CALCULATION OF BEARING CAPACITY FOR THE FOUNDATIONS SUBJECTED TO SEISMIC LOADS

by

F.M. Shikhiev[I], P.I. Jakovlev[II]

SYNOPSIS

A method for calculation of bearing capacity of a foundation is developed on the basis of safe stress state theory of loose media suggested by V.V. Sokolovsky and S.S. Golushkevich[1]. An inclined failure load is calculated as a function of bearing capacity dimensionless coefficients. For the calculation of a slope stability the expressions containing dimensionless coefficients are obtained. These coefficients help to evaluate the inclined load on the second side plane which corresponds to the safe stress state of an earth mass, provided the inclined uniform load on the first side plane and the direction of the inclined load on the second side plane are known.

INTRODUCTION

The methods for calculation of a foundation bearing capacity and stability of slopes not subjected to seismic loads are elaborated satisfactorily[2]. If it is necessary to take into account seismic loads, there are many suggestions to do it on the basis of a circle slip surface. The problems connected with the application of a safe stress state theory to the calculation of foundations under seismic conditions are not sufficiently developed. The numerical methods of this theory are very tedious and not convenient for engineering practice. That is why the development of simple closed-form solutions based on this theory and taking into account seismic loads is an important task.

I Professor, Odessa Institute of Marine Engineers, Odessa, USSR.

II Assistant Professor, Odessa Institute of Marine Engineers, Odessa, USSR.

BEARING CAPACITY OF A FOUNDATION

If a structure is subjected to vertical and horizontal forces, the stress epure of the structure toe is assumed practically to be trapezoidal. In order to simplify the process of calculation[3], the stress epure is replaced by a calculated uniform epure having a width equal to B (Fig.1) and inclined to the vertical line by an angle δ'. The angle of the reduced pressure deviation from the vertical line, ρ, within the section ED (reduced pressure is equal to a geometrical sum of a vertical pressure, n, and inclined pressure, $q/\cos\omega$) is determined by the formula:

$$\rho = arctg\left(\frac{q\,tg\omega}{q+n}\right);\quad n = c\cdot ctg\varphi;\quad q = \gamma t;\quad \omega = arctg\frac{j}{g};$$

$$G_{3cq} = \overline{ED}\cdot q/\cos\omega;\quad P = \overline{ED}\cdot n;\quad G_{ic} = G_i/\cos\omega,$$

where, c - earth cohesion; n - cohesion pressure; φ - angle of internal friction; γ - bulk weight; t - deepening of the structure toe; j - seismic acceleration; ω - angle of deviation of the resultant gravity force and the horizontal seismic force from the vertical line; G_i - weight of a given earth zone. In order to define the locations of the slip surfaces, it is necessary to determine the angles:

$$\vartheta = \frac{1}{2}\left(arccos\frac{\sin\delta'}{\sin\varphi} + \varphi - \delta'\right);\quad \varepsilon = \frac{1}{2}\left(\frac{\pi}{2} - \varphi - \rho + arcsin\frac{\sin\rho}{\sin\varphi}\right);$$

$$\alpha = \varphi + \varepsilon;\quad \theta = \pi/2 + \vartheta - \alpha;\quad \overline{ED} = BK;\quad K = a/\cos\alpha;\quad a = \sin\vartheta\, exp(\theta\, tg\varphi).$$

The value of the failure load, $R_{np.p}$, which corresponds to a safe equilibrium state of a foundation can be determined by successive construction of the polygons of forces for ECD; ECB and EAB zones. However, the value of the force, $R_{np.p}$, and the stresses $\sigma_{np.p}$ and $\tau_{np.p}$ can be defined more accurately and conveniently analytically using the formulas:

$$R_{np.p} = \gamma B^2 N_\gamma + BcN_c + BqN_q;\quad \sigma_{np.p} = \frac{R_{np.p}\cos\delta'}{B} - n;\quad \tau_{np.p} = \frac{R_{np.p}\sin\delta'}{B},$$

where, N_γ, N_c and N_q - the coefficients of bearing capacity of a foundation. The coefficients are calculated as follows:

$$b=\frac{\sin\vartheta\cos(\varphi-\vartheta)}{2\cos\varphi\cos\omega};\quad d=\frac{a^2-\sin^2\vartheta}{2\sin2\varphi\cos\omega};\quad i=\frac{K a\sin\varepsilon}{2\cos\varphi\cos\omega};$$

