# Different models of soil-structure interaction and consequent reliability of foundation structure

Radim Čajka

*Department of Building Structures, VSB – Technical University, 708 33 Ostrava, Czech Republic, radim.cajka@vsb.cz*

**Abstract:** In the calculation of structural reliability often variation of material characteristics and action effect is considered. The accuracy of reliability assessment depends on how precisely it is possible to grasp statistical concepts of material characteristics and action effect. In this paper author would like to discuss the fact that concerning foundation structures the highest variation in reliability assessment is not caused with material characteristics or load effect but in the model of soil-structure interaction itself. Above mentioned problem is demonstrated in the example of strip foundation / foundation slab.

**Keywords:** foundation structures, interaction models, FEM, elastic half space

## 1. Introduction

In buildings, the foundation structures are required to transfer all load components from the upper construction onto subsoil. Typically, attention is paid to the transfer of the vertical load components which is applied in the direction of Earth's attraction. The interaction between various types of environment has been discussed for several years. In order to define the state of stress more precisely, in particular that of foundation structures, it is essential to define, on one hand, how rigidity of the foundation structure influences the settling process and, on the other hand, how rigidity or elasticity of subsoil influences internal forces within constructions. First works about this topic include those written by Gorbunov-Posadov, Winkler and Pasternak (Cajka, 2008).

Application of numerical methods in practice started upon launch of computers. A general variational method for analysis of building constructions – Finite Element Method (FEM) – has been developed in detail by now. Several scientists were dealing with a surface model, the best known being a multi-parameter model of subsoil processed by (Kolář and Němec, 1989). Authors dealing with the state of stress in subsoil caused by vertical and horizontal forces include (Poulos and Davis, 1974). The other theory of soil–structure interaction and subsoil–foundation contact tasks were investigated (Abdel Rahman and Edil, 1991; Qian and Zhang, 1993; Reitinger and Svejda, 1998; Provenzano, 2003; Katzenbach, Schmitt and Turek, 2005; Cajka, 2003, 2005; Cajka and Manasek, 2005; Souli and Shahrour, 2012).

## 2. Foundation slab with stiff walls

Pregnancy of various models and stiffness of foundation in the foundation–subsoil interaction system was solved by the authors software in the example below taken from (Reitinger and Svejda, 1998). The software

5th International Conference on Reliable Engineering Computing (REC 2012)
Edited by M. Vořechovský, V. Sadílek, S. Seitl, V. Veselý, R. L. Muhanna and R. L. Mullen

ISBN 978-80-214-4507-9. Published by Ing. Vladislav Pokorný − LITERA

MKPINTER (Cajka, 2010) is based on FEM with thick slab theory (Mindlin, 1951), numerical integration (Davis and Rabinowitz, 1956) and nonlinear elastic half-space modified by means of the structural strength of the soil (Cajka, 2003, 2005, 2008).

Let us assume a foundation slab on subsoil. The slab is reinforced longitudinally with stiff walls. The subsoil is modelled by means of 3D FEM as a linearly elastic half-space. But non-linearity is not taken into account and the structural strength is not modified.

Dimensions and loading data are evident from Fig. 1 which was taken from (Reitinger and Svejda, 1998). But there is a correction in the Poisson's ratio for concrete and clayey subsoil which were evidently confused with each other. Results of the published solution are in Fig. 2.

The published example (Reitinger and Svejda, 1998) deals, for purposes of comparison, with an interaction task where a slab is located on a half-space and on Winkler's subsoil. The modulus of subsoil, $k = 1250$ kN·m$^{-3}$, was chosen in such a way so that subsidence in the defined *A* point could be same for the both models.

