Earthquake-resistant Design of Geotechnical Structures

- Procedure of Earthquake-Resistant Design of Geotechnical Structures

  1. Determination of design seismic loadings
     A. Construction locations of structures
     B. Importance level of structures
     C. Performance level of structures
     D. Soil type etc.
  2. Ground Response Analysis considering characteristics of Soil
     A. Peak acceleration at surface
     B. Profile of the maximum acceleration and shear strain with depth
  3. Evaluation of Liquefaction
     A. Simple prediction method
     B. Detail prediction method
  4. **Dynamic analysis of geotechnical structures**
     A. Pseudo static analysis with peak acceleration
     B. Dynamic analysis considering Soil-Structure Interaction
     C. Model tests with similitude

- Geotechnical structures for earthquake-resistant Design
  1. Foundations
  2. Slope
  3. Retaining walls etc.

1. Earthquake resistant Design of Foundations
   A. Foundations = substructure of a whole structure system
      ⇨ Structure design ⇔ Foundation Design
      E.g. Foundation Design -> Structure design: Soil Stiffness for modeling of whole system
      Structure Design -> Foundation Design: Design Load for foundation
   B. Flowchart of Earthquake resistant Design of Foundations
      i. Pseudo static analysis
         ⇨ Similar with static analysis but different loading and FOS
      ii. Shallow foundations
         ⇨ Sliding, overturning, bearing capacity, settlement
      iii. Pile foundation
         ⇨ Displacement, member forces

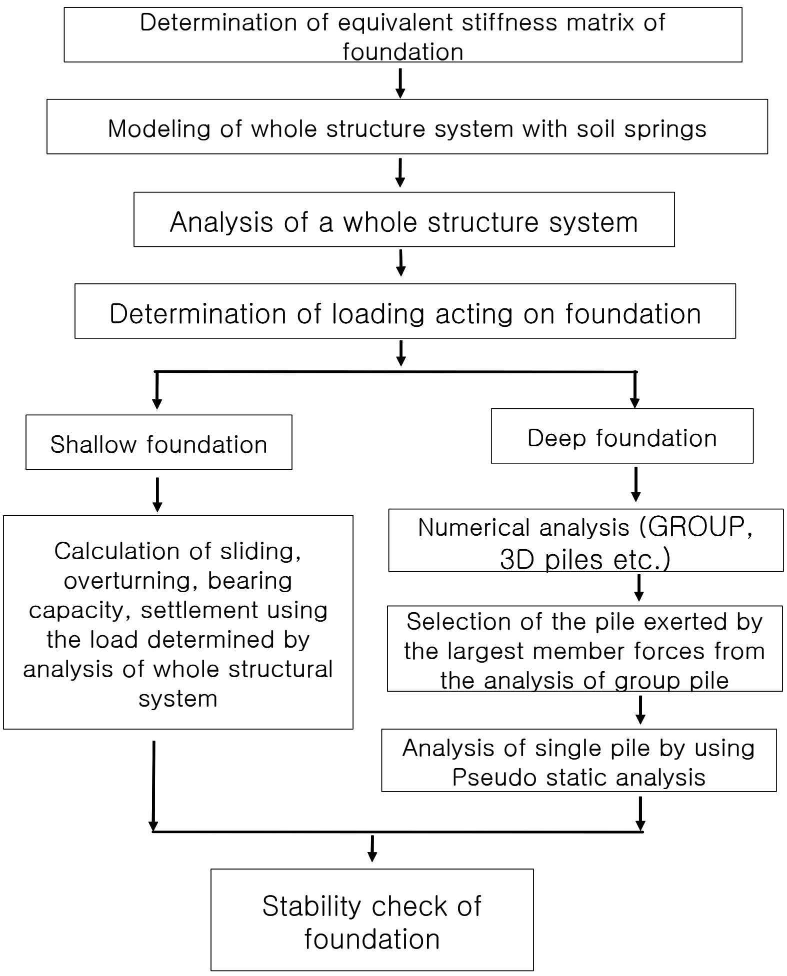


Fig. 1 flowchart of Earthquake resistant Design of Foundations

C. Modeling technique of foundation and soil

i. Fixed end

⇨ Simple but too conservative

ii. Spring (6th DOF spring, p-y spring)

