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Properties of Frozen Granular Soils and Their Use in Dam Construction

Propriétés des sols granulaires gelés et leur utilisation dans la construction des barrages

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SUMMARY

The use of frozen soil as a construction material is a question of great economic importance, especially in regions where cold periods often occur during the favourable construction season. Although placement and compaction of frozen soils in earth structures involves many problems with regard to settlement and the stability of the structure, it seems possible in many cases to avoid the disadvantages without reducing the margin of safety. The first part of this paper deals with the mechanical properties of frozen granular soils. Investigations were performed in the Swedish State Power Board's laboratory in order to study different methods for compacting frozen soils in earth embankments. Tests for determining compressibility and shear-strength properties of those soils are also described. The second part of the paper contains experiences and results, obtained from field tests and measurements in the Board's dams, which now are being constructed in the northern part of Sweden. In these dams, ranging in height from 85 to 100 m, placement of frozen soils is permitted to a certain extent.

SOMMAIRE

L'utilisation de sols gelés comme matériaux de construction revêt une importance économique particulière, surtout dans les contrées où des périodes de froid peuvent se présenter durant la saison favorable à la construction. Quoique le déplacement et le compactage des sols gelés en vue de construction en terre impliquent bien des problèmes de tassement et de stabilité, il paraît possible en bien des cas d'éviter les inconvénients sans réduire la tolérance de sécurité. La première partie de ce rapport traite des propriétés mécaniques des sols granulaires gelés. La Direction de l'Energie Electrique a, dans son laboratoire, réalisé des expériences dans l'étude des différentes méthodes de compactage des sols gelés dans les barrages en terre. Des essais de détermination des propriétés de compressibilité et de résistance au cisaillement de ces sols y sont aussi décrits. La seconde partie du rapport contient des expériences et résultats obtenus par des essais et des mesures en chantier effectués sur les barrages appartenant à la Direction de l'Energie Electrique, et qui sont actuellement en cours de construction dans le nord de la Suède. Pour ces barrages, dont la hauteur varie de 65 à 100 m, on admet jusqu'à un certain point l'utilisation de sols gelés.

THE USE OF FROZEN SOILS as construction material in earth embankments involves many disadvantages with regard to settlement and stability conditions. There is no doubt that in many cases it may be necessary to prohibit the use of frozen materials, particularly in the more vital parts of the structure. On the other hand, there are many projects where the use of frozen soils permits a more economical construction without reducing the necessary quality requirements. Especially in regions where cold periods occur during the favourable construction season, it may often be possible to place frozen gravel or sand in such a manner that the disadvantages with regard to settlement and stability can be eliminated.

In connection with the construction of a number of large dams in the northern part of Sweden the State Power Board began investigation of the properties of frozen coarse-grained soils, particularly gravel and sand. The first dam, where placement of frozen gravel was permitted to a certain extent, was the Messaure Dam, having a height of 100 m (Bernell, 1964). The experience thus obtained is being applied on two other dams, Seitevare and Letsi, having heights of 100 and 85 m respectively. For these dams provisions are made for using frozen soils as part of the fill.

COMPACTION PROPERTIES

In frozen soils a considerable part of the voids is occupied by ice and unfrozen water. Because of the cementation effect of ice, frozen coarse-grained soils exhibit cohesion. This property depends not only on the composition of the soil and

its moisture content but also on the structure and temperature of the ice. It is of great practical importance that a process of loading or vibrating on a frozen soil causes thawing of the ice shells which surround the soil particles. This effect is to a large extent dependent on the time rate at which the loading or vibrating takes place. Therefore, in all problems concerning the physical properties of frozen granular soils the time effect must be considered.

