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Stabilization of Soft Clay for Irrigation Structures for Efficient Use of Water

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Abstract: Clay-lime improvement is an effective means to improve soft clay soil. Lime stabilization especially improves the strength and the workability of the clay soil. In addition to that, lime improvement provides more resistance to the soil structure and to the effect of weather on the soil structure. The purpose of the study is to improve the irrigation structures constructed in soft clay in order to increase the efficiency of irrigation and drainage systems that would insure a proper and efficient water management system. This study has investigated lime stabilization of soft clay and the possibility of utilizing waste rock powder produced in crusher plants as a supplemental material for the lime stabilization in order to increase the strength of the soil structure. The purpose of the study was to apply the results especially in irrigation projects in order to avoid the problems of soft clay on irrigation structures in Sri Lanka. However, the results and conclusions can be considered for other regions, where the same type of soft clay problems exist. The Dutch Oostvaardersplassen (OVP) soft clay, which has a high plasticity, low shear strength and high natural water content and lime (house burned, locally made from the eastern part of Sri Lanka) and waste rock material (from local rock crushers from Sri Lanka) were chosen to carryout the investigations.

The results of unconfined compressive strength for different water contents of clay and also for different lime and waste rock powder contents show an excellent increase in strength and workability. The waste rock powder proved to increase the effect of lime stabilization. The strength improvement caused by waste rock powder is more significant for those soils, which have a low clay content. Since, in irrigation projects, a wide range of clay soils exist, this investigation may be useful to utilize waste rock powder in order to improve the quality and the durability of the foundation of irrigation structures in the long run.

Therefore, the application of lime and rock material improvement on soft clay in irrigation projects may be a useful approach to stabilize soft soils and improve medium scale shallow foundation irrigation structures, road embankments and canal embankments, including repairing canal leaks. It has also been found that by applying this method in irrigation projects in Sri Lanka, the stabilization cost for structures on soft clay can be significantly reduced compared to other methods.

Key words: Lime stabilization, soft clay utilization, waste rock powder, irrigation structures

1.0 Introduction

Soft clay is very common in many regions in the world. It has very poor engineering properties. The properties of this soft clay to accommodate irrigation structures, embankments for road works as well as irrigation canal embankments are very poor. It may affect the quality of the irrigation structures in irrigated fields. The replacement of such soil with a good quality soil causes additional investment and, moreover, dumping of large quantities of useless soil causes environmental problems. Therefore, reuse of this clay would be the best solution to this problem. The term 'soil improvement' is defined as the alteration of the properties of an existing soil to meet specified engineering requirements. The main properties that might need to be altered by the improvement are the strength (to increase the strength and thus stability and bearing capacity), the volume stability (to control the swell - shrink characteristic caused by changes in moisture content), durability (to increase the resistance to weather), the workability (to perform construction work easily) and the permeability.

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The purpose of this study was to improve soft clay to use it as a construction material and also to make foundations on this soil in irrigation schemes by using cheap and easily available materials. Lime is one of the cheapest available materials in Sri Lanka. Specially, along the eastern coast, local people produce a large amount of lime by family labour using local house made lime burners. Waste rock powder is a waste by-product from rock crushers. This dust from waste rock material creates environmental problems in many countries. The possibility of utilizing these two local, cheap materials to improve soft clays in order to improve the quality and the durability of the irrigation structures in irrigation schemes has been investigated. Accordingly, the laboratory testing on lime stabilization on soft clay and the influence of the rock powder in lime stabilization on soft clay soil was investigated. The change of engineering properties by adding lime to clay and also the adding of lime and rock powder to soft clay have been examined.

2.0 Methodology

The necessary samples like clay, lime and waste rock powder have been taken from Sri Lanka. However, a large amount of clay was needed for the tests. The clay samples were tested at the laboratory for different basic classification tests and the matching Dutch soft clay sample was selected for the laboratory tests. The Oostvaardersplassen (OVP) dutch soft clay, which has a high plasticity, low shear strength with high natural water content was chosen to carry out the investigations. The laboratory test scheme is given in Figure 1.

