Nonlinear interaction analysis of RC cylindrical tank with subsoil by adapting two kinds of constitutive models for ground and structure

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Abstract

In the paper, two kinds of constitutive models for ground and structure were adapted for the nonlinear interaction analysis of RC cylindrical tank with subsoil. It discusses deformational and incremental approaches to nonlinear FE analysis of soil-structure interaction including the description of behaviour of RC structure and the subsoil under short-term loading. Moreover, a non-linear elastic-brittle-plastic analysis of RC axisymmetric structures using finite element iterative techniques is presented. The constitutive laws for concrete and subsoil are developed in compliance with the deformational and plastic flow theories of plasticity. Two examples of FE analysis of soil-structure interaction were performed and the results have been analysed.

Keywords: RC tank, cylindrical shell, ground slab, elastic-plastic half space, deformation theory of plasticity, plastic flow theory

1. Introduction

The issue of soil-structure interaction has been the subject of extensive studies. This study analyses the impact of subsoil on stress resultants in the shell and ground slab of RC cylindrical tank, as well as their redistribution which appears mainly due to uneven subsidence and to some extend - cracks. In case of RC tanks, it is rather difficult to refer to publications comprising numerical elastic-brittle-plastic analysis and soil-structure interaction, however many publications deal with axisymmetric RC structures, with the paper of Phillips and Zienkiewicz [3] being among the first publications. The present paper discusses two concepts of nonlinear FE analysis of soil-structure interaction, including the description of RC structure, one based on deformation theory and the other - on plastic flow theory of plasticity. In the first case, the analysis of soil-structure interaction was conducted by own programme (namely an expanded FEAP version). That analysis was performed using the Lagrange quadrilateral isoparametric element. The second model was built using *Abaqus* software with 3-node axisymmetric shell elements (SAX2, for structure) and 8-node axisymmetric continuum elements (CAX8R, for soil).

2. Material modelling

2.1. Failure criterion for concrete

The failure criterion for concrete proposed by Podgórski [4] is used as the fracture law. Some amendments of the model were proposed by Lewiński [2] (and accepted by Podgórski). Utilizing the above failure criterion for concrete the five basic cracking patterns of rotationally symmetric structure (all the possible - see Fig. 1) can be distinguished. The position of the crack plain is defined as the perpendicular to the respective principal stress in concrete. Determination of a crack pattern at Gauss point depends on the configuration of the main stresses as well as positive or negative signs of their particular values.

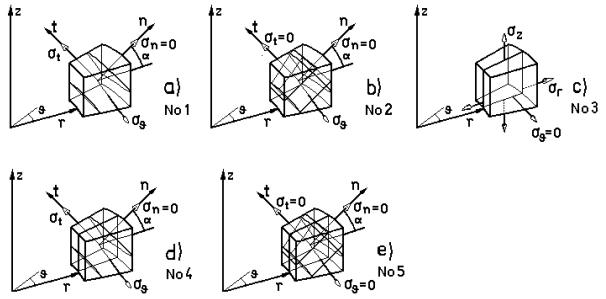

Figure 1: Cracking patterns of RC axi-symmetric structure [2].

2.2. Behaviour of concrete and soil

The concept of the model is based on the conventional deformation theory of plasticity. The octahedral-based elastoplastic model is utilized by using secant bulk K_S and shear G_S moduli. Similar assumptions are made for the subsoil. In the present paper the original description of Kupfer and Gerstle [1] has been modified by using corrections with respect to γ_{oct}:

$$\frac{G_S}{G_0} = f_c \frac{\sqrt{f_c^2 + 4abG_0^2\gamma_{oct}^2} - f_c}{2abG_0^2\gamma_{oct}^2} - \gamma_{oct} \cdot \omega \cdot (\alpha_1 \cdot \gamma_{oct} + \alpha_2 \cdot \omega_{23}) \quad (1)$$

$$\frac{K_S}{K_0} = \frac{G_S}{G_0} - \gamma_{oct} \cdot \omega \cdot (\alpha_1 \cdot \gamma_{oct} + \alpha_2 \cdot \omega_{23}), \quad (2)$$

where a, α_1, α_2, ω and ω_{23} are the numeral coefficients dependent on α_m, where $\alpha_m = 1000 \cdot f_c'/E_c$ for concrete and $100 \cdot R_c/E_0$ for soil. For concrete $b = 1$, while for soil b means an empirical relationship (taking into account the value of lateral pressure). In the performed numerical analysis, the value of lateral stress σ_r was taken into account instead of lateral pressure. In case of the incremental FE analysis, the "Smeared cracking" material model was adopted for concrete. An elastic - perfectly plastic material with the Coulomb-Mohr yield condition and the non-associated flow rule was applied for the soil.

2.3. Behaviour of steel

In the first case, the deformation model and tension stiffening effect (on the assumption that additional stress is carried by rebars) are taken into account. For the incremental Abaqus model the reinforcement was included with "Rebar" option. An elastic-plastic analysis with hardening steel model was used.

