Construction of a trial embankment on peaty ground using vacuum consolidation method for a highway construction project in Sri Lanka

Construction d'un remblai d'essai sur de la tourbe avec la méthode de consolidation atmosphérique pour un projet de construction d'autoroute au Sri Lanka

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ABSTRACT
A well instrumented trial embankment was built in order to study the effect of the vacuum consolidation method in improving the peaty ground for a highway construction project in Sri Lanka. The foundation soil mainly consisted of a 5 m – 6 m thick peat layer with high compressibility and low shear strength. The peat layer was improved by a combined vacuum and fill surcharge preloading method. An 11 m high fill surcharge was applied in stages in addition to the vacuum load to compensate the primary consolidation settlements and to minimize the secondary settlements that can take place in the actual structure. Construction of the vacuum system and embankment, the details of the field instrumentation and their observed behavior during the embankment construction period are presented in this paper. The improvement in the peaty soil due to the soft ground treatment was assessed from the data obtained through the field monitoring program and the results obtained from the laboratory and field tests carried out on improved and unimproved ground areas. The results indicate that the properties of the peaty soil have been improved significantly, providing the required control over future settlements while ensuring embankment stability.

RÉSUMÉ
Un remblai d'essai instrumenté a été construit afin d'étudier l'effet de la méthode de consolidation atmosphérique pour améliorer le sol de tourbe pour un projet de construction d'autoroute au Sri Lanka. Le sol de fondations est globalement constitué d'une couche de tourbe de 5 m – 6 m d'épaisseur possédant une forte compressibilité et une faible résistance au cisaillement. La couche de tourbe a été améliorée par une méthode combinant une précharge sous vide et par surcharge. Une surcharge de 11 m a été appliquée par étages en plus de la charge sous vide pour compenser les tassements primaires et pour minimiser les tassements secondaires qui peuvent avoir lieu dans la structure présente. La construction du système sous vide et du remblai, les détails de l'instrumentation sur site et les comportements observés pendant la période de construction du remblai sont présentés. Les améliorations apportées au sol de tourbe de part le traitement de sol mou ont été estimés grâce aux données obtenues par le programme de monitoring sur site et des résultats obtenus par des essais en laboratoire et sur site réalisés avant et après l'amélioration du sol. Les résultats montrent que les propriétés du sol de tourbe ont été améliorées significativement produisant le contrôle nécessaire vis-à-vis des tassements futurs tout en assurant la stabilité du remblai.

Keywords: highway embankment, vacuum consolidation, peaty soil, settlements

1 INTRODUCTION

The 128 km long proposed Southern Highway will improve access from Colombo the Capital city of Sri Lanka to the Southern region. Many parts of the road will traverse through flood plains and marshy ground consisting of very soft peat, organic soils, and clays. Ground improvement methods such as preloading, preloading with vertical drains, dynamic compaction have been proposed to improve the soft soil in order to control the post construction settlements and to ensure the stability of the highway embankment. However, when high embankments are constructed on peat deposits with high layer thickness, the above mentioned soft ground treatment methods may not be capable of consolidating the deeper soft peat deposits to the required level within the allocated time period. Further, it may not be possible to place an initial fill embankment and maintain the filling rates that match with the construction schedule without leading to stability problems, due to the soft soil being very weak. In such a situation, construction of an embankment using vacuum consolidation and surcharge fill will be the ideal solution as it further accelerates the consolidation process while reducing the required surcharge fill ensuring the stability of the embankment built on soft deposits. However, the vacuum consolidation technique has not been applied in Sri Lanka in the past and therefore a trial embankment was constructed using the vacuum consolidation method in the Southern Highway project in order to understand the performance of the method for improving the peaty soil found in Sri Lanka.

2 SITE CONDITION AND DETAILS OF THE TRIAL EMBANKMENT

The area selected for the trial embankment was a marshy land, mainly comprising of peaty soil located at Chainage 47+850 to 47+920 of the proposed Southern Highway route. The ground water level is almost at the surface. According to borehole investigations, the subsurface consists of a 5.5 m to 6 m thick peat layer followed by loose to medium dense sand. Laboratory test results indicated that the peat layer has a high moisture content and a void ratio in the range of 350% to 400% and 5.55 to 6.34 respectively. Furthermore, the results indicated that the engineering properties of the peat layer were poor with a high compressibility index of 2.65 and low undrained shear strength of 5 kPa to 23 kPa within the layer. As expected, the organic content of the peat is high and was found to be in the range of 60% to 70%. According to the above results, the peat found in

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the site can be categorized as fibrous peat with a high coefficient of permeability in the order of 10^{-7} m/s (Karunawardena 2007).

