THE GEOTECHNICAL ASPECTS OF MORAINE

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Abstract. Many geotechnical problems are connected with the construction of highways, earth dams, buildings and other structures in or on moraine[1] (till), as discussed at a symposium arranged by the Swedish Geotechnical Society (1970 *a*). Especially the densely compacted basal or lodgement tills (Swedish *bottenmorän, pinnmo*) cause major difficulties. It is, for example, often difficult to drive even heavily reinforced concrete piles into or through a layer of even loose till without breaking the piles, if boulders are present in the soil or the relative density is high, as is the case in a basal till. Such construction problems are common, since moraine covers approx. 75 % of the total area of Sweden. Furthermore, the methods used at present to determine the geotechnical properties of till *in situ* or in the laboratory are uncertain and expensive. The contact pressures which are allowed for spread footings or caissons on till are very low, partly because of the often large variations of soil properties which occur within the construction site. The differential settlements are frequently for moraines of the same magnitude as the maximum settlement. The excavation of till is generally very time-consuming and expensive, especially under water.

Till is generally an excellent foundation material. Its bearing capacity is, as a rule, very high. The deformations are generally small, even at relatively high load levels.

Some aspects of the classification of tills and the excavation and compaction of till when used as a construction material are reviewed below. It should, however, be pointed out that relatively little is known about the physical properties of till in comparison with such soils as clay, silt, sand and gravel. Some information on the geotechnical properties of till has been presented by Bernell (1957, 1970), Linell and Shea (1960), Jäckli (1962), Mitchell (1963), Gillberg (1965), Sauer and Monismith (1968), Lundqvist (1970) and Theill (1971).

[1]The term "moraine" has here been used as a synonym for till. Moraine is, however, a geological formation rather than a soil material like till.

CLASSIFICATION OF MORAINES

An attempt is being made at present to co-ordinate the different building codes in Sweden, Norway, Denmark and Finland. The implications of such a co-ordination for the classification of tills have been discussed by the Committee on Laboratory Testing of the Swedish Geotechnical Society. The Committee has proposed that the term "silt" should be introduced as a collective name for the frost-active soils, in agreement with the international use of this word. Silt will thus replace the Swedish *mjäla* and *finmo* (grain size 0.002—0.06 mm). If this proposal is accepted, the terms coarse silt (*grovsilt*), middle silt (*mellansilt*), and fine silt (*finsilt*) will replace the present terms fine mo (*finmo*), coarse mjäla (*grovmjäla*), and fine mjäla (*finmjäla*). The Committee furthermore proposes that the limiting grain size between the stone and the gravel fractions should be changed from 20 mm to 60 mm and the limiting grain size between the boulder and the stone fractions from 200 mm to 600 mm. The proposed changes have been justified by the fact that the proposed particle sizes agree better with the common use of the terms "boulder" and "stone" than the present diameters.

The proposed changes will also affect the classification of moraines. The Committee has proposed that tills should be divided into the following four main groups:

1. Rocky and stony tills (*block- och stenmoräner*) with a boulder and stone content exceeding 40 %.
2. Coarse-grained tills (*grovkorniga moräner*) with a boulder and stone conent of less than 40 % and a silt and clay content of less than 15 %.
3. Fine-grained tills (*finkorniga moräner*) with a combined silt and clay content exceeding 40 %.
4. Mixed-grained tills (*blandkorniga moräner*) with a boulder and stone content of less than 40 % and a combined silt and clay content of between 15 and 40 %.

The term clay till (*moränlera*) should, according to the Committee, only be used when the clay content of the combined silt and clay fractions exceeds 20 %. The parent material of clay till is generally shale or limestone.

The proposed changes of the fraction limits have been criticized, primarily because the meanings of the original terms "stone" and "boulder" will be changed and this will cause confusion if entirely new names are not introduced. It will be necessary to define these terms each time they are used, at least during a transitional period, if the fraction limits are changed without a corresponding change of the names of the fractions. (It has been suggested that the terms "new sand" (*nysand*), "new gravel" (*nygrus*), "new stone" (*nysten*) and "new boulder" (*nyblock*) should be introduced temporarily, in order to eliminate this difficulty.) The introduction of the term "silt" has not been criticized as severely, since an entirely new word has been proposed. The risk of mistakes is relatively small in comparison with that caused by a change of the fraction limits without a corresponding change of the name.

