WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.147657

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 4 2023

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pp. 227 – 245

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Research paper

Analysis of the effects of using various backfill materials in the buried pipelines construction

Barbara Kliszczewicz[1]

Abstract: In the article the effects of backfilling an underground, flexible pipeline, using natural materials (ground backfill) and modified materials, so called Lightweight Backfilling Materials (LBMs) were analyzed. These materials, thanks their lower density, have a positive effect on reducing the loads on the underground pipeline and, consequently, reducing deformations and stresses in its wall. LBMs include lightweight expanded clay aggregates, recycled tire chips used directly in the trench or mixed with the soil, foam concrete, foam glass (granules or plates), and expanded polystyrene, embedded in the ground in the form of blocks. The assessment of the effects of modifying the backfill of the underground pipeline was carried out by means of multi-variant numerical analysis in which models of the pipe-soil system in a plane strain state (2D model) were tested. In these models PEHD pipes were represented, with differential of their diameter (DN315, DN600) and stiffness (SDR), as well as trenches of various shapes (trench with vertical walls and with sloping walls). In the numerical calculations, two variants of trench filling were analyzed: full filling with soil and filling with selected LBMs (expanded clay aggregates, expanded polystyrene, tire chips mixed with soil) in layers separated in the backfill. The results of numerical calculations for particular variants of the models were analyzed in terms of the distribution of vertical displacements and stresses in the soil and pipe deformation. The received pipe deflections and circumferential stresses in their wall were related to the permissible values for PEHD pipes.

Keywords: pipelines, Lightweight Backfilling Materials, numerical analysis

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1. Introduction

Nowadays PEHD polyethylene pipes are widely used in water supply systems, sewage systems, low and medium pressure gas pipelines, and finally as drainage pipes. Pipelines made of this material are mainly built using the traditional trench method. Depending on the ground conditions, the pipes are laid in narrow trenches with vertical walls or in wide trenches with sloping walls, on bedding layers and then covered with soil to a height of approx. 0.3 m above the top of the pipe (customarily named *crown)*. The remaining part of the trench is most often filled with the soil that was set aside during the excavation (natural soil). In such a soil surrounding, the pipe transfers dead loads and another overburden loads, internal pressure (in the case of pressure pipes), transport loads, and in the particular case of mining areas – loads related to mining deformation of the surface area. The action of these complex load systems causes deformation of the flexible PEHD pipe and activation of the ground in the lateral zones (passive pressure) during the increase of the horizontal deformation [1–4]. The ongoing pipe deformation process stops when the pipe-soil system is established, and its scope and dynamics are independent of the pipe-soil stiffness relationship. The geometric parameters of the pipe (diameter, wall thickness), its strength parameters and material parameters of particular ground zones also play an important role in this process. The reaction of buried flexible pipes, including PEHD, to loads has been repeatedly analyzed analytically, laboratory and numerically (e.g. [5–8]). The main objective of these activities was to better understand the mechanism of operation of the pipe-soil system and to clarify the methods of determining pipe deflections.

Due to the significant role of loads in the process of pipe deformation, attempts are being made to develop a technology for the construction of underground pipelines using relatively light materials for full or partial filling of the trench. This solution has a beneficial effect on reducing the deformation of the pipe and stresses in its wall [9]. Lightweight backfilling materials (LBMs) include both natural materials, e.g. lightweight expanded clay aggregate (LECA) and industrially produced materials, e.g. expanded polystyrene block (EPS Geofoam), and finally waste materials used directly or mixed with soil, e.g. recycled tire chips mixed with soil (TDA/STCh). The use of these solutions leads to a more optimal design of pipes (possible reduction of wall thickness), in the case of using waste materials, it also has an ecological aspect (waste management). The condition for the effectiveness of the use of lightweight backfilling materials (LBMs) is, however, a good knowledge of the material parameters and the impact of placing them into the trench zone on the interaction between the pipes and the soil.

This publication attempts to investigate the effects of the use of selected lightweight backfilling materials (LBMs) in the case of PEHD pipes laid in trenches with vertical and sloping walls. This study was carried out using a multi-variant numerical analysis of the 2D model of the pipe-soil system, made in the ZSOIL program [10]. Three variants of partial filling of trenches with layers of lightweight expanded clay aggregate, expanded polystyrene block and recycled tire chips mixed with soil were considered in the analysis.

The assessment of the effects of using these layers was carried out by examining the stresses in the soil surrounding the pipe, as well as the deformation and stress of pipe ring, in the context of limited values. Conclusions were also formulated regarding the interaction of the analyzed pipes with the soil.

2. Numerical analysis of the pipe-soil system

2.1. Finite element modelling of buried pipe PEHD

The FEM models, built for numerical analysis in the ZSOIL program, represent an pipeline laid in the soil using the trench method. Models (2D, plane strain state) represent a cross-section of a pipeline of unit length, surrounded by soil (pipe-soil system). As variants, the models represent a pipeline laid in a narrow trench with vertical walls and a wide trench with sloping walls. The subject of the analysis are flexible PEHD pipes with DN315 and DN600 diameters, laid on a 0.2 m thick layer of bedding and covered with soil to a height of 0.3 m above the top of the pipe. The remaining part of the trench is filled with soil, into which a layer of selected LBMs with a thickness of 0.8 m was introduced in variants. The dimensions of the FEM models were adapted to the diameters of the analyzed pipelines and the conditions of their arrangement in narrow and wide trenches. These dimensions are as follows:

– DN315: narrow trench – $L = 3.0$ m, $H = 2.8$ m, wide trench – $L = 6.0$ m, $H = 3.3$ m.
– DN600: narrow trench – $L = 4.0$ m, $H = 3.5$ m, wide trench – $L = 6.0$ m, $H = 3.6$ m.

The dimensions of the trenches were adopted in accordance with [11], introducing the minimum working space between the trench wall and the outer diameter of the pipe with a width of 0.5 m. The thickness of the layer covering the pipe is 1.6 m (DN315) and 1.5 m (DN600), respectively.

On the upper edge of the models a leveling layer, whose task is to evenly transfer the load, with a thickness of 0.1 m was introduced. Variants of the pipe-soil system models with marked material zones are shown in Fig. 1.

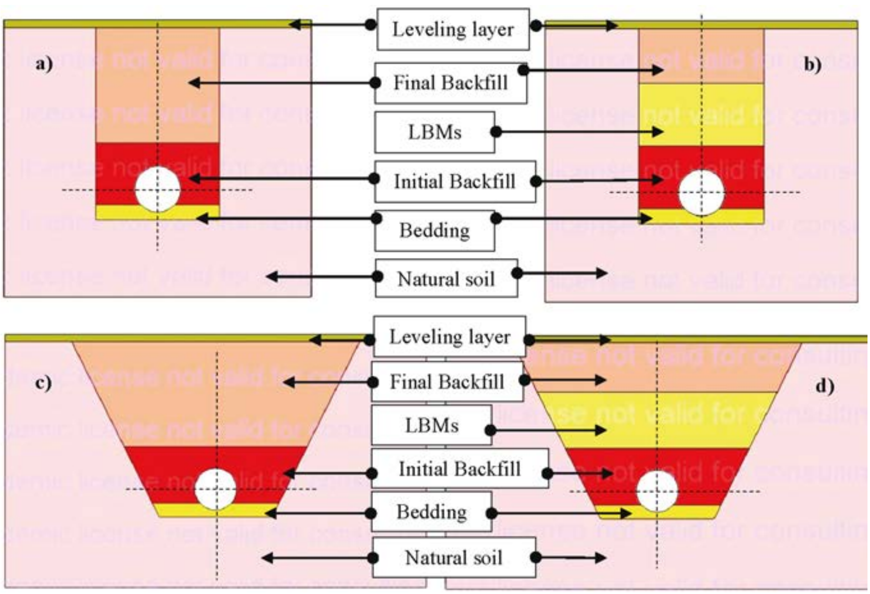

Fig. 1. Models of the pipe-soil system: a) narrow trench, filling with soil, b) narrow trench, filling with LBMs layer, c) wide trench, filling with soil, d) wide trench, filling with LBMs layer

