The Practical Application of Thermal and Freezing Methods to Soil Stabilization

By

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SUMMARY.- Principal practical methods for thermal soil stabilization are described, designed to strengthen the soil deep below the surface of a slope or under a foundation. Field data for two main types of heat treatment are compared.

For temporary stabilization of deep cuts, the so-called 'Quick-Freezing' method using liquefied gas is outlined, and exemplified from experience. Reference is also made to a newly developed injection technique using pressures higher than those of conventional grouting.

I.- INTRODUCTION

In recent years thermal soil stabilization has been attempted to prevent landslides in the U.S.S.R. and Rumania. This method aims at strengthening the soil deep below the surface of a slope or under a foundation.

The principle underlying this method is that structural changes of the clay minerals will produce stable soil particles when the temperature exceeds 400°C, and the strength obtained will not greatly diminish even under submerged conditions.

For the temporary stabilization of cuts which are deepened gradually, the so-called "alluvial grouting" technique has been used for about 10 years, to stop seepage through the gaps of the temporary timbering. However, conventional grouting techniques are not especially reliable for Japanese soils because these are often non-uniform. In contrast to these methods, the freezing method is the most reliable, except for a few cases. The conventional brine circulation method, though, is expensive and necessitates periods of relatively long duration to complete the desired freezing zone.

In this paper some practical applications of thermal soil stabilization and quick freezing by the use of liquefied gases are described. Also, a newly developed injection technique which uses pressures higher than those used in conventional grouting techniques is outlined.

II.- PRINCIPLES AND PRACTICAL APPLICATIONS OF THERMAL SOIL STABILIZATION

It is difficult to prevent local slope failures in fine grained soils with relatively high moisture content.

In recent years thermal soil stabilization has been attempted to prevent landslides and similar failures in the U.S.S.R. and Rumania. The principle involved in this method is that structural changes of the clay-minerals will produce stable soil particles at temperatures exceeding 400°C by the bonding of particles to each other, as is evident from Fig. 1. The increased strength obtained will not greatly diminish even under submerged conditions.

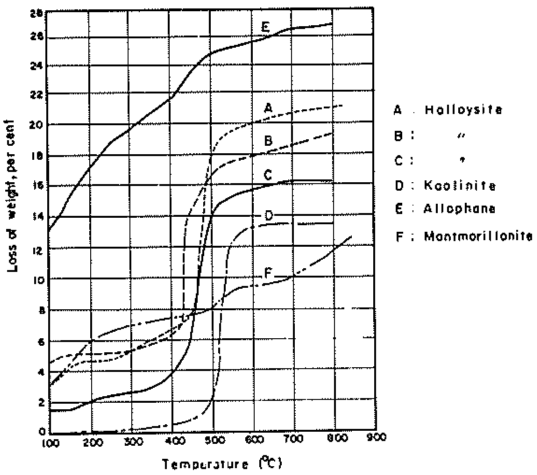

Fig. 1.- Loss of weight of various clay minerals

Practical application of the thermal treatment method is divided into two types:

The open (smoke-dust) type.
The closed (pressurized-burning) type.

The former is used in Rumania and consists of two bored holes connected together at the bottom. The burning equipment is placed over one of the two holes. The latter is commonly used in the U.S.S.R., and uses various fuels (gaseous, liquid or solid fuels) which are burned by means of a special burner placed over the closed hole with temperature controlled by keeping excess air pressures between 0.25 - 0.50 kg/sq cm. The heating of the soil is performed by infiltration of the compressed heated air through the soil pores. The air temperature must not exceed the fusion temperature (about 1,200°C in general) of the soil.

(a) A Practical Example of Slope Stabilization of a Railway Embankment

Widening of the existing railway embankment was requested to accommodate another track near Kanazawa in 1964. The brown clay at the widening section consists of weathered shale, and its principal characteristics are as follows:

Grading: Sand (2 - 0.05mm) 23 - 38%
Silt (0.05 - 0.005mm) 49 - 58%
Clay (0.005mm or less) 13 - 28%

Moisture Content: w = 44 - 59%, w_L = 48 - 62%
w_p = 29 - 35%, I_p = 19 - 30%

Dry Density: γ_d = 1.21 - 1.51 g/cc

Because local failures or slides often caused the new track to settle, thermal treatment of the soil was planned to strengthen the deep soil of the new embankment as shown in Fig. 2. A total of 45 burning holes with a diameter of 200 mm were bored in the widening section. Holes with a total length of about 7.5m were spaced about 2m from each other.

