EARTHQUAKE RESISTANT DESIGN OF QUAY WALLS

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SYNOPSIS

In order to investigate the stability of quay walls, the authors measured the dynamic active earth pressures of dry sand and submerged sand using a large vibrating soil bin in the laboratory. They analyzed the earth pressures and the pore water pressures during earthquake which were satisfying the observed values. In the analysis of earth pressures during earthquake, they assumed that the backfill was composed of the lower layer having the static angle of internal friction and the upper layer having the dynamic one.

1. Introduction

It is very important for earthquake resistant design of quay walls to know the effective earth pressure and the dynamic pore water pressure acting on the back of quay wall. As the results of the measurements, the following characteristics have been made clear. As the acceleration increases, the resultant force of backfill against the movable wall becomes larger, the relative height of its applied point becomes higher and the coefficient of wall friction decreases. The authors derived the formula of active earth pressure (effective earth pressure) during earthquake which satisfied the condition of these three characteristics mentioned above. Concerning the dynamic pore water pressure, the authors considered that it was composed of the excess pore water pressure caused by inertia force and the excess pore water pressure by deformation of backfilled sand under undrained condition.

2. Testing apparatus and test procedure

(a) The vibrating soil bin

Photo 1 shows the testing apparatus. The inside dimensions of the soil bin are 200 cm in length, 100 cm in width and 75 cm in depth. The total weight of the bin and the movable wall is 2.1 tons. The soil bin containing dense dry sand of 55 cm in depth weighs about 4 tons. Under this condition the soil bin can be vibrated with the frequency 3.3 Hz and maximum acceleration of 600 gals. The resultant force of earth pressures, the relative height of its applied point and the angle of wall friction are given from three load cells attached to the movable wall. The wall moves outward with velocity of 0.81 mm per minute at the top and 0.29 mm per minute at the bottom. Torque caused by the movable wall around the center of the supporting ring is cancelled by the one acting on the counter weight. A detailed imformation regarding testing apparatus and the test procedure for dry sand has been reported in the previous paper by Ichihara (1965)[1], (1973a)[2].

(b) Test procedure for submerged sand

After the movable wall was adjusted to the vertical, Toyoura sand was compacted in water using a vibrator to the depth of 55 cm.[3] Its dry unit weight was 1.59 g/cm^3. As shown in Photo 2 , five pore water pressure gauges

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were attached to the movable wall at the height of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm. The gauge has a porous metal filter covered with a fine wire net. The water pressure acting on the diaphragm through the filter were measured by a foil gauge. The dynamic experiments using only water in the soil bin were carried out to test the pressure gauges. The total force of water pressures calculated from the measured values with pressure gauges coincide with the one calculated from measurements of load cells.

3. Calculation method

(a) Calculation method of earth pressures during earthquake

In the upper layer having ϕ_0 shown in Figure 1 , the slip line B_0B_1 is +m slip line (η - characteristics) and the slip line OB_1 passing through the top of wall is -m slip line (ξ - characteristics). $\tilde{\sigma}$ and ψ on OB_1 are determined by the stresses during earthquake in the semi-infinite body, where $\tilde{\sigma}$ is the distance from the origin in Mohr's diagram in Figure 2, to the point of intersection of the Mohr-Coulomb envelope and ψ is the angle between x-plane and the major principal plane. As ψ on the back of wall is calculated from the wall friction, values of $\tilde{\sigma}$, ψ, x and y on the slip line A_1A_2 are integurated from the two equations for +m slip line by Sokolovski's method.[4)]

Four values of $\tilde{\sigma}$, ψ, x and y on the boundary line A_2B_1 are obtained from the values on the two slip lines A_1A_2 and A_1B_1 , solving Goursat problem. These values of $\tilde{\sigma}$ and ψ on A_2B_1 are translated into those concerning ϕ_{st} .

The values of $\tilde{\sigma}$, ψ, x and y on the back of wall A_2B_4 are calculated by the four values on A_2B_1 solving Cauchy, Goursat and Mixed Boundary problem. The normal stress σ_n and the shearing stress τ_{nt} on the back of wall are calculated using the values of $\tilde{\sigma}$ and ψ . In Figure 3, values of normal stress against the wall are shown for each angle of seismic intensity $\theta_0 = 0°, 10°, 20°$ and $30°$, where $\theta_0 = \tan^{-1}(\alpha/g)$, α is the horizontal acceleration and g is the gravitational acceleration. The distributions of earth pressures in the upper layer and the lower layer are both linear and earth pressures in the lower layer coincide with those in the case of the uniform backfill which is assumed to have a constant angle of internal friction ϕ_{st}.

