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PROBABILISTIC ANALYSIS OF THE BUILDING FOUNDATION PLATES CONSIDERING THE SSI EFFECTS

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Abstract: *This paper presents the results of the probabilistic and sensitivity analysis of the safety of the building foundation plate considering the variability of the soil stiffness, structure geometry, permanent and variable masses. The advantages and disadvantages of the deterministic and probabilistic analysis of the foundation plate resistance are discussed. The sensitivity analysis of the foundations to the variability of the soil properties provides the important information for designers. The affectivity of the probabilistic design methodology is presented on the example of building foundation plate with various structural system. The response surface method (RSM) for the analysis of the foundation plate reliability was used in program ANSYS. The probabilistic analysis gives us more complex information about the soil-foundation-structure interaction as the deterministic analysis.*

Keywords: Soil-Structure Interaction, Foundation plate, Probability, Sensitivity, RSM, ANSYS.

1. Introduction

Recent advances and the general accessibility of information technologies and computing techniques give rise to assumptions concerning the wider use of the probabilistic assessment of the reliability of structures using simulation methods (Baecher, 2003, Čajka, 2014, Janas, 2006, Keršner, 2006, Králik, 2006, 2009, Krejsa, 2016, Sýkora, 2013). Much attention should be paid to using the probabilistic approach in an analysis of the reliability of structures (Rosovský, 1995, Baecher, 2003, Čajka, 2014, Handbook 2, 2005, Králik, 2009).

The deterministic definition of the reliability condition has the form

$$R_d \geq E_d \tag{1}$$

and in the case of the probabilistic approach, it has the form

$$RF = R - E \geq 0 \tag{2}$$

where *RF* is the reliability function, which can be expressed generally as a function of the stochastic parameters X_1, X_2 to X_n, used in the calculation of *R* and *E*.

$$RF = g(X_1, X_2, ..., X_n) \tag{3}$$

The probability of failure is defined as best estimation of the numerical simulations in the form

$$p_f = \frac{1}{N}\sum_{i=1}^{N} I\left[g\left(X_i\right) \leq 0 \right] \tag{4}$$

where *N* is the simulation number, *g*(.) is the failure function, *I*[.] is the function with value 1, if the condition in the square bracket is fulfilled, otherwise is equal to 0.

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2. Building structural models with foundation plate

The resistance of the foundation plates of high-rise buildings were investigated using the deterministic and probabilistic analyses. The considered building are 20 storey overground and 3 storey underground with storey height of 3m. The three types of the high-rise building were considered. First model “D1” consists of two cores and columns system, the foundation plate with dimension 21x36m and 1.5m thickness. Second model “D2” consists of two central cores and columns system, the foundation plate dimension is 21x30m.

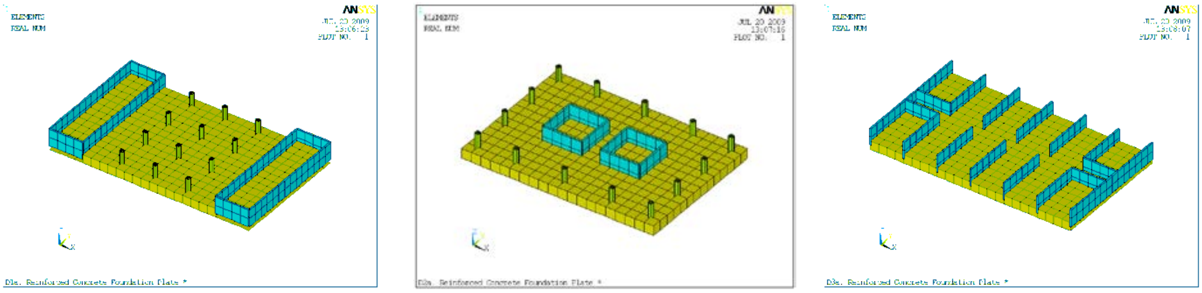

Fig. 1: Calculation models of foundation plate – D1, D2 and D3.

All columns in these buildings are 600/600mm in cross-section. The thickness of floor reinforced concrete plate is 220mm. All floor slabs have a permanent load of 0.5kN/m^2 and variable load of 2.0kN/m^2. The material properties of this concrete building are Young’s modulus, E = 30GPa and Poisson’s ratio μ = 0.2. The walls and foundation plate were modeled in software ANSYS using shell elements SHELL181, the Winkler subsoil by element SURFACE154 and the solid subsoil by element SOLID45. There are 544 shell, 13260 solid and 416 surface elements.