The trial embankment constructed measured approximately 70 m in length and 40 m in width as shown in Figure 1. The average height was around 11 m, crest width 22 m and side slope 1:1.5. The ground improvement was designed to control future settlements and to ensure the stability of the proposed embankment. The principle of ground improvement design for the embankment was to apply the surcharge by means of both vacuum pressure and embankment fill to compensate the primary consolidation settlements and to minimize the secondary settlements that can take place in the actual structure. In order to achieve the above, while applying vacuum pressure, a loose temporarily fill was constructed to induce the expected load on the foundation soil due to the construction of the highway embankment.

A 9.6 m fill surcharge was applied in addition to the vacuum load and 1.5 m platform soil. The fill was applied in stages, partly for the stability consideration and partly due to practical constrains in transporting the fill material. The fill used was a lateratic soil with an average weight of 18 kN/m^3.

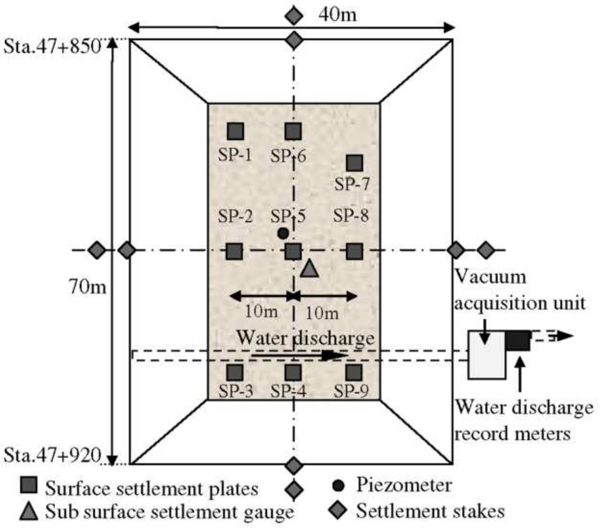

Figure 1. Plan of the embankment and instrumentation layout

3 BRIEF DESCRIPTION OF THE ADOPTED VACUUM CONSOLIDATION SYSTEM

The vacuum consolidation was carried out using the "Compact Vacuum Consolidation" (CVC) patent by Maruyama Industry, Japan. A brief description of the method adopted at the site is given below and the schematic construction is shown in Figure 2.

Initially, about a 1.5 m thick fill was constructed on the original ground surface to form a working platform for the band drain installation rig. Band drains were installed by a machine to a depth of around 6 m from the original ground surface in a square pattern with a spacing of 1 m. Thereafter, flexible horizontal drains (300 mm wide and 4 mm thick) were laid on top of the fill with a horizontal spacing of 1 m and then connected to the vertical band drains in order to ensure adequate horizontal drainage capacity. Subsequently, the tank systems used in the patent vacuum consolidation method called CVC were installed and connected to the designed pipe systems. Small ditches were excavated perpendicular to the horizontal drains at 20 m intervals and filled with aggregates after placing perforated pipes. Instrumentation such as settlement plates, displacement stakes, piezometers and differential settlement gauges were also installed at the designed depths. After installation of vertical, horizontal drains, pipes and separator tanks, the surface of the treatment area was covered by a protection sheet. Thereafter, an air tight sheet was laid on top and the periphery trench system was constructed to provide air tightness and the necessary anchorage at the boundary of the treatment area. Vacuum pressure was then applied using a patented vacuum pumping system by connecting the suction and water hoses to the vacuum pump. After confirming that there were no leaks through the air tight sheet, filling was commenced.

