Chapter 4 Earth Pressures and Water Pressures

[Public Notice] (Earth Pressures and Water Pressures)

Article 14

1 Earth pressures shall be set appropriately based on ground conditions considering the structure of the facility, surcharge, action of earthquake ground motions, etc.

2 The residual water pressure shall be set appropriately considering the structure of the facility, surrounding ground conditions, tide levels, etc.

3 The dynamic water pressure shall be set appropriately considering the structure of the facility, action of earthquake ground motions, etc.

1 General

(1) Earth Pressure (Relating to Item 1 of the Public Notice Above)

In setting an earth pressure, proper consideration should be given to earth pressure state, namely, whether it is an active or a passive earth pressure as a result of the behavior of the facility concerned, and the design situation, depending on the type of soil quality, such as sandy or cohesive, and the structural characteristics of the facility concerned.

(2) Residual Water Pressure (Relating to Item 2 of the Public Notice Above)

The residual water pressure mentioned herein refers to the water pressure arising from the difference in the water level between the front and rear sides of a facility. This difference must be taken into account in setting the residual water pressure of the facility.

(3) Dynamic Water Pressure (Relating to Item 3 of the Public Notice Above)

In verifying the performance of facilities subject to the technical standards, proper consideration should be given, as required, to the effects of the dynamic water pressure.

(4) Other

In verifying the performance of facilities subject to the technical standards, buoyancy should be considered, as required, in addition to these settings.

2 Earth Pressure

2.1 General

Soil behavior varies with physical conditions, such as grain size, void ratio, and water content, and with stress history and boundary conditions, which also affect earth pressure. The earth pressures discussed in this chapter are those exerted by ordinary soil. The earth pressures exerted by improved soil and reinforced soil will require separate consideration. (For example, refer to **Part III**, **Chapter 2**, **5.18 Active Earth Pressure of Geotechnical Materials Treated with Stabilizer**.) The earth pressure during an earthquake for the design mentioned herein is based on the seismic coefficient method concept and is different from the actual earth pressure generated, during an earthquake, due to dynamic interactions among structures, soil, and water. However, according to analyses of past damages due to earth pressures during earthquakes, the earth pressure discussed here can generally be used in performance verifications. The hydrostatic pressure and dynamic water pressure acting on a structure should be calculated separately.

2.2 Earth Pressures at Permanent State

2.2.1 Earth Pressures of Sandy Soil

(1) The earth pressures of sandy soil acting on the retaining wall of a structure and the angle of the failure surface from the horizontal surface can be calculated by using the following equations (see **Fig. 2.2.1**):

① Active earth pressure and the angle of the failure surface from the horizontal surface

$$p_{ai} = K_{ai}\left[\sum_{j=1}^{i}\gamma_j h_j + \frac{\omega\cos\psi}{\cos(\psi-\beta)}\right]\cos\psi \tag{2.2.1}$$

$$\cot(\zeta_i-\beta) = -\tan(\phi_i+\delta+\psi-\beta) + \sec(\phi_i+\delta+\psi-\beta)\sqrt{\frac{\cos(\psi+\delta)\sin(\phi_i+\delta)}{\cos(\psi-\beta)\sin(\phi_i-\beta)}} \tag{2.2.2}$$

where

$$K_{ai} = \frac{\cos^2(\phi_i-\psi)}{\cos^2\psi\cos(\delta+\psi)\left[1+\sqrt{\dfrac{\sin(\phi_i+\delta)\sin(\phi_i-\beta)}{\cos(\delta+\psi)\cos(\psi-\beta)}}\right]^2}$$

② Passive earth pressure and the angle of the failure surface from the horizontal surface

$$p_{pi} = K_{pi}\left[\sum_{j=1}^{i}\gamma_j h_j + \frac{\omega\cos\psi}{\cos(\psi-\beta)}\right]\cos\psi \tag{2.2.3}$$

$$\cot(\zeta_i-\beta) = \tan(\phi_i-\delta-\psi+\beta) + \sec(\phi_i-\delta-\psi+\beta)\sqrt{\frac{\cos(\psi+\delta)\sin(\phi_i-\delta)}{\cos(\psi-\beta)\sin(\phi_i+\beta)}} \tag{2.2.4}$$

where

$$K_{pi} = \frac{\cos^2(\phi_i+\psi)}{\cos^2\psi\cos(\delta+\psi)\left[1-\sqrt{\dfrac{\sin(\phi_i-\delta)\sin(\phi_i+\beta)}{\cos(\delta+\psi)\cos(\psi-\beta)}}\right]^2}$$

with

p_{ai}, p_{pi} : active and passive earth pressures, respectively, acting on the retaining wall in the *i*-th soil layer (kN/m^2)