From experiments made by the Swedish State Power Board during the construction of the Messaure Dam, it was found

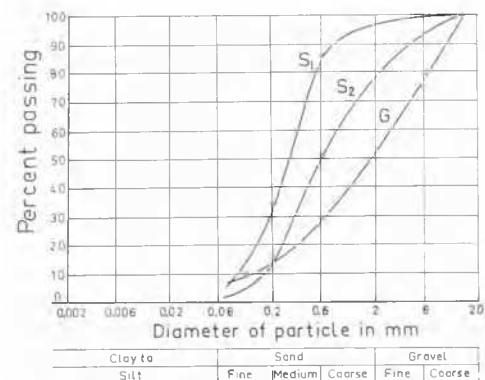


FIG. 1. Gradation of test materials. S_1 = sand, transition material from Messaure. S_2 = sand, filter material from Seitevare. G = gravel, shoulder material from Messaure.

that heavy vibrating equipment was most suitable for compacting frozen granular soils. For a given soil the effect of the equipment was essentially dependent on two factors, the water content of the soil and the duration of the vibrating process. The influence of these two factors on the degree of compaction has been investigated in the Board's laboratory.

Fig. 1 shows the gradation curves for two sandy soils, S_1 and S_2 , and a gravel material G. The soils S_1 and G were used as construction materials in the Messaure Dam; sand S_2 is to be used as filter material in the Seitevare Dam. In order to determine the most effective compaction equipment for these soils, they were tested in the laboratory with regard to their compaction properties in both the unfrozen and the frozen conditions. The compaction tests were carried out by vibrating normally loaded samples, as described below.

For each soil the tests were made in two series on representative material, passing the 16-mm sieve. In the first series only unfrozen material was used. After preparation the soil was placed in two layers in a cylinder, attached to a vibrating table. Each layer was lightly compacted first with a tamper; then a surcharge was applied, giving a normal pressure of 2 kg/sq.cm. In order to investigate the effect of vibrating, the dry density for samples having the same water content was determined after 1, 2, and 4 minutes. The second test series was carried out on material which had been stored at a temperature of -10°C before testing. In order to obtain a uniform distribution of the water content, the material had been continuously mixed and sprinkled with water during freezing. The testing procedure was the same as described above, except that vibrating was performed at a constant temperature of -10°C .

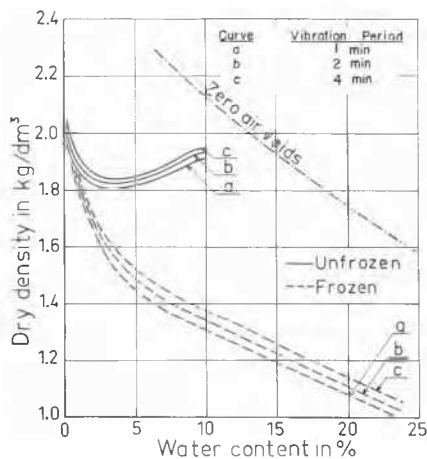


FIG. 2. Compaction tests on frozen and unfrozen sand S_2 .

The results from the compaction tests on sand S_2 are shown in Fig. 2. For unfrozen material the maximum dry density increased from 1.90 to 1.95 kg/cu.dm., when the vibration period was increased from 1 to 4 min. For the different samples the corresponding optimum water content varied within the limits 9–10 per cent.

The results from the second test series, performed on frozen samples, showed that the moisture content had a decisive influence on the dry density. If the moisture content was greater than 1–2 per cent, the dry density after compaction became less than the minimum value that was obtained in the first series on unfrozen material. If the moisture content exceeded about 6 per cent, the shape of the compaction curve became approximately an inclined straight line.

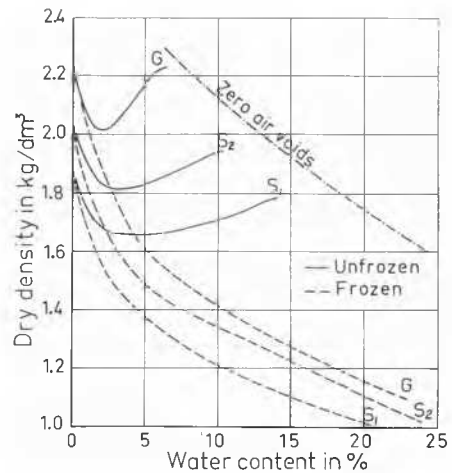


FIG. 3. Compaction curves for vibrated unfrozen and frozen soils. Gradation curves, see Fig. 1.