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In all models, the same boundary conditions were applied in the form of sliding supports, limiting only horizontal displacements on both vertical edges of the model, and non-moving supports on its bottom edge. The load of the models (*LF*) was applied on the upper edge, in the area above the trench. This load had static and uniform character. In the performed numerical analyses, which were incremental and iterative, the load increases linearly from $LF = 0$ to $LF = 150$ kN/m^2 (*Time Dependent* 0 to 5, *increment* 0.1).

Three- and four-node elements (*Continuum*) and *Beam* elements (PEHD pipe) were used to build models of the soil-pipe system.

2.2. Material parameters

The particular material zones represent the natural soil (cohesive, semi-compact soil), trench fill (medium compacted medium sand), backfill (medium compacted coarse sand), foundation (coarse, medium compacted sand) and optionally a layer of expanded clay (symbol: LECA), a layer of expanded polystyrene (symbol: EPS) and a layer of soil mixed with tire chips (40%) (symbol: TDA). The behavior of all materials under load, except EPS and PEHD, was described by the elastic-perfectly plastic Mohr-Coulomb (MC) failure criterion. EPS and PEHD were modeled as elastic materials. The parameters of the material zones, the parameters of the PEHD pipe and leveling layer are summarized in Table 1.

Table 1. Material parameters

Material	Young Modulus [MPa]	Poisson ratio [–]	Unit weight [kN/m^3]	Friction angle [°]	Cohesion [kPa]	Dilatancy angle [°]
Natural soil	15.0	0.3	22.0	22	25	0
Final Backfill	15.0	0.3	22.0	22	10	0
Initial Backfill	9.0	0.3	17.0	35	1.0	5.0
Bedding	6.0	0.3	17.0	35	1.0	5.0
LECA	2.52	0.2	6.0	36	2.0	6.0
EPS	5.69	0.25	0,2	–	–	–
TDA	3.982	0.25	12.5	36	20	6.0
Leveling layer	150.0	0.3	22.8	30	15.0	0
PEHD	700.0	0.45	9.4	–	–	–

Material parameters were adopted on the basis of literature data: soil [12, 13], LECA [14], EPS [15, 16] TDA [17], leveling layer [18], PEHD [18].

2.3. Numerical analysis program

In the numerical calculations, pipe-soil models representing narrow and wide trenches, filled only with soil or alternatively with layers of three different LBMs (LECA, EPS and TDA) introduced into the trench fill zone with soil, were used. In addition, in these models, pipe diameters (DN315, DN600) and $SDR = e_n/D$ series in the range of SDR 41, SDR 26, SDR 21 and SDR 11 were analyzed as variants. This corresponds to wall thicknesses of e_n = 7.7 mm, 12.1 mm, 15.0 mm and 28.6 mm for DN315 and e_n = 14.7 mm, 23.1 mm, 28.6 mm and 54.5 mm for DN600, respectively.

All in, numerical calculations were made for 64 model variants. Individual model variants are marked according to the following scheme: diameter_SDR_trench type_filling type. For example, DN600_SDR11_N_SOIL refers to a 600 mm diameter pipe variant, SDR11, laid in a narrow trench filled with soil, and DN315_SDR41_W_EPS refers to a 315 mm diameter pipe variant, SDR41, laid in a wide soil filled trench with EPS.

3. Results and discussion

The results of the multi-variant numerical calculations performed were analyzed in terms of assessing the impact of placing layers of LBMs into the backfill zone in relation to the traditional filling of the trench with soil. This assessment was made by analyzing the deformation of the subsoil and PEHD pipes and the stress states associated with these deformations. The analyzes were carried out taking into account the diversification of trench shapes and its filling, pipe diameters and their stiffness.

3.1. Deformation of soil and of buried pipes PEHD

The action of static loads (*LF*) and dead loads of the soil and of the pipe, automatically generated in the ZSOIL software, cause deformation of the pipe-soil model. The top edge of the model deflections and the pipe model ovalizes. The distributions and displacement values of the model nodes change depending on its variant, but in all analyzed cases the vertical component (*Displacement Y*) is dominant in the absolute displacements (ABS). Examples of deformed meshes of the model are shown in Fig. 2 (models 600_SDR41_N_SOIL, 600_SDR41_W_SOIL). The shapes of the deformed pipe in a narrow and wide trenches are different.

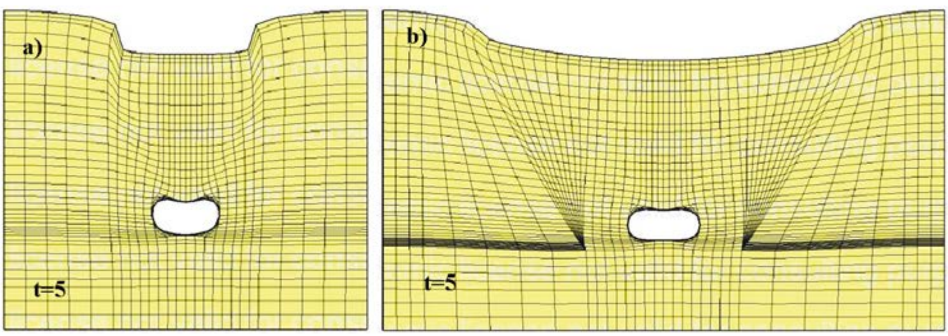

Fig. 2. Deformed mesh of models: a) 600_SDR41_N_SOIL, b) 600_SDR41_W_SOIL

The deformation of the subsoil was examined in two cases: by analyzing the deformation of the upper edge of the model and the distribution of vertical displacements of the model nodes, located in the backfill zone. In the first range, vertical displacements of the node situated on the upper edge of the model, on its vertical axis, were analyzed during the increase of the load (*LF*) – this point is marked in Fig. 3. The analysis was performed for models with a narrow and wide trench, filled only with soil and with optionally placed layers of LBMs. In these models, the PEHD pipe has the same stiffness (SDR41), while the diameter changes (DN315 and DN600). The results of these analyzes are shown in Fig. 3.

