Level III Reliability Based Design of Examples set by ETC10

Y. Honjo, T. Hara & T.C. Kieu Le
Gifu University, Japan

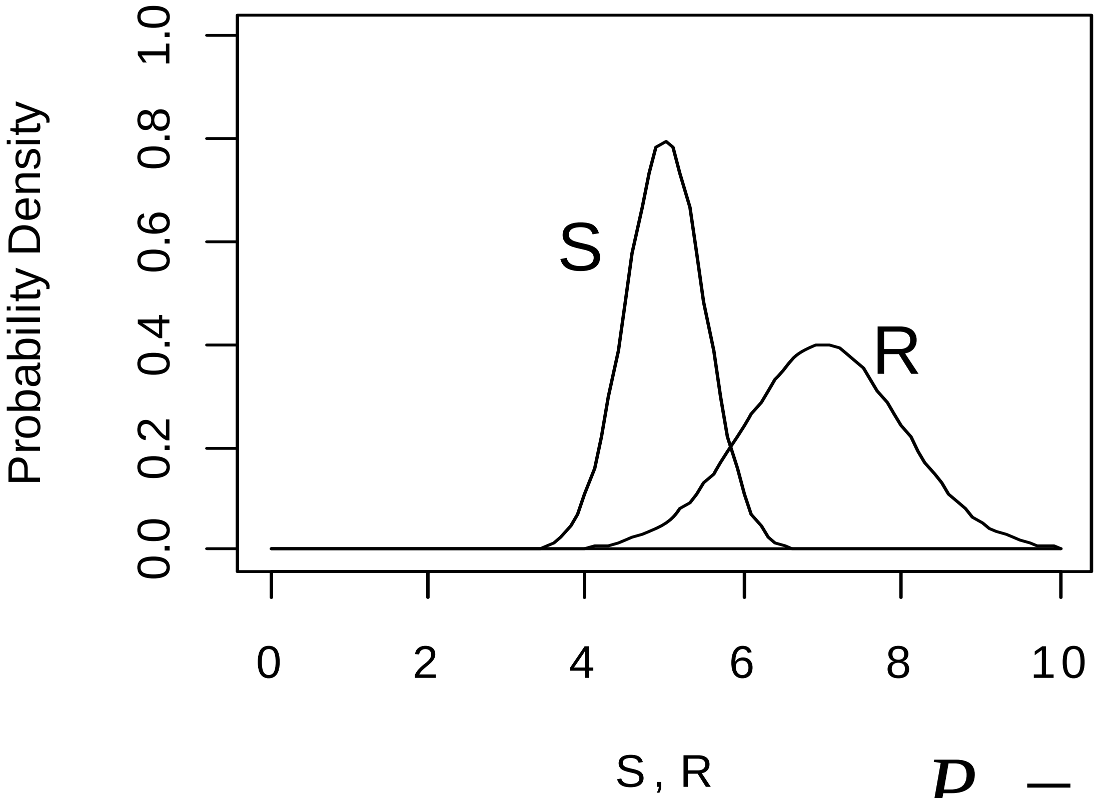
Table of contents

Table of contents

Classification of Reliability based Design in Structure Engineering

Design Method	Basic Variables	Reliability Assessment	Verification
Level III Full distribution	Random variables Probability distributions	Failure Probability	Cost Optimization etc.
Level II FORM and β	Random variables Mean, SD & Covariances (Distribution Free)	Reliability index β	Target β_T
Level I Partial factors	Deterministic variables	Partial factors LRFD	Verification formula

Level III RBD Full distribution approach

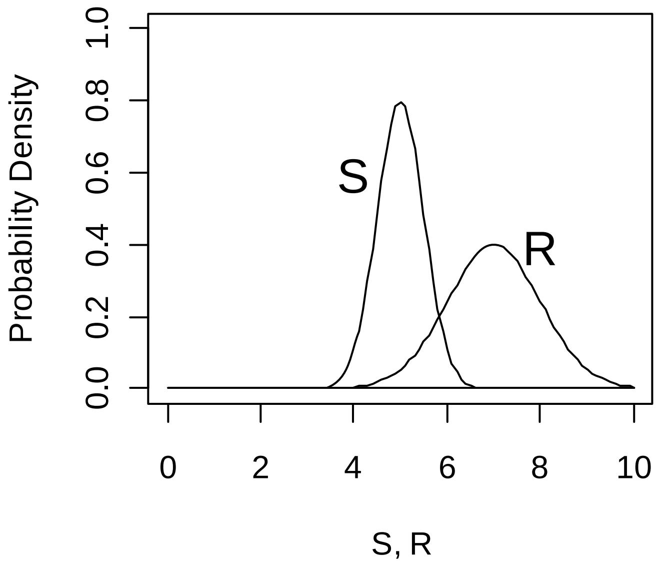


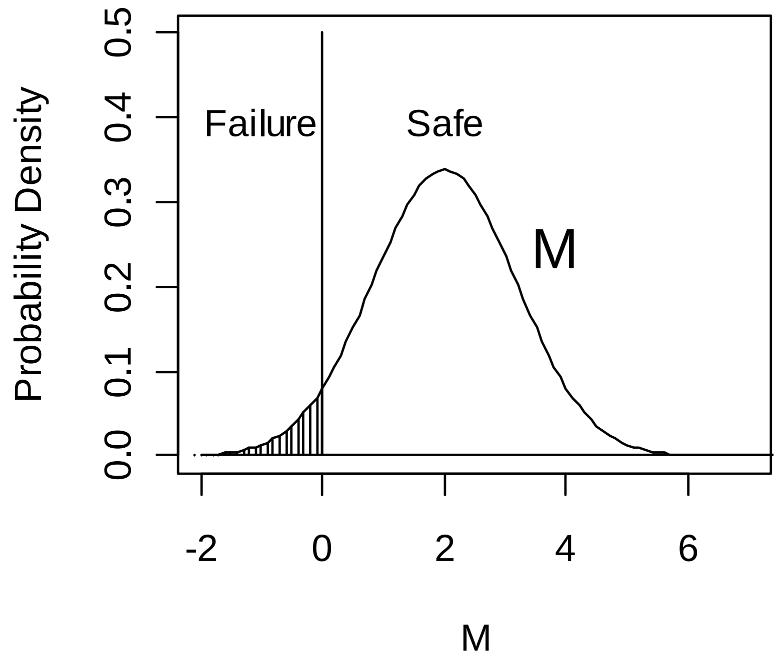
$$P_f = P\left[R \leq S\right]$$

Design structures so that

$$P_f \leq P_{fT}$$

Level III RBD Full distribution approach





$$M = R - S$$

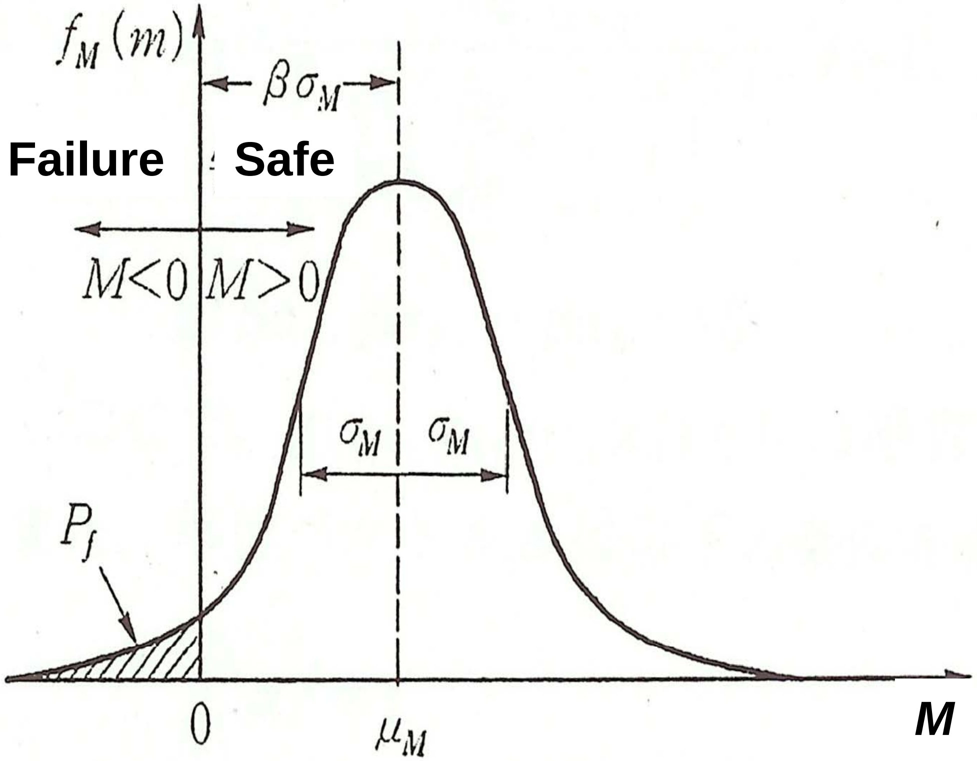
where R : resistance $R \sim N(\mu_R, \sigma_R^2)$ S : force $S \sim N(\mu_S, \sigma_S^2)$

M : safety margin, and $M \sim N(\mu_M, \sigma_M^2)$

where $\mu_M = \mu_R - \mu_S$, $\sigma_M^2 = \sqrt{\sigma_R^2 + \sigma_S^2}$

therefore, $P_f = P[M \leq 0]$

Level II RBD (reliability based design): FORM and Reliability Index



$$M = R - S$$

$$\rightarrow \beta = \frac{\mu_M}{\sigma_M} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

M : safety margin

R : resistance $\sim N(\mu_R, \sigma_R^2)$

S : force $\sim N(\mu_S, \sigma_S^2)$

β : reliability index

$$P_f = P[M \leq 0]$$

Table 1.3 Relationship between β and P_f (Normal distribution)

P_f	10^{-1}	5×10^{-2}	10^{-2}	10^{-3}	10^{-4}
β	1.28	1.64	2.32	3.09	3.72

Level II: Recommended β–values (examples)

Table 1.1 β recommended in EN 1990 annex B

Reliability class (RC)	Min β for 50 years for U.L.S.		Limit State	Target β for 50 years (RC2)
RC3	4.3		U.L.S.	3.8
RC2	3.8		Fatigue	1.5 – 3.8
RC1	3.3		S.L.S.	1.5 (irreversible)

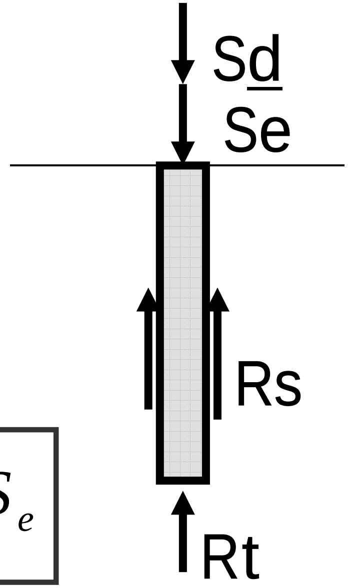
Table 1.2 Target β values (life time examples) in ISO2394

Relative cost of safety measures	Consequences of failure			
	little	some	moderate	great
high	0.0	1.5	2.3	3.1
moderate	1.3	2.3	3.1	3.8
low	2.3	3.l	3.8	4.3

Level I RBD: partial factors / LRFD format

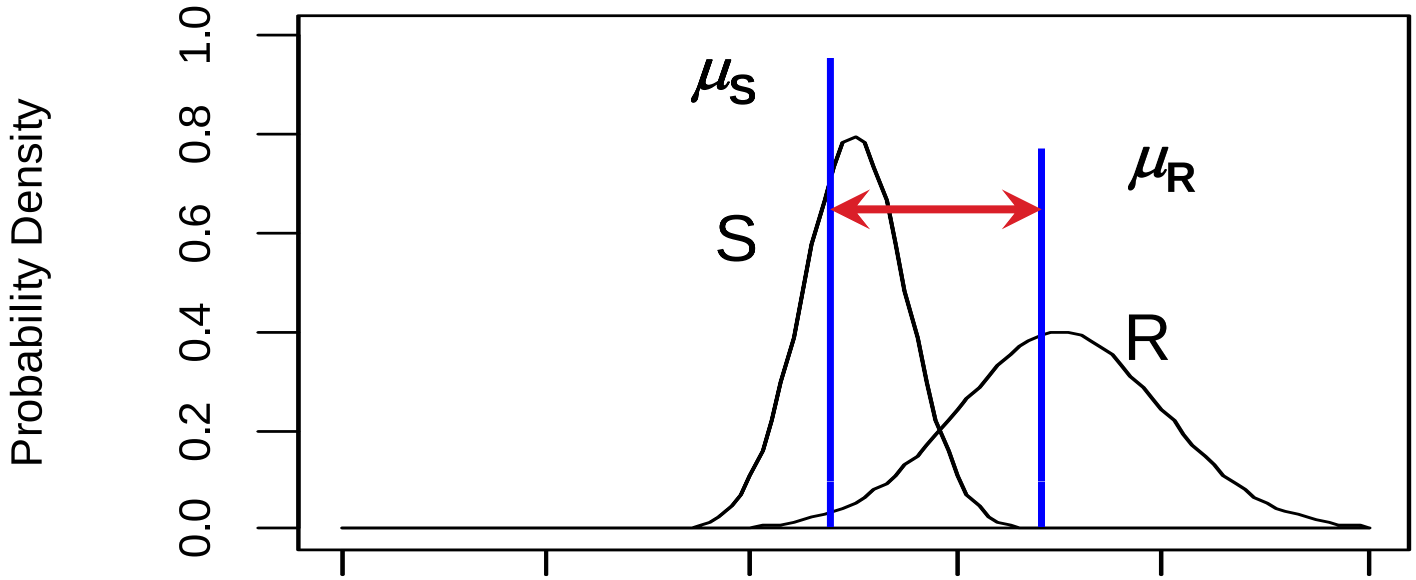
$$\frac{1}{F_s}(R_t + R_s) \geq S_d + S_e$$

$$R_t / \gamma_{Rt} + R_s / \gamma_{Rs} \geq \gamma_{Sd} S_d + \gamma_{Se} S_e$$



By determining partial factors based on Level II or III RBD, one can incorporate the intended safety margin (e.g. β_T) Into structures. This is the mission of code writers to fix these partial factor values in this way (code calibration).

Level I RBD: partial factors approach



Given the target reliability level (e.g. β_T),
and assuming σ_R^2 and σ_S^2 are known,
one determine the distance between μ_R and μ_S
by partial factors.

Table of contents

- RBD (Reliability Based Design) Level III, II and I
- Two sources of LSD in Structural Eurocodes
  (Structural vs. Geotechnical)
- Level III RBD: method employed in this study
  - Uncertainties and calculation procedure
- EX2-1: Pad foundation on homogeneous sand
  - SLS – design for settlement
  - ULS – design for stability
- EX2-5: Embankment on peat ground
- Conclusion
  - RSM (Response Surface Method)
  - General conclutions

Two sources of LSD in Structural Eurocodes

- **Structure Engineering**
  - Classic Reliability based Design by Fredenthal et al. (from 1940th)
  - FOSM by Cornell(1969) and FORM by Ditlevsen (1973); Hasofer & Lind (1974) etc.
  - Activities of JCSS (Joint Committee on Structural Safety)
  - Eurocodes 0,1,2,3 …

- **Geotechnical Engineering**
  - Brinch Hansen (1956, 1967) and Danish Code of Practice for Foundation Structures (LSD and partial factors of safety)
  - K.N. Ovesen et al., Draft model code for Eurocode 7 (1987)
  - Eurocode 7

Development of LSD and partial safety factors in Eurocode – Structural Design

1950-1960
Classic RBD
Freudenthal,
Shinozuka

FOSM
(Cornell、1968)
FORM
(Ditlevsen, 1973;
Hasofer & Lind,
1974etc.)
Rakowviz

1976-1990

JOSS
(joint committee
On Structural Safety)

First drafts of
Eurocodes
ISO2394

1990-date

EN1990
And other
Eurocodes

Development of LSD and partial safety factors in Eurocode – Geotechnical Design

Brinch Hansen (1956, 1967) and Danish Code of Practice for Foundation Structures

Partial safety factors LSD

K.N. Ovesen et al., Draft model code for Eurocode 7 (1987) ESSMFE

Eurocode 7

ENV 1997-1(1994) Cases A, B and C

EN1997-1(2004) Design Approaches 1,2 and 3

Partial safety factor: contributions from geotechnical engineering

A consistent code formulation of a detailed partial safety factor principle was started in the 1950's in Denmark before other places in the world. This development got particular support from the considerations of J. Brinch Hansen who applied the principles in the field of soil mechanics.

