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NUMERICAL MODELLING OF THE IMPACT OF UNDERGROUND MINING ON PIPELINES PART II – IMPACT OF DISCONTINUOUS DEFORMATIONS

Barbara KLISZCZEWICZ*

[a] Dr.; Faculty of Civil Engineering, Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
E-mail address: *Barbara.Kliszczewicz@polsl.pl*

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Abstract

Underground mining exploitation causes changes in the rock mass resulting in land surface deformations such as extensive subsidence basins (continuous deformations) or local collapses, cones, thresholds or crevices (discontinuous deformations). The impact of continuous deformations on buried pipelines is discussed in Part I of the paper. The formation of local discontinuous deformations is dangerous for building structures and for line facilities, including buried piping. The first part of the article presents the characteristic of discontinuous deformations and their classification, while the second part discusses the assumptions, scope and results of a numerical analysis of a pipe-soil system model undertaken with Z_Soil ver. 11.03 software. The analysis considers the case of situating a pipeline in the area of a local collapse.

Streszczenie

Podziemna eksploatacja górnicza wywołuje zmiany w górotworze, które skutkują deformacjami powierzchni terenu, w postaci rozległych niecek obniżeniowych (deformacje ciągłe) bądź też lokalnych zapadlisk, lejów, progów lub szczelin (deformacje nieciągłe). Wpływ deformacji ciągłych na podziemne rurociągi omówiono w I część artykułu. Tworzenie się lokalnych deformacji nieciągłych stanowi zagrożenie zarówno dla obiektów kubaturowych jak i obiektów liniowych, w tym podziemnych rurociągów. W pierwszej części artykułu przedstawiono charakterystykę deformacji nieciągłych i ich klasyfikację, zaś w drugiej – założenia, zakres i wyniki numerycznej analizy układu rura – grunt, wykonanej w programie Z_Soil ver. 11.03. W analizie tej rozpatrzono przypadek usytuowania rurociągu w rejonie lokalnego zapadliska.

Keywords: **Discontinuous deformations; Pipelines; FEM.**

1. INTRODUCTION

The condition of construction foundation is of fundamental importance for safety and usable properties of building structures. This applies also to buried pipelines for which stable laying in the ground is one of prerequisites for correct functioning and durability. Due to the development of technical infrastructure accompanying the expansion of strongly urbanised areas, buried pipelines and municipal facilities are constructed more and more often on areas with degraded construction subsoil. This holds true, notably, for areas subject to the effects of past and present underground mining exploitation. Post-excavation voids are what is left after former, shallow mining exploitation. If they are reactivated as a result of current exploitation, overloading of the land surface, mining tremors or groundwater movements, a threat is posed of local discontinuous deformations being created on the land surface [2], [4], [6], [8]. Works can be undertaken to strengthen the foundation by identifying the voids, which is possible with geophysical methods (seismic, electrical resistivity, electromagnetic, radar, gravimetric or temperature measurement methods [3], [5]). The situation is harder when discontinuous deformations occur in the foundation area of the a b

Figure 1.
Examples of discontinuous deformations: a) local collapse (http://bi.gazeta.pl/), b) crevice (own archive)

existing building structures. Considering buried pipelines, sudden local collapses are affecting their continuous support and in turn cause their additional effort state. Such effort states can be estimated approximately using simplified bar static charts. Numerical analyses, the example of which will be presented in this paper, offer an alternative.

2. CHARACTERISTIC OF DISCONTINUOUS LAND DEFORMATIONS

Discontinuous deformations related to mining operations are defined [3] as “interrupted continuity and displacement of subsurface soil particles”. The phenomena associated with the creation of discontinuous deformations are usually of rapid and unforeseeable nature, and of local range. Due to their strongly probabilistic character, it is hard to establish a cause-and-effect relationship between mining works and formation thereof. Considering the above characteristics, their forecasting is very limited. For this reason, it is difficult to indicate effective preventing measures in terms of construction activity.

