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Assessment of static and seismic bearing capacity factors for shallow strip foundations using the discontinuity layout optimization procedure

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Background & Motivation

Research, …

- Develop new methods for evaluating the bearing capacity of shallow foundations under static and seismic loadings.

… for which objectives ?

- Provide engineers with calculation tools and practical recommendations for the study and construction of shallow foundations.
- Provide project designers with realistic, economic and technically sustainable solutions.

Outline

1. Introduction

2. Theoretical formulation

3. Numerical simulation

4. Results and discussion

5. Summary and conclusion

1. Introduction

Examples of buildings damaged by earthquakes

San-Francisco, USA, 1906 (Mw=7.9)

Niigata, Japan, 1964 (Mw=7.5)

Izmit, Turkey, 1999 (Mw=7.4)

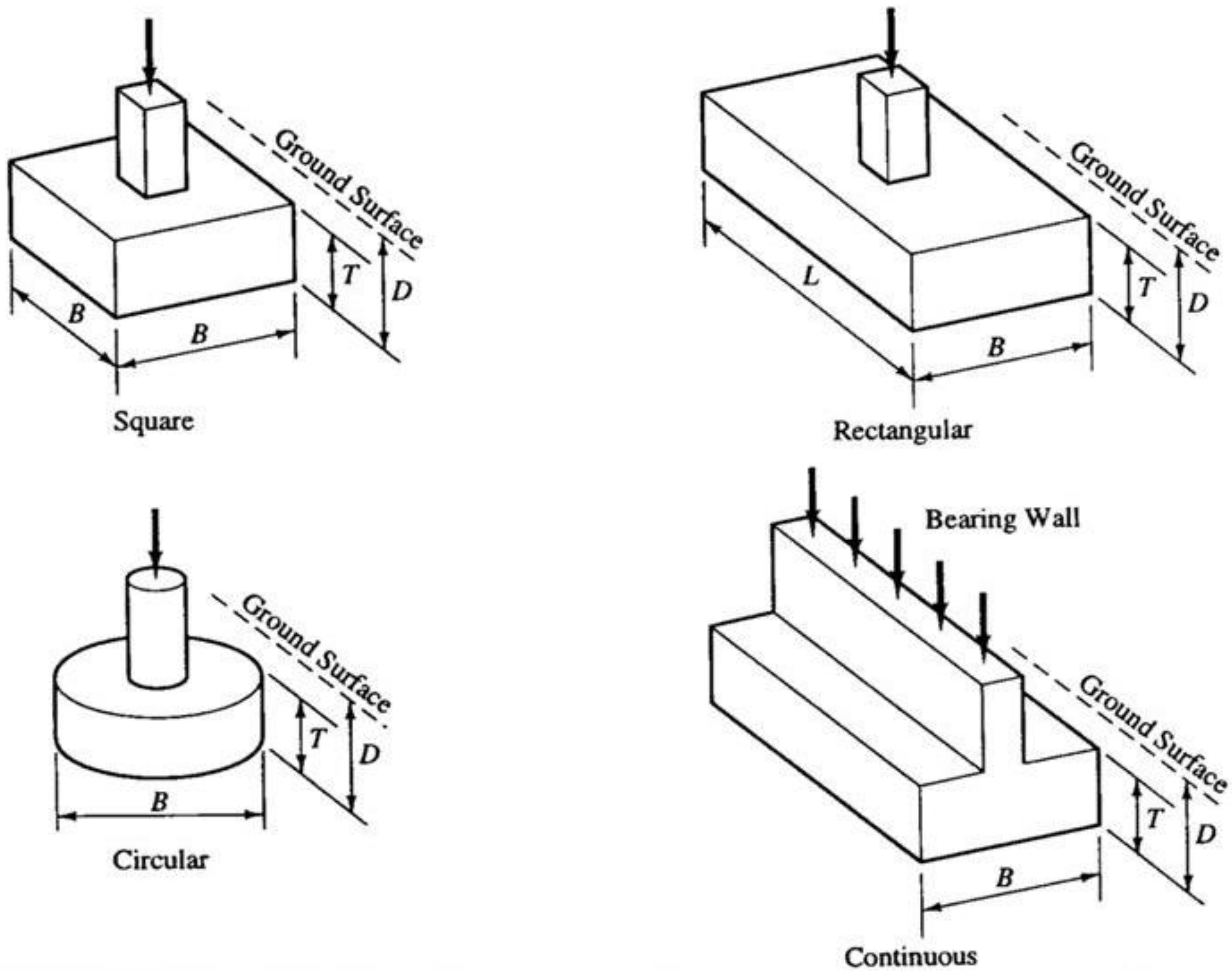
Boumerdès, Algeria, 2003 (Mw=6.8)

