Sensitivity of soil structure interaction for NPP footing bottom on static and seismic loading

Sensibilité de l'interaction de structure de sol pour le dessous de pied APM sur chargement statique et sismique

Ivan Vaníček, Daniel Jirásko
Geotechnical Department, Czech Technical University in Prague, Czech Republic, ivan.vanicek@cvut.cz

Martin Vaníček
Geosyntetika Ltd., Czech Republic

ABSTRACT: Paper is focused on the results of feasibility study of the safe foundation of nuclear power plant (NPP) in area with complicated subsoil conditions and subjected to seismic loading. The results presentation is divided into two parts. The first part concentrates on the static analytical evaluation of the foundations, which showed the necessity for subsoil improvement. Two methods were recommended, both guaranteeing acceptable settlement for static loading. The second more important part focuses on the numerical modelling of the soil structure interaction. Most of the soil properties were evaluated from the geotechnical ground investigation, however some of them were for the selected numerical model back calculated with respect to well approved analytical method of settlement calculation.

RÉSUMÉ : Document est axé sur les résultats de l'étude de faisabilité de la Fondation sûre de centrale Nucléaire dans la région avec des conditions compliquées sous-sol et soumis à des charges sismiques. La présentation des résultats est divisée en deux parties. La première partie se concentre sur l'évaluation statique analytique des fondations, qui ont montré la nécessité d'une amélioration du sous-sol. Deux méthodes ont été recommandées, les deux garante règlement acceptable pour le chargement statique. La deuxième partie plus importante porte sur la modélisation numérique de l'interaction entre la structure du sol. La plupart des propriétés ont été évaluées de la géotechnique sol sol enquête, cependant, certains d'entre eux étaient pour le dos de certains modèle numérique calculé en ce qui concerne la méthode analytique de calcul de la colonie approuvée bien.

KEYWORDS: Soil structure interaction, seismic loading transfer, subsoil improvement, heavy structures, seismic event movements

1 INTRODUCTION

Important large structures with large footprints a therefore large foundations area generally require to focus on the servisibility limit states, namly deformations. Typical example of such important structure is a block of nuclear power plant. The reason for higher importance of SLS is the large width of the foundation slab that predetermines high bearing capacity. In order to avoid irregular settlements, first condition is to find in the preselected area a place with reasonable uniform subsoil profile. After that the attention was focused on the geotechnical conditions under which it is possible to realize new nuclear power plant (NPP) for selected geological area with specified geotechnical characteristics and for expected seismic loading.

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

With the help of preliminary geotechnical investigation it was possible to specify the geological model of the wider preselected area, of which most simple interpretation is shown on Fig. 1. In principle it consists of 3 basic subsoil layers, (Vaníček and Vaníček 2014):

- Top layer with thickness of about 15 m is composed from the fine grained soils, marked as loess or loess loam, in lowest part as alluvial clays.
- Middle layer with thickness of about 13 to 20 m is composed from more permeable, coarser materials as gravel, sandy-gravel, sand. Ground water table was observed there.
- Bottom layer, pre-quaternary is on the top also coarser – gravel, sandy-gravel, sand; however gradually finer up to of clay character. Maximum depth in which tertiary clays were recorded was 44 m below surface.

With the help of this geological model it was possible to state that for selected wider area the section with a length of 200 m (similarly area 200 x 200 m) can be found where the surface and basic subsoil layers are practically parallel and horizontal and therefore to eliminate potential risk connected with differential settlement.

Laboratory and field tests were performed within the first phase of geotechnical investigation, enabling soil classification and determination of some mechanical physical properties. The obtained results are summarized on Fig. 1. Supplemented results of the geotechnical investigation outputs are on positive side:

- Top loess layers are on one side compressible however not sensitive to the structural collapse,
- Layer of sand is not sensitive to the liquefaction during seismic loading,
- Ground water level is relatively stable with minimal observed fluctuation and is not aggressive.

3 STATIC ANALYSIS

Feasibility study started with collection of basic data about different NPP isles produced worldwide, needed for settlement calculation as ground plan, contact pressure in the foundation bottom, etc. In most cases recommended depth of foundation was about 10 m with acceptable total settlement about 300 mm and acceptable differential settlement (inclination) 0.001.