Discontinuous deformations [2], [4], [8] may be caused by engineering and underground works (so-called anthropogenic origin) as well as by natural effects such as tectonic and landslide movements, karstic phenomena and erosion. The direct causes of discontinuous deformations include, most of all, shallow exploitation of beds, mainly in systems with longwall caving; reactivation of old, shallow mining headings; exploitation in proximity of faults or in the region of deposit outcrops; formation of so-called exploitation slopes or fires in the remnants of shallow deposits; as well as activisation of secondary voids formed in chemical or mechanical suffosion.

A hazard level for a structure with surface-type discontinuous deformations was indicatively classified, based on long-term observations, as small, medium and large, depending on the size of the collapse and geological and mining conditions [4] including, in particular, the thickness of roof rocks; a known method of eliminating headings connected with the surface; the existence of so-called “escape shafts”; fire events in the area of shallow coal exploitation; as well as suffosion and paraseismic events. Collapses with their diameter above 3.0 m are considered highly dangerous.

The classification of discontinuous deformations in the literature [2] relates to their shape (so-called generic classification), and surface-type deformations are distinguished (Fig. 1a) of a local reach and closed contour occurring as collapses, landslides and land upheavals and linear-type deformations with their clearly longitudinal course (Fig. 1b), assuming the form of cracks, crevices, ditches and terrain faults and bumps.

With regard to the level of exposure of building structures to discontinuous deformations with specific values, a quantitative deformation is used [2] the basis of which is a maximum dimension of the horizontal plan d of surface deformations and the width of a crevice s and terrain fault height h in linear deformations. Collapses with the diameter of $d \leq 3$ m are classified as small, with the diameter of $3 \text{ m} < d \leq 9$ m as medium, with the diameter of $9 \text{ m} < d \leq 18$ m as large, and when the diameter is $d > 18$ m, a collapse is classified as large.

3. THE IMPACT OF DISCONTINUOUS LAND DEFORMATIONS ON BURIED PIPELINES

The formation of local discontinuous deformations is dangerous for building structures [9] and for line facilities, including buried piping. The issue of the effort state of a pipeline in the conditions of a local discontinuous deformation in the form of a collapse may be considered more broadly, as non-homogenous support of a pipe structure. Such case can be considered not only in the conditions of local discontinuous deformations, but also when a pipe is laid carelessly in a trench, when uneven land depressions exist or in case of erosion effects. In each of these cases, a pipeline is not supported continuously along its length in the ground subbase and, as a consequence, while working according to the changed static patterns, is exposed to bending along the longitudinal axis. The distribution of generalised internal forces in the cross section is also changed.

In the calculation methods available, a pipeline laid in the area of a collapse is considered using a simplified static chart. A pipeline is treated as a beam with the set flexural stiffness EI, resting on the Winkler ground foundation [13]. A piece of the beam in the area of the collapse is represented by a span loaded with its own weight, the weight of the medium run through the pipe and the weight of the ground retained by the pipe when the ground mass is moving down and during the formation of a collapse. The longitudinal bending moment in a partially supported pipeline may also be determined considering different dimensions of a local collapse and the length of a straight pipe section between joints, e.g. between socket connections (Fig. 2) [10]. Depending on the length of spans (unsupported section), a pipe is treated as a beam with different static schemes (Fig. 2). This solution is indicative and does not consider the interwork between the pipeline and the ground.