Papua, New Guinea, 2013 (Mw=6.8)

Huallen, Taiwan, 2018 (Mw=6.4)

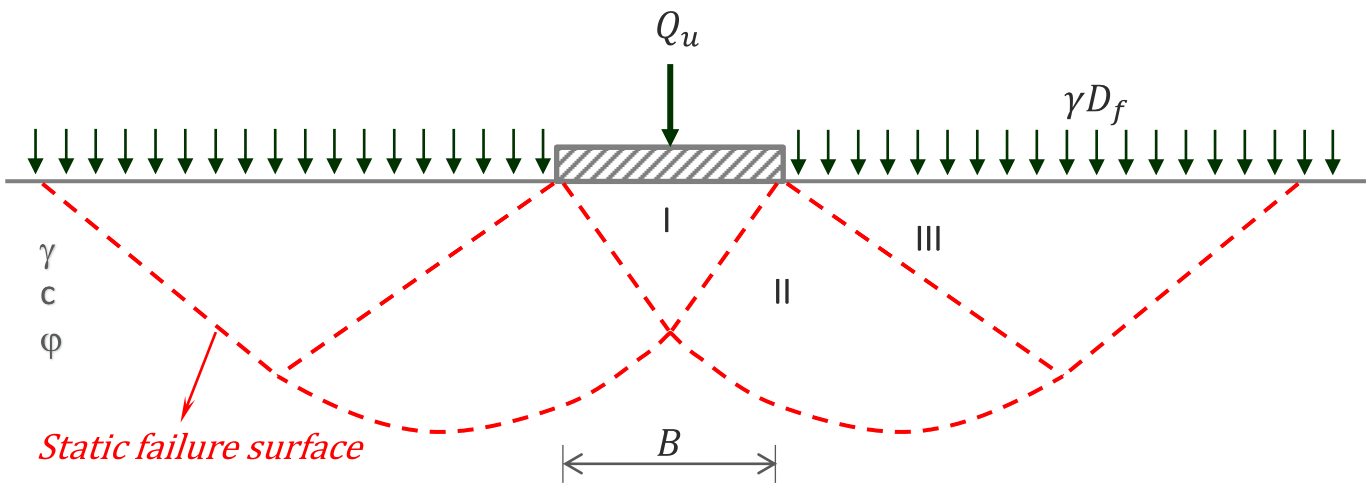
1. Introduction

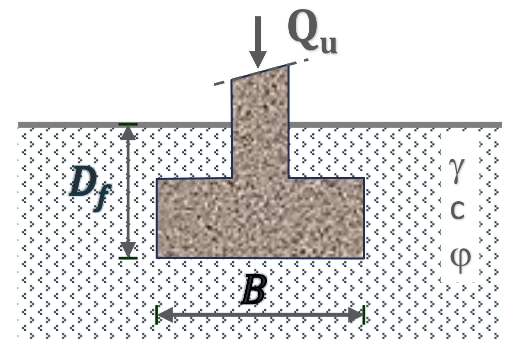
Types of shallow foundations

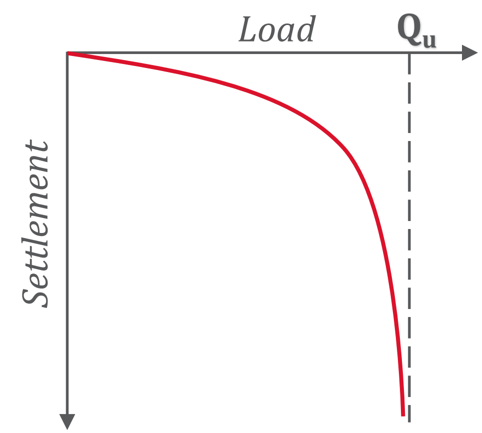


2. Theoretical formulation

