Observational Method to Prevent Failure of Embankment Treated with Vacuum Preloading

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ABSTRACT: The success of the vacuum preloading method relies on the effectiveness of the vacuum system in creating suction (negative pore pressures) to equalize the net positive excess pore water pressure generated in the subsoil during embankment filling. Therefore, the use of observational method to monitor the excess pore water pressure generated in the subsoil during embankment filling is an effective way of control and prevent failure. This paper presents a case history of two embankments constructed at the same site employing the vacuum preloading treatment with prefabricated vertical drains (PVD). One of the embankments failed with large cracks and settlement at the final stage of filling but the other one was successfully constructed. The findings from the Authors, who were involved in the investigation to identify the causes of failure are also presented.

1 INTRODUCTION

Professor R.B. Peck (1969) in the Ninth Rankine Lecture set out procedures for the observational method as applied to soil mechanics. The method provides a way of controlling safety during construction and at the same time minimizing construction costs, so long as the design can be modified during construction. Peck also identified two major applications for the observational method:

(a) *ab initio* : from inception of the project
(b) *best way out* : during construction when unexpected site problems develop.

The use of observational method on construction of embankment treated with vacuum preloading method is an effective way of control and prevent failure. This is because the success of the vacuum preloading construction relies on the effectiveness of the vacuum system in creating suction (negative pore pressure) to equalise or reduce the net positive excess pore water pressure generated in the subsoil during embankment filling. Therefore close monitoring of the pore water pressure in the subsoil during filling of the embankment is necessary to check and make sure that the pore water pressure generated in the subsoil is within the design limit to prevent shearing failure. If the excess pore water pressure exceeded the designed values, contingency measures like slowing down the filling rate, stop filling or increase suction until the problems are solved, have to be implemented.

Two embankments at the same site in Peninsular Malaysia namely Embankment A and Embankment B, were reviewed by the Authors. Other than measuring the settlements of the embankments with time, piezometers were also installed in the subsoil beneath the embankment at three different depths of 3m, 6m and 8m respectively in the very soft cohesive soil. The measurements of these piezometers were taken during construction of the embankment and during resting period. Embankment A failed not long after reaching the final height but Embankment B which is not far away from Embankment A which employed the same vacuum preloading ground treatment, did not failed.

2 VACUUM PRELOADING METHOD

The vacuum preloading method implies the use of an airtight membrane placed over the ground to be improved and sealed to the low-permeable soil along the edges. Suction tubes are put through the sealed membrane and connected to vacuum pumps. In order to ensure the uniform distribution of the suction pressure, a sand layer is placed on the ground beforehand. The suction (negative pressure) generated by the vacuum system causes the water in the pores of the soil to move towards the surface because of the hydraulic gradient set up. The flow of water in the subsoil is improved with the use of

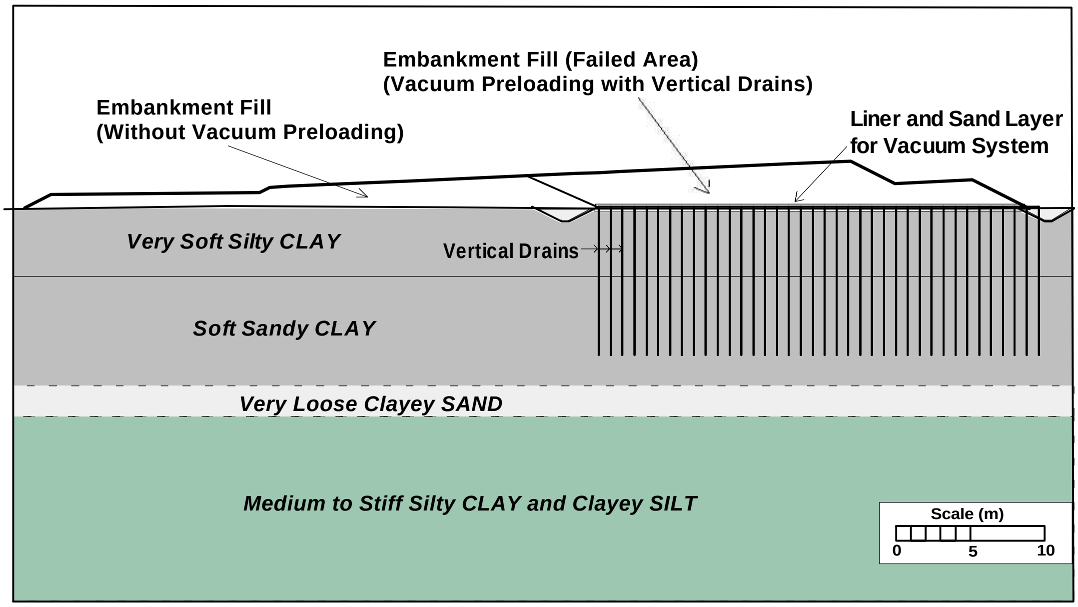

Figure 1 : Cross-Section of Embankment Treated with Vacuum Preloading Method

vertical drains. Figure 1 shows the typical cross section of the embankments reviewed.

