EC8 Webinars
Second Generation of Eurocode 8

prEN 1998-5:2021
Foundation system

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9 Foundation system

Three main topics

- Shallow foundations
- Pile foundations
- Design values and verifications

One associated Annex (informative)

- Annex E - Seismic bearing capacity of shallow foundations

9.1 General requirements

Main principle:

(1) The foundation of a structure in a seismic zone shall transfer the action effects in the structure for the seismic design situation, from the structure to the ground, without structurally unacceptable permanent displacements.

Attention to:

- Strain dependence and cyclic effects
- Verifications using material factor approach (MFA) or resistance factor approach (RFA), and same partial factors for materials as in design of structural members
- Different foundation types in the same structure imply additional requirements
- Force-based approach (FBA) and displacement-based approach (DBA)

9.2 Design values of the action effects

Force-based approach (FBA):

$$E_{\mathrm{Fd}} = E_{\mathrm{Fd,G}} \text{ "+" } \frac{\Omega_{\mathrm{d}}\gamma_{\mathrm{Rd}}}{\chi_{\mathrm{H}}} E_{\mathrm{Fd,E}}$$

non-seismic action effects

over-design = $(R_{\mathrm{di}}/E_{\mathrm{di}}) \leq q$

overstrength factor

Capacity design

design seismic action effects ($/q$)

amplitude of accepted permanent displ.

Details:

- To verify the foundation elements $\rightarrow \chi_{\mathrm{H}} = 1{,}0$

- DC1 $\rightarrow \Omega_{\mathrm{d}}\ \gamma_{\mathrm{Rd}} = 1{,}0$
- DC2 or DC3:
  - Raft or caisson foundations (and foundation beams designed to DC1) $\rightarrow \Omega_{\mathrm{d}}\ \gamma_{\mathrm{Rd}} = 1{,}25\ q_{\mathrm{R}}$
  - Isolated footings or non-yielding piles $\rightarrow \Omega_{\mathrm{d}}\ \gamma_{\mathrm{Rd}} = 1{,}25\ q_{\mathrm{R}}$ (overturning moment and shear); $\Omega_{\mathrm{d}}\ \gamma_{\mathrm{Rd}} = \Omega$ (vertical force, Ω as defined in DC2 for each material and structural type)
  - Yielding piles (and foundation beams designed to DC2 or DC3) $\rightarrow \Omega_{\mathrm{d}}\ \gamma_{\mathrm{Rd}} = 1{,}0$

9.2 Design values of the action effects

Force-based approach (FBA):

non-seismic action effects

over-design = $(R_{di}/E_{di}) \leq q$

overstrength factor

Capacity design

design seismic action effects $(/q)$

$$E_{Fd} = E_{Fd,G} \text{ "+" } \frac{\Omega_d \gamma_{Rd}}{\chi_H} E_{Fd,E}$$

amplitude of accepted permanent displ.

Details:

- DC2 or DC3:
  - For foundation soil capacity → $\Omega_d\ \gamma_{Rd}$ = 1,2 (bearing capacity) and 1,0 (sliding)

sliding is allowed, but it should take place before bearing capacity failure which may cause permanent tilting and is less controllable

9.3 Foundation horizontal connections

- Effects in the structure due to horizontal relative displacements between foundation elements should be calculated and designed for

May be up to 1,0 m above the bottom face of footings or pile caps

✓ Foundations are on the same horizontal plane and tie-beams or an adequate foundation slab are provided at the level of the footings or pile caps

✓ Adequate detailing of tie-beams and design for prescribed nominal axial force value

✓ Tie-beams may be omitted for ground category A or if relative foundation displacements are considered in the design of superstructure

9.4 Surface and shallow embedded foundations

Main principle (9.4.2.1.1):

(1) In accordance with the limit state under consideration, footings shall be verified against sliding failure, bearing capacity failure and rotational failure.

failure corresponds to unacceptable displ.