SOIL EXPLORATION

The geotechnical properties of till and thus the soil-exploration program are dependent on the parent material and on the distance the material has been carried by the ice during the glaciation. For example, the boulder content of tills originating from shales, sandstones and limestones is generally very low. Boulders are almost entirely lacking in the clay tills found in Jämtland and in Skåne. These clays are sedimentary deposits which have been re-worked by the ice. The boulder content generally decreases, while the silt and clay contents of tills increase with increasing distance from the source of the transported material.

The boulder content of a moraine deposit can in some cases be evaluated from the number of boulders which can be seen on the surface. However, the evaluation may be misleading, since the character of the till and the boulder content can vary with depth.

The exploration of till is generally very time-consuming and expensive. Especially the sampling of till is difficult, as was pointed out at a symposium arranged by the Swedish Geotechnical Society (1970 *c*). The sampling of clay till has been discussed by Nyman (1970).

The seismic-refraction method is frequently used in the exploratory phase, in order to get an indication of the layer sequence, if any, of a moraine deposit and the depth to the bedrock. In addition, the relative density of till and the location of the ground-water table can sometimes be estimated from the seismic velocity. It should, however, be noted that the seismic velocity of a till is affected by the grain-size distribution, by the relative density and by the degree of saturation and thus by the location of the ground-water table. The interpretation of seismic records is therefore difficult and uncertain. The application of the seismic-refraction method to geotechnical problems has been discussed at a symposium organized by the Swedish Geotechnical Society (1970 *b*).

The dry unit weight of till varies with the relative compaction. Loose till has generally a density of less than 1.7 t/m^3, while for dense till the dry unit weight is 1.9 to 2.1 t/m^3. If the dry unit weight exceeds 2.1 t/m^3, the relative density is said to be very high (Helenelund, 1970; Korhonen and Gardemeister, 1972).

It is generally not possible to determine a suitable foundation depth for footings or bridge abutments from seismic records alone. Nor has it up to now been possible to estimate the stone and boulder content of tills. A seismic investigation is therefore generally supplemented by soundings, sampling, test pits and test trenches.

Penetrometers, such as the Swedish weight and ram penetrometers, are in some cases used in Sweden to determine the suitable foundation depth of spread footings and of bridge abutments in till. The Swedish weight sounding method is sometimes used in loose till. In this method, a standardized screw-shaped, conical, steel point is forced down into the ground. The penetrometer is loaded axially by a number of weights with a total mass of 100 kg. The penetration resistance is determined by counting the number of half-turns required for every 20 cm of penetration of the point. The relative density is often judged to be low when the penetration resistance is less than 5 half-turns/20 cm penetration, to be medium between 5 and 15 half-turns/20 cm penetration and to be high when the penetration resistance exceeds 15 half-turns/20 cm penetration. The depth below the ground surface is also of importance for the interpretation of the test data, because of friction along the sounding rod and the effect of the overburden pressure on the measured penetration resistance.

The main disadvantage of the weight penetrometer is that the penetration depth is small in till. Especially dense tills are difficult to penetrate. Nor is it possible to penetrate stony tills or tills containing boulders. A possible indication of the stone or boulder content is the variation of the maximum penetration depth between different borings.

The Swedish ram sounding method is in some cases used to explore moraine. In this sounding method, a circular point is driven by a 63.5-kg hammer with 50 cm of free fall. The number of blow required to drive the penetrometer every 20 cm is counted. The relative density is considered loose, medium or dense, respectively, when the penetration resistance is less than 3 blows/20 cm penetration, between 3 and 10 blows/20 cm penetration or greater than 10 blows/20 cm penetration. The maximum penetration depth is considerably greater for the ram penetrometer than for the weight penetrometer. However, even the ram penetrometer is in most cases too light, especially when the soil contains stones and boulders and it generally cannot penetrate dense till (basal till). In Finland a heavier ram penetrometer has been developed. The mass of the hammer has been increased to 70 kg and the height of fall to 1.0 m. Even with this penetrometer it is difficult to penetrate dense to very dense till.

Hand-operated drilling machines of the Pionjär, Cobra and Wacker types are sometimes used to explore moraine deposits and the depth to bedrock. The time in seconds which is required for every 20 cm of penetration is recorded. The penetration rate is, however, dependent to a large extent on the condition of the machine, on the drilling depth and on the soil conditions. The interpretation of the driving records is very uncertain. The hand-operated drilling machines are primarily used to determine the minimum depth to the bedrock (the rock-free depth).