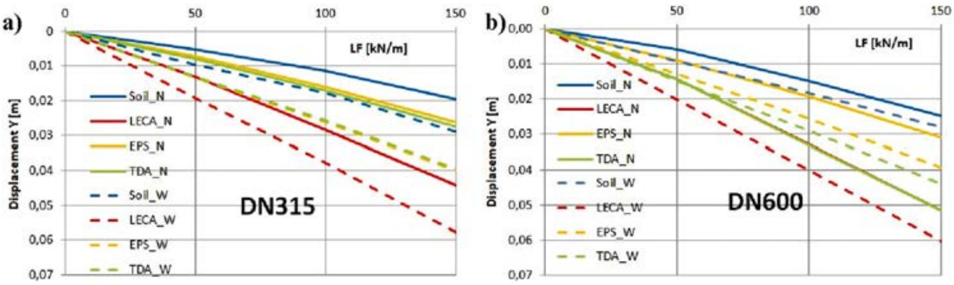

Fig. 3. Vertical displacements of the central point on upper model edge: a) narrow and wide trench – DN 315, b) narrow and wide trench – DN 600

The presented graphs show that, regardless of the size of the vertical pipe diameter, the displacement of the analyzed point are greater in case of wide trench. The placement of layers of LBMs material (especially LECA) increases the vertical displacements of the analyzed point in both types of trench.

Placement of LBMs layers significantly changes the distribution of vertical displacements of nodes, located in the backfill zone in comparison to filling the trench with soil only. This applies to both types of trenches, both pipe diameters and to all tested LBMs. For example, it is shown on the vertical displacement maps of the models 600_SDR41_N_SOIL, 600_SDR41_W_SOIL and 600_SDR41_N_LECA, 600_SDR41_W_LECA (Fig. 4). On all the maps of displacements the same scale of vertical components (0.0–6.1 mm) was used. In qualitative terms, the differences in the distribution of vertical displacements can be assessed as follows: the width of the trench clearly affects the change in the range of impacts of loads – the impact zone is definitely larger in the case of wide trenches. Placement of the LBMs (LECA layer) results in the accumulation of vertical displacements between the and the LBMs layer. At the same time, it causes an increase in the value of vertical displacements of the layer and a decrease in vertical displacements of the top point of the pipe (*crown*). The above observed trends in the distribution of vertical displacements apply to all analyzed models of the pipe-soil system.

The distribution of vertical displacements shown in Fig. 4 indicates that the layers of LBMs materials, somehow take over the effect of the *LF* load, accumulating vertical displacements.

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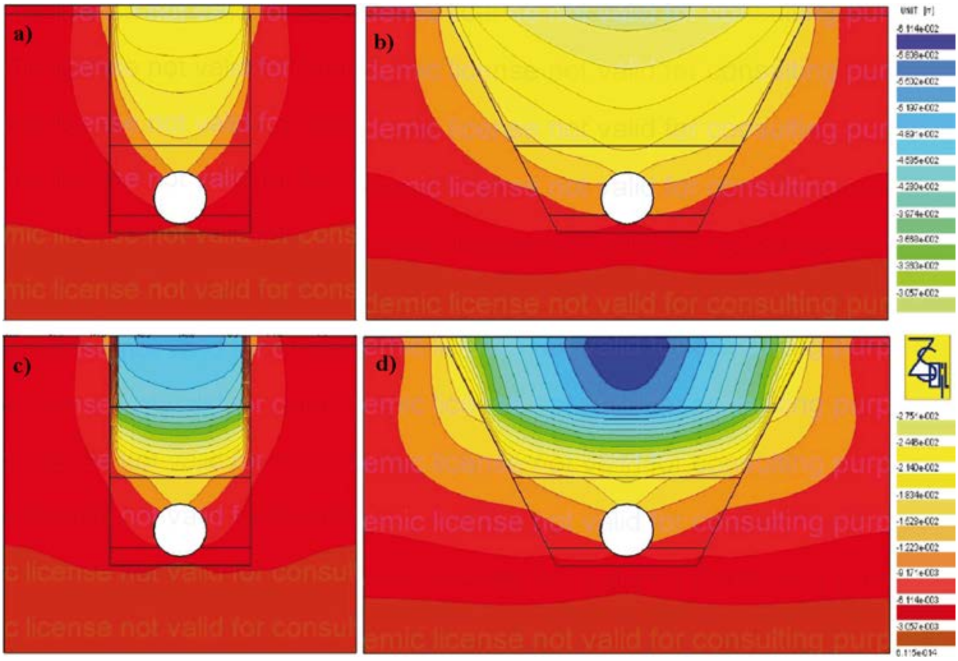

Fig. 4. Maps of displacements: a) 600_SDR41_N_SOIL, b) 600_SDR41_W_SOIL, c) 600_SDR41_N_LECA, d) 600_SDR41_W_LECA

The deformation of the PEHD pipe covered by traditional backfill and LBMs layers was examined by analyzing the distribution of vertical displacements of nodes in the top of the pipe (*crown*) – point is marked on the Fig. 5. This analysis was performed in relation to the value of the increasing load *LF*, for PEHD pipes with SDR 41 stiffness, diameters DN315 and DN600. The results of these analyzes are shown in Fig. 5. The vertical displacements of the top point of the pipe are clearly greater in the case of wider trenches, both for diameters DN315 and DN600. As a result of the unloading effect of

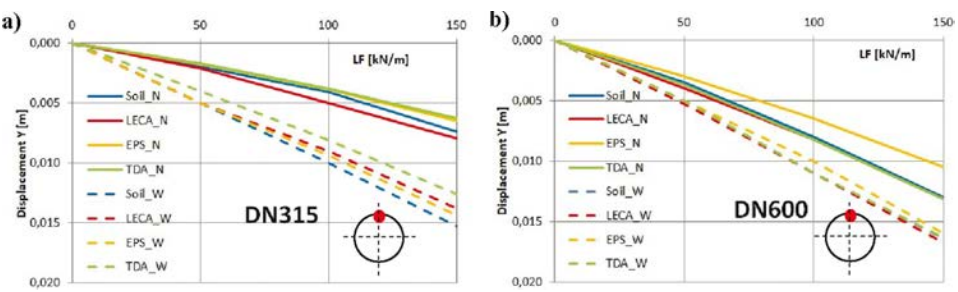

Fig. 5. Vertical displacements of the top point of pipe (*crown*): a) narrow and wide trenches – DN 315, b) narrow and wide trenches – DN 600

layers made of LBMs materials, the values of *crown* point's displacements in trenches with and without these layers are similar. This applies to both analyzed pipe diameters.

Deformation, in particular – pipe deflection, is essential for the proper functioning of PEHD pipes laid in the ground. For PEHD pipes, the value of the admissible deflection is 5%, which translates into a value of 15 mm for DN315 pipes and 30 mm for DN600 pipes, respectively. In the numerical analysis, the deflection of the pipe was determined as the difference in vertical displacements of its *crown* (top point) and *invert* (bottom point). Deflection values, expressed as a percentage, were determined for all built models. The distribution of these values for narrow and wide trenches, for diameters DN315 and DN600, for various pipe stiffness and various trench fillings is shown in Fig. 6.