(Ditlevsen and Madsen, *Structural Reliability Methods* (1996), p.31)

Purposes of this presentation

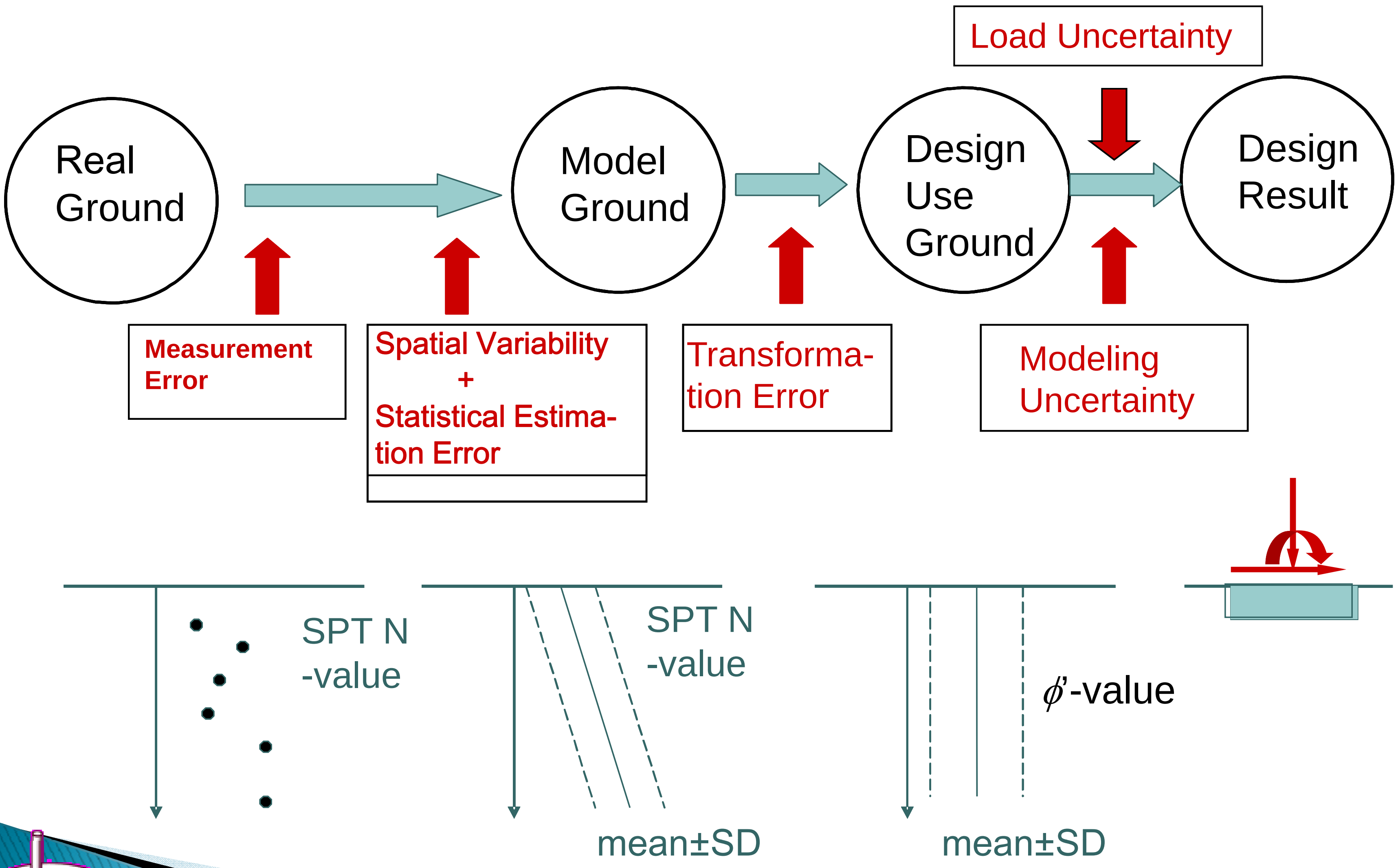
- Try to fill the gap between the two approaches, i.e. geotechnical and structural, or EC7 and other ECs.

- Estimate degree of reliability embedded in various design so as to make comparison of reliability possible among various design results.

Table of contents

- RBD (Reliability Based Design) Level III, II and I
- Two sources of LSD in Structural Eurocodes
  (Structural vs. Geotechnical)
- Level III RBD: method employed in this study
  - Uncertainties and calculation procedure
- EX2-1: Pad foundation on homogeneous sand
  - SLS – design for settlement
  - ULS – design for stability
- EX2-5: Embankment on peat ground
- Conclusion
  - RSM (Response Surface Method)
  - General conclutions

Uncertainties in Geotechnical Design



Procedures for different examples

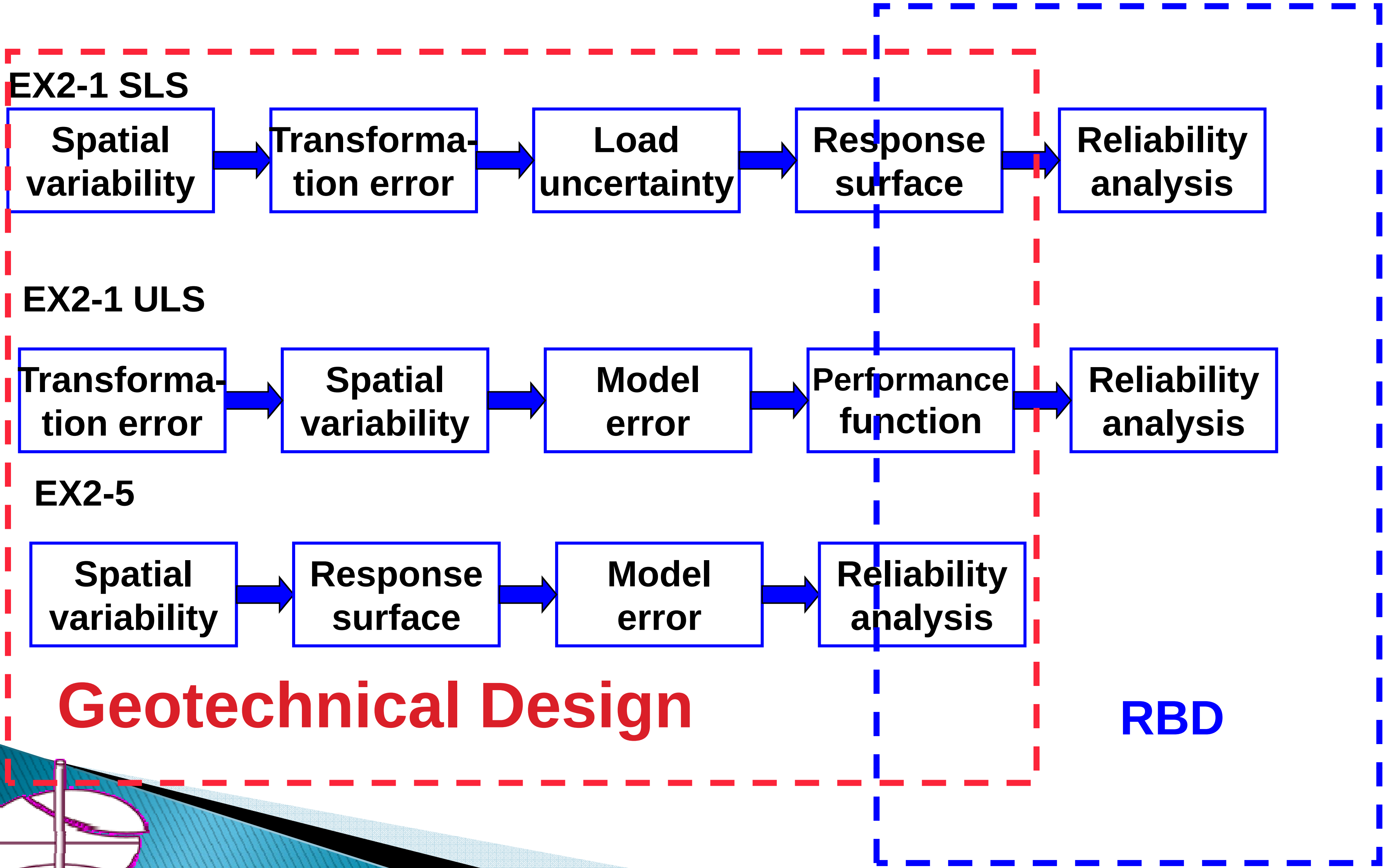
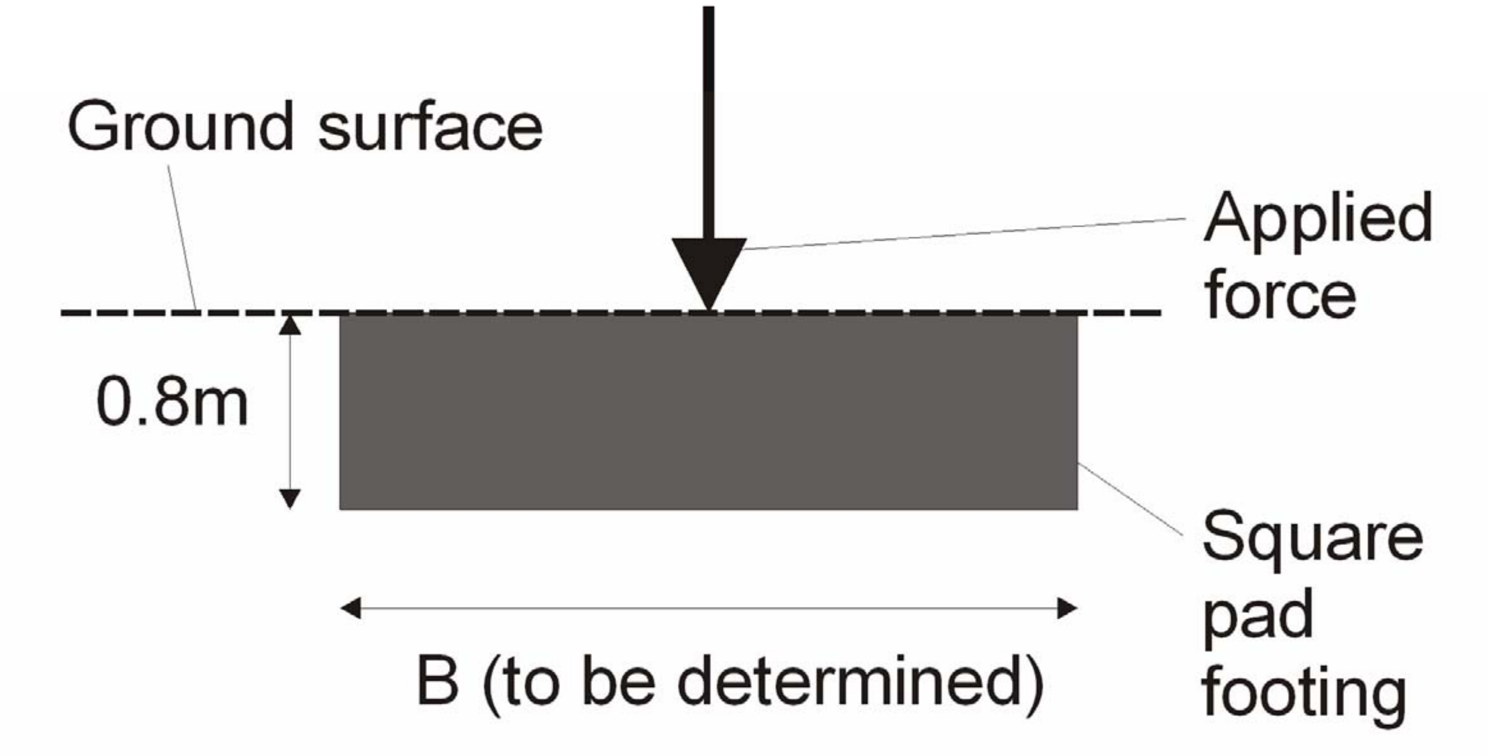


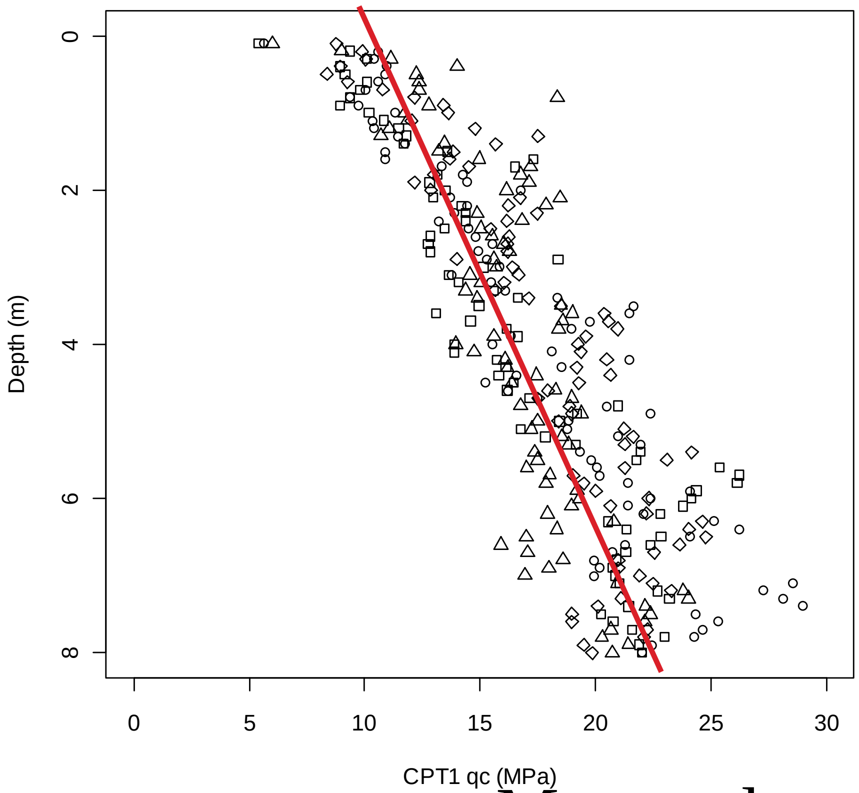
Table of contents

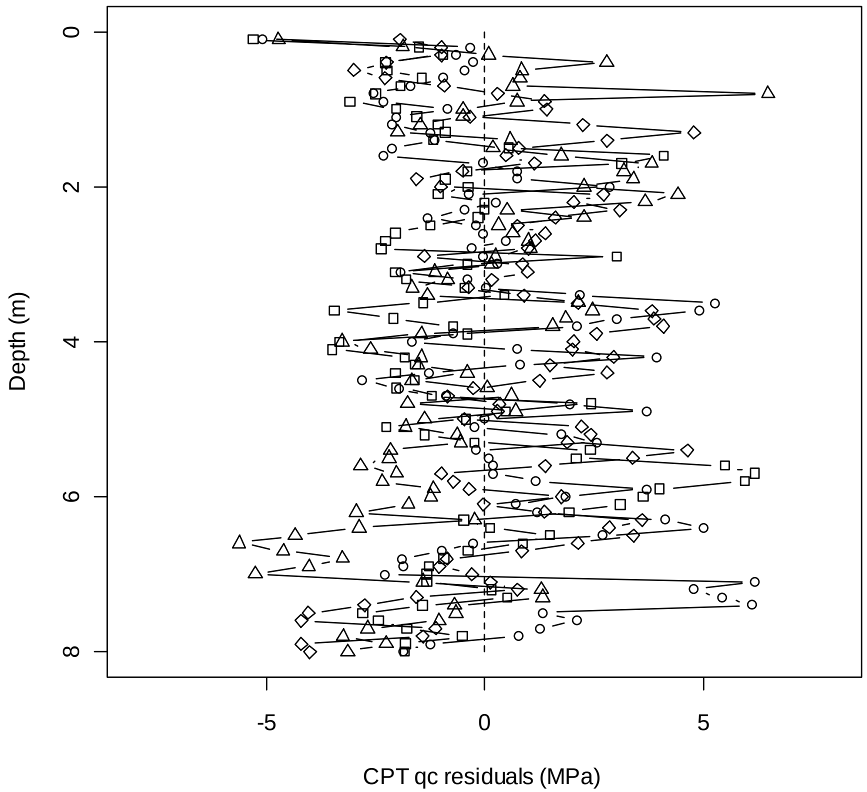
EX2-1: Pad foundation on sand



Spatial variability → Transformation error → Load uncertainty → Response surface → Reliability analysis