Hammer drills (*kedjematare*) are used extensively in moraine to determine the depth to bedrock and to get a rough estimate of the boulder content and of the relative density of the soil. By measuring the time required for every 20 cm of penetration, it is possible to estimate the number of boulders and the bedrock surface at the location of the borehole. The boreholes should, however, be extended at least 2 m into the assumed bedrock, since this "bedrock" surface may be a large boulder. Hammer drilling is sometimes combined with the acoustic method developed by Scandia-consult (Lundström and Stenberg, 1965). With this method a microphone is placed in the bedrock at the bottom of the borehole or on a rock outcrop, as illustrated in Fig. 1. By analysing the noise level at different frequencies, it is possible to determine whether a boulder or solid rock has been encountered. The noise pattern is entirely different in the two cases.

Rotary drilling by the Lindö, Exler, Alvik, JB, Duplex or Tiltex methods is sometimes used to estimate the stone and boulder contents and the depth to bedrock. A relatively large number of borings is, however, required, in order to make the determinations reliable. Rotary drilling is often time-consuming and therefore expensive.

The most accurate method of determining the boulder content and the boulder size, as well as the layer sequence, the density of the soil and other geotechnical properties, is with test cuts or test pits, using power shovels or tractors. The boulder content is determined by counting the number of boulders removed and by measuring their dimensions.

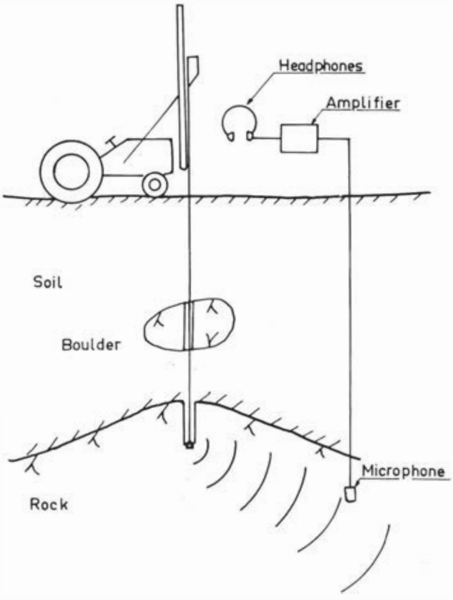

Fig. 1. Scandia-consult rock indicator (after Lundström and Stenberg, 1965).

The relative density of till can sometimes be determined directly in the field by the water-volumeter or by the sand-cone methods, if the boulder or stone content is low. In some cases also the radiometric (gamma-ray) method can be used. There is a lack at present of simple tools which can be used *in situ* to check the relative density or the compaction of till at the bottom of a shaft or of an excavation. It is possible that the density can be checked by measuring with an accelerometer the retardation when a free-falling weight strikes the bottom of the excavation.

The undrained shear strength of glacial-clay till (*moränlera*) is often determined by field-vane tests, by unconfined compression tests, or by undrained triaxial tests at a confining pressure equal to the total overburden pressure. Also load tests on plates with diameters of 5 to 15 cm have been used.

Moust Jacobsen (1967) found that the shear strength, as determined by plate load tests, was approximately 90 % of the vane-strength values. The average shear strength determined from unconfined or undrained triaxial tests was 40 % of the vane strength, when the height of the samples was twice the diameter and 93 % of the vane strength when the sample height was equal to the sample diameter. The shear strength was found to be independent of the direction of the failure plane.

Moust Jacobsen (1970*a*) has also pointed out the importance of a stiff testing machine when the deformation properties of a heavily over-consolidated clay till are being investigated.

EXCAVATION OF MORAINE

The total annual cost (1972) of the excavation of soils in Sweden is estimated to be about 750 million Sw. crowns. The annual excavation cost for sewers and water lines alone is about 100 million Sw. crowns. A large part of these costs is for the excavation of till.

The rippability of till is mainly dependent on the variations of the grain-size distribution can have appreciable effects. Clay till can, as a rule, be excavated inexpensively and without difficulty with relatively light equipment, while basal till is frequently extremely difficult to excavate, especially below the ground-water table. Blasting is sometimes required to loosen the soil.

The rippability of till is mainly dependent on the boulder content. There also seems to be a correlation between the rippability and the seismic velocity (Thurner, 1971).