⇨ How to determine the spring coefficients is very important

iii. Whole modeling (Solid and beam modeling of whole foundation and soil system)

⇨ Complicated and rigorous

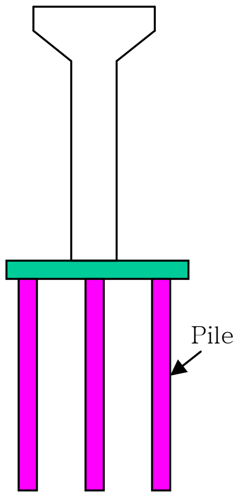


Fig. 2 Structure-foundation system

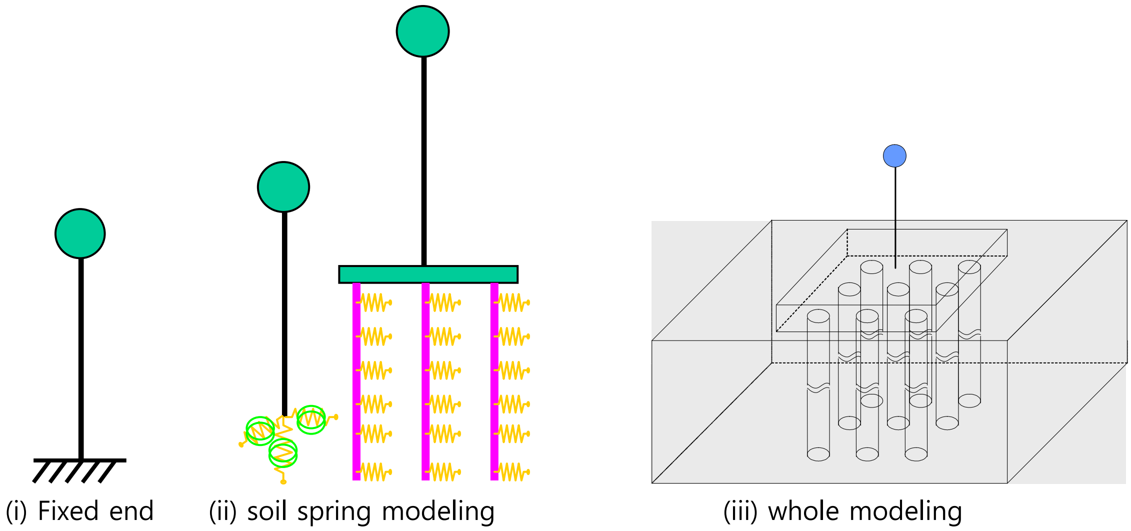


Fig. 3 modeling technique of structure-foundation system of Fig. 1

D. Shallow foundation

i. Flowchart

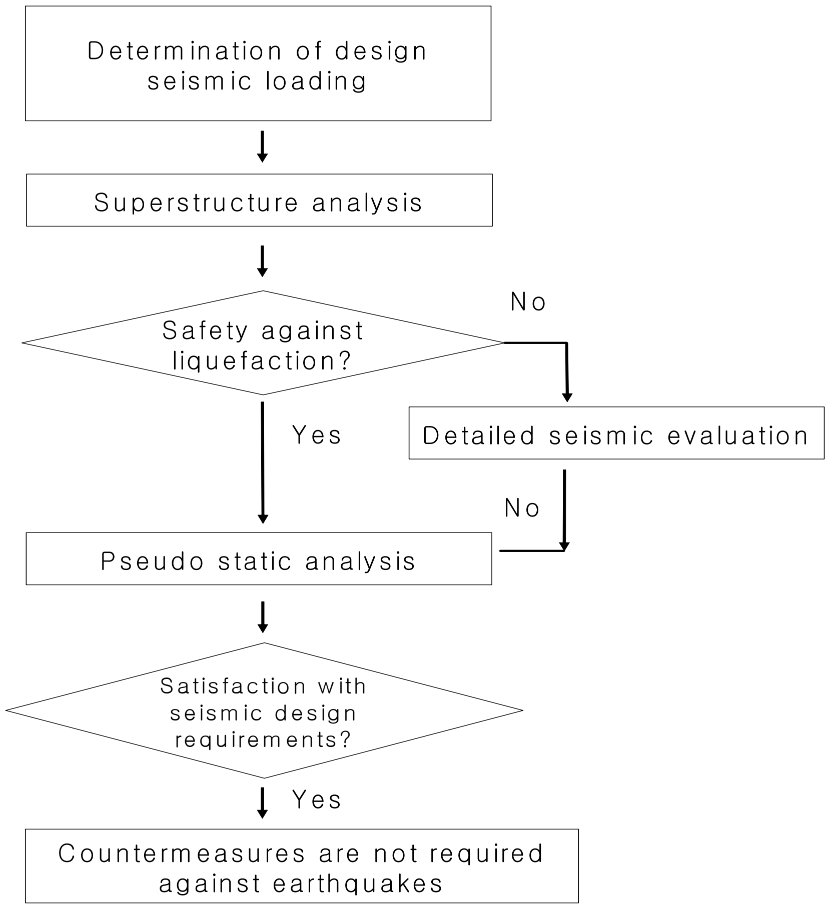


Fig. 4 flowchart of earthquake resistant design of shallow foundation

ii. Design requirements

- ⇨ Satisfaction with static requirements
- ⇨ No liquefaction
- ⇨ Factor of safety

Table 1 Factor of safety for shallow foundation

	Translation	Bearing Capacity	Overturning	Settlement
During earthquake	1.2	2.0	e < B/3	Allowable value
Ordinary	2.0	3.0	e < B/6	Allowable value

e : eccentricity, B : width of shallow foundation

E. Pile foundations

i. Considerations

⇨ Liquefaction : deterioration of vertical/lateral bearing capacity of soils

⇨ Batter pile : too excessive axial force at pile heads

⇨ Soil-Structure Interaction

A. Mechanical behaviors between piles and their surrounding soils

