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ANALYSIS OF FOUNDATION STABILITY OF MARINE RETAINING BUNDS, DURING CONSTRUCTION STAGES, USING EFFECTIVE STRESS

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Summary

Staged construction uses controlled rates of loading to enable soil strengthening via consolidation, in order to increase the foundation stability. The use of total stress analysis assuming instantaneous loading can sometimes lead to excessive conservatism as it makes no allowance for an effective strength gain that will occur during staged construction.

Experimental determination of consolidation parameters CV and A can allow an estimate to be made of the excess pore water pressure dissipation for any given length of time. The designer can then calculate the stability of the foundations at any given stage of construction using an appropriate effective stress stability analysis method.

Using effective stress analysis allows for an efficient design solution in which load timing can be manipulated to maintain adequate foundation stability. With an effective stress method design assumptions can be verified using piezometers to monitor the excess pore water pressures during construction.

Studies of three marine reclamation bund failures have verified that the effective stress method of analysis does give reasonable predictions of the actual factor of safety.

INTRODUCTION

As a load is placed on to a soil it induces excess pore water pressures (EPWP) within the soil. As the EPWP dissipates the load induced by construction is transferred from the pore water within the foundation soil, to the soil skeleton. This transfer of load from the water to the soil increases the effective stress in the soil which will generally increase the foundation stability. In terms of total stress, the consolidation that occurs as a result of EPWP dissipation will increase the undrained shear strength of the soil as the soil becomes denser.

Typically a design can be achieved that has a sufficient factor of safety (FOS) for the long-term (drained) condition. Difficulties can arise when trying to achieve an adequate FOS during construction. Total stress stability methods assuming instantaneous loading do not account for this strength gain and so can lead to excessive conservatism when construction is staged.

This paper describes a method of determining the rate at which the foundation strength gain occurs, making it possible to assess the structures stability at various stages of construction. This allows the construction rate to be timed so that adequate factors of safety are maintained at all times during the construction sequence.

The effective stress analysis method described is based on a combination of various classical soil mechanics principles. This method was used in order to study three marine reclamation retainment bund failures that have occurred around the Auckland, Waitemata harbour between 1995 and 1996. Each of the three failures of the rock retainment bund occurred during the period that the reclamation behind the bund was being filled. All three failures have subsequently been shown to exhibit adequate long term (drained) stability.

DISCUSSION

Bishop and Bjerrum (1) proposed that an effective stress analysis "is a generally valid method for analysing any stability problem and is particularly valuable in revealing trends in stability that would not be apparent from total stress methods" and advocated its use for analysing staged construction.

Calculation of effective stress

As the EPWPs induced by the applied load dissipate there is a decrease in water uplift pressures and hence an increase in effective vertical stress. All else being equal this increase in effective vertical stress will normally increase the frictional resistance along any shear surface and so will increase the stability of the bund.

In order to assess the rate at which the effective stress increases, the designer must assess:

- The excess pore water pressures induced within the foundation material due to initial and any additional loadings placed.
- The rate at which the pressures will dissipate at any given point within the soil foundations.

The designer can then use the EPWPs to analyse the stability of the bund and reclamation using conventional effective stress methods.

EPWP due to loading

The vertical stress (total) distribution induced by the loads can be estimated using contours of equal stresses or pressure bulbs from Teng (2).

The amount of EPWP initially induced by the increased vertical load will depend on the load's lateral distribution and the preconsolidation history of the foundation soils.

When an undrained saturated soil is loaded, a proportion of the load is initially supported by the pore fluid with the remainder being supported by the soil skeleton. The proportion of load supported by the pore fluid (i.e EPWP) is given by the pore pressure parameter A.

$$\text{i.e } \Delta u = A \Delta \sigma$$

where Δu = Change in excess pore water pressure

and $\Delta \sigma$ = Change in total stress

The pore pressure parameter A can be determined experimentally see Lamb and Whitman (3). Table 1 shows some typical vales for A.

Material (saturated)	Pore pressure parameter A
Very sensitive soft clays	>1
Normally consolidated clays	½ to 1
Over consolidated clays	¼ to ½
Heavily over consolidated sandy clays	0 to ¼

Table 1 Pore pressure parameter A, from Skempton and Bjerrum (4)

For saturated, soft, normally consolidated to slightly over consolidated soils all or most of the applied loading will initially be transmitted to EPWP rather than the soil structure. It is therefore a conservative approximation to assume that the EPWP induced within the foundation soils will be equal to 100% of the applied vertical load distribution (i.e A=1.0).