Expressions of bearing capacity for shallow strip foundations





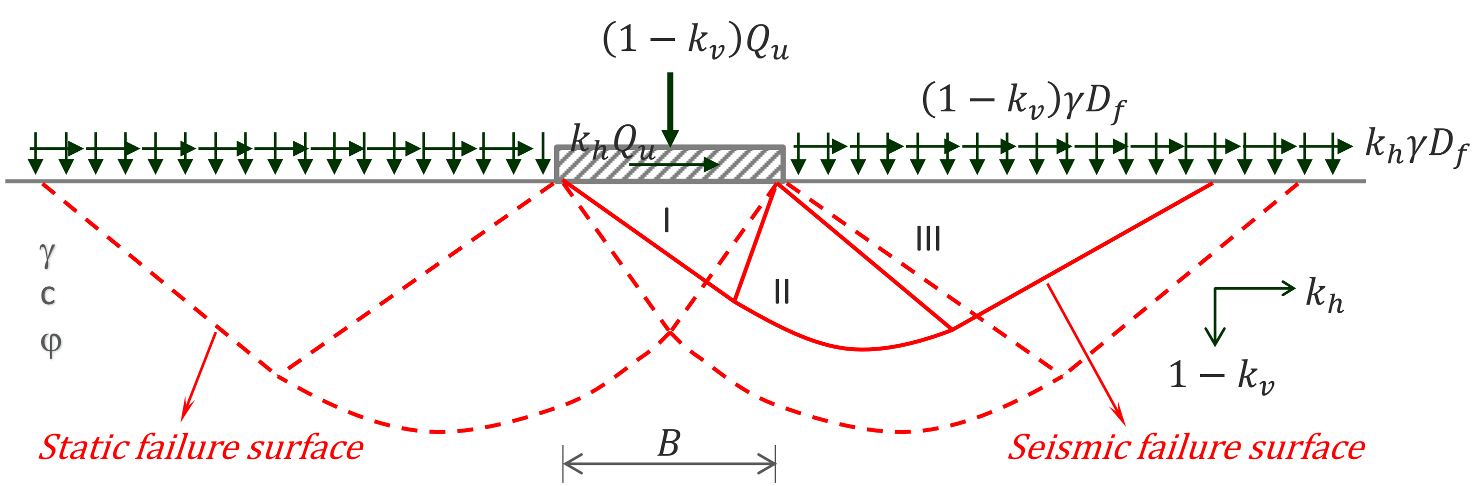


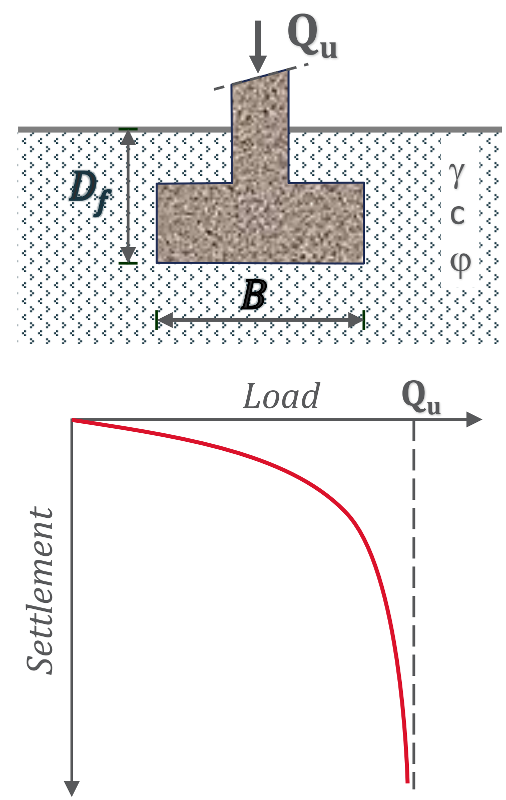
$$q_u^S = \frac{1}{2}\gamma B N_{\gamma S} + \gamma D_f N_{qS} + c N_{cS} \qquad \text{(Static loading)}$$

