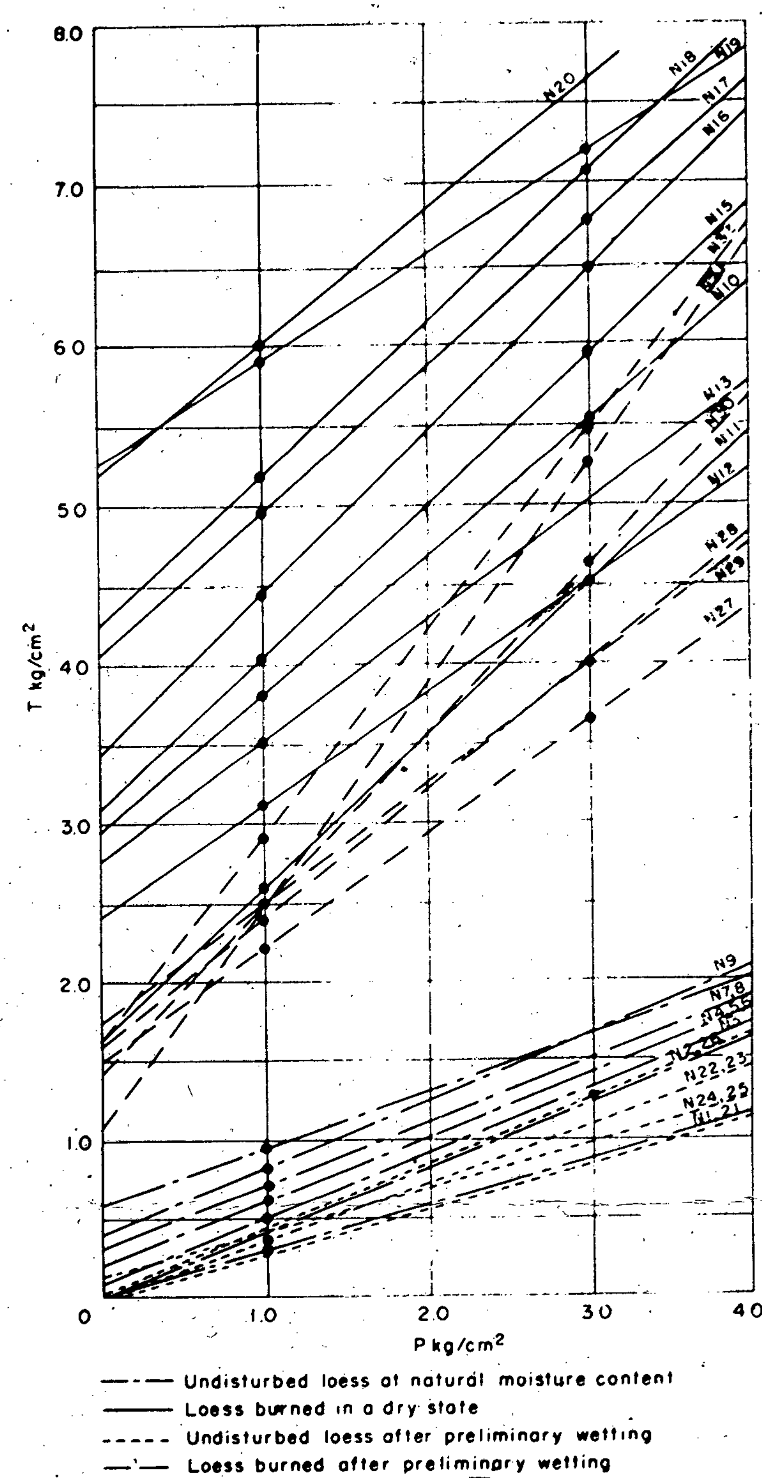

FIGURE 2

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).