$$\mu_{1\gamma}=\varepsilon+\omega-\operatorname{arctg}\left[\frac{(b+d)\sin(\alpha+\omega)}{(b+d+i)\cos(\varepsilon+\omega)\cos\varphi}-tg\varphi\right];\ (180^\circ>\mu_{1\gamma}>0^\circ);$$

$$\beta=\frac{\pi}{2}-\vartheta+\operatorname{arctg}\left[\frac{\exp(\theta\, tg\varphi)-\cos\theta}{\sin\theta}\right];\quad t=\sin(\delta'+\vartheta-\varphi);$$

$$m=\frac{a\cos\varepsilon}{tg\varphi\cos\alpha\cos(\varepsilon+\omega)};\quad S_\gamma=\frac{(b+d)\sin(\alpha+\omega)}{\sin(\alpha+\omega-\mu_{1\gamma})};\quad N_q=\frac{N_c\cdot K}{m\cos\omega};$$

$$\mu_\gamma=\operatorname{arctg}\left[\frac{b\cos(\omega-\beta)-S_\gamma\cos(\omega-\beta-\mu_{1\gamma})}{S_\gamma\cos(\omega-\beta-\mu_{1\gamma})\,tg(\vartheta+\omega)-b\sin(\omega-\beta)}\right];\ (180^\circ>\mu_\gamma>0^\circ);$$

$$N_\gamma=\frac{b\cos(\vartheta+\omega)\sin(\mu_\gamma-\vartheta-\omega+\varphi)}{t\cos(\mu_\gamma-\vartheta-\omega)};\quad N_c=-\frac{m\cos(\varepsilon+\omega)\cos(\alpha+\beta)}{t\sin(\beta+\vartheta)}.$$

The coefficients N_γ, N_c and N_q as well as K are dimensionless and depend only on the angles φ, δ', ρ and ω. By means of a computer they are calculated for all practically encountered cases. The results obtained allow to draw a diagram of a bearing capacity of a foundation and determine a safety factor [3,4].

LIMIT STRESS STATE OF AN EARTH WEDGE AND STABILITY OF A SLOPE

Reduced seismic pressure, q_{1c}, and an angle of seismic pressure deviation from the normal, ρ_{1c}, towards OA is equal to (Fig. 2):

$$q_{1c}=\sqrt{(q'_{1c})^2+c^2ctg^2\varphi+2q'_{1c}\,c\cdot ctg\varphi\cos\rho'_{1c}};$$

$$\rho=\operatorname{arctg}\left(\frac{q'_{1c}\sin\rho'_{1c}}{q'_{1c}\cos\rho'_{1c}+c\cdot ctg\varphi}\right),$$

where, q'_{1c} and ρ'_{1c} - known values of a real seismic pressure and an angle of seismic pressure deviation from the normal to OA. In order to locate the slip surfaces, the angles should be calculated:

$$\Delta_1 = \arcsin(\sin\rho_{1c}/\sin\varphi);\ \theta_1 = 0.5(\pi/2 + 2\beta_1 - \varphi - \rho_{1c} - \Delta_1);$$
$$\theta_2 = \pi/2 - \varphi - \theta_1;\quad \rho = \pi/2 + \beta_1 - \theta_1;\ \eta = \pi/2 + \varphi - \rho;$$
$$\Delta_2 = \arcsin(\sin\rho_{2c}/\sin\varphi);\ \varepsilon = 0.5(\pi/2 - \varphi - \rho_{2c} + \Delta_2);$$
$$\omega_0 = \pi/2 - \varphi - \varepsilon;\quad \theta = \pi + \beta_1 + \beta_2 - \rho - \varepsilon,$$

where, ρ_{2c} – a known angle of deviation of a reduced pressure from the normal to OD. The unknown force, P_{2c}, corresponding to a safe equilibrium state of an earth wedge (slope) can be determined by successive construction of the polygons for OAB, OBC and OCD zones. However, this force can be defined more accurately and conveniently analytically:

$$P_{2c} = K_1 \ell_1 (\gamma \ell_1 N_\gamma + q_{1c} N_q);\quad \overline{OD} = K_1 \ell_1,$$