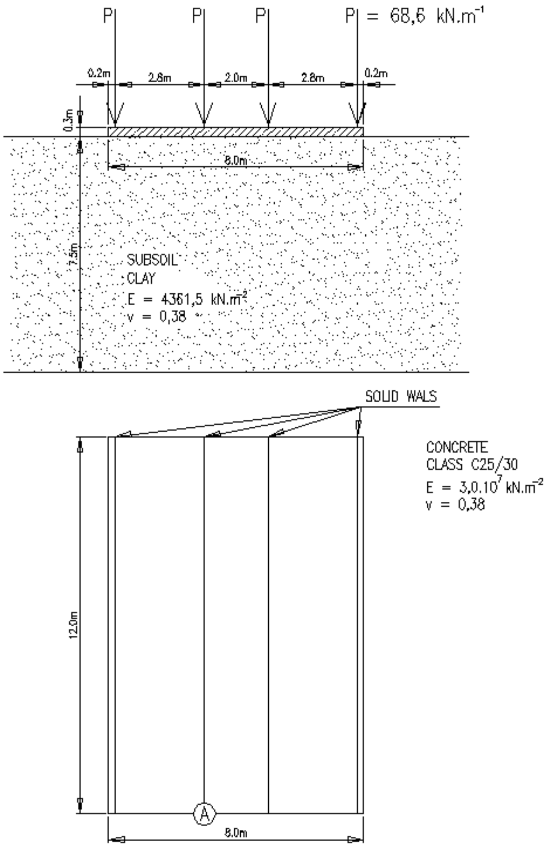


*Figure 1*. Foundation slab with longitudinal walls

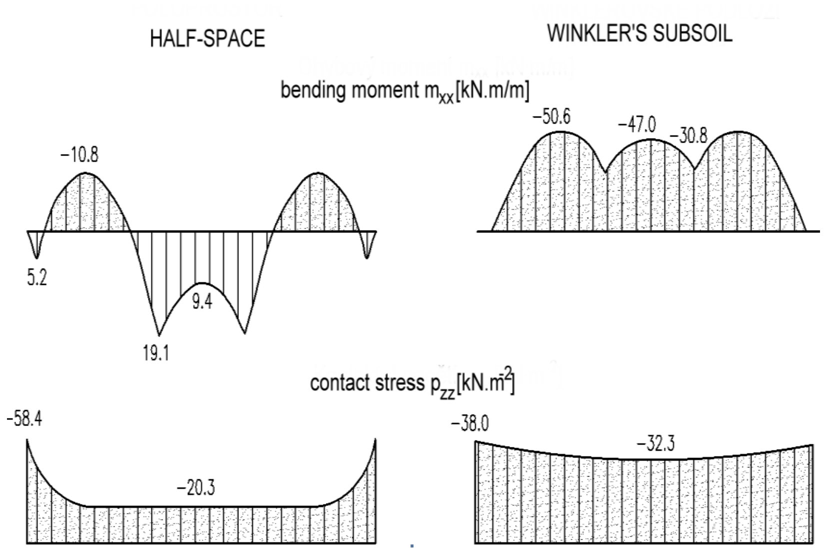


*Figure 2*. Internal forces in the transversal direction obtained by solution of a slab in a subsoil model with 3D elements and in a Winkler's subsoil model according to 1

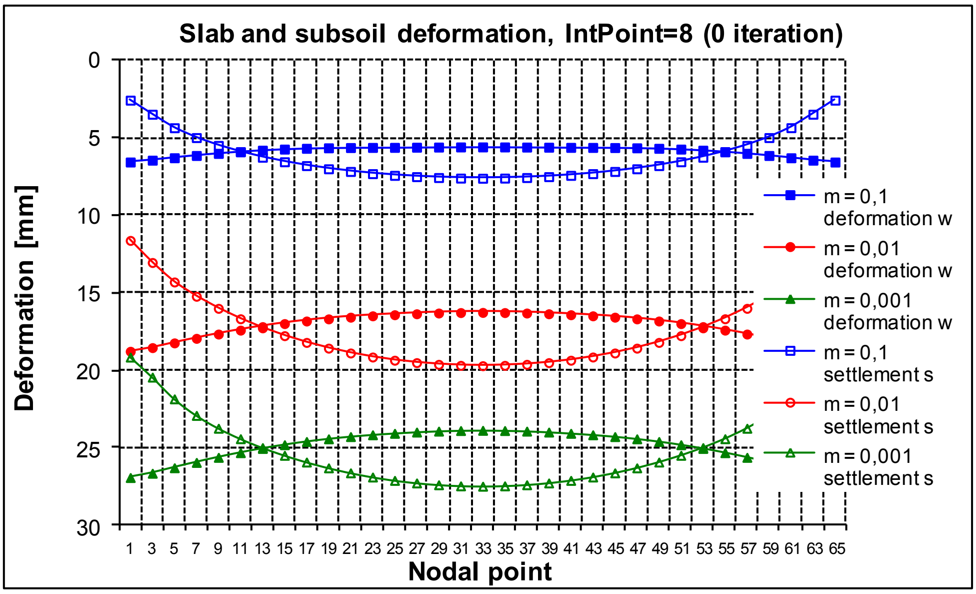


*Figure 3*. Deformation of the slab and settlement of subsoil vs. structural strength of the soil in subsoil of a contact element – without iterations

