NUMERICAL 3D ANALYSIS OF BURIED FLEXIBLE PIPELINE

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Abstract

The subject of the analysis is soil interaction of a PVC flexible pipeline with its surface loaded uniformly across a certain area. When such an interaction is taken into account in classical calculations, soil is usually replaced with a largely simplified analogue (a system of vertical and horizontal pressure) and a spatial pipeline structure is replaced with a pipe ring representing a characteristic cross-section of a pipe in the plane state of strain (2D model). With such an approach, the considered calculation scheme is naturally far from the reality. Unlike analytical calculations, numerical analyses allow to take into consideration the spatial character of a pipeline laid in the ground (a 3D model of a pipe-soil system). Numerous factors may be additionally included influencing the scope and character of interaction between a pipe and soil, such as pipe deformability resulting from a pipeline's material parameters, a method of incorporating a pipeline into the soil (excavation and non-excavation methods) or load increase in time. The article presents the assumptions, programme and results of a 3D numerical analysis of a pipe-soil system model undertaken with Z_Soil software. The model analysed consists of a rectilinear section of a PVC pipe and the surrounding mass of strongly stratified soil. The pipe is modelled according to its flexibility, while an elastic-plastic model was applied for soil modelling with Hardening Soil – Small isotropic strengthening considering a non-linear change in soil stiffness for small strains (10^{-6} – 10^{-3}). It is essential to take such variable soil stiffness into account in modelling the structure-to-soil interaction. The outcomes of the analysis performed are presented mainly graphically by listing the maps of model deformation, maps of stress and strain of the soil mass and pipe structure and diagrams of characteristic displacements of pipe points, and the diagrams of generalised internal forces in a pipeline.

Keywords: Soil-pipelines interaction, numerical analysis, FEM

Introduction

A number of engineering problems that not always could have been resolved through analytical calculations can now be solved with numerical analyses using the Finite Element Method (FEM). The Finite Element Method (FEM), known for nearly 50 years, has been effectively implemented in various computer software packages aiding the designing and analysis of engineering structures, such as ABAQUS, ANSYS, ABC PŁYTA, CESAR, HYDROGEO, MAFEM, PLAXIS, ROBOT or Z_SOIL. An increasingly higher computational capacity of modern computers and relatively broad availability of specialised software is also important. A contemporary engineer is thus endowed with tools enabling to perform multi-variant analyses of a structure, its optimisation or expert evaluation of failure modes.

The use of extended, geotechnically oriented computer packages (e.g. Z_Soil) for solving the aspects of buried structures, especially for analysing buried piping systems, seems to be particularly attractive. Such structures are interworking with the surrounding soil in a specific manner (Gerscovich, D.M.S., Sieira A.C.C.F., Fereira A.M., 2008, Goltabar, A. M,; Shekarachi M., 2010). When such interaction is taken into account in classical calculations, soil is usually replaced with a largely simplified analogue, and the considered calculation scheme is far from the reality. Unlike in analytical calculations (ATV-DVWK-A127P, 2000, Janson, L.E, 1996, Kuliczkowski, A., 2004, Madryas, C., Kolonko, A., Wysocki, L., 2002) where a pipe ring (2D) is usually considered, numerical analyses allow to take into consideration the spatial character of a pipeline with the surrounding soil (3D).

A concept of a virtual, discrete model of a pipe-soil structure system has to be developed first of all in order to employ numerical methods for solving the aspects of interaction. The model should reflect a representative part of the considered pipe structure together with the adjoining and interworking subsoil mass. The efficiency of the numerical analysis carried out, hence the credibility of the results obtained, is dependent on the correctness of the input data entered, including, notably, the correctly selected model geometry (dimensions of the substrate mass interworking with the structure), the correct entering of material parameters of the structure and subsoil, selecting the appropriate constitutive model of individual material zones and the correct mapping of the set of the acting loads or complex technological processes. The applied constitutive model of subsoil is especially significant and should reflect soil behaviour in the conditions of the working loads, including plastic characteristics of soil. A constitutive soil model is often selected based on the necessity to introduce specific parameters which are highly diversified depending on individual models and not always estimable though geotechnical tests. Hence the natural tendency to employ an elastic-perfectly plastic Mohr-Coulomb model whose parameters (Young's modulus E, Poisson's ratio ν, internal friction angle ϕ, and cohesion c) are easily identifiable. This model does not allow to take into consideration specific phenomena taking place in soil when loads are acting, e.g. non-linear soil stiffness for small strains (10^{-6} – 10^{-3}) which are significant in analyses of structure and soil interactions. An elastic-plastic model with Hardening Soil Small Stiffness isotropic strengthening implemented in Z_Soil software offers such a possibility (Truty, A., Obrzud, R., 2011).