Similar results were also obtained for sand S_1 and gravel G. Although experience had shown that sand S_1 could not suitably be placed in the dam in frozen condition, it was tested in order to determine the influence of the finest fractions. For comparison, the compaction curves for the three tested soils are illustrated in Fig. 3. The curves correspond to a vibrating period of 2 min. for each layer and a surcharge of 2 kg/sq.cm. From these curves it is seen that the influence of vibrating on the dry density is much more significant when the soil is in unfrozen condition than when it is frozen. It is of great practical importance that the moisture content in a frozen soil must be less than 1 per cent, if the required density should be equal to the maximum value that can be obtained for the same material in unfrozen condition.

For comparison unfrozen material from each soil was also tested in accordance with the modified Proctor method. In Table I the values of dry density γ_d and Proctor optimum water content w_0 are given for the different soils. From the results in Table I, it is seen that the maximum density γ_{max} and the optimum water content w , obtained on unfrozen soils in the vibrating tests, agreed well with the Proctor values. Vibrating tests on frozen soils, containing a water content w , resulted in very low values of the dry density γ_f . For the different soils γ_f varied from 62 to 69 per cent of the maximum value γ_{max} .

TABLE I. COMPACTION TESTS ON UNFROZEN AND FROZEN SOIL

Test material	Modified Proctor test, unfrozen soil		Vibrating test			
	γ_d (kg/cu. dm.)	w_0 (per cent)	Unfrozen soil γ_{max} (kg/cu. dm.)	Unfrozen soil w (per cent)	Frozen soil γ_f (kg/cu. dm.)	γ_f/γ_{max} (per cent)
Sand S_1	1.80	12	1.79	14	1.12	63
Sand S_2	1.96	10	1.95	10	1.34	69
Gravel G	2.23	6	2.23	7	1.52	68

The results from the compaction tests show that the water content has a decisive influence on the dry density of frozen granular soils and that the gradation of the soil is less important. Both sand and gravel can be properly compacted, provided the moisture content is very low.

SHEAR-STRENGTH PROPERTIES

Investigations, made by Tsytoich (1941) and Vialov and Skibitsky (1955), show that the shear strength of frozen soils depends on a number of factors associated with the structure and the physical properties of ice. The most important factor, however, is the cohesion effect. Because of the plastic and rheological properties of ice, the strength of frozen soils varies considerably under the effect of a constant external pressure. Therefore, in problems concerning the shear strength it must be taken into account that the instantaneous strength may be several times greater than the continuous value. In most practical problems the continuous strength is of greatest interest. But if frozen soils are used as construction material in earth embankments, the instantaneous strength must also be considered. In the Board's laboratory drained triaxial shear tests are carried out in order to determine the instantaneous shear strength and its variation with the soil temperature.

The investigations were made on gravel G, the gradation of which is shown in Fig. 1. Material, passing the 16-mm sieve, was dried and stored at various temperatures less than 0 C. During storing the gravel was mixed with water so that a moisture content of 3 per cent was obtained. After freezing the material was placed in cylinders and each sample was vibrated to the same density, 1.8 kg/cu.dm. In order to determine the influence of soil temperature, the tests were performed at various temperatures less than 0 C. During testing the temperature in each sample was kept constant. The cell pressures used were 3, 6, and 9 kg/sq.cm. Each sample was loaded at a rate of 3 kg/sq.cm. per minute and the test was continued until the deviator stress remained approximately constant, indicating plastic failure.