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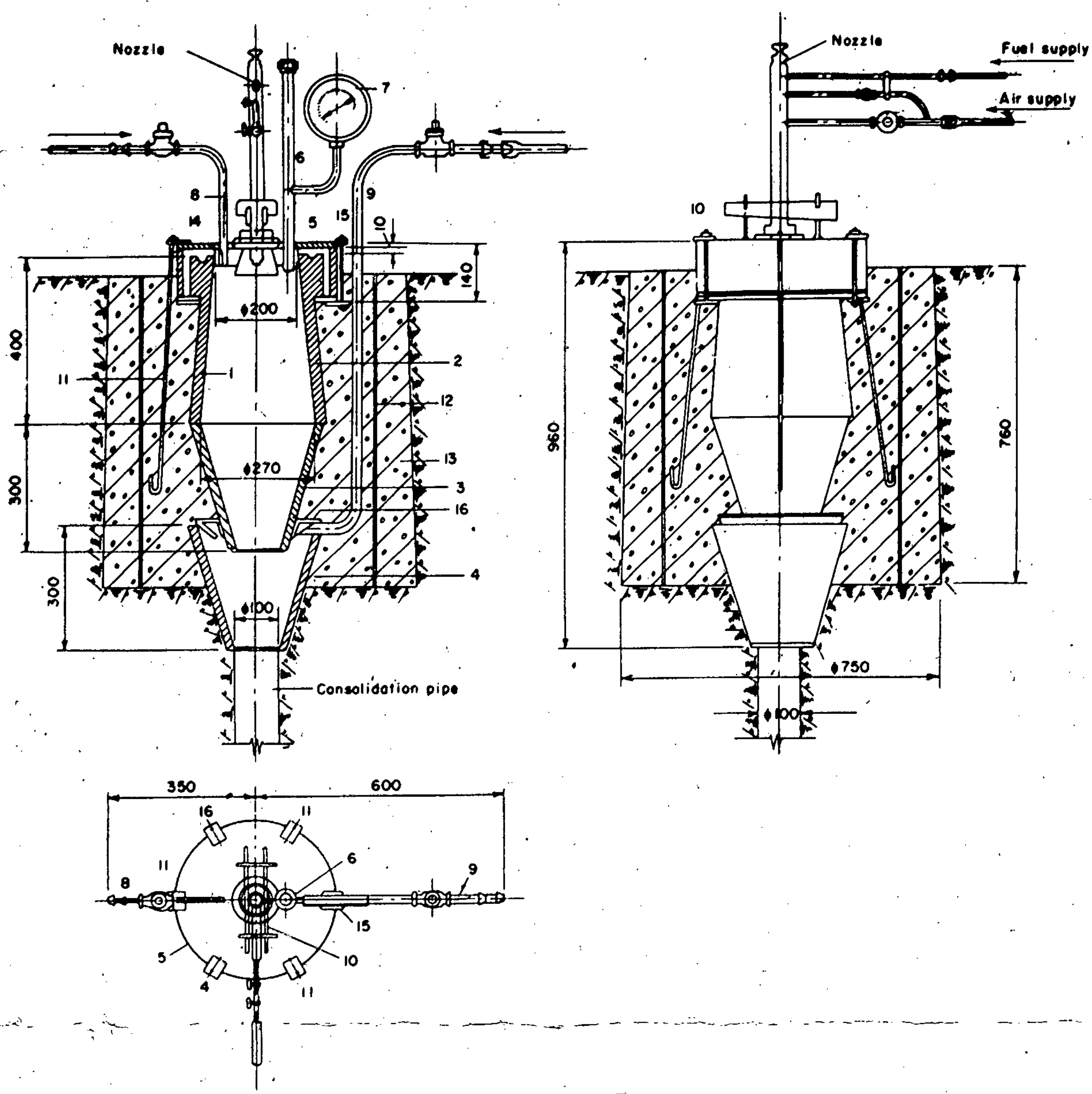

FIGURE 3

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.

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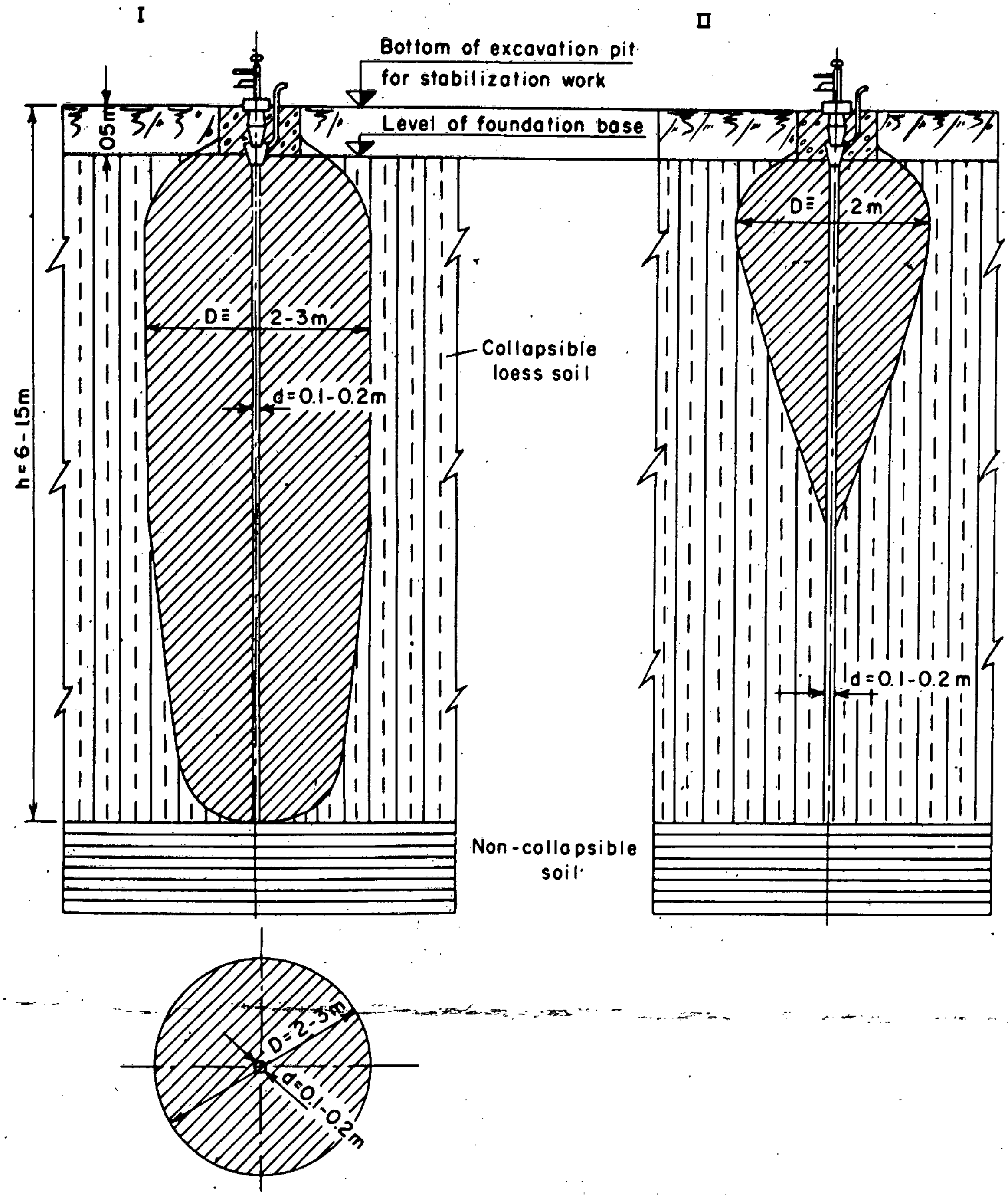

