Design and Performance of Highway Embankments Constructed Over Sri Lankan Peaty Soils

Conception et performance de remblais d'autoroute construits sur sols tourbeux au Sri Lanka

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ABSTRACT: The construction of the Southern Expressway in Sri Lanka involved extensive ground improvement work as many parts of the Expressway traverses through flood plains and marshy ground consisting of very soft peat, organic soils, and clays. Depending on the ground conditions, various ground improvement methods including remove and replacement, preloading, preloading with vertical drains, dynamic compaction and vacuum consolidation were applied to improve the soft soil to build the embankments with heights varying from 2m to 12m. 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. 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. The results of the post construction surface settlement monitoring of the expressway carried out up to date reconfirm that the ground improvement work was very successful and the expected residual settlements are well below the allowable limit of the contract.

RÉSUMÉ : La construction de la Southern Expressway au Sri Lanka a nécessité un important travail d'amélioration des sols. En effet plusieurs sections de la voie rapide traversent des zones inondables et du sol marécageux constitué de tourbes très meubles, de sols organiques et d'argiles. Selon les conditions du sol, différentes méthodes d'amélioration (excavation et remplacement, préchargement, préchargement avec drains verticaux, compactage dynamique et consolidation sous vide) ont été utilisées pour renforcer le sol mou et construire des remblais de tailles allant de 2 à 12m. La performance de l'amélioration des sols a été évaluée par rapport au degré de consolidation, à l'amélioration des propriétés techniques et physiques, à l'augmentation de la pression de préconsolidation et au gain de résistance au cisaillement de la tourbe. Les résultats indiquent que les propriétés de la tourbe ont été améliorées significativement, permettant le contrôle nécessaire des tassements à venir tout en assurant la stabilité des remblais. Les résultats du suivi après construction des tassements en surface sur la voie rapide confirment que l'amélioration des sols a été une réussite et les tassements résiduels prévus sont très inférieurs aux limites imposées contractuellement.

KEYWORDS: peat, embankment, monitoring, secondary consolidation, over consolidation ratio

1 INTRODUCTION

The Southern Highway is Sri Lanka's first E Class highway that links the Sri Lankan capital Colombo with Matara, a major city in the south of the island. The 96 km long section from Colombo to Galle was completed and opened to traffic in November 2011. Many parts of the highway traverses through flood plains and marshy ground consisting of very soft peat, organic soils, and clays. Especially, in the major flood plains of Welipenna river, Bentota river and Gingaga river areas, thick peat and organic clay deposits were found. The construction of road embankments over peat deposits is quite problematic, and thus, it is often done after first improving the properties of the peaty soil through the utilization of appropriate ground-improvement techniques.

This paper presents the ground improvement methods applied in the Southern Expressway between Ch.0.000 km to Ch.66.500 km to improve the peaty soil, with some background information on the design methodology. In the first 34.5 km of the highway, about 50% of the area is covered in soft ground and from 34.5 km to 66.5 km, the area covered by soft ground is around 12 km. In this project, embankments of about 4 km in length were constructed by improving the peaty soil mainly through the application of the heavy tamping method. The length of the embankments that were built by improving the peaty soil by vacuum assisted surcharging was around 2.5 km. The problems encountered during ground improvement and embankment construction work and the solutions given for the same are highlighted and discussed. The details of the laboratory and field investigations carried out before and after ground improvement, field instrumentation program and field monitoring program that was carried out during and after the construction of highway embankment to assess the soft ground improvement are presented.

2 TYPICAL SUBSOIL CONDITION OF SOFT GROUND

Many geotechnical investigations have been carried out since the inception of the project in order to assess the condition of the soft ground. At the preliminary stage, to provide information to bidders and to facilitate initial designs, boreholes were carried out at 500 m intervals. After commencement, boreholes were carried out at about every 50 m intervals in order to provide the necessary information for the detailed design.

Site investigation consisted of bore holes with Standard Penetration Test (SPT), hand augering, Cone Penetration Test with pore pressure measurement (CPTu) as in-situ testing and a series of laboratory tests such as index property tests, unconsolidated undrained triaxial compression tests and conventional consolidation tests.