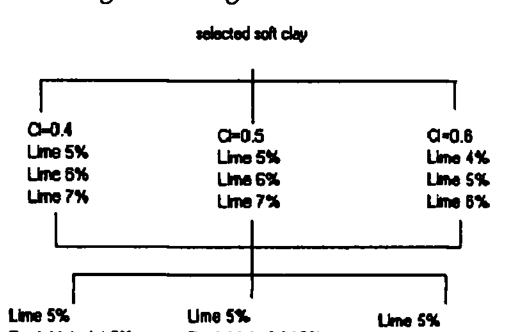


Figure 1. Laboratory test procedures

Three water contents (Consistency index - CI), which are very common during construction in irrigation projects, were chosen and the water content of the clay was adjusted accordingly. For these different water contents different percentages of lime were added as shown in Figure 1. For one of these water contents (Consistency index 0.5), with the same percentage of lime (5%), three different rock powder percentages were added as shown in Figure 1. The laboratory testing procedure was also developed to show how easy and simple it is to apply this stabilization process to improve soft clay in irrigation projects, even by farmers, with technical assistance. This stabilization procedure is given below.

Initially, the water content of the clay was adjusted and the clay was levelled as a layer. Thereafter, the clay was ribbed. These ribs on the clay allow the stabilizer to infiltrate in the clay and react with the clay particles easily. In irrigation projects tractors can easily do this ribbing, on the clay layers. Then, different percentages of lime were added to the clay. This lime was uniformly spread on the ribbed clay cake and left for 24 hours to react with the clay particles. Since the lime that was used in this investigation was collected from locally made house lime burners, relatively higher percentages starting from 3% to 7% were selected in this testing. These percentages were calculated from the dry weight of the natural clay.

Then the mixing was performed. In practice this mixing can also be done by tractors or by agricultural hand tools, depending on the volume of the soil to be stabilized. The efficiency of mixing should be ensured in accordance with the lump size of the mixed product. When the lime and clay are added together, gradually, with time, the clay particles become courser material by making small lumps. According to the past research investigations a 5 mm lump size is the most efficient mixing indication when the clay is added to lime, because the efficient influence depth of lime in clay was found to be around 2.5 mm. Therefore, lump size is an important factor that determines the mixing efficiency of the clay-lime mixture. Also these 5 mm lumps were found during the laboratory mixing. Therefore, such lumps should be maintained in the field as well in order to ensure the same strength gain.

The next step was to compact the mixture. This compaction also simulated a 5 ton compacting roller energy that can be easily found in an irrigation field. The compacted samples were cured for a period up to 45 days. This curing was done under normal room temperature of around 20°C. During the curing period each specimen was wrapped to prevent water loss from the samples. The unconfined compressive strength of the samples was tested at different intervals such as 7 days, 14 days, 21 days, 28 days, 35 days and 42 days and recorded.

3.0 Unconfined Compression Test Results and Discussion

The samples were tested for unconfined compressive strength for different curing periods. The results are shown in Figure 2.

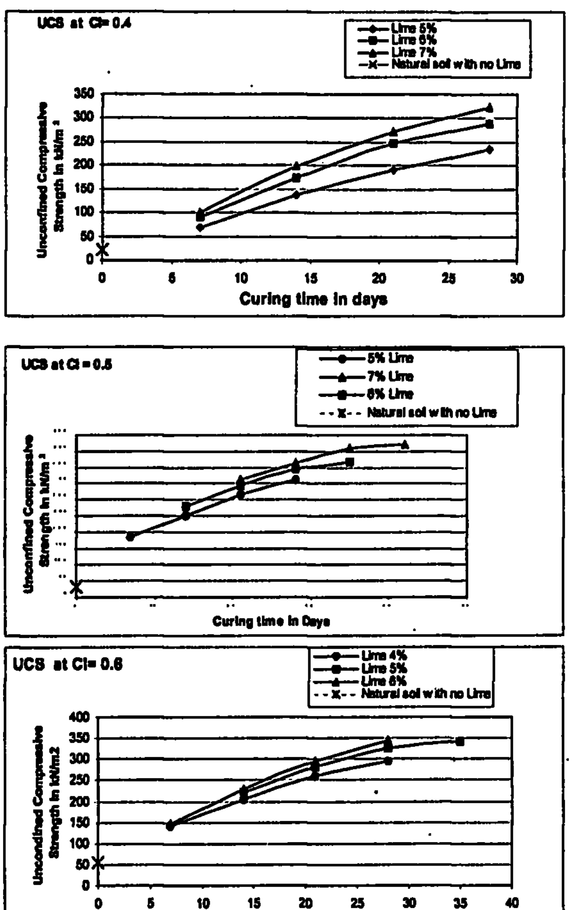


Figure 2. Unconfined compressive strength test result

From Figure 2, it can be seen that the strength of the clay increased considerably with curing. The strength gain during the first month was tremendous. The strength increased with the curing period as well as with the lime content. The rate of strength gain was reduced during the second month. During the initial stage CaO (quick lime) reacted with pore water of the clay and generated more heat. Therefore, considerably large amounts of pore water were absorbed and evaporated due to this hydration process. During this process the workability of the wet clay increased tremendously.