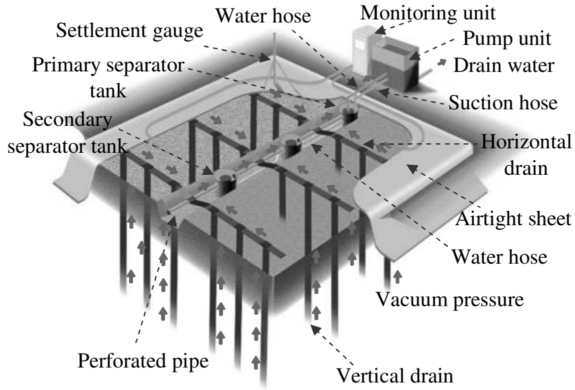

Figure 2. Schematic construction of compact vacuum consolidation

4 FIELD MONITORING PROGRAM AND RESULTS

An extensive monitoring program was carried out to understand the field behavior of the foundation soil. The locations of the instrumentation are shown in Figure 1. Nine nos. of surface settlement plates were placed on top of the airtight sheets. The differential settlement gauge was installed on the top surface of the sand layer found just below the peat layer. An electric type piezometer was installed in the middle of the peat layer. The settlement stakes were installed at four sides of the embankment along the transverse and longitudinal sections as shown in Figure 1. The vacuum pressure monitoring unit was used to measure the vacuum pressure at the pump and under the sheet. In addition, a water discharge meter was used to measure the rate and the total discharged water flow due to the vacuum operation. The automatic data acquisition unit was connected with the piezometer, vacuum pressure monitoring unit and water discharge meter to keep continuous records.

The loading curve that shows the placement of the fill, the surface settlement of the settlement gauge installed under the center of the embankment, the observed vacuum pressure under the sheet and the pore water pressure (PWP) in the piezometer installed in the middle of the peat layer, water discharge rate and cumulative water discharge with time are shown in figures 3(a), 3(b), 3(c) and (3d) respectively.

According to Figure 3(a) the soil has been consolidated under the fill load of 11.1 m in addition to the vacuum pressure. The observed surface settlement under the center of the embankment is around 1.94 m. The filling was started after about 40 days of vacuum application. According to Figure 3(c), at the beginning, vacuum pressure increased up to 35 kPa and then started to decrease. Even though the vacuum pump was capable of generating a suction pressure of about 90 kPa, the average vacuum pressure created under the sheet was around 15 kPa to 20 kPa. Therefore, the difference between the measured pore water pressure and the estimated hydrostatic pressure was around -15kPa against the expected designed value of -70 kPa. This may be due to the effect of the underneath sand layer, or intermediate sand layers, or inadequate edge revetment depth. The difference in the negative pressure which was considered as a surcharge load in the design of ground improvement was compensated by placing an equivalent height of the fill thickness.

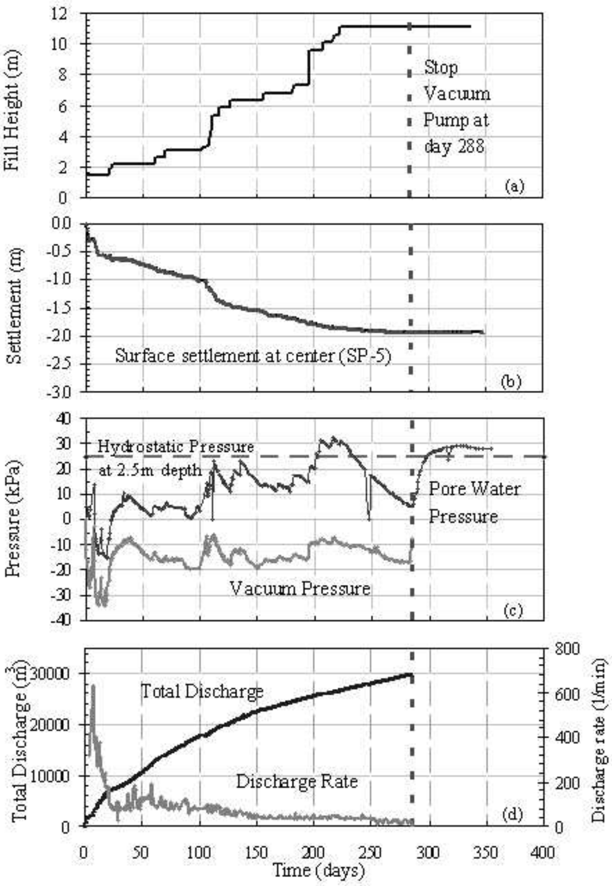

Figure 3. Loading curve and monitoring data during construction period

The water discharge rate was high at the beginning of the vacuum application and the placement of the fill and gradually decreased with time as indicated in Figure 3(d). According to Figure 3(d), the total water discharge volume is 30,000 m^3 and the settlement volume under the trial embankment is around 30% of the total water discharged by pumps.