The investigation identified that the soft ground area of the highway mainly consisted of peat, organic clay, alluvial clay and lose sand deposits. The distribution of soft soil deposits along the highway trace from Kottawa to Kurundugahahetekma is shown in Figure 1. Silty clay and silty sand were found as a top soil in most of the lowland areas up to a depth of 1.5 m to 3.0 m. This was followed by the sand to lateritic soil and the thickness of the layers varied from 1 m to 5 m.

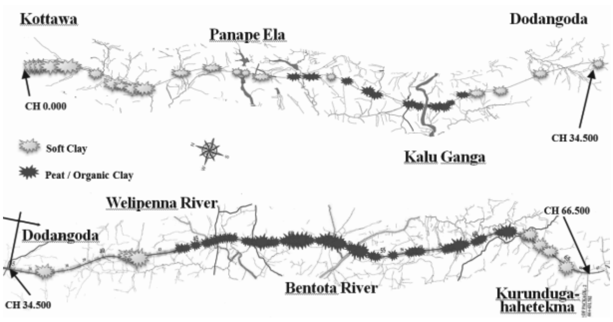

Figure 1. Distribution of soft ground areas

In the flood plains of Panape, Kalu Ganga, Welipenna and Bentota river areas sub soil consisting of mainly peat, organic clay, very soft inorganic clay and silt layers was found. The total average thickness of the compressible layer was in the range of 4 m to 11 m. In some areas loose silty sand layers were present under the above compressible layers. In the valley areas between hillocks, instead of cohesive inorganic clays, very loose to loose silt and sand were found ranging from 0.5 m to 4m thickness. The details of the Geotechnical properties of the subsoil have been given in Karunawardena and Nithiwana (2009) and Karunawardena and Toki (2011).

3 SOFT GROUND IMPROVEMENT DESIGN

Soft ground improvement design had to be carried out in order to control the settlements and to ensure the stability of the highway embankment as required in the technical specification. According to the technical specification, the embankment had to be designed and constructed by improving the soft ground in order to control the continued settlement to 15cm at the road center after a period of 3 years following the acceptance of the paving. In addition, the maximum residual differential settlement had to be not more than 0.3% change in grade over longitudinally within 3 years after construction. In order to achieve the above criteria, most or all of the primary settlement and some of the secondary settlement that would have occurred under the final embankment height alone were forced to take place by improving the soft ground.

The soft ground was improved mainly by using the following methods based on the subsoil conditions. Soft clay of shallow thickness was improved by placing a surcharge load. Shallow peat and organic clay deposits were removed and replaced with rock in order to support the embankments. The subsoil with relatively thick soft clay layers were improved by installing vertical drains and placing a surcharge load. The embankments on the relatively thick peat and organic deposits were constructed by improving the ground by heavy tamping method and the vacuum consolidation method from 0.0 km to 34.5 km and from 34.5 km to 66.5 km respectively.

In rock replacement method, all compressible layers of the sub soil were removed and replaced with rock, completely eliminating the settlements. In the ground improvement method of application of surcharge load with or without vertical drains, future settlement of the highway embankment was controlled as required in the contract by designing an appropriate surcharge load. Most or all of the primary settlement and some of the secondary settlement that would have occurred under the final embankment height alone were forced to take place under the surcharge load. In addition, it was expected that the soil beneath the embankment would become over consolidated or stiffer due to the surcharging of ground. The aim of applying the surcharge was to eliminate 100% of primary consolidation settlement and enough secondary settlement such that the residual settlement is within acceptable performance limits. The residual settlement for a given length of time after construction was estimated as the remaining secondary settlement that occurs during the required time after the eliminated equivalent time of secondary compression has elapsed. In the design of surcharge, it was expected to have 1.1 over consolidation ration (OCR) for inorganic clays and 1.2 to 1.3 OCR for peat and organic clays in order to reduce the secondary settlements during the operation period.