EX2-1(SLS): Trend and Random Components of CRT qc



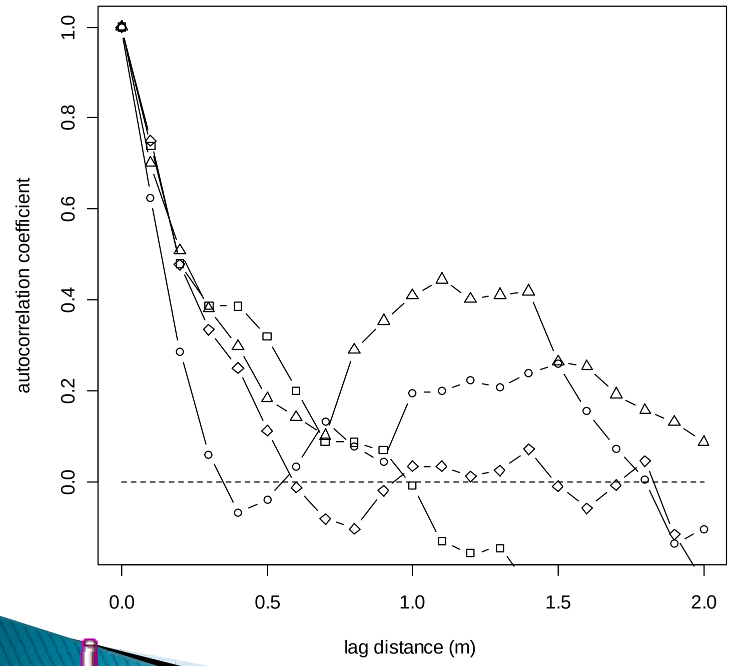


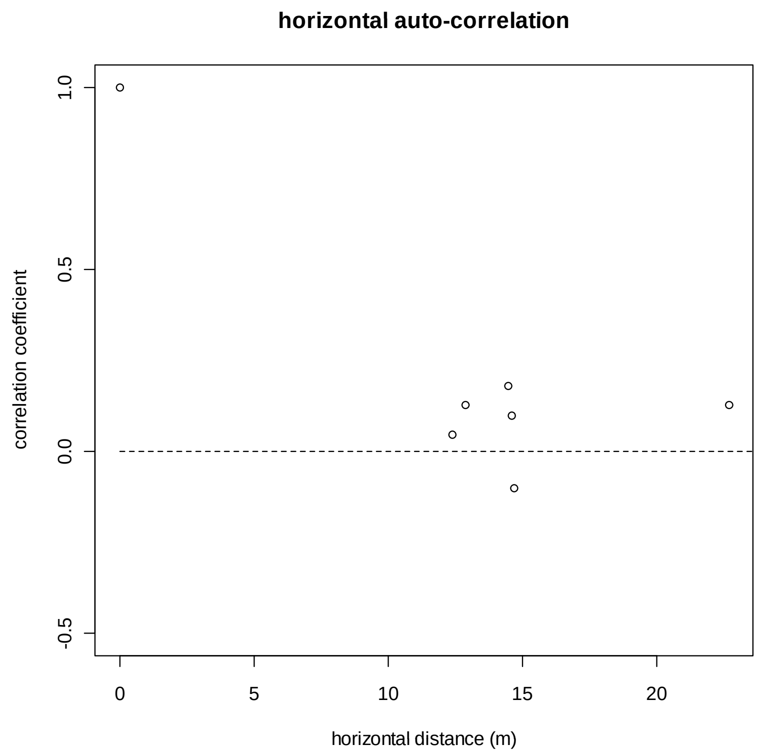
$$\text{Mean value: } q_c = 10.54 + 1.66z \text{ (MPa)}$$

$$\text{Standard deviation: } 2.28 \times 0.7 = 1.60 \text{ (MPa)}$$

Spatial variability → **Transformation error** → **Load uncertainty** → **Response surface** → **Reliability analysis**

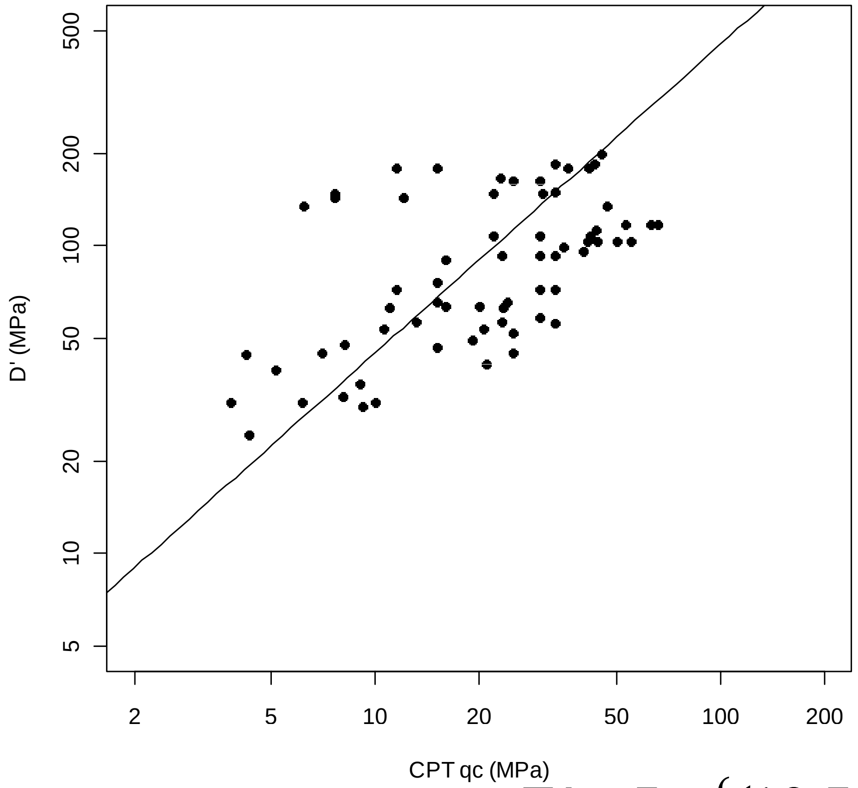
EX2-1(SLS): estimation error – auto correlation of CPT qc





Spatial variability	→	**Transforma-tion error**	→	Load uncertainty	→	Response surface	→	Reliability analysis

EX2-1(SLS): from qc to Young modulus E'



Mean value: $q_c = 10.54 + 1.66z$ (MPa)

Standard deviation: $2.28 \times 0.7 = 1.60$ (MPa)

$$D' = 5(q_c - \sigma'_{v0})$$

$$E' = D' \frac{(1+\nu')(1-2\nu')}{(1-\nu')}$$

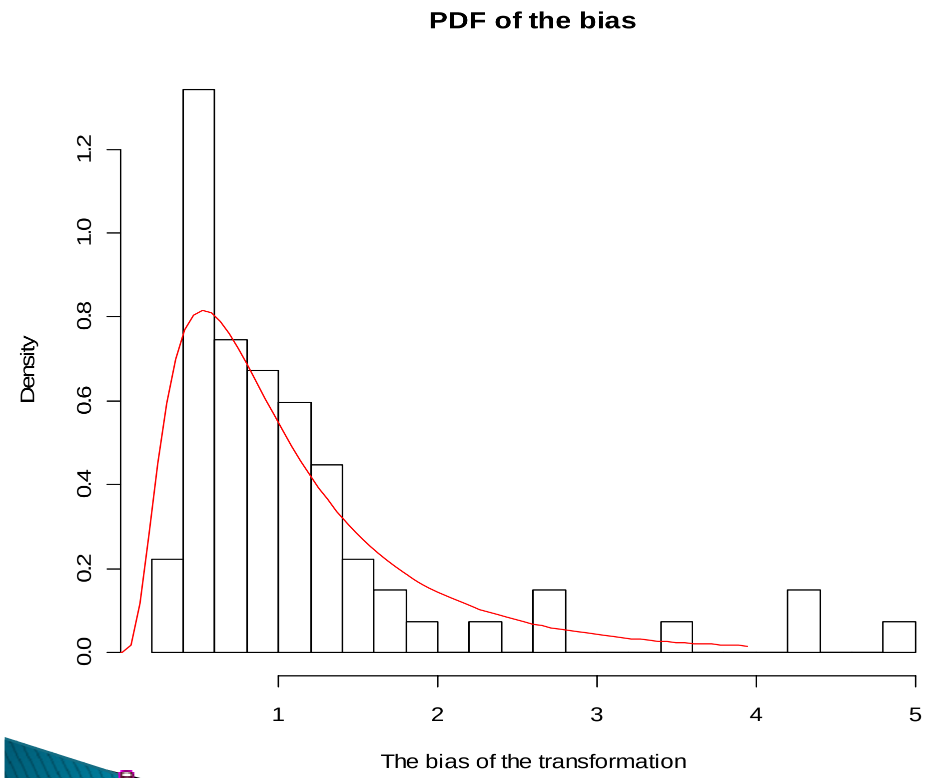
NCHRP (2007)

$$E' = 5 \times \{(10.54 + 1.66z) - 0.02z\} \times \frac{(1+0.2)(1-2\times 0.2)}{(1-0.2)}$$

$$= 47.43 + 7.38z \quad (MPa)$$

Spatial variability → Transformation error → Load uncertainty → Response surface → Reliability analysis

EX2-1(SLS): from qc to E'

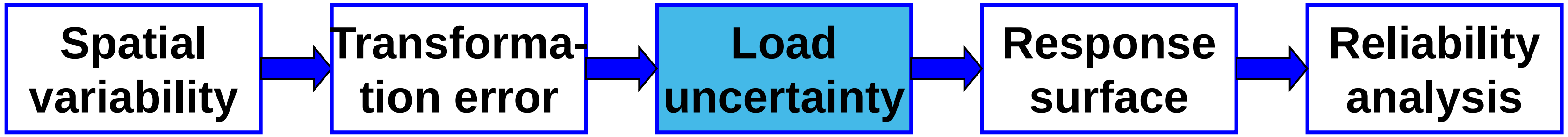


$$\delta_E = \frac{5(q_c - \sigma'_{v0})}{D'}$$

Mean of δ_E = 1.14

SD of δ_E =0.94

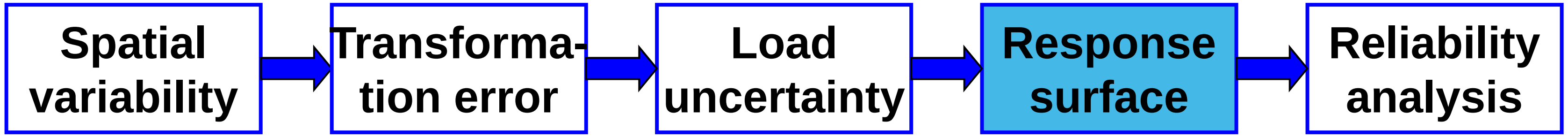
Following Lognormal distribution



EX2-1(SLS): Load Uncertainties

Permanent load (Gk)	δ_{Gk}	1.0	0.1	Normal[(2)]
Variable load (Qk)	δ_{Qk}	0.6	0.35x0.6 =0.21	Gumbel distribution

Based on JCSS(2001) and Holicky, M, J. Markova and H. Gulvanessian (2007).



EX2-1(SLS): Geotechnical design tools -> 3D PLAXIS Elastic analysis (5 cases)

Table 2.2 The settlement of the pad foundation by 3D PLAXIS

Width B (m)	4	3	2	1	0.5
Settlement s (mm)	4.24	6.51	9.32	16.13	24.59

the relationship between B and s:

$$s = 17.0 - 9.73 \log B \quad (7)$$

($R^2 = 0.989$), the perfect fit

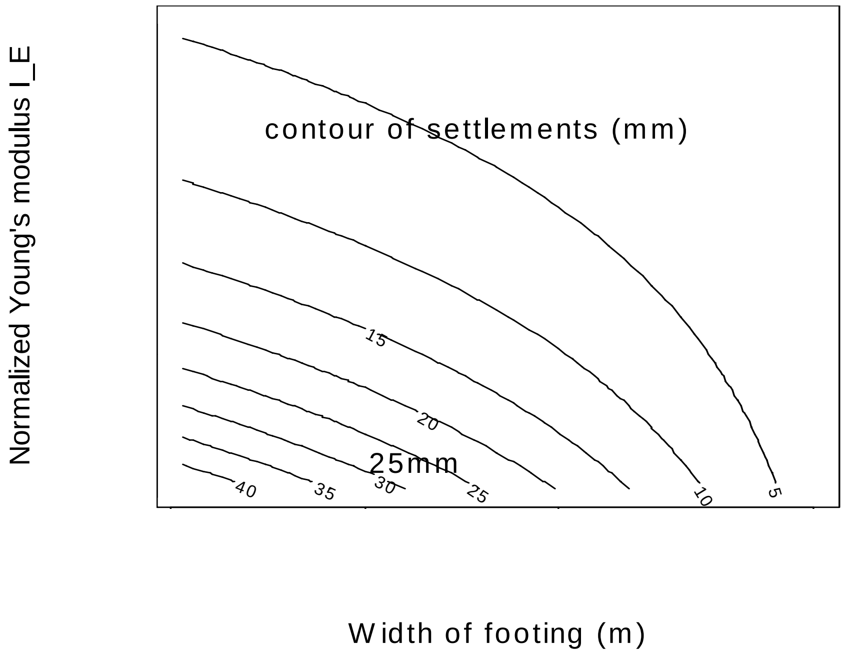
it is expected that the settlement would be double if Young's modulus is half:

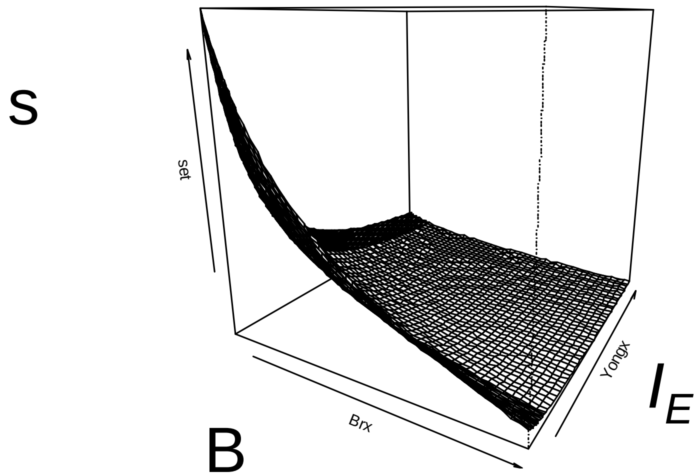
$$s = (17.0 - 9.73 \log B) / I_E \quad (8)$$

I_E: a normalized Young's modulus.