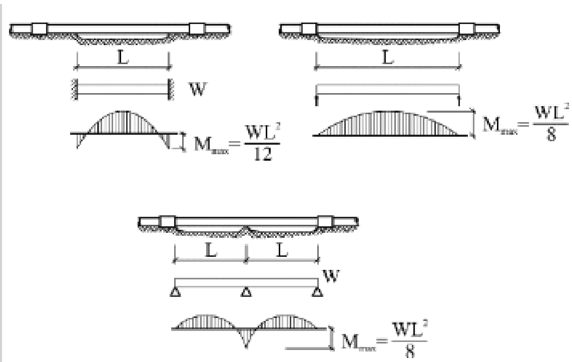

Figure 2.
Calculation charts of pipeline laid in the area of collapse: a) beam fitted rigidly from both sides, b) freely supported beam, c) double-span beam [10]

4. NUMERICAL MODELLING OF THE IMPACT OF COLLAPSE ON PIPELINE

A 3D numerical analysis of a pipe – soil system model was performed (with Z_Soil acad. ver.11.03 software) to reflect the behaviour of a pipeline laid in the ground within the reach of a local collapse [12]. The model is representing a straight section of a flexible PVC-U pipeline with the diameter of ϕ500, length of 40 m and wall thickness of 19.1 mm laid in homogenous ground. The layer of ground covering the pipe is 2.0 m. An irregularly shaped collapse located in the lower zone of the pipe support is situated in the central part of the pipe segment at the section of 2.0 m. The pipeline was modelled according to its flexibility, and a large-area elastic-plastic model was applied for soil modelling with Hardening Soil – Small isotropic strengthening [1], [7], [11]. The basic characteristics of the model are described in part I of the paper. The analysis programme includes only the modelling of the collapse formation process over time, without a load working onto the model surface. The modelling of the process was performed introducing a procedure of reducing soil parameters (c – cohesion and φ – internal friction angle) in the material zone, representing the collapse area. Such modelling is possible in Z_Soil software only using a constitutive Mohr-Coulomb model. The initial values of $c = 20$ kN/m^2 and $\varphi = 270$ were introduced in this area.

The soil mass is dimensioned 6 m x 4 m x 22 m. The model was built of elements consisting of eight nodes (the number of model nodes: 20,582, the number of *Continuum* type elements reflecting the soil mass: 17,920). The pipeline was modelled with the *Shell* type elements (the number of elements: 840). The number of *Boundary Conditions* supports: 3,283. A general view of the mode is shown in Fig. 3, while Fig. 4 shows the location and shape of a collapse inside the soil mass model.

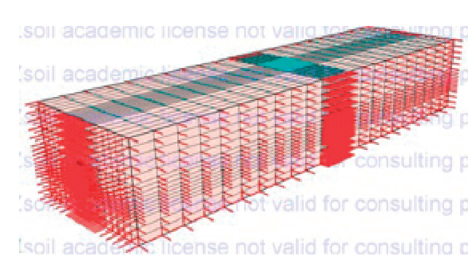

Figure 3.
General view of 3D numerical model the pipeline-soil system

The results of the numerical analysis were shown as graphics by juxtaposing the maps of displacements and stresses in the soil mass, images of pipeline deformation and distribution of stresses in the pipeline coating in order to make a qualitative assessment of the collapse's impact on the analysed pipeline