In Fig. 4 the deviator stress $\sigma_1 - \sigma_3$ at failure is plotted

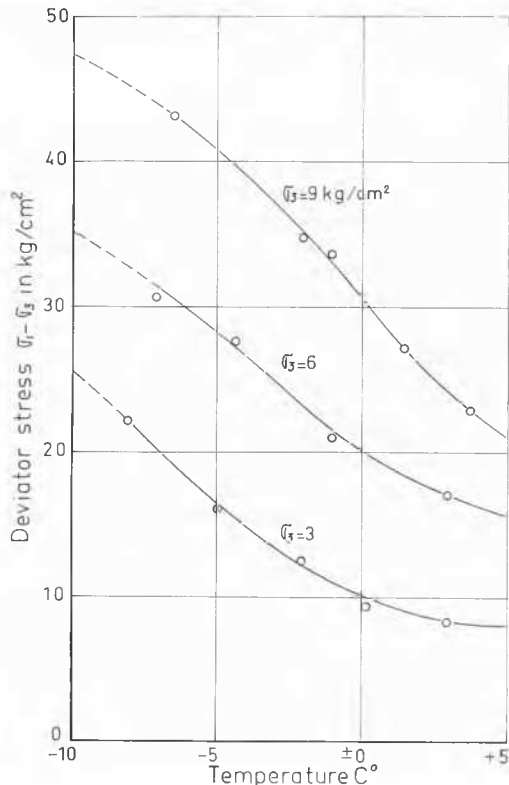


FIG. 4. Frozen gravel G. Influence of temperature on maximum deviator stress at failure.

against temperature for a number of tests at each cell pressure. The values of $\sigma_1 - \sigma_3$ correspond to an axial strain of 10 per cent. From the curves in Fig. 4 it is seen that at temperatures less than 0 C the deviator stress increases considerably with decreasing temperature. In the temperature range between 0 to -10 C the increase of deviator stress is approximately proportional to the decrease in temperature.

Investigations have shown that the instantaneous shear strength τ_f of frozen granular soils is determined by the expression:

$$\tau_f = c_t + \sigma \cdot \tan \varphi_t \quad (1)$$

where the parameters c_t and φ_t vary with temperature. For gravel G, used in the shear tests, the influence of temperature is shown in Fig. 5.

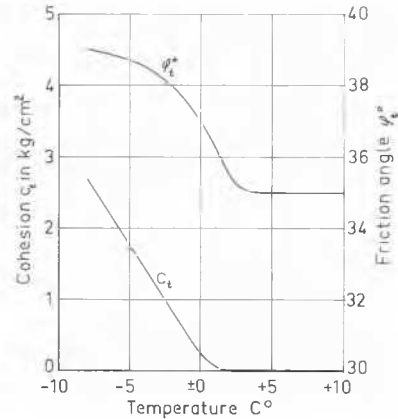


FIG. 5. Influence of temperature on shear strength parameters c_t and φ_t .

Generally the application of Eq 1 to the stability calculations of winter fills leads to an overestimation of the stability. Because of the time effect, the instantaneous strength decreases to an ultimate value which can be determined by performing long-term tests.

COMPRESSIBILITY PROPERTIES

In frozen soils, subjected to a constant load, a large part of the settlement occurs as a result of partial thawing of the ice shells which surround the grains. For a given soil the magnitude of these settlements depends both on the physical properties of the ice and on the density of the soil, obtained after compaction. In most cases, however, it is of greater interest to know the magnitude of the primary settlements developing during the thawing periods. These settlements follow the fluctuations of the soil temperature and are also associated with secondary settlements, caused by unsatisfactory compaction of the material.

Because of the plasticity of ice, the compressibility of a frozen soil varies considerably with time of loading. Therefore, if a granular soil is subjected to a constant normal pressure, the relationship between compressibility and settlement is rather complicated. In the Board's laboratory the compressibility properties of frozen sand and gravel have been studied and the results thus obtained are compared with test results from the same soils in unfrozen condition. The following tests were carried out on gravel G (see Fig. 1) in order to determine the variation of the compressibility with time of loading.