ϕ_i : angle of shear resistance of the *i*-th soil layer (°)

γ_j : unit weight ofsoil in each soil layer (kN/m^3)

h_j : thickness of each soil layer, or depth from the top of the *i*-th soil layer for which the earth pressure is being calculated to the earth pressure calculation level (m)

K_{ai}, K_{pi} : coefficients of active and passive earth pressures, respectively, in the *i*-th soil layer

ψ : angle of batter of the retaining wall from the vertical plane (°)

β : angle of the ground surface from the horizontal plane (°)

δ : angle of wall friction (°)

ζ_i : angle of the failure surface of the *i*-th soil layer from the horizontal plane (°)

ω : surcharge per unit area of the ground surface (kN/m^2)

(2) The earth pressures at the permanent state are based on Coulomb's earth pressure theory.

(3) The earth pressure at rest as expressed by **equation (2.2.5)** may be used when there is little displacement due to the wall being confined.

$$p = K_0\left(\sum_{j=1}^{i}\gamma_j h_j + \omega\right) \tag{2.2.5}$$

where

K_0 : coefficient of earth pressure at rest

(4) Angle of Shear Resistance of Soil

It is possible to use the results of soil tests and/or to estimate the angle of shear resistance of soil by using reliable estimation formulas. For the angle of shear resistance of backfilling material, refer to **Part II**, **Chapter 11**, **5.3 Backfilling**.

(5) Angle of Wall Friction

The angle of wall friction normally has a value of ±15°–20°. It can be estimated as one-half of the angle of shear resistance of backfilling material.

(6) Unit Weight of Soil

The wet unit weight γ_t should be used for soil above the residual water level and the submerged unit weight γ' be used for soil below the residual water level. For the unit weight of backfilling material, refer to **Part II**, **Chapter 11**, **5.3 Backfilling**.

(7) Calculation Formula for the Resultant Force of Earth Pressure

The resultant force of earth pressure can be calculated at each layer. The objective force for the *i*-th layer can be calculated using **equation (2.2.6)**.

$$P_i = \frac{p_{iu} + p_{il}}{2} \frac{h_i}{\cos\psi} \quad \textbf{(2.2.6)}$$

where

P_i : resultant force of earth pressure acting on the retaining wall in the *i*-th soil layer (kN/m)

p_{iu} : earth pressure acting on the retaining wall at the top level of the *i*-th soil layer (kN/m^2)

p_{il} : earth pressure acting on the retaining wall at the bottom level of the *i*-th soil layer (kN/m^2)

h_i : thickness of the *i*-th soil layer (m)

Moreover, the horizontal and vertical components of the resultant force of earth pressure can be calculated using **equations (2.2.7)** and **(2.2.8)**.

$$P_{ih} = P_i \cos(\psi + \delta) \quad \textbf{(2.2.7)}$$

$$P_{iv} = P_i \sin(\psi + \delta) \quad \textbf{(2.2.8)}$$

where

P_{ih} : horizontal component of the resultant force of earth pressure

P_{iv} : vertical component of the resultant force of earth pressure

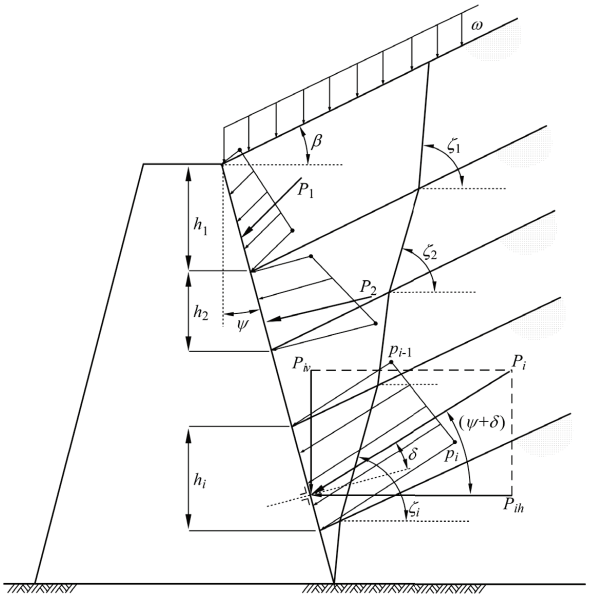

Fig. 2.2.1 Earth Pressures

2.2.2 Earth Pressures of Cohesive Soil

(1) The earth pressures of cohesive soil acting on the retaining wall of a structure can be calculated using **equations (2.2.9)** and **(2.2.10)**.