For a laterally confined, saturated material where no lateral displacement of the soil is possible, A will be 1.0 regardless of the soil properties.

Material densities

The use of soil and rock densities in calculating the applied loadings needs careful consideration. The effective load of the porous bund will vary because uplift pressures within the bund will vary due to tidal fluctuations. Eventually the soils will consolidate under the maximum load applied which occurs at low tide. During the finite period of construction the foundation soils will probably only consolidate towards the mean load applied. Densities should therefore be calculated using:

- Bulk density for material placed above mean sea level
- Buoyant density for any material placed or removed from below mean sea level

Once the initial EPWP distribution has been calculated the rate at which the EPWPs dissipate should be determined.

EPWP dissipation

The EPWP dissipation within the soil foundation can be estimated in a number of ways. The most accurate is by using a finite difference model. The finite difference model can be calculated using a simple spreadsheet but more specialised commercial software is also available. For a quick check or for less detailed projects where dissipation can be assumed to be in a vertical direction only, a one dimensional finite difference model can be adopted. For a uniform initial EPWP distribution, vertical dissipation can be approximated using "degree of consolidation" curves from Lambe and Whitman (3).

Dissipation modelling equations

Based on Terzaghi's Consolidation theory the governing differential equation relating excess pore-water pressure, position and time can be derived as:

$$\frac{\partial u}{\partial t} = Cv \frac{\partial^2 u}{\partial z^2} \qquad (1)$$

where CV = coefficient of consolidation
u = excess porewater pressure
t = time
z = drainage distance

This equation can be developed into a model with dissipation in one dimension. The EPWP in the cell x=n, y=n at t=n+1 assuming vertical dissipation only, is given by equation (2).

$$u(y_n,t_{n+1}) = u(y_n,t_n) + \beta\left(u(y_{n+1},t_n) + u(y_{n-1},t_n) - 2u(y_n,t_n)\right) \quad (2)$$

and with two dimensional dissipation

$$u(x_n,y_n,t_{n+1}) = u(x_n,y_n,t_n)+\beta\big(u(x_{n+1},y_n,t_n)+u(x_{n-1},y_n,t_n) +u(x_n,y_{n+1},t_n)+u(x_n,y_{n-1},t_n)-4u(x_n,y_n,t_n)\big) \quad (3)$$

where β is a dimensionless coefficient

$$\beta=\frac{Cv\,\Delta t}{z^2} \quad (4)$$

and z = the distance between cell centres

The coefficient of consolidation (CV) can be directly measured from an oedometer test, described in NZS 4402:1986.

As for all finite difference models accuracy is proportional to the time step (Δt). Appropriate selection of boundary conditions is also essential. The excess porewater pressures will be zero at any free surface and will be zero a large horizontal distance from the applied load. The designer must also assess whether double or single drainage is occurring within the foundation layers. If single drainage is occurring, at the horizontally impervious boundary dissipation will only occur horizontally and vertically away from the boundary. The EPWP in the model cells above the horizontal impervious boundary can be modelled using equation (5).

$$u(x_n,y_n,t_{n+1}) = u(x_n,y_n,t_n)+\beta\big(u(x_{n+1},y_n,t_n)+u(x_{n-1},y_n,t_n) +u(x_n,y_{n+1},t_n)-3u(x_n,y_n,t_n)\big) \quad (5)$$

The initial loading and any subsequent lifts in bund or reclamation height should be added to the model at the appropriate time steps.

The uplift pressures within the soil foundations at a given time can be determined by adding the EPWP to the static background water pressures. For soils below mean low water, the static water pressures will closely correspond to a piezometric level at mean sea level.

Figure 1 shows the EPWP calculated beneath a marina bund 13 months after the rock bund was placed. The reclamation fill was progressively raised over the same 13 month period. Single drainage was assumed to occur because of the underlying lower permeability mudstone.

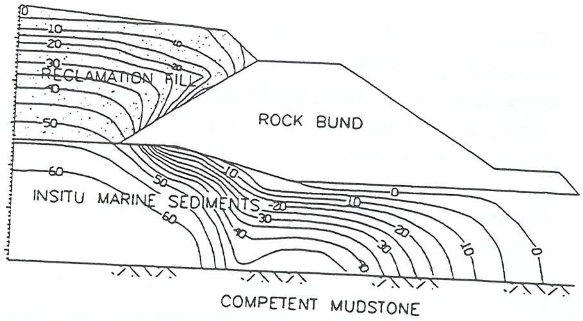

FIGURE 1: EPWP beneath a marina bund 13 months after bund placement

Calculation of FOS

The construction should be staged so that easy checks can be made on stability and the rate of construction can be controlled by the designer. The FOS at any of the proposed stages can be easily calculated using an effective stress stability analysis. Estimates of uplift pressures at each stage can be derived from the method described above.