3. Computational examples

The computational example of nonlinear FE analysis of RC tank with cylindrical shell (with inner radius of 6.90 m, height of 5 m, thickness of 20 cm) connected to the ground slab (with depth of 20 cm) supported on elasto-plastic subsoil is given. For the deformational analysis the following properties of concrete has been adopted: f_c = 20 MPa, E_c = 20 GPa, ν_c = 0.167; subsoil with a strength: R_c = 0.08 MPa, E_0 = 12 MPa, ν_0 = 0.35; steel reinforcement has been adopted as f_y = 355 MPa, E_s = 210 GPa. The vertical reinforcement of the shell: ∅ 16/20 cm and horizontal: ∅ 20/20 cm have been adopted on both sides, while in the ground slab – the radial reinforcement and the peripheral one: ∅ 18/13 cm. Near the junction of the shell with the slab, the hoop bars are concentrated: ∅ 20/12 cm. The following soil parameters were introduced for incremental FE analysis: E = 12 MPa, ν = 0.35, c' = 9 kPa, φ' = 10°, ψ = 0. The assumed soil parameters correspond to soft clay. For incremental analysis the concrete properties have been adopted as specified above. In regards to reinforcement, it was assumed that f_u = 510 MPa.

4. Results and conclusions

Analytical results are presented in Figures 2 to 6.

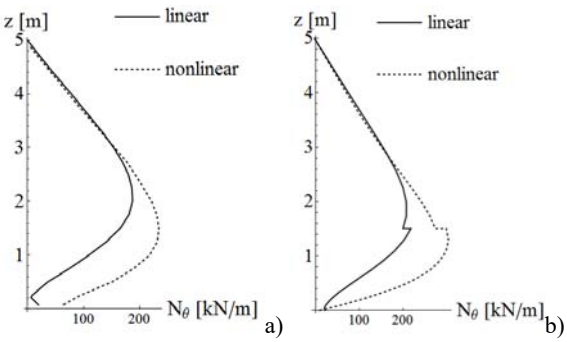

Figure 2: Circumferential forces in tank wall due to hydrostatic pressure for both models a) deformational [2], b) incremental.

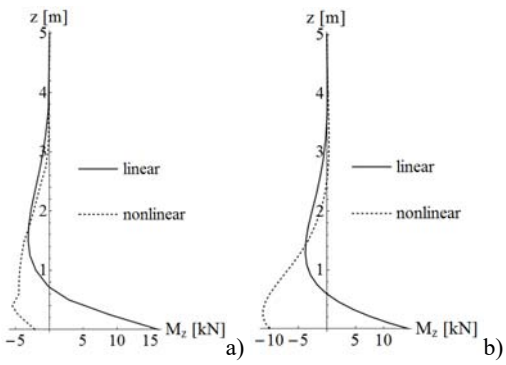

Figure 3: Bending moment in the tank wall due to hydrostatic pressure for both models a) deformational [2], b) incremental.

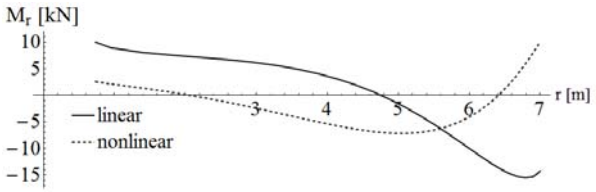

Figure 4: Radial moments in the slab for the incremental model.

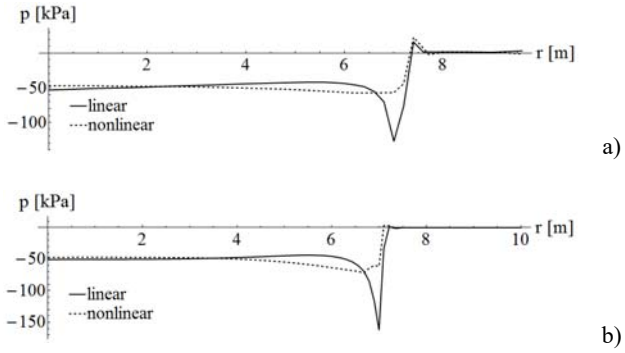

Figure 5: Distributions of the ground reaction for both models a) deformational [2], b) incremental.

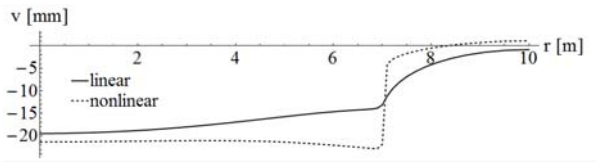

Figure 6: Distributions of the ground subsidence for the incremental model.

The comparative analysis was performed for incremental and small-strain stiffness constitutive models. The subsoil reaction is redistributed due to development of plastic strains in the soil. Different values of bending moments at the joint of the slab with the cylindrical shell result from nonlinear behaviour of the ground under the slabs in both cases as well as stress redistribution in the substrate soil. The results of the analysis indicate that in the case of structural concrete and subsoil of normal strength, the scope of the redistribution is not very large, whereas in the case of weak subsoil (or concrete) the redistribution range is quite wide. According to the incremental analysis, a change of the value of the effective angle of internal friction of the soil from 22° to 10° may cause a change in the sign of the bending moment in the shell.

References

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