Calculated total settlement was in all cases higher than accepted, about 550 mm. Calculation model was taking into account so called structural strength, specifying that the settlement for the load increase above geostatic vertical pressure about 20 to 40 % is close to zero. This calculation model was approved in the Czech Republic, e.g. Vaníček and Vaníček (2008, 2013). Settlement calculation based on the theory of elastic half space was much higher. Therefore, it was concluded that the subsoil improvement is needed.

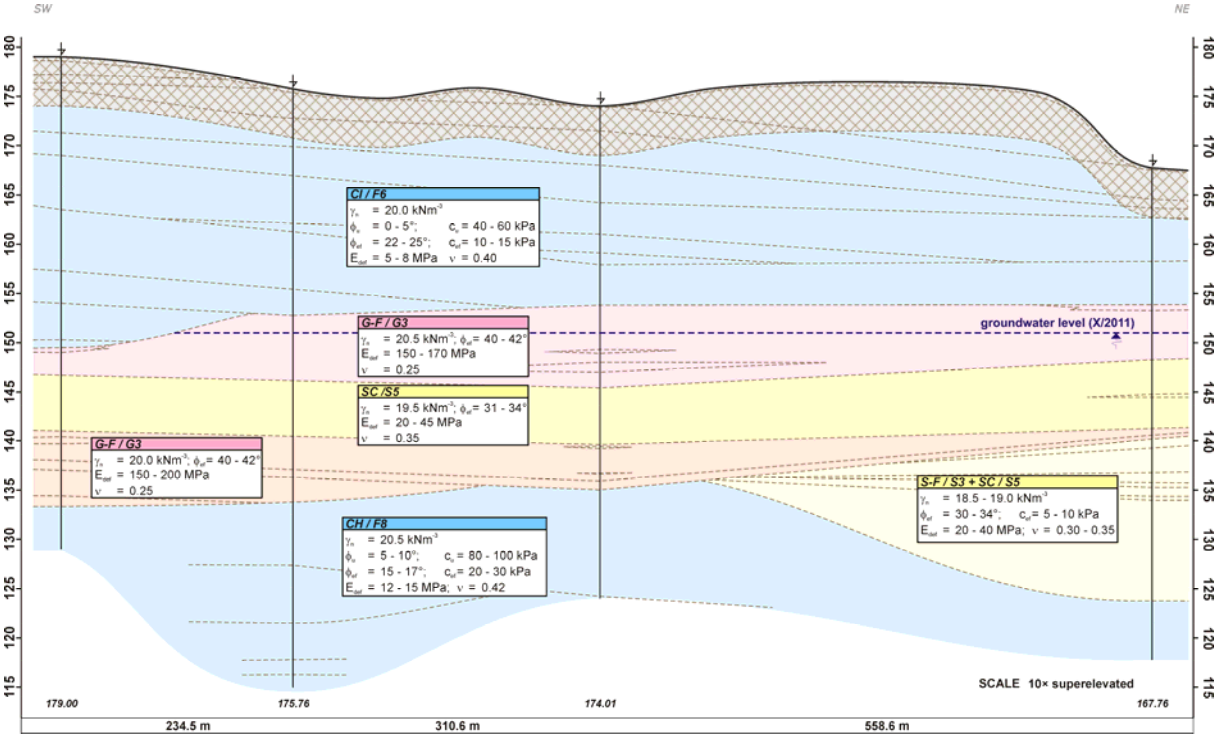

Figure 1. Geological and geotechnical model of the locality

3 .1 *Subsoil improvement*

Two basic methods were proposed for the subsoil improvement. The first one is based on the subsoil replacement, when the part of compressible layer (loess) is substituted by sandy-gravel cushion. The total thickness of the reinforced cushion is assumed between 4.5 to 6 m, so it means that still 2.0 to 3.0 m of fine soil remained there, to protect ground water in lower gravel from potential contamination from the surface. Piles, which are embedded into gravel layer, are used for the second method. In the upper part they are interconnected by reinforced concrete slab. However in both cases 0.5 m thick very well compacted gravel layer is proposed between the zone of improvement and foundation slab, Fig. 2.