When the water content increased, the density of the sample decreased because of it's less close packing due to the water content, which led to low strength. However, due to the hydration process the reduction in water content made the soil more workable in order to perform good compaction. This provided a good strength to the soil treated structure. Even at the higher water content at CI = 0.4 for the lowest lime content of 4% at least it gained a strength increase of around 240 kPa at the end of the first month of curing. The clay minerals were natural pozzolanas and had the ability to react with lime added to the soil to produce cementitious products. The lime added to clay soil resulted in an increase in the pH to a value in excess of 12 with resultant increase in solubility of siliceous and alumina hydrates from the clay as well as rock minerals. Initially, these hydrates were in gel form to bind the soil particles, to form a bond, which eventually crystallized into silicate / aluminate hydrates. This reaction resulted in a gain in strength because the crystallized structure binds the clay particles together and provides more strength to the clay structure. However, the process was relatively slow because the lime had to diffuse through the soil structure and make reactions with those minerals.

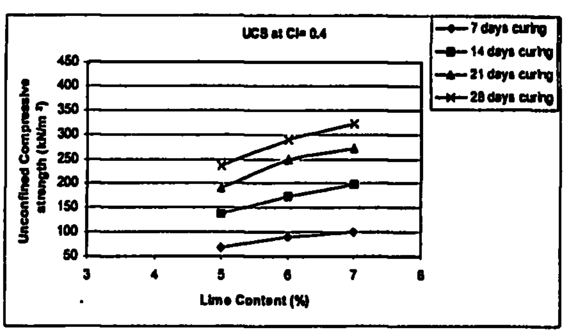
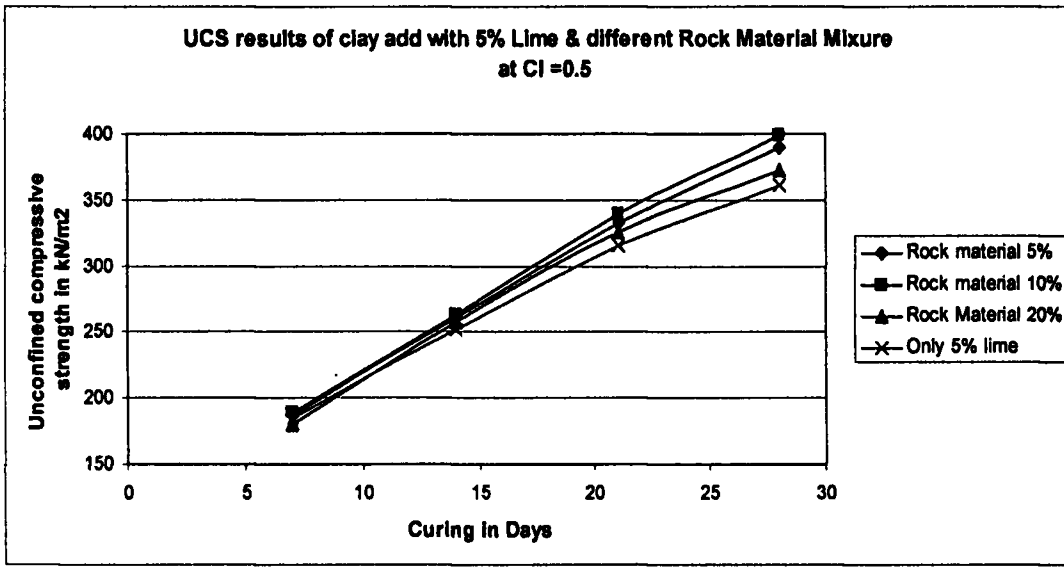


Figure 3. Unconfined compressive strength test result with different lime content in constant curing period



(a)