Effective strength parameters can be established by:

- confined triaxial testing
- preloading a test structure to failure

The critical case for bund stability will occur at low tide when the water surcharge on the toe is at a minimum. This case should be analysed using the lowest tide likely to occur during the construction period, noting that barometric pressures can further reduce the predicted low tide levels significantly. All of the failures studied occurred at or very close to low tide.

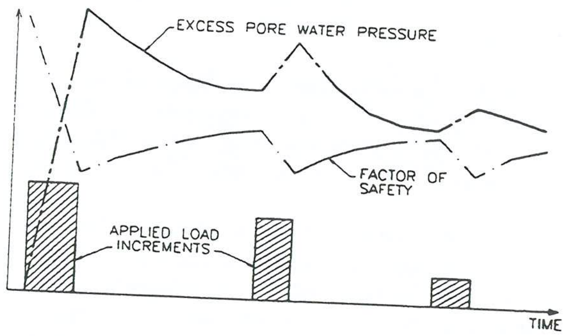

FIGURE 2: Schematic relationship between staged load application, EPWP and FOS.

As the EPWP increase immediately as further load increments are applied, critical times during construction will be as the loadings are applied. Figure 2 schematically shows how the FOS changes relative to the load sequencing.

Monitoring

Piezometers with low water volume requirements such as pneumatic piezometers, should be installed, preferably prior to bund construction. Early installation will give background pore water pressures and will show the peak pressures as well as the initial and most rapid excess pore pressure decrease.

Standpipe piezometers are not suitable for this situation as they require large fluid volume changes to register small changes in pressure which will affect the pressures in the surrounding soils.

Settlement monitoring is a good indication that pressures are dissipating or increasing (ie. settlement will stop) as expected, it is however difficult to get a correlation of EPWP from settlement.

It is important that the piezometers are installed by, or at least supervised by an experienced geotechnical engineer who is familiar with piezometer installation and understands the implications of defective monitoring equipment.

To achieve the best results from piezometer monitoring, the piezometer tips should be installed close to the most likely failure plane were EPWPs are expected to be greatest.

Alarm levels should be set on piezometer pressures, and construction of any stage should not commence or proceed until pressures have dissipated to pre-established safe levels.

Construction programming

It is important to consider the amount of time which will be required for pressure dissipation during the construction programme. If possible the construction programme should be flexible to allow for delays in construction should slower than anticipated pore pressure dissipation occur.

Accuracy of determining FOS

For the actual failures studied the degree of field testing was reasonably good and the model used was reasonably detailed. The factors of safety calculated using the described method were in the range of 0.93 to 0.98 for each of the study failures.

The greatest uncertainty exists in estimating the rate of pore pressure dissipation from consolidation theory, see Bishop and Bjerrum (1). The observed rate of settlement of structures is invariably quicker than that calculated from oedometer test results carried out on small samples, see Simons and Menzies (5). This is because thin layers or lenses of sand or rootholes can result in higher permeabilities which will cause faster than expected dissipation of EPWP.

The assumptions made during design can and should be verified during construction using piezometer monitoring.

If the settlements of the structure are anticipated to be large the following factors may affect the rate at which dissipation occurs.

- Drainage length will shorten with time as the soil compresses.
- As the structure settles a larger proportion of the load will become buoyant and so may reduce the effective vertical stress.
- As the soils consolidate and become more dense there may be a decrease in permeability.

The significance of each of the above factors will be project specific and so should be considered independently by the designer.

Conclusions

Invariably the critical time for the stability of structures placed over soft saturated foundations is during construction, when excess pore water pressures induced by applied loading remain high within the foundation soils.

The use of total stress analysis assuming instantaneous loading can sometimes lead to excessive conservatism as it makes no allowance for an effective strength gain due to dissipation of excess porewater pressures.

Experimental determination of consolidation parameters CV and A can allow an estimate to be made of the EPWP dissipation at any given time. The designer can then calculate the stability of the structure at any given stage of construction using an appropriate effective stress analysis.

Using effective stress analysis allows for an efficient design solution where the rate of construction can be controlled to maintain adequate foundation stability. The assumptions made in design can be verified using piezometers to monitor the excess pore water pressures during construction.

References

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