Annex 1 (by K. Lesny):

Model Uncertainty of Bearing Capacity Analysis for Shallow Foundations

The following summary is based on the references given below.

The model uncertainty of ULS bearing capacity analysis has been evaluated on the base of a comprehensive database of load tests on shallow foundations. The database contained 549 cases of load tests compiled from various publications and from own model test data, for details see references below. Table 1 summarized the test data.

Most cases in the database related to foundations subjected to vertical-centric loading in or on granular soils. Tests of foundations subjected to combined loadings (vertical-eccentric, inclined-centric and inclined-eccentric) were mainly small scale model tests performed in *controlled soil conditions* (in laboratories using soils of known particle size and controlled compaction).

Table 1. Summary of model tests in database

Foundation type	Predominant soil type				Total
	Sand	Gravel	Mix	Others	
Plate load tests B ≤ 1m	346	46	2	72	466
Small footings 1 < B ≤ 3m	26	2	4	1	33
Large footings 3 < B ≤ 6m	30	--	1	--	31
Rafts & Mats B > 6m	13	--	5	1	19
Total	415	48	12	74	549

Notes:
"Mix": alternating layers of sand or gravel and clay or silt

"Others": either unknown soil types or other granular materials like loamy Scoria

To define the ULS failure load of each test several failure criteria were examined:

- Minimum Slope failure criterion by Vesic (1975)
- Log-log load-settlement curve method by de Beer (1967)
- Two-slope criterion described in NAVFAC (1986)

For most test results the corresponding load-settlement curves did not show a clear peak, hence interpretation of the failure loads was difficult. In addition, many load tests were not carried out to failure, making them unsuitable for the analysis. This was especially the case for larger foundations for which failure would be associated with very large loads and excessive displacements. It was finally found that the Minimum Slope failure criterion provided the most consistent interpretation when establishing the measured bearing capacity from the load tests.

For establishing the calculated bearing capacity the basic bearing capacity equation by Vesic (1975) was used. Numerous analytical expressions for the different factors (bearing capacity, shape, depth and inclination factors) were analysed to find the most consistent expressions.

Uncertainties of this design method were expressed as bias = ratio of measured over calculated bearing capacity including all sources of uncertainties such as scale effects, variation of soil properties and their interpretation, capacity interpretation etc. Biases were studied according to loading types (vertical-centric, vertical-eccentric, inclined-centric and inclined-eccentric) and soil conditions (natural (field) and controlled (laboratory) soil conditions). Figure 1 shows the biases for vertical-centric loading.

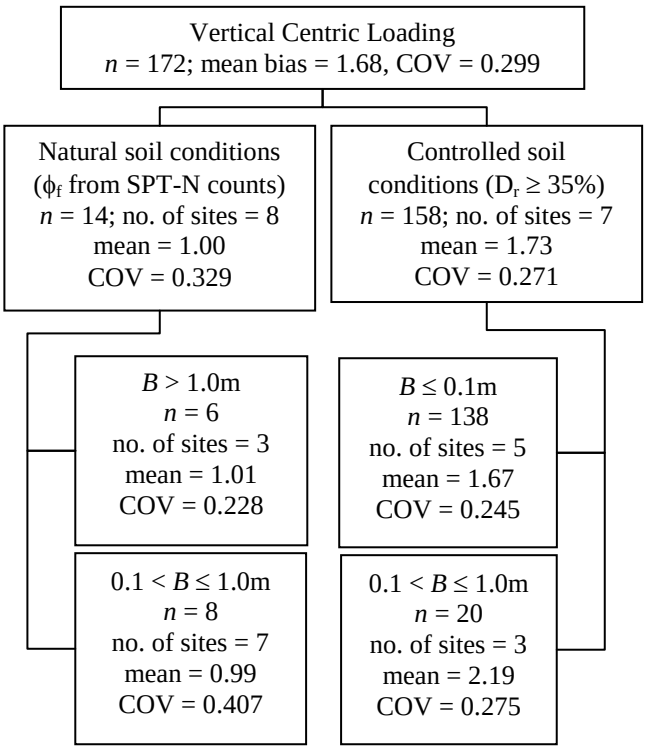

Figure 1. Summary of biases for footings under vertical-centric loading differentiated according to soil conditions and model scale (Paikowsky et al., 2010)

Figure 1 reveals that there might be a relation between the footing size and the bias. Laboratory small scale model tests (very small footings tested in controlled soil conditions, general failure) show a larger bias than larger footings especially in natural conditions where general shear failure is not always reached. However, this is superposed by the test conditions (natural versus controlled soil conditions, i.e. soil variability, measurement errors etc.), so the differences in the bias cannot only be attributed to scale effects.

For vertical-eccentric loading cases, the bias had a mean of 1.81 and COV of 0.349. For inclined-centric loading cases, the bias had a mean of 1.43 and COV of 0.295. Inclined-eccentric loading cases were distinguished into positive or reversible and negative moment, which also affect the bias (positive moment: mean = 1.41, COV = 0.278, negative moment: mean = 2.03, COV = 0.094).

Results show the conservatism in the design method, the influence of site (soil conditions), some influence of the model scale and a very strong influence of the loading situation.

Based on the statistical parameters for the bias in different design situations, different resistance factors for different loading conditions were calibrated for a target reliability of $\beta_T = 3.0$ and lognormal distributions for loads and resistance from FOSM and MC simulations.

References:

Lesny, K.; Paikowsky, S. G. (2011): Developing a LRFD procedure for shallow foundations; Proceedings of the 3rd International Symposium on Geotechnical Safety and Risk, ISGSR 2011, eds. N. Vogt, B. Schuppener, D. Straub, G. Bräu, pp. 47-65, Federal Waterways Engineering and Research Institute, Karlsruhe

Paikowsky, S. G.; Canniff, M. C.; Lesny, K.; Kisse, A.; Amatya, S; Muganga, R. (2010): LRFD design and construction of shallow foundations for highway bridge structures; NCHRP Report 651, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

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