Embankments on Soft Clays

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Introduction

Embankments on soft clays are relatively well understood and the number of researches presently performed on related topics is rather limited. This presentation is thus mainly a general overview on the behavior of clay foundation under embankments. However, some avenues for research exist and are indicated.

Behavior during construction

Observation of clay foundation behavior during embankment construction has shown several features that have important consequences on stability, pore pressures at the end of construction, settlements and lateral displacements. The main features are that there is partial consolidation during the early stages of construction, whereas the clay is in its overconsolidated domain, and that the preconsolidation pressure is generally reached during construction (Tavenas and Leroueil, 1980).

Stability

Stability of embankments on soft clays is generally examined by limit equilibrium analyses; another approach is to use deformation analyses, generally based on finite element methods (Leroueil et al., 2001). Ladd (1991) defined three types of stability analyses: (a) effective stress analysis (ESA); (b) total stress analysis (TSA); and (c) undrained strength analysis (USA).

Except at the time of failure, effective stress analyses (ESA) overestimate the factor of safety.

The undrained strength analysis (USA) has been advocated by Ladd and Foott (1994). The SHANSEP technique they proposed is however complex and ignores the influence of microstructure on strength.

Numerous approaches have been proposed for total stress analyses (TSA). They can be based on: vane shear strength; a combination of compression, extension and direct simple shear strengths (Recompression technique); UU strength; DSS strength; large strain strength (USALS); a fraction of preconsolidation pressure; a fraction of net tip resistance obtained with the piezocone. In practice, it is recommended to consider at least two of these methods and to take into account local experience (Leroueil et al., 2001).

An alternative to limit equilibrium stability analyses is the use of deformation analyses, such as FEM analyses. One example is briefly presented in comparison with other more conventional approaches.

Pore pressures

Due to partial consolidation of the clay foundation during construction, the vertical effective stress generally reaches the preconsolidation pressure during construction. As a consequence, the excess pore pressures to dissipate after construction are given by the difference between the final effective stress profile and the preconsolidation pressure profile (Tavenas and Leroueil, 1980).

Settlements

The total settlement is the sum of four components (Leroueil et al., 1985 & 1990):

$$S = S_{ri} + S_u + S_{primary} + S_{secondary}$$

in which:

- S_{ri} is the reconsolidation settlement from σ'_{vo} to σ'_p.
- S_u is the undrained shearing settlement occurring during construction.
- $S_{primary}$ is the primary consolidation settlement occurring after construction. According to Hypothesis A (Ladd et al., 1977), the accumulated strain at the end of primary consolidation in situ is equal to that at the end of primary consolidation on a thin specimen in the laboratory. According to Hypothesis B (Ladd et al., 1977), creep would occur during primary consolidation in situ and, consequently, the accumulated strain at the end of primary consolidation in situ is larger than that at the end of primary consolidation on a thin specimen in the laboratory. According to Mesri et al. (1994), Hypothesis A would be valid. However, from this author's experience, and because clay behaviour is strain rate dependent whatever the soil is during primary or secondary consolidation, Hypothesis A is not valid and underestimates field settlement (Leroueil, 1996). However, because of several compensating factors, sampling disturbance in particular, the 24hrs oedometer test results can be used for evaluating the end of primary consolidation settlements of ordinary embankments.
- $S_{secondary}$ is the secondary consolidation settlement that occurs after the end of primary consolidation in situ.

Consolidation

Post-construction consolidation occurs in the normally consolidated domain and its rate is controlled by the coefficient of consolidation associated with the normally consolidated domain. It is however important to have in mind that c_v values graphically deduced from laboratory consolidation tests underestimate field values (Leroueil et al., 1985 & 1990).

Lateral displacements

The lateral displacements directly reflect the effective stress path followed during construction and after. They can relatively simply be related to settlements (Tavenas et al., 1979).

Evaluation of strength under embankments for staged construction

Contrarily to first-stage loadings for which many failures have been observed, there have been very few well documented failures during staged construction. As a consequence, stability methods have not been calibrated and are generally extension of methods used for first-stage construction.