① Active earth pressure

$$p_{ai} = \sum_{j=1}^{i} \gamma_j h_j + \omega - 2c_u \tag{2.2.9}$$

② Passive earth pressure

$$p_{pi} = \sum_{j=1}^{i} \gamma_j h_j + \omega + 2c_u \tag{2.2.10}$$

where

p_{ai} : active earth pressure acting on the retaining wall in the *i*-th soil layer (kN/m^2)

p_{pi} : passive earth pressure acting on the retaining wall in the *i*-th soil layer (kN/m^2)

γ_j : unit weight of soil in each soil layer (kN/m^3)

h_j : thickness of each soil layer, or depth from the top of the *i*-th soil layer for which the earth pressure is being calculated to the earth pressure calculation level (m)

ω : surcharge per unit area of the ground surface (kN/m^2)

c_u : undrained shear strength of cohesive soil (kN/m^2)

(2) The earth pressures of cohesive soil are complex. The equations above are based on expedient calculation methods and must be applied with care.

(3) The active earth pressure can be calculated using **equation (2.2.9)**. If the calculated earth pressure has a negative value (meaning that the soil is pulled), the pressure should be assumed to be zero in the calculations of the stability of the wall body.

(4) **Equation (2.2.5)** in **Part II, Chapter 4, 2.2.1 Earth Pressures of Sandy Soil** can be used for the earth pressure at rest.

(5) Undrained Shear Strength of Cohesive Soil

The undrained shear strength of cohesive soil should be determined using an appropriate method. For the calculation, refer to **Part II, Chapter 3**, **2.3.3 Shear Characteristics**.

(6) Wall Friction

In case of cohesive soil, the wall friction force due to the cohesion between the soil and retaining wall should be ignored in principle.

(7) Unit Weight of Cohesive Soil

The unit weight of cohesive soil should be estimated by conducting a soil test. The wet unit weight γ_t should be used for soil above the residual water level and the submerged unit weight γ' be used for soil below the residual water level.

2.3 Earth Pressures during Earthquake

2.3.1 Earth Pressures of Sandy Soil

The earth pressures of sandy soil acting on the retaining wall of a structure during an earthquake and the angle of the failure surface from the horizontal surface can be calculated by using the following equations:

(1) Active Earth Pressure and the Angle of the Failure Surface from the Horizontal Surface

$$p_{ai} = K_{ai}\left[\sum_{j=1}^{i}\gamma_j h_j + \frac{\omega\cos\psi}{\cos(\psi-\beta)}\right]\cos\psi \qquad \textbf{(2.3.1)}$$

$$\cot(\zeta_i - \beta) = -\tan(\phi_i + \delta + \psi - \beta) + \sec(\phi_i + \delta + \psi - \beta)\sqrt{\frac{\cos(\psi+\delta+\theta)\sin(\phi_i+\delta)}{\cos(\psi-\beta)\sin(\phi_i-\beta-\theta)}} \qquad \textbf{(2.3.2)}$$

where

$$K_{ai} = \frac{\cos^2(\phi_i - \psi - \theta)}{\cos\theta\cos^2\psi\cos(\delta+\psi+\theta)\left[1+\sqrt{\dfrac{\sin(\phi_i+\delta)\sin(\phi_i-\beta-\theta)}{\cos(\delta+\psi+\theta)\cos(\psi-\beta)}}\right]^2}$$

(2) Passive Earth Pressure and the Angle of the Failure Surface from the Horizontal Surface

$$p_{pi} = K_{pi}\left[\sum_{j=1}^{i}\gamma_j h_j + \frac{\omega\cos\psi}{\cos(\psi-\beta)}\right]\cos\psi \qquad \textbf{(2.3.3)}$$

$$\cot(\zeta_i - \beta) = \tan(\phi_i - \delta - \psi + \beta) + \sec(\phi_i - \delta - \psi + \beta)\sqrt{\frac{\cos(\psi+\delta-\theta)\sin(\phi_i-\delta)}{\cos(\psi-\beta)\sin(\phi_i+\beta-\theta)}} \qquad \textbf{(2.3.4)}$$

where

$$K_{pi} = \frac{\cos^2(\phi_i + \psi - \theta)}{\cos\theta\cos^2\psi\cos(\delta+\psi-\theta)\left[1-\sqrt{\dfrac{\sin(\phi_i-\delta)\sin(\phi_i+\beta-\theta)}{\cos(\delta+\psi-\theta)\cos(\psi-\beta)}}\right]^2}$$