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FIGURE

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.

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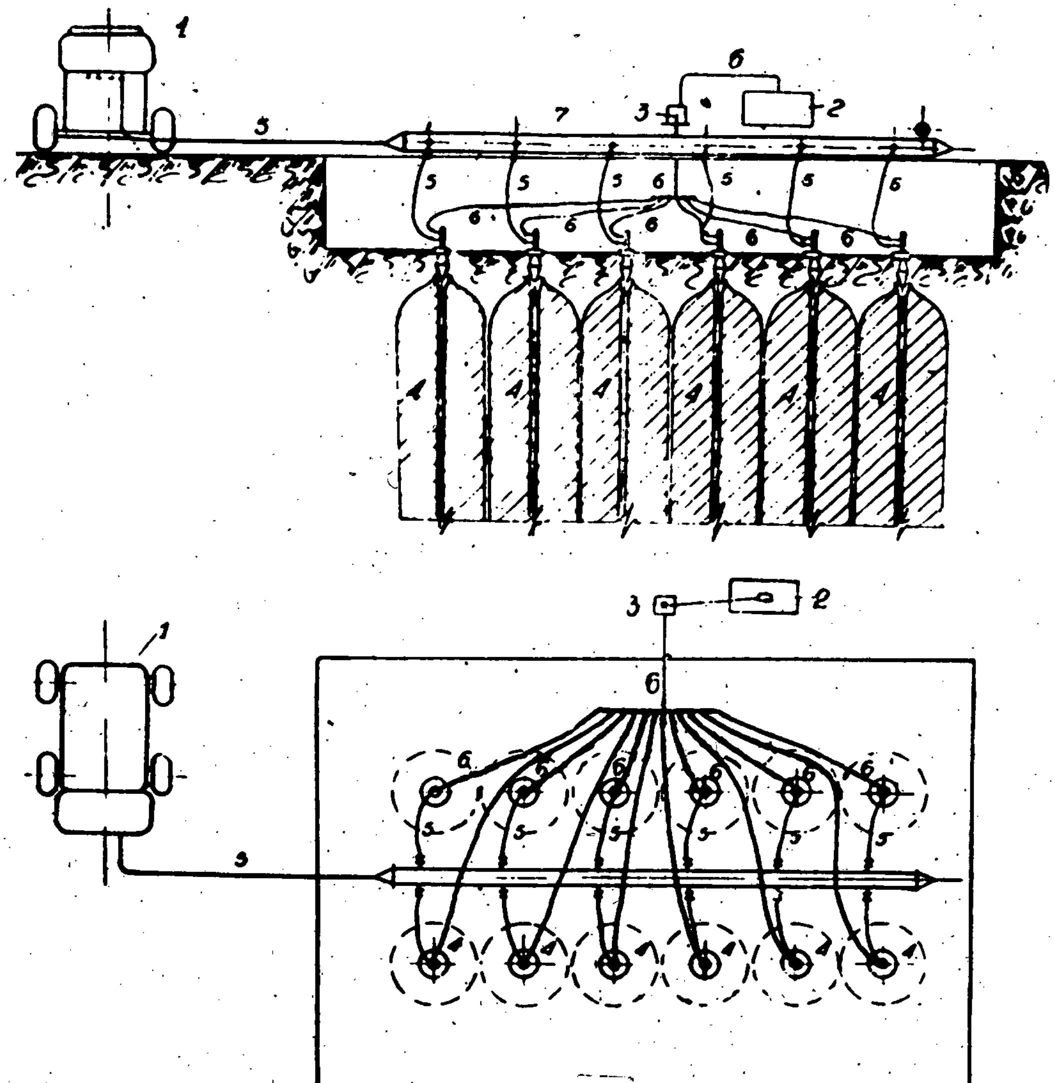

FIGURE 5

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.

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