B. Variation of soil profile and soil properties with depth

C. Pile spacing, superstructures etc.

⇨ Interaction between piles and submerged slopes

A. likely to install piles for pile-supported wharves on submerged slopes which is highly possible to move and slide during earthquakes

⇨ Dynamic group effect

A. In the case that C.T.C. of piles is less than 6 times of diameter of pile

⇨ Separation of pile and its surrounding soils

A. Decrease of vertical/lateral bearing capacity

ii. Flowchart

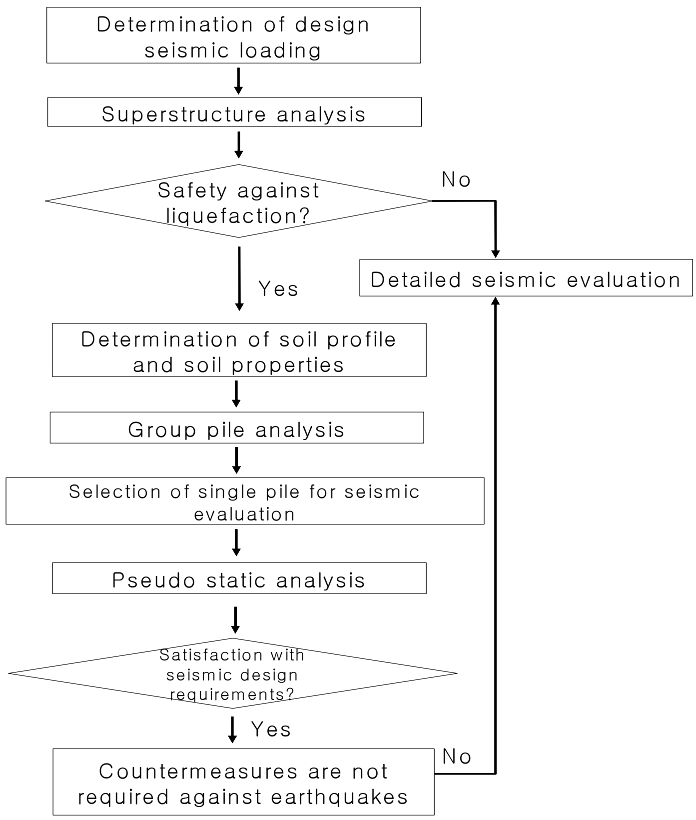


Fig. 5 flowchart of earthquake resistant design of pile foundation

iii. Design requirements

- ⇨ Satisfaction with static requirements including displacement requirement
- ⇨ OLE(Operating Level Earthquake)
  - A. Only elastic deformation is allowable
  - B. Same criteria with static conditions
    - i. 1% of Diameter of pile if D > 1500mm
    - ii. 1.5 cm if D <= 1500mm
- ⇨ CLE(Collapse Level Earthquake)
  - A. Displacement (=elastic displacement X displacement ductility coefficient) < allowable maximum displacement
  - B. Allowable maximum displacement is usually increased by 50% of ordinary condition