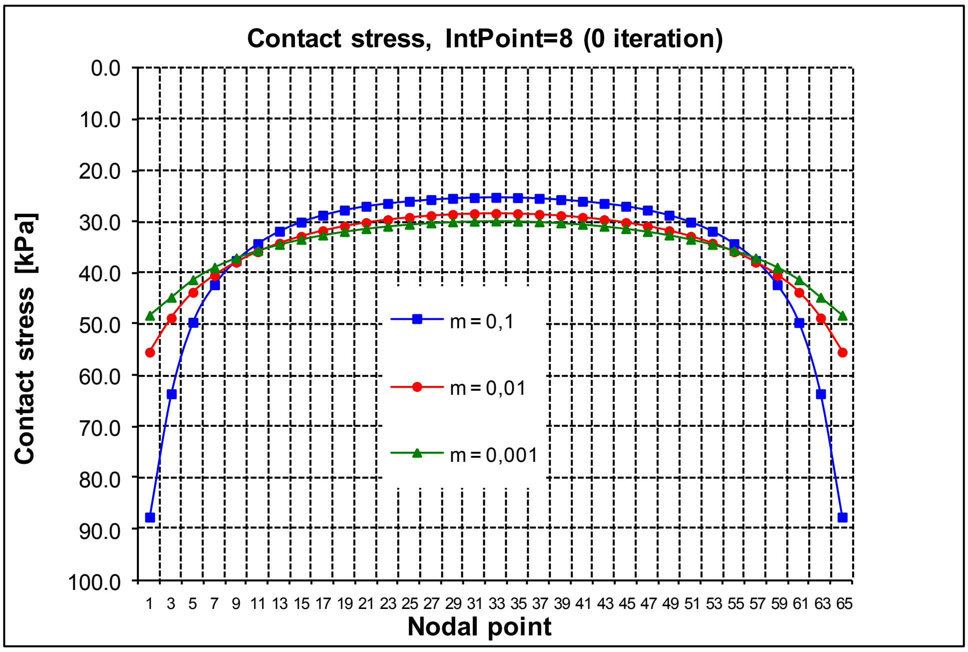


*Figure 4*. Contact stress vs. structural strength of the soil in subsoil and depth of the deformation zone if a contact element is used – without iterations