The excavation costs for till vary in general with depth and with the boulder content. Till located close to the ground surface is generally loose and can be excavated without difficulty down to a depth of 0.5 to 1 m, even with relatively light power shovels. A medium-dense, stony till is often found below this surface layer with a silt content which is generally higher than that of the overlying surface layer. Dense to very dense basal till is generally found just above the bedrock. Thus the difficulties in excavating a till cannot be evaluated, as a rule, from the properties of the surface layer.

The soil-classification system which is still in use in Sweden was developed as early as 1956 (STF, 1959). This system is based on the tools which were used when excavation was done primarily by hand. Therefore the classification system cannot be used directly to predict the capacity of modern, heavy, power shovels (Fig. 2) or bulldozers. In this system, soils are classified in four major groups (A, B, C and D). Tills belong to groups B, C or D. Loose tills which can be loosened with a spade are placed in group B, while hard tills, in which a crowbar or a pickaxe is required to loosen the soil belong to group C. Hard Till, in which blasting is required to loosen the soil, is classified in group D. The system has been criticized because it is not detailed enough. The variation of the properties of the soils which belong to either group C or group D are too large to give a reliable indication of the excavation costs or of suitable equipment. This system is, furthermore, not entirely objective, since the classification is dependent on the person actually handling the spade, the pickaxe or the crowbar.

At present, the Swedish National Road Board is investigating the diggability of soils, especially of tills. Considerable progress in this area can thus be expected in the near future. Also the Swedish Transport Research Commission (TFK, 1966) has taken up the classification of soils with respect to diggability.

The seismic velocity has been used extensively in the United States as an index of rippability. Church (1965) has reported a relationship between the seismic velocity and the excavation costs and suitable excavation methods.

A new classification system has been developed in Finland which relates diggability to the physical properties (Korhonen *et al.,* 1971; Korhonen and Gardemeister, 1972). This classification system purposely does not take into account the influence of the ground-water level, frost, topography, working conditions, skill of the workers or seasonal changes. In this Finnish system, soils are divided with respect to their diggability into the following four soil groups: organic soils (E), fine-grained soils (H), coarse-grained soils (K) and tills (M), as shown in Table 1. Each group has three different classes (1, 2 and 3). The excavation difficulties and the costs increase in general from E to M and with increasing index number. Tills are divided into the classes M1, M2 and M3. Class M1 includes loose stoneless or stony tills which contain only a few boulders. The stoneless or stony tills with normal density and low boulder content are placed in class M2. Class M3 includes the dense or cemented tills, as well as stony tills. The stone content (grain size 60 to 600 mm)

Fig. 2. Excavation of till with power shovel.

Table 1. Classification of soils with respect to diggability (after Korhonen and Gardemeister, 1972).

Soil group	Diggability class	Soils	Swedish weight sounding method, penetration resistance	Swedish ram sounding method, blows/m	Seismic velocity	
					Above ground water-level, m/s	Below ground water-level, m/s
E	E1	Ooze, mud	< 0.5 kN			
	E2	Peat	< 0.5 kN			
	E3	Peat	< 0.5 kN			
H	H1	Clays	< 1 kN			1100–1500
	H2	Silts	< 150 half-turns/m			1100–1500
	H3	Dry crusts	> 10 half-turns/m		< 300	
K	K1	Sand	> 50 half-turns/m	> 50	200–500	1200–1600
	K2	Gravel	> 50 half-turns/m	> 50	400–800	1500–1800
	K3	Boulder soils or stony soils	—	—	500–1100	1600–1900
M	M1	Loose stoneless or stony till	—	< 300	700–1000	1600–1900
	M2	Medium dense stoneless or stony till	—	300–700	800–1400	1800–2000
	M3	Dense till	—	> 700	1200–1600	2000–2300
		Very stony till	—	(> 400)	1200–1600	2000–2300
		Till with boulders or an abundance of boulders or rocky soil	—	—	1200–1600	2000–2300

of these tills frequently exceeds 40 to 50 %. The stone content is less than 10 % for "stone-free" tills, between 10 and 30 % for stony tills and larger than 30 % for very stony tills. The boulder (> 600 mm) content is in the same way less than 10 % for boulder-free tills, between 10 and 30 % for bouldery tills and larger than 30 % for very bouldery tills. The unit weight in this Finnish system is less than 1.9 t/m^3 for loose till, between 1.9 and 2.1 t/m^3 for medium-dense till and larger than 2.1 t/m^3 for dense till.

