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Load-displacement characteristics of retaining walls

Les caractéristiques de charge et déplacement des murs de soutènement

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SYNOPSIS: The determination of passive pressure on retaining walls when forced into dense sand is considered with different modes of motion. Considering the angle of dilation of the dense sand to be constant, finite element analysis is carried out to construct zero extension line field. The wall movement then is applied to the zero extension line net to calculate shear strain in sand. Using the relationship between shear strain and angle of internal friction, the direction of traction on zero extension line net is evaluated. Finally applying equations of equilibrium the passive pressure on the wall is calculated. It is shown that the simple zero extension line net consisting of Rankine, mixed and Goursat zones give passive pressure on the wall very close to the general field generated by the finite element method. Thus closed form solution is obtained yielding values of passive pressure coefficients at different depths for rotation and translation of the wall.

1 INTRODUCTION

Zero extension line field proposed by Roscoe (1970) has been used by James and Bransby (1970, 1971), Bransby and Milligan (1975) and Wroth (1976) to explain strain patterns behind retaining walls. Habibagahi and Ghahramani (1979), Ghahramani and Clemence (1980) and Behpoor and Ghahramani (1987) extended the work to determine static and dynamic passive pressures and bearing capacity coefficients. Bhandari (1987) recommended that displacements are more important (for dynamic loading) in such problems.

In the present work, the zero extension line field is used to predict both the strain pattern and stresses behind retaining walls with dense sand backfill for translation, rotation about bottom and rotation about the top of the wall. Thus load-deformation curves are presented for predicting passive earth pressure coefficients for various degrees of wall movements.

2 THEORY

The background of the theory has been presented in the above references. The zero extension line field is composed of mixed, Goursat and Rankine zones as shown in Fig. (1). The angles i_1 and i_2 are used to show the slope of the soil surface and the slope of the wall, respectively. β_q is found to be

$$\beta_q = \frac{\pi}{4} - \frac{\nu}{2} - \frac{\delta_q}{2} + \tfrac{1}{2}\mathrm{Sin}^{-1}\left(\frac{\mathrm{Sin}\,\delta_q}{\mathrm{Sin}\,\phi}\right) \qquad (1)$$

where δ_q is the angle of surcharge q with the normal to the soil surface, ϕ is the angle of shearing resistance and ν is the angle of dilation of sand and is defined as

$$\mathrm{Sin}\,\nu = \frac{dV/V}{d\gamma_{max}} \qquad (2)$$

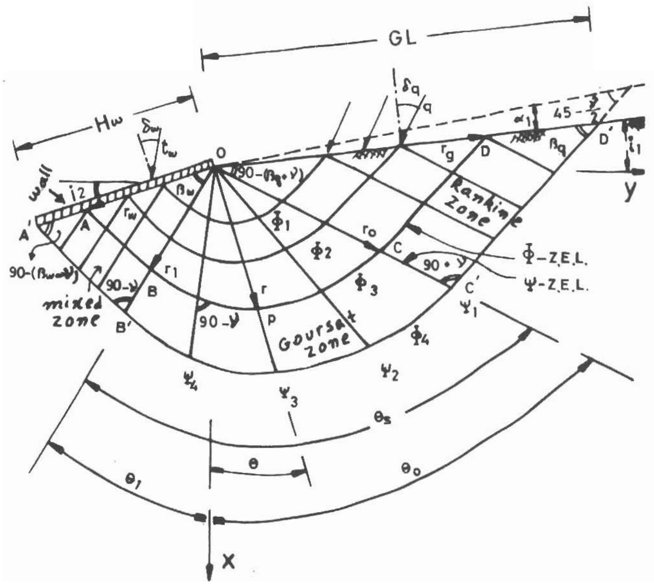

Figure 1. Simple zero extension line field behind the retaining wall.

in which dV/V is the volumetric strain and γ_{max} is the maximum angular shearing strain.

The work by James and Bransby (1971) showed that for dense sand the angle of dilation ν is constant up to large shearing strains. Thus it is found that

$$\theta_s = \frac{\pi}{2} - i_2 + i_1 + \nu + (\beta_q - \beta_w) \qquad (3)$$

$$\theta_o = \beta_q + \nu + i_1 \qquad (4)$$

$$\theta_1 = \beta_w - \frac{\pi}{2} + i_2 \quad (5)$$

where β_w is the angle that mixed zero extension lines make with the wall and is related to δ_w, the angle that traction on wall makes with the normal to the wall, by the following formula:

$$\beta_w = \frac{\pi}{4} + \frac{\nu}{2} - \frac{\delta_w}{2} - \tfrac{1}{2}\mathrm{Sin}^{-1}\left[\frac{\mathrm{Sin}\delta_w \mathrm{Cos}\delta_{dm}}{\mathrm{Sin}(\delta_{dm}+\nu)}\right] \quad (6)$$

In the above formula δ_{dm} is the angle that traction makes with zero extension line in mixed zone. Similarly δ_{dG} and δ_{dR} can be defined as the angles that traction makes with zero extension lines in Goursat and Rankine zones, respectively.