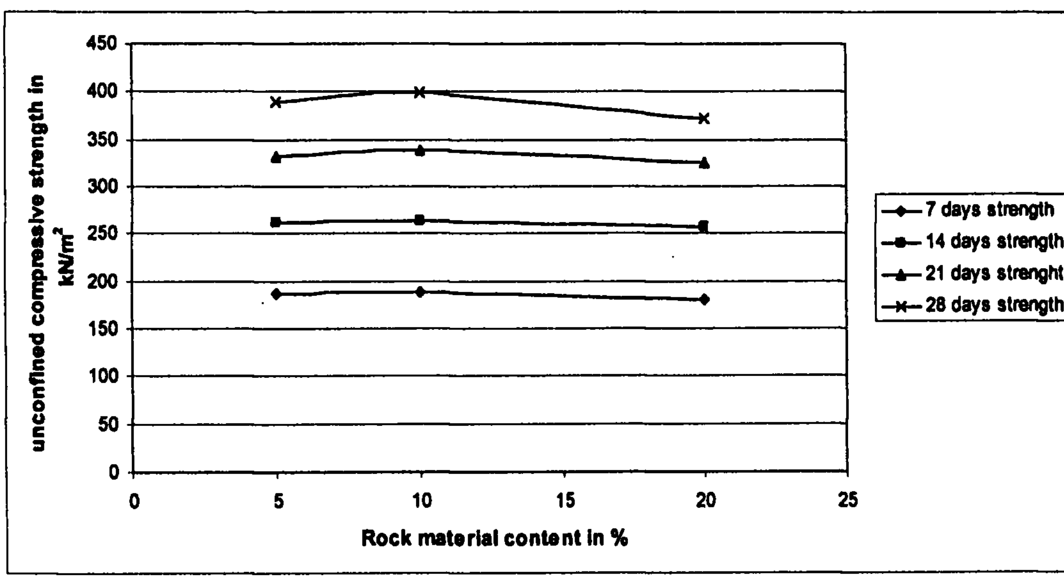


Figure 4. Unconfined compressive strength results for clay lime and rock material mix

From Figure 3, it may be observed that the rate of strength gain decreases with increasing lime content. This shows that a certain lime percentage provides the maximum strength gain and adding more lime than this percentage to this clay is not economical.

The other major objective in the research was to find the influence of the rock material on lime stabilization. It is proposed that the fine fraction of the rock material be applied in lime stabilization with clay. The finer particles passing through the 70 - 100 m sieve were used to add with lime for the soft clay improvement. Because the coarser rock particles can be utilized in road and canal embankments in between the stabilized layers as drain layers. This improves the consolidation property of the embankments. Also, the finer waste rock particles cause relatively more environmental pollution. The waste rock material was added to clay with 5% lime as shown in Figure 1 and the results are shown in Figure 4.

Figure 4 (a) shows that the rock material influenced the lime stabilization. More strength gain was observed when rock material was added to 5% lime with clay. This strength gain was relatively higher than the strength gain when only 5% lime was added to clay at the same consistency 0.5. The rock material supplies more SiO2 and Al2O3 and even calcites that accelerate the gel formation and crystallization process. This leads to the gain of more strength. However, the process of gaining strength is rather slow, because the rock material mainly influences the lime stabilization process during the pozzolanic long-term reaction stage.

Figure 4 (b) shows that 20% rock material mixed with 5% lime and clay showed relatively less gain in strength when compared to 5% and 10% rock material contents. The reason was that when the percentage of finer particles increased in the soil structure, the friction between the particles reduced, which led to failure during the unconfined compressive strength testing. Therefore, adding higher percentages of waste rock powder is not economical and provides less improvement as well.

Therefore, from all the above results, it can be derived that the lime content, waste rock material content, clay content, water content of the soft clay and the curing period play an important role in lime stabilization. The possibility of using rock powder as a supplementary material in lime stabilization is useful to gain more strength. This gain in strength depends on mixing efficiency and the compaction effort as well.

4.0 Application in Irrigation Projects

4.1 Construction procedure

The construction procedure will have to be in accordance with the specifications. The mix on site stabilization is especially suitable in irrigation project works. The main advantages of this method are economy and simplicity. It is more particularly suitable for remote areas. The disadvantage, however, is the mixing efficiency and the difficulties in making a layer thickness of more than 20 cm during the stabilization process.