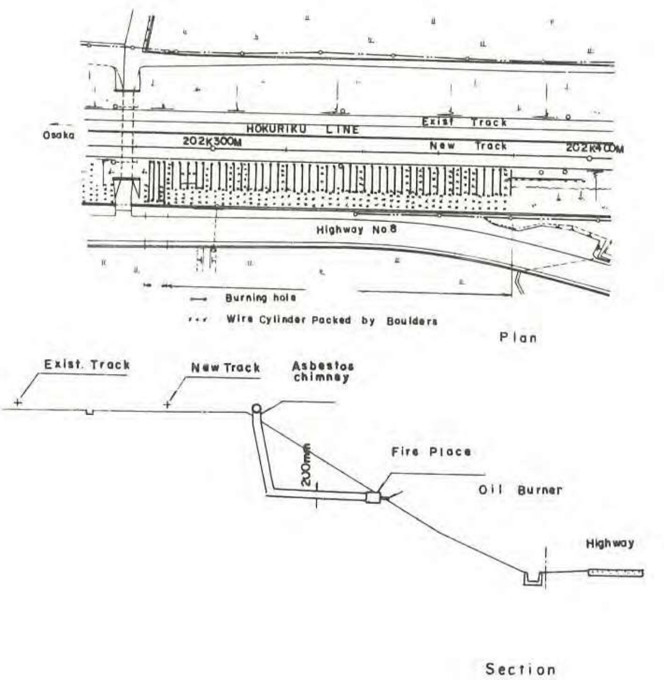

Fig. 2.- Thermal stabilization of the new embankment near Kanazawa

About 10 conventional type oil burners were fired at once by the use of heavy petroleum oil. Fig. 3 shows a typical diagram of the temperature change throughout each treatment. Treatment was continued until the temperature rose to 300°C about 30cm from the center of the hole. In general it took about 10 days to reach the abovestated temperature. The fuel consumed amounted to approximately 5 l/hr, and the mean total quantity was about 1,200 l/hole.

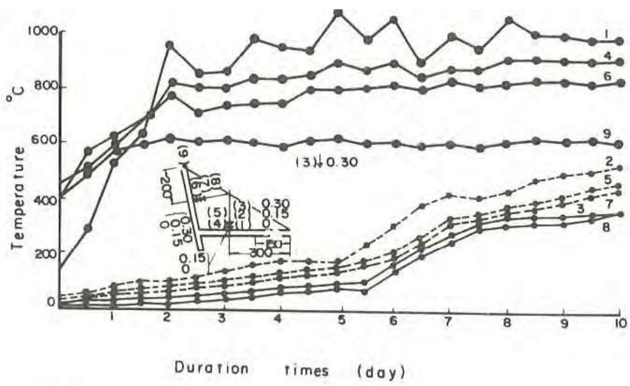

Fig. 3.- Typical diagram ot temperature change during treatment

The compressive strength of burned soil samples collected from each portion of the slope is shown in Fig. 4. As shown, the mean stabilized volume was about 7.4 cu m/hole, which consisted of burned soil from both the A and the B zones. Soil strength in the A-zone was about 10 to 20 times the original strength, even after total immersion. That of the B-zone was also higher than the original, whereas the strength of soil in the C-zone was reduced at once to the original by immersion.

