SOIL IMPROVEMENT TECHNIQUES

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RINGKASAN

Masalah tapak bina semasa dan setelah siap pembinaan sesuatu projek adalah banyak. Kehadiran air tanah, darjah pengkemasan dan perlekatan antara zarah serta kepenuhan liang mempunyai pengaruh yang besar dalam sifat dan kelakunan tanah. Terdapat beberapa cara memperelokkan tanah dan usaha telah dibuat, menerusi kertas kerja ini, untuk menerangkan penggunaan kawalan air tanah, pengkemasan cara mekanikal dan penggunaan bahan kimia dalam pengelokan tanah. Namun demikian pemilihan sesuatu cara tertentu bergantung kepada jenis tanah yang terdapat di kawasan pembinaan itu.

SYNOPSIS

The foundation problems faced during and after finishing the construction of a project are numerous. The presence of groundwater, the degree of densification and particulate cementation and void filling have immense contribution in the soil characteristics and performance. Several techniques of soil improvement are available and attempts have been made, in this paper, to explain the utilisation of groundwater control, mechanical means of densification and the usage of chemicals in the treatment of soils. The choice of a particular method is dependent on the type of soil available at site.

Introduction

The construction activities are done on, in or with soils. As the availability of suitable construction sites decreases, the need to utilize poor soils for foundation support and earthwork construction increases. In addition, it is becoming increasingly necessary to strengthen the ground under existing structures to ensure stability against adjacent excavation or to improve resistance to vibratory, siesmic or other special loadings. Furthermore, many hundreds of recent successful projects have shown that through the use of suitable reinforcement materials and systems, the use of nature's most abundant material – soil – can be greatly extended.

The basic concepts of soil improvement ; namely drainage, densification, cementation, reinforcement, drying and heating, were developed hundreds or thousands of years ago and remain valid to-day. The coming of machines in the nineteenth century resulted in vast increases in both the quantity and quality of work that could be done. Among the most significant development of the past fifty years are the introduction of vibratory methods for densification of cohesionless soils, new injection and grouting material and procedures, and new concepts of soil reinforcements.

The aim of this paper is to synthesize the present state-of-the-art of soil improvement into a form presumably suitable for direct application. Because of the extensive scope of the subject, brief coverage of the areas will be discussed.

METHODS AND SCOPE

Groundwater Control

Open excavation may be straight forward or difficult, depending on the soil and groundwater conditions. Terzaghi (5) postulated that with no water in soils there would be no soil mechanics.

There are two cases to be considered here, (a) the case of an excavation into a sandy soil penetrating below the level of groundwater, and (b) the case of a sheeted excavation through an impermeable bed into sand charged with water under pressure.

Considering case (a); unless precautions are taken, the size of a hole dug in a fine sand below water level will begin to slump soon after excavation penetrates below water level. As digging continues, the slumping becomes progressively worse as seepage carries fines, from the ground into the excavation, and the sides of the excavation become unstable and collapse.

Now consider case (b); if without taking any precaution, a cofferdam or braced excavation is sunk through clay into an underline acquifer of sand containing water under pressure, then there will be a sudden in rush of water and sand at the point when the upward pressure of water at the toe of the piles exceeds the downward weight of the remaining soils within the excavated area. This can be prevented either by having a sufficient penetration of the piles or by reducing the pressure head in the acquifer beneath the cofferdam or braced excavation.

It follows, therefore, that in order to avoid unstable ground conditions it is necessary to control groundwater in the neighbourhood of a proposed excavation. Groundwater control may be achieved by:

1. Some geothechnical process which more or less permanently excludes groundwater from a proposed foundation area by forming a relatively impermeable barrier around the area; e.g. sheet piling, grouting in a diaphragm wall.

2. Some geotechnical process which lowers the water levels or water pressures either temporarily or permanently in the region of a proposed foundation area.

The summary of the main methods of groundwater control are given in Table 1.