In the Finnish system, the diggability can be estimated from penetration tests and from the seismic velocity, as indicated in Table 1.

CONSTRUCTION DIFFICULTIES IN MORAINES

Large boulders cause major difficulties during the sinking of caissons and during the driving of casing for piers. Small boulders inside the casing can often be lifted with a grab. Blasting is generally required when the boulders are large. Boulders may also be a problem during the excavation of slurry trench walls. The hard granite boulders are difficult to fracture, even with large chisels. They cause extensive wear of the cutting edges of the chisels and contribute appreciably to the often high costs for the excavation of slurry trench walls. If the boulders are embedded in loose sand or silt, they are frequently pushed down by the chisels into the underlying soil without being fractured.

Boulders and stones also cause considerable difficulties during the driving of sheet piles, due to fracture of the locks and bending of the sheet piles. It is generally not possible to drive even heavy sheet piles more than a few tenths of a metre into dense till (basal till). In a stability analysis, a sheet-pile wall is often assumed to be anchored at the toe by a row of steel dowels.

The dowels which are drilled into the underlying rock (as shown in Fig. 3*a*) are assumed to resist the lateral earth pressures acting on the lower part of the wall. If the piles cannot be driven down to bedrock, as is frequently the case in basal till, and there is a space between the sheet piles and the underlying rock surface, the dowels will be subjected to a very high bending moment and may deform and break. An additional row of tiebacks may then be required to prevent toe failure, as illustrated in Fig. 3*b*.

The inclined tiebacks cause, however, an increase of the axial force in the sheet-pile wall which theoretically is equal to the total lateral earth pressure acting on the wall when the inclination of the ties is 45°. If the pene-

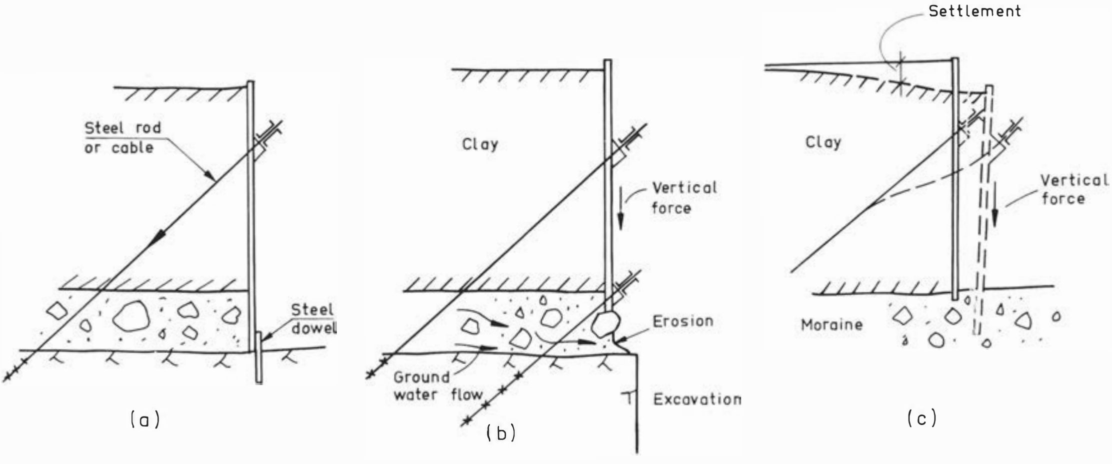

Fig. 3. Construction problems for sheet-pile walls in moraine.

tration resistance of the sheet-pile wall is too small at the toe, the wall will settle, as shown in Fig. 3*c*. Due to the inclination of the tiebacks, the wall will also move laterally. When tiebacks are inclined at 45°, the lateral displacement of the wall at the level of the tiebacks will be the same as the settlement of the wall. The lateral displacement may cause settlements behind the wall to a distance approximately corresponding to the depth of the excavation. As a result, adjacent structures may be damaged. If the dowels are replaced by tiebacks, there will be a further increase of the axial force in the sheet-pile wall and a further increase of the settlements. Erosion at the toe of a sheet-pile wall due to the flow of ground water may also contribute to settlements and to the lateral displacement of the wall, as illustrated in Fig. 3*b*.