Table 2 Displacement ductility coefficient for piles

Port and harbor structures	Type	displacement ductility coefficient				
		Concrete pile			Steel pile	
		Within ground	Pile head	Batter pile head	Vertical	Vertical + batter
Pile-supported wharves	PS Concrete	1.5	3.0	1.5	-	-
	Steel or Composite of steel and concrete	-	-	-	5.0	3.0
Gravity quay wall	PS Concrete	2.0	5.0	2.5	-	-
	Steel or Composite of steel and concrete	-	-	-	5.0	3.0

2. Earthquake resistant Design of Slopes
   A. Design criteria
      i. Factor of Safety
         ⇨ Pseudo static analysis, limit equilibrium analysis
      ii. Displacement
         ⇨ Newmark sliding block method
         ⇨ Dynamic numerical analysis
   B. Pseudo static analysis
      i. Factor of safety with circular failure surface
      ii. Seismic forces => pseudo static force(= horizontal seismic coefficient X Weight of slices)
      iii. Horizontal seismic coefficient = (1/2)x a_{max}

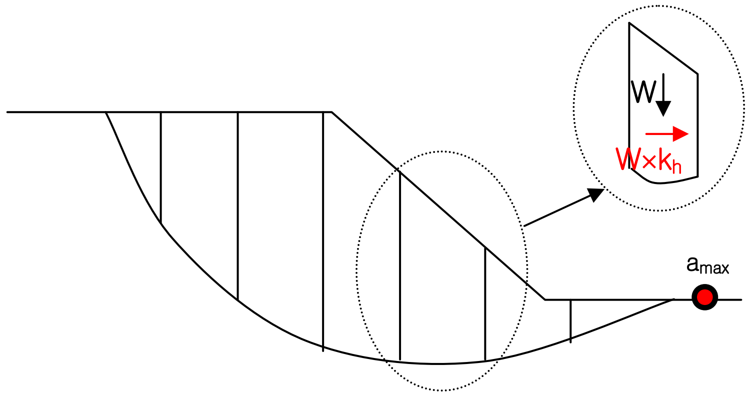
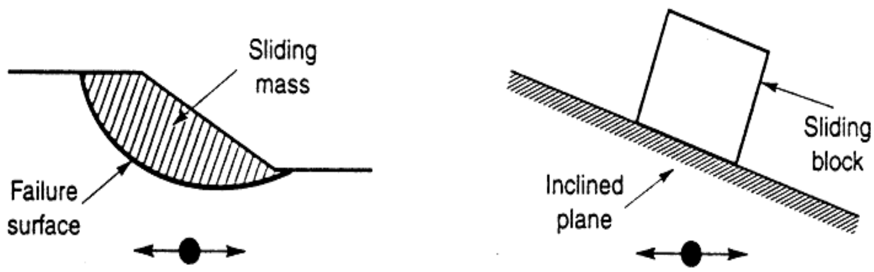
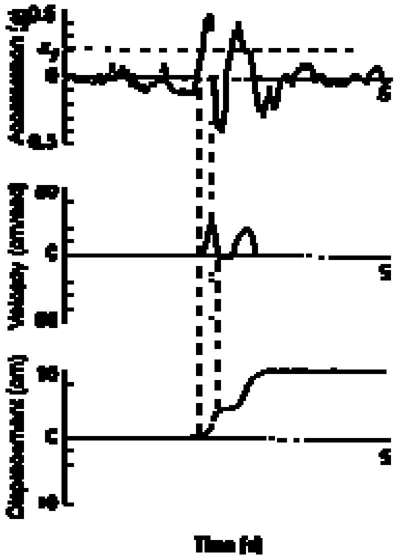