The advantages of using the vacuum preloading methods are as follows :

(a) The suction generated is about 80 kPa which is equivalent to about 4m of fill. Therefore, the low embankment (usually less than 4m) can be constructed in a single stage with shorter time.

(b) Vacuum preloading causes isotropic stress increment (both the increases in vertical and horizontal directions are the same) in the subsoil, therefore does not pose stability concern and also increase the rate of consolidation.

(c) Vacuum preloading also reduces the lateral outward movement of the subsoil under loading (undrained creep).

The effectiveness of the method is dependent on many factors like the pump capacity, the airtight seal between the edge of the geomembrane and the subsoil and integrity of the geomembrane at the ground surface and effectiveness of the vertical drains, etc.

3 THE SITE

The embankments were constructed on a very soft silty Clay of 4.5m thick and underlain by a layer of soft sandy Clay to a depth of about 12m. Beneath these very soft to soft cohesive soils is a layer of loose clayey Sand follows by layers of medium to stiff silty Clay and sandy Clay. The subsoil profile is also shown in Figure 1. Figure 2 shows the undrained shear strength (s_u) profile of the subsoil obtained from the field vane together with the adopted design values. The sensitivity of the soft clay generally ranges from about 2 to about 10 and can be categorized as sensitive to extra sensitive clays according to definition of sensitivity by Skempton and Northey (1952).

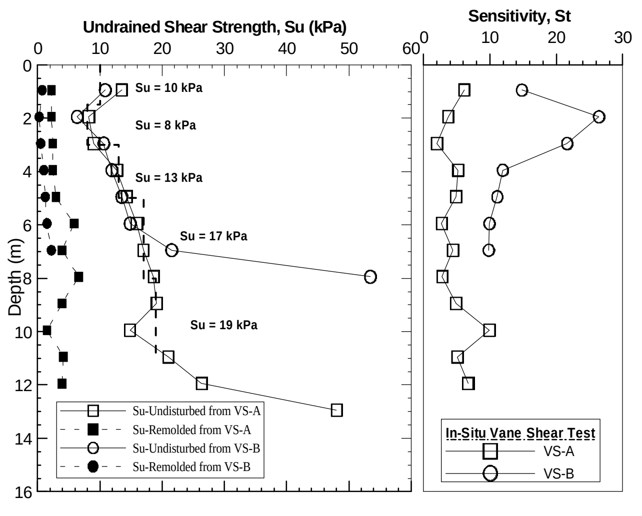

Figure 2 : Undrained Shear Strength Profile

4 CONSTRUCTION & MONITORING

Instruments like piezometers, settlement gauges and vacuum meters have been installed with the intention to monitor the performance of the embankments treated using vacuum preloading. For this case history investigated by the Authors, only the results of the piezometers showing the response of pore water pressures will be discussed as the results of the settlement monitoring and vacuum meters did not show any trend to indicate signs of failure.