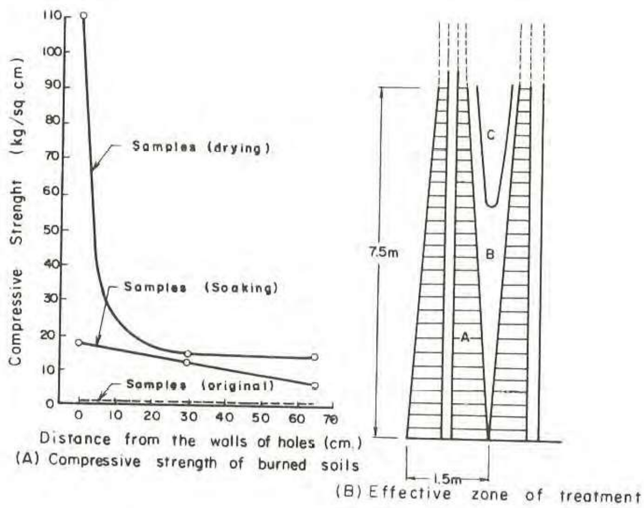

Fig. 4.- Compressive strength of each sample and effective zone of thermal treatment.

(b) The Combustion Treatment of Ground Consisting of Disposed Waste

The closed type treatment is commonly used for gas-permeable "Loess" soils in the U.S.S.R.; however, this can hardly be used in Japan because Japanese fine grained soils are mostly of too low a permeability for either water or gas.

Instead of thermal treatment of the soil, combustion treatment for waste was experimentally performed for ground in a part of the housing development area near Fukuoka, where waste had formerly been dumped.

The principal waste characteristics were as follows:

Water Content:	w = 48 - 73%
Organic Content:	14 - 19%
Wet Density:	γ = 1.03 - 1.23 gr/cc

A total of 227 burning holes with a diameter of 130 or 160mm were bored in the waste. The depths of these holes varied from 2 to 6m and were spaced 5m apart.

Fig. 5 shows the outline of the typical burning system. Principal equipment consisted of special type burners, a geared type oil pump and two rotary type air blowers. (head: 2,000mm water, delivery volume: 40 cu m/min, power: 30 kWh). Fuel oil piping (16mm dia., total 250m length) and air supply pipes (180mm dia., total 200m length) were used. A firing unit was placed over each hole and consisted of an iron cover plate, a reinforced fireproof concrete slab, and a furnace made of fire bricks. Treatment was continued until the burning had proceeded to a radius of about 1 m. It took about 7 to 15 days in general, and the mean total quantity of fuel was about 760 l/hole. The mean burned volume was presumed to be about 12.6 cu m.

(c) Thermal Calculations

Principal data for calculation of the thermal efficiency of the two treatments are shown in Table I.

TABLE I. PRINCIPAL DATA FOR THERMAL CALCULATIONS

Items	Open type (Kanazawa)	Closed type (Fukuoka)
Wet density kg/cu m	1800	1100
Moisture content %	50	60
Heat cap. of soils or wastes kcal/kg °C (C_s)	0.2	0.3
Heat cap. of water kcal/kg °C (C_w)	1.0	1.0
Latent heat of water kcal/kg (C_L)	540	540
Burned volume per hole cu m	7.4	12.6
Actual consumption of fuel per hole kg	1200	760
Ditto per unit volume kg/cu m	162	60

Theoretical consumption of fuel for these two treatments is as follows:

A. For slope stabilization by the open-type treatment

Dry soil weight $(W_s) = \dfrac{1800}{1 + 0.5} \approx 1200$ kg/cu m

Weight of pore water (W_w) = 1800-1200 = 600 kg/cu m

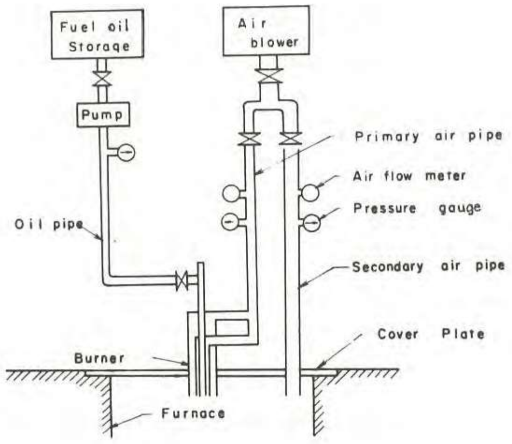

Fig. 5.- Closed type burning system

The maximum heating temperature is estimated at about 800°C.