Resisting mechanisms for sliding:

- Friction shear at the base ($V_{Rd,1}$), friction shear at vertical sides parallel to seismic action (if cast-in place, $V_{Rd,2}$), and passive earth pressure on vertical sides perpendicular to seismic action (limited in FBA, $V_{Rd,3}$)

Resisting mech. for bearing capacity:

- Resisting vertical stresses at the base, and shear and normal forces on vertical sides (if cast-in place) – for vertical force and overturning moments

9.4 Surface and shallow embedded foundations

Sliding verification:

FBA

$$V_{\mathrm{Ed}} \leq V_{\mathrm{Rd,1}} + V_{\mathrm{Rd,2}} + 0{,}3\, V_{\mathrm{Rd,3}}$$

$$V_{\mathrm{Rd,1}} = F_{\mathrm{Rd}} = \left(N_{\mathrm{Ed}} - U\right)\frac{\tan\delta_{\mathrm{f}}}{\gamma_{\delta}}$$

Action effects in superstructure without considering sliding

χ_{H}	1,25	1,5	1,75
Range of permanent displacements (mm)	≤ 15	20 to 50	50 to 100

NOTE Values of χ_{H} in Table 9.1 are calibrated for the recommended values of material factors and global resistance factors. Values of χ_{H} for other values of the material factors or global resistance factors are not provided in this standard.

DBA (non-linear)

- Sliding accepted at SD or NC
    - If acceptable for the superstructure and lifelines
- $\chi_{\mathrm{H}} = 1{,}0$
- Full $V_{\mathrm{Rd,3}}$ may be activated

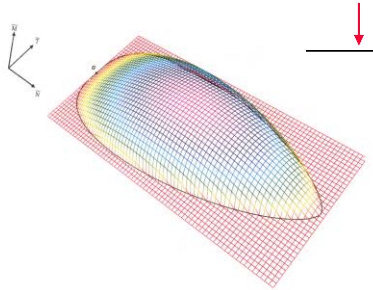
9.4 Surface and shallow embedded foundations

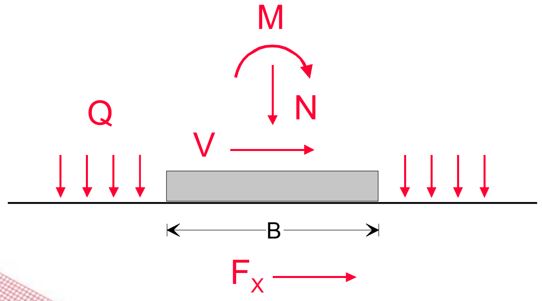
Bearing capacity verification:

FBA

- Combination of N_{Ed}, V_{Ed}, and M_{Ed} in the seismic design situation

Annex E for interaction surface + inertia forces on ground, or EC7-3





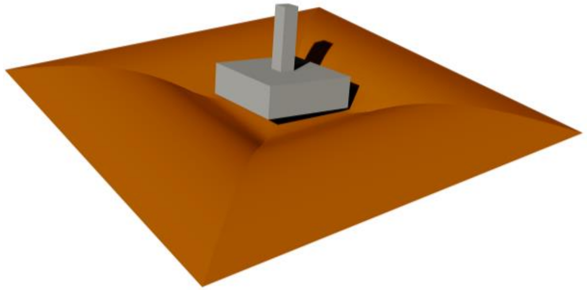
In both FBA and DBA

- Same χ_{H} as for sliding
- Inertia forces in ground (may be neglected in several cases)
- In undrained conditions, use total stresses in general (may use effective stresses if excess pore water pressure built-up is limited)

9.4 Surface and shallow embedded foundations

Rotational failure verification:

- **Uplift allowed at any LS** (seismic protection by rocking and uplift allowed if permanent rotations and settlements are acceptably small)
- FBA if uplifted area is <1/3, otherwise non-linear DBA



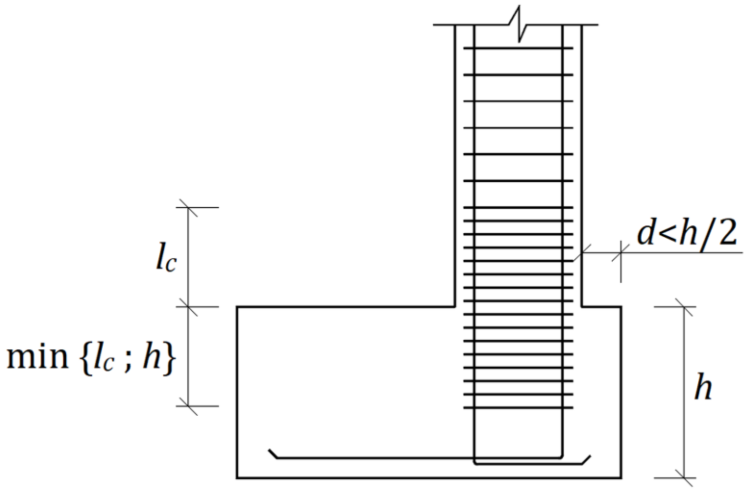
Verification of settlements:

- Check for free-field conditions in low seismic action class
- Additional foundation settlement for moderate and high seismic action classes
- Ground improvement if needed, global resistance factor for bearing capacity may also be adopted

9.4 Surface and shallow embedded foundations

- Requirements for raft foundations are similar to the ones for footings

- Structural design and detailing rules, supported on EN 1998-1-2



9.5 Pile foundations

Main principle (9.5.2):

(2) Piles shall be designed to resist action effects given in a) and b):

a) inertial forces and moments transmitted by the superstructure in the seismic design situation;

b) kinematic action effects of the deformation of the surrounding ground due to the passage of seismic waves.

➢ Combination of inertial and kinematic action effects, as well as different components of the seismic action

✓ Foundation piles may develop inelastic structural deformations, if verified and detailed for that → **Yielding piles**

9.5 Pile foundations

- Kinematic effects may be neglected:
  - In CC1 structures or
  - For low seismic action class or
  - Stiff and medium ground classes or
  - No strong stiffness contrast in successive layers:
    - "if the shear wave velocity ratio between two successive layers along the pile length, excluding layers thinner than 3 diameters, does not exceed 2,0 and if the equivalent shear wave velocity in the shallowest five diameters is larger than 150 m/s"

- Battered (inclined) piles should also be designed for residual action effects after the earthquake

9.5 Pile foundations

Methods of analysis (9.5.3)

And no contribution if minimum pile spacing < 6 D

Group of piles:

- Cap base-ground interface strength and stiffness limited to 30% of full contact assumption
- In FBA, limit to 30% of horizontal passive resistance of ground in front of the cap

DBA

- Analysis of inertial and kinematic effects to provide maximum displacement of the piles and corresponding curvature demand
- Numerical methods with appropriate boundary conditions and consideration of gapping between the pile and soil (if unfavourable)

Gapping tends to increase the flexibility of the system and to reduce the forces transmitted to the superstructure, but it can also increase the internal forces in the pile and its displacements

9.5 Pile foundations

Methods of analysis

FBA

- Analysis of inertial effects to provide forces and moments transferred by the superstructure to the top of each pile, the corresponding deflection and rotation, and the distribution of internal forces along the piles

May assume seismic motion only due to vertically propagating shear waves

- Analysis of kinematic effects to provide, at least, the bending moments at the pile head and at the interface between layers of different stiffness

In pile groups, may be determined considering a single pile in the group

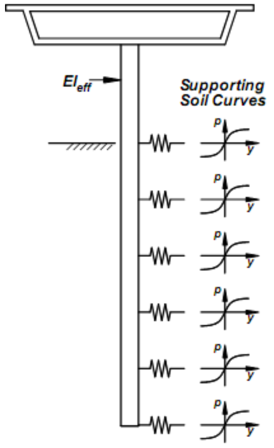
9.5 Pile foundations

Methods of analysis

FBA

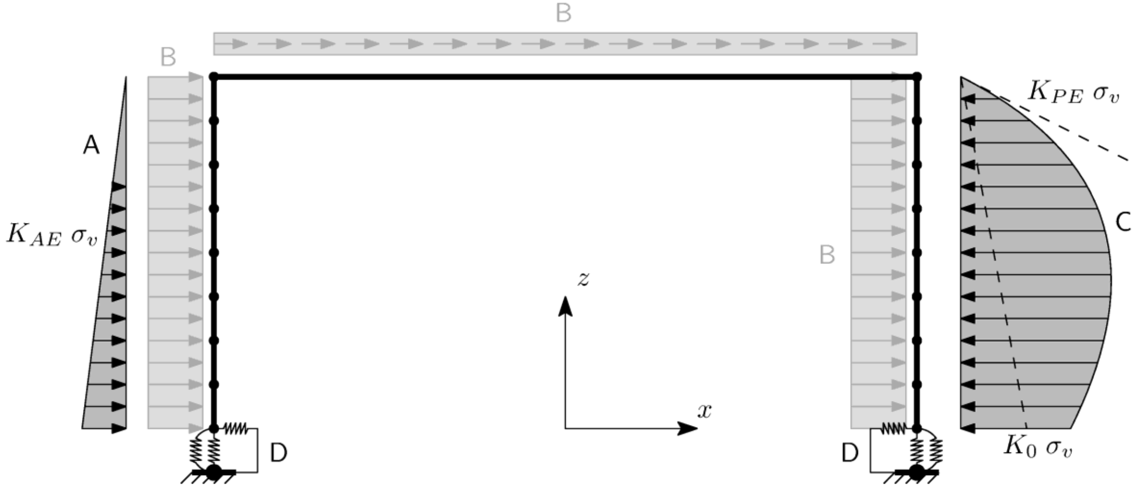
- Analysis considering:
  - ✓ bending stiffness of the piles
  - ✓ distribution of ground reactions along the piles
  - ✓ fixity condition at the pile head
  - ✓ pile-group effects (may be significant even if negligible for static case)
- Pile-ground interaction may be represented by independent linear springs (as for static), with ground stiffness consistent with level of deformation
- Lateral deflection:
  - ❖ Small – linear elastic analysis and solutions may be used → < max(0,01D or 10 mm)
  - ❖ Large – non-linear behaviour taken into account