4 EMBANKMENT CONSTRUCTION ON PEATY SOILS

Embankments over peaty deposits in the Southern Expressway between Ch. 0.000 km to Ch 34.500 km were constructed by improving the peaty soil using the heavy tamping method whereas vacuum consolidation technique was applied to improve the peaty soil in the Section between Ch.34.500 km to 66.500 km. This Chapter presents the details of the heavy tamping method and the vacuum consolidation techniques applied in the project.

4.1 Heavy Tamping Method

Heavy tamping method was designed to enforce the settlements that would be caused by the construction of earth embankment on soft ground by applying impact energy. Different energy levels had to be imparted by considering the anticipated settlement of the compressible layer under the respective designed embankment heights. In the estimation of settlements, all primary consolidation settlements and secondary settlements at the end of 3 years after construction were considered. First, the soft soil which was to be consolidated, was overlain by a working platform of lateritic soil to facilitate the movement of machinery. Then, a strong type fibre drain (band drain) was installed by a machine in the soft subsoil in a square pattern with a spacing of 1 m in order to prevent high excess pore water pressure development in the underneath soil due to the applied energy. The required energy was applied to the soil by dropping a large weight on the ground surface repeatedly in phases on a grid pattern over the entire full base width of the embankment using multiple passes.

During tamping, once the depth of the crater formed by pounder exceeded the height of the pounder, the crater was back filled and leveled with soil. The dimension of the crater was recorded in order to calculate the volume of soil introduced. The above process was continued in all phases of the tamping operation. Using the crater fill volumes, the enforced settlement was calculated and if the enforced settlement was less than what was required then another phase of tamping was introduced until the required settlement was achieved.

After application of heavy tamping, borehole investigation was carried out in order to assess the ground improvement. Investigations revealed that the layer thickness of peat has been reduced to 20% to 50% of its original thickness after the heavy tamping. The SPT values of peat layer at a 3m to 4m depth increased from 0 to a range of 4 to 8. Consolidation test results showed that the value of the compression index (c_c) and coefficient of secondary consolidation (c_α) has decreased significantly. It was also noted that the pre-consolidation pressure, P_c , of peaty soil has increased from 32, to as high as 85. This increase of pre-consolidation pressure means the peaty soil is in an over-consolidated state during the service life of the highway. All these observations confirmed that the expected primary and secondary consolidation settlements due to the embankment load would be very small in the areas improved by heavy tamping.

However, it was observed that the peat layers at the deeper depths had not achieved the above improvement. This was investigated and it was found that the practically possible improvement depth that could be achieved in the present operation was about 3.5 m to 4 m. These underneath deeper soft layers were improved after the heavy tamping operation by keeping a surcharge load for a sufficient period of time as reported by Karunawardena and Toki (2011). Figure 2 illustrates the major steps in the heavy tamping ground improvement method adopted in the project.

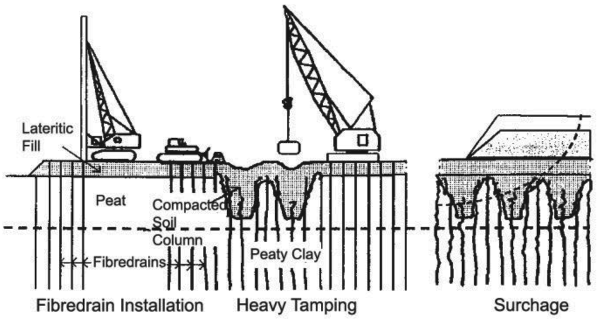

Figure 2. Major steps in heavy tamping ground improvement

4.2 *Vacuum consolidation method*

In the application of vacuum consolidation method, about a 1.0 m to 1.5 m thick fill was constructed on the original ground surface to form a working platform for the band drain installation machine. Band drains were installed by a machine up to a designed depth 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 system was 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, electrical piezometers and differential settlement gauges were also installed at the designed depths. After installation of vertical drains, horizontal drains, perforated 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 vacuum pumping system patented by Maruyama Industry Co. Ltd, Japan 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.

It was expected to apply the surcharge by means of a vacuum pressure of 70kPa to compensate the primary consolidation settlements and to minimize the secondary settlements that can take place in the proposed highway embankment. However, in many areas the applied vacuum pressure was less than the designed value and therefore the above designed surcharge was applied by means of both vacuum pressure and embankment fills. The designed load was kept until the expected settlement completed.