The inclinometers that were installed to measure the horizontal movement of the subsoil were damaged during the construction period. However stability stakes that were installed at the toe of the embankment functioned and the stability of the embankment was assessed by the method proposed by Matsuo and Kawamura (1977). In addition, the stability was checked by studying the pore water pressure behavior underneath the foundation and according to Figure 3(c), the pore water pressure was maintained below the hydrostatic pressure during most of the construction period.

5 ASSESSMENT OF THE GROUND IMPROVEMENT

The objective of the ground improvement was to control the future settlement of the highway embankment to less than 150 mm by the end of 3 years after construction in accordance with the contract condition. In order to achieve this, it was planned to eliminate all primary consolidation settlements and to minimize secondary settlements that would have occurred under the final embankment loads. In addition, the improvement of shear strength properties of the peaty soil was expected to ensure the stability of the embankment.

The performance of the ground improvement was evaluated in terms of the degree of consolidation, improvement of the physical and engineering properties, increase in preconsolidation pressure and gain in shear strength of the peaty soil.

5.1 *Estimation of the Degree of consolidation*

Before termination of the vacuum operation and the removal of surcharge, the ground improvement achieved was investigated by calculating the degree of consolidation using the observed field settlements. The degree of consolidation is calculated as the ratio of the current settlement to the ultimate primary settlement. In the present work, ultimate primary settlement and the degree of consolidation were estimated by means of the Asaoka (1978) and hyperbolic methods (Tan et al.1991) using the measured field settlement data.

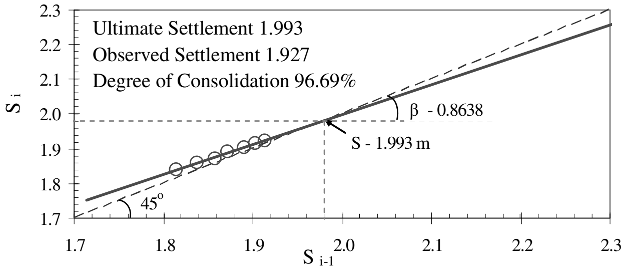

Figure 4. Graphical plot of Asaoka method (SP-5)

The graphical plot of the Asaoka method based on the observed settlement under the center of the embankment (SP-5) is shown in Figure 4. It is seen that the achieved degree of consolidation is around 96% and a similar value was obtained from the hyperbolic method as well.

Alternatively, the degree of consolidation was estimated based on the pore water pressure measurements. As shown in Figure 3(c), the pore water pressure returned to hydrostatic level (static equilibrium) some time after the vacuum pump was stopped, thus confirming that the major primary consolidation settlement was completed by that time.

5.2 *Improvement of physical and engineering properties*

A comprehensive site investigation was carried out in the improved area as well the adjacent unimproved area in order to assess the ground improvement.

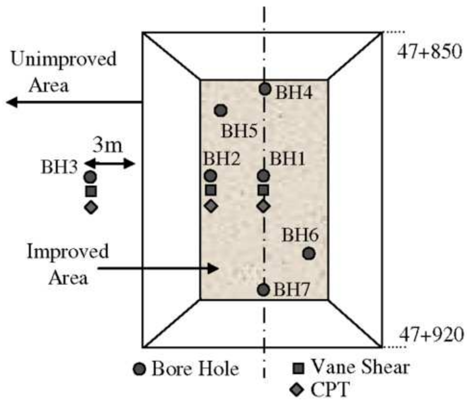

Figure 5. Investigation locations

Site investigation comprised of advancing of bore holes with Standard Penetration Test (SPT), collection of undisturbed soil samples, performing of Field Vane Shear Test and Cone Penetration Test (CPT) at the marked locations as shown in Figure 5.

The observed subsoil profiles deduced from the borehole investigation is shown in Figure 6. In the same figure recorded SPT values are also plotted along the depth. The summary of laboratory test results for the improved and unimproved area is given in Table 1.