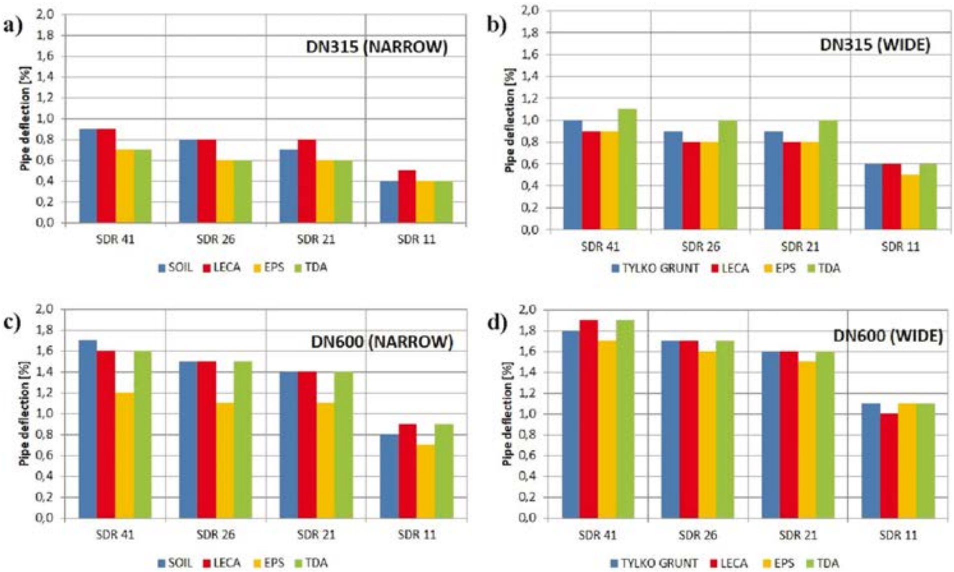

Fig. 6. Vertical displacements of the top point of pipe (*crown*): a) narrow and wide trenches – DN 315, b) narrow and wide trenches – DN 600

Pipe deflections (Fig. 6) vary, but they do not exceed the admissible deflection in any variant. Generally, it can be stated that the deflections of pipes with a diameter of DN315 are twice as small as the deflections of pipes with a diameter of DN600. Greater width of the trench increases the deflection of the pipes, this applies to both diameters.

The use of layers of LBMs materials affects pipes deflections in different ways. This is due to the different relationships between the stiffness of the pipes, the stiffness of the materials placed in the trench and foundation zones. Placement of the EPD layer reduces pipe deflections, regardless of the shape of the trench and the diameter of the pipe and SDR. On the other hand LECA layers act similarly to backfill soil, pipe deflections are comparable. The smallest effect of deflection reduction is observed in the case of the use of the TDA layer. It can also be seen that a greater diversification of deflections is visible at case SDR41 and SDR11.

3.2. State of stress in soil and in buried pipes PEHD

The state of stress in the soil is related to the acting loads. In the initial phase, ($t = 0$, $LF = 0$), the stresses in the soil result from the dead weights of each layers. These stresses increase as the load increases ($t = 5$, $LF = 150$ kN/m^2), and their distribution also changes. In addition, the change in the distribution of these stresses is influenced by layers made of LBMs. For example, it is shown in the maps of vertical stresses in the ground (Vertical stress), generated for the models 600_SDR41_N_SOIL, 600_SDR41_W_SOIL and 600_SDR41_N_LECA, 600_SDR41_W_LECA (Fig. 7). The stress distribution varies depending on the value of the *LF* load, the type of trench (narrow or wide trench) and the type of trench backfill (soil only or with LECA layer).

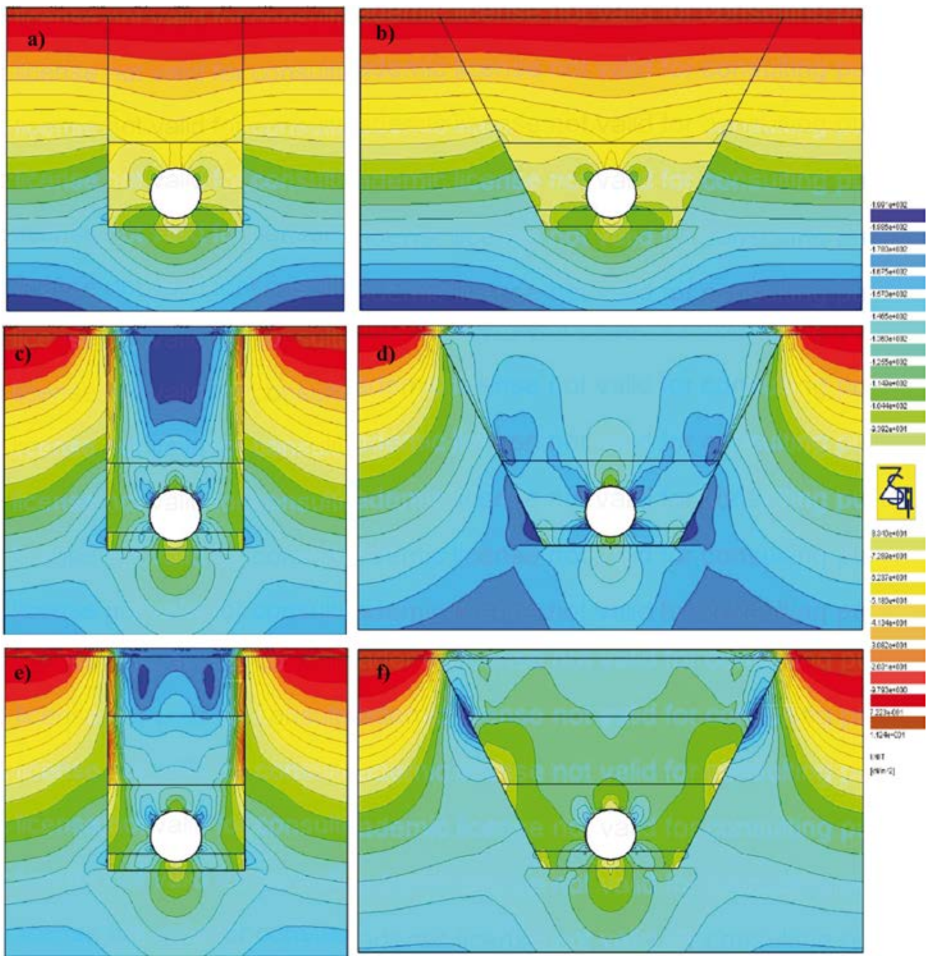

Fig. 7. Maps of vertical stress: a) 600_SDR41_N_SOIL ($t = 0$), b) 600_SDR41_W_SOIL ($t = 0$), c) 600_SDR41_W_SOIL ($t = 5$), d) 600_SDR41_W_SOIL ($t = 5$), e) 600_SDR41_W_LECA ($t = 5$), f) 600_SDR41_W_LECA ($t = 5$)

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The effect of placing layers of various LBMs materials on the values of vertical stresses in the soil above the pipe is shown in the diagrams, made for models DN600 SDR 41 (narrow trench and wide trench) in two calculation steps: $t = 0$, $LF = 0$ and $t = 5$, $LF = 150$ kN/m^2 (Fig. 8).