Heat capacity of the soil $(Q_s) = W_s.C_s.T \approx 192,000$ kcal

Heat capacity of the pore water $(Q_w) = W_w.(C_w.T + C_L)$
$\approx 384,000$ kcal

Total heat capacity $(Q) = Q_s + Q_w \approx 576,000$ kcal/cu m

Theoretical fuel consumption $= \alpha = \dfrac{Q}{Q_o} = 57.6$ kg/cu m

where Q_o represents the unit heating capacity of the fuel (about 10,000 kcal/kg).

B. Burning by the closed type treatment

Weight of dry wastes $(W_s) = \dfrac{1100}{1 + 0.6} \approx 690$ kg/cu m

Weight of pore water (W_w) = 1100-690 = 410 kg/cu m

Heat capacity of the wastes $(Q_s) \approx 166,000$ kcal

Heat capacity of the water $(Q_w) \approx 263,000$ kcal

Total heat capacity $(Q) \approx 429,000$ kcal/cu m

Theoretical fuel consumption $= \alpha = 42.9$ kg/cu m

According to the above theoretical values and to Table I, the heat effect (defined by the percentage of the theoretical fuel consumption to the actual) may be calculated. In slope stabilization by the open type treatment, the heat efficiency was about 36%, and in burning by the closed type treatment about 72%.

(d) Some factors in Thermal Stabilization

As stated above, use of the closed type treatment will be desirable in thermal stabilization because its heating effects are more effective than those of the open type treatment in general; however, simultaneous control of many individual burners will necessitate very complicated techniques to adjust the combustion of each burning hole, especially for the closed type treatment.

Recently it has been sought to develop a heating air circulation system in which heating air would be produced at a central furnace and circulated between groups of individual holes and the furnace by means of a closed circuit system.

The injection of some kind of inflammable and/or cooling material should also be investigated in order to keep a satisfactory combustion in the closed type of treatment.

III. THE PRINCIPLES AND PRACTICAL APPLICATIONS OF QUICK FREEZING

As stated earlier, freezing is a reliable method for temporary soil stabilization of deep cuts, including shaft sinking, shield or pipe thrusting, tunnelling, construction of frozen earth storages, etc.

Artificial freezing itself has a long history; about one century. But the conventional brine-circulation method is relatively expensive and requires a long time to accomplish the expected zone of freezing.

It is sought to overcome these difficulties by so-called "Quick Freezing", which aims at the effective usage of liquefied gases. Liquefied Nitrogen or Liquefied Carbonic Acid is chiefly used for these purposes, by means of freezing pipes as shown in Fig. 6. Recently a combined method which consists of a period of initial freezing by the use of liquefied gas, and another period by the brine circulation method simply to maintain the freezing condition has been tried. This is shown in Fig. 7.

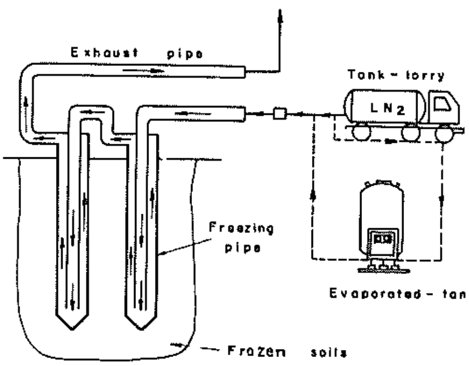

Fig. 6.- Quick freezing by liquefied gases

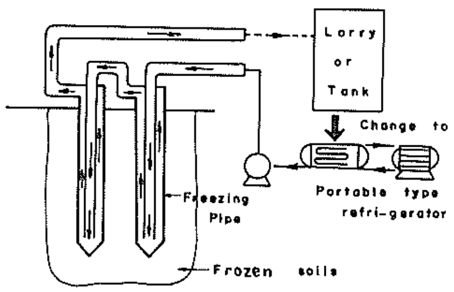

Fig. 7.- Combined method of quick freezing and conventional brine circulation

Comparisons of freezing time and unit cost as between conventional and quick freezing are shown in Figs. 8 and 9. The temperature difference between the freezing pipe and the surrounding soil is only about 40° to 50°C in the former method, whereas in the latter it will reach 100 to 150° or more. This is the principal reason for the great time reduction in quick freezing.