- where $N_{\gamma S}(\varphi)$, $N_{qS}(\varphi)$ and $N_{cS}(\varphi)$ are the static bearing capacity factors

2. Theoretical formulation

Expressions of bearing capacity for shallow strip foundations





$$q_u^S = \frac{1}{2}\gamma B N_{\gamma S} + \gamma D_f N_{qS} + cN_{cS} \qquad \text{(Static loading)}$$

- where $N_{\gamma S}(\varphi)$, $N_{qS}(\varphi)$ and $N_{cS}(\varphi)$ are the static bearing capacity factors

$$q_u^E = \frac{1}{2}\gamma B N_{\gamma E} + \gamma D_f N_{qE} + cN_{cE} \qquad \text{(Seismic loading)}$$

- where $N_{\gamma E}(\varphi,\theta)$, $N_{qE}(\varphi,\theta)$ and $N_{cE}(\varphi,\theta)$ are the seismic bearing capacity factors, and $\boldsymbol{\theta = tan^{-1}\left(\frac{k_h}{1-k_v}\right)}$ such as k_h and k_v are the horizontal and vertical seismic coefficients

2. Theoretical formulation

Static bearing capacity factors

- **Terzaghi (1943)**

$$N_{\gamma S} = \frac{1}{2}\tan\varphi\left(\frac{K_{p\gamma}}{cos^2\varphi} - 1\right)$$

$$N_{qS} = e^{\left(\frac{3\pi}{2}-\varphi\right)\tan\varphi}/2cos^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

- **Vesic (1973)**

$$N_{\gamma S} = 2\left(N_{qS} + 1\right)\tan\varphi$$

$$N_{qS} = e^{\pi\tan\varphi}\, tan^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

- **Meyerof (1963)**

$$N_{\gamma S} = \left(N_{qS} - 1\right)\tan 1.4\varphi$$

$$N_{qS} = e^{\pi\tan\varphi}\, tan^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

- **Chen (1975)**

$$N_{\gamma S} = 2\left(N_{qS} + 1\right)\tan\varphi\tan\left(\frac{\pi}{4}+\frac{\varphi}{5}\right)$$

$$N_{qS} = e^{\pi\tan\varphi}\, tan^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

- **Brinch-Hansen (1970)**

$$N_{\gamma S} = 1.5\left(N_{qS} - 1\right)\tan\varphi$$

$$N_{qS} = e^{\pi\tan\varphi}\, tan^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

- **Eurocode 7 (2004)**

$$N_{\gamma S} = 2\left(N_{qS} - 1\right)\tan\varphi$$

$$N_{qS} = e^{\pi\tan\varphi}\, tan^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\varphi$$

2. Theoretical formulation

Seismic bearing capacity factors

- **Richards et al. (1993)**

$$N_{\gamma E} = \tan \alpha_{aE}\left(N_{qE} - 1\right)$$
$$N_{qE} = K_{pE}/K_{aE}$$
$$N_{cE} = \left(N_{qE} - 1\right)\cot \varphi$$

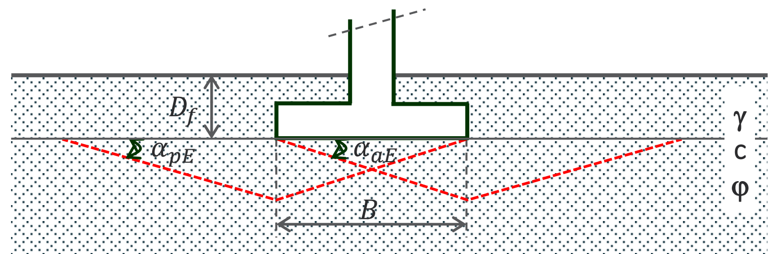
- **Budhu and Al-Karni (1993)**

$$N_{\gamma E} = \left(1 - \frac{2}{3}k_v\right)e^{-\beta_\gamma}$$
$$N_{qE} = (1 - k_v)e^{-\beta_q}N_{qS}$$
$$N_{cE} = e^{-\beta_c}N_{cS}$$

$$\beta_\gamma = \frac{9(k_h)^{1.1}}{1 - k_v} \qquad \beta_q = \frac{5.3(k_h)^{1.2}}{1 - k_v} \qquad \beta_c = \frac{4.3(k_h)^{1+D}}{1 - k_v}$$

$$D = c/\gamma H \qquad H = \frac{0.5B}{\cos\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)}e^{\left(\frac{\pi}{2}\tan\varphi\right) + D_f}$$