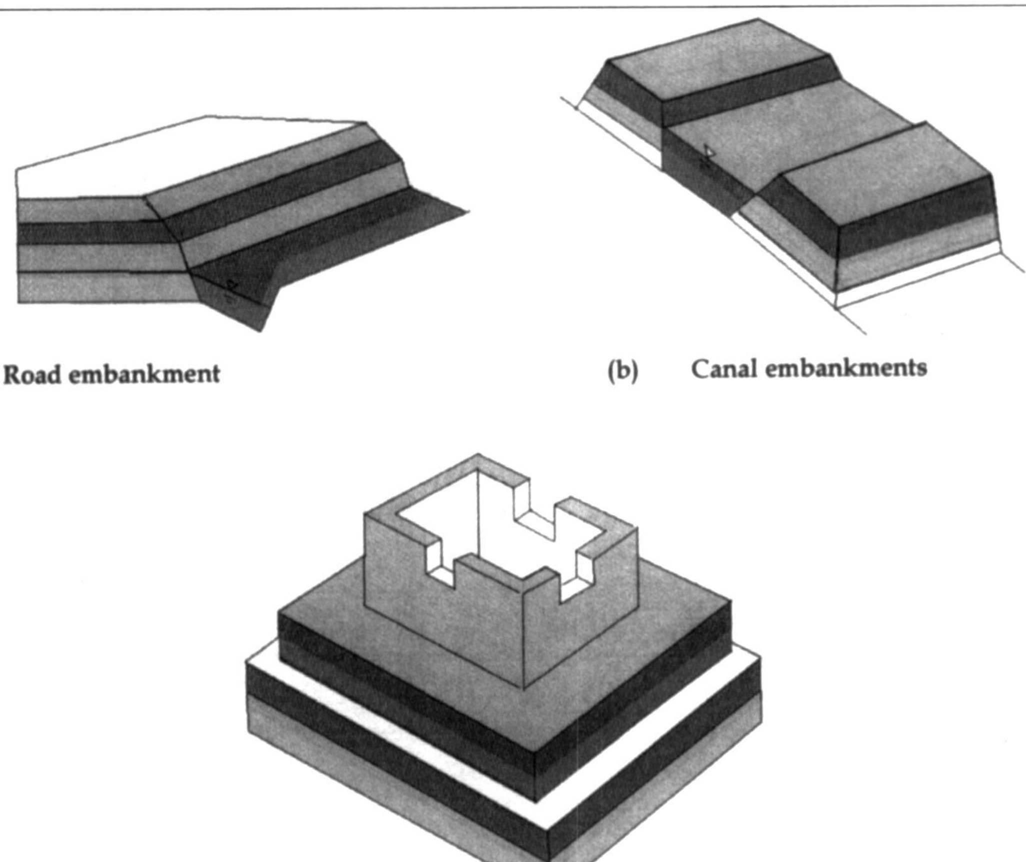
For the construction of water regulating structure foundations on soft soil, the soft soil should be excavated for a designed depth in order to carry out the stabilization process. Initially, the clay should be levelled and ribs should be formed on the clay layer and then the stabilizers (lime and waste rock material) spread on the ribs. Then the mixing should be performed and the layers should be compacted. This procedure should be repeated for the required design depth. Finally, after curing the stabilized layers, the structure can be constructed on the stabilized soil. This stabilization can be performed with normal agricultural hand tools and for the compaction hand compactors can be accommodated. However, this should be decided dependent on the volume of the soil that should be stabilized based on the dimensions of the structure foundation and the load from the structure. Otherwise, machineries can be used. Good mixing and the required compaction should be ensured in order to expect the required strength gain.