The notations p_{ai}, p_{pi}, K_{ai}, K_{pi}, ζ_i, ω, γ_i, h_i, ψ, β, δ, and ϕ_i are the same as those defined in equations (2.2.1) to (2.2.4) in **Part II, Chapter 4, 2.2.1 Earth Pressures of Sandy Soil** according to **Part II, Chapter 4, 2.2 Earth Pressures at Permanent State**. The composite seismic angle θ is defined as follows:

θ: composite seismic angle (°) shown as follows:

(a) $\theta = \tan^{-1}k$

(b) $\theta = \tan^{-1}k'$

where

k and k' are as shown below:

k : seismic coefficient

k' : apparent seismic coefficient

(3) The apparent seismic coefficient shall be in accordance with **Part II, Chapter 4, 2.3.3 Apparent Seismic Coefficient.**

(4) The earth pressure during an earthquake is based on the theories proposed by Mononobe[1)] and Okabe[2)].

(5) Angle of Wall Friction

The angle of wall friction normally has a value of ±15° or less. It can be estimated as one-half of the angle of shear resistance ϕ of backfilling material.

(6) Earth Pressure Below Residual Water Level

The earth pressure distribution above or below the residual water level can be determined respectively by using the seismic coefficient in air or the apparent seismic coefficient shown in **Part II, Chapter 4, 2.3.3 Apparent Seismic Coefficient** at each boundary plane.

(7) Coefficient of Earth Pressure

The coefficient of earth pressure and the angle of the failure surface can be obtained from the diagrams in **Fig. 2.3.1**.

(8) The earth pressure theory assumes that the soil and the pore water behave integrally. Thus, the equations mentioned above cannot be applied to liquefied soil. For liquefied soil, it is necessary to evaluate the seismic stability of the ground and structures with dynamic effective stress analysis or model tests.