Fig. 6 Pseudo static analysis of slopes

   C. Newmark sliding block method
      i. Calculation of displacement of slope during earthquakes
      ii. Definition
         ⇨ Yielding acceleration : acceleration when FOS of slope becomes 1
      iii. Assumption
         ⇨ Sliding mass in slope = rigid sliding block on inclined plane
         ⇨ Displacement occurs only when earthquake acceleration exceeds yielding acceleration
      iv. Permanent displacement of sliding mass = twice integration of acceleration difference between earthquake acceleration exceeding yielding acceleration and yielding acceleration



(a) conceptual diagram



(b) Calculation of permanent displacement

Fig. 7 Newmark sliding block method

D. Design requirements

i. Satisfaction with static requirements

ii. No liquefaction

iii. To ensure the safety against CLE(Collapse Level Earthquake) of 2^{nd} importance level (return period = 500 years)

iv. Pseudo static analysis

v. Criteria of FOS = 1.1

vi. Allowable displacement

⇨ OLE : 10 cm

⇨ CLE : 30 cm

3. Earthquake resistant Design of Retaining walls
   A. Design criteria
      i. Factor of Safety
         ⇨ Pseudo static analysis, limit equilibrium analysis
      ii. Displacement
         ⇨ Richard-Elms method(upper bound of displacement)
         ⇨ Whitman-Liao method(average of displacement)
         ⇨ Dynamic numerical analysis
   B. Forces acting on the wall during earthquakes
      i. Static components
         ⇨ Static water force in front of the wall
         ⇨ Static water force in the back of the wall
         ⇨ Static earth pressure in the back of the wall
      ii. Dynamic components
         ⇨ Dynamic water force in front of the wall
         ⇨ Dynamic water force in the back of the wall
         ⇨ Dynamic earth pressure in the back of the wall
         ⇨ Inertia force of the wall

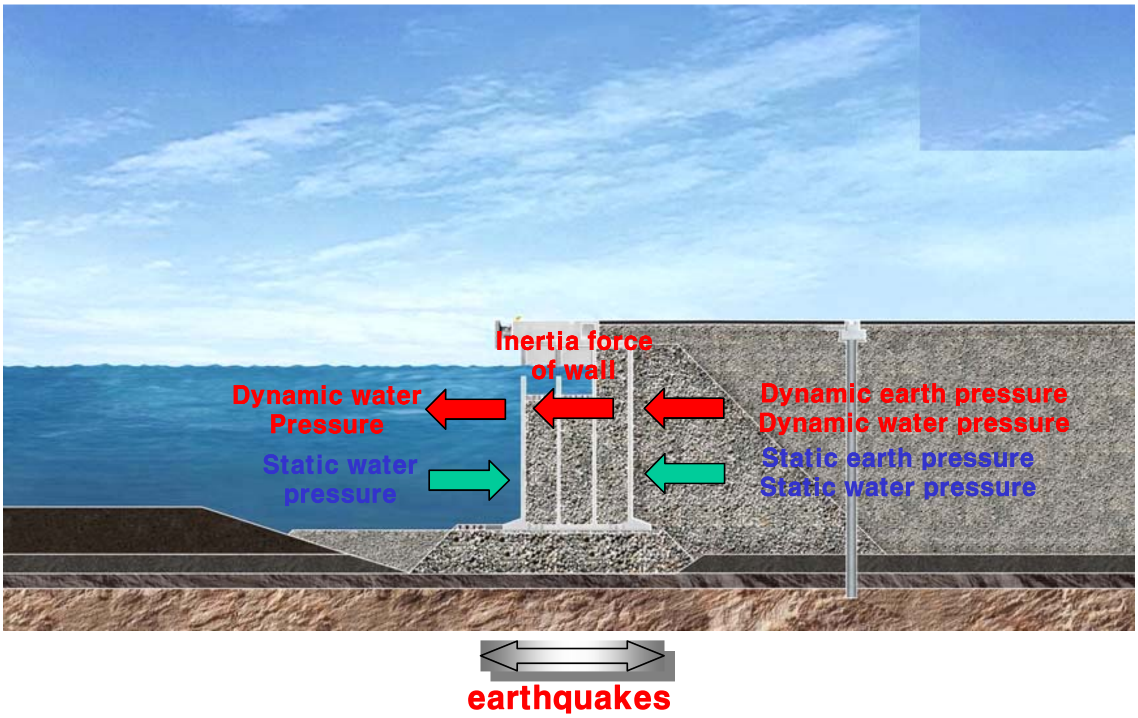


Fig. 8 Forces acting on the wall during earthquakes

C. Horizontal seismic coefficient for pseudo static analysis

i. Horizontal seismic coefficient k_h = 1/2×a_{max}

ii. Horizontal seismic coefficient k_h = (1.5 or 1.0) ×a_{max} only when displacement of wall is restrained

iii. Maximum acceleration, a_{max}

⇨ Maximum acceleration at surface without backfill if height of wall is smaller than 10 m

