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Behavior of Soft Clay Treated with Vibro Stone Columns under Earthen Embankment Loads – Field Study

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Abstract. Construction of high earthen embankments on soft clays experience geotechnical concerns like excessive settlement, low bearing capacity and side slope stability. In the present case, performance of a 10m high earthen embankment constructed over marine clay treated with vibro stone columns is studied. The subsoil below earthen embankment consists of 13m thick soft clay which cannot support required loadings. Hence, ground improvement using vibro stone columns was considered as optimal solution to improve shear strength of the subsoil, accelerate consolidation, and enhancing bearing capacity. A selected portion of embankment was fully instrumented with settlement gages, inclinometers, and piezometers for monitoring its performance. The present study discusses the observed results with respect to design soil parameters and its behavior of treated soft clays. In addition, Pre and Post ground improvement soil investigation test results are reviewed to confirm improvement of soil stiffness.

Keywords: Earthen Embankment, Soft Clays, Vibro Stone Columns, Performance monitoring.

1 Introduction

The construction of embankments over problematic soils such as soft, compressible ground is unavoidable due to lack of suitable land for infrastructure and other developments. The geotechnical engineering tasks consist of ensuring the global stability, controlling surface settlements, and enhancing bearing capacity. Various methods such as Prefabricated Vertical Drains (PVDs), Concrete piles, Stone columns and geosynthetic reinforcement etc., have been developed for economical and safe construction of high embankments resting over soft ground [1,11,12].

Eventually, the final choice from variety of techniques depends upon the subsoil conditions, project cost and time of completion including long-term construction advantages. Stabilizing soft ground by installation of vibro stone columns has numerous benefits such as improved bearing capacity, accelerated consolidation, decrease horizontal deformations, increased slope stability and mitigating liquefaction [2,4,5,6,8,10,13]. Especially, the degree of improvement of in-situ soft clays depends on two factors, when stone columns are used. The first one is introducing stiffer aggregate columns in the soft soil, and the second is consolidation of the surrounding soil during the loading process.

Review of embankments built over treated soft ground using vibro stone columns are presented in this paper. Earthen embankment of 10 m high was constructed over 13m deep soft marine clay treated with vibro stone columns. Behavior of embankment during construction stage is monitored through instrumentation such as settlement markers and inclinometers. Interpretation of the observed data is carried out to understand performance of the embankment in service condition (observational and analytical methods). Further, improvement between intercolumn stiffness was studied by comparing pre and post penetration testing results. A careful watch over soil investigation, design process and post construction monitoring over the entire process is thoroughly monitored to assess reliable prediction of embankment performance.

2 Project Environment

The project site is situated in West Coast of India. Anticipated load intensity due to 10m tall earthen embankment was about 200 kPa and expected unimproved surface settlement was more than a meter. This made practicing engineer's attention over global stability. In addition, the construction site falls under Seismic Zone-IV having Peak Ground Acceleration (PGA) of 0.24g and earthquake magnitude of 7.5. These conditions posed a question of cyclic softening in the event of earthquake.

2.1 Sub-Soil Conditions

About 6 eCPTs and 3 boreholes data was available to understand the in-situ subsoil conditions. Soil investigation was carried out up to 30m below Existing Ground Level (EGL). The subsoil comprising of 1m thick filled soil followed by very soft to firm silty clay up to the depth of 13m below EGL. There is occasional presence of silt lenses between 4m and 7m deep. This layer is further underlain by dense to very dense silty sand followed by hard clayey silt up to termination of borehole. Ground water table was encountered almost at surface (say 1m below EGL) during the time of investigation. SPT-N vs depth and cone resistance (q_c) & friction ratio (R_f) vs depth are presented in **Fig. 1**.

2.2 Geotechnical Concerns

Since the subsoil conditions below the proposed embankment being soft clay, it will undergo excessive long-term settlements and will experience global stability. Further, project location falls under seismic zone -IV, hence it will prone to liquefaction/cyclic softening in the event of earthquake.

3 Ground Improvement Works

The subsoil within the project site comprising of soft in nature results in high settlements, low bearing capacity and inadequate global stability. This condition demands appropriate ground improvement technique. Further rate of settlements needs to be accelerated, so that permissible settlements in service condition can be controlled within the performance requirements. Ground improvement technique using vibro stone columns was chosen in this project addressing geotechnical challenges, satisfying project schedule and cost economics.