H – depth of failure zone from surface



$$K_{aE} = \frac{\cos^2(\varphi - \theta)}{\cos\theta\cos(\theta + \delta)\left[1 + \sqrt{\frac{\sin(\varphi + \delta)\sin(\varphi - \theta)}{\cos(\theta + \delta)}}\right]^2}$$

$$K_{pE} = \frac{\cos^2(\varphi - \theta)}{\cos\theta\cos(\theta + \delta)\left[1 - \sqrt{\frac{\sin(\varphi + \delta)\sin(\varphi - \theta)}{\cos(\theta + \delta)}}\right]^2}$$

$$\theta = \tan^{-1}\left(\frac{k_h}{1 - k_v}\right)$$

$$\alpha_{aE} = \alpha + \tan^{-1}\left\{\frac{\sqrt{(1 + \tan^2\alpha)[1 + \tan(\delta + \theta)\cot\alpha]} - \tan\alpha}{1 + \tan(\delta + \theta)(\tan\alpha + \cot\alpha)}\right\}$$

$$\alpha_{pE} = -\alpha + \tan^{-1}\left\{\frac{\sqrt{(1 + \tan^2\alpha)[1 + \tan(\delta - \theta)\cot\alpha]} + \tan\alpha}{1 + \tan(\delta + \theta)(\tan\alpha + \cot\alpha)}\right\}$$

$$\alpha = \varphi - \theta$$

δ – soil-footing interface friction angle

3. Numerical simulation

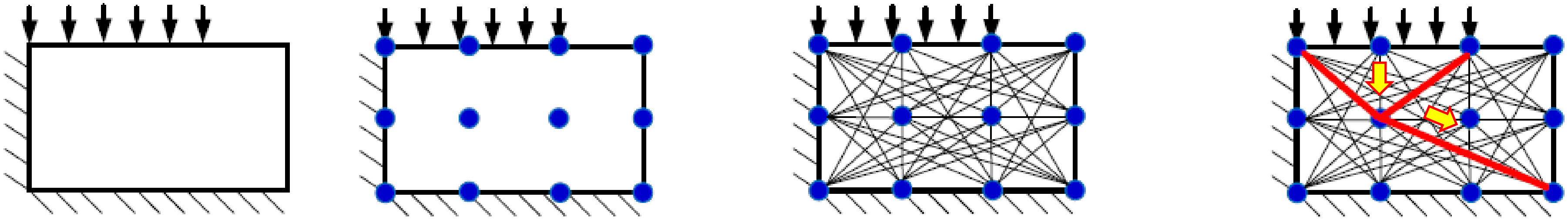
Software used and procedure followed

- **Software**

  $LimitState: GEO$

- **Procedure**

  $Discontinuity\ Layout\ Optimization\ Procedure\ (Smith\ and\ Gilbert, 2007)$



1. Initial problem *2. Discretization by nodes* *3. Interconnection of nodes with potential discontinuities* *4. Identification of critical subset of discontinuities by optimization*

