A DAM ON A THIN SOFT LAYER

BARRAGE SUR UNE COUCHE MINCE D'ARGILE MOU

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SYNOPSIS A method is suggested for determining the construction period of an embankment dam, erected on a thin soft soil layer. The shear strength of the subgrade is calculated by taking into account the degree of consolidation, using experimental curves $\phi = f(w)$ and $c = f(w)$, which indirectly include the pore pressure.
The shortest construction period for the required safety factor for each construction stage is obtained by interpolation from the corresponding safety factor curve in relation to the construction period.
The method can be also applied to other structures erected on thin soft layers.

INTRODUCTION

When erecting a dam on a thin soft soil layer there arises the problem of the maximum construction rate. This rate is governed by the condition that in no stage of the construction work should the shear stress, resulting from the loading, attain the shear strength, corresponding to the respective degree of consolidation. On the basis of a concrete example an approximation method for solving this problem is suggested.

The Poroy Dam will be laid on a complex of silty and sandy clays of an average depth of 11 m. Underneath lie dense, pervious sands and sandy gravels ($k = 8.10^{-2}$ cm/sec) 1-1.5 m deep, followed by rock. The clays of the upper part of the subgrade have a clearly expressed muddy character and are of a very soft consistency. The ground water level almost reaches the surface of the terrain. Fig. 1 shows a section through the maximum profile of the dam.

The calculations showed that the uppermost soft layer, about 4 m deep, should be removed since the dam could not be laid on it. Because of the short construction schedule of the dam (two years), the muddy clays would have inevitably been pushed aside, which could have caused a detrimental differential settlement of the dam.

It was necessary, therefore, to decide to what degree the remaining soil complex was a reliable ground for the erection of this dam.

The solution of such soil mechanical problems, as we know, is complicated by a number of circumstances, the most important being the variation of the subgrade shear strength in time. With the progress of consolidation the shear strength increases. Another factor is the gradual, and not sudden, loading of the ground.

The method applied in this case for solving the problem was developed by MASLOV (1949,

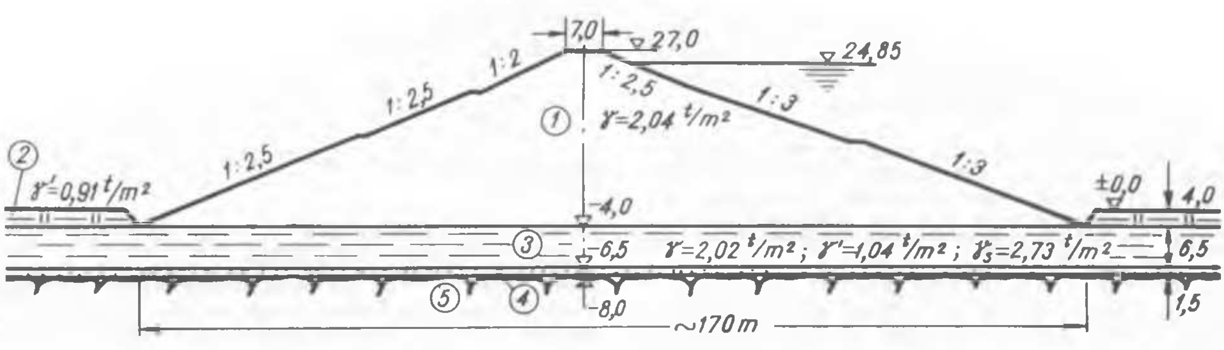

Fig.1 Cross-section through the earth-fill dam and geological profile
1 - embankment; 2 - muddy clays; 3 - silty sandy clays; 4 - dense pervious sands and sandy gravels; 5 - rock.

1961, 1963, 1968). The evaluation of the degree of stability of the subgrade is carried out by taking into account the normal stresses. The following reasons justify the application of this method:

1. The subgrade complex can be assumed as adequately homogenous.
2. The clays, constituting this complex, are saturated.
3. Reliable triaxial tests are not available. The pore pressure in the ground will not be measured during construction and subsequently.
4. This method makes possible a simple and elegant modelling of the natural conditions, provided the above-mentioned points are taken into consideration.

We are not going to describe here in detail this method, which has been published in the above-mentioned references. We shall only briefly explain its main points.