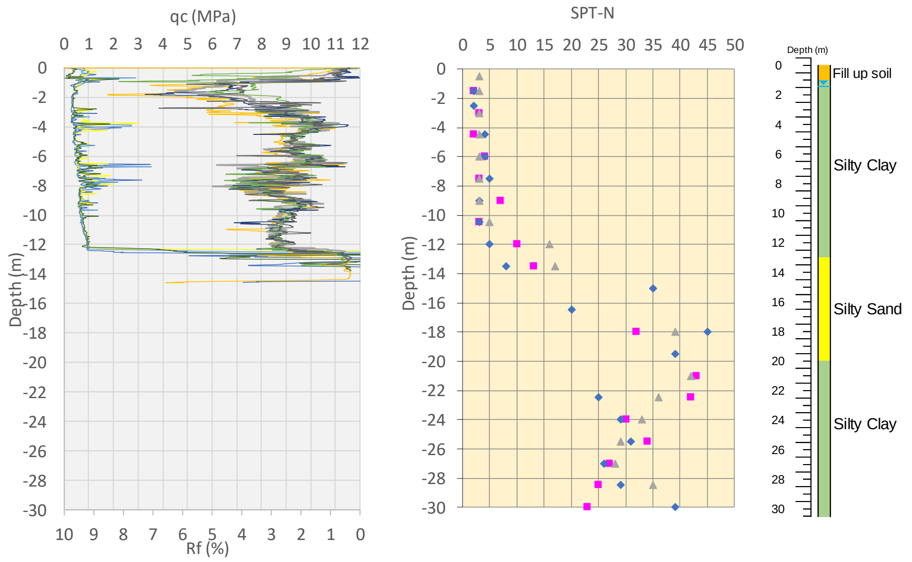

Fig. 1. Cone resistance (q_c), friction ratio (R_f) & SPT-N vs depth

Typical arrangement of vibro stone columns is illustrated in **Fig. 2**. Advantage of slow rate of embankment filling was considered to accelerate the consolidation and to elude most of the excessive settlements. Ground improvement design is carried out according to Priebe's design methodology [9] using "Keller Improvement Designer" (KID) software. Time rate consolidation analysis of treated ground is done using radial drainage consolidation theory [7]. Vibro stone columns with Area Replacement Ratio (ARR) of 20% and treatment depth of 13m below EGL were finalized. Further, 1m thick granular blanket was laid above cut off level of vibro stone columns to form connectivity between columns for pore pressure dissipation when embankment loading is done.

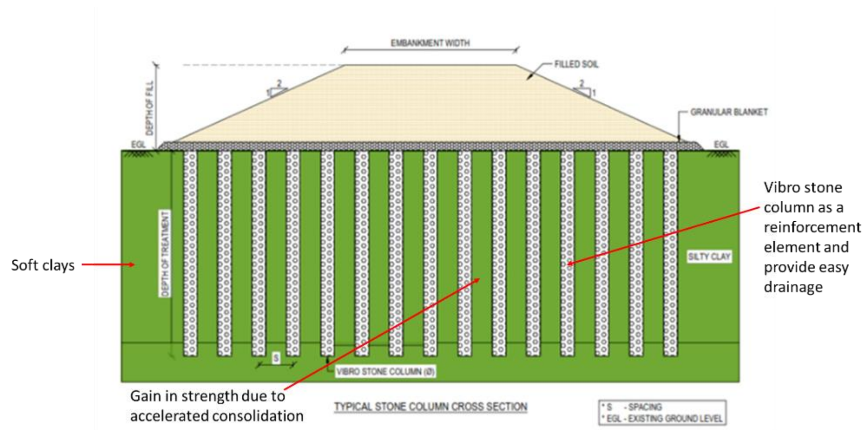

Fig. 2. Typ. cross section illustrating ground improvement scheme

4 Construction & monitoring

A selected stretch of embankment (10m fill plus 1m buffer to match the top level after construction stage settlement) was built over the treated ground in 2 months duration. Slow rate of filling (say 0.4m to 0.5m/day) was maintained during construction of embankment. After reaching the desired top level of embankment, it was held for sufficient rest period to satisfy 95% of consolidation. Loading of embankment is monitored in such a way that majority of settlements are completed during construction leaving serviceability settlements which are well within the permissible limits. Asaoka et al. 1978 was considered for interpretation of degree of consolidation [3]. Six settlement plates and two inclinometers were installed to monitor settlements and lateral movements, daily. Key observations are listed below.

- Recorded settlements are in the range of 579mm to 619mm.
- Rate of settlement was gradually decreased and stabilized after 70 days of waiting period.
- 95% to 97% of consolidation was achieved within 90 days of rest period.
- The balance long term settlements, approx. 30mm to 35mm will occur during service life of embankment.

Embankment loading and observed vs predicted settlements are presented in **Fig. 3**. Degree of consolidation using Asaoka's method is presented in **Fig. 4**.