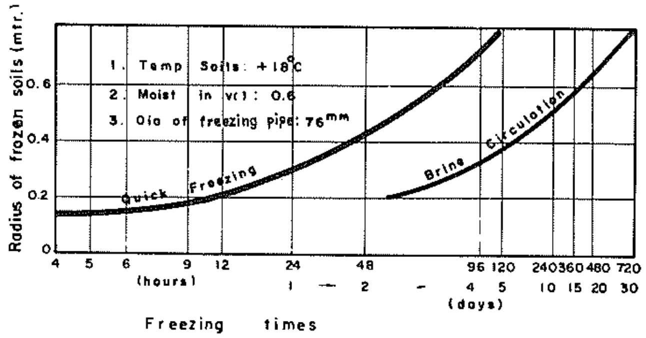

Fig. 8.- Comparison of freezing times for the quick and conventional freezing methods

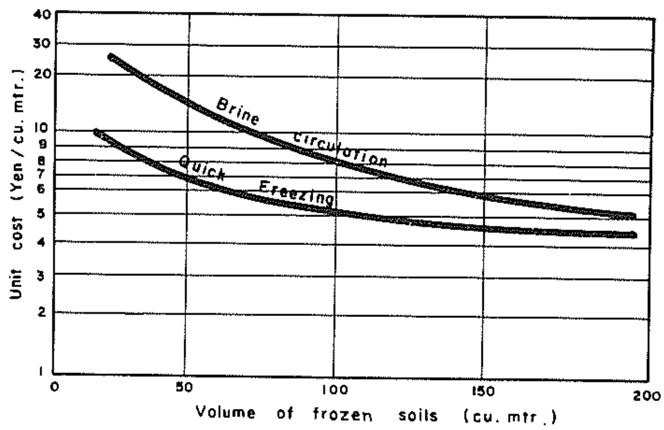

Fig. 9.- Comparison of costs for the quick and conventional freezing methods

Moreover, only a simple piping system is used in quick freezing and the gases are transported by tank or from the plant to the site; whilst a very complicated system, including refrigerator and heat exchangers must be used for the brine circulation method. Furthermore, legal authorisation must be obtained in Japan for the use of a high pressurized cooling medium (10 - 30 kg/sq cm).

Table II shows the thermal characteristics of liquefied gases. The cooling capacities of liquefied gases in the applied conditions are as follows:

A. Liquefied Nitrogen:

72.5 kcal/kg at -100°C, 1 atm
83.7 kcal/kg at -50°C, 1 atm

B. Liquefied Carbonic Acid:

about 74 kcal/kg at - 30°C, 1 atm

TABLE II. THERMAL CHARACTERISTICS OF LIQUEFIED GASES

Kind of Gas	Boiling point °C	Melting point °C	Latent heat at Boil. pt. kcal/kg
Carbonic Acid	-	-79	139
Oxygen	-183	-218	51
Nitrogen	-196	-210	48

By comparison, the freezing time of the former gas is faster than for the latter; however the temperature distribution of the former gas is non-uniform along the axis of the freezing pipe, whilst that of the latter is almost constant. But it is necessary to use special pressurized freezing pipes for the latter gas, as shown in Fig. 10. The internal pressure for these must be kept at about 6 kg/sq cm or more, because Liquefied Carbonic Acid will transform to the solid state under pressures less than 6 kg/sq cm.