3 DISPLACEMENT FIELDS

If the displacement normal to wall at depth r_w is Dr_w, it can be shown that the displacements of zero extension line nodes are normal to Ψ-lines. The nodal displacement along a Φ-line in mixed zone can be given as

$$U_{r_m} = \frac{Dr_w}{\mathrm{Cos}\beta_w} \quad (7)$$

which means that the straight Φ-lines in the mixed zone translate. In the Goursat zone, it can be shown that the logarithmic spiral Φ-lines rotate about O and again in the Rankine zone the straight Φ-lines translate. Thus knowing the wall displacement, the displacement in all three zones can be evaluated.

4 SHEAR STRAINS

Knowing the displacement fields, shear strains can be evaluated. In the mixed and Rankine zones shear strains are equal along a Φ-line and can be given as

$$\gamma_{max,R} = \gamma_{max,m} = \frac{1}{\mathrm{Cos}\beta_w \mathrm{Cos}(\beta_w - \nu)}\left(\frac{dDr_w}{dr_w}\right) \quad (8)$$

In the Goursat zone along Φ-line shear strain is found to be

$$\gamma_{max,G} = \frac{1}{\mathrm{Cos}\beta_w \mathrm{Cos}(\beta_w - \nu)}\left(\frac{Dr_w}{r_w} + \frac{dDr_w}{dr_w}\right) \quad (9)$$

It should be noted that there is a discontinuity in shear strain field between Goursat and neighbouring zones.

5 STRESS FIELDS

The stress fields are evaluated using a similar procedure to that of Behpoor and Ghahramani (1987). Thus the pressure on wall at depth r_w is found to be

$$p = K_{p_q} \cdot q + K_{p_\gamma} \cdot r_w \cdot \gamma \quad (10)$$

where K_{p_q} is the passive pressure coefficient due to surcharge q and K_{p_γ} is the passive pressure coefficient due to dense sand behind the wall, with unit weight equal to γ, at depth r_w of the wall. It can be shown that the coefficients of passive pressure are obtained by the following relations:

$$K_{p_q} = \frac{\mathrm{Cos}\delta_w}{E} De^{K\theta_s} \quad (11)$$

$$K_{p_\gamma} = \frac{\mathrm{Cos}\delta_w}{E}(C + Be^{-K\theta_1} + Ae^{K\theta_s}) \quad (12)$$

where A, B, C, D, E and K are given below:

$$A = \frac{\mathrm{Cos}(\beta_w - \nu)\mathrm{Cos}(\beta + \nu)\mathrm{Sin}(\delta_{dR} + \theta_o)}{\mathrm{Sin}\beta_q \cdot \mathrm{Cos}(2\delta_{dR} + \nu)} \cdot e^{\theta_s \tan\nu} \quad (13)$$

$$B = \frac{\mathrm{Cos}(\delta_{dG} + \nu)}{\mathrm{Cos}(\delta_{dm} + \nu)} \cdot \frac{\mathrm{Cos}(\beta_w - \nu)\mathrm{Cos}\lambda}{\mathrm{Cos}(2\delta_{dG} + \nu)\mathrm{Cos}\nu} \cdot e^{-\theta_1 \tan\nu} \cdot [\mathrm{Cos}(\theta_1 + \delta_{dG} + \lambda)e^{K'\theta_1} - \mathrm{Cos}(\theta_o + \delta_{dG} + \lambda) \cdot e^{K'\theta_o}] \quad (14)$$

in which

$$K' = \tan\lambda = \tan(2\delta_{dG} + \nu) + 2\tan\nu \quad (15)$$

$$C = \frac{\mathrm{Sin}\beta_w \cdot \mathrm{Sin}(\delta_{dm} + \theta_1)}{\mathrm{Cos}(2\delta_{dm} + \nu)} \quad (16)$$

$$D = \frac{\mathrm{Cos}\nu \cdot \mathrm{Sin}(\beta_q + \delta_q + \delta_{dR} + \nu)}{\mathrm{Sin}\beta_q \cdot \mathrm{Cos}(2\delta_{dR} + \nu)} \quad (17)$$

$$E = \frac{\mathrm{Cos}\nu}{\mathrm{Cos}(\beta_w - \nu)} \cdot \frac{\mathrm{Cos}(\delta_w + \beta_w + \delta_{dm})}{\mathrm{Cos}(2\delta_{dm} + \nu)} \quad (18)$$

$$K = \tan(2\delta_{dG} + \nu) + \tan\nu \quad (19)$$

the developed angle of traction δ_d in different zones can be evaluated for φ of the zone by the following formula:

$$\tan\delta_d = \frac{\mathrm{Sin}\phi - \mathrm{Sin}\nu}{\mathrm{Cos}\nu} \quad (20)$$

