NRC Publications Archive Archives des publications du CNRC

Undrained strength anisotropy in embankment stability analysis

Law, K. T.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

Canadian Geotechnical Journal, 15, 2, pp. 306-309, 1978-05

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=d24e1f56-b254-462a-b545-5acd133b0c1a>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=d24e1f56-b254-462a-b545-5acd133b0c1a>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Copy 1

6532

TH1
N21d
0.767

National Research
Council Canada

Conseil national
de recherches Canada

UNDRAINED STRENGTH ANISOTROPY IN EMBANKMENT STABILITY ANALYSIS

by K. Tim Law

Reprinted from
Canadian Geotechnical Journal
Vol. 15, No. 2, May 1978
p. 306-309

03633

DBR Paper No. 767
Division of Building Research

Price 10 cents

OTTAWA

NRCC 16594

NOTE

Undrained strength anisotropy in embankment stability analysis

K. TIM LAW

Division of Building Research, National Research Council of Canada, Ottawa, Ont., Canada K1A 0R6

Received May 9, 1977

Accepted January 11, 1978

An approximate stability analysis taking strength anisotropy into account is proposed, from which various correction curves are established. Examination of these curves shows that there is one particular constant correction factor applicable to most practical situations of embankment construction. This can be written as $S_a = 0.95C_m$ where S_a is the available subsoil strength and C_m the mean strength from the vertical and horizontal specimens. This expression is shown to be in agreement with existing field experience.

Une méthode approximative d'analyse de stabilité qui tient compte de l'anisotropie de résistance et qui a permis de mettre au point diverses courbes de correction est proposée. L'examen de ces courbes montre qu'il existe en particulier un facteur de correction constant qui est applicable aux cas les plus pratiques de construction de remblais. Cette correction se présente sous la forme suivante: $S_a = 0.95C_m$ où S_a est la résistance disponible dans la fondation et C_m est la résistance médiane provenant de mesures sur des échantillons horizontaux et verticaux. Il est démontré que cette expression est en accord avec les observations de cas existants en nature.

Can. Geotech. J., 15, 306-309 (1978)

Introduction

Recent research in undrained shear strengths demonstrates that strength anisotropy and rate effect are of great importance in the stability of embankments founded on soft clays. An attempt to account for both factors has been based on records of failure from which an empirical relationship was established (Bjerrum 1972; Dascal and Tournier 1975). As shown by Schmertmann (1975), this approach is subject to a number of uncertainties that might invalidate its general application. To improve the approach, it is necessary to study each factor separately. This note proposes a correction factor for the effect of anisotropy.

Stability Considerations with Anisotropy

Studies to establish a functional relationship for strength anisotropy in soils have been conducted by a number of researchers (e.g. Casagrande and Carrillo 1944; Lo 1965; Davis and Christian 1971). In this study, a functional relationship in terms of the square of the direction cosine (Lo 1965) is assumed. With reference to Fig. 1, the strength variation is written as

$$[1] \quad C_i = C_h + (C_v - C_h) \cos^2 i$$

where i is the angle between the major principal stress and the vertical and C_v , C_h , C_i are the strengths for vertical, horizontal and inclined specimens, respectively (C_v and C_h can also be

$$C_i = C_h + (C_v - C_h) \cos^2 i$$

FIG. 1. Definition of i .

determined from active and passive tests on vertical specimens).

Consideration of moment equilibrium of an embankment on the soil (Fig. 2) leads to the following approximate expression of the safety factor F :

$$[2] \quad F = \int_{-\alpha}^{\alpha} \frac{2C_i r^2 d\theta}{h\gamma_f r^2 \sin^2 \alpha}$$

FIG. 2. Definition of geometric parameters for stability analysis.

where: r is the radius of the slip circle; 2α is the subtended angle at the centre of the slip surface lying in the subsoil; h , γ_f are the height and density of the embankment, respectively.

Derivation of the foregoing equation is based on a critical circular slip surface represented by the midpoint circle (Taylor 1937), on a vertical tension crack through the embankment and on r being greater than h .

Noting that $i = \beta - \theta$, where β is the angle between the failure plane and the minor principal stress (Fig. 2), one obtains from [2]

$$[3] \quad F = 4\alpha S_a / h\gamma_f \sin^2 \alpha$$

where S_a , the average available strength over the slip surface, is given by

$$[4] \quad S_a = C_v \left[\frac{(1+R)}{2R} + \frac{R-1}{4R\alpha} \sin 2\alpha \cos 2\beta \right]$$

where $R = C_v/C_h$.