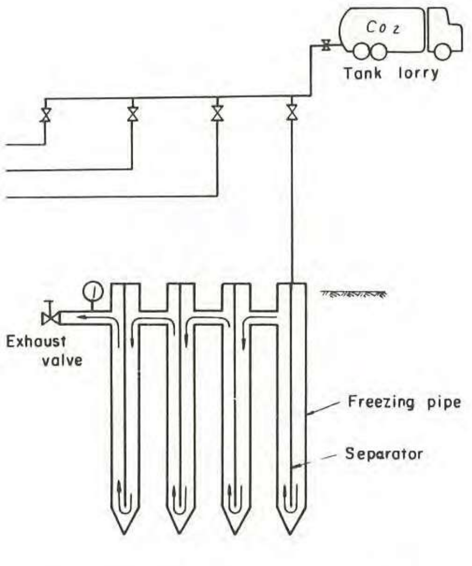

Fig. 10.- Pressurized freezing pipes for Liquid Carbonic Acid

Thermal characteristics of ordinary soils are shown in Table III. Therefore, necessary cooling capacities to freeze the soil unit volumes will be calculated by the following method:

Total cooling capacity = $Q = Q_1 + Q_2 + Q_3$ kcal/cu m

where Q_1 = cooling capacity necessary to lower the subsoil temperature (T_o°) to the freezing point (T_s°)

Q_2 = latent heat of freezing of the soil

Q_3 = cooling capacity required to lower the temperature of the frozen soil (T_f°).

$$Q_1 = \gamma_2 . C_2 . (T_s - T_o) \text{ kcal}$$

$$Q_2 = \frac{W' . L_i . 1000}{1} \text{ kcal}$$

where L_i = 79.5 kcal/kg (Latent Heat to freeze pore water).

$$Q_3 = \gamma_1 . C_1 . (T_o - T_f)$$

TABLE III. THERMAL CHARACTERISTICS OF SATURATED SOILS

Water in vol. in %	W'	0.3	0.4	0.5	0.6
Wet density kg/cu m	before freez	2.26	2.08	1.90	1.72
	after "	2.22	2.03	1.84	1.65
Specific heat kcal/kg °C	before freez C_2	0.32	0.37	0.43	0.49
	after " C_1	0.26	0.27	0.29	0.32
Heat conductivity kcal/m hr °C	before freez	1.87	1.62	1.41	1.22
	after "	2.63	2.52	2.41	2.31

(a) Quick Freezing for a Shield Starting

A shield with a diameter of 2.7 m will be started from a shaft near Yokohama as shown in Fig. 11. Soil at the site consists of very soft sandy silts which would be be squeezed out into the shield at starting after breaking the concrete wall of the shaft.

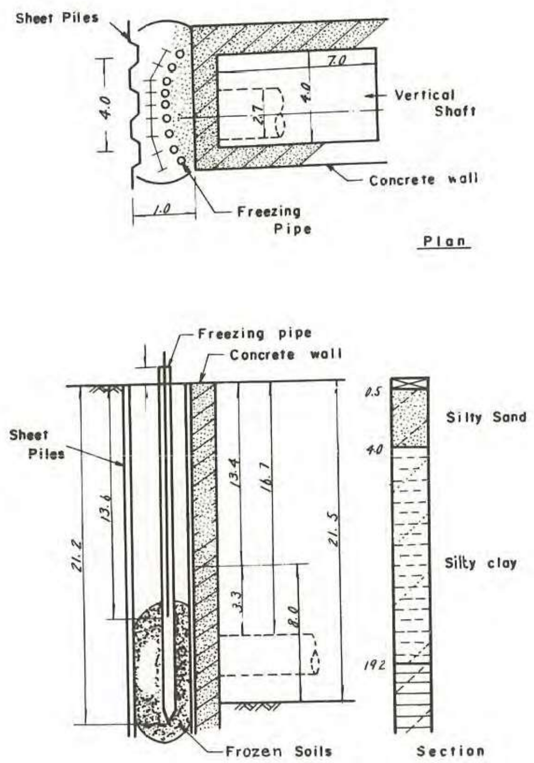

Fig. 11.- Quick freezing for shield starting

Freezing pipes with a diameter of 76 mm and a length of about 22 m were put in the ground at 0.5 m intervals. The expected volume of the frozen soil was estimated at about 53 cu m, and about 88 tons of Liquefied Nitrogen was supplied over a period of 6 days. The shield was started in safety 5 days after commencement of the gas-supply. Freezing pipes were cut out for the shield thrusting. The soil remained in a frozen condition for about 5 days after the end of the gas-supply.