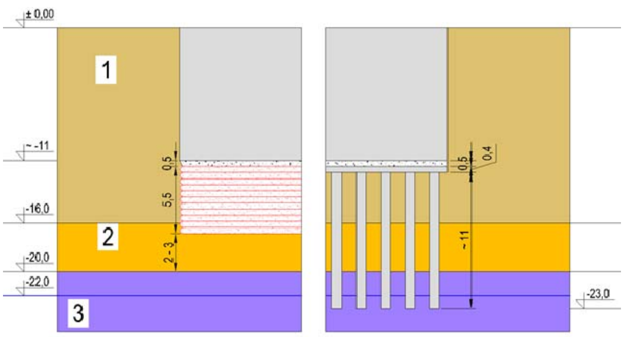

Figure 2. Subsoil improvement options
– 1.loesses, 2.alluvial clays, 3.gravels

3 .2 *Results for static analysis*

For detailed analysis only two representatives of the NPP island were selected as data for them were more complex and they at the same time represent plants with “lower” energy output (1200 MW) and “higher” (1800 MW).

Analytical methods for settlement counting with above mentioned calculation method proved a great impact of subsoil improvement, for sandy-gravel cushion the total settlement is about 160 mm and for improvement with piles only about 60 mm. So it means that the condition for total settlement (300 mm) is for static loading fulfilled.

Subsequently numerical calculation method was used. Planar (2D) solution was applied for the geometrical model 2 × 200 m and depth 100 m, and software PLAXIS (2D v 2012 Manuals) was used, based on FEM. Finite element spacing was adapted to the boundary conditions with detailed spacing around places of concentration of stresses. With the help of parametric study it was approved that the constitutive model “Hardening soil small strain model” is closest to the analytical solution using principle of structural strength, giving roughly the same values of total settlement. This specified model can define different stiffness of soil for both virgin loading and for repeated loading/unloading.

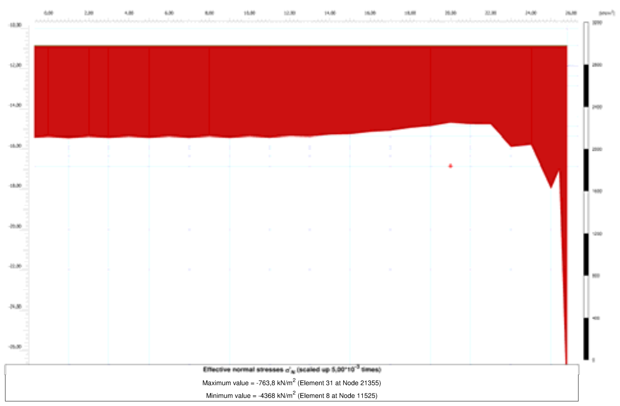

Figure 3. Distribution of contact pressure in footing bottom for sandy-gravel cushion subsoil improvement

For selected and verified numerical model the large parametric study of SSI for both basic cases of NPP and for different subsoil improvement was performed (Vaníček & Vaníček, 2014). The results e.g. showed that contact pressure in the footing base is relatively constant with excesses at the end of slab. However small plastic zones are there confined with no marks of further propagation. Fig. 3. The results of vertical deformation for subsoil improved by sandy-gravel cushion approved that just before the top of tertiary clays the deformation values are close to zero. For subsoil improved by piles vertical effective stresses are presented on Fig. 4

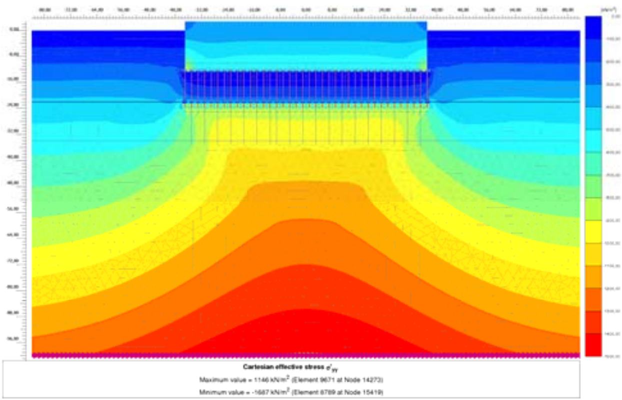

Figure 4. Vertical effective stresses for piled subsoil improvement

4 SEISMIC ANALYSIS

The purpose of the second part of the study was to comfirm that the behaviour of both subsoil and the structure itself is in acceptable levels during the seismic event.

4 .1 *Determination of design seismic level*

The shear wave propagation properties have been studied during the geophysical site investigation as it is the most important aspect in horizontal behaviour of soil structure interaction analysis. Shear wave velocity propagation increases with depth. Soils close to the surface has the shear wave velocity of 150m/s and the velocity at the model depth at 100m is 1200m/s. According to the IAEA the site belongs to the SL2 class.