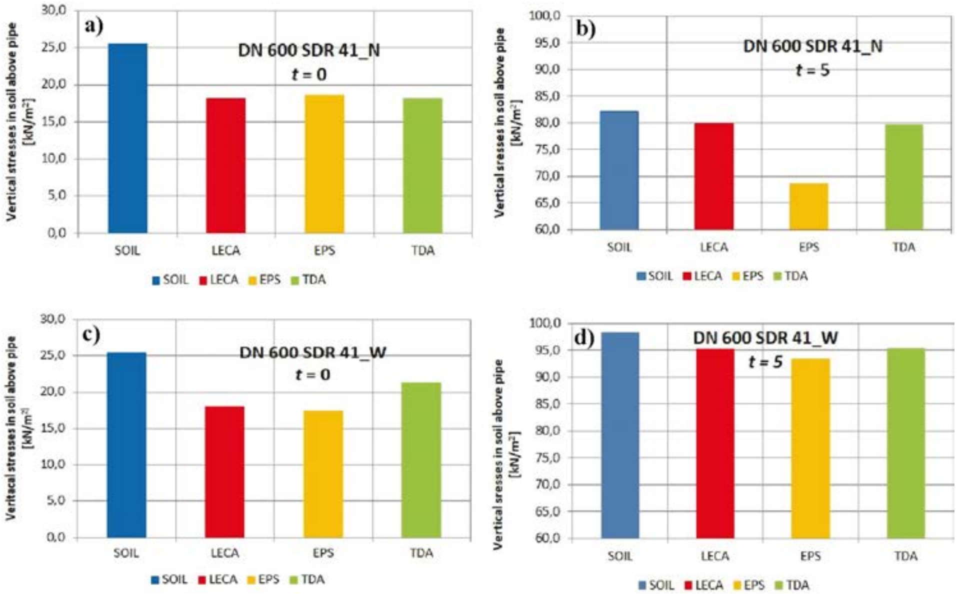

Fig. 8. Vertical stresses in soil above pipe for different LBMs: a) DN600_SDR41_N ($t = 0$), b) DN600_SDR41_N ($t = 5$), c) DN600_SDR41_W ($t = 0$), d) DN600_SDR41_W ($t = 5$)

In the case of using layers of LBMs materials, the values of vertical stresses above the pipe (Fig. 8) are lower than the values of vertical stresses when filling is with soil only. This proves the unloading nature of the introduced layers made of various LBMs (LECA, EPS, TDA). Reduction of the stress value varies depending on the type of material and the shape of the trench in both analyzed loading steps ($t = 0$ and $t = 5$). The relieving effect is most pronounced in the case of a wide trench at full load, especially when EPS layers are used. Placing of LBMs layers also affects the change in the distribution of stress values in the layer above the pipe over the entire width of the model. For example, this is shown for the DN600 SDR 41_W model (Fig. 9). After placing of LBMs layers, the vertical stresses in the entire trench zone are reduced, this applies to all the analyzed types of materials. At the same time, there is a slight increase in vertical stresses outside the trench zone.

The stresses in the ring (pipe section) were determined by analyzing the values of circumferential bending moments M_z and circumferential normal forces N_x, resulting from soil pressure in the backfill zone (variants – soil only or the use of LBMs layer). The action of loads causes a complex state of stress (bending combined with compression) in the ring. The circumferential bending moments M_z have different sign (±), the circumferential normal forces N_x are compressive (–). The distribution of moments M_z and forces N_x is

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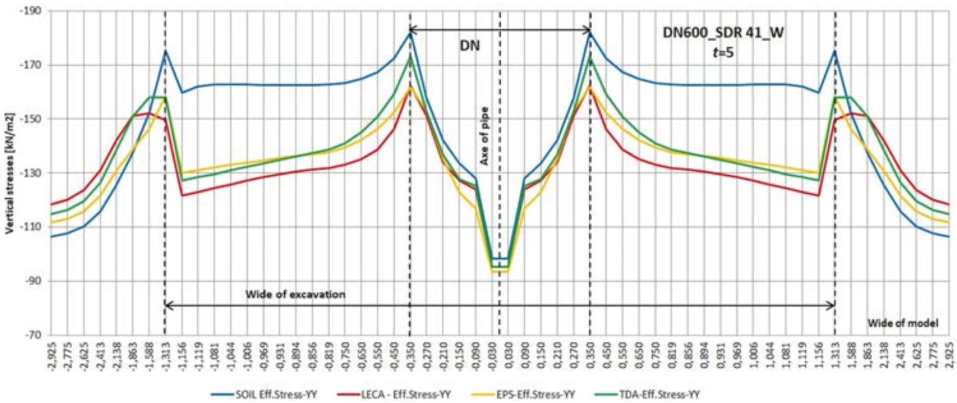

Fig. 9. Vertical stresses distribution in the zone above the pipe, model DN600_SDR41_W (t = 5)

shown, for example, for the DN600_SDR_41 model – placing in a narrow and wide trench, only in the soil (SOIL) and with the use of an EPS layer (Fig. 10).

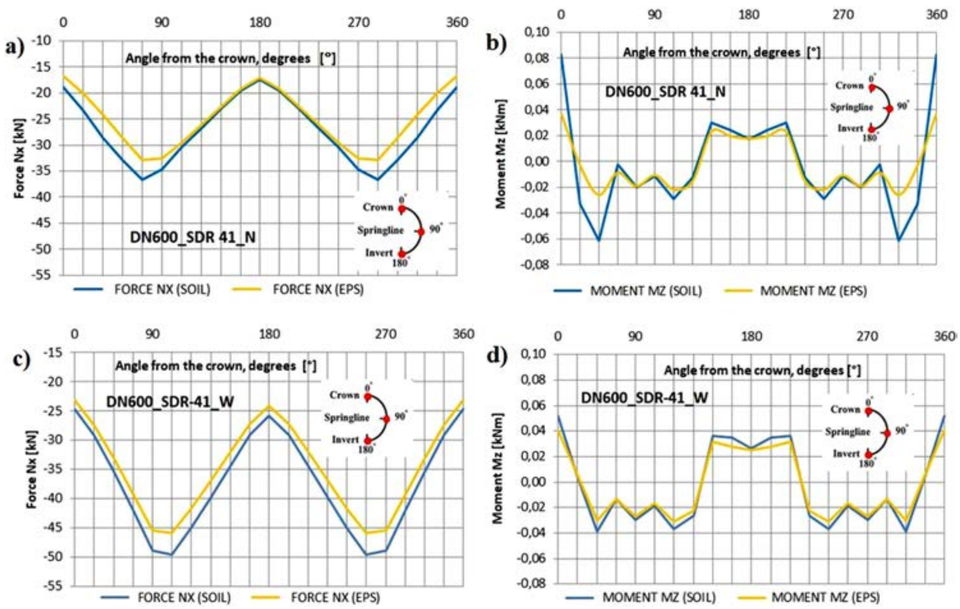

Fig. 10. Diagrams of forces N_x and moments M_z and for model DN600_SDR 41_SOIL/EPS
a), b) narrow trench, c), d) wide trench

When comparing the values and distributions of moments M_z in the models filled with soil only (SOIL) and with the EPS layer, the differences occur in the top part of the pipe ring (±30°) in models with a narrow trench. This is due to the fact, that in a narrow trench the possibility of free deformation of the pipe in the horizontal direction is limited, which increases the bending moments in the top part of the pipe. In the case of a wide trench, the normal forces N_x are almost twice as large as in the case of a narrow trench. Placing of EPS layers reduces the values of forces N_x and moments M_z in both types of trenches.

The stresses in the pipe wall were determined taking into account the simultaneous action of normal forces and bending moments in the section with the area of $F = 1.0 \cdot e_n$ [m^2]. Extreme values of normal forces N_x and bending moments M_z were obtained for the DN600_SDR 41 model. Therefore, the stress values were determined for this model, taking into account different trench shapes (narrow and wide trenches) and its various fillings (soil only, LECA, EPD, TDA). The distribution of stress values is shown in Fig. 11.