Numerical analyses also permit to reflect the activity of complex loads of a buried pipeline over time, such as surcharge's load, traffic loads or the impact of underground mining exploitation (horizontal soil strains of the tensile or compressive nature, a vertical terrain curvature or the impact of the local collapse) (Kliszczewicz, B., 2010).

Description of the analysed problem

A rectilinear section of a PVC pipe laid in the ground, loaded partially with a uniformly distributed surface load (surcharge's load) and with the load of the soil underneath the pipe, is considered in the presented analysis. A numerical, spatial (3D) model of a pipe-soil system was created in Z_Soil programme – academic version 11.03 (ZSOIL.PC 2011 User Manual. Zace Services Ltd., 2011). As the subsoil is stratified non-uniformly and due to the specifically situated surface, uniformly distributed surface load, the only acceptable variant of model geometry is a spatial 3D model including the entire pipe-soil system.

The model of the system consists of soil mass dimensioned 10.0 x 6.0 x 12.0 m. An excavation zone, 1.6 m wide, 3.8 m deep and 12.0 m long, was designated in the centre of the mass. A PVC pipe with the diameter of DN630 mm and wall thickness of 0.0154 m was laid in the excavation on a 0.1 m thick levelling layer. The layer of the soil covering the pipe is 3.0 m thick. Two material zones were established in the excavation zone, representing a layer of sandy pipeline bedding and pipeline backfill. The sandy bedding is lying in the direct surrounding of the pipe and is 0.1 m thick above the top point of the pipe. The remainder of the excavation is filled with backfill soil. Apart from the excavation, the non-uniform distribution of two layers of virgin soil separated with a layer of clayey soil with strongly differentiated thickness is considered in the soil mass model. Geometric parameters of the individual soil layers (varied thickness of layers) were entered with the *Boreholes* feature, thus simulating the entering of geotechnical data obtained from soil tests in geotechnical bores situated in the corners of the soil mass.

The basic load on the soil mass, and indirectly also on the pipeline, is modelled as a uniformly distributed load with intensiveness of 100.0 kN/m^2. The load was applied onto the top surface of the model, non-symmetrically in relation to the longitudinal axis of the pipe. The analysis programme includes a simulation of uniform increase of the load in twenty time intervals.

The soil mass model was constructed of rectangular elements consisting of eight nodes of the *Continuum* type while the pipe coating was modelled with the *Shell* type elements. The model incorporates 14344 elements (including 13904 of the *Continuum* type and 440 of *Shell* type) and 16376 nodes. The boundary conditions introduced in the model enable the free longitudinal movement of its vertical planes and to support and prevent movement in two directions in its bottom plane (3037 *Boundary conditions* type nodes). Contact elements were introduced at the interface of the pipe coating with the soil (440 C*ontact elements*) due to highly varied rigidity of the pipe material and its surrounding soil. Fig. 1 shows a view of the analysed pipe-soil system model. The supports of the *boundary conditions* were not shown above the image to make it clearer. The designations of the relevant material zones are consistent with those given in Table 1.