The SL2 class means that the seismic event to be analyzed has a return period of 10000 years. The design seismic event is characterized by the peak ground acceleration (PGA) in all three directions. With respect to the site specific measured values and IAEA recommendations the design PGAs are as follows:

- PGA_{hor} = 0,195g a PGA_{vert} = 0,101g at model base
- PGA_{hor} = 0,349g a PGA_{vert} = 0,214g at the top of gravels

With these values, artificial accelerographs of 20s seismic event with steps of 0,002s for all three directions have been generated (see Fig. 5 for x direction).

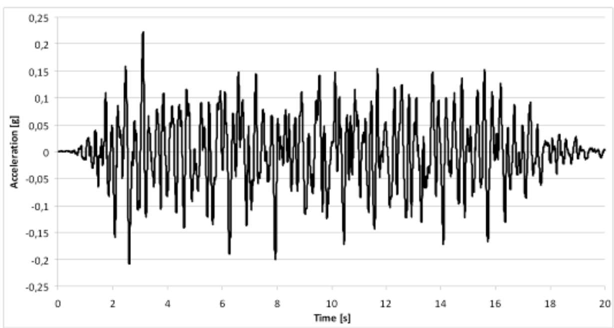

Figure 5. Accelerograph for x direction at the level of 20m BGL

4 .2 *Seismic wave propagation modelling in subsoil*

Semianalytical method was used to transform the accelerographs from the level -20m to the base of numerical model (-100m). The obtained accelerograph was after that slightly modified as such that the accelerographs calculated by the FEM numerical model are compatible with the input accelerographs at the level of -20m. For the numerical modelling FEM program PLAXIS 2D was used.

4 .3 *Soil structure interaction results for seismic loading*

Many different models were recommended for seismic or cyclic loading (e.g. earliest by Mroz, Norris and Zienkiewicz 1978), however again software PLAXIS 2D and “Hardening soil small strain model” under plain strain conditions was used. From the view of boundary conditions the software is using an adsorption boundary for which the model is using viscose boundary (dashpot).

Numerical modelling has been performed for the amended accelerographs for each time step for the section of (2×200m) × 100m (Vaníček & Vaníček, 2015).

During the study several runs of analyses have been done, for both sizes of nuclear blocks, for three different alternatives of subsoil improvement and for both sets of accelerographs, in total 12 analyses. The results of numerical modelling can be visualized in many ways, e.g. residual deformations after the seismic event (total, horizontal, vertical), extreme deformations during the event (positive, negative, vertical, horizontal, total), extreme accelerations during the event (total, horizontal, vertical). Nevertheless, the best option is to present a video of the event to see the movement of the whole system, unfortunately it can’t be presented in paper.

On Fig. 6 the residual horizontal deformations of the whole model for the case of piled subsoil improvement and higher output reactor block is presented. On Fig. 7 the maximum total accelerations generated during the event in the modelled area is presented. On both figures, it can be seen that the influence of boundary conditions is significant, however does not influence the results for the actual NPP building and hence the presented results.

5 CONCLUSION

The feasibility study of SSI approved the possibility to realize NPP for given geological, geotechnical conditions, as well for recommended seismic conditions. Numerical modelling is giving very clear imagination about movement of the studied object during seismic event as well about residual vertical or horizontal deformation after this seismic event.

Nevertheless, for the next step it is recommended to realize another more specific geotechnical investigation according to the demands of the IAEA. To apply 3 D numerical model to be able to study not only own nuclear island but also other buildings close to it, with the possibility to study impact of the construction technology.

Finally, the results of the numerical modelling should be validated with the help of other methods of SSI modelling, as e.g. via physical centrifuge model (Ghosh and Madahushu 2007 or Ha and Kim 2014) or via large-scale seismic test (Graves, Tang and Liao 1996).