- **Method**

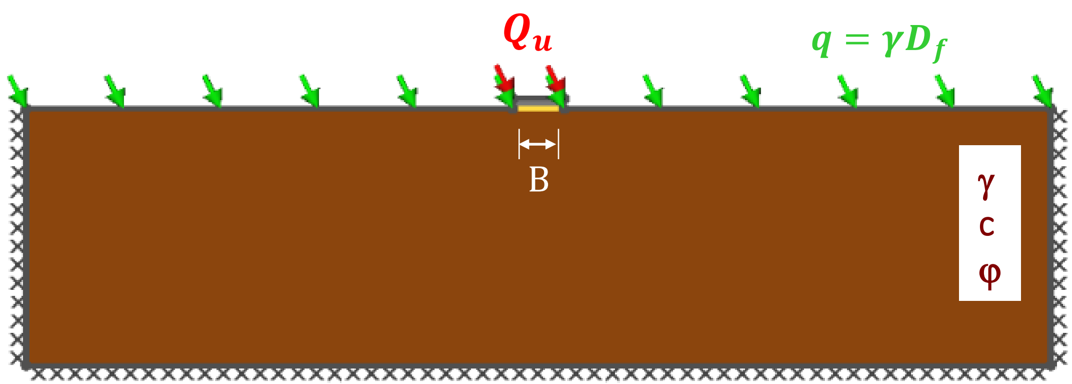
  $Ultimate\ Limit\ State\ (ULS):\ minimum\ value$ of the $upper\ bound\ limit\ analysis$

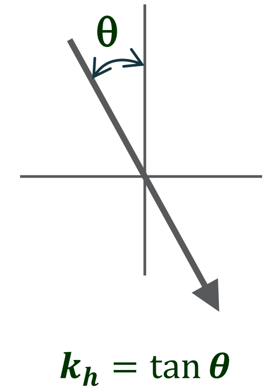
- **Seismic loading**

  $Pseudo-static\ approach$

3. Numerical simulation

Calculation model considered





Geomechanical parameters fixed

Bearing capacity factor	$N_\gamma = 2q_u/\gamma B$	$N_q = q_u/q$	$N_c = q_u/c$
Soil unit weight, γ	$\gamma \neq 0$	$\gamma = 0$	$\gamma = 0$
Soil cohesion, c	$c = 0$	$c = 0$	$c \neq 0$
Surcharge, q	$q = 0$	$q \neq 0$	$q = 0$
Soil friction angle, φ	It ranges from 0 to 45° in 1° increment		
Soil-footing interface, δ/φ	Smooth: δ=0, Rough: δ=φ, Concrete: δ=2φ/3		
Horizontal seismic coefficient, k_h	It ranges from 0 (static loading) to 1 in 0.1 increment		

$q_u = \frac{1}{2}\gamma B N_\gamma + q N_q + c N_c$ *(ultimate bearing capacity)*