6 ANALYSIS

For a given wall movement, and by considering ν to be constant for dense sand, the zero extension line net remains unchanged. From shear strain formulae (Eq. 8 and Eq. 9), shear strains can be evaluated. Knowing shear strain and the relation between φ and shear strain (James and Bransby

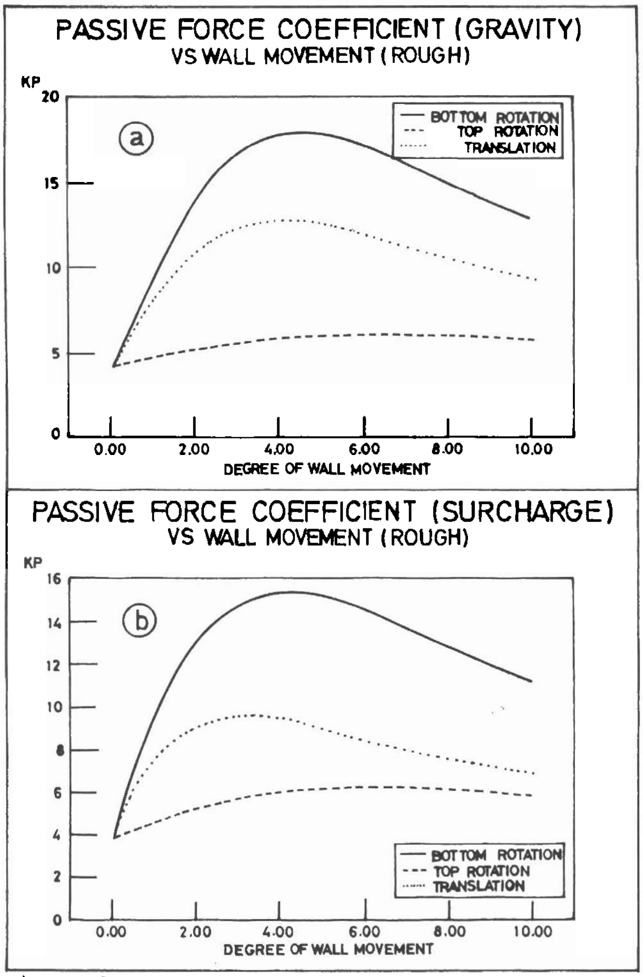

Figure 2. K_p versus wall movement for (a) gravity and (b) surcharge.

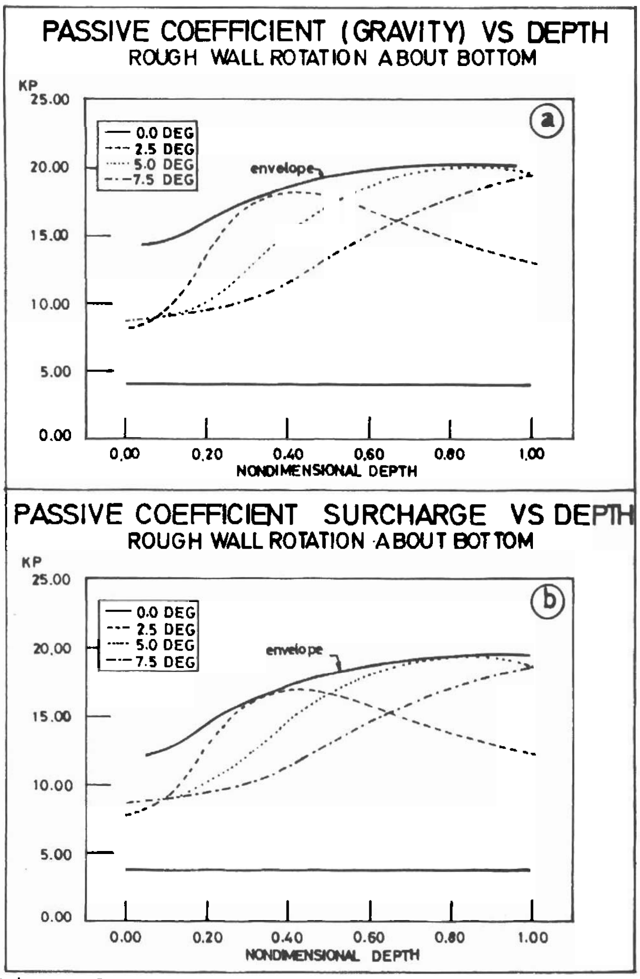

Figure 3. K_p versus depth of wall for rotation about bottom, (a) gravity and (b) surcharge.