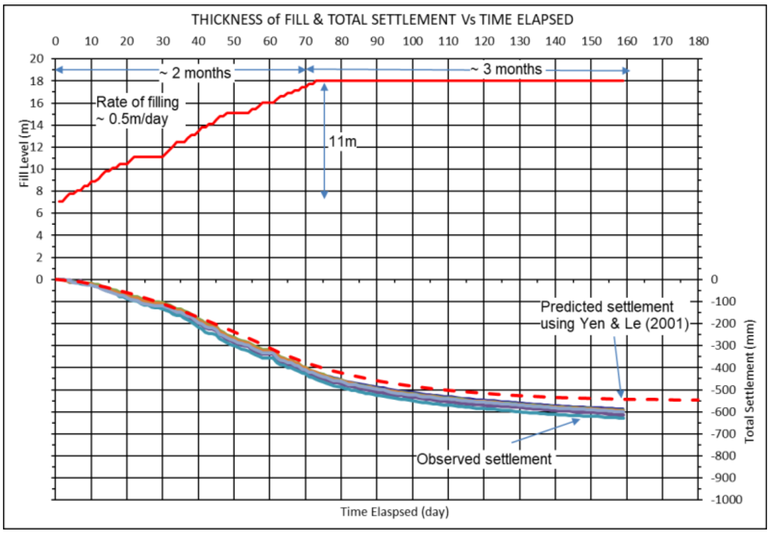

Fig. 3. Plot showing embankment height and observed vs predicated settlements

5 Post Treatment Soil Investigation

Efficacy of improved ground was checked by conducting 5 post eCPTs and 2 boreholes. The exploration depth of post treatment BHs and eCPTs were limited up to the treatment depth. Post improvement results indicate considerable improvement in SPT-N and q_c values when compared to in-situ conditions. It shall be noted that improvement in the subsoil stiffness (constrained modulus) as the result of the consolidation of clay layer is in line with design assumption. The results of Post SPT-N and eCPTs against depth are plotted in **Fig. 5**.

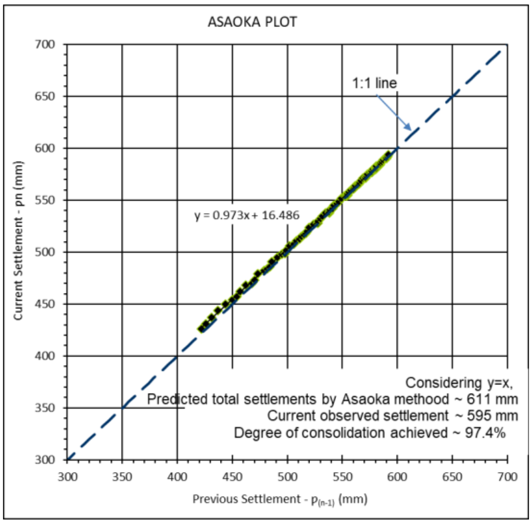

Fig. 4. Estimation of total settlement and degree of consolidation (Asaoka 1978)

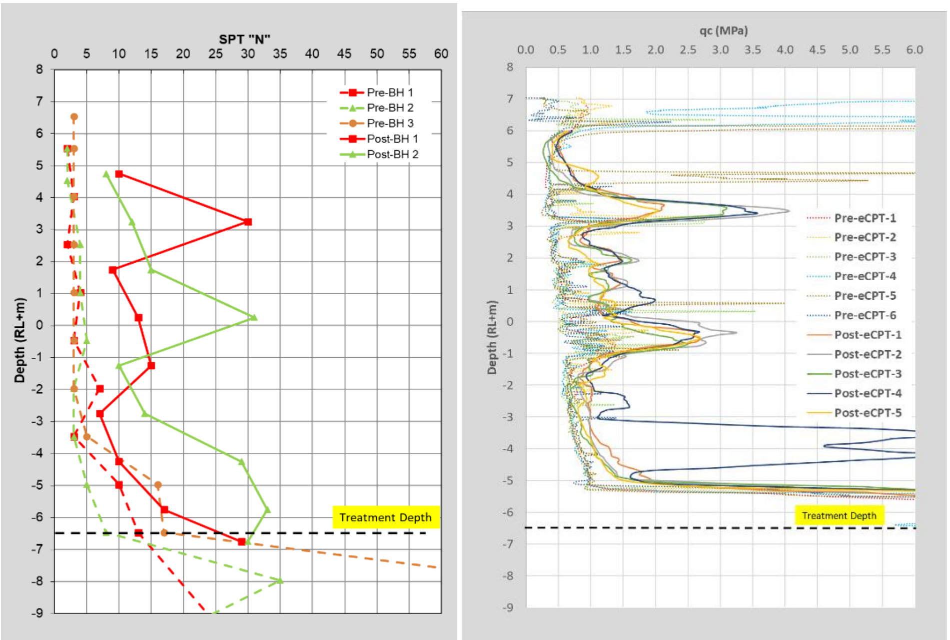

Fig. 5. Comparison of (a) pre & post SPT-N & (b) pre & post cone tip resistance (q_c)

6 Conclusions

Ground improvement using vibro stone columns successfully demonstrated the performance criteria of 10m high embankment in the present case. Embankment loading acts like preloading which increases the effective stress and reduces the compressibility of weak ground through consolidation. Proposed ground improvement scheme is not only addressed the service stage settlements but also accelerated the rate of settlements. Around 95% consolidation achieved within 90 days of rest period via effective radial drainage. Pre and post soil investigation results clearly indicates improvement of shear strength and soil stiffness of the treated ground. This implies more than 1/10 reduction in the estimated service stage settlement compared to unimproved case. The design approach used has been verified and substantiated in comparison with field monitoring and in situ test results.

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