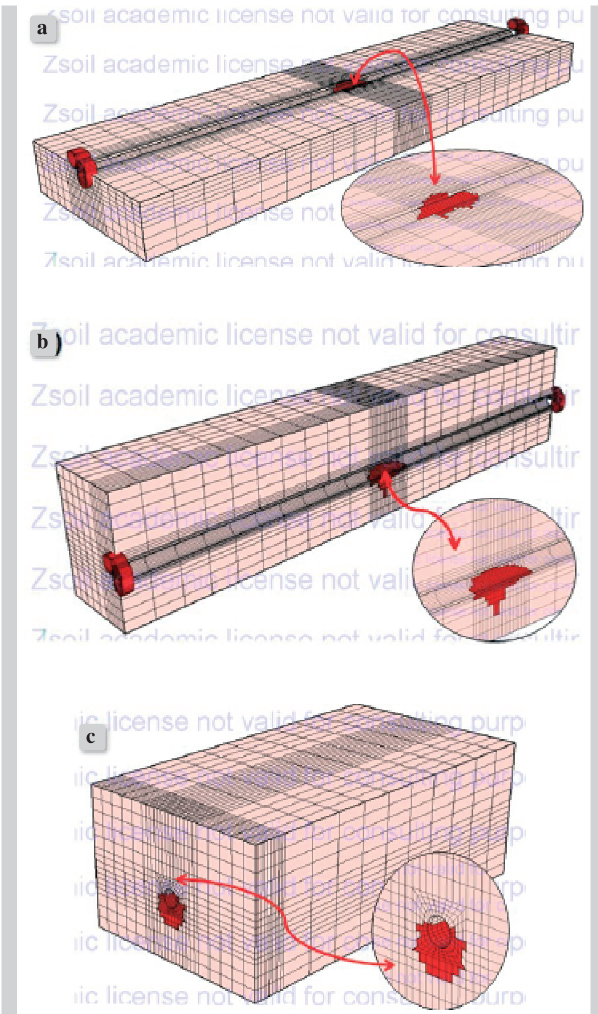

Figure 4.
Cross section of the pipeline – soil system model showing the location and shape of the collapse: a) horizontal cross section, b) vertical longitudinal section, c) cross section

The zones of soil displacement in the collapse area are shown in Fig. 5. Soil is displaced over the pipe as well as in the zone underneath the pipe, and displacements in the lower zone are more intensive (maximum soil displacement in the lower zone of the pipe support is 12 mm).

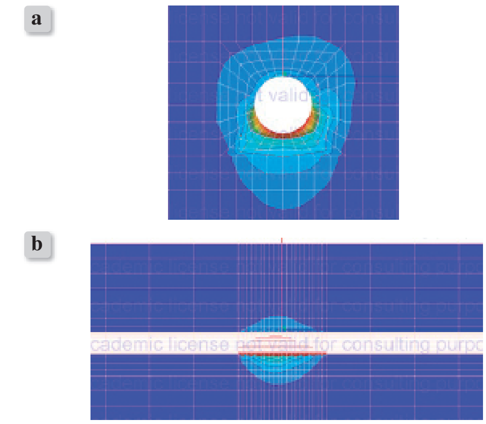

Figure 5.
Map of resultant displacements in the soil mass in the collapse area: a) cross section of the soil mass (fragment), b) longitudinal section of the soil mass (fragment)

As the collapse is forming, so is disturbed the state of stress in the soil mass. This is shown with an example of the map of vertical stresses in the soil (Fig. 6).

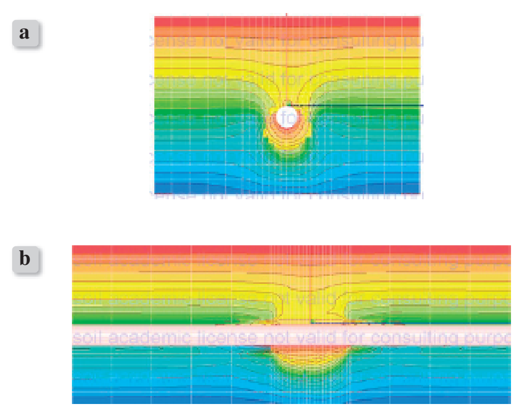

Figure 6.
Maps of vertical stresses in soil: a) cross section of the soil mass in the collapse area, b) longitudinal section of the soil mass

The maps are illustrating the uniform distribution of vertical stresses in the side zones of the model (σ_{max} = 60 kN/m^2) and strong changes in the course of the isoline of such stresses in the direct surrounding of the pipe and collapse.

Once the local collapse is formed, a PVC_U pipe is locally adapting its shape partially to the deforming soil (Fig. 7). Due to high rigidity of the pipe, a maximum displacement of its lower constituent part is small, i.e. around 1.5 mm.