Spatial variability → **Transformation error** → **Load uncertainty** → **Response surface** → **Reliability analysis**

EX2-1(SLS): The contour and a bird view of the Response surface





$$s = (17.0 – 9.73 \log B)/I_E$$

Spatial variability → Transformation error → Load uncertainty → **Response surface** → Reliability analysis

EX2-1 (SLS): Performance Function of settlement

$$s = \frac{(17.0 - 9.73\log(B))}{I_E \cdot \delta_E}\left(\frac{\gamma \cdot D_f \cdot B^2 + G_k\delta_{Gk} + Q_k\delta_{Qk}}{\gamma \cdot D_f \cdot B^2 + G_k + Q_k}\right)$$

$$= \frac{(17.0 - 9.73\log(B))}{I_E \cdot \delta_E}\left(\frac{20 \cdot B^2 + 1000\delta_{Gvk} + 750\delta_{Qvk}}{20 \cdot B^2 + 1750}\right)$$

Basic variables	Notation
Estimation error of spatial average of *E'* for 2(m) depth.	I_E
Transformation error on *E'*	δ_E
Permanent load	δ_{Gk}
Variable load	δ_{Qk}

Spatial variability → **Transformation error** → **Load uncertainty** → **Response surface** → **Reliability analysis**

EX2-1(SLS): List of basic variables

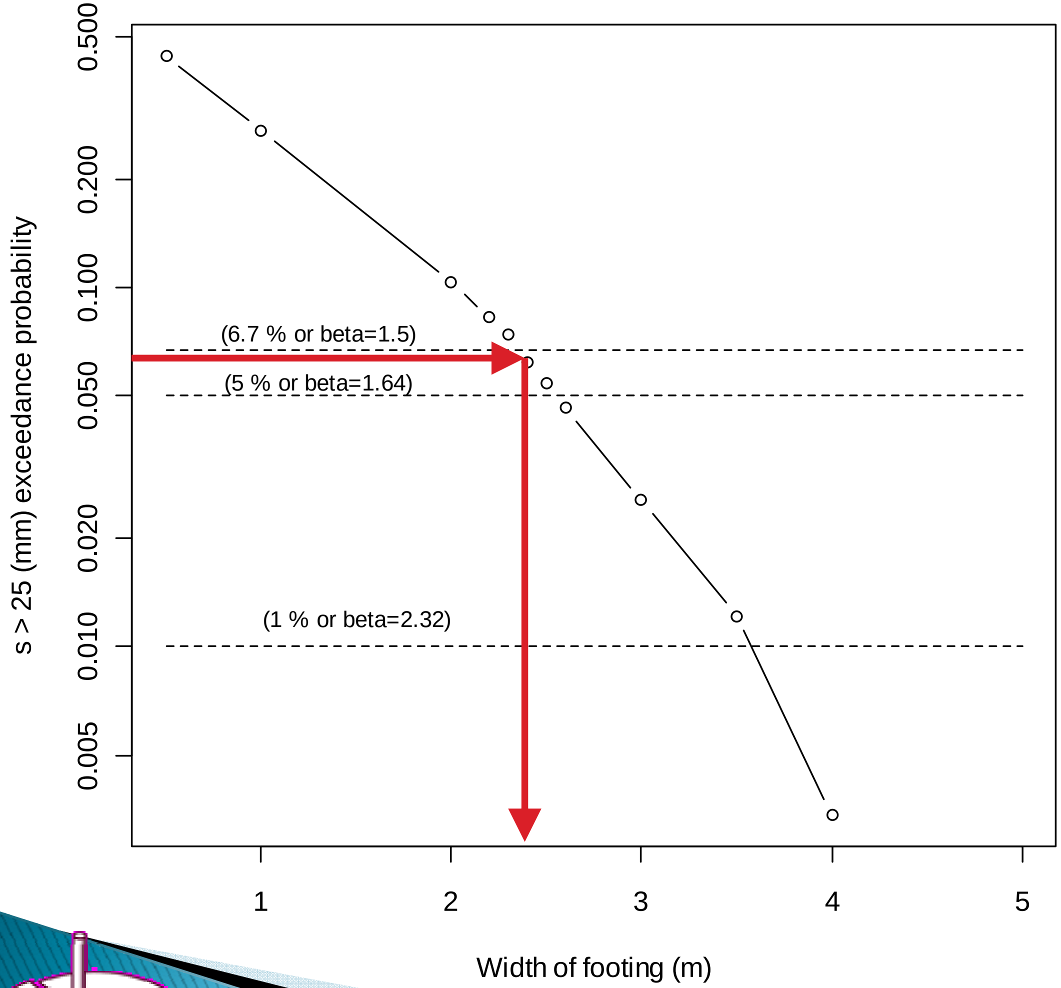
Basic variables	Notation	mean	SD	Distribution type
Estimation error of spatial average of *E'* for 2(m) depth.	E	E'=47.43 + 7.38 z (MPa)	7.2(MPa) COV=0.12(1) at z=1.5(m)	Normal
Transformation error on *E'*	δ_E	1.14	0.94	Lognormal
Permanent load	δ_{Gk}	1.0	0.1	Normal(2)
Variable load	δ_{Qk}	0.6	0.35x0.6 =0.21	Gumbel distribution(2)

(Note 1) COV at about *z*=1.5 (m) is calculated to represent estimation error of *E'* based on limited number of samples.

(Note 2) Based on JCSS(2001) and Holicky, M, J. Markova and H. Gulvanessian (2007).

Spatial variability → Transforma-tion error → Load uncertainty → Response surface → **Reliability analysis**

EX2-1(SLS) settlement: results



SLS:

the settlement < 25 (mm)

After 100,0000 MCS runs. (R language)

if $\beta \geq 1.5$ (i.e. 6.7% exceedance in 50 years)

B > 2.4 (m)

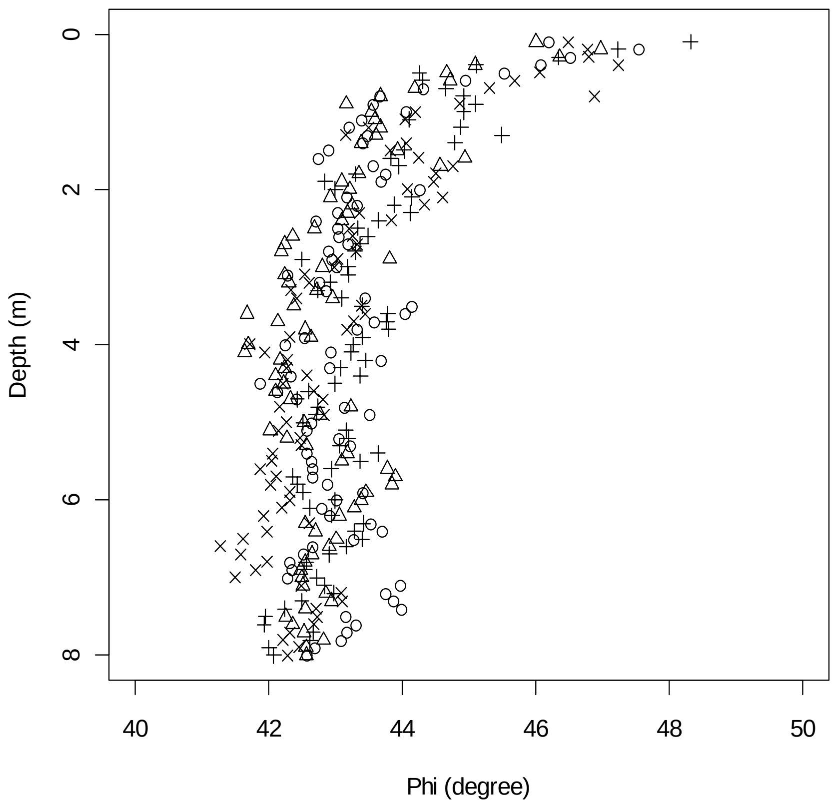
Table of contents

- RBD (Reliability Based Design) Level III, II and I
- Two sources of LSD in Structural Eurocodes

  (Structural vs. Geotechnical)
- Level III RBD: method employed in this study
  - Uncertainties and calculation procedure
- EX2-1: Pad foundation on homogeneous sand
  - SLS – design for settlement
  - ULS – design for stability
- EX2-5: Embankment on peat ground
- Conclusion
  - RSM (Response Surface Method)
  - General conclutions

Transformation error → Spatial variability → Model error → Performance function → Reliability analysis

EX2-1(ULS): CPT q_c to ϕ'



$$\phi'_{tc} = 17.6 + 11.0\log\left(\frac{\left(q_c/p_a\right)}{\left(\sigma'_{v0}/p_a\right)^{0.5}}\right)$$

where p_a = atmospheric pressure(0.1MPa)

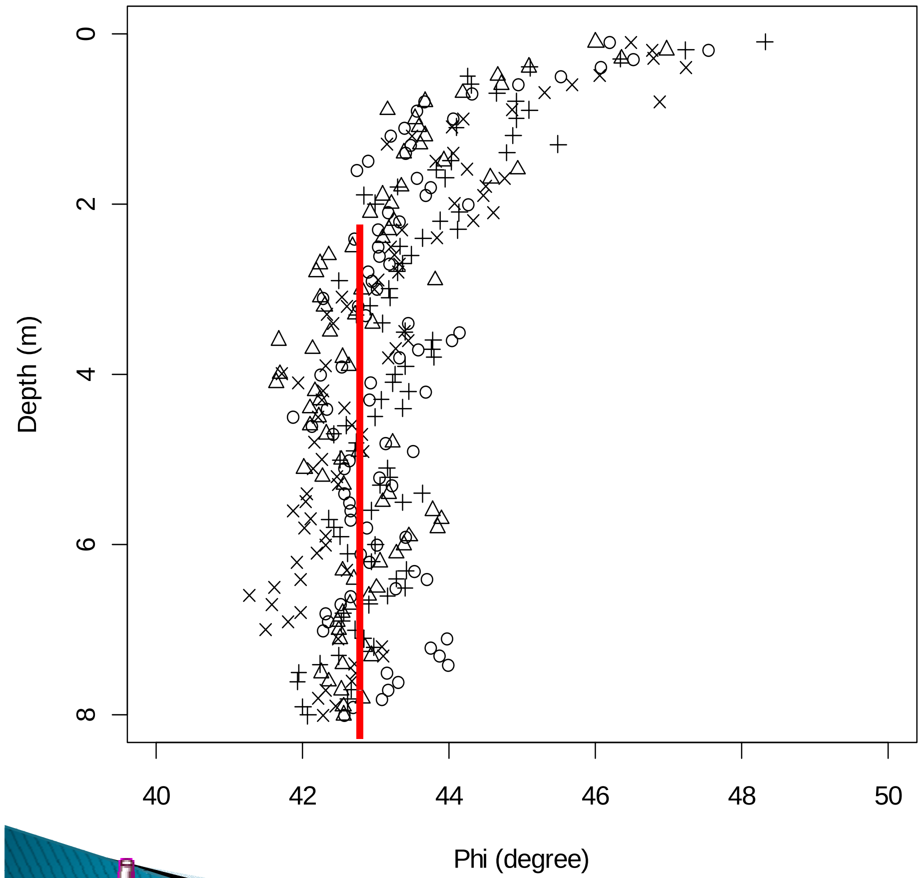
σ'_{v0} = effective overburden stress.

SD for transformation =2.8 (degree).

(Kulhawy et al. 1990)

Transformation error → **Spatial variability** → Model error → Performance function → Reliability analysis

EX2-1(ULS): spatial variability of ϕ'



spatial average of ϕ'_{tc} = 42.8 (degree) and SD=0.60 (degree).

Transforma-tion error → Spatial variability → **Model error** → Performance function → Reliability analysis

EX2-1(ULS): Model error in bearing capacity estimation

$$R_u = A_e\left\{\kappa.q.N_q.S_q + \frac{1}{2}.\gamma_1.\beta.B_e.N_\gamma.S_\gamma\right\}$$

$$\kappa = 1 + 0.3\frac{D_f{}'}{B_e} = 1 + 0.3\frac{0.8}{B_e} = 1 + \frac{0.24}{B_e}$$

$$q = \gamma_2.D_f = 20\times 0.8 = 16\ (\mathrm{kN/m^2})$$

$$N_q = \frac{1+\sin\phi}{1-\sin\phi}.\exp(\pi.\tan\phi)$$

$$S_q = \left(\frac{q}{q_0}\right)^{-1/3} = \left(\frac{16}{10}\right)^{-1/3} = 0.86$$

$$\gamma_1 = 20\ \left(\mathrm{kN/m^3}\right)$$

$$\beta = 0.6$$

$$N_\gamma = \left(N_q - 1\right)\times\tan(1.4\phi)$$

$$S_\gamma = \left(\frac{B_e}{B_0}\right)^{-1/3} = \left(\frac{B_e}{1.0}\right)^{-1/3} = B_e^{-1/3}$$

where A_e = the effective area of the foundation ($=B_2$),

B_e = effective width (in this case $B_e = B$),

κ and β = shape factors for N_q

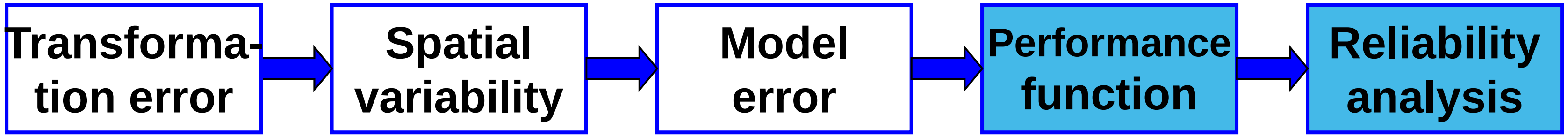
N_g, q = overburden pressure at the foundation bottom,

D'_f = embedded depth (m),

S_q and S_γ = scale factor for N_q and N_γ.

B_0 and q_0 = reference width and load respectively.

Kohno et.al (2009) Model error: the bias =0.894 with SD = 0.257.