Minimizing F gives an expression for evaluating α , that is,

$$[5] \quad \alpha = \frac{\tan \alpha}{2} \left[1 - \frac{R-1}{R+1} \cos 2\beta \right]$$

with $0 < \alpha < \pi/2$.

For an isotropic soil, $R = 1$ and $\alpha = 66.8^\circ$. With substitution in [3], one obtains a stability number, $C_v/F\gamma_f h = 0.181$. This is identical to Taylor's findings (1937) for this particular case. A similar observation was also made by Menzies (1976) for a bearing capacity problem.

For the anisotropic case, evaluation of α requires a knowledge of the value of β . Undrained tests with consolidation pressure at or below the *in situ* value have been reported by Lo (1965), Wong

(1972), and Law and Lo (1976). In these tests β was found to lie between 50 and 60° with a probable mean of about 56° . These values were used in computing α and the results are shown in Fig. 3. It can be seen that α lies in a narrow range of about 58 – 70° . Table 1 shows some values of α from failure records obtained from investigations in which an attempt was made to locate the failure surface. Although the records cover a reasonably wide range of plasticity index, the observed value of α falls within the computed limits.

Estimating Correction Due to Anisotropy

Though S_a can be computed using [4], simplification will result if the following general equation expressible in graphical form is considered:

$$[6] \quad S_a = \mu_r C_r$$

where $C_r = C_v$, C_h or C_m ; C_m is the arithmetic mean of C_v and C_h ; and μ_r is the correction factor

FIG. 3. Variation of α with β and strength ratio.

TABLE 1. Values of α observed from actual failures

Site	Index properties (%)				*Method of locating slip surface	α	Reference
	W	W_L	W_p	I_p			
Rupert	40	33	19	14	I, V	57	Dascal and Tournier (1975)
Portsmouth	50	38	22	16	V	60	Ladd (1972)
Saint-Alban	73	47	25	22	C, V, W	60	LaRochelle <i>et al.</i> (1974)
Matagami	90	85	38	47	P	66	Dascal <i>et al.</i> (1972)
Bangkok	140	150	65	85	W	65	Eide and Holmberg (1972)

*C = cone penetrometer, I = inclinometer, P = piezometer, V = field vane, W = wood sticks.

corresponding to C_v . In the case of C_m , for instance,

$$[7] \quad \mu_m = 1 + \frac{(R - 1) \sin 2\alpha \cos 2\beta}{2(R + 1) \alpha}$$

where α is determined from [5] or Fig. 3.

It should be noted that by virtue of the integration in [2], the variation of strength along the slip surface is taken into account when μ_c in [6] is used. This is different from the correction factor proposed for a similar purpose by Bjerrum (1972) in which case μ varies from point to point along the slip surface. Equation 6 proposed here is therefore much easier to apply.

Figure 4 shows the variations of μ with typical values of R at $\beta = 56^\circ$. Depending on the strength chosen, the correction factor may vary from 0.6 to 1.8. In other words, an indiscriminate choice of strength value without due regard to anisotropy may result in a wide range of possibilities from an underestimation of about 60% to an overestimation of 40%.

Of particular interest in Fig. 4 is the relative insensitivity of μ_m to the strength ratio. Within practical limits, therefore, a single approximate correction factor of 0.95 is deemed adequate. Hence,

$$[8a] \quad S_n = 0.95C_m$$

or

$$[8b] \quad S_n = 0.48(C_v + C_h)$$

Case Histories

The close agreement as derived in the previous section between the available strength accounting for anisotropy, S_n , and the arithmetic mean of C_v and C_h is supported by two case histories.

FIG. 4. Various correction curves for anisotropy.

The first case is a failure of an embankment in Portsmouth, New Hampshire, constructed over a soft sensitive marine deposit (Ladd 1972; Ladd and Foott 1974). C_v and C_h were determined with the consolidated undrained, plane strain active and passive tests, respectively. Using the mean of C_v and C_h , a safety factor of 0.95–1.02 was found, depending on the method of analysis. This record definitely supports [8].

The second case, also reported by Ladd and Foott (1974), is a stable test embankment on Boston Blue clay. The mean of C_v and C_h , again

determined with the plane strain active and passive tests, was used in the stability calculation with a resulting safety factor of 1.5. Comparing the results from other strength data (field vane and unconfined compression), the authors concluded that the mean of C_v and C_h gave an assessment most consistent with the observed performance of the embankment. This record is again in line with the finding of the last section.