→ Non-linear independent *p–y* and *t–z* springs or equivalent-linear strain-dependent springs

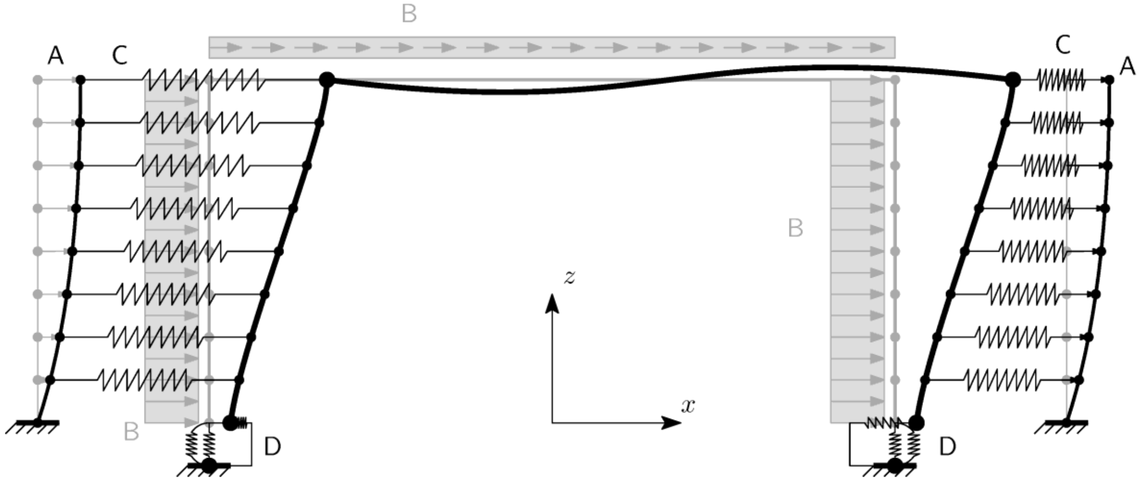


9.5 Pile foundations

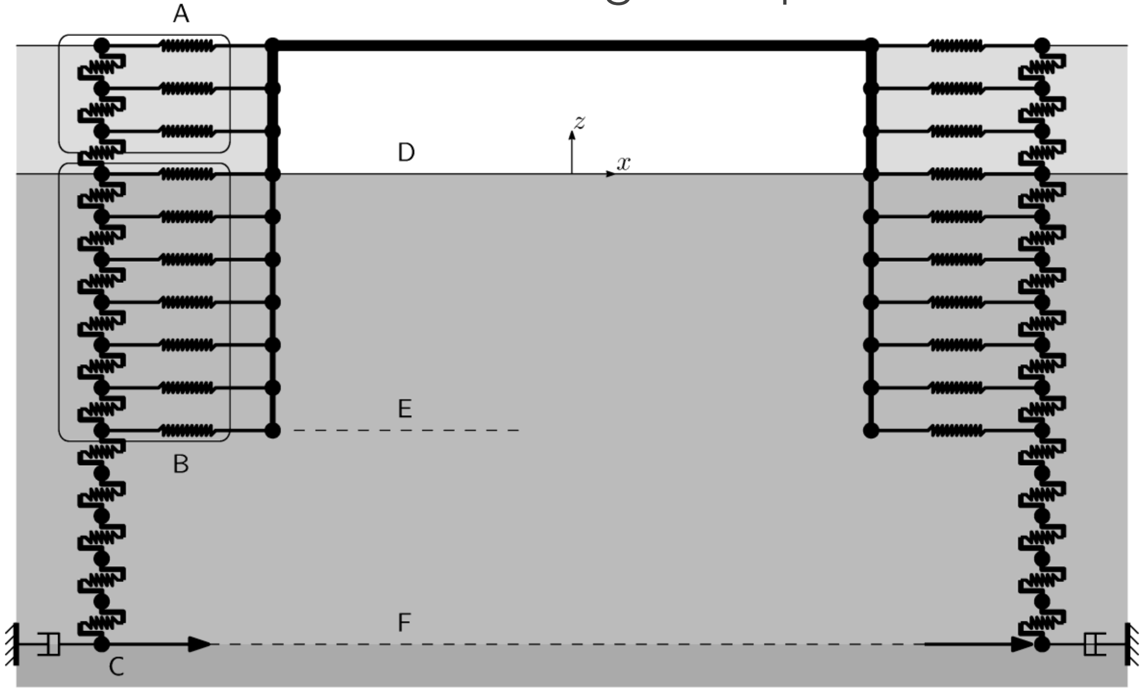
Methods of analysis



FBA modelling example of integral-abutment bridge (prEN 1998-2:2022)



DBA modelling example



9.5 Pile foundations

Design verifications (9.5.4)

(1) The pile-soil system shall be designed to carry the forces transmitted by the superstructure to the piles heads. In addition, each pile shall be designed to carry the combination of axial loads, bending moments and shear forces in the seismic design situation.

Specific detailing requirements, namely for in-ground and pile head plastic hinge regions

- Design at SD and NC for yielding or non-yielding, avoiding brittle mechanisms and instabilities

Shear resistance verification with overstrength factor $\gamma_{Rd} = 1,2$ applied to the lateral bearing capacity of soil-pile system

9.5 Pile foundations

Design verifications

- **FBA**

$$\begin{cases} N_{\mathrm{Ed}} \leq N_{\mathrm{Rd}} \rightarrow \text{with } \chi_{\mathrm{H}} = 1{,}0 \\ V_{\mathrm{Ed}} \leq V_{\mathrm{Rd}} \end{cases}$$

Lateral bearing capacity with:

Action effects vs. ultimate ground resistance as in EC7-3

χ_{H}	1,25	1,5	1,75
Range of permanent displacements (mm)	≤ 15	20 to 50	50 to 100

NOTE Values of χ_{H} in Table 9.2 are calibrated for the recommended values of material factors and global resistance factors. Values of χ_{H} for other values of the material factors or global resistance factors are not provided in this standard.