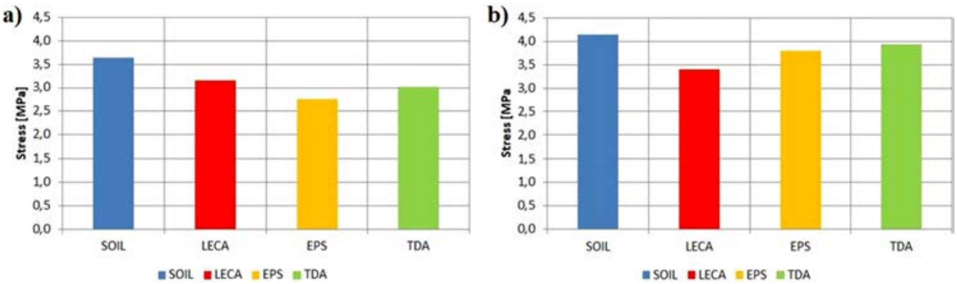

Fig. 11. Extreme stress in the pipe wall – model DN600 SDR41: a) narrow trench, b) wide trench

Stress values do not exceed the permissible value (for PE80 $\sigma_{lim} = 6.4$ MPa). The effect of using layers of LBMs materials in the form of reducing stress values is visible. For the narrow trench, the greatest reduction was obtained with the use of the EPS layer, for the wide trench – with the introduction of the LECA layer.

4. Conclusion

Numerical modeling of the pipe-soil system makes it possible to study the effects of using layers of LBMs in trenches of various shapes and widths (narrow trench and trench with inclined walls).

The presented multi-variant numerical analysis of the pipe-soil system models does not allow for the formulation of universal conclusions regarding the effects of using layers of selected LBMs (leca aggregate, expanded polystyrene, rubber waste mixed with soil) as a partial filling of trenches. Although the analysis was performed for 64 different models, it should be remembered that specific values of material parameters of individual soil zones (natural soil, bedding, initial backfill, final backfill) were introduced into the calculations. This is important for the calculation results, which depend on the mutual relationship of the stiffness of particular layers. In addition, FEM analyzes are approximate. Therefore, the presented analysis should be treated as an academic study, on the basis of which trends in the studied effects can be commented on.

The performed numerical calculations provided such a wide range of results in terms of node displacements and stresses in model elements that only some of them were presented

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in the article, those in which extreme analyzed values were obtained. The results make it possible to assess the effects of applying layers of selected LBMs materials in the analyzed trenches, including pipe deflections and stresses, occurring both in the soil and in the pipe walls. This was the main aim of the research. On the basis of the obtained results it is also possible to formulate conclusions that go beyond this main objective, and concern the interaction of the tested PEHD pipes with the soil.

The interaction of the pipe with the soil is illustrated by the horizontal displacements of the model nodes (*springline* point), which proves the horizontal deformation of the pipe. The nature of this interaction is influenced by a number of factors, including soil parameters, pipe diameters and SDR, and the type of trench (trench with vertical or inclined walls). Based on the analysis of the obtained calculation results, it can be concluded that the use of layers of selected LBMs materials (leca, expanded polystyrene, rubber waste mixed with soil) also affects the interaction of PEHD pipes with the ground. Although the values of horizontal displacements are small, one can talk about certain tendencies of this influence. Horizontal pipe deformations increase with increasing trench width and decreasing pipe stiffness (Fig. 12). This applies to both analyzed pipe diameters. Horizontal displacements for pipes with stiffness SDR 41 to SDR 21 remain at a similar level, they decrease at SDR 11. The effect of placing layers of LBMs materials varies for pipes DN315 and DN600 depends on the width of the trench.

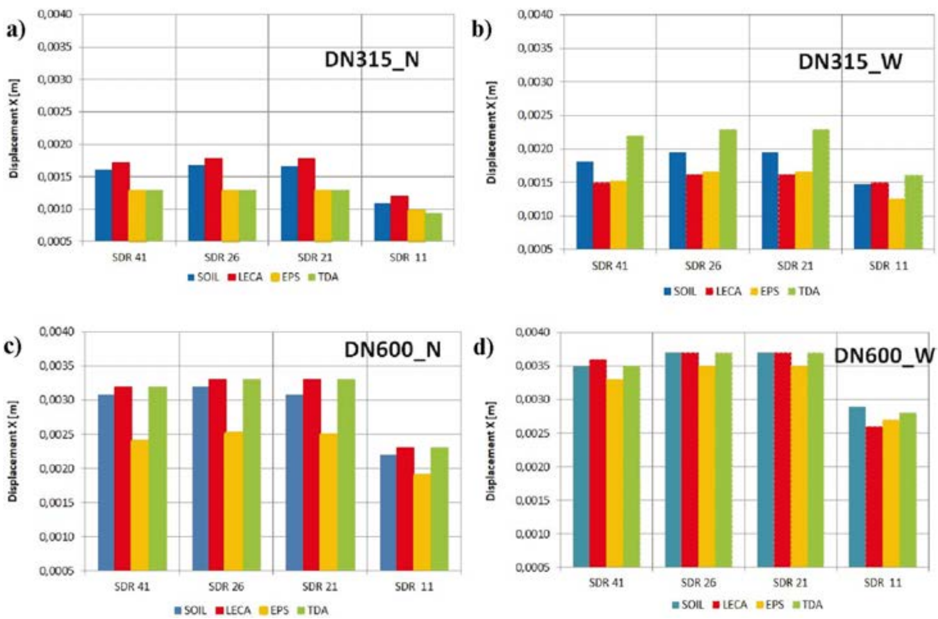

Fig. 12. Horizontal displacements: a) DN315 – narrow trench, b) DN315 – wide trench, c) DN600 – narrow trench, b) DN600 – wide trench

In the case of narrow trenches, for the diameter of DN315, placing of LECA layers increases horizontal displacements, while EPS and TDA layers reduce these displacements.

For the DN600 diameter, the LECA and TDA layers increase the horizontal displacements, the EPS layers reduce the horizontal deformation. In turn, in the case of wide trenches, for the diameter of DN315, both LECA and TDA layers influence the increase in horizontal displacements, while EPS layers reduce horizontal deformation. For the DN600 diameter, the effect of layers from all LBMs materials is similar.

The impact of the application of LBMs layers on the deflections of PEHD pipes was analyzed by comparing the deflections of pipes in a trench filled only with soil with the deflections occurring when these layers were placed into the trench. The pipe deflections vary depending on the width of the trench and the type of its filling as well as on the diameter and stiffness of the pipe. The deflections of pipes laid in trenches filled only with soil decrease with increasing pipe stiffness. Larger values of deflections occur in the case of wide trenches, this applies to both analyzed pipe diameters. These intuitively perceptible tendencies change when layers of the analyzed LBMs are introduced into the trench zone, which causes changes in pipe deflections (Fig. 6). The effectiveness of these changes is varied and can be characterized as follows:

- the application of layers of expanded clay (LECA) either does not change the deflections of pipes covered only with soil, or changes them to a very small extent.
- the introduction of layers of expanded polystyrene (EPS) reduces pipe deflections. This applies to both types of trenches and both analyzed pipe diameters.
- the introduction of layers of rubber waste mixed with soil (TDA) varies depending on the type of trench. In the case of trenches with vertical walls, a reduction in pipe deflections was observed, and it is more visible in the case of pipes with a diameter of DN315. In the case of trenches with inclined walls, the deflections increase (DN315) or do not change (DN600).

It should be emphasized that the registered changes in deflections are small, but they are undoubtedly related to the diversification of material parameters and the stiffness of the LBMs layers. However, the pipe deflections determined in the numerical analysis of the pipe-soil system do not exceed the limited value.