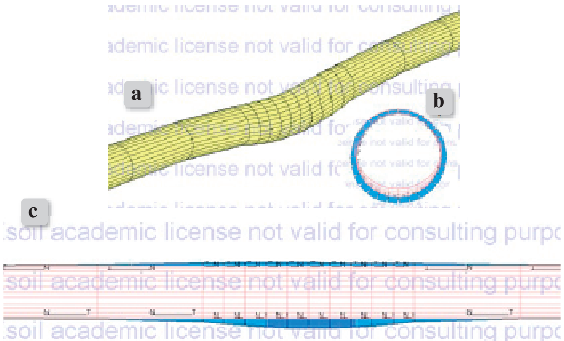

Figure 7.
Visualisation of pipe deformation in the collapse area: a) 3D view, b) cross section deformation, c) longitudinal section deformation

The change of pipeline support conditions in the formation zone of the local collapse, and consequently changes in pipeline loads and pipe deformation, are influencing the distribution of stresses in its coating. The maps of stresses (Fig. 8) in the longitudinal and circumferential direction in the pipe coating are shown in the figures, including a fragment of the pipeline in the collapse areas. The stresses in the longitudinal direction reach values within the range of σ_{max} = 1028 kN/m^2 (stretching, the lower constituent part of the pipe) to σ_{min} = -643 kN/m^2 (compression, the upper constituent part of the pipe). The distribution of stresses in the circumferential direction is complex, the extreme values span between σ_{max} = 650 kN/m^2 to σ_{min} = -524 kN/m2. The reduced stresses calculated on the basis of values of circumferential and longitudinal stresses (Hubera-von Mises hypothesis) reach the maximum value of 1.5 MPa, accounting for approx. 12% of the values of stresses permitted for such type of pipelines.

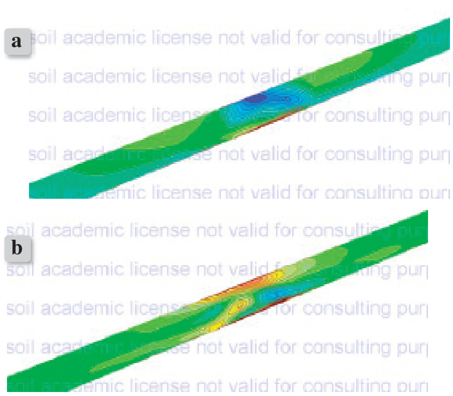

Figure 8.
Visualisation of stresses in the pipeline coating: a) in the longitudinal direction, b) in the circumferential direction

5. SUMMARY

Discontinuous mining deformations are posing a substantial threat to buried pipelines located within the range of such deformations. Land collapses, especially, being often the effect of reactivating old mine headings, are resulting in losing the continuity of pipeline support. This has an adverse effect on the change of conditions of appropriate functioning of the pipe and, as a consequence, reduces durability, and in extreme cases may cause pipe damage.

As no analytical methods for estimating the effort state of the pipeline located in the collapse area are available, numerical analyses are an effective tool for investigating the system of the interworking structures: a pipeline and the ground space with a local void. Information is acquired, as a result of the analysis, about a pipe structure's deformation and effort state as well as about effects occurring in the ground space (displacements, stresses). An important advantage of the analysis is that plastic characteristics of ground can be taken into account as well as the execution of the loading process according to time.

The numerical analysis performed has indicated a significant effect of the incomplete support of a pipeline on the deformation and distribution of generalised internal forces in the pipeline wall. The collapse impact zone is largely exceeding its dimension. A spatial deformation of the analysed flexible pipeline is clearly visible in this zone and clearly disrupted distribution of stresses in the pipeline coating, both, in the longitudinal and lateral direction. It should be highlighted that in order to show the impact of the local collapse on the effort state of the pipeline, the stresses are determined for the pipe - soil system model in which no surface loads were introduced, which could have increased pipe deformation and its state of effort. The analysis results should be considered as a qualitative illustration of the phenomena taking place in the ground space and in the pipeline coating during the formation of a local collapse. The results obtained are, therefore, up to date for the adopted constitutive soil model and for the material parameters introduced for calculation of values.

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