The qualitative evaluation of the subgrade stability is effected by comparing the angle of maximum deviation Θ_{max} (between the resulting stress and the normal to the critical plane through a given point) with the angle of internal friction ϕ_w; thus, the condition for stability is

$$\Theta_{max} < \phi_w \quad .. \quad .. \quad .. \qquad (1)$$

Θ_{max} is determined from the condition of limit equilibrium of O.Mohr

$$\sin \Theta_{max} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2 + 2\gamma(z + D + h_c)}, \qquad (2)$$

where
σ_1 and σ_2 are the principal stresses, in t/m^2;
γ is the average unit weight of the soil, in t/m^3;
z is the depth of the considered point under the foundation base, in m;
D is the depth of foundation, in m;

$$h_c = \frac{c_w}{\gamma \cdot \mathrm{tg}\, \phi_w}, \text{ in m}; \quad .. \quad .. \quad .. \quad .. \qquad (3)$$

c_w and ϕ_w are the cohesion in t/m^2, and the angle of internal friction of the subgrade, respectively, established for a given water content, as will be shown below.

The analysis showed that for certain characteristic points of the ground the inequality (1) is fulfilled, both for the whole construction period and for the intermediate stages of the erection of the earth-fill dam, according to Fig.2.

When determining the principal stresses in equation (2), the solutions of the theory of elasticity are used, which are valid for loading an elastic isotropic semi-infinite space. In our case, however, the subgrade is of a limited depth, since the thickness of the compressible layer is small with respect

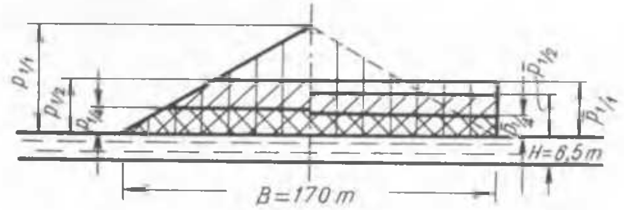

Fig.2 Construction stages

p - maximum load at the end of each construction stage; $\bar{p}$ - reduced load at the end of each construction stage;
1/4 - intermediate period 1/2 year;
1/2 - intermediate period 1 year;
1/1 - whole period 2 years

$p_{1/4} = 18.4\ t/m^2$ $\quad \bar{p}_{1/4} = 15.7\ t/m^2$
$p_{1/2} = 34.7\ t/m^2$ $\quad \bar{p}_{1/2} = 25.2\ t/m^2$
$p_{1/1} = 63.2\ t/m^2$ $\quad \bar{p}_{1/1} = 31.6\ t/m^2$

to the height and the width of the dam. To our knowledge there are no publications on the determination of the principal stresses for a triangular or a trapezoidal load on a soil layer of a limited depth. Since we did not consider these results to be sufficiently reliable, we conducted the analysis as follows:

The calculation of the subgrade stability is carried out using the safety factor

$$F = \frac{\tau_{fw}}{\tau_{max}}, \quad .. \quad .. \quad .. \quad .. \quad .. \qquad (4)$$

where
τ_{fw} is the shear strength at a given water content;
τ_{max} is the shear stress in the subgrade due to the load of the dam.

The shear stress τ_{max} in the subgrade due to the load of the dam is determined with the formula of L.K.Jurgenson (CREAGER et al,1966; MASLOV, 1949). It is valid for a thin layer ($H < \frac{B}{4}$) under a uniform strip load and is of the following type:

$$\tau_{max} = \bar{p}\, \frac{2H}{B}\ (t/m^2) \quad .. \quad .. \quad .. \qquad (5)$$

The notations $\bar{p}$, H and B are indicated in Fig.2.

We assume that the load at each construction stage, including the final, is a uniform, reduced load $\bar{p}$. It is determined from the condition that the total load on the width B, caused by the trapezoidal, respectively the triangular load, for each stage, should be equal to the total loading from the respective reduced uniformly distributed (rectangular) load on the same width B.

The shear strength τ_{fw} is determined by the formula

$$\tau_{fw} = p.\mathrm{tg}\,\phi_w + c_w. \quad \ldots \quad (6)$$

The method for determining the shear strength as a function of the water content w was developed by MASLOV (1949, 1961). The angle of internal friction ϕ_w and the cohesion c_w of the subgrade are obtained from the diagram in Fig.3. The method for plotting the curves