3. Layered subsoil model

The consideration of SSI effects is very important during the design process of the high-rise building (Králik, 2006). The influence of the variability of the soil stiffness characteristic to the structure are not negligible (Baecher, 2003, Kotrasová, 2015, Králik, 2009, Melcer, 2016, Sucharda, 2018).

Tab. 1: The mechanical characteristic of the layered subsoil.

	Original subsoil							*Strengthened subsoil*					
Point	Soil	h_i	γ	E_{def}	ν	c_{ef}	φ_{ef}	Soil	γ	E_{def}	ν	c_{ef}	φ_{ef}
	typ	[m]	[kNm^{-3}]	[kPa]	-	[kPa]	[deg]	typ	[kNm^{-3}]	[kPa]	-	[kPa]	[deg]
1	G2	2,7	20	15330	0.43	0	31	G2+	23	75735	0.20	10	31
2	CH	3.5	19	17810	0.42	10	16	CH+	23	33747	0.42	10	16
3	ML	1.0	23	12728	0.46	18	25	Soilcret	25	900000	0.20	80	20
4	ML	2.8	19	11142	0.30	18	22	Soilcret	25	900000	0.20	80	20
5	SC	9.5	19	10266	0.40	10	28	SC	19	10266	0.40	10	28
6	CH	4.5	19	18692	0.35	10	16	CH	19	18692	0.35	10	16
7	SC	4.0	19	14953	0.35	10	28	SC	19	14953	0.35	10	28
8	CH	1.0	19	19938	0.35	10	16	CH	19	19938	0.35	10	16
9	SC	5.0	19	16200	0.35	10	28	SC	19	16200	0.35	10	28

The subsoil was considered as the layered medium typical to the environs of the City Bratislava (Table 1). The stiffness of the original subsoil is poor for the foundation of the high-rise buildings usually. The system KELLER propose the effective technology [Králik, 2006] of the soil upgrading (Table 1). The subsoil can be modeled by 3D FEM model or simple 1D Winkler model.

4. Loading and Load Combination

The loading and load combination in the case of the deterministic as well as the probability calculation is different due to requirements of Eurocode 1990 (Handbook 2, 2005) and JCSS 2000 (JCSS, 2001), too. In the case of deterministic and probabilistic calculation of the structure the load combination is considered according to ENV 1990 as follows:

➲ ***Fundamental combination – deterministic method***

$$E_d = \gamma_g G_k + \gamma_q Q_k + \gamma_s \psi_{os} S_k \tag{5}$$

where G_k is the characteristic value of the permanent loads, Q_k - the characteristic value of the variable loading, S_k - the characteristic value of the snow loading, ψ_{os} - the combination factor according to ENV 1990 (ψ_{os} = 0.6). The load factors γ_g, γ_q, and γ_s are considered for the ultimate limit state (γ_g = 1.35; γ_q = 1.5; γ_s = 1.5) and serviceability limit state (γ_g = 1.0; γ_q = 1.0; γ_s = 1.0) in accordance with requirements of ENV 1990.

➲ ***Fundamental combination– probabilistic method***

$$E = G + Q + S = g_{var} G_m + q_{var} Q_m + s_{var} S_m \tag{6}$$

where G_m is the mean value of the permanent loads, Q_m - the mean value of the variable loading, S_m - the mean value of the snow loading, g_{var}, q_{var}, s_{var} are the variable parameters defined in the form of the histogram calibrated to the load combination in compliance with Eurocode.

5. Uncertainties of Input Variables

The random distribution of the input variables is considered on the base of the requirements ENV 1990. These values are calibrated to the ultimate limited state.

Tab. 2: Probabilistic model of input parameters.

Name	Quantity	Mean value	Variable paramet.	Histogram	Mean	Stand. deviation	Min. value	Max. value
Soil	Layer stiffness	$k_{i,m}$	k_{i_var}	Normal	1.00	0.300	0.574	1.433
Material	Young's modul.	E_m	$e_{\_var}$	Normal	1.00	0.100	0.526	1.407
Action	Permanent	G_m	$g_{\_var}$	Normal	1.00	0.100	0.526	1.407
	Variable	Q_{m1}	$q_{\_var}$	Gama	0.60	0.350	0.005	4.073
	Snow	S_m	$s_{\_var}$	Gama	0.35	0.245	0.003	1.953
Model	Action uncertaint	θ_E	$e_{\_var}$	Normal	1.00	0.100	0.526	1.407
	Resist. uncertaint	θ_R	$r_{\_var}$	Normal	1.00	0.100	0.526	1.407