Changes in the distribution of **vertical stresses in the soil** were studied by comparing their distribution in the case of pipes laid in trenches with vertical and inclined walls, filled only with soil, and in trenches with layers of LBMs (Fig. 7 and 8). The acting loads, the type of trench and its filling affect the distribution of vertical stresses in the soil. In the starting phase ($t = 0$, $LF = 0$), the stresses in the soil result from the weights of the soil above the pipe, their distribution and values change as the applied load increases, reaching largest values at $t = 5$, $LF = 150$ kN/m^2. Due to the flexibility of PEHD pipes, the positive earth arches, characteristic of flexible pipes are visible, reducing the stress above the pipe. The type and width of the trench are important for the distribution of vertical stresses above the pipe. In the case of a narrow trench filled with soil, stress accumulation is observed in the zone under the surface layers and a strong variability of these stresses in the side zones, related to the friction of the backfill material against the walls of the trench. When layers of LBMs are placing, a clear unloading effect is observed (Fig. 8). This effect is particularly visible for pipes with the lowest stiffness (SDR 41), it applies to all analyzed materials and both pipe diameters. Reduction of vertical stresses in the zone above the pipe is the greatest when using a layer of extruded polystyrene (EPS) in both types of trench. The reduction in the value of vertical stresses with the use of other materials (LECA and TDA) is visible in the case of a wide trench. In this type of trench, the introduction of layers of LBMs also results in a significant reduction of vertical stresses along the entire width of the trench (Fig. 9).

Reducing pipe loads (vertical stresses in the soil in the zone above the pipe) caused by the placing of LBMs layers also results in a decrease in the value of bending moments M_z and normal forces N_x in the pipe ring (Fig. 10). As a consequence, stresses in the pipe wall are also reduced (Fig. 11). The reducing effect of these layers is most visible in the case of a narrow trench and EPS layer. In the wide trench, the greatest reduction of stress occurred when the LECA layer was placed. The stress values in the pipe ring of the pipe-soil system determined in the numerical analysis do not exceed the limiting value (for PE80 $\sigma_{lim} = 6.3$ MPa).

The above-described differentiation of the effects of the use of LBMs materials in terms of pipe deflections and their effort is difficult to comment unequivocally. This is due to the fact that the interaction of the analyzed HDPE pipes with the soil is influenced by many factors at the same time. Obtaining a more unambiguous assessment of the effects of using layers of LBMs in trenches requires extending the scope of analyzes to include pipes of larger diameters, laid in trenches of greater depth.

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Analiza efektów stosowania różnych materiałów zasypkowych w budowie podziemnych rurociągów

Słowa kluczowe: rurociągi, materiały LBMs, analiza numeryczna

Streszczenie:

Współcześnie rury polietylenu PEHD stosowane są szeroko w systemach zaopatrzenia w wodę, kanalizacji, gazociągach niskiego i średniego ciśnienia czy wreszcie jako rury drenażowe. Rurociągi z tego materiału budowane są głównie metodą tradycyjną, wykopową. W zależności od warunków gruntowych rury układane są w wykopach wąskich, o ścianach pionowych lub w wykopach szerokich, o ścianach nachylonych, na warstwach podsypkowych a następnie obsypywane gruntem na wysokość ok. 0,3 m ponad górny punkt rury. Pozostała część wykopu najczęściej wypełniania jest gruntem, który został odłożony przy wykonywaniu wykopu (grunt rodzimy). W takim otoczeniu gruntowym rura przenosi obciążenia związane z ciężarem warstw nadkładowych, ciśnieniem wewnętrznym (w wypadku rur ciśnieniowych), obciążenia komunikacyjne a w szczególnym przypadku terenów górniczych – obciążenia związane z górniczą deformacją terenu. Działanie tych złożonych układów obciążeń wywołuje deformację elastycznej rury PEHD i aktywizację gruntu w strefach bocznych (parcie bierne) w trakcie narastania poziomej deformacji [1–4]. Przebiegający w czasie proces deformacji rury ustaje w momencie ustalenia się równowagi w układzie rura-grunt, a jego zakres i dynamika jest zależna od relacji sztywności rury i gruntu. Istotne znaczenie w tym procesie odgrywają także parametry geometryczne rury (średnica, grubość ścianki), jej parametry wytrzymałościowe oraz parametry materiałowe poszczególnych stref gruntowych. Reakcja podziemnych rur elastycznych, w tym PEHD, na działanie obciążeń była wielokrotnie analizowana analityczne, laboratoryjnie a także numerycznie, np. [5–8]. Głównym celem tych analiz było lepsze poznanie mechanizmu działania układu rura-grunt oraz doprecyzowanie metod wyznaczania ugięć rur.

W związku z istotną rolą obciążeń w procesie deformacji rury podejmowane są próby opracowania technologii budowy podziemnych rurociągów z wykorzystaniem stosunkowo lekkich materiałów, tzw. lightweight backfilling materials (LBMs), do pełnego lub częściowego wypełnienia wykopu [9].

Takie rozwiązanie ma na celu odciążenie rury i w konsekwencji zmniejszenie jej deformacji oraz naprężenia w jej ściance. Do materiałów typu LBMs zaliczyć można zarówno materiały naturalne, np. keramzyt (LECA) jak i wytwarzane przemysłowo, np. polistyren spieniony (EPS Geofoam) czy wreszcie materiały odpadowe (skrawki z opon) stosowane bezpośrednio lub mieszane z gruntem (TDA/ STCh). Zastosowanie tych rozwiązań prowadzi do bardziej optymalnego projektowaniem rur (ewentualne zmniejszenie grubości ścianek), a w wypadku stosowania materiałów odpadowych ma także aspekt ekologiczny (zagospodarowanie odpadów). Warunkiem skuteczności stosowania LBMs jest jednak dobra znajomość parametrów materiałowych tych materiałów oraz wpływu wprowadzenia ich w strefę wykopu na interakcję rur z gruntem.

W niniejszej publikacji podjęto próbę zbadania efektów zastosowania wybranych materiałów typu LBMs w budowie podziemnych rurociągów PEHD. Badanie to przeprowadzono za pomocą wielowariantowej numerycznej analizy modelu 2D układu rura-grunt, wykonanej w programie ZSOIL [10]. Modele FEM, zbudowane na potrzeby analizy numerycznej, reprezentują rurociąg PEHD ułożony w gruncie metodą wykopową. Modele te typu 2D (płaski stan odkształcenia) przedstawiają przekrój poprzeczny rurociągu o jednostkowej długości, otoczonego gruntem (układ rura-grunt). W analizie rozpatrzono dwa warianty kształtu wykopu (wąski o ścianach pionowych i szeroki o ścianach nachylonych) oraz trzy warianty częściowego wypeł nienia wykopów warstwami keramzytu (ozn. LECA), bloczkami z polistyrenu spienionego (ozn. EPS), odpadami gumowymi zmieszanymi z gruntem (ozn. TDA). Obliczenia wykonano dla 64. różnych modeli układu rura-grunt. Przedmiotem analizy były podatne rury PEHD, o średnicach DN315 i DN600 i zróżnicowanych sztywnościach (SDR 11, SDR 21, SDR 26 i SDR 41). Rury ułożone zostały na warstwie podsypki o grubości 0,2 m i obsypane gruntem (obsypka) na wysokość 0.3 m ponad górny punkt rury. Pozostała część wykopu wypełniona była wyłącznie gruntem (ozn. SOIL), lub wariantowo gruntem, do którego wprowadzano warstwę materiałów LBMs (grubość warstw 0.8 m). Na górnej krawędzi modeli, w strefie o szerokości odpowiadającej szerokości wykopu, przyłożono obciążenie *LF*, o charakterze statycznym, równomiernie rozłożonym. W wykonanych analizach numerycznych, które miały charakter przyrostowo-iteracyjny, obciążenie to narastało liniowo od wartości 0 do wartości 150 kN/m^2. Warstwy gruntu, keramzytu i odpadów gumowych zmieszanych z gruntem modelowano za pomocą modelu Mohra–Coulomba, warstwę EPS ora z rurę PEHD – w zakresie sprężystym.