The boundary conditions in the calculation mentioned above are written as follows.

<u>$\tilde{\sigma}$ and ψ on the line OA_1</u>

$$\tilde{\sigma} = \gamma \cdot r \cdot S$$
$$\psi = (\theta_0 + \Delta_0)/2$$
$$S = \cos \alpha_2 (1 - \lambda)/\cos^2 \phi \cos \theta_0$$
$$\lambda = \sin^2\theta_0 + \cos \theta_0 \sqrt{\sin^2\phi - \sin^2\theta_0}$$
$$\alpha_2 = (\theta_0 - \Delta_0)/2 + \mu - \theta_0$$
$$\Delta_0 = \sin^{-1}(\sin \theta_0/\sin \phi)$$
$$\mu = \pi/4 - \phi/2$$

where γ is the unit weight of sand and r is the radius vector in polar coordinate.

on the back of the wall

$$\psi = (\Delta_1 - \delta)/2$$
$$\Delta = \sin^{-1}(\sin\delta/\sin\phi)$$

where δ is the angle of wall friction, in the calculation δ is assumed that $\delta = 2\phi/3$.

In the case that the region of slip lines on the surface of backfill are overlapped by the region of the slip lines on the back of wall, the method of stress discontinuous line was used. When −m slip line OA_1 enters into the wall, for instance, $\theta_0 = 20^\circ$ and $\phi = 42^\circ$, Sokolovski describes that the earth pressure on the wall should be calculated by the stresses in the semi-infinite body[5]. However, the values of earth pressure calculated in this way is 1.4 times as large as the observed one. Only in these case the authors assumed that $\psi = 0.4\,\psi_0$ where ψ_0 is the value of semi-infinite body in earthquake condition. The coefficient of earth pressure K is shown as the following equation which is derived from the relation between $\tilde{\sigma}$ and ψ on +m slip line.

$$\sigma = \gamma \times K$$

$$K = \frac{1 - \sin\phi\cos 2\psi}{\cos\phi\ \cos\theta_0}\{\cos(\theta_0 - \phi) + \sin(\theta_0 - \phi)\tan(\psi - \mu)\}$$

(b) Calculation of pore water pressures during earthquake

The excess pore water pressures caused by inertia force can be obtained as the difference between two dynamic earth pressures which are calculated from the author's method of calculation using the submerged unit weight γ' and two coefficients of seismic intensity $\theta_1 = \tan^{-1}\{G_s\alpha/(G_s - 1)g\}$ and $\theta_2 = \tan^{-1}(\frac{\alpha\gamma_{sat}}{g\gamma'})$, where G_s is the specific gravity of sand and γ_{sat} is the saturated unit weight. The excess pore water pressures caused by deformation can be given from the following equation. $\Delta u = B\{\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)\}$, where $\Delta\sigma_1$ and $\Delta\sigma_3$ are increments of stresses in backfilled sand from static state. The values of dynamic pore water pressures obtained by the calculation using A = −0.2 and B = 0.9 coincide with the measured values.

4. Comparison of calculated values with observed ones

Figure 4 shows the relations between the resultant force of earth pressures acting on the wall and the angle of seismic intensity. The observed resultant horizontal force of earth pressures increases corresponding to the increase of acceleration. The computed values coincide well with the observed ones. Figure 5 shows the relations between the relative height of applied point of resultant force and θ_0. Figure 6 shows the relations between the coefficient of wall friction and θ_0. The computed values follow well the observed ones.

Figure 5 shows the distribution of dynamic pore water pressures at the horizontal acceleration of soil bin α = 300 gals. The observed dynamic pore water pressure differed from the values obtained by Westergaard's formula.

The ratio of the resultant force of measured dynamic pore water pressure to the values by Westergaard's formula is 0.58 . The observed pore water pressures coincide with the values which are calculated by adding the excess pore water pressure caused by deformation to ones by inertia force.

5. Conclusions

(1) The characteristics of the measured dynamic active earth pressures acting on the wall were interpreted well by the author's method of calculation assuming $\phi_0 = \phi_{st} (1 - \tan \theta_0)$ and $u_0 = 0.6\ H$.

(2) The measured dynamic pore water pressure were explained well with the excess pore water pressure by inertia force and the excess pore water pressure by deformation of backfilled sand under undrained condition.