Mechanical Means of Improving Soil Properties

This is usually achieved by a compaction process (i.e. an increase in the density of a non-saturated soil). The most obvious method is rolling and the effect is considerably enhanced by vibration. The size distribution characteristic of the soil is a controlling factor e.g. well-graded material can be compacted much better than those with uniform grading. An important category is Deep Compaction, viz;

1. Loose granular materials especially fine sands may be strenghtened by vibroflotation (sometimes called vibro-compaction). In this system a special machine resembling a very large poker vibrator is lowered into the soil. Water jets fixed to its base cause the machine to "jet" itself into a hole formed as the vibrated soils settles to a denser state. Extra sand or gravel is tipped into the annular space around the "vibroflot" which is then gradually withdrawn leaving a dense wide "pile" of strong compact soil with good load bearing capacity.

   The ground is improved to a radius of 1.5 to 2.5 m with a bearing capacity of approximately 100 kN/m^2 at a spacing of 3m centres, and greater bearing with closer centres (1).

2. Cohesive soils are improved by vibrating the machine into the ground usually without water and stone is then tipped into the base of the hole formed. The vibrator is used to compact this stone (40 – 100 mm) and force it against the surrounding soil. More stone is added and is compacted by the machine in successively higher layers to form a column of good vertical support. The composite system formed gives a bearing capacity of 100 to 200 kN/m^2 or even more in certain cases. The technique is not advisable for peat layers as columns depend their permanent stability upon the lateral pressure from the surrounding ground. The columns also act as vertical drains accelerating the consolidation and associated strenghthening of the ground. The treatment is called vibro-replacement. The majority of vibroflots can work up to 10 m depth although there are some which can go up to 15 m. One modification offered is to inject grout through the stabilizing fines as the vibroflot is withdrawn to strengthen or to reduce the permeability of, the adjacent ground. (1)

3. Dynamic Consolidation is another form of deep compaction in which a large weight between 98 kN to 196 kN is dropped from a height of up to 25 m. This high energy tamping can cause a substantial improvement in soil strength to depths of as much as 12 m. Although the system is very effective in granular soils it works well in low permeability silty materials by partial liquefaction of the soil as high pressure are developed. A new network of drainage channels is created by the dynamic loading and this dissipates the excess pore pressures with corresponding increase in strength.

This improvement technique depends on tamping in a sufficient number of passes at appropriate energy levels. (3)

Improving Soil Properties Using Chemicals

In this case the soil properties are changed by a chemical reaction and the job, usually referred to as chemical stabilization, has a wide coverage which includes grouting processes and soil cement. In stricter sence it covers the mixing of commercial chemicals with soil to produce strong or impermeable layers. Most chemicals are expensive in comparison with Portland Cement and bitumen so that the advantages gained in properties are invariably outweighed by cost. The latter cost may in turn be increased by the problems of mixing in site as the soil concerned may be of a difficult consistency. Grouting and cement are discussed separately below.

Soil Cement

The economy of stabilization of soil by cement depends upon the fact that aggregate does not have to be imported to the site. The proportion of cement required is about 10% of the soil which approaches the cement-aggregate ratio for a low-strength concrete. Where cohesive soils (clays, silts) are cement stabilized, the strength is very much lower than stabilized sands and gravels and the resultant layer should be regarded as a sub-base rather than a base. Soil cement was developed as an alternative to a compacted gravel sub-base for those territories where the cost of hauling aggregates several hundred miles outweighs the use of cement to stabilize the local soil. For road purposes it requires base and wearing coats. It behaves as a flexible (i.e. non-tensile) material, but is inferior to a good compacted gravel.

Cement or lime treatment of the top 200 mm of subgrades of cohesive fine granular soils is applied in some European highways and railways. The main benefit is to allow construction traffic to move on the site at an early stage of work. There may be some long term protection from weathering and leaching effects due to the provision of extra calcium ions during the treatment.

Filters

This is a material sufficiently fine to prevent the passage through its voids of particles of the material against which it is laid out but coarse enough to dissipate seapage pressure in the water flowing towards it. It should not erode internally nor migrate into drainpipes or other apertures. Filters can have their grading designed for specific sites for the general problem of protection against cohesive soils. D_{10} size need not be below 0.1 mm. That is, a fine sand is adequate for static conditions, for example behind a retaining wall.