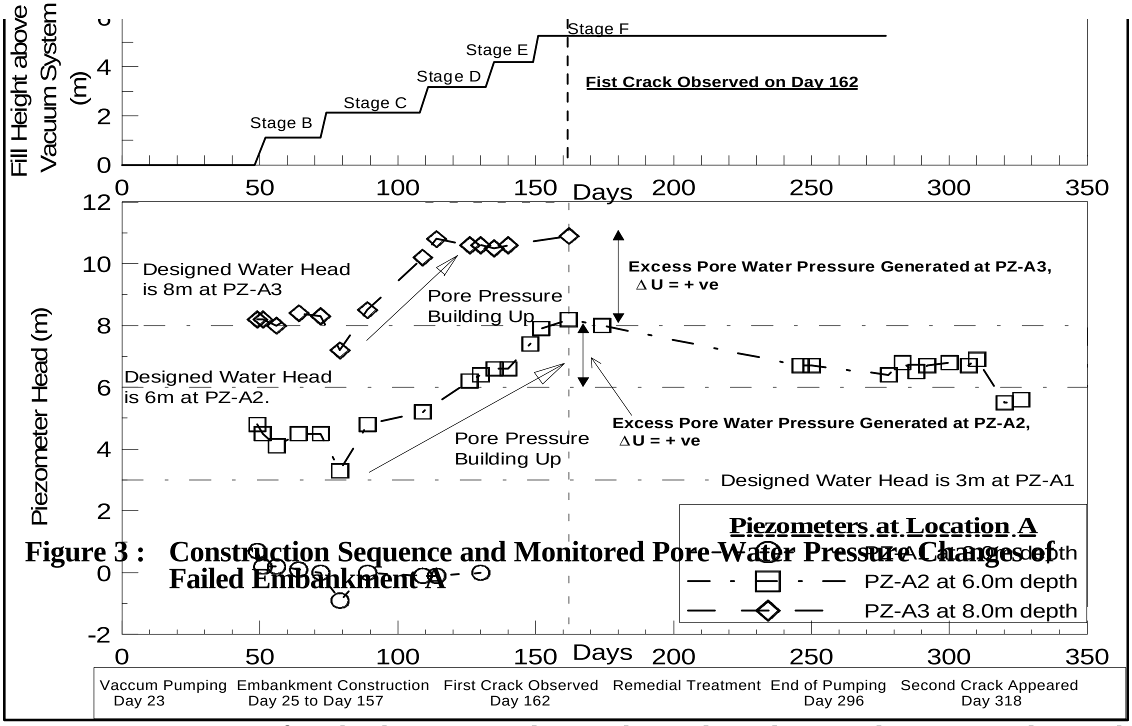

Figure 3 : Construction Sequence and Monitored Pore-Water Pressure Changes of Failed Embankment A

The construction sequence of Embankment A and changes of pore water pressures of the piezometers in the subsoil at depths 3m, 6m and 8m throughout the construction are shown in Figure 3. Embankment A failed not long after reaching the final height.

As shown in Figure 3, from Stage C filling onwards, the pore water pressures measured from piezometers PZ-A2 and PZ-A3 at depths of 6m and 8m respectively increased until failure at Day162 after reaching the final fill height. Piezometer PZ-A1 at 3m deep did not show increase in pore water pressure until it was out of order after Day 130. In brief, the measurement from piezometers PZ-A2 and PZ-A3 at Embankment A indicated that the vacuum suction at these depths were not functioning properly to prevent increase in pore water pressures in the cohesive subsoil with respect to the filling.

The trend of increase in pore water pressures have been observed for more than one month but no contingency action was taken by the Contractor, who was also responsible for the design, to investigate the causes and to stop filling until the pore water in the subsoil return to the allowable design values.

The independent analyses carried out by the Authors employing both Undrained Strength Analysis (Ladd & Foott, 1974; Ladd, 1991) and Effective Stress Method also indicate that the design of the vacuum preloading was acceptable if the vacuum system performed as designed. Therefore, if the Contractor had taken the initiative to review the monitoring results of the piezometers installed in the subsoil as part of the required procedures for vacuum preloading method, the failure could have been prevented because the trend of increase in the pore water pressures in the subsoil was very clear and easily identified.

Embankment B, which was not far away from Embankment A and employed the same vacuum preloading ground treatment, was successfully constructed. Figure 4 shows the changes of pore pressures in the piezometers at different depths throughout the construction of Embankment B. The filling sequence is also presented in the same figure for easy reference. The pore pressures in all the piezometers installed were within the designed range indicating the vacuum suction performed as per design. This finding further confirms that the failure of Embankment A was not due to design but rather due to lack of proper construction control.