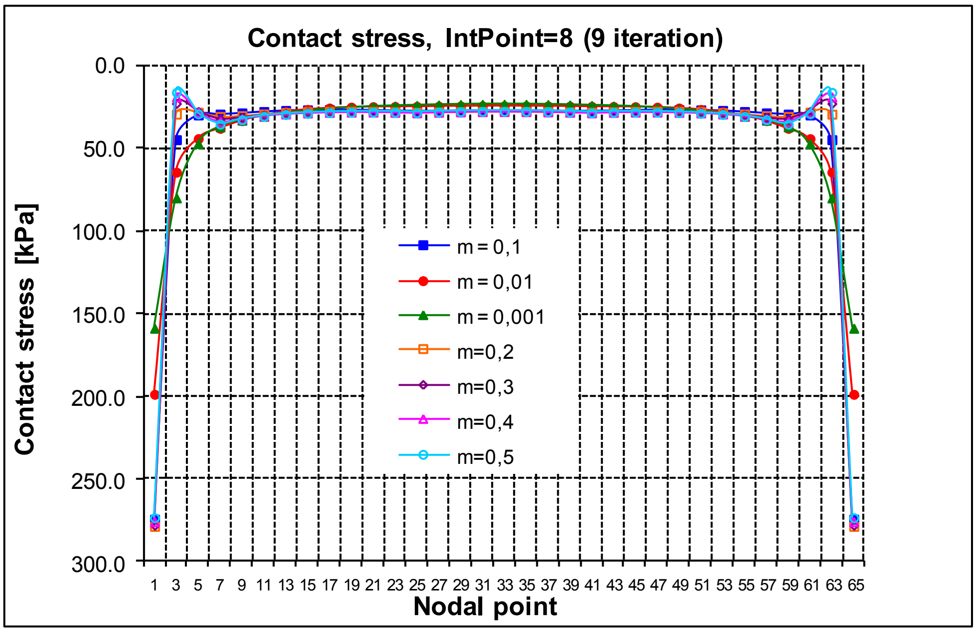


*Figure 5*. Contact stress vs. structural strength of the soil in subsoil and depth of the deformation zone if a contact element is used – 9$^{th}$ iteration

The same example can be used for an iteration task consisting in a slab on an elastic half-space which is modified by means of the structural strength of the soil pursuant to ČSN 73 1001, CSN EN 1997-1 and CSN EN 1992-1-1.

A typical representative of the mentioned parameters of the subsoil is clayey soil, F4 class, with solid consistence. The reference value of the modulus of plasticity is $E_{def} = 4 - 6$ MPa. Poisson's ratio is $\nu = 0.35$, volumetric weight is $\nu = 18{,}5\ \mathrm{kN \cdot m^{-3}}$ and the coefficient of structural strength of the soil in subsoil is $m = 0.2$. The calculation was also carried out for other coefficients − $m = 0.1$; 0.3; 0.4 and 0.5 − which model various rigidities of the subsoil. The coefficient which approaches zero for $m = 0.01$ and 0.001 model *the subsoil of a standard linear elastic half-space.*

*If the deformation and state of stress in soil environment are modelled by means of 3D finite elements and if a sufficiently big domain is chosen, the results should be same as those calculated from explicitly derived relations.*

The solution to a 3D task of a linear elastic half-space is among few tasks which have been derived from general equations of the theory of elasticity and fulfil all conditions applicable to solutions in a closed shape.

*Thus, the Finite Element Methods as well as the approximate numerical method should have, or at least should converge to, same results for the task if the 3D element should be regarded as a correctly derived element.* If the domain of the 3D subsoil (or 3D subsoil, in case of a planar task) is made smaller the results are different for 3D FEM elements because the domain and, in particular, the depth of the domain are chosen by estimates. This situation indicates well presence of non-compressible subsoil (such as rock) which corresponds to the specified zero deformations on the lower edge of the area. In other cases, the scope of the domain should be determined by calculations.