EX2-1(ULS): Reliability analysis by MCS

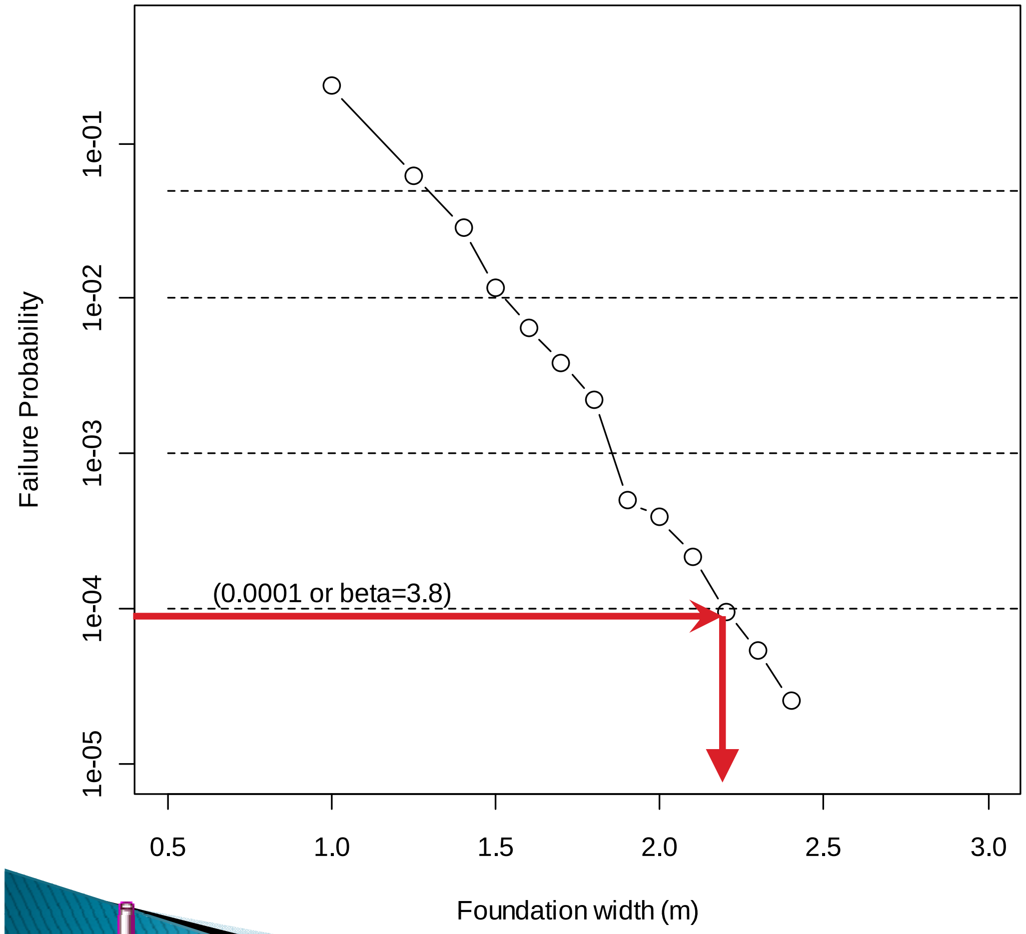
$$M = Ru(B,\ \phi'_{tc}) \cdot \delta_{Ru} - G_k \cdot \delta_{Gk} - Q_k \cdot \delta_{Qk}$$

where *M* = safety margin, *Ru* = bearing capacity of the foundation,
Gk =1000(kN), *Qk* = 750(kN) , B=width of footing

Basic variables	Notation	Mean	SD	Distribution type
Spatial variability	ϕ'_{tc}	42.8	0	Deterministic variable
Transformation error from q_c to ϕ'_{tc}	ϕ'_{tc}	42.8	2.8	Normal
R_u estimation error	δ_{Ru}	0.894	0.257	Lognormal
Permanent action	δ_{Gk}	1.0	0.1	Normal
Variable action	δ_{Qk}	0.6	0.35x0.6=0.21	Gumbel distribution

Transforma-tion error → Spatial variability → Model error → Performance function → **Reliability analysis**

EX2-1(ULS): results of the reliability analysis



After 100,000 MCS runs

$\beta = 3.8$
(i.e. 10^{-4} failure probability for 50 years design working life.)

B=2.2 (m)

Summary of EX2-1: Pad foundation

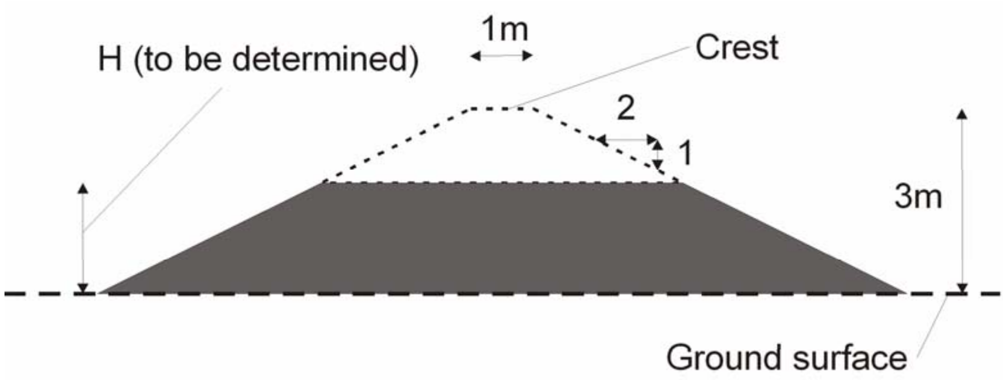
Limit state	*Target β for 50 years design working life. (P_f)*	*Required width (m)*
S.L.S.(s < 25 mm)	1.5 (0.067)	B > 2.4 (m)
U.L.S.(stability)	3.8 (10^{-4})	B > 2.2 (m)

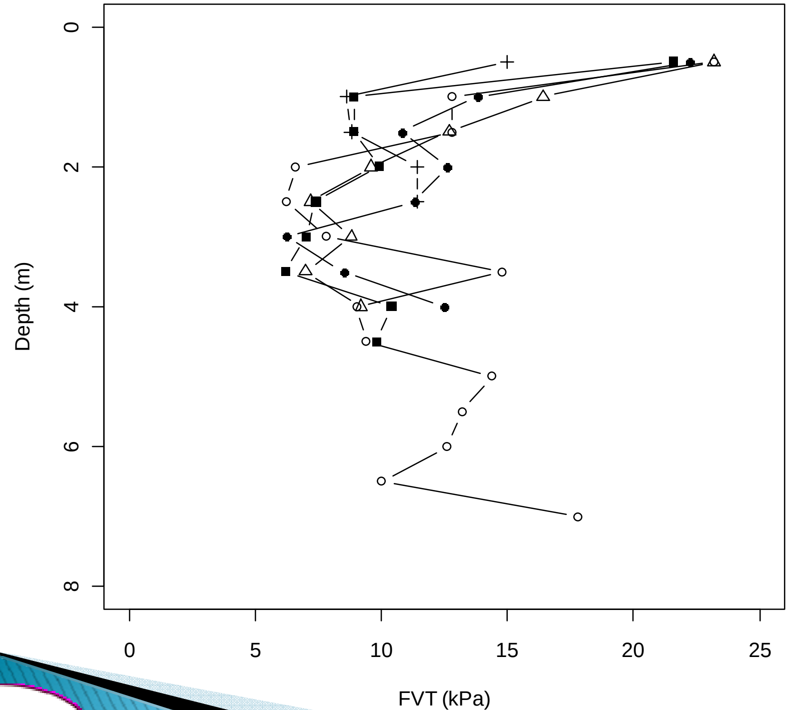
Summary of EX2-1: Pad foundation

1. If all average values obtained for basic variables
   - SLS: only 0.5 (m) -> 2.4 (m) (4.8 times)
   - ULS: 0.85 (m) for -> 2.2 (m) (2.6 times)
2. The uncertainty components contributing the design
   - the conversion of *qc* to Young's modulus for settlement (SLS).
   - the model error in the bearing capacity equation for bearing capacity (ULS).
   - The contribution of spatial variability of soil properties on total uncertainty is not as large.

Table of contents

EX 2-5 : EMBANKMENT OF SOFT PEAT





- An embankment on a soft peat with final height 3 (m)
- determine the first stage embankment height.

- The Embankment material

  γ=19 (kN/m3) ,

  ϕ'_k=32.5 (degree).
- Top soil : normally consolidated clay (γ=18 (kN/m^3) and γ' = 9 (kN/m^3)
- 3 to 7 (m) thick peat layer with γ'=2 (kN/m^3) overlaying
- Pleistocene sand of γ'=11 (kN/m^3) and ϕ'_k=35 (degree).
- 5 filed vane test (FVT) results are given whose testing interval is 0.5 (m)

Spatial variability → **Response surface** → **Model error** → **Reliability analysis**

EX 2-5 : Spatial variability of soil and modeling

Undrained shear strength of the topsoil

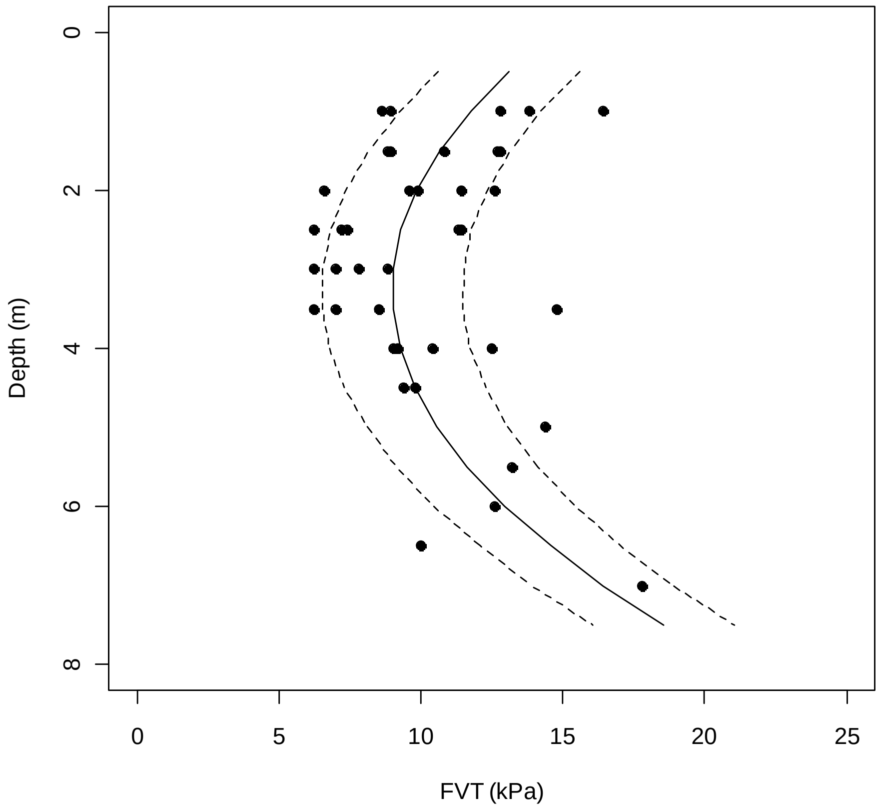
Mean (kPa)	*SD (kPa)*	*COV*
21.04	3.44	0.163

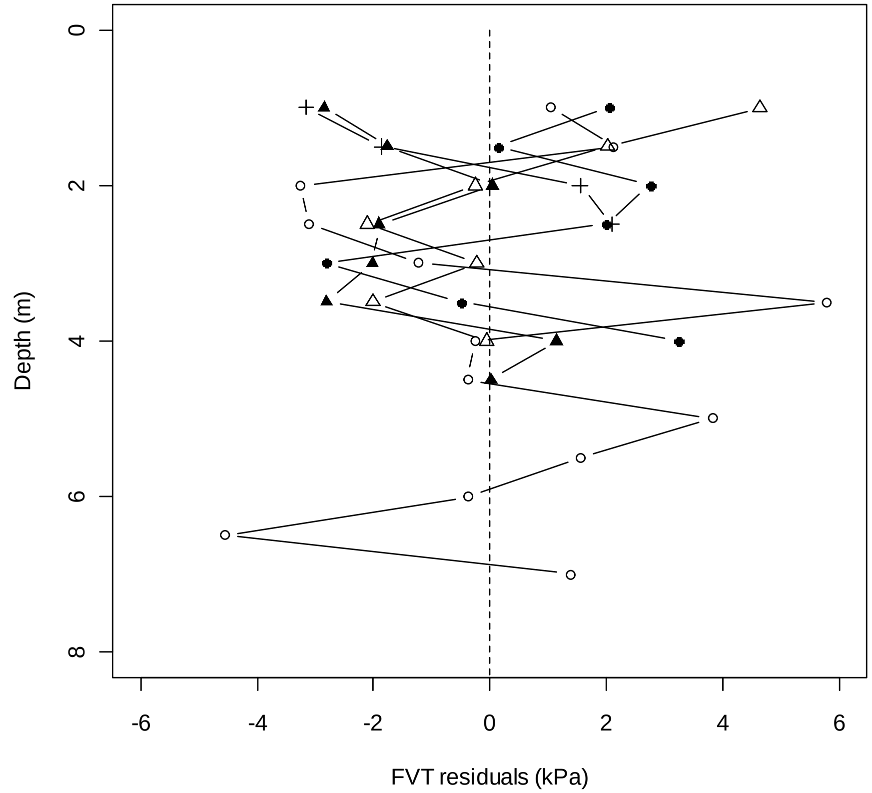
Alternative models fitted to *su* of the peat layer

Models	*Trend (kPa)*	*SD*	*AIC*	*Note*
Constant	10.33	2.89	196.52	
Linear	9.3677 + 0.3221z (9.40) (1.085)	2.85	197.30	R^2 = 0.031 (t-values)
Quadratic	14.73 - 3.51z + 0.536z^2 (9.04) (3.42) (3.85)	2.40	185.82	R^2 = 0.314 (t-values)

Spatial variability → **Response surface** → **Model error** → **Reliability analysis**

EX 2-5 : Spatial variability of soil and modeling





su = 14.73 - 3.51*z*+0.536*z*2 (kPa)

the SD of the *su* -> 2.40 x 0.5 = 1.20 (kPa).

Spatial variability → **Response surface** → Model error → Reliability analysis

EX2-5: Range of values used in obtaining RS (135 cases)

h (m)	I_{peat}	$I_{topsoil}$	D_t (m)
1, 1.5, 2, 2.5. 3	0.5, 0.75, 1.0	0.5, 0.75, 1.0	0.5,0.75, 1.0

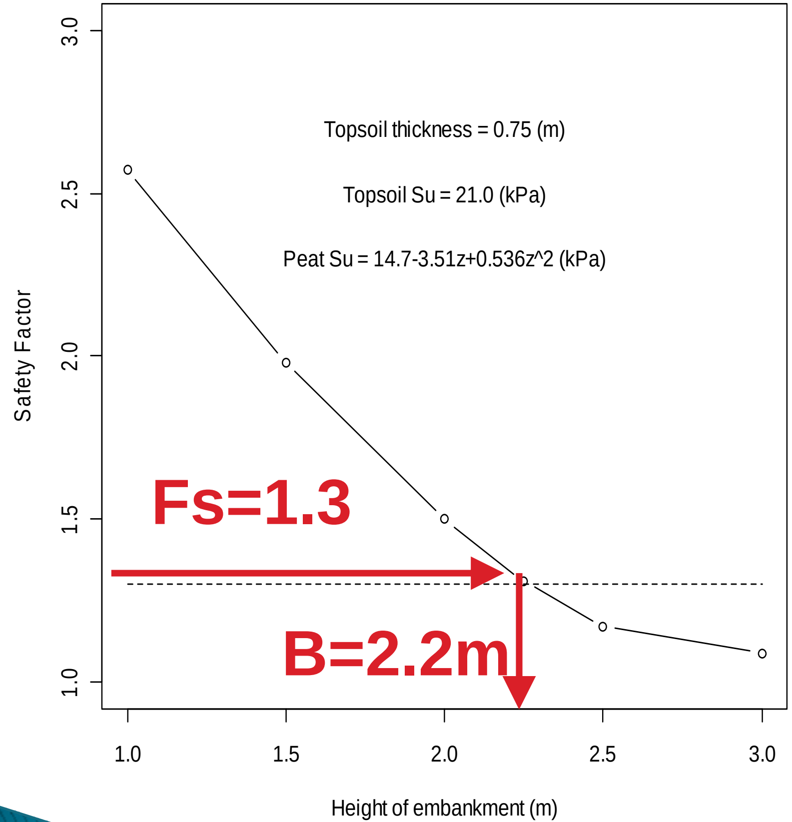
$$I_{peat} = s_u / (\text{mean of } s_u \text{ of the peat layer})$$