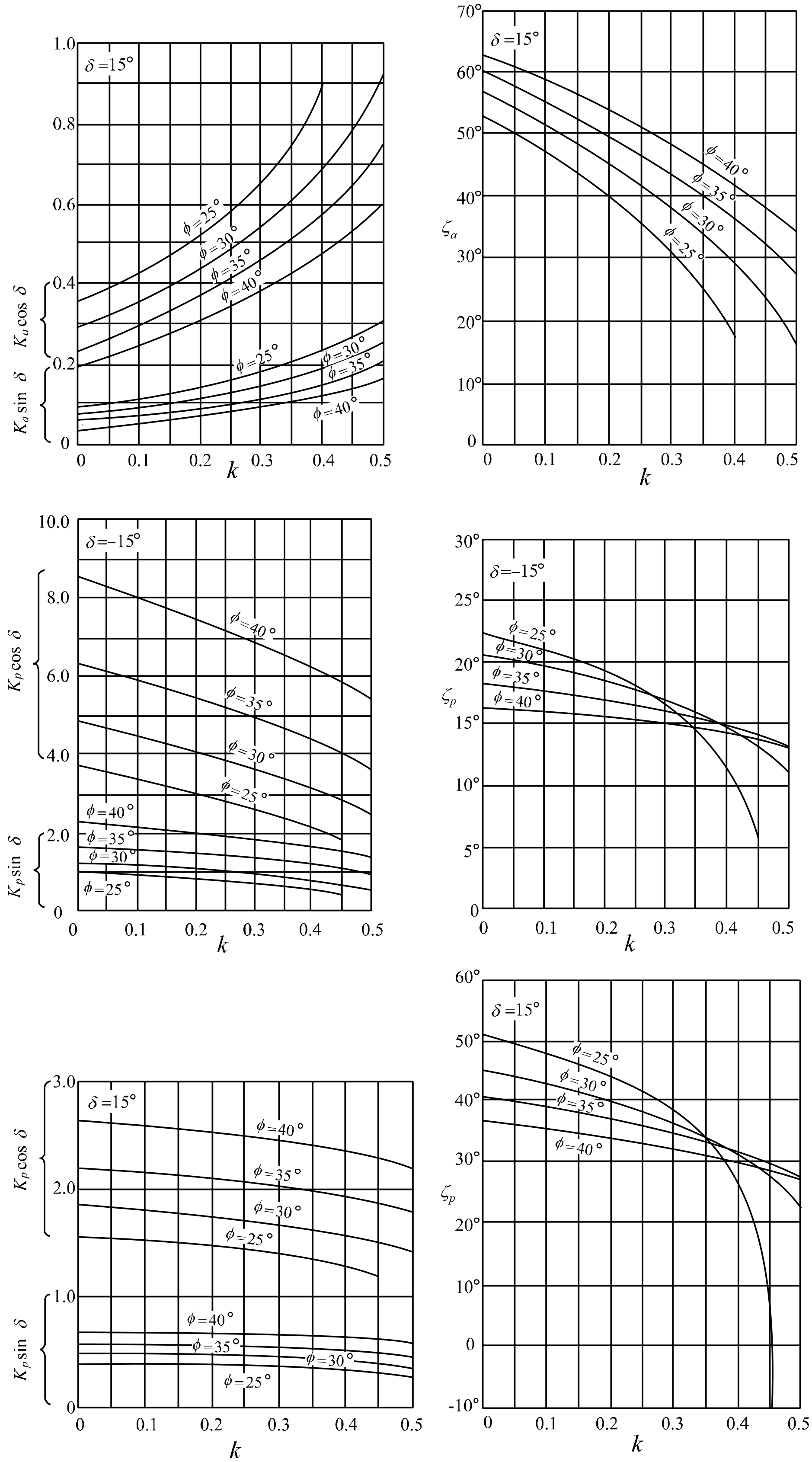

Fig. 2.3.1 Coefficient of Earth Pressure and Angle of Failure Surface

2.3.2 Earth Pressures of Cohesive Soil

The earth pressures of cohesive soil acting on the retaining wall of a structure during an earthquake and the angle of the failure surface from the horizontal surface can be calculated as follows:

(1) Active Earth Pressure during Earthquake

The active earth pressure shall be calculated using an appropriate earth pressure formula which takes the seismic coefficient into account so that the structural stability will be secured during an earthquake. Generally, the active earth pressure during an earthquake can be calculated using **equation (2.3.5)** and the angle of the failure surface from the horizontal surface using **equation (2.3.6)**.

$$p_{ai} = \frac{\left(\sum_{j=1}^{i} \gamma_j h_j + \omega\right)\sin(\zeta_a + \theta)}{\cos\theta \sin\zeta_a} - \frac{c_u}{\cos\zeta_a \sin\zeta_a} \qquad \textbf{(2.3.5)}$$

$$\zeta_{ai} = \tan^{-1}\sqrt{1 - \left(\frac{\sum_{j=1}^{i} \gamma_j h_j + 2\omega}{2c_u}\right)\tan\theta} \qquad \textbf{(2.3.6)}$$

where

p_{ai} : active earth pressure (kN/m^2)

γ_j : unit weight of the soil (kN/m^3)

h_j : thickness of the soil layer

ω : surcharge per unit area of the horizontal surface (kN/m^2)

c_u : undrained shear strength of cohesive soil (kN/m^2)

θ : composite seismic angle expressed as $\theta = \tan^{-1} k$ (°) or $\theta = \tan^{-1} k'$ (°)

k : seismic coefficient

k' : apparent seismic coefficient

ζ_{ai} : angle of the failure surface from the horizontal surface (°)

(2) Passive Earth Pressure during Earthquake

The passive earth pressure shall be calculated using an appropriate earth pressure formula so that the structural stability will be secured during an earthquake.

There are many unknown factors concerning the method for determining the passive earth pressure of cohesive soil during an earthquake. Conventionally, however, **equation (2.2.10)** given in **2.2.2 Earth Pressures of Cohesive Soil** in this chapter for obtaining the earth pressure of cohesive soil is used in line with the methods for calculating earth pressures at permanent state. At present, **equation (2.2.10)** can be used as an expedient method.

(3) The apparent seismic coefficient should be used to calculate the earth pressure of cohesive soil under the sea bottom during an earthquake. The apparent seismic coefficient can be set as zero when calculating the earth pressure at a depth of 10 m from the sea bottom or deeper. However, if the earth pressure at a depth of 10 m below the sea bottom becomes less than the earth pressure at the sea bottom, the latter should be applied.

2.3.3 Apparent Seismic Coefficient

(1) The earth pressure acting on the soil below the water level during an earthquake can be calculated according to the procedures outlined in **Part II, Chapter 4, 2.3.1 Earth Pressures of Sandy Soil** and **Part II, Chapter 4, 2.3.2 Earth Pressures of Cohesive Soil** by using the apparent seismic coefficient which is determined from the following equation (see **Fig. 2.3.2**):

$$k' = \frac{2\left(\sum \gamma_{ti} h_i + \sum \gamma_{sat\,j} h_j + \omega\right) + \gamma_{sat} h}{2\left\{\sum \gamma_{ti} h_i + \sum \left(\gamma_{sat\,j} - 10\right) h_j + \omega\right\} + \left(\gamma_{sat} - 10\right) h} k \qquad \textbf{(2.3.7)}$$

where

k' : apparent seismic coefficient

γ_{ti} : unit weight of soil in the *i*-th soil layer above the residual water level (kN/m^3)

h_i : thickness of the *i*-th soil layer above the residual water level (m)