For both unfrozen and frozen samples, the moisture content at compaction was 3 per cent and the dry density after

vibrating equal to 1.8 kg/cu.dm. During testing the temperature of the frozen samples was kept constant at -10°C . In Fig. 6 the full line a shows the relation between void ratio and compressibility for unfrozen samples. The results of similar tests, performed on frozen samples, are represented by the dash line b. If the process of loading is interrupted,

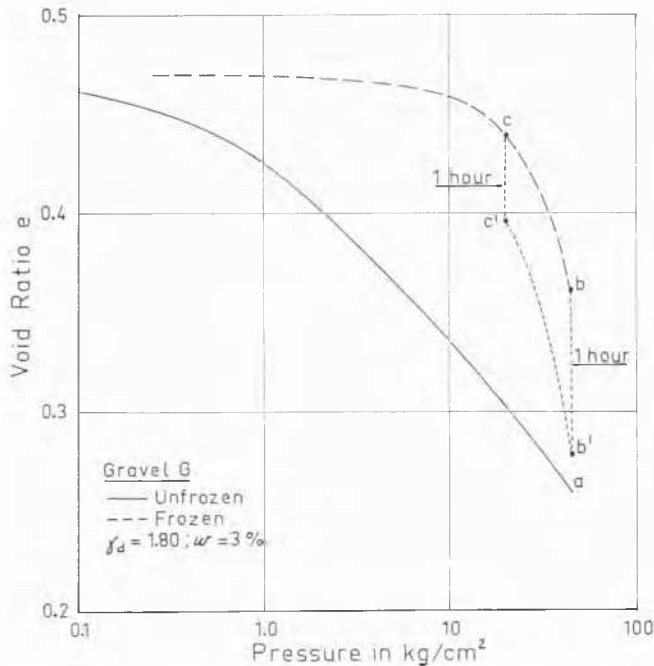


FIG. 6. Compression tests on unfrozen and frozen gravel G.

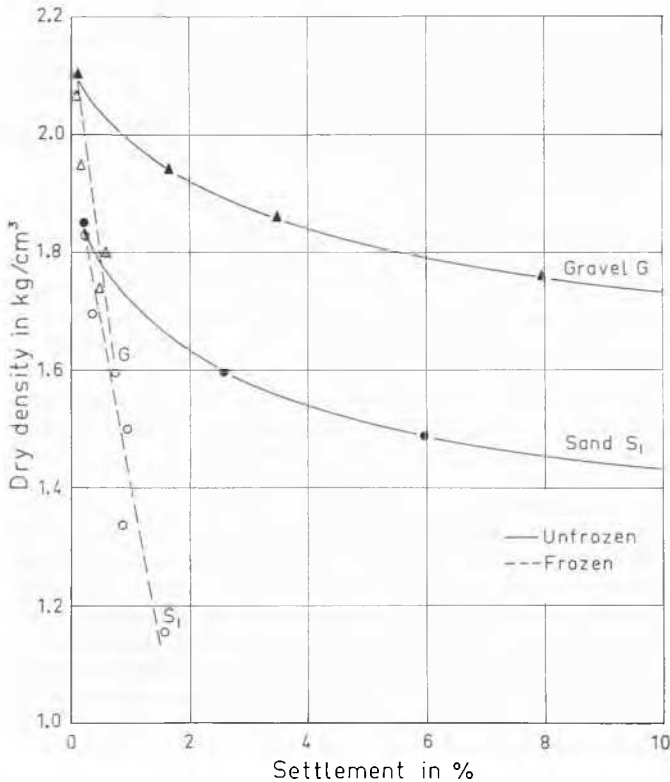


FIG. 7. Relation between dry density and settlement for unfrozen and frozen samples, subjected to a constant normal pressure of 3 kg/sq.cm.

the void ratio decreases rapidly at constant load, as indicated by the vertical step $c-c'$. At increasing pressure the slope of the curve $c'-b'$ increases at a rapid rate and merges into the curve that would have been obtained for unfrozen material.

For soils, having a moisture content greater than 3 per cent, a rapid decrease of the void ratio was also found when the pressure exceeded 10 kg/sq.cm. However, in order to obtain a satisfactory compaction of frozen soils, it is necessary to use material having a very low moisture content. Generally the degree of compaction must be specified with regard to the settlements that can be permitted from thawing of the material. The following tests were carried out on sand S_1 and gravel G (see Fig. 1) in order to determine the differential settlements developing in the soils during thawing.