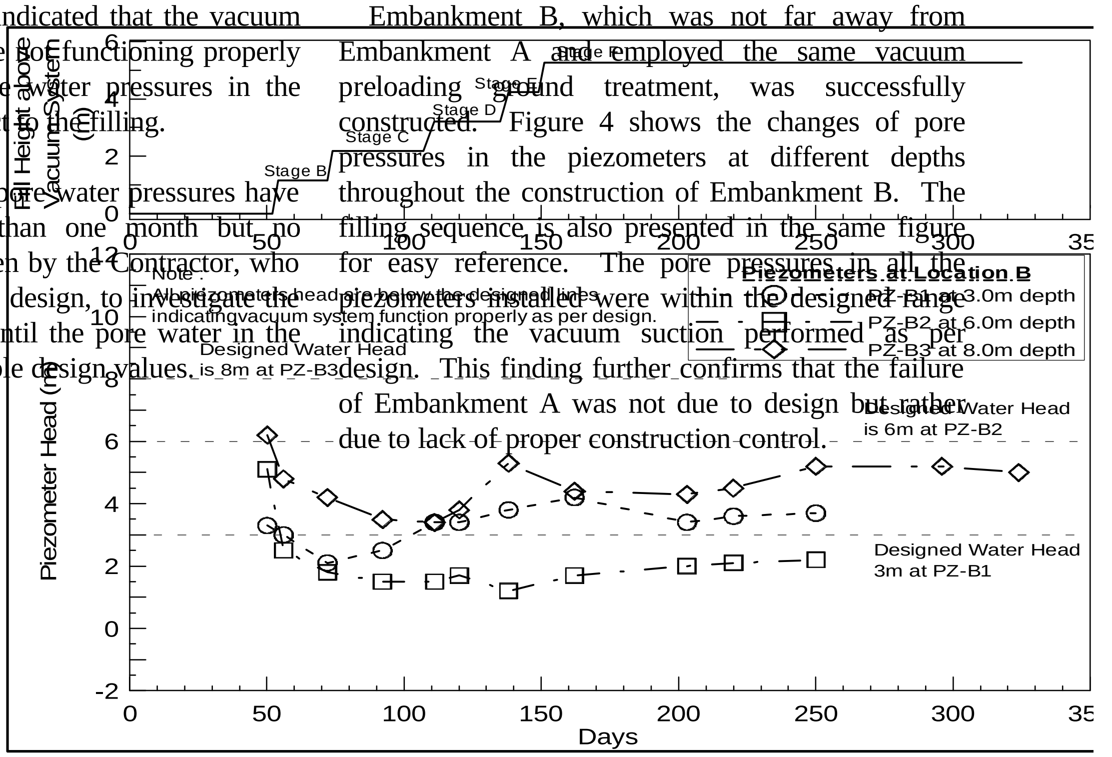

Figure 4 : Construction Sequence and Monitored Pore Water Pressure Changes of Successfully Constructed Embankment B

The observations from two embankments clearly show the importance of observational approach when employing vacuum preloading method for embankment construction. It also shows the effectiveness of the observational approach in identifying problems well before failure provided that the site engineer supervising the work and the design engineer constantly review the monitoring results obtained from the site. In brief, the failure of Embankment A would had been prevented if engineers had observed the changes of pore water pressure in PZ-A2 and PZ-A3 and take necessary action.

5 RECOMMENDED CONSTRUCTION CONTROL

It is very important for the engineer responsible for the design of the vacuum preloading system to be involved in supervision and monitor the performance of the system during construction and also post construction. The monitoring results should be immediately reviewed once available and compared with the allowable design limit to check for any abnormities that could cause failure or influence the expected performance of the treatment. Some details on the construction control of embankment are described by Tan & Gue (2000).

Following are some of the general procedures to be implemented :

(1) Instruments to be used are :
  - Piezometers (preferably vibrating wire type) at different depths of the subsoil to be treated.
  - Settlement Gauges on the original ground level before filling to measure the settlement of subsoil.
  - Extensometers (e.g. Sondex probe extensometer, spider magnet type, etc) to measure the settlement at different depths of the subsoil.
  - Settlement Markers on top of the embankment after reaching the final filling level.
  - Displacement Markers or Inclinometer at the toe of the embankment to measure lateral displacement.

(2) During filling, the frequency of monitoring should be daily or alternative day depending on the Factor of Safety (FOS) against slip failure for each stage of filling. Usually, the FOS is higher for the early stages of filling but as the height of the embankment increases, the FOS reduces. In brief, if the FOS is critical, the monitoring should be daily.

(3) After completion of each stage of filling and during the rest period, the frequency of monitoring can be reduced depending on the allowed rest period, some general guidelines are as follows :
  - Once a week for one month
  - Once every two weeks for two months
  - Once a month for the rest of the rest period.

(4) The design engineer should closely coordinate with the supervising engineer at site. If possible, the design engineer should be at site monitoring the performance of the ground treatment during filling.

(5) The monitoring results should be interpreted, checked and reviewed immediately after reading at site. These results should be compared with allowable design values and ultimate design values to evaluate the relative FOS at site. If the monitoring results is doubtful, redo the monitoring. If necessary, carry out back analyses with the monitored results.

(6) If the monitored values exceeded the allowable design values, contingency measures should be taken such as :
  - Increase the frequency of monitoring.
  - Stop filling or slow down the filling rate.
  - Find out the causes of the abnormal results.
  - Analyses should be carried out incorporating the findings from the monitoring results to validate the design parameters used (e.g. soil strength, unit weight, etc.).

6 CONCLUSION

The case history has shown that the observational method can achieve its main objectives – assurance of complete safety during construction. However, it is very important for the engineers to remember that no matter how good the monitoring scheme installed and methods employed, if the personnel involved (design engineer and supervising engineers) are not committed and do not review the data constantly and compared with allowable design values, the design will not benefit from the observational method.

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