It is considered that the development of calculation method of effective earth pressures and pore water pressures during earthquake gives a contribution to the earthquake resistant design of quay walls.

References

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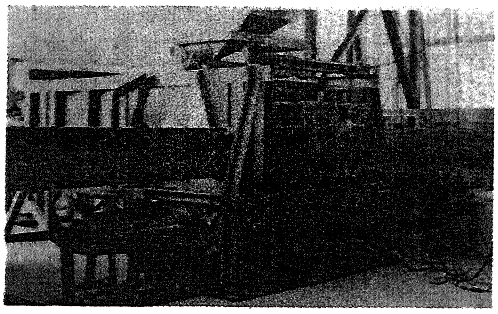

Photo 1 Vibrating soil bin

Photo 2 Water pressure gauges attached to the movable wall

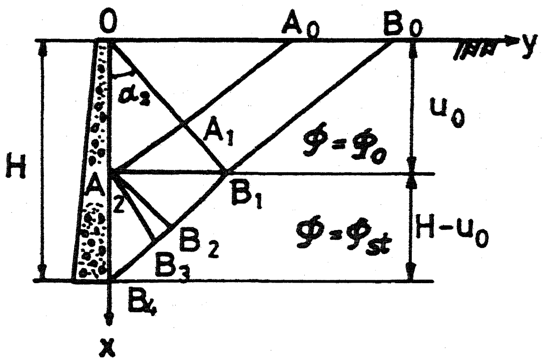

Fig.1 Illustrations of slip lines in the backfill

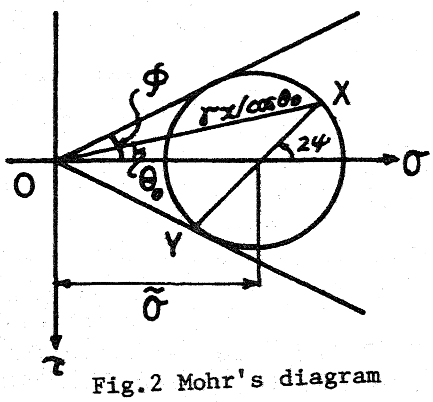

Fig.2 Mohr's diagram

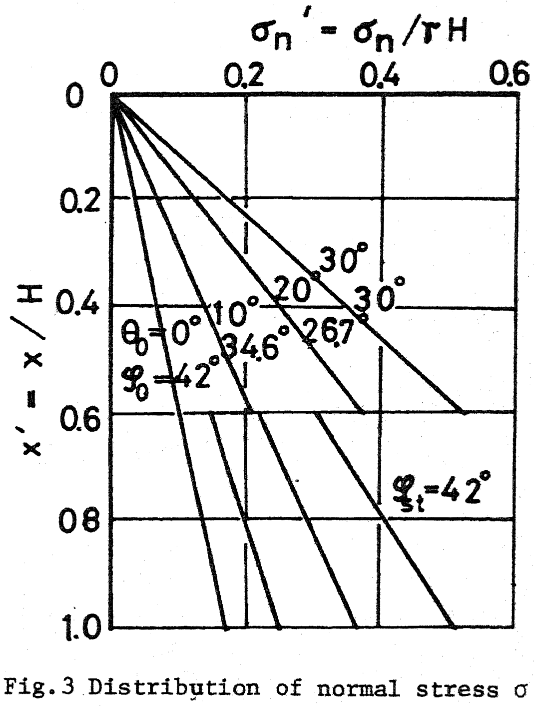

Fig.3 Distribution of normal stress σ for various values of θ_0
(σ' and x' are the dimensionless values)

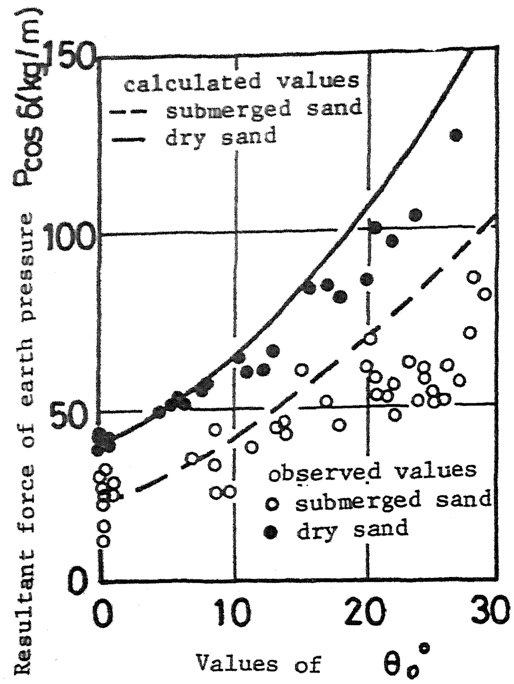

Fig.4 Comparison of measured horizontal force of earth pressures with the calculated values