(b) Quick Freezing for a Shield Thrusting

A small-scale shield with a diameter of 2 m was thrust in gravelly soil with plenty of seepage in the suburbs of Tokyo.

Freezing pipes with a diameter of 50 mm and a length of 5.5 m were inserted in a horizontal direction on the upper half of the shield as shown in Fig. 12.

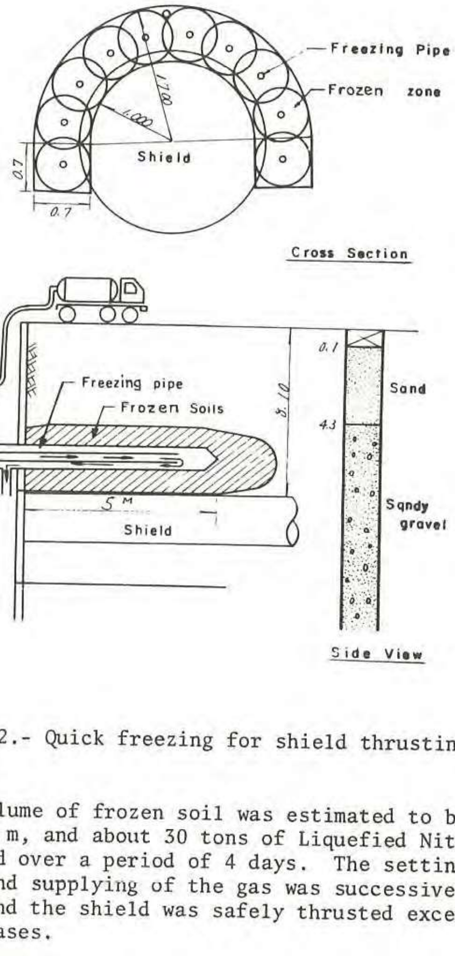

Fig. 12.- Quick freezing for shield thrusting

The volume of frozen soil was estimated to be about 21 cu m, and about 30 tons of Liquefied Nitrogen was supplied over a period of 4 days. The setting of the pipes and supplying of the gas was successively repeated, and the shield was safely thrusted except for a few cases.

Often grouting with cement suspension, combined with a silicate solution, was undertaken to protect against excessive seepage, especially at the base of the shield.

C. The combined method of initial quick freezing with subsequent brine circulation for a large-scale shaft.

A vertical shaft with an inside diameter of 9 m was sunk in the center of Tokyo for the construction of large-scale underground telephonic utilities, as shown in Fig.13. Soil at the site principally consisted of sandy soil with fine to medium grain size. Freezing pipes with a diameter of 76 mm and a length of 16.5 m were put in the ground and spaced about 0.5 m from each other (doubled rows).

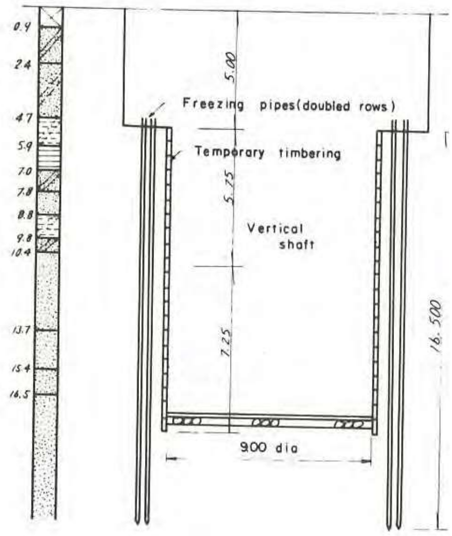

Fig. 13.- Quick freezing for shaft sinking

Initial quick freezing was combined with the brine circulation method. This was selected for the freezing method because of time saving, and because the working space of the site was too limited to install large-scale refrigerators.