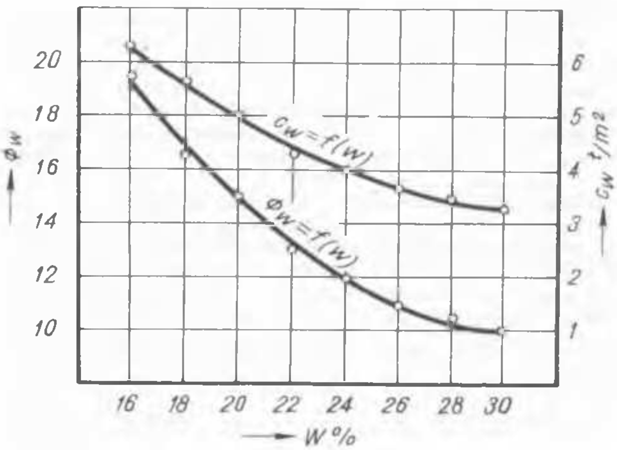

Fig.3 Strength parameters ϕ_w and c_w in relation to the water content w

$\phi_w = f(w)$, respectively $c_w = f(w)$, will not be described here. It is given in detail in the already mentioned works by N.N.Maslov. The idea to use formula (4) for determining the safety factor of the subgrade for different time intervals after construction starts, that is, for different degrees of consolidation of the subgrade, is as follows. Since the subgrade is saturated*/, it is evident that the degree of consolidation will result in a decrease of its water content. Thus, if we knew the water content w_t of the subgrade at the time t after the beginning of consolidation, that is, after starting the erection of the earth-fill dam, then we can immediately take the corresponding parameters ϕ_w and c_w from the curves in Fig.3. With the aid of formula (6) we obtain the respective shear strength τ_{fw} for the maximum load p and with formula (5) the maximum shear stress τ_{max} in the subgrade at the given moment. After substituting these values in equation (4) we obtain the corresponding safety factor.

*/ It should be noted that the method can also be applied to partially saturated soils. In such case the curves in Fig.4 should be expressed as function of the unit weight of the dry soil too, that is $\phi_w = f(w, \gamma_d)$ (MASLOV, 1968); the calculations should be further conducted as required.

To solve the problem the following steps should be taken.

1. The curves $\phi_w = f(w)$ and $c_w = f(w)$ are experimentally drawn up (MASLOV, 1949, 1961) for the saturated subgrade. It should be pointed out here that one of the advantages of this method is the fact that the pore pressure is indirectly included in the curves, so that it is not necessary to establish it experimentally. This is often connected with considerable difficulties. Therefore, the pore pressure participates in an indirect way in the further calculations. Fig.3 gives these curves in our case. They have been established from the results of about 70 shear tests.

2. The mean compression curve e = f(p) of the subgrade is experimentally determined. Fig.4 shows this curve in our case as an average of 7 tests. The coefficient of consolidation c_v is established.

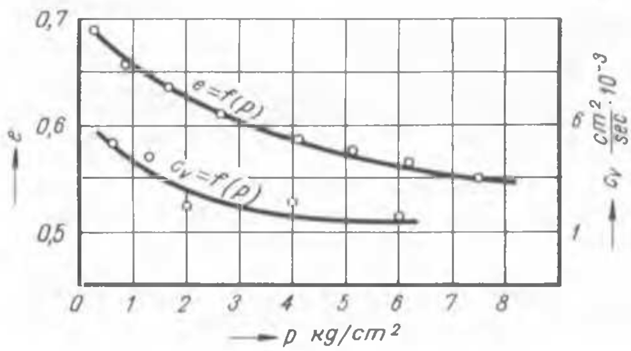

Fig.4 e-p and c_v-p curves

Fig.4 gives also the mean curve $c_v = f(p)$, which is determined after TAYLOR (1954) from the settlement-time curves (28 in all) for the different samples of the subgrade at different stages of loading. As this curve indicates, c_v varies little in a comparatively wide range of loading (for example, within the range of p = 1.0 kg/cm² to p = 6.0 kg/cm² c_v varies from 2.0 to $4{,}0.10^{-3}$ cm²/sec). That is why we use an average $c_v = 3{,}0.10^{-3}$ cm²/sec.

3. The average initial and final water content of the subsoil is determined. In our case the initial water content of the nonloaded subgrade established from undisturbed samples is w_{in} = 24% at the average.

The final water content w_{fin}, that is, the value which will appear in the subgrade after consolidation under the completed dam, is determined. For a load of $p + p_\gamma$, where $p = 31.2{,}04 = 63.2$ t/m², we take from the compression curve $e_{fin} = 0.555$. Then $w_{fin} = \frac{0.555}{2.73} = 20.3\%$.