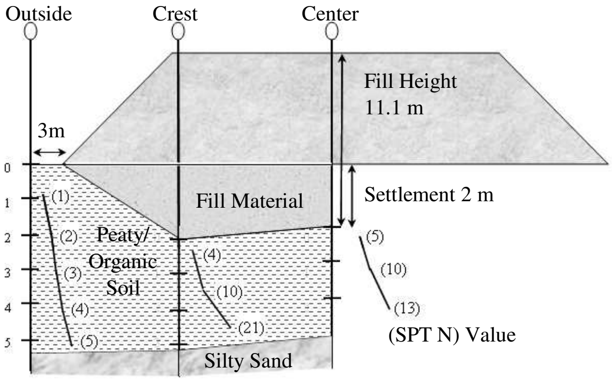

Figure 6. Subsoil profile of improved and unimproved area

According to the subsurface profile, the initial thickness of the peat layer has been reduced by 50%-60% after ground improvement. The above reduction agreed well with the percentage change of water content and void ratio values obtained from peaty soil collected from the improved and unimproved areas. Subsequently, consolidation tests revealed the significant reduction in the compression index which is proportional to primary consolidation settlement. The compression index of the peat layer has reduced from a range of 2.65 to 2.13, to as low as 0.90 as a result of the ground improvement. The average reduced value is about 1.65.

Table 1. Summary of laboratory test results

Location	Depth (m)	W_n %	e_o	c_c	c_α	c_u (kPa)
Improved Area – BH1	3.0	227	4.21	1.80	0.055	85
	3.5	266	4.50	1.95	0.061	120
Improved Area – BH2, 5	3.5	141	1.81	0.90	0.037	55
	4.5	168	1.94	1.94	0.048	70
Unimproved Area – BH3	2.5	370	5.54	2.13	0.110	22
	3.5	398	5.58	2.65	0.120	33

The reduction of secondary compression is very important as the secondary compression phenomenon is dominant in the peaty soil. The results of long term consolidation tests carried out in the improved and unimproved peaty samples are shown in Table 1. It reveals that the coefficient of secondary consolidation has reduced from a range of 0.10 to 0.13 to a range of 0.03 to 0.06. Subsequently the ratio of C_α / C_c has decreased from 0.050 to 0.029 due to ground improvement. The estimation carried out based on the above information assures that the residual settlement would be less than 150 mm by the end of 3 years after construction as required in the contract.

5.3 *Increase in preconsolidation pressure*

It was expected that the subsoil will behave in an over consolidated state during the service life of the structure after the completion of ground improvement. This criterion can be verified by the preconsolidation pressure evaluated through the consolidation test. Consolidation test results indicated that the preconsolidation pressure of the peaty soil found under the embankment has increased from 28 kPa – 38 kPa range to 160 kPa – 180 kPa range after ground improvement as shown in Figure 7. The expected load induced on the peaty layer due to the proposed embankment is around 140 kN/m^2. Therefore, the subsoil will behave under the over consolidated state with an Over Consolidation Ratio (OCR) of 1.2 to 1.3 during the service life of the highway and hence will only give rise to very small settlements in the future.

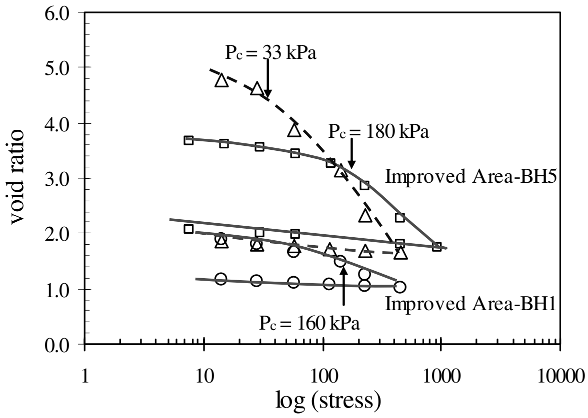

Figure 7. Consolidation test results

5.4 *Increase in shear strength*

The SPT, Field Vane Shear and CPT test results indicate that the strength has improved in the compressible layer due to ground improvement and as a result the status of the compressible layer has been changed form very soft to medium stiff state.

The strength gained due to ground improvement was investigated by calculating the increments of undrained shear strength of peaty soil to the increments of effective stress $(\Delta c_u / \Delta \sigma_v')$. The strength of the peaty soil was calculated based on the unconsolidated undrained triaxial and field vane shear test results. The obtained strength gain ratio based on the triaxial test results are around 0.25 - 0.48.

6 CONCLUSION

An 11 m high trial embankment has been successfully constructed on a marginally stable peaty ground using simultaneous application of vacuum and fill surcharge. The field monitoring data carried out at the site indicates that the primary consolidation settlements of the foundation soil under the applied load were almost completed. Investigations carried out at the site show that both physical and mechanical properties of the peat have improved significantly. As a result of the ground improvement, the subsoil will behave under the over consolidated state during the service life of the highway. Therefore, it can be confirmed that future settlements of the embankment would be very small and within acceptable limits as required in the specification.

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