The volume of frozen soil was estimated to be about 510 cu m, and about 606 tons of Liquefied Nitrogen was supplied over a period of 12 days for initial quick freezing. This was converted immediately into a brine circulation method to maintain the frozen condition. Two refrigerators with a capacity of 65,000 kcal per hour were used in this project over a period of 35 days, by which time the excavations were finished. In this case, if the conventional brine circulation method had been used throughout the whole working period, refrigerators with a total capacity of 260,000 kcal per hour and a working time of about 70 days or more might have been necessary.

(c) Some Considerations about Quick Freezing

As stated earlier, quick freezing is a more reliable method than the alluvial grouting technique as a temporary stabilization method for deep cuts. However, this method should be used only partially and on relatively small-scale projects because it is still too expensive to use on large-scale projects.

In the abovementioned "combined method", freezing times will be reduced to about 60 or 70% of the conventional brine circulation method, and the power of the refrigerators will also be reduced to about one half of the latter. Therefore, the combined method is suitable for relatively large-scale works. Although further cost analyses are necessary, it may be reduced to about 70 to 80% of the conventional method.

Liquefied Carbonic Acid is everywhere more easily available than is Liquid Nitrogen. Also, the piping system for the former is simpler and more economical than the latter, as shown earlier.

Heating losses of the entire freezing system will reach about 30 to 60% in general for freezing. Those resulting from the use of Liquefied Carbonic Acid will be lower but more detailed research related to the use of Liquefied Carbonic Acid is necessary.

Also, further investigations are necessary to ensure uniform gas-supply to each freezing pipe, and also a more precise method of measuring subsoil temperatures throughout the treatment, than the chromel-alumel thermocouples used.

IV. OTHER METHODS FOR TEMPORARY STABILIZATION

As stated earlier, the conventional grouting technique is not especially reliable for non-uniform Japanese soils. Grouts will often escape to the weak points, which consist of lenses, seams, natural or artificial cavities, including any existing old ducts or pipes, etc. Packers and other special techniques used in rock grouting usually cannot be employed in alluvial grouting. R.H. Karol has described the effectiveness of a method which uses a shorter gel time with a long pumping time to realize the greatest degree of uniformity of penetration in stratified deposits. In this case, the grout is forced later into the opening previously left in the least pervious stratum. However, this method is used only for single polymeric grouting fluids.

A new injection technique which aims at the formation of waterproof grouted walls or films has been developed by the use of pressures higher than those used in conventional grouting techniques. Pressures of about 100 to 250 kg/sq cm are used. Grouted walls formed by this method have a width of about 1.2 to 2.6 m between injection holes, and a thickness of about 0.15 to 0.25 m, but this varies according to soil conditions.

This method can be performed more simply as well as more speedily (and the formation of grouted walls by this method are achieved more accurately as well as more reliably) than with the conventional grouting technique, although some problems still remain unsolved.

An epoch-making new grouting method named "TACSS" has been developed in recent years in Japan. "TACSS" means "Takenaka Aqua-reactive Chemical Stabilization System". A single fluid is injected into the soil and reacts directly with pore water to form an hydrophobic and unhydrated gel. Another important feature of the TACSS system is that this chemical grout itself expands during reaction. This enables the chemical grout to actively penetrate into the soil and enlarge its permeation zone without being affected by the underground seepage flow. There have already been some practical applications in overcoming seepages which had very high pressures of about 50 to 60 kg/sq cm or more. This special kind of work has been performed mostly in deep coal mines almost 500 to 600 m below the ground surface.

Some recent examples of temporary stabilization have included the use of in-situ piles of quick lime to prevent the heaving of very soft cohesive soils in deep open cuts; utilizing the water absorbing, thermal, osmotic and chemical hardening effects of quick lime.

Although there are many temporary stabilization methods for slopes and cuts, the most reliable (and, furthermore, the most inexpensive method) is a dewatering technique which consists of the wellpoint system, Siemen's wells or ejector-wells used together with temporary timbering. In general, however, these wells will often cause a loosening of nearby or soft soil.

Apart from temporary stabilization, the so-called "underground continuous walls", termed "concrete diaphragms" in European countries, have been used for about 5 to 10 years. Combined with anchoring techniques as a substitute for temporary timbering, they can be used subsequently as permanent walls for basement or underground utilities.

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