where, the coefficients of slope bearing capacity, N_γ and N_q, as well as parameter K are dimensionless values depending on the angles ω, φ, β_1, β_2, ρ_{1c} and ρ_{2c}. These coefficients are calculated as follows:

$$b = \frac{\sin\eta\sin\rho}{2\cos\varphi\cos\omega};\ d = \frac{\sin^2\eta[\exp(2\theta\,tg\varphi) - 1]}{2\sin 2\varphi\cos\omega};\ K_1 = \frac{\sin\eta\exp(\theta\,tg\varphi)}{\sin\omega_0};$$
$$n = \frac{\sin(\theta_1 + \rho_{1c} - \beta_1)}{\sin(\theta_1 + \omega)};\ i = \frac{\sin^2\eta\sin\varepsilon\exp(2\theta\,tg\varphi)}{2\cos\varphi\sin\omega_0\cos\omega};\ f_q = \frac{n\sin(\theta_1 + \omega)}{\cos\varphi};$$

$$\mu_{1\gamma} = arctg\left\{\frac{b}{b\,ctg(\theta_2 - \omega) + (d + i)[ctg(\theta_2 - \omega) + ctg(\theta_1 + \omega)]}\right\};\ (180^\circ > \mu_{1\gamma} > 0^\circ);$$
$$f_\gamma = \frac{(d + i)\sin(\theta_2 - \omega)}{\sin(\theta_2 - \mu_{1\gamma} - \omega)};\quad \psi = \varepsilon + \varphi + arctg\left[\frac{\exp(-\theta\,tg\varphi) - \cos\theta}{\sin\theta}\right];$$
$$m_\gamma = \cos(\mu_{1\gamma} + \omega) - tg(\psi - \beta_2)\sin(\mu_{1\gamma} + \omega);$$
$$\mu_\gamma = arcctg\left\{\frac{i[tg(\psi - \beta_2)\cos\omega + \sin\omega] + f_\gamma m_\gamma tg(\beta_2 + \omega_0 - \omega)}{i[\cos\omega - tg(\psi - \beta_2)\sin\omega] - f_\gamma m_\gamma}\right\};\ (180^\circ > \mu_\gamma > 0^\circ);$$
$$N_\gamma = -\frac{i\cos(\beta_2 + \omega_0 - \omega)\cos(\mu_\gamma + \varepsilon - \beta_2 + \omega)}{K_1\cos(\beta_2 - \mu_\gamma + \omega_0 - \omega)\cos(\rho_{2c} + \varepsilon)};\ N_q = -\frac{f_q\cos(\theta_2 + \psi - \beta_2)\cos\varphi}{K_1\sin(\psi + \omega_0)\cos(\rho_{2c} + \varepsilon)}.$$

At first, the distribution of pressure along the side plane OD may be assumed uniform. However, the trapezoidal contour of the epure lies closer to precise solutions. Taking into account the fact that the influence of the volumetric forces at the point O is not yet felt, we may obtain

$$q_{2c}^{O} = q_{1c} N_q ; \quad q_{2c}^{D} = 2\gamma \ell_1 N_\gamma + q_{1c} N_q .$$

The shown pressure epure of the side plane OD helps to construct the epure of real pressure[3]. The obtained formulas allow to solve also a reverse problem. If the values P_{2c}, ρ_{2c}, ρ_{1c} and ℓ_1 are set, then

$$P_{1c} = P_{2c} \frac{1}{K_1 N_q} - \gamma \ell_1^2 \frac{N_\gamma}{N_q} .$$

The coefficients N_γ, N_q, K_1 were computed for many practically encountered cases, the tables and diagrams were also compiled. The particular cases of this solution are: the problems of a foundation bearing capacity ($\beta_1 = \beta_2 = 0$), the problems of active and passive earth pressure on the wall at $C=O$ (in this case, ρ_{2c} is equal to the angle of earth friction along the wall). During calculation the signs of the angles β_1, β_2, ρ_{1c} and ρ_{2c} must be observed [3]. The angles , and are positive in Fig.2 while the angle β_2 is negative.