- Earlier seismic codes, including EN 1998-5:2005, demanded that the piles remain structurally elastic after the design earthquake. However:
  - Pile yielding is not as concentrated as in columns above ground, but instead distributed over a much greater length of the pile due to soil confinement. As a result, the plastic hinge rotation is likely small enough to have no detrimental effects
  - Inelastic response of piles may have a beneficial effect on the overall response of the superstructure

9.5 Pile foundations

Design verifications

- **DBA (non-linear)**
  - Displacement demand vs. capacity
  - Capacity from plastic hinge strain or rotation limits in pile material
  - Two-step verification of yielding piles:
    1. Action effects and resistances expressed either in terms of generalised deformations or in terms of generalised forces. Critical zones definition as where $E_{\mathrm{Fd}} \leq R_{\mathrm{d}}$ in terms of generalized forces
    2. But, in critical zones, the verification should check the deformation demand against the deformation capacity of the pile, subjected to the axial force in the seismic design situation

9.5 Pile foundations

Design verifications

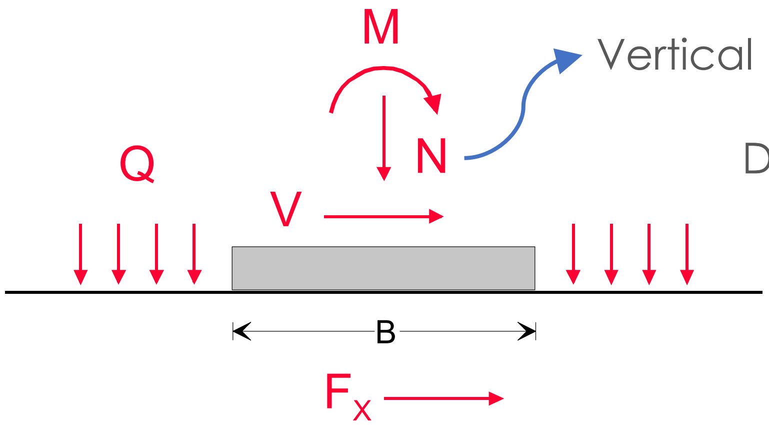
- Special care with piles crossing potentially liquefiable layers, considering:
  - passive-type forces exerted by the moving soil layers above the liquefied layer
  - kinematic constraints imposed on the pile deformation by the superstructure
  - magnitude of the liquefied soil displacements
  - negative skin friction (in post-earthquake situation)