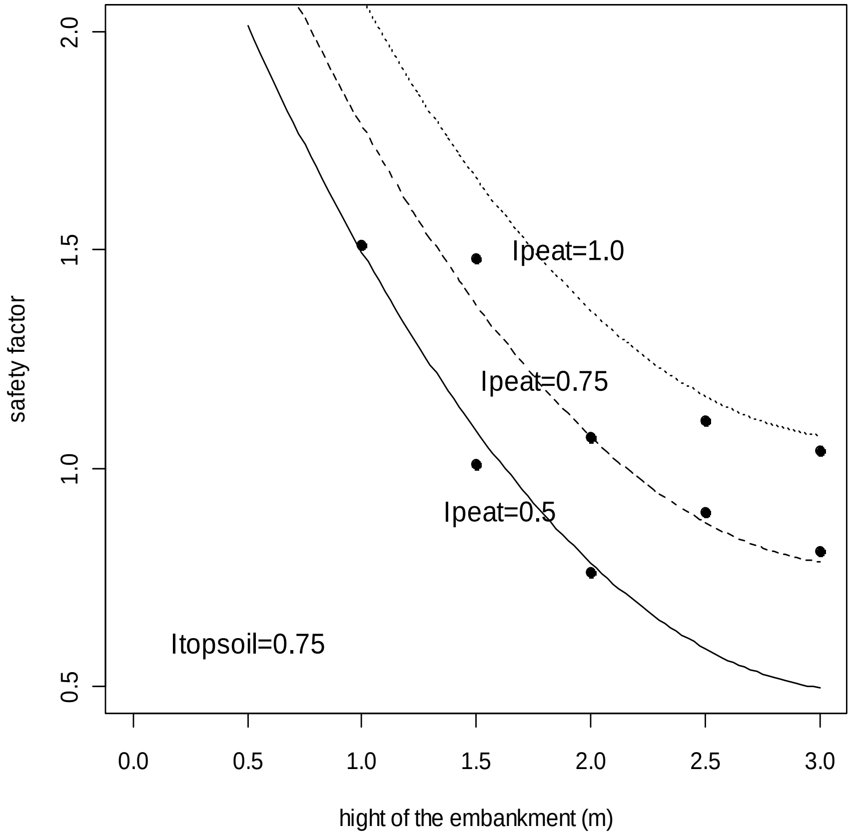
$$I_{topsoil} = s_u / (\text{mean of } s_u \text{ of the topsoil}) = s_u / 21.04$$

model	equation	r.s.e.	R^2
Linear	F_s=0.948-0.449 h + 1.154 I_{peat} + 0.272 $I_{topsoil}$ + 0.047 D_t	0.0985	0.823
Quadratic	Fs=1.783-1.351 h + 0.213 h^2 + 1.156 I_{peat} + 0.272 $I_{topsoil}$ + 0.091 D_t	0.0533	0.949
logalismic	Fs=0.595-0.915 log(h) + 1.181 I_{peat} + 0.272 $I_{topsoil}$ + 0.079 D_t	0.0645	0.924

Spatial variability → **Response surface** → **Model error** → **Reliability analysis**

EX2-5: Height vs. Fs and Response surface

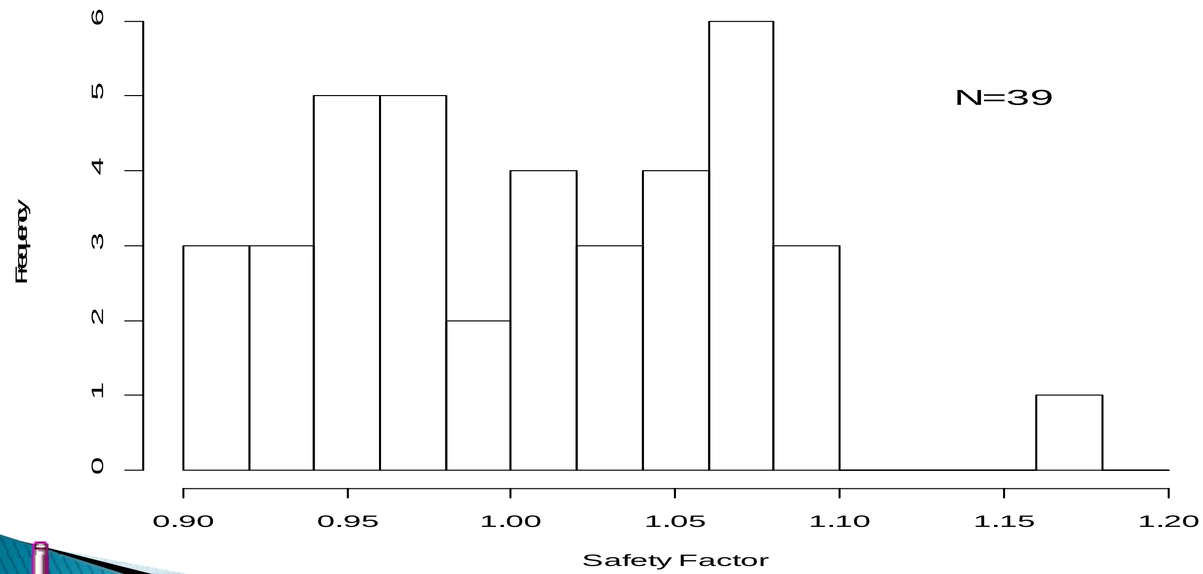




Spatial variability → Response surface → **Model error** → Reliability analysis

EX2-5:Model error in stability analysis of embankment

39 failure cases of embankment on soft ground by FV/UU compression tests and $\phi'=0$ circular slip method, and Fs distributed between Fs= 0.9 to 1.1.

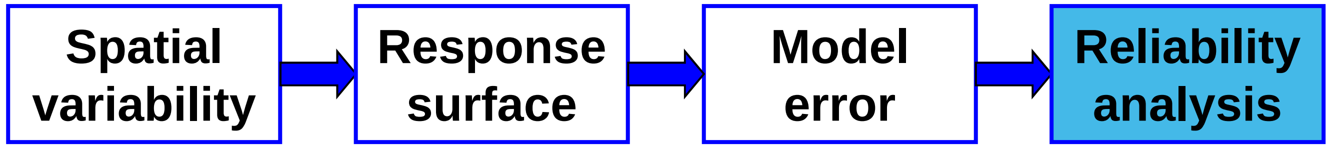


Model error (Matsuo and Asaoka, 1976)

Spatial variability → **Response surface** → **Model error** → **Reliability analysis**

Basic variables	Notations	mean	SD	Distribution
Topsoil s_u (kPa)	s_{upeat} (I_{peat})	21.04 (1.0)	3.44 (0.163)	Normal
Peat s_u (kPa)	$s_{utopsoil}$ $(I_{topsoil})$	$14.73-3.51z+0.536z^2$ (1.0)	1.20 (0.13)(1)	Normal
Topsoil thickness	D_t	[0.5, 1.0] (m)		Uniform(2)
Model error	δ_{Fs}	[0.9, 1.0]		Uniform(3)
Unit weight of embankment	γ_f	19.0(kN/m^3)	-	Deterministic
friction of embankment	ϕ_f	32.5 degree	-	Deterministic
Unit weight of topsoil	γ_c	9.0(kN/m^3)	-	Deterministic
Unit weight of peat	γ_P'	2.0(kN/m^3)	-	Deterministic
friction of sand	ϕ_s	35 degree	-	Deterministic
Unit weight of sand	γ_s'	11.0(kN/m^3)	-	Deterministic

(Note 1) su topsoil (at z=4.0(m)) = 14.73 - 3.5x4.0 + 0.53x4.02 = 9.27, COV=1.20/9.27=0.13
(Note 2) It is assumed that the boundary of the topsoil and the peat layer lies somewhere between z = 0.5 to 1.0 (m).
(Note 3) Based on Matsuo and Asaoka (1976).



EX2-5: reliability analysis by RS and MCS

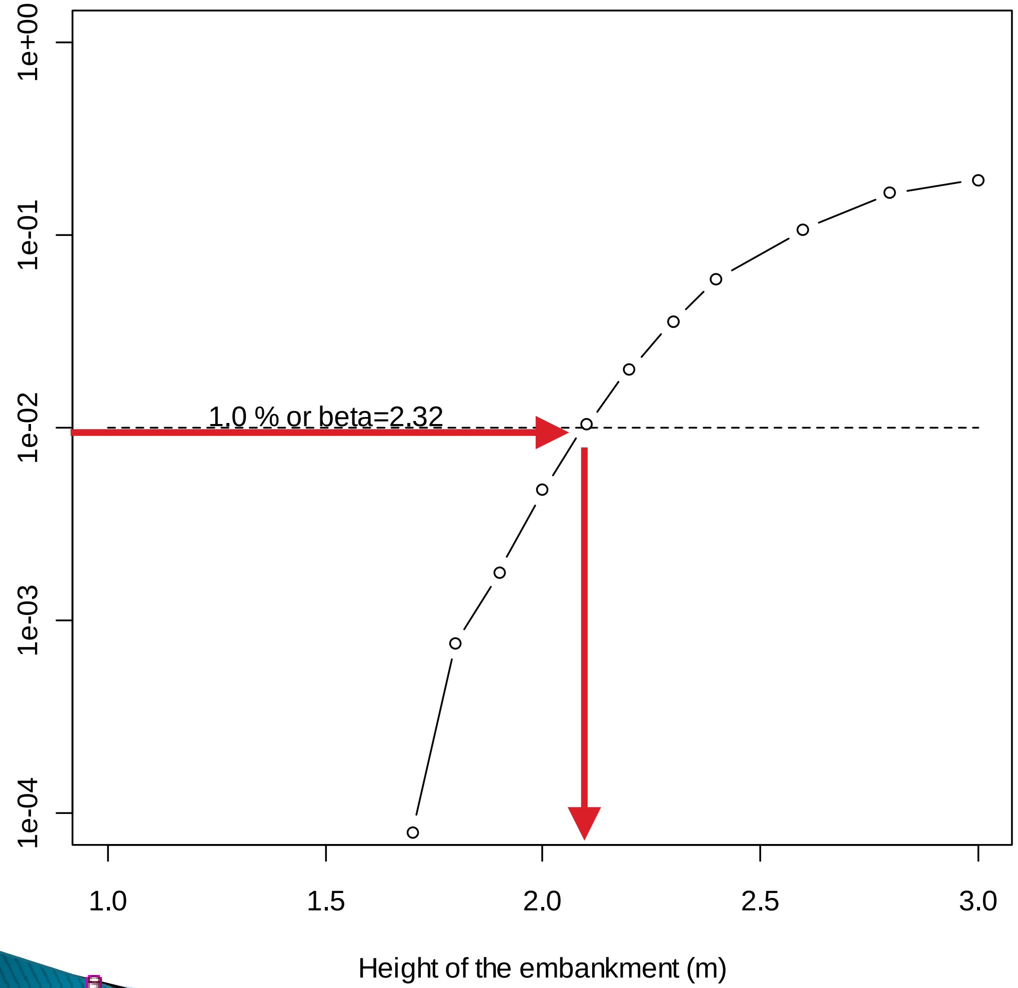
The response surface for the safety factor

$$Fs=(1.783-1.351\,h + 0.213\,h^2 + 1.156\,I_{peat} + 0.272\,I_{topsoil} + 0.091\,D_t)\,\delta_{Fs}$$

After 100,000 MCS runs, to obtain $Pf = P\,[\,Fs \leq 1.0\,]$

Spatial variability → Response surface → Model error → **Reliability analysis**

EX2-5: Result of the reliability analysis



For $\beta = 2.32$,

the first stage embankment height should be less than 2.1 (m).

EX2-5: Summary and discussions

Based on the RS, one can evaluate the contribution of each basic variable to the safety of the embankment. For example,

- The effect of the height of the embankment becomes less as the embankment height increase, which is indicated by the quadratic function.
- 10% reduction of peat strength reduces the safety factor by 0.12. The reduction is 0.027 in case of the topsoil strength.
- 0.1 (m) change of the topsoil layer thickness changes the safety factor by 0.01.

$$Fs=(1.783-1.351\,h + 0.213\,h^2 + 1.156\,I_{peat} + 0.272\,I_{topsoil} + 0.091\,D_t)\,\delta_{Fs}$$

Table of contents

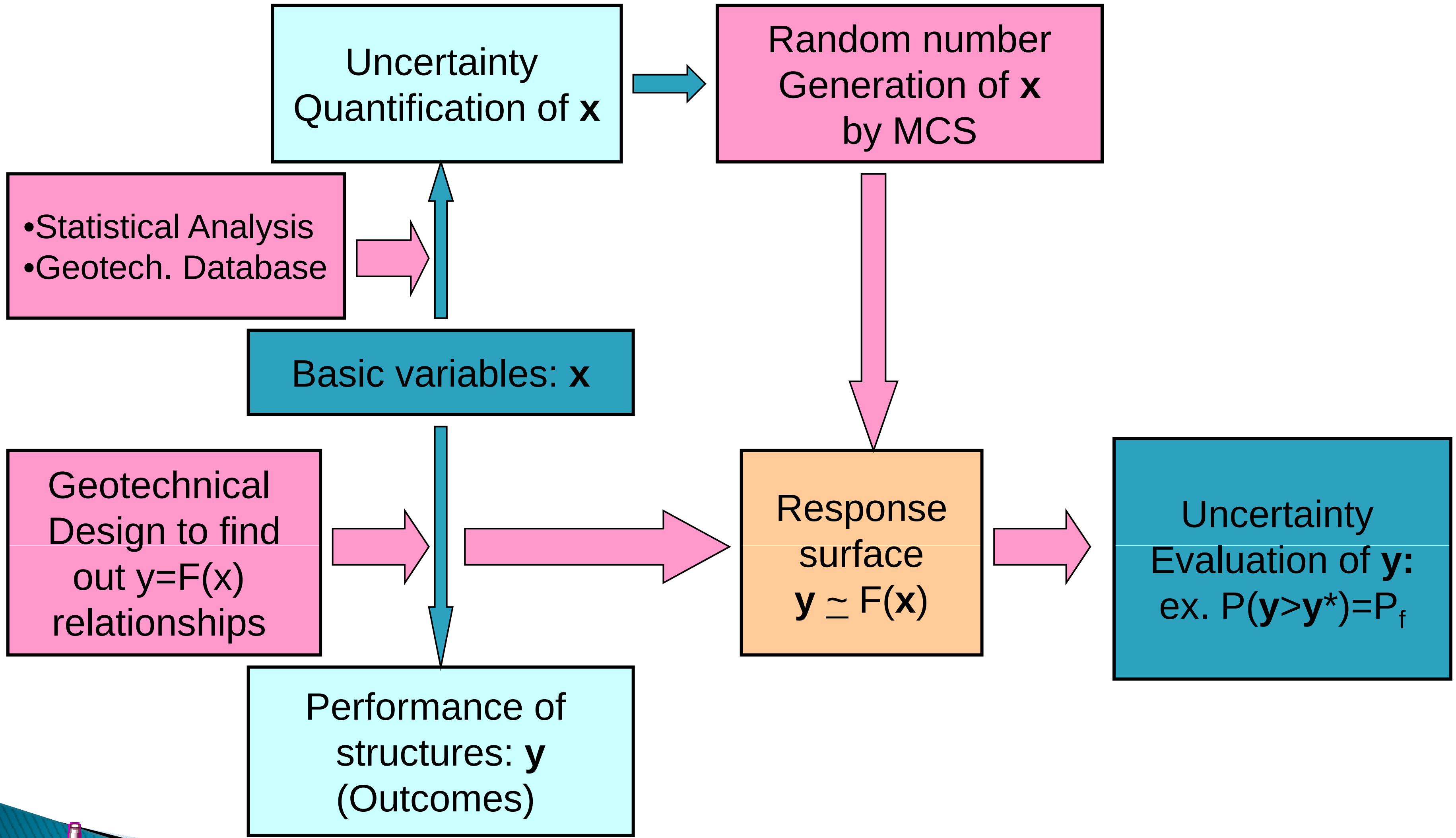
Conclusions

1. Three out of six examples (*i.e.* EX2-1, 5 and 6) set by ETC10 – Evaluation of Eurocode 7 – has been solved by using Level III reliability based design.
2. it is not soil properties spatial variability that controls the major part of the uncertainty in many geotechnical designs.
3. The error in design calculation equations, transformation of soil investigation results (*e.g.* SPT N-values, FVT, CPT *qc*) to actual design parameters (*e.g. su, f'*, resistance values), and statistical estimation error are more important factors.