γ_{satj} : saturated unit weight of soil in the *j*-th soil layer above the layer for which the earth pressure is being calculated below the residual water level (kN/m^3)

h_j : thickness of the *j*-th soil layer above the layer for which the earth pressure is being calculated below the residual water level (m)

ω : surcharge per unit area of the ground surface (kN/m^2)

γ_{sat} : saturated unit weight of soil in the soil layer for which the earth pressure is being calculated below the residual water level (kN/m^3)

h : thickness of soil layer for which the earth pressure is being calculated below the residual water level (m)

If this soil layer continues, with no change in the soil property, down below the bottom of the retaining wall of the structure on which the earth pressure acts, the thickness of the portion below the bottom of the wall shall not be included in the thickness of the soil layer for which the earth pressure is being calculated.

k : seismic coefficient

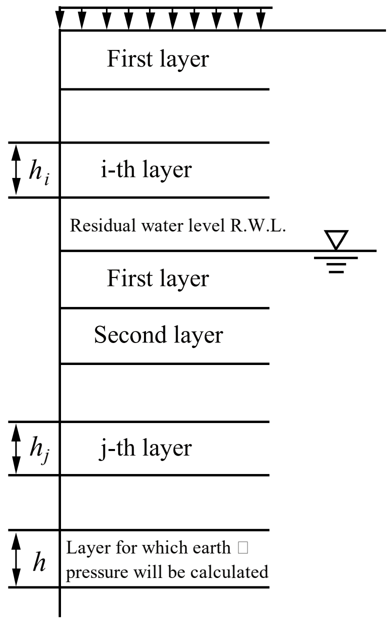

Fig. 2.3.2 Symbols for Apparent Seismic Coefficient

(2) **Equation (2.3.7)**[3)] can be used to calculate the apparent seismic coefficient, which will also be used to calculate the earth pressure during an earthquake, as it can be applied to light-weight filling materials and other new materials and is believed to be the most rational method.

(3) On the assumption that soil grains and water move in an integrated manner in soil under the water level during an earthquake, the force of the earthquake ground motion acting on the soil would be the product of the soil's saturated weight multiplied by the seismic coefficient. Moreover, since the soil under the water level is subject to buoyancy, the vertical force acting on the soil is the soil's underwater weight. Therefore, the resultant force on the soil under the water level during an earthquake would be different from that in the air. When calculating the earth pressure during an earthquake, the equation for determining the earth pressure during an earthquake for soil in the air can also be used for soil under water by applying the apparent seismic coefficient deduced from the composite seismic angle.

The vertical force acting on soil under water includes the weight of the soil layers above the layer for which the earth pressure is being calculated as well as the surcharge. Hence, the apparent seismic coefficient is affected by these factors.

[References]

1) Mononobe, N.: Seismic Civil Engineering, Riko-Tosho Publishing, 1952
2) Okabe, S.: General Theory on Earth Pressure and Seismic Stability of Retaining Wall and Dam, Journal of JSCE Vol. 10, No. 6, p. 1277, 1924
3) Arai, H. and T. Yokoi: Study on the characteristics of earthquake-resistance of sheet pile wall (Third Report), Proceedings of 3rd conference of PHRI, p. 103, 1965

3 Water Pressures

3.1 Residual Water Pressure

(1) When mooring facilities or similar facilities have watertight structures or when backfilling materials and backfilling soil (hereinafter referred to in this paragraph as "backfilling") have low permeability, there is a time delay in changes in the water level in the backfilling as opposed to the water level at the front, and the difference of water level appears. In performance verifications on mooring facilities or similar facilities, what needs to be checked is the condition where the water level in the backfilling is higher than that at the front, and that difference is at its greatest. The residual water pressure refers to the water pressure acting on the mooring facilities or similar facilities under this condition.

The magnitude of the residual water level difference varies depending on the permeability of the wall and its surrounding materials making up a mooring facility or a similar facility as well as the tidal range. The general values for the residual water level difference by structural type are shown in sections relating to performance verifications of the respective facilities. Values other than these general values can be used when determining the residual water level difference from surveys conducted on similar structures located nearby or from permeability checks carried out on the wall and its surrounding ground.