1971), angle of shearing resistance ϕ can be evaluated. Then developed angles of traction δ_{dR}, δ_{dm} and δ_{dG} are determined (Eq. 20), leading to evaluation of passive pressure coefficients due to surcharge and gravity (Eq. 11 and Eq. 12). Thus the load-deformation characteristics are obtained. The assumption of constancy of ν and using symple zero extension line net was tested for sensitivity. A finite element program was written for a constant angle (90-ν) field but not bounded by logarithmic spirals. The distance OD' in Fig. (1) was varied between 0.8 to 1.2 of that of the symple zero extension line net and it was shown that the pressure on the major part of the wall remained unchanged. Thus the pressure predictions by symple zero extension line field is not sensitive to change of ν.

7 RESULTS

The passive pressure coefficients for the whole depth of wall K_{wp_q} and K_{wp_γ} for use in the following formula:

$$P_w = K_{wp_q} \cdot q \cdot H + \tfrac{1}{2} K_{wp_\gamma} \cdot \gamma \cdot H^2 \qquad (21)$$

in which H is the depth of wall and P_w the total force on it, is presented in Fig. (2) for rotation and translation of the wall with a dense sand backfill for which $\nu = 15^o$. The degree of wall movement in this figure is defined as the maximum wall displacement over H, the depth of the wall, converted to degrees. Comparing Fig. (2) with the experimental work of James and Bransby (1970) gives remarkable similarity.

Results for distribution of passive pressure coefficients versus non-dimensional depth of the wall for various degrees of wall movements are shown in Fig. (3) for rotation about bottom and Fig. (4) for translation.

From Fig. (2) it is seen that for the same degrees of wall movement, highest relative pressures are encountered for rotation of the wall about the bottom, then for translation and finally for rotation about the top, as also has been measured experimentally. Also the drop of passive coefficient after about 5 degrees rotation about bottom as predicted by theory, compares favorably with experimental result of 7 degrees (Roscoe, 1970); the predicted maximum K_p of 18 compares

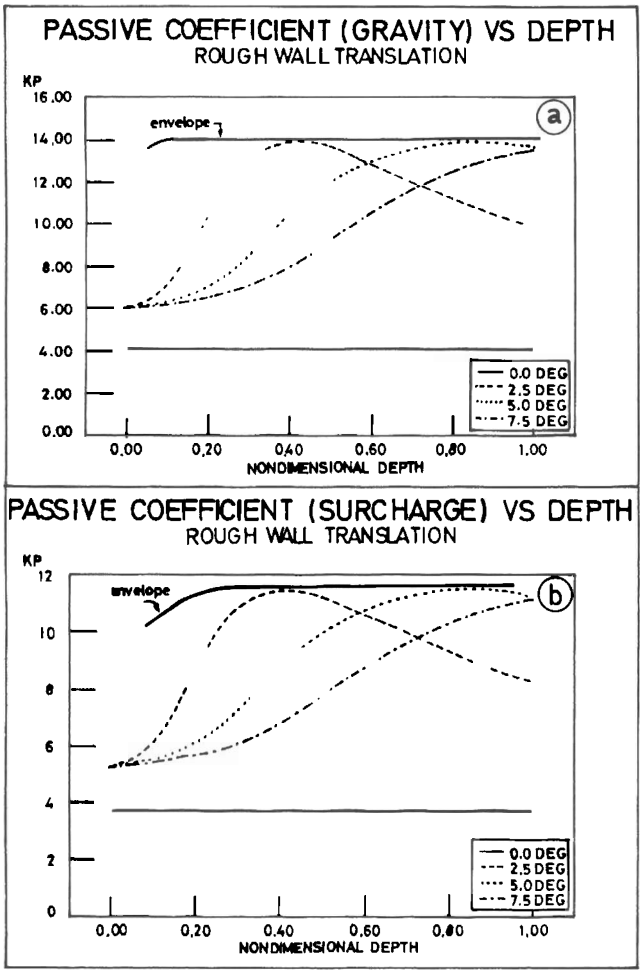

Figure 4. K_p versus depth of wall for translation, (a) gravity and (b) surcharge.

well with experimental result of 18; and for translation K_p of 13 by theory compares favorably with experimental result of 11.5. For rotation about the top, the theoretical result of 6 for K_p is lower than experimental result of 7.6. However the pressure distribution match better with experimental results on upper part of the wall.

8 CONCLUSIONS

(1) The symple zero extension line field is capable of predicting load-displacement characteristics of retaining walls with dense sand backfill.

(2) The predicted results of passive pressure coefficients versus wall movement are comparable to experimental results. Best comparison is found for rotation of wall about the bottom.

(3) The pressure results are not sensitive to the change of angle of dilation, if proper stress-strain curve of $\sin\phi$ versus shear strain is used to predict the stress pattern.

(4) The curves presented in Fig's (2), (3) and (4) can be used to calculate passive wall forces due to the various wall displacements.

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