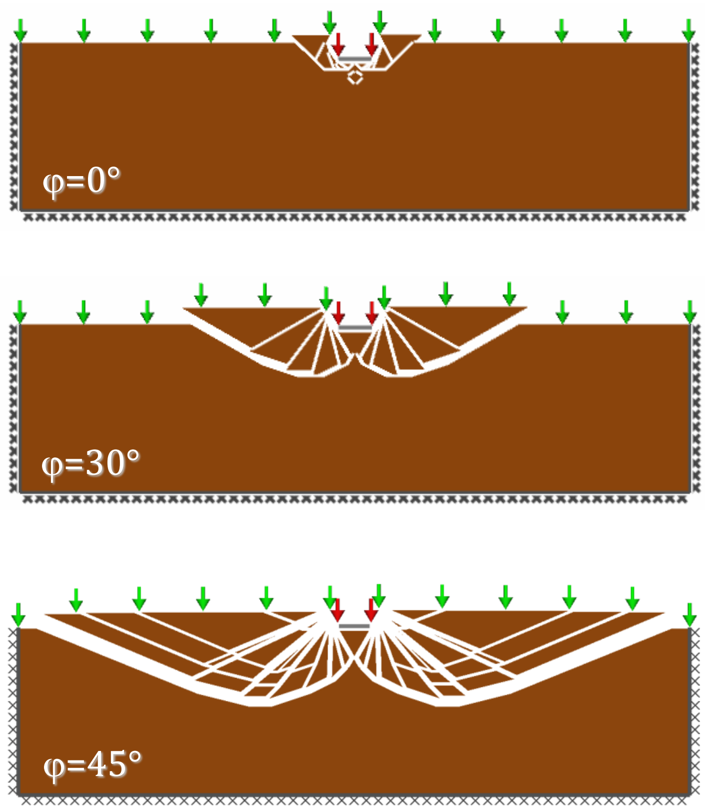
B: footing width

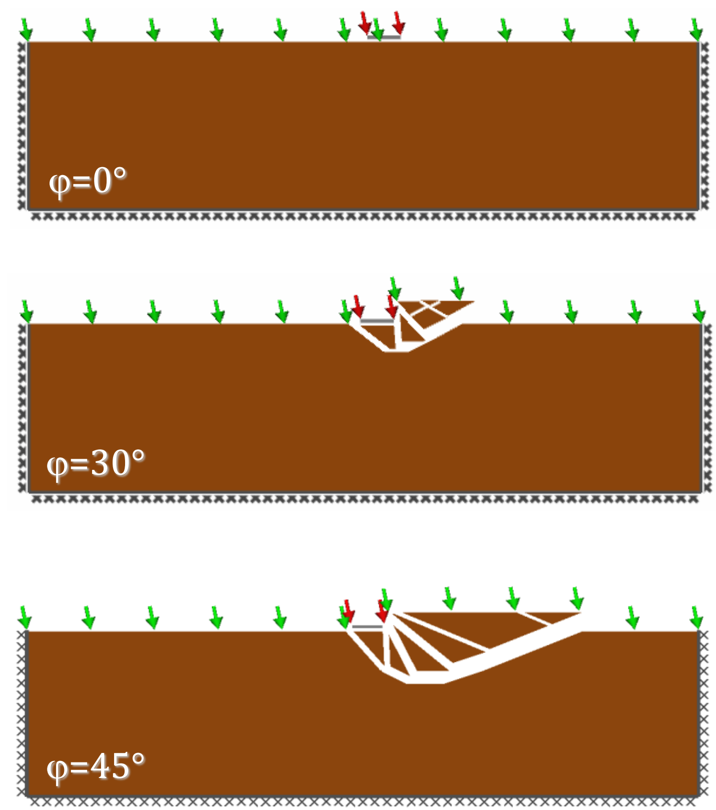
δ: soil-footing interface friction angle

Failure mechanisms

Static loading (k_h=0)

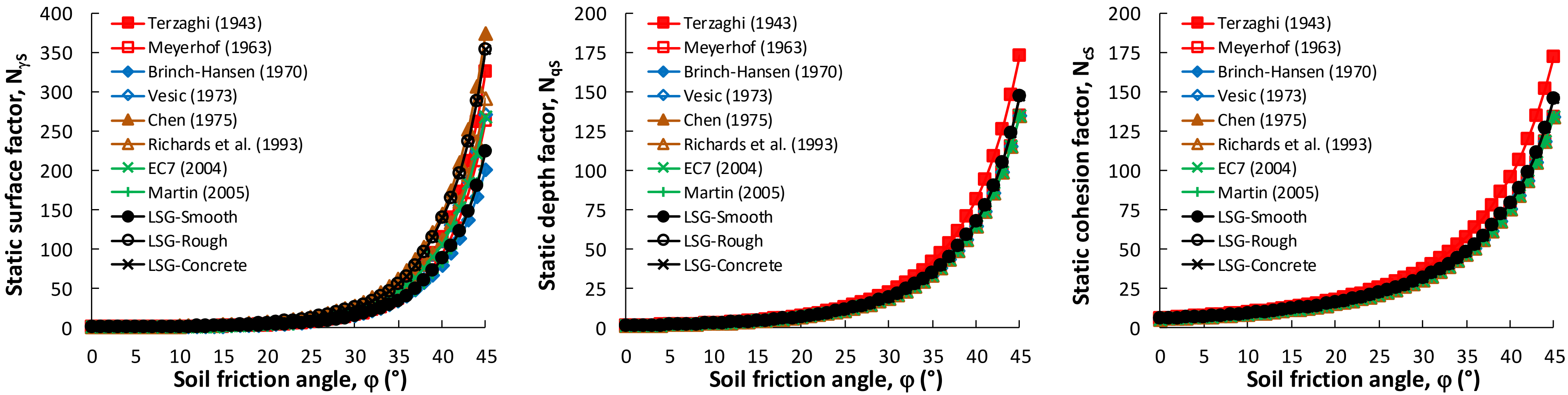
Seismic loading (k_h=0.2)