Also for soil settlements in non-liquefiable soils

Annex E (informative) - Seismic bearing capacity of shallow foundations

Scope

- Calculation of the seismic foundation bearing capacity of strip, rectangular and circular surface and embedded foundations

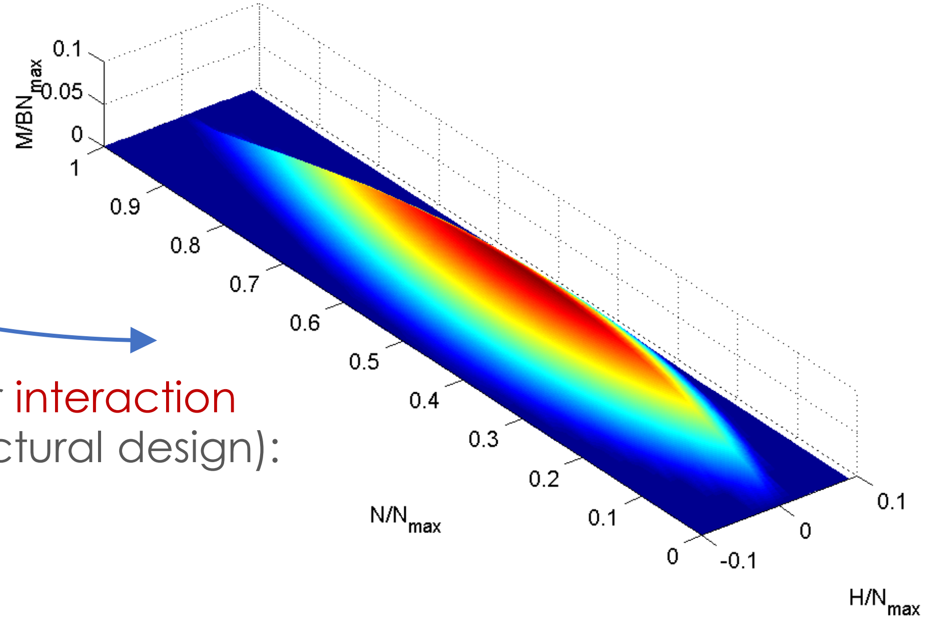


Vertical bearing capacity N_{max} as in EC7-3

Dimensionless generalised forces:

$$\begin{cases} \overline{N} = \dfrac{N_{\mathrm{Ed}}}{N_{\mathrm{max}}} \\ \overline{V} = \dfrac{V_{\mathrm{Ed}}}{N_{\mathrm{max}}} \\ \overline{M} = \dfrac{M_{\mathrm{Ed}}}{B\ N_{\mathrm{max}}} \\ \overline{F} = \kappa \dfrac{\rho a_{\mathrm{H}} B}{\bar{c}} \end{cases}$$

And expressions for interaction diagram (as in structural design):



Annex E (informative) - Seismic bearing capacity of shallow foundations

Scope

- Use of a global resistance factor in the foundation bearing capacity calculations

Dimensionless generalised forces with global resistance factor:

$$
\begin{cases}
\overline{N} = \dfrac{\gamma_{\mathrm{R}} N_{\mathrm{Ed}}}{N_{\mathrm{max}}} \\
\overline{V} = \dfrac{\gamma_{\mathrm{R}} V_{\mathrm{Ed}}}{N_{\mathrm{max}}} \\
\overline{M} = \dfrac{\gamma_{\mathrm{R}} M_{\mathrm{Ed}}}{B\ N_{\mathrm{max}}} \\
\overline{F} = \kappa \dfrac{\gamma_{\mathrm{R}} \rho a_{\mathrm{H}} B}{\bar{c}} \ or\ \overline{F} = \kappa \dfrac{\gamma_{\mathrm{R}} \alpha_H}{tan\, \varphi'}
\end{cases}
$$

Thank you for your attention