Sheet-pile walls in till are frequently constructed of vertical or inclined soldier beams, which are placed in pre-drilled holes. The soldier beams may consist of H-beams, channels or rails, as shown in Fig. 4, which are held in place by wales and tiebacks. Wooden boards are placed between the vertical soldier beams as the soil is excavated in front of the wall. The boards are wedged against the soil to decrease the settlements behind the wall. When boards are not used, the exposed surface can be gunited, so that a concrete shell is formed between the soldier beams. The shell is generally reinforced by a steel net. Above the ground-water table, the exposed soil surface between the soldier beams can often be left unsupported.

It is often difficult to drive piles in tills with boulders. The piles are frequently ruptured when a boulder is encountered. Especially the driving of prestressed concrete piles is affected by boulders, since this pile type is relatively brittle. It is generally possible to decrease the number of broken piles by increasing the longitudinal reinforcement in the lower part of the pile or by providing the piles with rock shoes. Some piles should have inspection pipes, so that their straightness after the driving can be checked with a tell-tale or with an inclinometer.

BEARING CAPACITY OF MORAINE

The ultimate bearing capacity and the geotechnical properties of tills, such as shear strength, compressibility and permeability, are to a large extent dependent on the silt and clay content. The allowable bearing pressure for spread footings, rafts and cast-in-place concrete piles or caissons in dense basal till (*bottenmorän*) is limited by the 1967 Swedish Building Code (BABS, 1967) to 0.4 or 1.0 MN/m^2, depending on the properties of the till.

The text on till in the code is very brief. The present text is about the same as that included in the 1958 Code. The brevity reflects the lack of knowledge of the properties and behaviour of till under load and the lack of suitable field and laboratory equipment for the testing of tills with stones and boulders. The allowable bearing pressure for other types, except basal till, is the same as for gravel, sand or silt depending on the relative density and the composition of the till. The allowable bearing pressure σ_m for this type of till may be calculated from the equation

$$\sigma_m = BN\,(1-B/3L),$$

where B is the width, L is the length of the footing in metres, and N is a coefficient which is dependent on the relative density of the till and on the location of the ground-water table. The bearing pressure is limited to 0.6 MN/m^2 for a gravelly till and to 0.5 or 0.3 MN/m^2 for a sandy till when the relative density is high and low, respectively.

The allowable bearing capacity of a clay till when the footing is located close to the ground surface may be calculated for $D/B \leqslant 2.5$ from the following equation

$$\sigma_m = 1.7\,(1 + 0.2\,D/B)\,(1 + 0.2\,B/L)\,c_u + \gamma g D,$$

where D is the depth below the ground surface, B is the width, L is the length of the footing, c_u is the undrained shear strength of the soil and γ is the unit weight.

When $D/B < 2.5$, the bearing capacity can be calculated from the equation

$$\sigma_m = 2.5\,(1 + 0.2\,B/L)\,c_u + \gamma g D.$$

The maximum allowable bearing pressure is 0.5 MN/m^2. Since the undrained shear strength of clay till generally exceeds 0.2 to 0.3 MN/m^2, the maximum allowable bearing pressure of 0.5 MN/m^2 generally governs the design.

According to the 1967 Code, the bearing capacity of a silty till should be calculated from the equations which govern the bearing capacity of either coarse-grained or fine-grained soils. The lowest of the calculated values obtained should be used.

The allowable bearing pressures are based on a nominal safety factor of 3.0 with respect to failure (collapse) of the foundation. The actual safety factor is generally much larger than 3.0, especially for coarse-grained soils, since conservative values of the angle of internal friction have been used in the calculation of the ultimate bearing capacity. For tills (except clay till) the actual factor of safety is probably 10 to 100.

The Swedish Geotechnical Society has recently appointed a committee with the task of investigating the possibility of increasing the allowable bearing pressure for coarse-grained soils, including tills.

The bearing capacity of piles in clay till is often calculated from the undrained shear strength c_u, as evaluated from field-vane tests or undrained, direct-shear tests. The unit point resistance is generally taken as 9 c_u and the unit shaft resistance as $\alpha\, c_u$, where α is a reduction coefficient. Dennersten (1968) found from load tests on two driven concrete piles that $\alpha = 0.39$ to 0.42 two days after the driving.

Settlements of tills are generally not considered in Sweden in the design of foundations. The 1967 Code states that it is necessary to consider the settlement of coarse-grained soils only when the soil is loose and the ground is subjected to vibrations. Moust Jacobsen (1970 *b*) has discussed the evaluation of settlements from oedometer tests.