5 ASSESSMENT OF THE SOFT GROUND IMPROVEMENT

The continuous assessment of the improvement of soft ground was carried out by conducting the field monitoring program. In addition, the soft ground improvement was assessed by conducting appropriate field and laboratory testing.

5.1 *Field monitoring program*

The improvement of the soft ground was monitored through the measurement of settlement and the excess pore water pressure during the construction period. Settlement plates were installed at the top of the soft layer or on top of the pioneer layer and piezometers were installed at the middle of the soft layer. The settlement stakes were installed near the toe of the embankments to check the stability during the construction. In addition to the above, in the areas improved by vacuum consolidation, a vacuum pressure monitoring unit was used to measure the vacuum pressure at the pump and under the air tight sheet. Also, a water discharge meter was used to measure the rate and the total discharged water flow due to the vacuum operation. An automatic data acquisition unit was connected with the piezometer, vacuum pressure monitoring unit and water discharge meter to keep continuous records.

The decision to remove the surcharge was made on the basis of the monitoring data obtained during the surcharge period. The aim was to eliminate 100% of primary consolidation settlement and enough secondary settlement such that the residual settlement was within acceptable performance limits. The primary consolidation settlement was assessed by estimating the degree of consolidation and in this project it was estimated by the method outlined by Asaoka (1978). The degree of consolidation was also calculated based on the pore water pressure (PWP) measurements, and laboratory consolidation testing of peaty samples after the treatment program. The comparison of the degree of consolidation for each method for some areas improved by the vacuum consolidation method is shown in Table 1.

Table 1. Estimation of the degree of consolidation

Location	Degree of Consolidation		
	Asaoka Method	Laboratory Data	PWP
Ch. 45.380 – Ch. 45.430	97.83%	83.10% 73.87%	79.46%
Ch. 47.850 – Ch. 47.920	97.10%	100.00% 100.00%	100.00%
Ch. 52.950 – Ch. 53.000	97.57%	80.21% 90.91%	100.00%
Ch. 53.660 – Ch. 53.730	96.65%	96.70% 83.62%	68.71%

If the degree of consolidation from the PWP measurement is assumed to be accurate, Asaoka Method accurately estimates the degree of consolidation in treatment areas Ch.47.850 to Ch.47.920 and Ch.52.950 to Ch.53.000 whereas Asaoka method over predicts the degree of consolidation in treatment areas Ch. 45.380 to Ch. 45.430 and Ch.53.660 to Ch. 53.730. However, in treatment area Ch.53.660 to Ch.53.730 the degree of consolidation from the laboratory test results agreed very well with the same estimated from the Asaoka method. Therefore, based on this investigation it can be concluded that the degree of consolidation estimated from the Asaoka method is reasonably accurate.

In order to assess the secondary settlements, for each monitoring point, the long-term settlement was predicted by extrapolating the secondary settlement rate over a period of 3 years. Predictions were made by preparing a plot of displacement against log (time) for each settlement plate, with the best-fit line through the data extended to define the likely settlement after 3 years. The surcharge was removed only after confirming the residual settlement by considering both the primary and secondary consolidation settlements as described above.

5.2 *Investigation to confirm the ground improvement*

Site investigation was carried out to assess the actual ground improvement in the areas improved by the vacuum consolidation method just before the removal of surcharge. Investigation was carried out in the improved as well the adjacent unimproved area in order to assess the ground improvement. Investigation revealed that initial thickness of the peat layer has been reduced by 50%-60% after ground improvement. The above reduction agreed reasonably with the percentage change of water content and void ratio values obtained from peaty soil collected from the improved and unimproved areas. Consolidation tests revealed that 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. The results of long term consolidation tests carried out in the improved and unimproved peaty samples show that 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 (Karunawardena and Nithiwana, 2009).