Summary and Conclusion

Strength anisotropy is important in embankment stability. Indiscriminate use of any strength may lead to either overconservative or dangerous consequences. When the slip surface is circular with subsoil strength defined in terms of the square of the direction cosine [1], three correction curves are established, depending on the strength used. These curves give correction factors that would account for the strength variation along the entire slip surface. Of particular importance is the correction factor based on the mean strength from vertical and horizontal specimens or, alternatively, from active and passive tests on vertical specimens. This factor has been shown to be relatively constant over the usual range of anisotropy and found to be consistent with field experience.

Acknowledgement

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

- BJERRUM, L. 1972. Embankments on soft ground. Proceedings, ASCE Specialty Conference on Performance of Earth and Earth-supported Structures, Purdue University, Lafayette, IN, Vol. 2, pp. 1-54.
- CASAGRANDE, A., and CARRILLO, N. 1944. Shear failure of anisotropic soils. *Journal of the Boston Society of Civil Engineers*, XXXI(2), pp. 74-87. Also 1953. *In Contributions to soils mechanics 1941-1953*. Boston Society of Civil Engineers. pp. 122-135.

- DASCAL, O., and TOURNIER, J. P. 1975. Embankment on soft and sensitive clay foundation. *ASCE Journal of the Geotechnical Engineering Division*, 101(GT3), pp. 297-314.
- DASCAL, O., TOURNIER, J. P., TAVENAS, F., and LAROCHELLE, P. 1972. Failure of a test embankment on sensitive clay. Proceedings, ASCE Specialty Conference on Performance of Earth and Earth-supported Structures, Purdue University, Lafayette, IN, Vol. 1, Part 1, pp. 129-158.
- DAVIS, D. H., and CHRISTIAN, J. T. 1971. Bearing capacity of anisotropic cohesive soils. *ASCE Journal of the Soil Mechanics and Foundations Division*, 97(SM5), pp. 753-769.
- EIDE, O., and HOLMBERG, S. 1972. Test fills to failure on the soft Bangkok clay. Proceedings, ASCE Specialty Conference on Performance of Earth and Earth-supported Structures, Purdue University, Lafayette, IN, Vol. 1, Part 1, pp. 159-180.
- LADD, C. C. 1972. Test embankment on sensitive clay. Proceedings, ASCE Specialty Conference on Performance of Earth and Earth-supported Structures, Purdue University, Lafayette, IN, Vol. 1, Part 1, pp. 101-128.
- LADD, C. C., and FOOTT, R. 1974. New design procedure for stability of soft clays. *ASCE Journal of the Geotechnical Engineering Division*, 100(GT7), pp. 763-786.
- LAROCHELLE, P., TRAK, B., TAVENAS, F., and ROY, M. 1974. Failure of a test embankment on a soft sensitive Champlain clay deposit. *Canadian Geotechnical Journal*, 11, pp. 142-164.
- LAW, K. T., and LO, K. Y. 1976. Analysis of shear-induced anisotropy in Leda clay. Proceedings, Conference on Numerical Methods in Geomechanics, Blacksburg, VA, Vol. 1, pp. 329-344.
- LO, K. Y. 1965. Stability of slopes in anisotropic soils. *ASCE Journal of the Soil Mechanics and Foundations Division*, 91(SM4), pp. 85-106.
- MENZIES, B. K. 1976. An approximate correction for the influence of strength anisotropy on conventional shear vane measurements used to predict field bearing capacity. *Geotechnique*, 26, pp. 631-634.
- SCHMERTMANN, J. H. 1975. Measurement of *in-situ* shear strength. Proceedings, ASCE Specialty Conference on *In-situ* Measurements of Soil Properties, North Carolina University, Raleigh, NC, Vol. II, pp. 57-138.
- TAYLOR, D. W. 1937. Stability of earth slopes. *Journal of the Boston Society of Civil Engineers*, XXIV (3), pp. 197-246. Also 1940. *In Contributions to soil mechanics 1925-1940*. Boston Society of Civil Engineers. pp. 337-386.
- WONG, P. K. K. 1972. Strength and stress-strain relations of a sensitive clay. Ph.D thesis, Civil Engineering Department, Queen's University, Kingston, Ont.