The settlements are sometimes estimated from tests

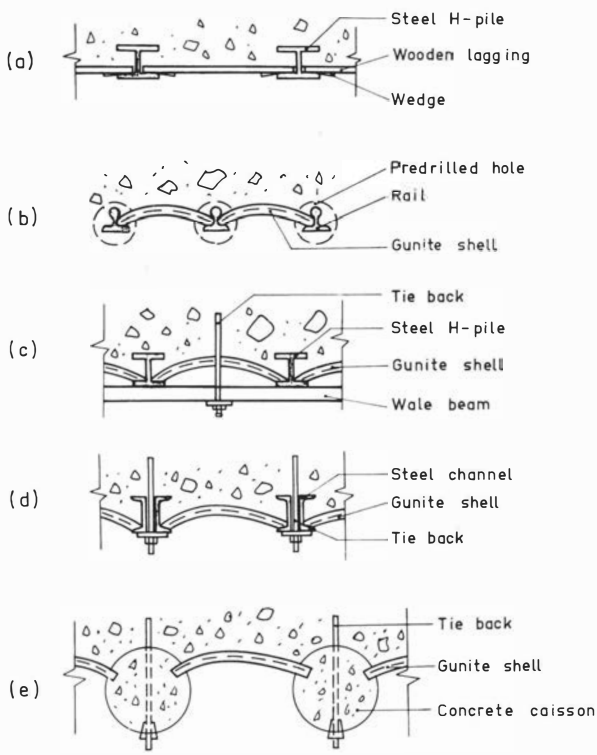

Fig. 4. Examples of retaining walls which have been used in moraine.

on compacted soil samples, from which stones and boulders have first been removed (Reinius and Thurner, 1968; Reinius, 1969; Högberg, 1970). The soil is first often preloaded to at least the anticipated allowable contact pressure and then unloaded. The deformation modulus obtained when the soil is thereafter reloaded is generally used in settlement calculations. The calculated settlements are, however, frequently two to three times larger than the actual settlements. Hansbo (1970), Högberg (1970), and Hansbo and Torstensson (1971) have, on the other hand, found a good agreement between measured and calculated values.

The settlements can also be calculated by plate-load tests with circular or square steel plates. The plate diameter should be at least 30 cm for coarse-grained soils. The deformation modulus of the soil is generally evaluated from the load tests by the theory of elasticity. Klohn (1965) reports that the deformation modulus of a dense till, as evaluated from field observations or from plate-load tests *in situ*, was much larger than that determined by laboratory tests. The settlements of clay till have also been calculated from pressiometer tests (Hansbo *et al.*, 1968; Hansbo, 1970).

The settlement of basal till which has been heavily pre-loaded during the last glaciation will normally be small when the applied load is less than the maximum overburden pressure. The maximum overburden pressure at Stockholm has been about 20 to 30 MN/m^2, since the ice sheet there was estimated to have been about 2000 to 3000 m thick. It should thus be possible to allow for caissons on basal till in the Stockholm area a maximum contact pressure of 5 to 10 MN/m^2 without excessive settlements and with a sufficiently high safety factor.

The boulders are often oriented with their largest dimensions in the direction of the movement of the ice sheet. As a result, the differential settlements in the direction parallel with the movement will, according to Helenelund (1970), probably be smaller than in the perpendicular direction.

The soil at the bottom of an excavation may, however, be loosened during the excavation below the ground-water table, due to seepage. This loosening can be prevented by keeping the water level in the excavation higher than the surrounding ground-water table or by using drilling mud. When drilling mud is used, there is also a danger that mud may be trapped between the concrete and the bottom during the pouring of the concrete, which may cause excessive settlements of the caisson.

STABILITY OF SLOPES IN MORAINE

The stability of till slopes is generally good above the ground-water table. The unsupported excavation depth may be relatively great, especially in dense till. In Sweden the stability of slopes in coarse-grained tills is generally calculated from the angle of internal friction, as determined from drained direct-shear or triaxial tests on recompacted samples.

The short-term stability of cuts in clay till is often calculated from the shear strength, as determined by unconfined compression tests or from field-vane tests. In a long-term stability analysis, the shear-strength parameters (c and φ), as determined from drained direct-shear tests on "undisturbed" or re-compacted samples are used.

Breth (1967) has analysed a slide which occurred in a till during the filling of the Kauner Valley reservoir in Austria. The sliding occurred at a calculated angle of internal friction which was lower than that determined by triaxial tests.