(2) The characteristic value of the residual water pressure caused by the difference in water level between the front and rear sides of a facility can be calculated using the following equation (see **Fig. 3.1.1**):

① When y is less than h_w

$$p_{w_k} = \rho_w g y \tag{3.1.1}$$

② When y is equal to or greater than h_w

$$p_{w_k} = \rho_w g h_w \tag{3.1.2}$$

where

p_w : residual water pressure (kN/m^2)

$p_w g$: unit weight of water (kN/m^3)

y : depth of the soil layer from the residual water level at the back of the facility to the level for which the residual water pressure is being calculated (m)

h_w : water level difference between the residual water level at the back of the facility and the water level at the front of the facility when the former is higher than the latter (m)

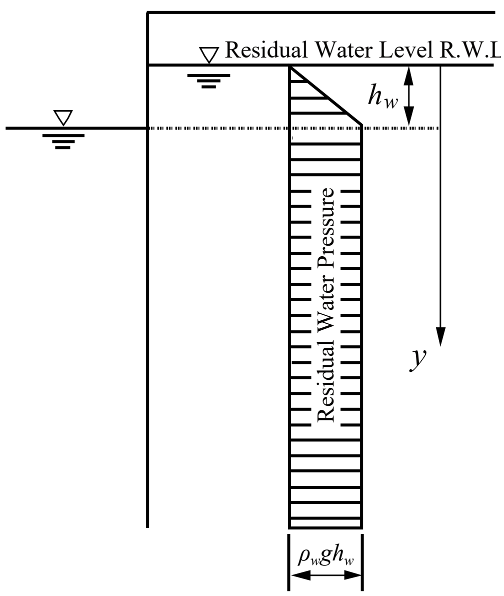

Fig. 3.1.1 Residual Water Pressure

(3) The residual water level difference is determined taking into consideration whether the wall is well drained or poorly drained, as well as the tidal range. Normally, the height h_w will be 1/3–2/3 of the anterior tidal range.

(4) After a facility is completed, the permeability of its wall and surrounding materials may diminish with time. Therefore, when the anterior tidal range is sizable, it would be preferable to take that into consideration in determining the residual water level difference.

3.2 Dynamic Water Pressure

(1) Items (2) through (8) below should be followed when using performance verification equations that make use of the characteristic value of the dynamic water pressure, whereas item (9) should be followed in performing verifications that use techniques, such as the finite element method, for taking the effects of the dynamic water pressure into consideration.

(2) Normally, methods based on the dynamic water pressure on steady oscillation[1)] are used for calculating the characteristic value of the dynamic water pressure. However, in view of the phase relationship of other actions, when a particular need arises, the dynamic water pressure on irregular oscillation should be calculated.

Also, if a liquid occupies spaces inside a facility, the dynamic pressure of the liquid must be taken into consideration. If the dynamic water pressure is acting on both sides of the facility, the sum of the resultant force of the dynamic water pressure becomes twofold. The dynamic water pressure need not be considered in the following cases:

① When performance verifications can be performed without taking the dynamic water pressure directly into consideration due to structural characteristics;

② When using verification methods that do not take the dynamic water pressure directly into account. This would require sufficient records of results.

More specifically, this would be in the following cases:

(a) Dynamic water pressure of pore water in the caisson filling

(b) Dynamic water pressure of pore water in backfilling materials and backfilling soil of mooring quay walls or similar facilities

(c) Dynamic water pressure in designing reinforcement arrangement for caisson bottom slabs

(3) The dynamic water pressure acting on a vertical wall of an underwater structure during an earthquake can be calculated using the following equation:

$$p_{dw} = \pm\frac{7}{8} k_h \rho_w g \sqrt{Hy} \qquad \textbf{(3.2.1)}$$

where

p_{dw} : dynamic water pressure (kN/m^2)

k_h : seismic coefficient

$\rho_w g$: unit weight of water (kN/m^3)

y : depth of the dynamic water pressure calculation level from the still water level (m)

H : depth of water (m)

The resultant force of the dynamic water pressure and its acting height can be calculated by using the following equation:

$$P_{dw} = \pm\frac{7}{12} k_h \rho_w g H^2$$
$$h_{dw} = \frac{3}{5} H \qquad \textbf{(3.2.2)}$$

Here, P_{dw} and h_{dw} are the following values, and k_h, ρ_w, and H are equal to the values of k_h, ρ_w, and H in **equation (3.2.1)**, respectively.