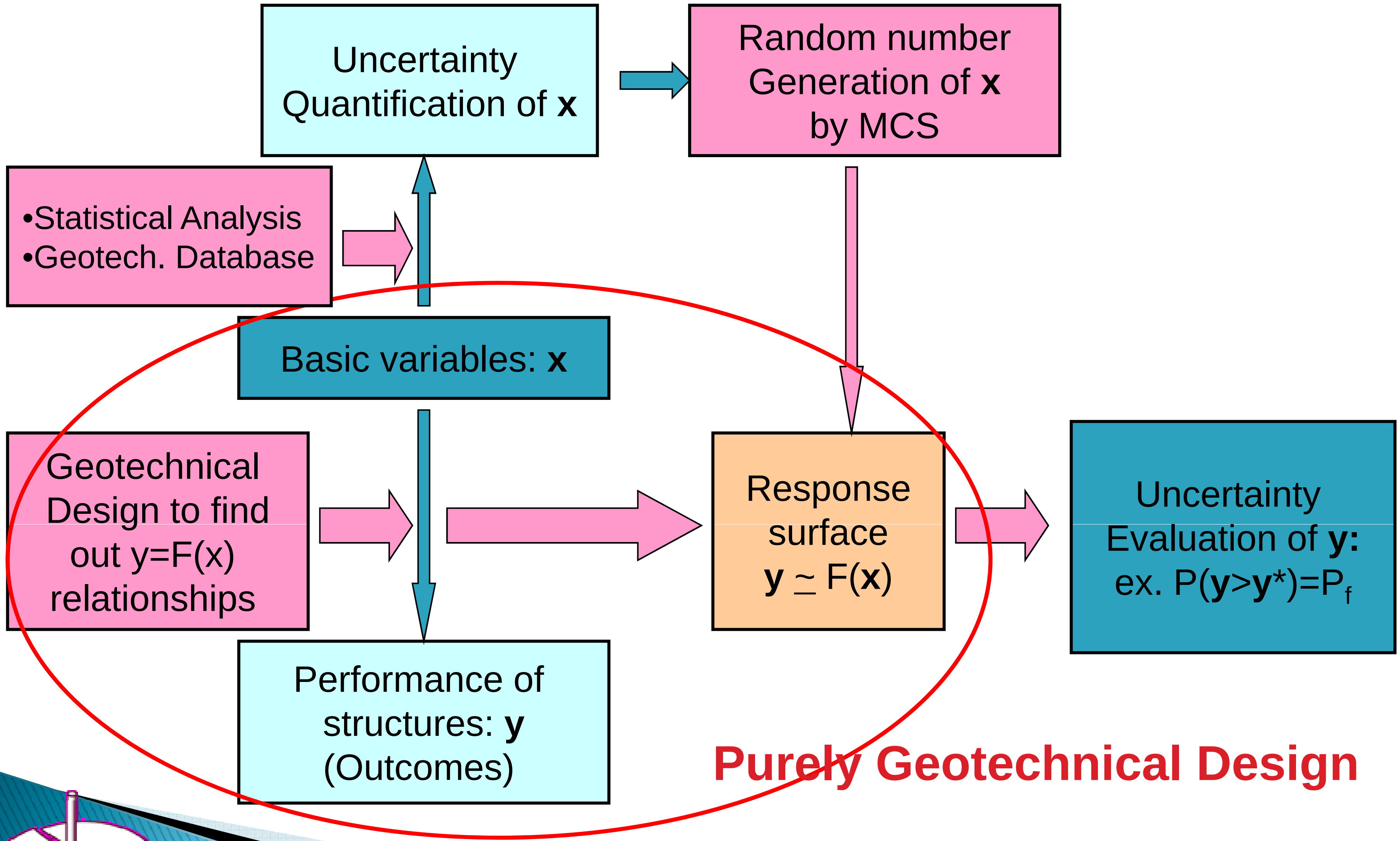
Table of contents

- RBD (Reliability Based Design) Level III, II and I
- Two sources of LSD in Structural Eurocodes
  (Structural vs. Geotechnical)
- Level III RBD: method employed in this study
  - Uncertainties and calculation procedure
- EX2-1: Pad foundation on homogeneous sand
  - SLS – design for settlement
  - ULS – design for stability
- EX2-5: Embankment on peat ground
- Conclusion
  - **General conclusions**
  - RSM (Response Surface Method)

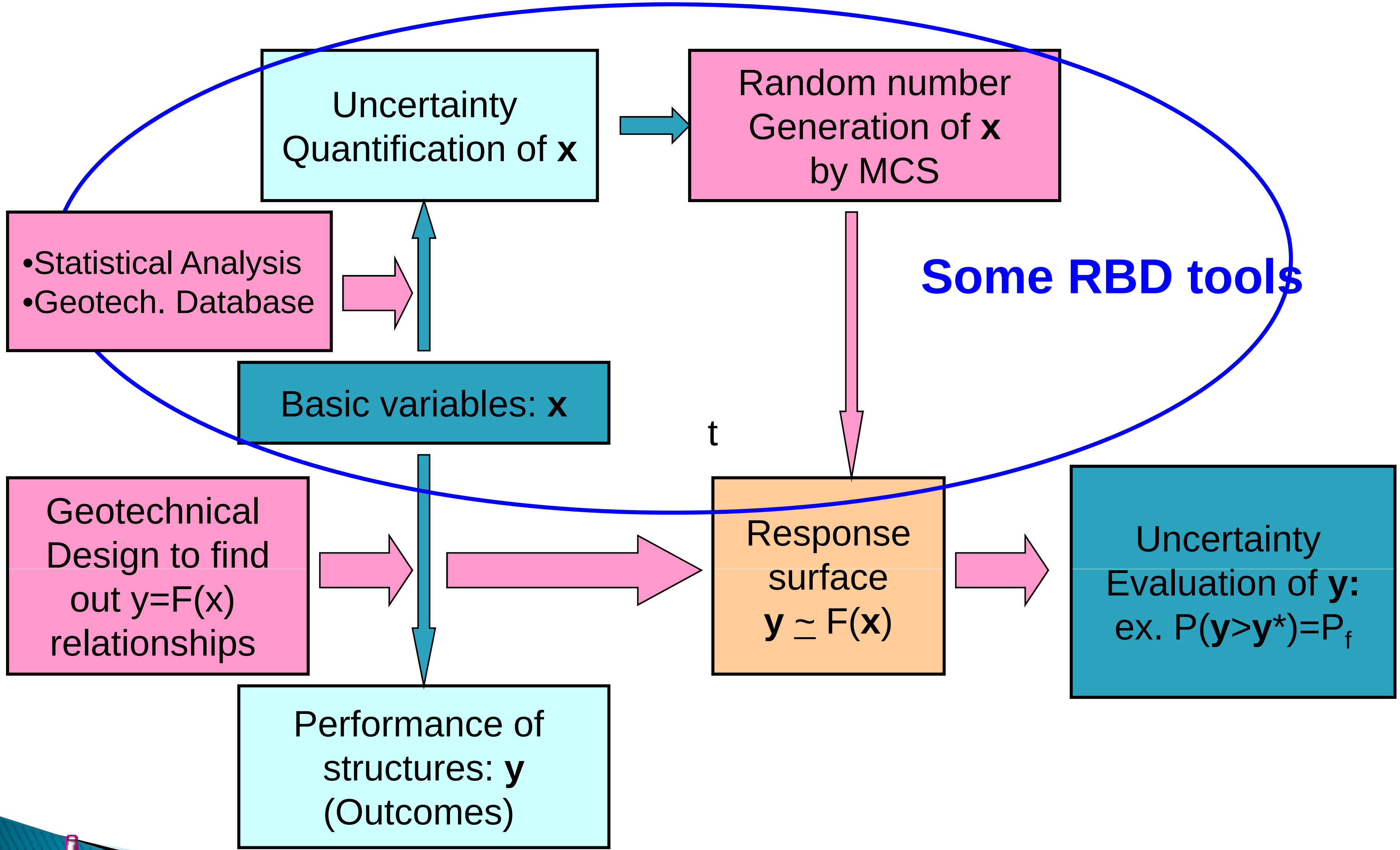
RBD by response surface method



RBD by response surface method



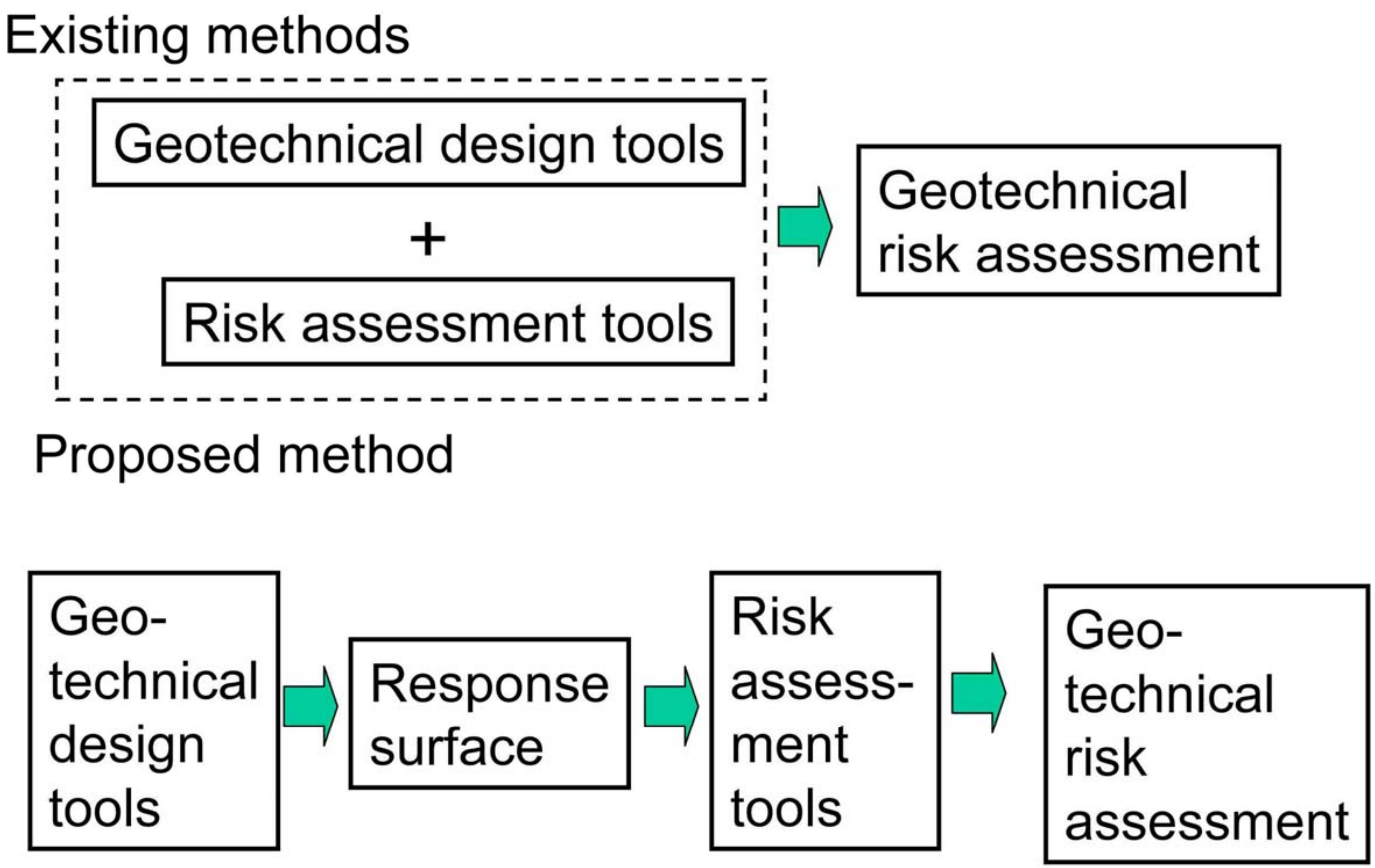
RBD by response surface method



Merits of RSM (response surface method)

1. Release geotechnical engineers from the uncomfortable feelings for RBD tools by separating geotechnical design part and RBD part.
2. Monte Carlo simulation, a very straightforward tool, is only RBD tool employed.
3. The response surface (RS) itself contains considerable amount of useful design information.
4. Direct geotechnical designers to make the most of their knowledge, experiences and engineering judgments in obtaining the RS.

RBD by response surfaces

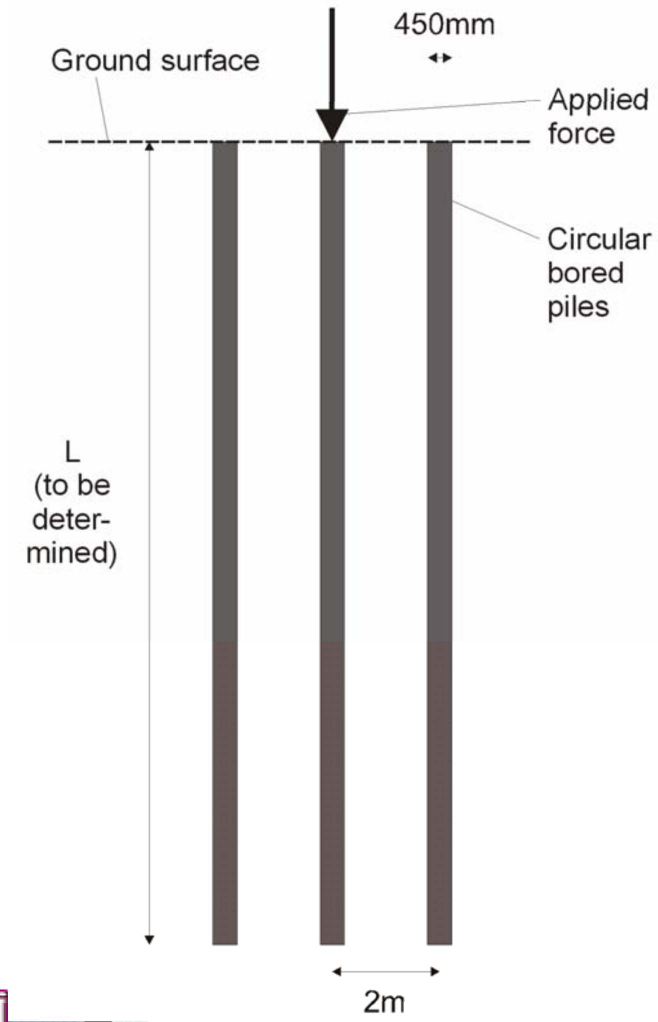



Thank You for Your Attention

References

- Galanbos, T.V. (1992): Design Code, in Engineering Safety, ed. D. Blockley, McGraw-Hill Book Com.
- Mayerhof, G.G.(1992) Development of limit state design, Proc. Int. Sym. on limit state design in geotechnical engineering, vol. 1, pp.1-12.
- Brinch Hansen, J. (1967): The philosophy of foundation design: criteria, safety factors and settlement limits, Bearing Capacity and Settlement of Foundations, ed. A. Vesic, Duke University.