4. From formula

$$w_t = w_{in} - (w_{in} - w_{fin})\, T_v \quad .. \quad .. \quad (7)$$

we obtain the water content of the saturated subgrade after a given time t. In this formula T_v is the time factor, determined by the well-known formula of Terzaghi-Fröhlich, deduced for a linearly increasing loading on a layer:

for $v \leqslant 1$

$$T_v = v\left\{1 - \frac{8}{\pi^2} \cdot \frac{1}{vMT} \sum_{1,3,5,\ldots}^{m=\infty} \frac{1}{m^4}\left[1-\exp(-m^2 vMT)\right]\right\}; \quad (8a)$$

for $v \geqslant 1$

$$T_v = 1 - \frac{8}{\pi^2} \cdot \frac{1}{MT} \sum_{1,3,5,\ldots}^{m=\infty} \frac{1}{m^4}\left\{\exp\left[-m^2(v-1)MT\right] - \exp(-m^2 . v . MT)\right\}, \quad (8b)$$

where

$v = \frac{t}{T}$;

t is the time from the start of construction;

T - the construction period;

$M - c_v \left(\frac{\pi}{2H}\right)^2$;

c_v - coefficient of consolidation;

2H - twice the depth of the subgrade, since the layer is half-closed.

5. By means of w_t we take the corresponding ϕ_w and c_w from the curves in Fig.3.

Then the shear strength τ_{fw} of the subgrade at the time t after construction starts is determined from formula (6) for the load p. The shear strength τ_{max} of the subgrade, again after the time t, is obtained from formula (5) for a load $\bar{p}$.

The calculation results are given in Table I. The last two columns of the table are given for comparison and refer to a sudden loading of the subgrade. T_v^* is determined by the formula (TERZAGHI-FRÖHLICH, 1936)

$$T_v^* = 1 - \frac{8}{\pi^2} \sum_{1,3,5,\ldots}^{m=\infty} \frac{1}{m^2} \exp(-m^2 . MT) \quad .. \quad .. \quad (9)$$

Although T_v^* differs considerably from T_v, which is determined for a linear increase of the loading, the respective safety factors F and F^* are almost equal. Therefore, the error in determining the safety factor in similar cases will not be significant, if the relatively simpler formula (9), for which there exist tables and diagrams, is used.

On the basis of the above considerations we suggest the following approximation method for determining the minimum construction period in erecting a dam on a thin, relatively soft layer. The safety factors F are established as already shown, for different construction periods T and for different construction stages, provided that the loading of the subgrade grows linearly until it reaches a maximum value. Then all the construction stages up to a certain dam height take place in corresponding periods of time t. T is chosen according to concrete conditions, for example 1, 2, 4 years. The stability of the subgrade is analyzed for different stages after construction starts, again according to concrete conditions, for example $t = \frac{T}{4}, \frac{T}{2}$, T, 2T, ... Since the load p grows linearly, its value is $\frac{p}{4}, \frac{p}{2}$, p, p, ..., respectively, at the end of each stage. Thus, for every separate T, respectively t, the safety factors F are calculated using formulae (4) to (8). The final minimum construction period for each separate construction stage is obtained by interpolation.

In case of a very soft thin layer it can occur that $F < F_{min}$ for $t < T$. Then the required safety cannot be attained within a reasonable time T, since the degree of consolidation in the early stages does not differ essentially for different T. Thus the method indicates that a number of remedial measures may have to be considered in the design, for instance, flattening of slopes or provision of loading berms on the embankment, removal of the soft material, acceleration of consolidation by means of vertical sand drains, etc.

TABLE I - Calculation Results for a Construction Period T of Two Years

t	T_v	w_t	ϕ_w	c_v	p	τ_{fw}	$\bar{p}$	τ_{max}	F	T_v^*	F^*
years	-	%	o	t/cm²	t/cm²	t/cm²	t/cm²	t/cm²	-	-	-
T/4	0.065	23.8	12.0	4.0	18.4	8.0	15.7	1.20	6.6	0.376	7.0
T/2	0.182	23.3	12.2	4.1	34.7	11.7	25.2	1.93	6.1	0.530	6.4
T	0.500	22.1	12.9	4.4	63.2	18.9	31.6	2.42	7.8	0.731	8.2
2T	0.837	20.9	13.9	4.7	63.2	20.4	31.6	2.42	8.4	0.911	8.5

CONCLUSION

The method suggested enables the determination of the construction rate of a dam on a thin, soft soil layer. The following factors are taken into account: on the one hand, the shear stress in the subgrade, which increases with the increase in the load, and, on the other, the increase in the shear strength with the advance of consolidation.

The solution is based on mean laboratory compression curves, as well as on mean curves for the strength parameters of the soil related to its water content, which decreases with the increase in the loading and in time. Besides, some well-known solutions from the theory of consolidation are used.

The construction rate for the different stages of the building of the dam can be determined by this method.

An advantage of the method is that the laboratory strength parameters related to the water content indirectly include the action of the pore pressure, thus avoiding its determination.

A shortcoming of the method is the approximate determination of the shear stress in the thin layer, which makes the method not rigorous. In case of a more precisely calculated shear stress in the thin layer the method could be more exact.

Besides for dams, this method can be applied also for other structures, erected on a thin soft layer.

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