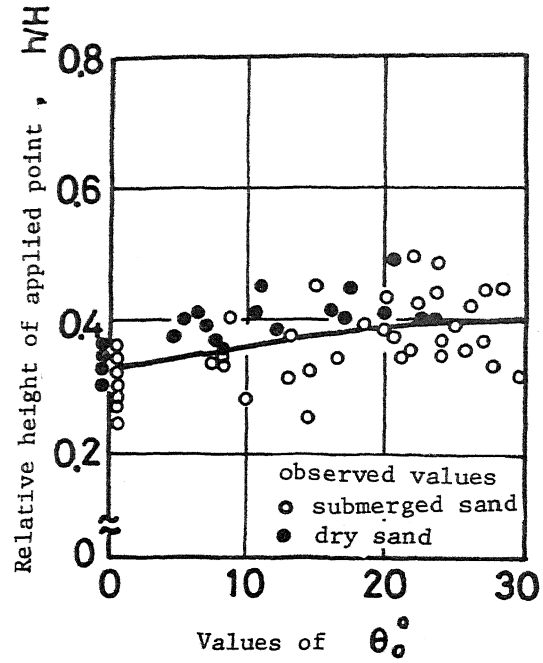

Fig.5 Comparison of measured relative height of applied point of resultant force with the calculated values

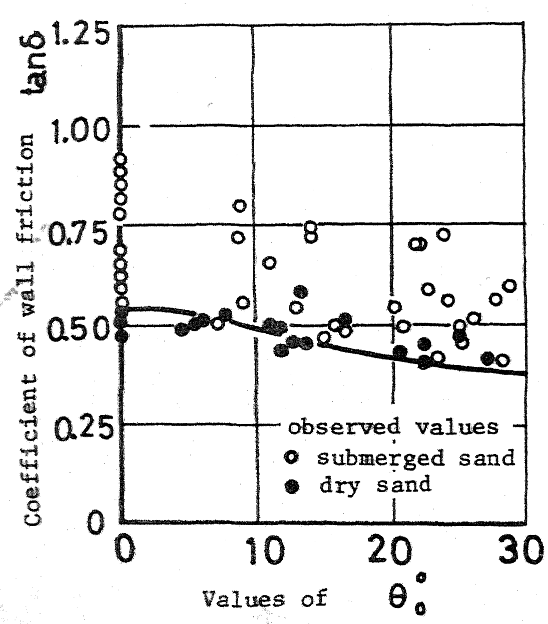

Fig. 6 Comparison of measured coefficient of wall friction with calculated values

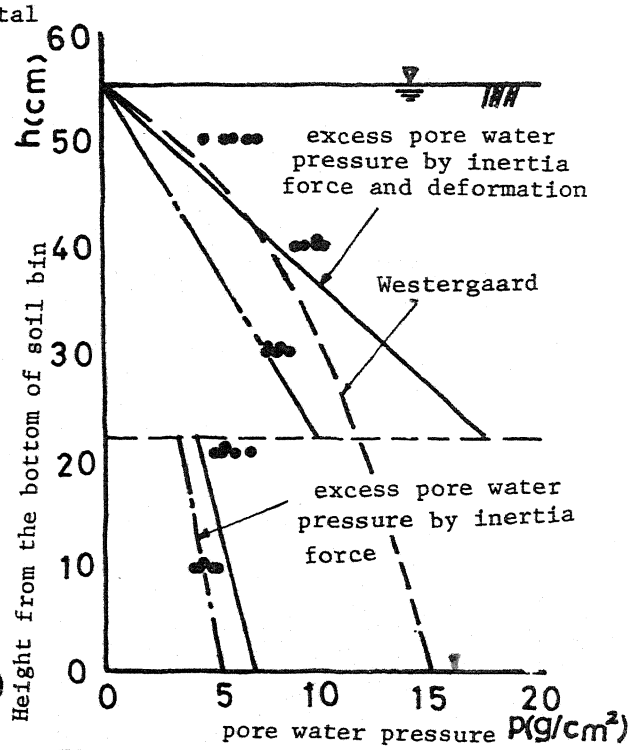

Fig.7 Comparison of measured values of dynamic pore water pressure with the calculated values