6. Criteria of safety and reliability of the building foundation

Reliability of the bearing structures is designed in accordance of standard requirements ENV 1992 for ultimate and serviceability limit state. The foundation reinforced concrete plate is designed on the bending and shear loads for ultimate limit state function as follow (Králik, 2009)

$$g(M) = 1 - M_E / M_R \geq 0, \qquad g(V) = 1 - V_E / V_R \geq 0 \tag{7}$$

where M_E, V_E are design bending moment and design shear force of the action and M_R, V_R are resistance bending moment and resistance shear force of the structure element.

The settlement w_E of the building is determined by the limit settlement w_R in the form (Králik, 2009)

$$g(w) = 1 - w_E / w_R \geq 0 \tag{8}$$

where w_E is the vertical displacement, w_R is the limit value of building settlement (w_R = 120mm).

7. Comparison of deterministic and probabilistic analyses

Probabilistic and deterministic calculation of the resistance of the foundation plate for three types of wall and columns configuration was realized on the models *D*1, *D*2 and *D*3 (see tab. 3). The comparison of the deterministic and probabilistic analyses on the same soil model D3 (Table 4) show us that the maximal difference between the 95% quantile and mean deterministic value of the output quantity is equal 83% of the settlement in the model D3, 7% of the bending moment in the model D2, 13% of the shear forces in model D1. The scatter of the values of the internal forces from the deterministic and probabilistic analysis on the same soil model is lower as the difference between various soil models. The probabilistic results give us the less conservative values than the deterministic analysis.

Tab. 3: Comparison of the deterministic and probabilistic analyses.

Model		w_{max} [mm]			M_{max} [kNm]			V_{max} [kN]		
		5%	50%	95%	5%	50%	95%	5%	50%	95%
D1	D	-	-	-115.48	-	-	262.67	-	-	767.73
	P	-66.41	-86.24	-111.18	191.23	228.16	265.89	453.57	554.16	668.88
D2	D	-	-	-118.461	-	-	163.436			609.791
	P	-71.7262	-90.6528	-114.422	107.814	129.283	151.942	371.049	449.407	535.619
D3	D	-	-	-102.85	-	-	285.51	-	-	543.16
	P	-70.224	-80.6565	-99.3563	158.4675	189.21	220.65	255.885	308.625	365.67

Note: D = deterministic, P = probabilistic analysis; kvantil for 5 and 95% probability to no exceedance.

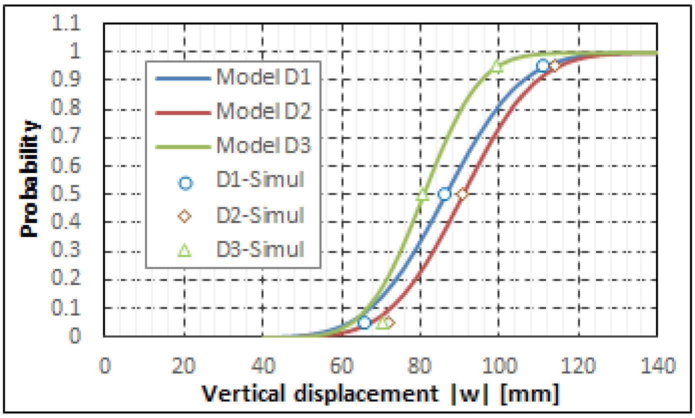

Fig. 2: Fragility curve of foundation plate.

8. Conclusions

This paper presented the results of the probabilistic and sensitivity analysis of the safety of the foundation plate considering the variability of the soil stiffness, structure geometry, permanent and variable masses. The advantages and disadvantages of the deterministic and probabilistic analysis of the foundation plate resistance were analyzed [9]. On the example of three type of the high rise buildings the affectivity of the probabilistic design methodology was presented. The approximation method RSM of simulation for the analysis of the foundation plate reliability was used on program ANSYS. The comparison of the deterministic and probabilistic analyses on the same soil model D3c show us that the maximal difference between the 95% quantile and mean deterministic values of the internal forces are minor as 13%. The scatter of the output quantities between Winkler simple model and solid soil model is higher than the differences between the deterministic and probabilistic analysis in the same soil model. The probabilistic analysis gives us more complex information about the soil-structure interaction than the deterministic analysis [9].

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