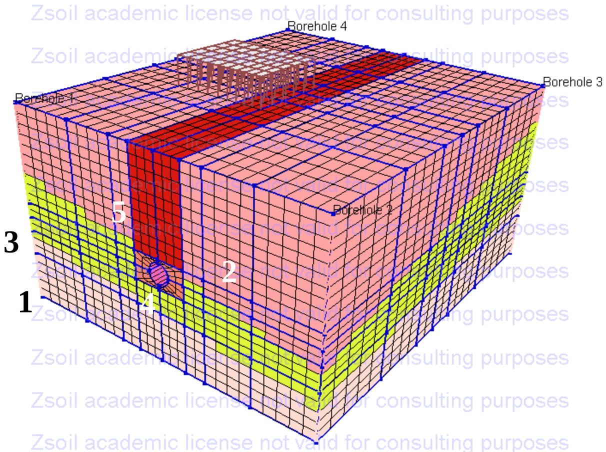

Fig. 1. View of the pipe-soil system model.

The pipeline is modelled within its elastic range, and a large-size elastic-plastic model with Hardening Soil – Small isotropic strengthening was used for describing soil behaviour with the working load. The model considers, in particular, the relationship between stiffness and effective stresses, plastic flow, changes in volume during plastic flow and changes in stiffness with a rising amplitude of deviator strain (Truty, A., 2008). The model was described thoroughly by its creators (Schanz, T., Vermeer, P.A., Bonier P.G., 1999, Benz, T., 2006). Table 1 lists the selected parameters of individual soil layers used in the material zones of the soil mass model. The detailed, extended material parameters of the individual layers were generated automatically in Z_Soil software using the *Estimate parameters for HS model* feature.

Table 1.

Soil designation in model	Soil characteristic	Young modulus unl./rel. at ref. stress E_u^{ref} [kN/m^2]	Hardening parameter H [kN/m^2]	Hardening parameter M [kN/m^2]
Virgin soil 1	Clay	10 000	4776	0,762
Virgin soil 2	Clay	80 000	45480	1,129
Virgin soil 3	Silt	12 500	4195	1,135
Virgin soil 4	Sand	80 000	49270	1,207
Virgin soil 5	Sand	80 000	49270	1,207

Presentation of the analysis results

A uniformly distributed load of the surcharge causes soil mass deformation shown with a deformed net of the pipe soil system model (Fig. 2a) and 3D visualisation of the vertical displacements map (Fig. 2b), generated in Z_Soil software. In order to show the progress of the deformation inside the soil mass model in Fig. 3a and 3b, maps were shown of resultant displacements in characteristic sections of the model, i.e. in planes perpendicular and parallel to the pipe axis. It is pointed out by analysing the maps that the impact of the surcharge's load, most important directly in the place of its application, covers a significant area of the soil mass and reaches the pipeline placement zone. The maximum vertical displacements of nodes on the soil mass model reach 0.019 m. The pipe model is also subject to the deformation as shown in Fig. 4. The maximum vertical displacements of the pipe model nodes are 0.003 m and occur in the central part of the pipe model.

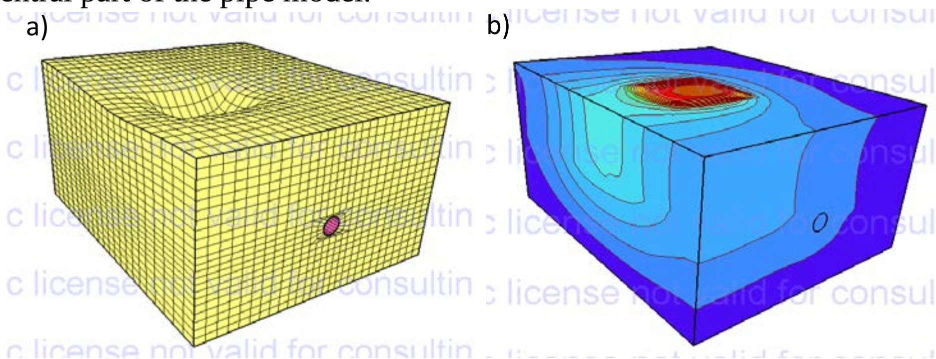

Fig. 2. Deformation of the pipe-soil system model: a) deformation of model surface, b) map of resultant displacements ABS.