Consolidation test results also indicated that the pre-consolidation pressure of the peaty soil found under the embankment has increased as shown in Table 2. Table 2 also shows the expected load induced on the peaty layer due to the proposed embankment and the subsoil over consolidation ratio. According to the data in Table 2, the sub soil will behave under the over consolidated state with an OCR of 0.98 to 1.33. It should be noted here that even though the applied vacuum pressure and the fill surcharge load is adequate to yield an OCR value in the range of 1.2 to 1.3, sometimes the calculated OCR is less than that the anticipated value. This might be due to the inaccurate Preconsolidation Pressure (P_c) value obtained from the consolidation test as a result of sample disturbance.

Table 2. Increment of preconsolidation pressure and undrained cohesion

Location	Expected Load (kPa)	P_c (kPa)	OCR	C_u (kPa)	C_u / σ'_v
Ch.45.380-Ch.45.430	160.0	180	1.13	79.0	0.49
		160	1.00	57.0	0.36
Ch.47.850-Ch.47.920	145.0	200	1.37	55.0	0.36
		180	1.25	70.0	0.45
Ch.52.950-Ch.53.000	152.5	150	0.98	41.5	0.27
		170	1.11	38.2	0.25
Ch.53.660-Ch.53.730	150.0	170	1.13	54.0	0.36
		147	0.98	50.5	0.34

The strength gained due to ground improvement was investigated by calculating the ratio between the undrained shear strength of peaty soil and the effective stress (C_u / σ'_v). The ratio between the undrained shear strength of peaty soil and the effective stress (C_u / σ'_v) after the treatment program was obtained to be 0.25 to 0.49.

5.3 *Observed settlement after pavement construction*

The surface settlement of the highway embankment constructed over the improved soft ground was monitored by installing the settlement markers at 50 m intervals after construction of the road pavement. Initially, for about a 6 month period, before the road was opened to traffic, surface settlement was monitored at both the center and the edge of the embankment. The observed settlements were in the range of 0 mm to 5 mm in most of the ground improved sections except at very few locations where high embankments were constructed over thick peat deposits improved by the vacuum consolidation method. The observed surface settlement in those areas was around 10 mm to 20 mm at the end of six months after the construction of pavement. After the highway was opened to traffic in November 2011, settlement monitoring was carried out only along the edge of the highway embankment due to safety reasons. The observed total surface settlement up to September 2012, ten months after the highway was opened to traffic, is shown in Figure 3. The observed settlement was less than 5 mm in most of the sections and in only two locations the settlement exceeded 20 mm. The maximum observed settlement was 35 mm and the settlement prediction using the monitoring data indicates that the estimated residual settlement is less than 15 mm at the end of 3 years after the handing over of the project.

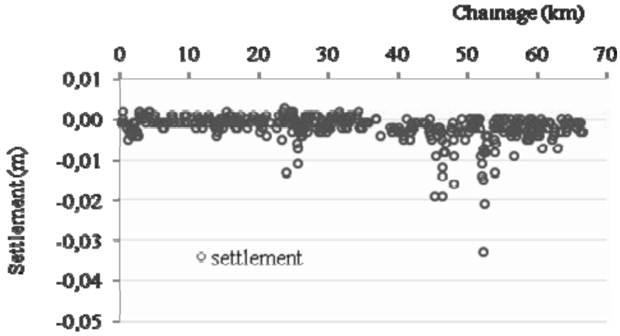

Figure 3. Results of the surface settlement monitoring

6 CONCLUSION

This paper presents successful application of ground improvement work carried out in the construction of Southern Highway project in Sri Lanka. Ground improvement methods such as heavy tamping method and vacuum consolidation techniques were applied to construct the high embankments over thick peaty deposits. In both methods, a surcharge load had been applied to over consolidate the peaty soil. Field monitoring data obtained during the construction period indicates that the primary consolidation settlement due to final load of the highway embankment has already been completed and the secondary settlement had been reduced to control the residual settlement within acceptable performance limits. Investigations carried out at the site show that both physical and mechanical properties of the peat have improved significantly and the peaty soil will behave in an over consolidated state with a ratio of 1.2 to 1.3 during the service life of the highway. The results of the post construction surface settlement monitoring of the expressway carried out up to date reconfirm that the ground improvement work was successful and the expected residual settlements are well below the allowable limit in the contract.

7 ACKNOWLEDGEMENTS

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