Various design criteria have been proposed mainly as the result of past experimentation by United States government agencies. More recently work in Czechoslovakia and East Germany has led to more complex criteria supported by design charts for application to specific work. Filters must be designed when

protecting soils coarser than silts but for soils in static condition, a sand complaying with BS 882, will act for all silts and finer soils.

However for these same static conditions the introduction of a suitable geotextile, (a fine filter fabric) – will add filter qualities to a coarse backfill. For dynamic conditions, for example below mobile cranes and below railway track foundations, criteria for track blanketing sands have been developed by the more advanced railways. Research is in progress into the effectiveness of geotextile filters to control fine soils under dynamic conditions. (4)

Grouting

The normal grouting processes involve producing fluids of low viscosity with regard to the soil treated with the object of achieving a high penetration into the voids of the soil. (The special case of grouting of Embankment slips involves high viscosities and involves different techniques. It is not penetration grouting whereas track grouting is.) It is not possible to grout clay.

Apart from embankment and track grouting which are not discussed here the applications of grouting are: –

(1) Void filling for load transfer, e.g. behind tunnel linings, in the hearting of viaduct piers, behind retaining walls. The effect of grouting here is to transfer the loading from the soil mass, or from live loading, to the masonry skin. The grout must have substantial strength and corrosion resistance to form a permanent part of the structure. Is should be noted that it is an important function of the grout to transmit and distribute stresses to the lining consequent upon displacing water which previously filled the void. This replacement of fluid pressures by proper stress distribution is as important in relieving distress in the structure as the strengthening effect. In some cases such as filling voids between a footing and the foundation soil (underpinning) or placing as auxiliary arch to a bridge by a grouted stone construction inside formwork, it is desirable to have an expanded grout to ensure full contact and to counteract shrinkage. Expanding agents (usually aluminium powder) are added to the grout. These depend upon the chemical reaction with portland cement for their effect and should not be used in the presence of certain aerating agents (e.g. Teepol).

(2) **Voids filling for impermeability.** This is to prevent water ingress to excavations, to control quicksand conditions, to reduce frost heave, and to resist scour in river beds and behind sea walls etc. In all these cases the cheapest and strongest grout is chosen consistent with site conditions such as water movement (tides etc.) size of soil void, time of set required, and length of hose.

A special case is the fire in ash fills which is gradually extinguished by grouting air passages around the seat of the fire. The technique requires constant (daily) temperature checks to monitor and direct the effect of the pattern of grouting.

It is not possible to produce a temperature plan of the affected area and expect to grout from this at a later date. The system is very economical for embankments up to 6, 6 m high. Above this height treatment costs rise rather quickly.

(3) Strengthening of soil and fill. The best application for this is where cement-sand or cement p.f.a. mixes are possible. This is restricted to sites with high permeability fills and gravels. For finer materials, clay cement grouts may be used but the costs would be substantial compared with alternative construction measures.

Type of Grout

The different grouting materials generally rise in cost as they become more complex to obtain lower viscosity. As the viscosity goes down the penetrating capacity into finer soils goes up but the grout strength tends to go down. In the sequence of increasing penetration efficiency they are:

Cement-sand
Cement alone, or Cement-p.f.a
Cement-bentonite, or Bentonite-p.f.a
Cement-bentonite-silicate
Bentonite or Bentonite-silicate
Silica-gel processes (one and two shot)

One shot chemical grouts, e.g. TDM, Chrome lignin, formaldehyde, acetate and various polymer grouts.

The bentonite should be chosen according to the mix concerned; special clays are available for use with p.f.a. The proportion of bentonite required is very small so that its cost per unit volume of grout is not more than that of portland cement. The effectiveness of any type of grout is controlled by the type of equipment available to mix and place it and above all by the knowledge and experience of the grouting supervisor.