When considering staged construction, it appears useful to refer to the compression curve and soil conditions along that curve, at the considered time, for discussing strength that can be mobilized during further loading. In multiple stage construction, clay foundation is generally normally consolidated.

As for first stage loading, there are three possible approaches for studying stability: ESA, USA and TSA.

The effective stress analysis (ESA) can provide a factor of safety representative of the situation at the considered time, but not for further loading.

The undrained strength analysis (USA), advocated by Ladd (1991), uses strength defined as $S_u = \alpha\sigma'_{vc}$ where σ'_{vc} is the vertical effective stress under the embankment and α is a factor that depends on the soil and local mode of failure that can be compression, extension or simple shear in the SHANSEP approach. Two remarks can be made: (a) in particular due to arching phenomena under embankments, it is not easy to define effective vertical stress; (b) when subjected to horizontal shear stress during consolidation, as it is the case under embankments, the strength mobilized in simple shear conditions is larger than that measured in conventional direct simple shear test (Ladd, 1991).

Total stress analyses (TSA) have been examined (Leroueil et al., 2001). An increase in undrained shear strength is observed under embankments; the main conclusions are:

- The vane shear strength, that is corrected for a first-stage loading does not need to be corrected for further stage loadings.
- The increase in net tip resistance ($q_T - \sigma_{vo}$) obtained with the piezocone under an embankment directly indicates the increase in undrained shear strength.

Another approach consists in associating settlements with vertical effective stress on the compression curve and then with strength. A case history is used for illustrating this aspect.

Challenges

The behavior of soft clay foundations under embankments is well understood and failures are now rather seldom. So, present researches are focused on some technologies aiming at improving soils and soil response: Vacuum preloading and electro-osmosis that generate consolidation of the clay deposit and increase its strength without loading; reinforcement of embankments that improves stability (Leroueil and Rowe, 2001). There are also researches that are associated with new problems: in relation with high-speed trains; in relation with widening of existing embankments. There are finally research needs for validating numerical models.

Some references

Ladd, C.C. 1991. Stability evaluation during staged construction. J. Geotech. Engrg. Div., ASCE, 117(4): 540-615.

Ladd, C.C. and Foott, R. 1994. A new design procedure for stability of soft clays. J. Geotech. Engrg. Div., ASCE, 100(7): 763-786.

Ladd, C.C., Foott, R., Ishihara, K., Schlosser, F. and Poulos, H.G. 1977. Stress-deformation and strength characteristics. State-of-the-Art Report. Proc. 9th Int. Conf. on Soil Mech. And Found. Engrg., Tokyo, Vol. 2: 421-494.

Leroueil, S. 1996. Compressibility of clays: Fundamental and practical aspects. J. Geotech. Engrg., ASCE, 122(7): 534-543.

Leroueil, S. and Rowe, R.K. 2001. Embankments over soft soil and peat. Chapter 16 of the “Geotechnical and Geoenvironmental Engineering Handbook”, Kluwer Pub., pp. 463-499.

Leroueil, S., Demers, D. and Saihi, F. 2001. Considerations on stability of embankments on clay. Soils & Foundations, 41(5): 117-127.

Leroueil, S., Magnan, J.P. and Tavenas, F. (1985, 1990). Embankments on Soft Clays. Published in French (1985) by Lavoisier, Technique et Documentation, Paris; published in English (1990) by Ellis Horwood, Chichester, England.

Mesri, G., Lo, D.O.D. and Feng, T.W. 1994. Settlement of embankments on soft clays. Proc. Conf. on Vertical and Horizontal Deformations of Found. and embankments: Settlement ’94, Geotech. Spec. Publ. No. 40, ASCE, Vol. 1: 8-56.

Tavenas, F. and Leroueil, S. 1980. The behaviour of embankments on clay foundations. Canadian Geotech. J., 17(2): 236-260.

Tavenas, F., Mieussens, C. and Bourges, F. 1979. Lateral displacements in clay foundations under embankments. Canadian Geotechnical J., 16(3): 532-550.