In embankment construction the soft soil material should be loosened and then, layer after layer, the soft soil should be stabilized with admixtures for the required height. The loosening can be done using tractors with special rotovaters in the irrigation projects. The number of passings over the soil during the loosening action should be decided on site, depending on the clay type. Thereafter, the spreading of stabilizer should be performed. Spreading the stabilizers at the required dosage rate can be carried out manually. Then, mixing of soil with stabilizer should be done efficiently. As mentioned before 5 mm lump size is a good indication of a proper and efficient mixing. The mixing can be performed by normal agricultural machinery, such as disc harrows, ploughs, etc. Since tractors are not heavy - duty machinery to carryout this type of stabilization work, the stabilizing layer thickness should be limited to a maximum value of 20 cm. The rolling, levelling and trimming activities should follow after the mixing. This initial light compaction and levelling ensures the minimization of evaporation, reduces possible damage from rain and reduces the risk of carbonation, especially in the case of embankment constructions. The final compaction is a very important aspect. The strength of the stabilized soil is directly dependent on the compaction effort and the required compaction should be achieved in order to ensure the high strength. Proper compaction is also necessary to reduce the air voids in the soil, so that the water absorption by the stabilized soil can be reduced. The final stage of compaction should be performed on the day following the trimming and levelling process. During the final compaction process the necessary compaction should be ensured. Specially, in hotter climates, due to evaporation and carbonation the final compaction should be completed as soon as possible. In the cool climates delay in lime stabilization is less critical. These procedures should be repeated layer after layer for the required height of the embankments. The coarse rock material can be used as drain layers between each stabilized layer for a thickness of around 5 cm in embankment construction.

Finally, curing is to be performed around 3 - 7 days. During the period of curing the top layer can be covered with impermeable sheets to reduce the moisture loss as much as possible. Proper curing is important to ensure the reduction of shrinkage and carbonization from the top layer. This ensures that sufficient water is retained in the layers for the hydration reactions. These procedures should be applied during the stabilization process as shown in Figure 5.

4.2 Small canal embankment seepage repairs

The permeability of the soil can also be reduced by this improvement method. This reduces the seepage and the leakage losses of the canal banks. The soil should be improved with admixtures (lime and waste rock powder) with the same method and then compacted at the centre as a core at necessary places, where the leaks or seepage occur along the canal bank as shown in Figure 6. This can reduce the waterlogging in the fields and roads adjacent to the canal. The water loss from the canal can also be reduced. The height of this core should be well above the water level as well as below the lowest water levels in the canal.



(a) Road embankment

(b) Canal embankments

(c) Irrigation water regulating structure
(4mX4mX0.2m foundation base 3mX3mX1.5m division structure)
referred for example calculations in this article

Figure 5. Stabilization of soft soil in Irrigation projects

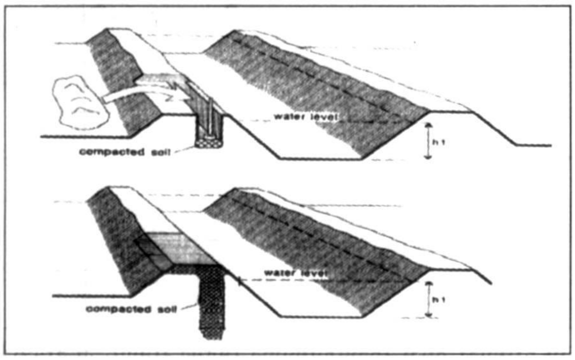


Figure 6. Small canal embankment leak repairs or reducing permeability

4.3 Stabilization of soft soil underneath shallow irrigation structure foundations

In general, most of the irrigation structures have shallow foundations. The irrigation structures with a shallow foundation, like culverts, division structures, water regulating gate structures, etc. can be constructed on top of the stabilized soft soil. The foundation base slabs can be laid on top of the stabilized layers to improve the stability and the quality of the structure. The depth of the stabilized layers should be designed considering the weight and the bearing capacity of the soil.

4.3.1 Design of stabilized layer depth

In this research the stabilized layer depths were designed using the Plaxis computer model. For example, the water regulating structure as shown in Figure 5(c) has been considered. The maximum pressure of this structure is around 30 kPa and the allowable bearing capacity of the soil at the foundation slab of the structure is 18 kPa. Therefore, this structure cannot be accommodated by this soft soil without stabilizing the soft clay. The case was analysed by PLAXIS and the results are shown in Figure 7.

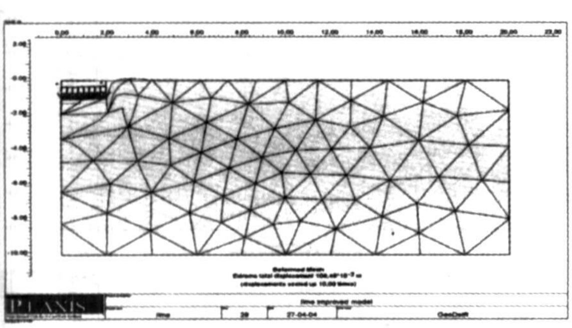


Figure 7. Lime and rock material improved stabilized result

Based on the analysis it was found that this structure required 0.8 m depth of lime rock material improved layer underneath the foundation slab in order to carry this structure safely on this soft soil. This method was compared with other methods, like replacing the soft clay with good quality construction material - sand or gravel - in order to carry this structure. The PLAXIS result of the analyses with sand is given in Figure 8.