Bentonite

This material mixed with water at proportions of the order 5% provides a new method for excavating in granular soils with a high water table. No shuttering is required. As excavation proceeds, the bentonite slurry is poured into the hole whilst the soil is grabbed by machine from below liquid level. The slurry pressure supports the side of the excavation. Concrete is placed by tremie after foundation level is reached and the slurry is then pumped out. Instead of concrete alternate fill material special layers may be introduced as a non-structural water cut-off in the ground.

Bentonite posesses the property of thixotropy, which means that the material in suspension goes to a solid state with a low but definite shear strength when left at rest. Upon sufficient agitation it becomes a liquid which can be pumped and regains its "strength" when left at rest ("thixostropic regain"). This is not a true set; however, if bentonite slurries have silicates or cement added to them then an irreversible set does occur.

Table 1: APPLICATIONS OF METHODS FOR GROUNDWATER CONTROL (2)

Method	Soils suitable for treatment	Uses	Advantages	Disadvantages
PERMANENT EXCLUSION OF GROUND-WATER				
1. Sheet piling	All types of soil (except boulder beds)	Practically unrestricted	Well-understood method using readily available plant. Rapid installation. Steel can be incorporated in permanent works or recovered	Difficult to drive and maintain seal in boulders. Vibration and noise of driving may not be acceptable Capital investment in piles can be high if re-usage is restricted. Seal may not be perfect.
2. Diaphragm walls (structural concrete)	All soil types including those containing boulders (rotary percussion drilling suitable for penetrating rocks and boulders by reverse circulation using bentonite slurry)	Deep basements. Underground car parks. Underground pumping stations. Shafts. Dry docks, etc.	Can be designed to form part of a permanent foundation. Particularly efficient for circular excavations. Can be keyed into rock. Minimum vibration and noise. Treatment is permanent. Can be used in restricted space. Can be put down very close to existing foundation	High cost may make it uneconomical unless it can be incorporated into permanent structure. There is an upper limit to the density of steel reinforcement that can be accepted

3. Slurry trench cut-off (Wanapum method or paroi mince)	Silts, sands, gravels and cobbles	Practically unrestricted. Extensive curtain walls round open excavation	A rapidly installed, cheaper form of diaphragm wall. Can be keyed into impermeable strata such as clays or soft shales	Must be adequately supported. Cost increases greatly with depth. Costly to attempt to key into hard or irregular bedrock surfaces
4. Thin, grouted membrane	Silts and sands	As for 3	As for 3	The driving and extracting of the sheet pile element used to form the membrane limits the depth achievable and the type of soil. Also as for 3
5. Contiguous-bored pile walls	All soil types, but penetration through boulders may be difficult and costly	As for 2. Underpasses in stiff clay soils	Can be used on small and confined sites. Can be put down very close to existing foundations. Minimum noise and vibration. Treatment is permanent	Ensuring complete contact of all piles over their full length may be difficult in practice. Joints may be sealed by grouting externally. Efficiency of reinforcing steel not as high as for 2
6. Cement grouts	Fissured and jointed rocks	Filling fissures to stop water flow (filler added for major voids)	Equipment is simple and can be used in confined spaces. Treatment is permanent	Treatment needs to be extensive to be effective
GROUTED CUT-OFFS				
7. Clay/cement grouts	Sands and gravels	Filling voids to exclude water. To form relatively impermeable barriers (vertical or horizontal). Suitable for conditions where long-term flexibility is desirable, e.g. cores of dams	Equipment is simple and can be used in confined spaces. Treatment is permanent. Grout is introduced by means of a sleeved grout pipe which limits its spread. Can be sealed to an irregular or hard stratum	A comparatively thick barrier is needed to ensure continuity. At least 4 m of natural cover needed (or equivalent)
8. *Silicates, Joosten, Guttman and other processes*	*Medium and coarse sands and gravels*	As for 7 but non-flexible	Comparatively high mechanical strength. High degree of control of grout spread. Simple means of injection by lances. Indefinite life. Favoured for underpinning works below water level	Comparatively high cost of chemicals. Requires at least 2 m of natural cover or equivalent. Treatment can be incomplete in silty material or in presence of silt or clay lenses
9. Resin grouts	Silty fine sands	As for 7 but only some flexibility	Can be used in conjunction with clay/cement grouts for treating finer strata	High cost so usually economical only on larger civil-engineering works. Requires strict site control
FREEZING				
10. Ammonium/brine refrigeration	All types of saturated soils and rock	Formation of ice in the voids stops water	Imparts temporary mechanical strength to soils. Treatment effective from working surface outwards. Better for large applications of long duration	Treatment takes time to develop. Initial installation costs are high and refrigeration plant is expensive. Requires strict site control. Some ground heave
11. Liquid nitrogen refrigerant	As for 10	As for 10	As for 10, but better for small applications of short duration or where quick freezing is required	Liquid nitrogen is expensive. Requires strict site control. Some ground heave
TEMPORARY EXCLUSION OF GROUND-WATER BY GROUND-WATER LOWERING				
12. Sump pumping	Clean gravels and coarse sands	Open, shallow excavations	Simplest pumping equipment	Fines easily removed from ground. Encourages instability of formation