4. Results and discussion

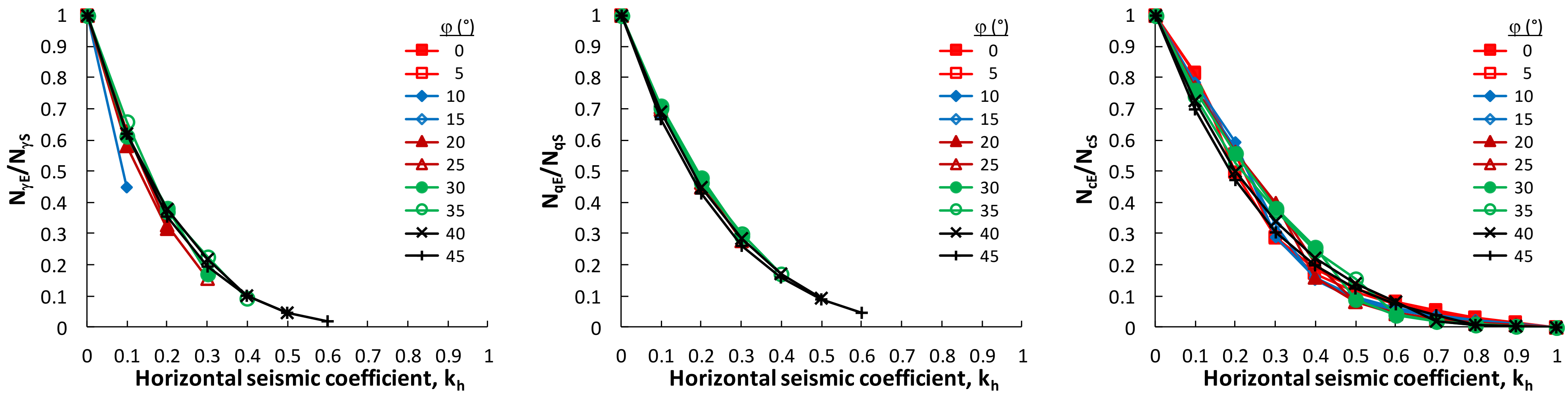
Static bearing capacity factors



- The soil static bearing capacity factors greatly increase with the soil friction angle for smooth and rough footings, as well as for concrete footings.
- Unlike the surface factor, depth and cohesion factors do not depend on the roughness of the soil-footing interface.
- Moreover, unlike plasticity calculations, the DLO procedure based on the limit analysis theory does not detect the non-associativity effect of the soil behavior law, nor the evolution of the corresponding strains.

4. Results and discussion

Seismic bearing capacity factors



- All bearing capacity factors seem to be greatly affected by seismic action.
- When tan(φ) > k_h, the adequate soil bearing capacity factor cannot be calculated because of the fluidization phenomenon of cohesionless dry soils which behave like a viscous flow.
- When k_h > 0.6 (catastrophic earthquakes), only coherent soils can have some bearing capacity.
- Moreover, except the surface factor, depth and cohesion factors do not appear to be affected by the inertia effect of the foundation massif. In any case, recent works show that the inertia effect of foundations massif does not seem excessive.

Summary and conclusion

Calculation results provide the following main conclusions:

- *The predicted values of static bearing capacity factors confirm those obtained by other calculation methods such as the limit equilibrium method and the limit analysis theory using other calculation approaches such as the finite elements method or the finite differences method.*
- *Seismic action appears to significantly affect these bearing capacity factors (i.e. the bearing capacity of shallow strip foundations).*
- *Both soil static and seismic bearing capacity factors show that the Terzaghi's superposition formula is not satisfied.*

These results also show that the DLO procedure can be a fairly satisfactory alternative in evaluating the bearing capacity of shallow strip foundations. This procedure can therefore be the long-awaited solution for engineers and researchers.

However, the criteria of a good interpretation of the experimental and/or numerical data are largely based on the good sense of engineer, his intuition and his experience.

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Thank you!

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