⇨ Maximum acceleration in backfill considering magnification of acceleration if height of wall is larger than 10 m

D. Dynamic earth pressure

i. Mononobe-Okabe method

⇨ Expansion of Coulomb theory (adding equivalent seismic force to Coulomb's earth pressure)

⇨ Including the static earth pressure

ii. M-O dynamic earth pressure

$$P_{AE} = \frac{1}{2} K_{AE} \gamma H^2 (1 - K_v)$$

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

$$\tan\psi = \frac{K_h}{1 - K_v}$$

where, γ : unit weight of backfill soil(tf/m)

ϕ : internal friction angle of backfill soil(°)

β : inclination angle of backfill surface from horizontal line(°)

θ : internal friction angle of backfill soil(°)

δ : wall friction(°)

$$\varphi = \tan^{-1}\frac{K_h}{1 - K_v}$$

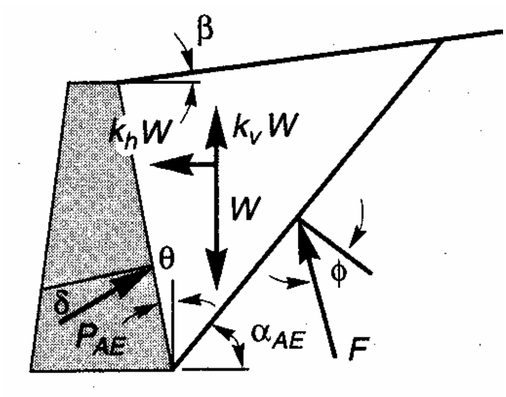


Fig. 9 forces acting on wall in M-O method

iii. Permeability coefficient in backfill

⇨ k < 5x10-4 m/sec

$$\gamma^* = \gamma_{sub}$$
$$\psi = \tan^{-1}\left(\frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w}\frac{k_h}{1-k_v}\right)$$
$$F_{WD} = 0$$

⇨ k > 5x10-4 m/sec

$$\gamma^* = \gamma_{sub}$$
$$\psi = \tan^{-1}\left(\frac{\gamma_d}{\gamma_{sat} - \gamma_w}\frac{k_h}{1-k_v}\right)$$
$$F_{WD} = \frac{7}{12}k_h\gamma_w H'^2$$

iv. Locations where M-O dynamic forces are acting

⇨ M-O dynamic earth force : 0.5 H

A. Static component : (1/3)H

B. Dynamic component : 0.6 H

※ H: height of wall

E. Inertia force of wall

i. Inertia force = mass of wall x horizontal seismic coefficient

F. Dynamic water force

i. Westergaard's solution

$$F_{FWD} = \frac{7}{12} k_h \gamma_w H_w{}^2$$

ii. Locations where dynamic water forces are acting

⇨ 0.4H

iii. Dynamic water force in backfill should be considered when the permeability is large(k > 5x10-4 m/sec)

G. Design method considering displacement of wall

i. Richard-Elms method

⇨ Upper bound of displacement

⇨ $$d_{perm} = 0.087 \frac{v_{max}^2 a_{max}^3}{a_y^4}$$

A. v_{max} : maximum velocity (m/sec)

B. a_{max} : maximum acceleration (m/sec2)

C. a_y : yielding acceleration (m/sec2)

ii. Whitman-Liao method

⇨ Average of displacement

⇨ $$d_{perm} = \frac{37 v_{max}^2}{a_{max}} \exp\left(\frac{-9.4 a_y}{a_{max}}\right)$$

H. Design requirements

i. Satisfaction with static design requirements

ii. No liquefaction

iii. Criteria of FOS = 1.1 (translation, overturning, bearing capacity)

iv. Allowable displacement

⇨ OLE : 10 cm

⇨ CLE : 30 cm