P_{dw} : resultant force of dynamic water pressure (kN/m)

h_{dw} : depth of the acting point of the dynamic water pressure resultant force from the still water level (m)

(4) In the case where water occupying a space in the shape of a cuboid is subject to an earthquake ground motion that causes vibrations in the direction parallel to one side of the cuboid, the dynamic water pressure acting on a wall surface perpendicular to the vibration direction can be calculated using the following equation in consideration of the shape of the cuboid (see **Fig. 3.1.2**):

$$p_{dw} = \pm \frac{7}{8} c k_h \rho_w g \sqrt{Hy} \quad \textbf{(3.2.1)Reference}$$

where

p_{dw} : dynamic water pressure (kN/m^2)

k_h : seismic coefficient

$\rho_w g$: unit weight of water (kN/m^3)

y : depth of the dynamic water pressure calculation level from the still water level (m)

H : depth of water (m)

L : length of the space occupied by water in the vibration direction (m)

c : correction factor

When $\frac{L}{H} < 1.5$, $c = \frac{L}{1.5H}$

When $\frac{L}{H} \geq 1.5$, $c = 1.0$

The dynamic water pressure acting on the bottom can be calculated using the following equation:

$$p_{dw} = \pm \frac{7}{8} c k_h \rho_w g H \frac{\cosh\left(\frac{\pi}{2}\frac{x}{H}\right) - \cosh\left(\frac{\pi}{2}\frac{L-x}{H}\right)}{1-\cosh\left(\frac{\pi}{2}\frac{L}{H}\right)} \quad \textbf{(3.2.3)}$$

where

x : distance from the wall surface perpendicular to the vibration direction to the dynamic water pressure calculation point (m)

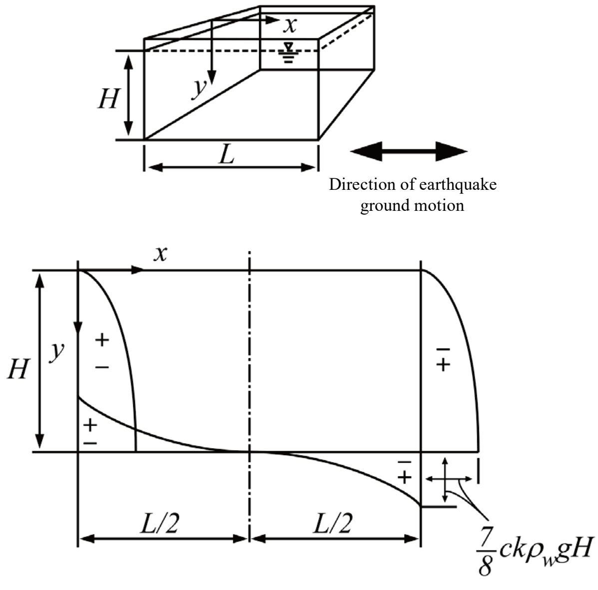

Fig. 3.1.2 Dynamic Water Pressure Exerted by Water in a Cuboid-Shaped Hollow

(5) The action of the dynamic water pressure both in the front and the back of the wall is directed toward the sea.

(6) When **equation (2.3.7)** in **Part II, Chapter 4, 2.3.3 Apparent Seismic Coefficient** is used for a structure, the dynamic water pressure acting on the front side of its wall should be directed seawards, while the dynamic water pressure on the rear side of the wall need not be considered.

(7) Where the wall is inclined, the dynamic water pressure acting on that surface is smaller than that acting on a vertical wall. This is because the direction of the motion of water particles toward the wall surface is diverted diagonally upwards along the inclined surface. The dynamic water pressure in this case can be calculated using the method proposed by Zanger et al.[2)].

(8) The dynamic water pressure acting on a structure that has a complex shape due to an inclined and/or submerged wall can be determined by solving an equation of motion that takes into account the compressibility of water. An equation of motion of water particles in two dimensions is given by **equation (3.2.4)**.

$$\left.\begin{aligned} -\frac{\partial \sigma}{\partial x} &= \rho_w \frac{\partial^2 u}{\partial t^2} \\ -\frac{\partial \sigma}{\partial y} &= \rho_w \frac{\partial^2 v}{\partial t^2} \end{aligned}\right\} \qquad \textbf{(3.2.4)}$$

where

u : displacement of water particles in the x direction

v : displacement of water particles in the y direction

σ : dynamic water pressure

ρ_w : density of water

When the bulk modulus of water is expressed as E_v, the relationship between the volumetric strain of water $\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$ and dynamic water pressure is given by the following equation:

$$\sigma = -E_v \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad \textbf{(3.2.5)}$$

The dynamic water pressure under different conditions can be calculated by solving **equations (3.2.4)** and **(3.2.5)** under the boundary condition.

(9) In the verification of deformation using a finite element method, such as the FLIP[3)], the effects of the dynamic water pressure are generally considered in the form of an added mass matrix[4)] in formulations. In this case, the solutions of the formulas are approximated on the assumption that the fluid is incompressible.

(10) The dynamic water pressure acting on a steel pipe or similar structure in water is affected by the inertial force acting on water inside the pipe and the inertial force acting on nearby seawater (added mass) that behaves in an integrated manner with the steel pipe. For details, refer to **Part III**, **Chapter 5**, **5.2.3 Actions**.

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