EX 2-6 : PILE FOUNDATION IN SAND



Determine bored pile length *L* (m) (*D* = 0.45 m) spaced 2.0 (m) centres

permanent load = 300 (kN)

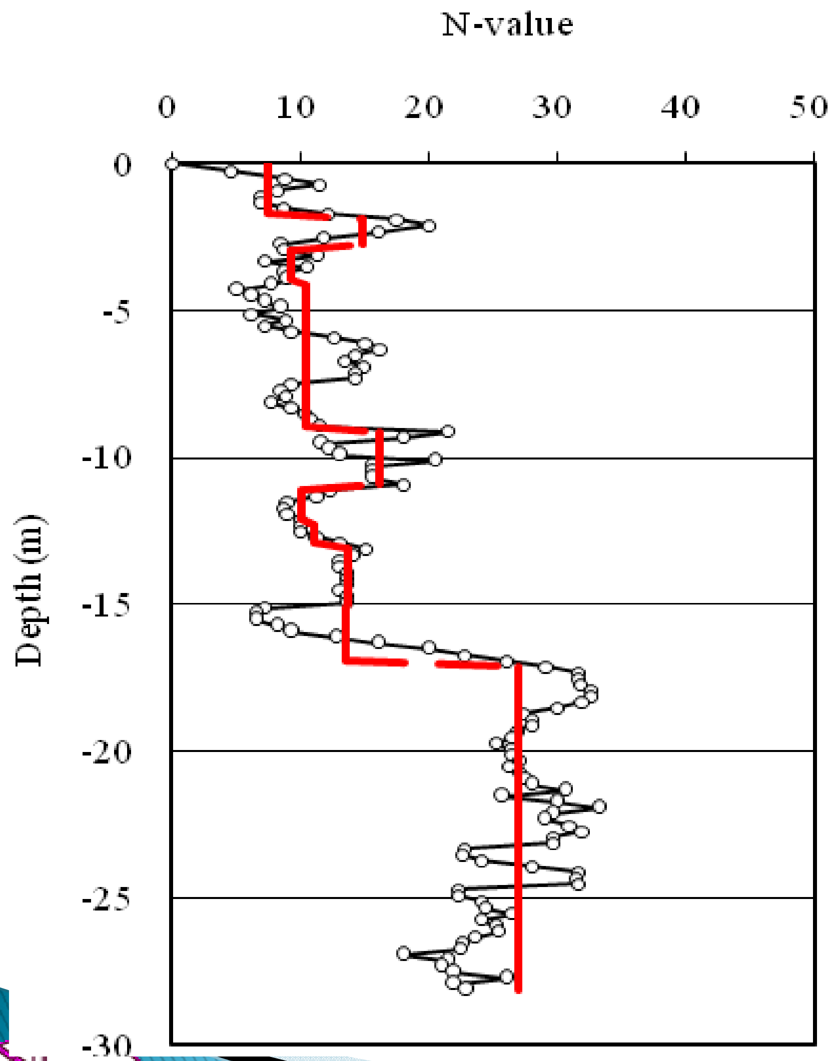
vertical variable load=150 (kN).

Pleistocene fine and medium sand covered by Holocene layers

EX2-6: Mean and SD of converted SPT-N of each layer

layer	Soil description	Depth (m)	Mean (SPT N)	SD (SPT N)
1	Clay with sand seams	0.0 - 1.9	7.5	3.66
2	Fine sand	1.9 - 2.9	14.8	4.58
3	Clay with sand seams	2.9 - 4.0	9.2	1.44
4	Fine silty sand	4.0 - 9.0	10.3	3.22
5	Fine silty sand with clay & peat seams	9.0 - 11.0	16.2	3.31
6	Clay with sand seams	11.0 - 12.3	10.1	1.45
7	Clay with peat seams	12.3 - 13.0	11.1	1.51
8	Clay with peat seams	13.0 - 15.0	13.7	0.54
9	Fine sand	15.0 - 17.0	13.6	7.24
10	Fine sand	17.0 -	27.0	3.71

EX 2-6 : PILE FOUNDATION IN SAND
Transformation of qc to SPT-N



$$\frac{q_c / p_a}{N} = 5.44 D_{50}^{\ 0.26}$$

where
p_a = atmospheric pressure,
D_{50} = 50% grain size of soil.
No bias in the conversion but SD is 1.03.

Kulhawy and Mayne (1990, Fig. 2.30),

EX2-6: Performance function or RS

$$M = U\delta_f \sum_{i=1}^{n} \delta_{ti} f_i(\delta_t N_i)L_i + \delta_{qd} q_a(\delta_t N_n)A_p - \delta_{Gk} G_k - \delta_{Qk} Q_k$$

where,

δ_f : uncertainty of estimating pile shaft resistance, f_i, by SPT-N

δ_{qd} : uncertainty of estimating pile tip resistance, *qd*, by SPT-N

δ_t : uncertainty of transformation from CPT *qc* to SPT-N

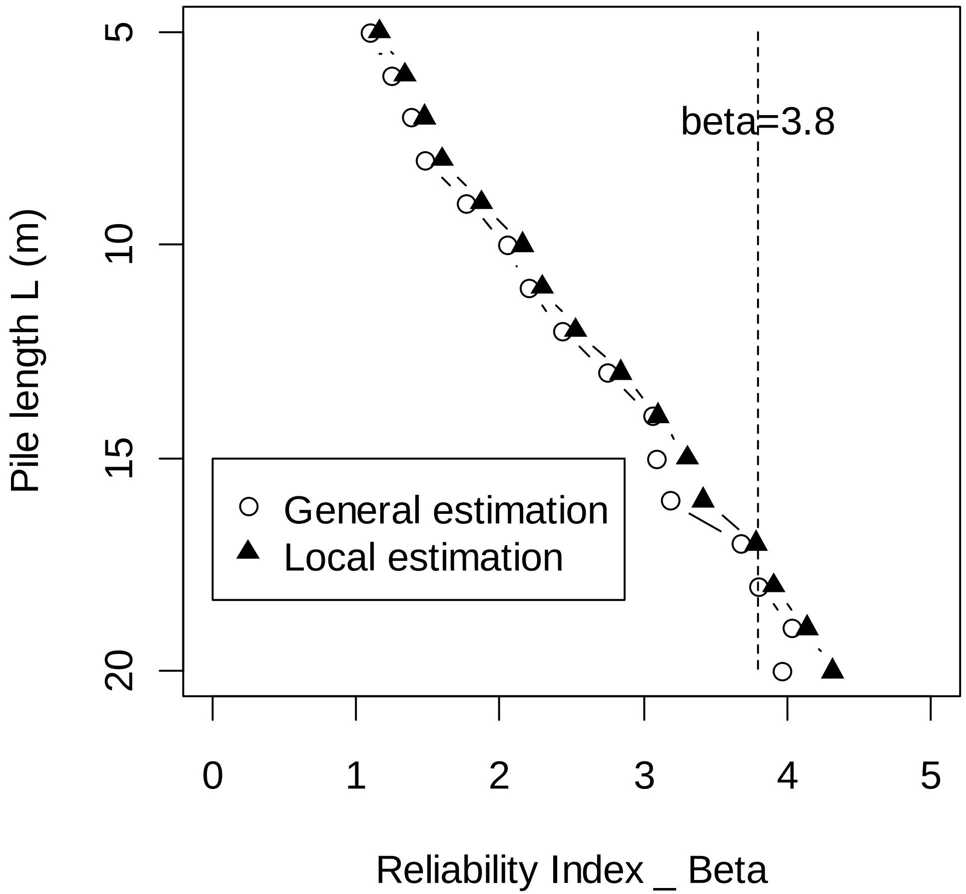
δ_{Gk} : uncertainty on characteristic value of permanent load.

δ_{Qk} : uncertainty of characteristic value of variable load.

EX2-6: Statistical properties of the basic variables

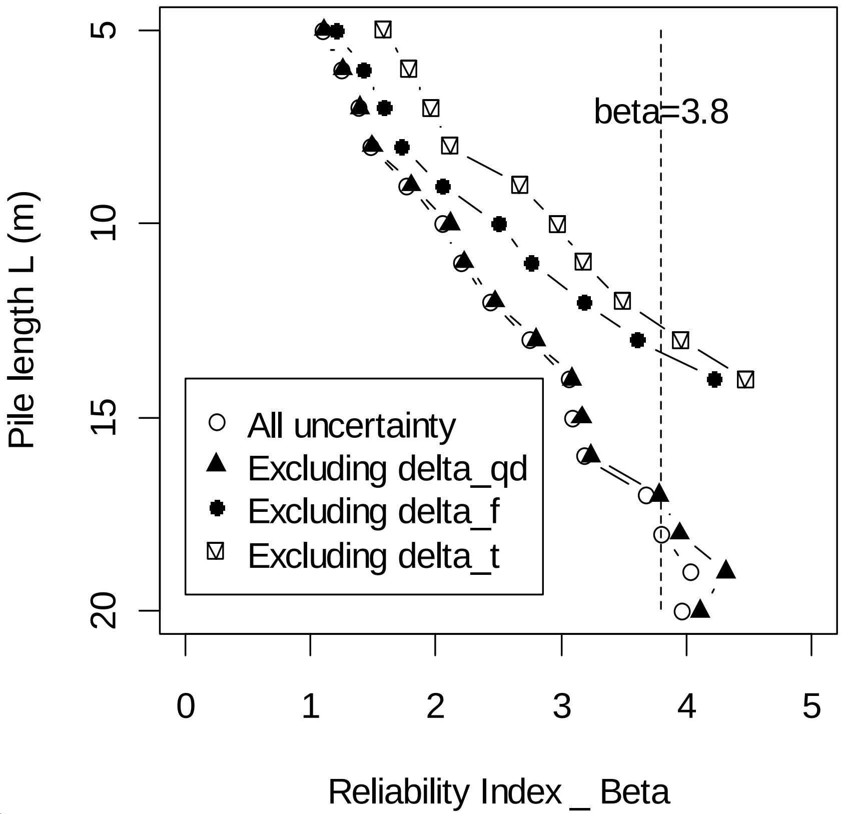
Basic variable	Mean	SD	Distribution	Note
δ_{Gk}	1.0	0.1	N	G_k = 300 (kN) (1)
δ_{Qk}	0.6	0.21	Gumbel	Q_k = 150 (kN) (1)
δ_f	1.07	0.492	LN	Okahara *et.al* (1991)
δ_{qd}	1.12	0.706	LN	Okahara *et.al* (1991)
δ_t	1	1.03	LN	Kulhawy & Mayne (1990)
N1	7.51	3.66	N	unit: SPT N-value
N2	14.80	4.58	N	unit: SPT N-value
N3	9.24	1.44	N	unit: SPT N-value
N4	10.33	3.22	N	unit: SPT N-value
N5	16.17	3.31	N	unit: SPT N-value
N5	10.08	1.45	N	unit: SPT N-value
N7	11.14	1.51	N	unit: SPT N-value
N8	13.68	0.54	N	unit: SPT N-value
N9	13.56	7.24	N	unit: SPT N-value
N10	26.98	3.71	N	unit: SPT N-value

EX 2-6 : PILE FOUNDATION IN SAND – results



pile length of more than 18 (m) is necessary for b=3.8

EX 2-6 : PILE FOUNDATION IN SAND – results



$\beta =$	*2.3*	*3.1*	*3.8*
Consider all uncertainty	11.5	15.0	18.0
Excluding δ_{qd}	11.3	15.0	17.1
Excluding δ_f	9.5	12.0	13.3
Excluding δ_t	8.4	11.0	12.7

Development of LSD – Structural Engineering

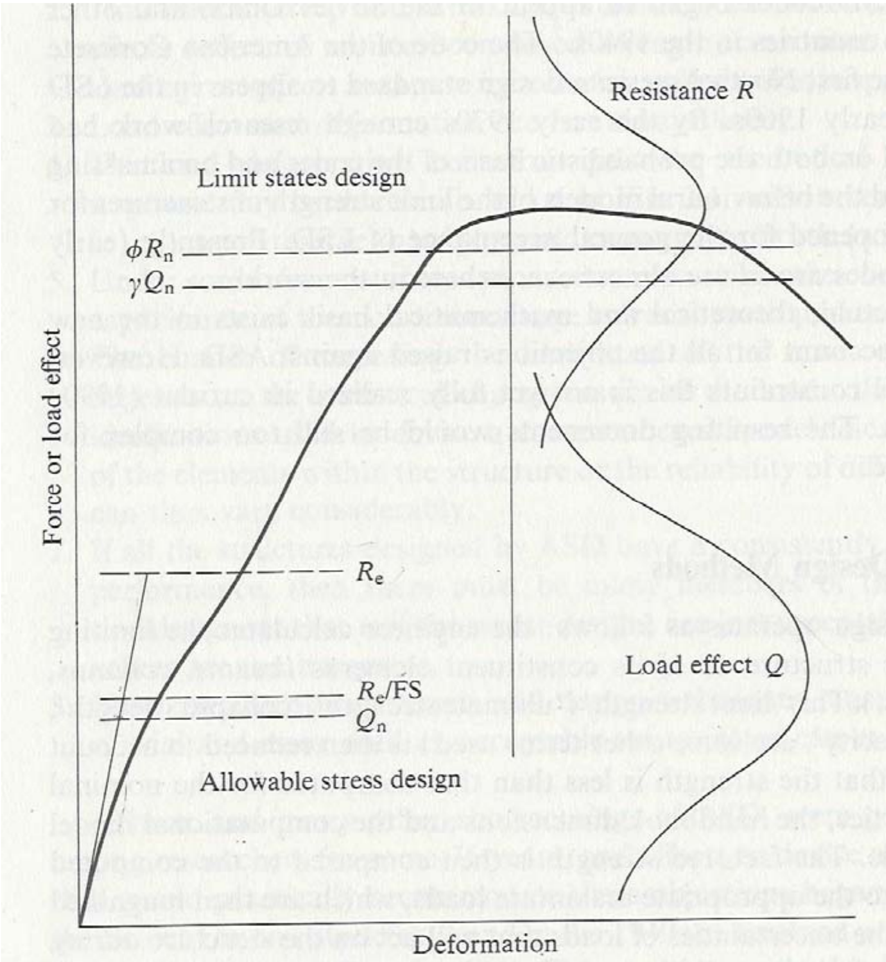


Figure 3.2 Comparison of ASD and LSD methods.

(Galambos, 1992)

19th Century

ASD (Allowable Stress Design)

1920 th

Ultimate Strength Design researches in USSR and Eastern Europe

After World War II

Classic Reliability Based Design

(Freudenthal, 1945 etc.)

LSD (Limit State Design)

FOSM (First Order Second Moment Method) (Cornell、1968)

1970 th

FORM (First Order Reliability Mehtod)

(Ditlevsen, 1973; Hasofer & Lind, 1974etc.)

Development of Structural Eurocodes

(JCSS, Joint Committee on Structural Safety)

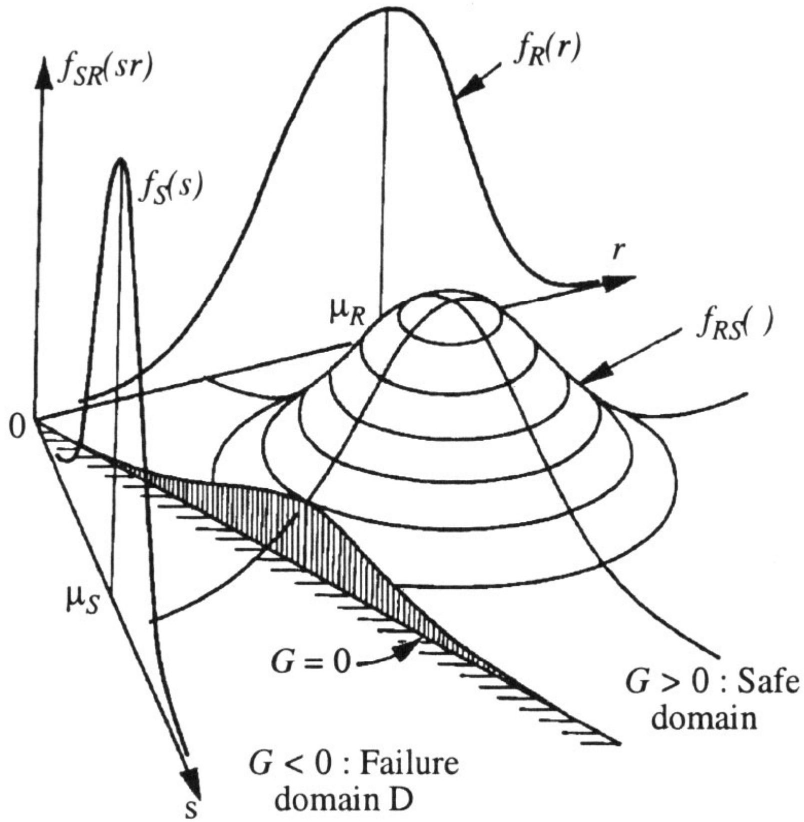
Procedures for different examples

Spatial variability → Transformation error → Load uncertainty → Response surface → Reliability analysis

Transformation error → Spatial variability → Model error → Performance function → Reliability analysis

Spatial variability → Response surface → Model error → Reliability analysis

Level III RBD (reliability based design): Full distribution approach



Failure probability is obtained By integrating portion of the distribution in failure region.

$$P_F = \iint_D f_{RS}(r, s)\,dr\,ds$$