13. Wellpoint systems with suction pumps (including the machine-laid horizontal system)	Sandy gravels down to fine sands (with proper control can also be used in silty sands)	Open excavations including rolling-pipe trench excavations. Horizontal system particularly pertinent for pipe trench excavations outside urban areas	Quick and easy to install in suitable soils. Economical for short pumping periods of a few weeks	Difficult to install in open gravels or ground containing cobbles and boulders. Pumping must be continuous and noise of pump may be a problem in a built-up area. Suction lift is limited to about 4.0–5.5 m, depending on soils. If greater lowering is needed, multi-stage installation is necessary
14. Bored, shallow wells with suction pumps	Sandy gravels to silty fine sands and water-bearing rocks	Similar to wellpoint pumping. More appropriate for installations to be pumped for several months or for use in silty soils where correct filtering is important	Generally costs less to run than a comparable wellpoint installation, so if pumping is required for several months costs should be compared. Correct filtering can be controlled better than with points to prevent removal of fines from silty soils	Initial installation is fairly costly. Pumping must be continuous and noise of pump may be a problem in a built-up area. Suction is limited to about 4.0–5.5 m, depending on soils. If greater lowering is needed, multi-stage installation is necessary
15. Deep-bored filter wells with electric submersible pumps (long-shaft pumps with motor mounted at well head used in some countries)	Gravels to silty fine sands and water-bearing rocks	Deep excavations in, through or above water-bearing formations	No limitation on amount of drawdown as there is for suction pumping. A well can be constructed to draw water from several layers throughout its depth. Vacuum can be applied to assist drainage of fine soils. Wells can be sited clear of working area. No noise problem if mains electricity supply is available	High installation cost
16. Electro-osmosis	Silts, silty clays and some peats	Open excavations in appropriate soils or to speed dissipation of construction pore pressures	In appropriate soils can be used when no other water-lowering method is applicable	Installation and running costs are usually high
17. Electrochemical consolidation	Soft clays	Improve shear strength of soft clay without causing settlement	See Uses	Installation and running costs are usually high
18. Drainage galleries	Any water-bearing strata underlain by low permeability strata suitable for tunnelling	Removal of large quantities of water for dam abutment, cut-offs, etc.	Very large quantities of water can be drained into gallery and disposed of by conventional large-scale pumps	Very expensive. Galleries may need to be concreted and grouted later
19. Jet eductor system using high-pressure water to create vacuum as well as to lift the water	Sands (with proper control can also be used in silty sands and sandy silts)	Deep excavations in space so confined that multi-stage wellpointing cannot be used. Usually more appropriate to low-permeability soils	No limitation on amount of drawdown. Raking holes are possible	Initial installation is fairly costly. Risk of flooding excavation if high-pressure watermain is ruptured. Optimum operation difficult to control

Conclusion

Soil improvement is a necessity in construction. Groundwater needs a proper control to reduce the hazards of level alteration. The choice of improvement technique depends largely on the nature and composition of soils at site.

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