6 ACKNOWLEDGEMENTS

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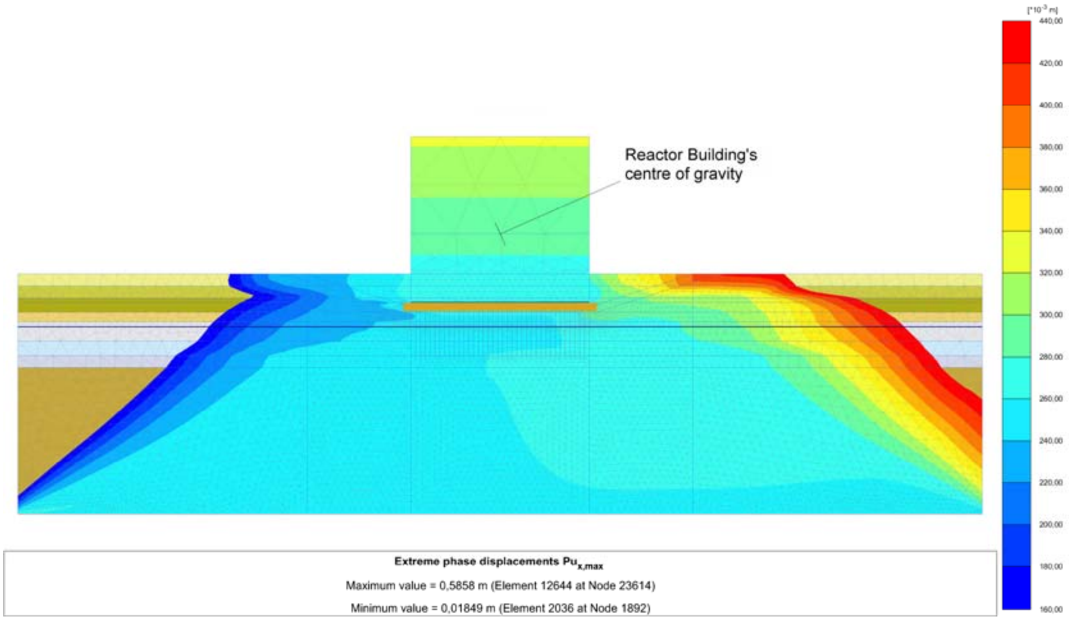

Figure 6. Maximal horizontal deformation during the seismic event - Subsoil improvement by geogrid reinforced sandy-gravel cushion.

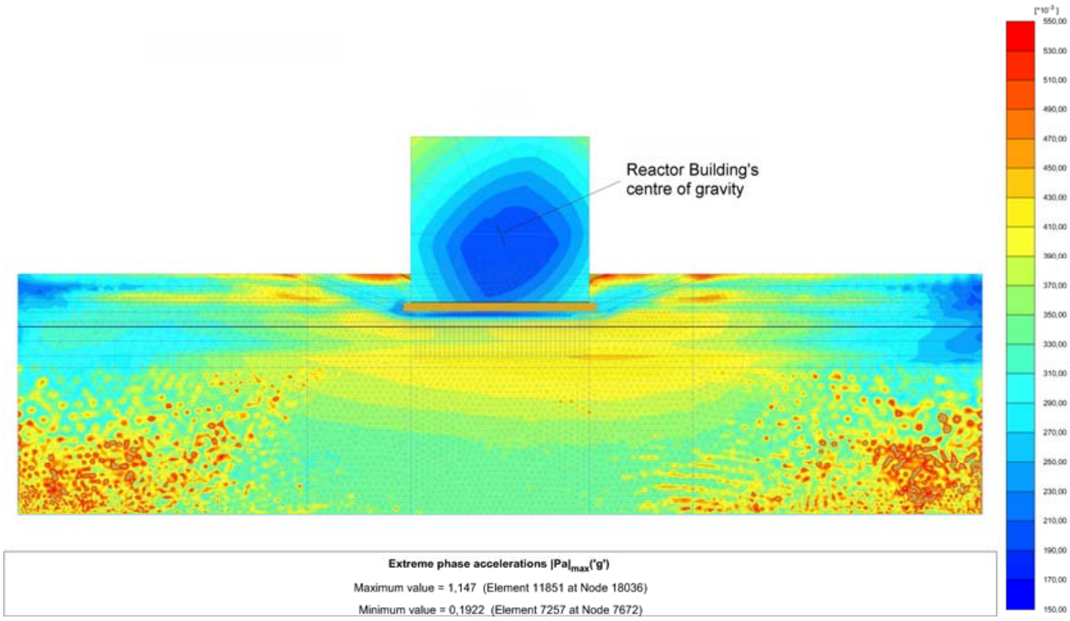

Figure 7. Maximal acceleration [g] during the seismic event - Subsoil improvement by geogrid reinforced sandy-gravel cushion.

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