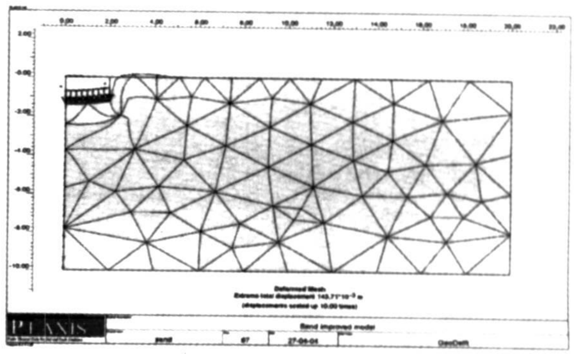


Figure 8. Sand layer stabilization result

The sand layer replacement method required a compacted sand layer depth of 1.1 m in order to carry the same structure with the same safety factor on this soft soil. This is more costly compared to the lime rock material improvement method. The initial settlement of the structure in both methods was relatively high due to the low elastic modulus of the soft clay. However, this settlement is relatively low with lime rock material improvement compared to replacement by sand. Therefore, the lime rock material improvement method gives better results and requires less depth of the improved layer underneath the foundation to carry this structure on this soft clay.

4.3.2 Feasible depth of excavation on soft clay

Safe excavation in soft clay soils for foundation construction is another important aspect. The consideration of the groundwater table depth and the excavation without collapse of the soil structure should be taken into account to formulate recommendations for the depth of excavation. A reasonable safe side slope of 1:2 can be applied during excavation. A safety factor of at least 2 is preferable for calculating the safe excavation depth. The soft Oostvaardersplassen clay was taken into account for the purpose of this design of a safe excavation by the computer model M- STAB. Assuming the construction can be carried out during a relatively dry season, a groundwater table depth of 3 m was considered in this analysis. The results of the minimum safety factor for the different depths of excavations are given below.

Excavation depth	Minimum safety factor
2 m	3.10
3 m	2.35

Excavation during the dry season gives a higher safety and there is a deeper groundwater table. Since most of the construction is carried out during the dry season the feasible depth of excavation can go up to 3 m.

Accordingly, a range of different types of irrigation structures (around 30 very common irrigation structures in irrigation field), starting from relatively small structures to large structures, were taken into account and the same design procedure was adopted in order to analyse the feasibility of the required depth of the stabilized layer. The structures were different weirs, culverts, head works, division structures and gates. The necessary thicknesses of the stabilized layers were designed under fully saturated conditions by using the PLAXIS model. Figure 9 shows the results of this analysis. The required depth of the stabilized layer is plotted against the maximum load of the structure for different structures.

From Figure 9 it can be observed that different structures depend on their super structural arrangement and they take their own trend