The samples, containing frozen material with a temperature of -10°C , were compacted to various densities. Each sample was subjected to a constant normal pressure of 3 kg/sq.cm. The temperature was kept constant at -10°C for 1 hour and thereafter the temperature was slowly increased to $+5^{\circ}\text{C}$. In Fig. 7 the dash lines show the relation between dry density and settlement for frozen samples after loading for one hour. The full lines represent the total settlements for the different samples after thawing during a sufficiently long time.

From the tests it is found that the settlement of a frozen soil, subjected to a constant pressure, increases slowly with decreasing density of the compacted soil. This relation seems to be fairly independent of the grain size distribution. The results also show that for dense compacted soils the thawing process is associated with relatively small settlements. On the other hand, from the curves in Fig. 7 it is also seen that the settlements increase rapidly with decreasing density. Since the moisture content has a decisive influence on the density, the result leads to the conclusion that the magnitude of the settlements, developing during the thawing periods, is determined mainly by the amount of ice and water mixed in the frozen material during compaction.

THE USE OF FROZEN SOILS IN DAM CONSTRUCTION

According to the Board's specifications (Bernell, 1964), placement of frozen granular soils is permitted only in those parts of the shoulder fills where they will not present any serious disadvantages with regard to future settlements and stability conditions. In order to avoid subsequent settlements, the height of winter-placed fill is restricted and must be low enough that the frost can disappear during the following summer period. In order to control the temperature conditions in the fill, temperature measuring devices are placed during construction. The results of such measurements, made in dams in the northern part of Sweden, show that the height of a fill of frozen gravel must be less than five metres if the development of permafrost conditions is to be avoided.

In connection with the construction of the Messaure Dam, different methods for compacting frozen granular soils were investigated. Field tests were made on frozen gravel G (see Fig. 1) and for comparison similar tests were also carried out on the same gravel in unfrozen condition. The material was placed in 30-cm layers and each layer was compacted by four to eight passes of the equipment. In the test series the compaction effect of the following equipment was investigated: Caterpillar D 8, vibrating sheepsfoot roller, weight 4.1 tons, and vibrating roller, weight 3 tons. From the tests it was found that the sheepsfoot roller was the most suitable. For gravel, having a moisture content of 2–3 per cent, the degree of compaction after four passes became 80–85 per

cent of the modified Proctor value, determined on unfrozen soil. After liberal watering of the fill during the summer period, the density increased to 90 per cent of the maximum Proctor value.

Other investigations have shown that the temperature conditions have a great influence on the compaction results, if the natural moisture content of the soil exceeds about 3 per cent. This information is in accordance with results obtained from laboratory investigations. Therefore, if gravel is to be placed and compacted in frozen condition, the moisture content must be very low.

In the Board's dams the main part of winter-placed material consists of rockfill. Also for such material the permissible height is restricted with regard to the temperature conditions. The specifications also prescribe that winter-placed rockfill should be liberally sluiced before placement of summer fill commences. Experience has shown that the best method for minimizing the settlements is to concentrate gravel fill in the bottom layers and thereafter proceed with rockfill during the coldest winter months. When the rockfill is sluiced in the spring, the bottom layers become saturated. Sluicing facilitates the thawing process and also eliminates the risk of long-term settlements in the bottom layers.

The use of frozen gravel and rockfill as construction material in dams involves many problems of design and construction. But the difficulties must be weighed against the advantages obtained. Even a restricted use of frozen material permits better planning of the work and more economical dam construction in areas with adverse climatic conditions.

REFERENCES

- BERNELL, L. (1964). Measurements in the Messaure Dam, a rockfill structure with wet-compacted moraine core. *Trans. Eighth International Congress on Large Dams*, Vol. 2, pp. 317-33.
- (1964). Placement of rockfill under winter conditions. *Trans. Eighth International Congress on Large Dams*, Vol. 3, pp. 671-7.
- TSYTOVICH, N. A. (1957). The fundamentals of frozen ground mechanics (new investigations). *Proc. Fourth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 116-19.
- VIALOV, S. S., and A. M. SKIBITSKY (1957). Rheological processes in frozen soils and dense clays. *Proc. Fourth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 120-4.