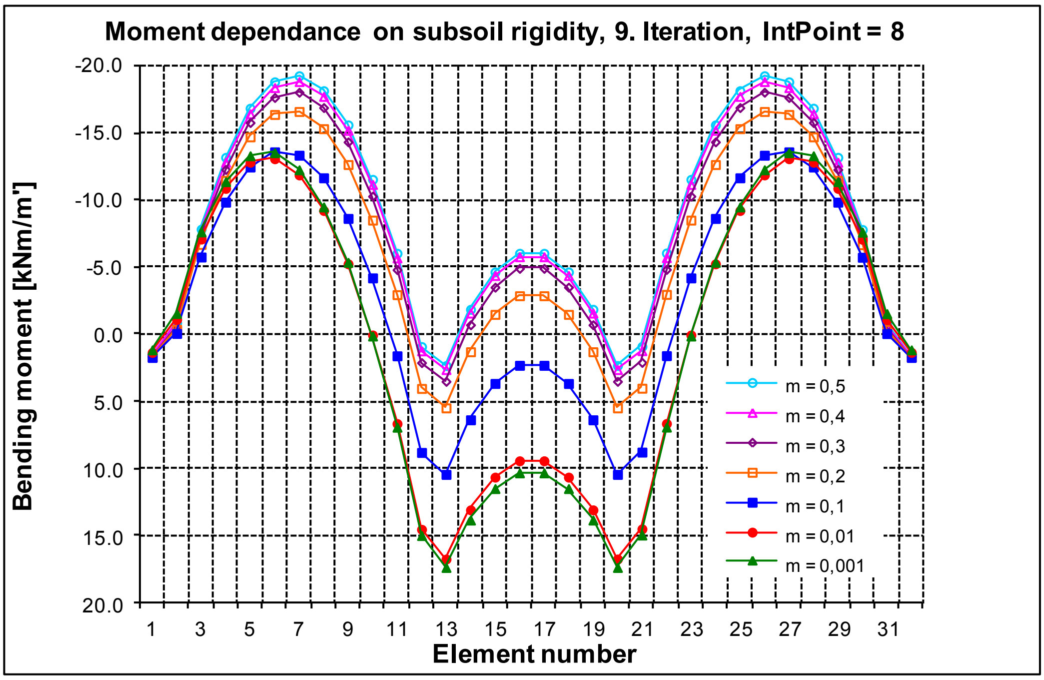


*Figure 6.* Transversal moment vs. structural strength of the soil in subsoil and depth of the deformation zone if a contact element is used

Results of the FEM interaction method are clear from Fig. 3 to Fig. 6 where development of the subsoil settlement and deflection of the slab is plotted for calculations without iteration ($0^{th}$ iteration step). The figures also show development of the contact stress for the initial ($0^{th}$ iteration) iteration and for the last iteration step ($9^{th}$ iteration) and development of bending moment in a slab for various rigidities of the subsoil. *The used contact element (Cajka, 2003, 2005, 2008) satisfies non-linear deformation properties of subsoil pursuant to ČSN 73 1001 and European Standards CSN EN 1997-1 and CSN EN 1992-1-1. Solution results achieved with the structural strength coefficient being close to zero (m = 0.01 through m = 0.001) correspond to a big deformation zone. The solution with non-real settlement and moments converges towards results of iteration of a slab on a linear elastic half-space (without influence of structural strength of the soil) and, in turn, towards the solution achieved if FEM 3D elements are used in line with (Reitinger and Svejda, 1998).*

## 3. Convergence towards the exact solution

As it follows from general formulation of FEM, theory of integral computations and accuracy of numerical integrations (Davis and Rabinowitz, 1956), *two key factors affect the convergences towards the theoretically exact solution of the stress and deformation in the foundation- subsoil model (Cajka, 2008):*

- division of the construction into finite elements, the applied slab theory and the degree of the approximation polynomial of the element (the convergence of the slab),
- approximation accuracy of development of the subsoil settlement and stress which is influenced by the number of Gaussian integration points. The number of the Gaussian integration points determines the degree of a polynomial which approximates development of stress in a linearly elastic half-space (the convergence of subsoil).

The convergence of a slab element towards the exact solution has been verified for a freely supported slab without any subsoil. An even continuous load and a single load in the centre of the slab were considered. It follows from the comparison of the results with the exact solution from the literature that the solution converges in accordance with the FEM theory.

*Accuracy of the numerical integration in calculations of the stress and settlement of the half-space was tested in reference examples which were confronted to data available in the literature. Comparison calculations indicate that an acceptable technical accuracy is reached when 6 integration points are used.*

Because development of the contact stress influences deformation of both the slab and subsoil, it is clear that the division of the construction into finite elements affects directly description of the contact stress development in the subsoil. The more finite elements are used, the more accurate is the contact stress.

In each iteration step, it is possible to check vertical balance as a difference in the sum of the load and the resulting force (the integral) of the contact stress. The more iteration steps are used, the lesser is the difference.

The fineness of the FEM network division influences also calculations of the stress and settlement of the half-space because the network divides the domain of the loaded half-space which is being integrated into partial sub-domains where the individual increases in stress caused by the elements should be added up. *The more elements are available, the less integration points are needed for the same accuracy (Cajka, 2008). From the mathematical point of view, this finding results also from the characteristics of the composite integration formulae in integration of partial intervals and FEM convergence.* New possibilities of FEM solution and decreasing the time for solvers and integration procedures offer the methods of parallel programming (Konečný, Brožovský and Křivý, 2010).

## Acknowledgements

This outcome has been achieved with the financial support of the Ministry of Industry and Trade of the Czech Republic, program TIP, project No. FR-TI2/746 Rheological sliding joint with thermo-controlled viscoelastic properties.