REFERENCES

1. Golushkevich, S.S. (1957), "Statics of a limit state of earth masses", Gostechizdat, Moscow, p.288.
2. Evdokhimov, P.D. (1956), "Strength of foundations and stability of hydrotechnical structures built on soft soils", Gosenergoizdat, Moscow, p.271.
3. Jakovlev, P.I. (1974), "Methods of bearing capacity calculation for hydrotechnical structures on the basis of a safe equilibrium state", Reclaminformbjuro MMF, Moscow, p.65.
4. Shikhiev, F.M., Jakovlev, P.I. (1968), "Calculation of bearing capacity for the foundations subjected to seismic loads", "Osnovanija, fundamenty i mekhanika gruntov", No.1, pp.25-27.

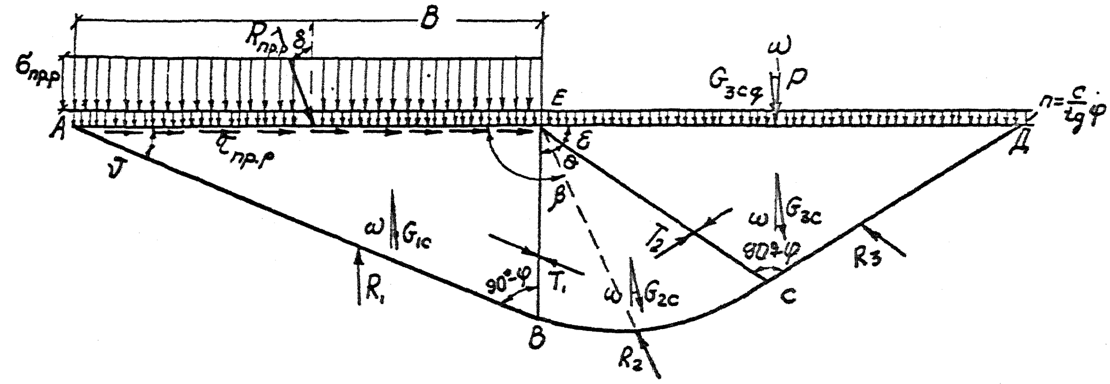

Fig.1. Slip surfaces while calculating
a foundation bearing capacity

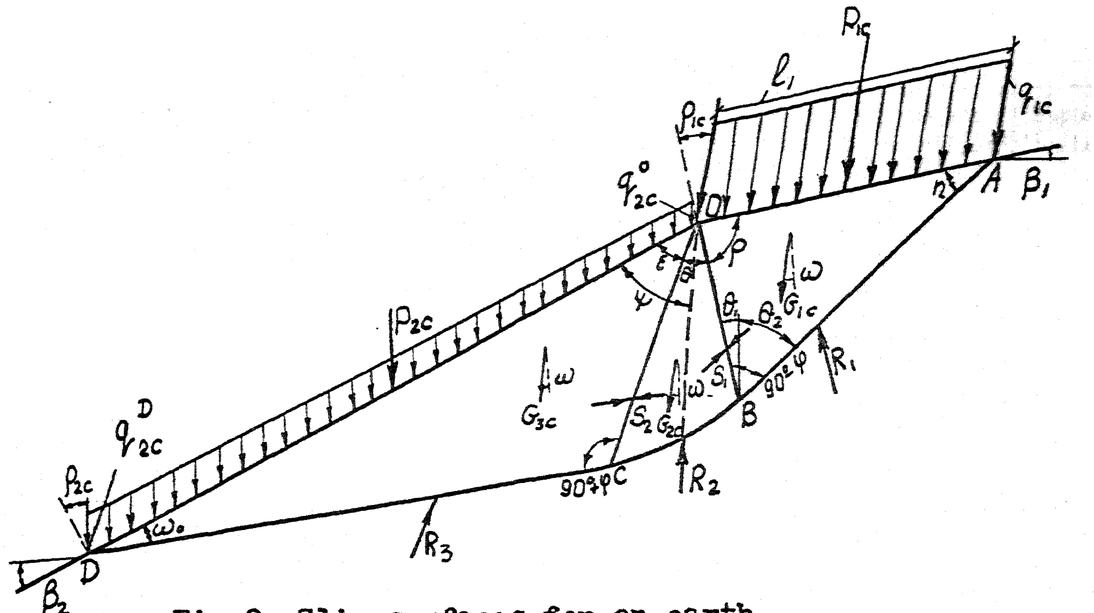

Fig.2. Slip surfaces for an earth
wedge (slope)