COMPACTION OF MORAINE

Tills are frequently used in Sweden, Finland, Russia and Canada as core material in earth dams, in canal linings or in fills. Bukin (1968 *a* and *b*) has described several dams in Russia in which till was used successfully without compaction. Some separation of the material was observed during the excavation and during the dumping of the till into water. The separation was found to be serious when the boulder content exceeded 25 % and the content of fines was less than 30 %.

To obtain in an earth dam a stable core with a low permeability or a fill with low compressibility, it is necessary to compact the till in layers at a water content close to the optimum. If the permeability of the till is low, high excess-pore pressure may develop during the compaction, if the water content of the soil is relatively high and the silt and clay content exceeds about 15 %. The permeability decreases, however, rapidly with increasing water content during the compaction. If the water content is high, the shear strength of the soil may be low before consolidation. This low shear strength may result in excessive deformations of an earth dam during the construction (Linell and Shea, 1960).

The permeability of gravelly or sandy tills is generally high ($k > 0.3 \cdot 10^{-3}$ cm/s) when the silt and clay content is less than 4 %. The excess-pore pressures which develop in these soils during compaction are generally low.

The stress-strain properties are affected by the compaction water content and by the grain-size distribution. A till which has been compacted dry of optimum is generally brittle, especially when the soil is coarse-grained. A till which has been compacted wet of

Fig. 5. Compaction of till for an earth-dam core by a vibratory roller.

optimum generally behaves like ductile material, especially if the soil is clayey. A strain of 20 % or more is frequently required during undrained triaxial tests to reach the peak strength. Culley (1970) points out the improvements of the stress-strain properties and the reduced freeze-thaw effects which can be obtained at a high relative compaction and at a low compaction water content.

The compressibility increases and the coefficient of consolidation decreases generally with increasing silt and clay content of the till. An increase of the silt and clay content from 5 to 10 % can result in a reduction of the coefficient of consolidation by 99 %. The compressibility of a well-compacted till is generally low. Often the settlements of earth dams are much smaller than those calculated from laboratory tests. Reinius (1969) reports that the maximum settlement of the crest for the 81-m-high earth dam at Höljes in Sweden after three years was only 74 mm. This value was much less than the calculated value.

Compacted clay till has been used in fills below structures (Gynnerstedt *et al.*, 1968). It was recommended that the relative compaction ($\gamma_d / \gamma_{d,max}$) should be at least 95 % with respect to the maximum dry density, as determined by the standard Proctor compaction test. Clay till has also been used in highway fills (Theill, 1971).

Different types of compaction equipment are used for till, as indicated in Table 2. Vibratory rollers and plate vibrators are primarily used in stony or coarse-grained tills which contain boulders. Heavy vibratory rollers must be used when the till contains boulders or large stones, since the layer thickness should be at least 50 % larger than the diameter of the largest boulder present in the soil. Tractors and rubber-tyred rollers are mainly used in fine-grained tills. Sheepsfoot rollers are suitable for the compaction of clay till. It may also be advantageous to use vibratory sheepsfoot rollers in clay till.

Table 2. Equipment used for compaction of till.

Equipment	Soil	Layer thickness
Vibratory rollers		
10 to 15 tons	Till with boulders Stony till Gravelly till Sandy till	70 to 100 cm
3 to 5 tons	Stony till Gravelly till Sandy till Silty till	30 to 50 cm
Plate vibrators		
100 to 500 kg	Gravelly till Sandy till Silty till	15 to 30 cm
Tractors		
10 to 30 tons	*Wet method*: Sandy till *Dry method*: Silty till	 30 cm 15 cm
Rubber-wheeled rollers		
10 to 50 tons	Silty till Clayey till	20 to 30 cm
Sheepsfoot rollers		
	Clay till	15 to 20 cm

CONCLUDING REMARKS

The use of till as construction material will probably increase in the future, as readily available resources of gravel and sand are exhausted. It is likely that in the near future tills will be used more extensively in embankments, in fills for roads and airfields, and below buildings, as well as for back-fill material behind basement and retaining walls and behind bridge abutments. The use of tills in road construction has been discussed by Waters and Woodford (1956) and by Lake and Woodford (1958). However, the restrictions which have to be placed on tills with respect to permeability, shear strength, compressibility and frost activity must be determined before the general use of moraine as construction material can be recommended.

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