## References

ČSN 73 1001 Zakládání staveb. Základová půda pod plošnými základy. Foundation of structures. Subsoil under shallow foundations. 8/1988, Z1 9/2009, zrušena 04/2010

ČSN EN 1997-1 (73 1000) Eurokód 7: Navrhování geotechnických konstrukcí - Část 1: Obecná pravidla. Eurocode 7: Geotechnical design - Part 1: General rules, ČNI 9/2006

ČSN EN 1992-1-1 (73 1201) Eurokód 2: Navrhování betonových konstrukcí - Část 1-1: Obecná pravidla a pravidla pro pozemní stavby. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings ČNI 11/2006

Abdel-Rahman, M. A. and Edil, T. B. (1991), An Integration Algorithm for Constitutive Models with Two Intersecting Yield Surfaces. Computer-Aided Civil and Infrastructure Engineering, 6: 99–108. doi: 10.1111/j.1467-8667.1991.tb00180.x

Qian, L. and Zhang, H. (1993), An improved Non-reflecting Boundary Method for Soil-Structure Interaction Analysis. Computer-Aided Civil and Infrastructure Engineering, 8: 291–297. doi: 10.1111/j.1467-8667.1993.tb00214.x

Provenzano, P. (2003), A Fuzzy-Neural Network Method for Modeling Uncertainties in Soil-Structure Interaction Problems. Computer-Aided Civil and Infrastructure Engineering, 18: 391–411. doi: 10.1111/1467-8667.00326

Katzenbach, R., Schmitt, A. and Turek, J. (2005), Assessing Settlement of High-Rise Structures by 3D Simulations. Computer-Aided Civil and Infrastructure Engineering, 20: 221–229. doi: 10.1111/j.1467-8667.2005.00389.x

Souli, M. and Shahrour, I. (2012), A coupling method for soil structure interaction problems. Int. J. Numer. Anal. Meth. Geomech.. doi: 10.1002/nag.2080

Čajka, R. (2003) Numerical Analysis of Contact Pressure under Shallow Foundation. International Symposium on Shallow Foundations FONDSUP 2003, 5.-7. November 2003, Paris, France, ISBN 2-7208-0355-3.

Čajka, R. (2005) Soil – structure interaction in case of exceptional mining and flood actions, COST 12 – Final Conference Proceedings, 20th – 22nd January 2005, University of Innsbruck, Austria, ISBN 04 1536 609 7.

Čajka, R., Manasek, P. (2005) Building structures in danger of flooding. IABSE Conference on Role of Structural Engineers Towards Reduction of Powerty, February 19-22, 2005, New Delhi, India, ISBN 3-85748-111-0

Čajka, R. (2008) Interakce základových konstrukcí s podložím (in Czech). Monografie, Ediční středisko VŠB – TU Ostrava, leden 2008, 177 s., ISBN 978-80-248-1754-5

Čajka, R. (2010) Program MKPINTER pro řešení interakce mezi základovou konstrukcí a podložím pomocí izoparametrických prvků s využitím Jacobiánu transformace a numerické integrace (in Czech). Software evidenční AR-SW-2010-04, ARMING spol. s r.o. 2010

Davis, P., Rabinowitz, P. (1956) Abscissas and Weights for Gaussian Quadratures of High Order. Journal of Research of the National Bureau of Standards, Vol. 56, No.1, January 1956, pp.35-37.

Kolář, V., Nemec, I. (1989) Modelling of Soil Structures Interactions. Praha, Academia 1989. 336 s,

Konečný, P., Brožovský, J., Křivý, V. (2010) Towards Parallel Computing using the Simulation-based Reliability Assessment Method. In Proceedings of the First International Conference on Parallel, Distributed and Grid Computing for Engineering. Pécs : Civil Comp Press, Hungary, 2010, ISBN 978-1-905088-29-4

Mindlin, R.D. (1951) Influence of Rotatory Inertia and Shear on Flexural Motions of Isotropic, Elastic Plates. Journal Appl. Mechanic 18, 1951, č.1, str. 31-38

Poulos H.G., Davis, E.H. (1974) Elastic Solutions for Soil and Rock Mechanics. John Wiley & Sons, Inc., New York 1974

Reitinger, R., Švejda, L. (1998) Výpočet vrstevnatého podloží metodou konečných prvků (in Czech). Stavitel, 5/98, pp. 32 –33.