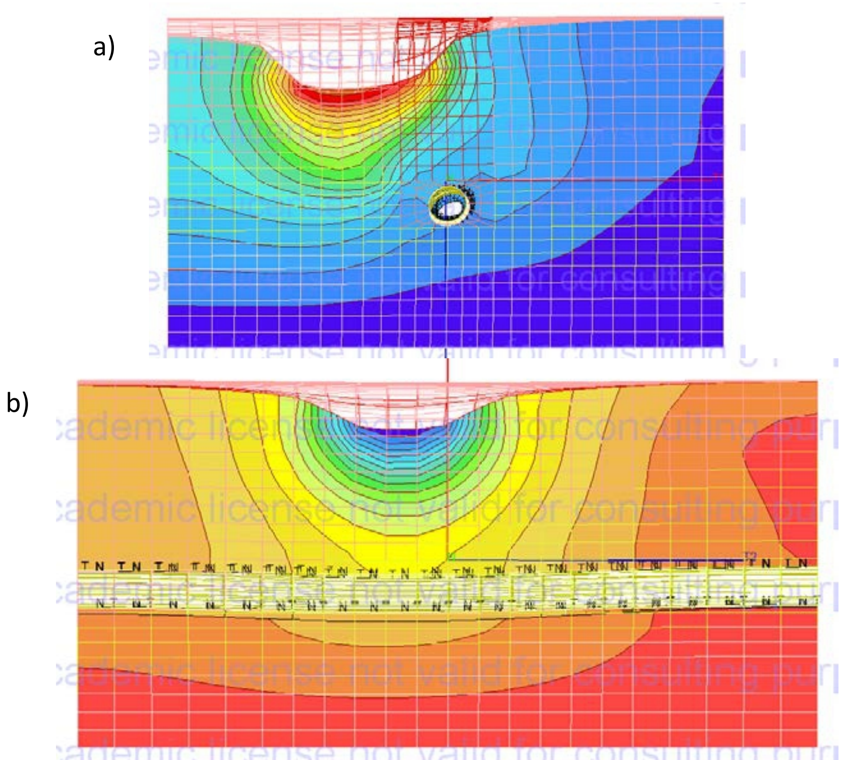

Fig. 3. Maps of vertical displacements directly in the load working zone in characteristic sections of the model: a) section perpendicular to the longitudinal axis of the pipe, b) cross-section of longitudinal axis.

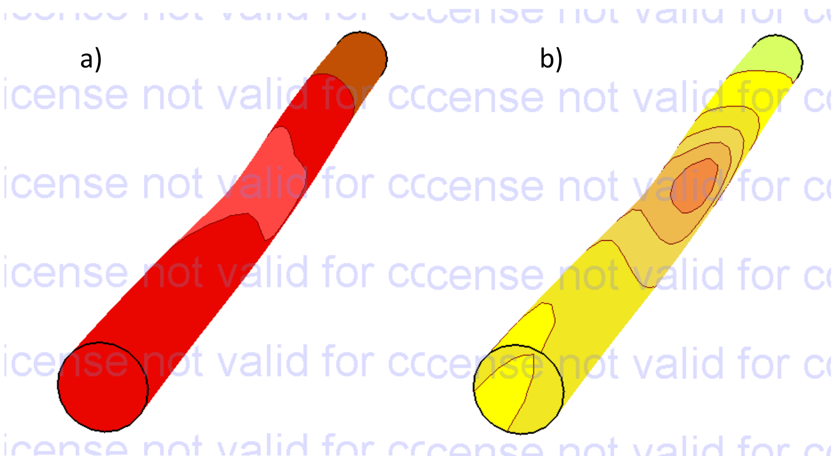

Fig. 4. Pipe coating deformation: a) map of vertical displacements, b) map of horizontal displacements.

The maps of effective stresses presented in Fig. 5 show irregular progress of the isoline of stresses in the soil mass associated with introducing into the numerical model five material zones with diverse parameters.

