Influence of spatial variations in soil properties on structural reliability

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The longitudinal variation of soil properties has a major influence for many types of structures (pavements, buried pipes, foundations, railways...) since it induces stresses and/or displacements that cannot be predicted when assuming homogeneity.

Variations in the longitudinal profile of a pavement: IRI

Longitudinal control of railway track shape
1-2
non linear behaviour of soil and building materials

3
non linear behavior of interface

4
effect of boundary conditions on load redistributions

Ground spatial variability

Soil and structural stiffnesses
The simplest case: when variability reduces to uncertainty

It is the role of the engineer, who must define design values

(“cautious estimate... » - Eurocodes)

Duncan (2000) : 3-sigma rule

“a conscious effort should be make the range between higher conceivable value and lower conceivable value as wide as seemingly possible, or even wider, to overcome the natural tendancy to make the range too small”
Influence of correlation length:
(a) when it reduces to purely geometrical causes

Distance between supports
D

Variance reduction below shallow foundation $\Gamma(B, \lambda)$

Correlation coefficient between the two settlements $s$ and $s'$ (Tang, 1984)

$$\rho(s, s') = \frac{\sum_k (-1)^k L_k^2 \Gamma_s^2(L_k)}{2 B B' \Gamma_s(B) \Gamma_s(B')}$$

$k = 0 - 3$

$L_0 = D - B/2 - B'/2$, $L_1 = D + B$, $L_2 = D + B + B'$, $L_3 = D + B'$

$\Gamma^2(x)$ variance reduction function

(depends on the shape of the autocorrelation fct)
When it reduces to purely geometrical causes: differential settlement

3 dimensions (B, D and λ) govern the problem

\[ \text{Var}(\Delta) = 4 \left( \frac{\lambda}{B} \right)^2 \left( \frac{B}{\lambda} - 1 + e^{-B/\lambda} \right) \cdot (1 - \rho(s, s')) \cdot \text{Var}(\text{so}) \]

Var (so) comes from the magnitude of local scattering of soil properties

\textbf{Variance reduction below the foundation}\n\[ \Gamma(B, \lambda) \]

\textbf{Correlation between supports fct \((D, \lambda)\)}
When the influence of correlation length reduces to purely geometrical causes

Monte-Carlo simulations for 32 values of $\lambda$ and 4 values of $D$ (250 simulations, $q = 300$ kPa, $E = 10$MPa)

Variance reduction below the foundation $\Gamma(B, \lambda)$

Correlation between supports fct $(D, \lambda)$
When it reduces to purely geometrical causes: about reliability

Variance reduction below the foundation $\Gamma(B, \lambda)$ for both indiv. and diff. settl.

Correlation between supports fct $(D, \lambda)$

$d_{\text{mean}} \leq \left(\frac{2}{\sqrt{\pi}}\right) \text{s.d.} \approx 1.128 \text{s.d.}$

$95\%$ fractile of differential settlement / s.d. individual settlement

$d_{95} \leq (1.96\sqrt{2}) \text{s.d.} \approx 2.77 \text{s.d.}$

Possibility to adopt conservative rules, without knowing $\lambda$
(b) Explaining the influence of correlation length: when it **does not** reduce to purely geometrical causes

Several dimensions (defining the structure geometry and the soil correlation scale) have an influence

Several stiffnesses (soil $E_s$ and structure $[E_c, J, L]$) have an influence

**Requires a detailed modelling of both:**
- soil **heterogeneity**
- materials response and soil/structure **interaction**

Ex. 1: buried pipes
Ex. 2: piled-raft foundation

**Statistics and geostatistics**

**Mechanics and material modelling**
Example 1: buried pipes (sewer)

The problem is driven by two ratios:

- length ratio: $\lambda / D$
- stiffness ratio: $k \text{ (soil) } / EI \text{ (pipe)}$

Statistical analysis of bending moments $M95$

$k \text{ (MN/m$^3$)}$

$\lambda / D$

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Example 1: buried pipes (sewer)

Focus on the connection stiffness influence (stiffness $\leftrightarrow$ fictitious length)

Random variables: $k$ (c.v., $\lambda$), $M_{\text{lim}}$, $CS_{\text{lim}}$

Statistical analysis of bending moments (ULS) and of misalignments (SLS)

- $P_{\text{fULS}} (M_{\text{max}} < M_{\text{lim}})$, $\beta_{\text{ULS}}$
- $P_{\text{fSLS}} (CS_{\text{max}} < CS_{\text{lim}})$, $\beta_{\text{SLS}}$
Example 1: buried pipes (sewer)

with $\lambda = 3 \text{ m} = D$, c.v. $(M_{\text{lim}}) = 0.15$, c.v. $(S_{\text{lim}}) = 0.2$

It is difficult to satisfy target reliability levels both at SLS and ULS.

It demands a not too heterogeneous soil, and a stiff enough connection.
Example 2: piled-raft foundation

2 reference solutions (q = 400 kN/m):
- $k \rightarrow 0$ (stiff raft)
  $\Rightarrow$ uniform load in all piles = 1.38 MN
- $k \rightarrow \infty$ (stiff piles)
  $\Rightarrow$ load $R_3 = 1.63$ MN

$\lambda = 10$ m
Example 2: raft foundation on piles

The response is statistically driven by:
- a length ratio $\lambda/D$
- a stiffness ratio $EIh^3/k$

Results from engineer’s estimates highly underestimate stresses
Example 2: raft foundation on piles

- Deterministic F.S. = 2.7
- Reliability index (Cornell)
  \[ \beta = \frac{\mu_R - \mu_E}{\sqrt{\sigma_R^2 + \sigma_E^2}} \]

\( \mu \) is mean, \( \sigma \) is c.o.v.
E regards load effect and R regards pile strength

\( \beta \) depends on:
- soil variability (c.v. and \( \lambda \)),
- pile variability (c.v.),
- structural model (interaction)

Correlation length:
- Effect of soil variability
- Effect of corr. length and interaction

\( \lambda = 4 \text{m} \)
Trying to synthetize interaction?

- no
  - Influence of statistics
    - $cv(E), \text{pdf}(E)$
  - Influence of variability reduces to uncertainty
    - choice of design values
    - (the challenge is to link design values and safety level)

- yes
  - full interaction?
According the problem complexity

Full interaction?

- no
  - Influence of geometry/scales
  - ratio $\lambda/D$

- yes
  - Influence of geometry AND stiffness
  - ratio $\langle \frac{E_{cI}}{E_{sJ}} \rangle$
  - ratio $\langle \frac{E_{cI'}}{E_{sJ}} \rangle$

« Worst » value of $\lambda/D = fct$ (stiffnesses, type of output)
- enables to reduce the costs of geotechnical investigations and of Monte-Carlo simulations ($\lambda$ is no longer a variable or an unknown)

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Conclusions

(1) Disorders/damage depend on
- soil properties (scatter, correlation length $\lambda$)
  - structural geometry (D, B…)
  - mechanical behaviour of the system

(2) Accounting for spatial variability of soil enables the description of main phenomena:
  differential settlements, load redistributions

(3) Predicting safety/reliability levels requires to reproduce these effects and
  to input data representative of soil randomness

(4) Identifying «worst cases» (worst ratios) can enable
  the use of deterministic models
  while including the statistical effects of randomness

Accounting for damage sensitivity
  must be the following step