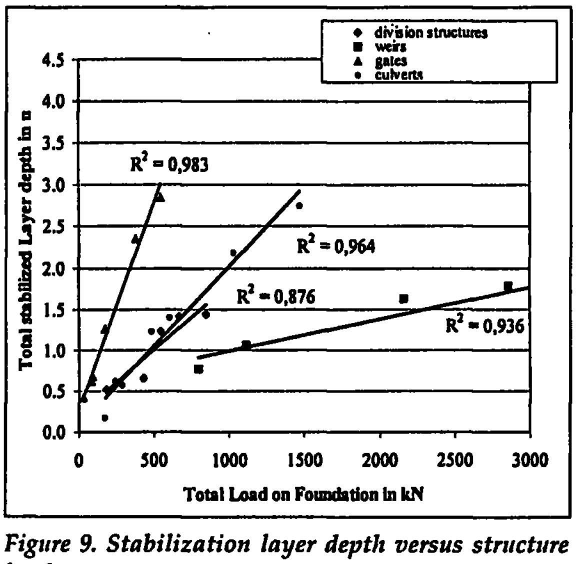


Figure 9. Stabilization layer depth versus structure load

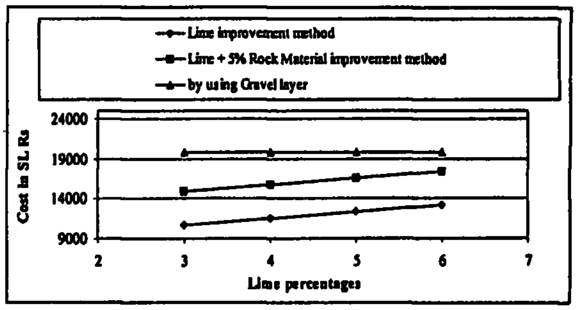


Figure 10. Economic analysis for stabilization cost for the structure shown in Figure 5(c)

against the stabilized layer thicknesses. It is obvious that if the safe excavation is allowed to make an excavation around 2 - 3 m around 90% of the irrigation water regulating structures these can be accommodated by this stabilization method. Therefore, these results show that this method of soil improvement is feasible in irrigation projects. Likewise, different types of structures for different types of soil can be analysed and constructed by adopting this stabilization method. Taking into account the skill of labourers and equipment availability, this improvement method can be extended. For this PLAXIS model some of the unknown parameters for the soft clay were taken from a textbook (Balkema. A.A, 1996). This was chosen based on the laboratory unconfined strength results.

5.0 Economic Analysis

Based on the PLAXIS results an economic analysis was carried out with respect to the stabilisation of the structure as shown in Figure 5(c). Both methods were compared at Sri Lankan material market prices in order to compare the cost of stabilization.

The minimum price of good quality sand was used for the analysis. Depending on the difficulties, availability and the distance of transport the price of foreign materials, like sand and gravel differs. However, the rock material can be found only close to the rock quarries. Based on the results of the above analysis by adopting the lime rock material improvement method a significant amount of cost can be saved compared to other methods. On top of that it should be realized that utilizing waste rock material and the lime source and improving the same soft clay as a construction material has a significant economic benefit from an environmental impact point of view. Therefore, from all the above results, using lime and utilizing waste rock material to improve soft clay is a very useful approach to reduce soft clay problems in irrigation projects.

6.0 Conclusions

6.1 Clay lime improvement

The soft clay reacts with lime and substantially improves its strength. The hydration of quick lime (CaO) with pore water of the clay produces hydrated lime $Ca(OH)_2$ and causes a decrease in the water content of the clay. During this process the workability of the clay increases well. The strength increases with the curing period. The strength of the sample decreases with increasing water content of the clay. The optimum lime content depends on the water content of the clay and increases with increasing water content in the clay. Compared to the improvement in the second month, the first month gain in strength is tremendous. During the lime modification process, especially in the first two weeks, the workability of the soil increases very well. The long-term gain in strength can be achieved until the lime reacts with clay in presence of enough water in the soil. However, this process is relatively slow, because the lime diffuses slowly through the soil structure and makes the reaction with the soil proceed even for a few years. Due to the reduction in the water content by lime addition to soft clay, it is easy to perform the compaction in the natural stage. Compaction is an important phenomenon that influences the strength.

6.2 Clay lime rock powder improvement

The waste rock powder influences the lime stabilization and adds more strength to the clay soil. Rock material can be used as a supplemental material in lime stabilization. The improvement is not so significant in the short-term. However, it has influence with ageing by making more pozzolanic reactions in the long-term. The significance of the strength gain depends on the clay content of the soils.

6.3 Application on irrigated fields

The method of improving the soft clay with lime and rock material to construct irrigation structures and embankments is feasible and efficient to improve the strength and workability of soft clay. In the case of constructing irrigation structures the depth of excavation to make stabilized layers depends on the depth of the groundwater table at the location. Most of the irrigation shallow foundation structures can be accommodated by this stabilization method in the irrigation projects. By adopting this method significant cost savings can be obtained compared to the application of other stabilization methods, such as gravel or sand. It is also economically feasible to go even up to the optimum lime content with the optimum rock material content mixture in order to achieve maximum strength on this soil compared to the cost of using sand or gravel in the irrigation projects to carry out this stabilization based on Sri Lankan material market prices. Coarser rock material can be used as drain layers in road embankments as well as in canal embankments above the maximum water level in canals in order to improve the consolidation properties of the soft soil.

Acknowledgement

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