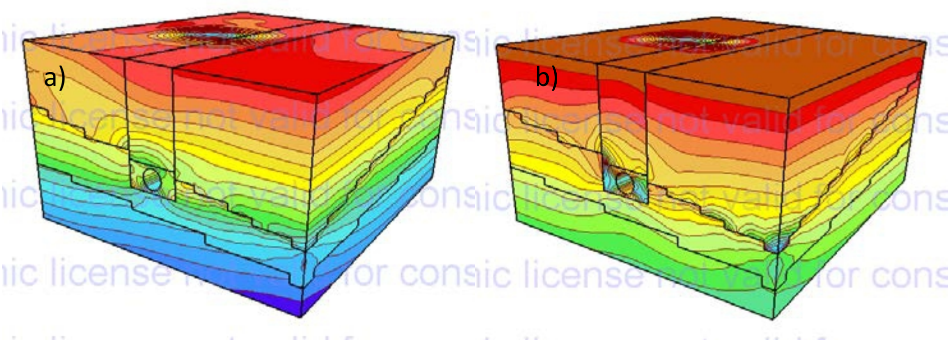

Fig. 5. Maps of effective stresses in the soil mass: a) stresses σ_{xx}, b) stresses σ_{yy}.

The effort state of the pipe coating, with a uniformly distributed load working onto the model surface, can be illustrated, notably, by creating diagrams of generalised internal forces in the vertical cross-section situated immediately within the load working zone

(Fig. 6).

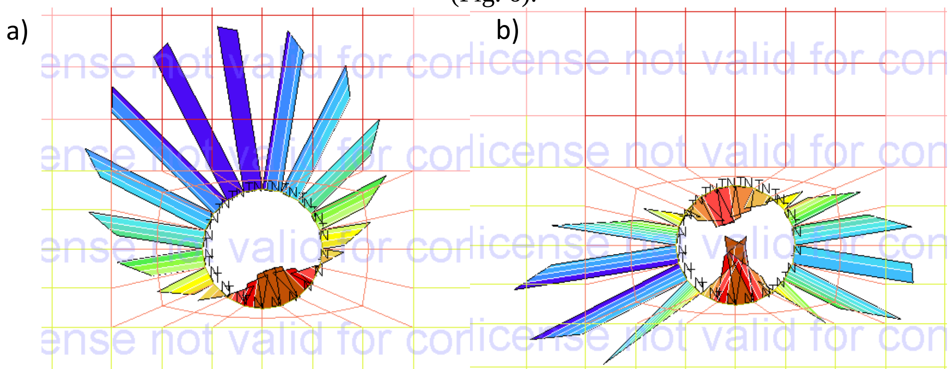

Fig. 6. Diagrams of generalised internal forces in the vertical cross-section of the pipe situated immediately within the load working zone: a) diagram of circumferential axial forces, b) diagram of circumferential bending moments.

The distributions of axial forces and bending moments clearly indicate the non-uniform circumferential effort state of the pipe. A decisively higher effort state exists in the surcharge's load working zone. This is naturally related to non-uniform pipe deformation.

Conclusion

The presented 3D numerical analysis of interaction of a pipeline structure with stratified subsoil loaded across a certain area has enabled to evaluate the effort state of the pipe and the changes taking place in the soil mass. The impact of the load is particularly evident in the sub-surface soil layers immediately within the load working area. A distribution zone of the stresses excited by a load working within the entire soil mass, especially in the direct surrounding of the pipelines, can also be identified. Considering the stratification of the subsoil with a layer of low-bearing ground with varied thickness and the fact of varied material parameters in the zones of virgin soil, bedding and backfill in the excavation, one can observe clear disturbances in the distribution of stresses in the direct surrounding of the pipe (excavation) and in the further zones of the soil. As the load is situated specifically as shifted in relation to the pipe axis, the deformation and effort state of the pipe side surface is non-uniform. This signifies irregular distribution of generalised internal forces in such structure.

Such results of the activity of surface loads onto the pipe structure situated in stratified subsoil are identifiable only by building numerical pipe-soil system models and by analysing their behaviour when simulating the activity of loads. The reliability of the outcomes obtained is linked to the correct construction of the model including correct model dimensions, discretisation density, selection of appropriate material parameters and an adequate constitutive model of soil and of the modelled structure. Numerical analyses can be regarded as an attractive tool for examining limit states of the bearing capacity and serviceability of buried piping.

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