Wykonane obliczenia numeryczne dostarczyły bardzo szeroką paletę wyników w zakresie przemieszczeń węzłów i naprężeń w elementach modeli. W artykule zaprezentowano tylko niektóre z nich, głównie te w których uzyskano ekstremalne analizowane wartości. Prezentowana wielowariantowa analiza numeryczna modeli układu rura-grunt nie pozwala jednak na sformułowanie uniwersalnych wniosków dotyczących efektów zastosowania warstw z wybranych materiałów jako częściowego wypełnienie wykopów. Wynika to z faktu, iż do obliczeń wprowadzono konkretne wartości parametrów poszczególnych stref materiałowych. Ponadto analizy MES mają charakter przybliżony. Należy zatem traktować prezentowaną analizę jako pewne studium przypadku, na podstawie którego można skomentować tendencje w badanych efektach. Poniżej zaprezentowano podsumowanie i wnioski z wykonanych obliczeń numerycznych:

Interakcję rury z gruntem ilustrują poziome przemieszczenia węzłów modeli (punkt boczny *Springline*), świadczące o poziomej deformacji rury. Na charakter tej interakcji wpływa szereg czynników, w tym parametry gruntu, średnice i sztywności SDR rur oraz rodzaj wykopu. Na podstawie analizy uzyskanych wyników obliczeń można stwierdzić, że stosowanie warstw z wybranych materiałów LBMs również wpływa na interakcję rur PEHD z gruntem. Mimo, że wartości poziomych przemieszczeń są niewielkie, można mówić o pewnych tendencjach tego wpływu. Poziome deformacje rur wzrastają wraz ze wzrostem szerokości wykopu oraz obniżaniem się sztywności rury. Dotyczy to obu analizowanych średnic rur. Przemieszczenia poziome dla rur o sztywnościach SDR

41 do SDR 21 utrzymują się na zbliżonym poziomie, maleją przy SDR 11. Wpływ wprowadzenia warstw z materiałów LBMs jest zróżnicowany dla rur DN315 i DN600 i zależny od szerokości wykopu. W wypadku wykopów wąskich, dla średnicy DN315, wprowadzenie warstw LECA wpływa na zwiększenie poziomych przemieszczeń, natomiast warstwy EPS i warstwy TDA przemieszczenia te zmniejszają. Dla średnicy DN600 warstwy LECA i TDA wpływają na zwiększenie poziomych przemieszczeń, warstwy EPS wpływają na zmniejszenie deformacji poziomej. Z kolei w wypadku wykopów szerokich, dla średnicy DN315, na zwiększenie przemieszczeń poziomych wpływają zarówno warstwy LECA jak i TDA, warstwy EPS wpływają na zmniejszenie deformacji poziomej. Dla średnicy DN600 wpływ warstw ze wszystkich materiałów LBMs jest zbliżony.

Wpływ wprowadzenia warstw z materiałów LBMs na ugięcia rur PEHD analizowano porównując ugięcia rur w wykopie wypełnionym wyłącznie gruntem z ugięciami występującymi przy wprowadzeniu do wykopu tych warstw. Wyznaczone ugięcia rur są zróżnicowane w zależności szerokości wykopu i rodzaju jego wypełnienia oraz od średnicy i sztywności rury. Ugięcia rur ułożonych w wykopach wypełnionych wyłącznie gruntem maleją wraz ze wzrastająca sztywnością rur. Większe wartości ugięć występują w wypadku wykopów szerokich, dotyczy to obu analizowanych średnic rur. Te intuicyjnie wyczuwalne tendencje zmieniają się przy wprowadzeniu w strefę wykopu warstw z analizowanych materiałów LBMs, które wywołują zmianę ugięć rur. Efektywność tych zmian jest zróżnicowana, można ją scharakteryzować następująco:

- wprowadzenie warstw z keramzytu (LECA) albo nie zmienia ugięć rur obsypanych wyłącznie gruntem, albo zmienia je w bardzo niewielkim stopniu.
- wprowadzenie warstw z polistyrenu spienionego (EPS) zmniejsza ugięcia rur. Dotyczy to obu typów wykopów i obu analizowanych średnic rur.
- wprowadzenie warstw z odpadów gumowych zmieszanych z gruntem (TDA) jest różne w zależności od typu wykopu. W wypadku wykopów o ścianach pionowych zaobserwowano zmniejszenie ugięć rur, przy czym jest to bardziej widoczne w wypadku rur o średnicy DN315. W wypadku wykopów o ścianach nachylonych ugięcia wzrastają (DN315) lub nie ulegają zmianie (DN600).

Należy podkreślić, że zarejestrowane zmiany ugięć są niewielkie lecz są niewątpliwie związane ze zróżnicowaniem parametrów materiałowych i sztywnością warstw LBMs. Ugięcia rur, wyznaczone w analizie numerycznej układu rur-grunt nie przekraczają wartości dopuszczalnej.

Zmiany rozkładu naprężeń pionowych w gruncie badano porównując ich rozkład w wypadku rur ułożonych w wykopach o ścianach pionowych i nachylonych, wypełnionych wyłącznie gruntem i w wykopach z warstwami z materiałów LBMs. Działające obciążenia, rodzaj wykopu i jego wypełnienie wpływają na rozkład naprężeń pionowych w gruncie. W fazie początkowej ($t = 0$, $LF = 0$) naprężenia w gruncie wynikają z ciężarów gruntu nad rurą, ich rozkład i wartości zmieniają się w trakcie narastania przyłożonego obciążenia osiągając wartości ekstremalne przy $t = 5$, $LF = 150$ kN/m^2. W rozkładzie naprężeń pionowych w gruncie widoczne jest charakterystyczny dla rur podatnych tzw. pozytywne sklepienie, redukujące obciążenia nad rurą. Istotne znaczenie dla rozkładu pionowych naprężeń nad rurą ma rodzaj i szerokość wykopu. W wypadku wykopu wąskiego wypełnionego gruntem obserwowana jest kumulacja naprężeń w strefie pod warstwami nawierzchniowymi oraz silna zmienność tych naprężeń w strefach bocznych, związana z tarciem materiału zasypkowego o ściany wykopu. Przy wprowadzeniu warstw z materiałów LBMs obserwowany jest wyraźny efekt odciążający. Efekt ten jest szczególnie widoczny dla rur o najmniejszej sztywności (SDR 41), dotyczy wszystkich analizowanych materiałów, obu średnic rur. Redukcja naprężeń pionowych w strefie nad rurą jest największa w wypadku zastosowania warstwy z polistyrenu ekstrudowanego (EPS) w obu typach wykopu. Obniżenie wartości naprężeń pionowych przy zastosowaniu pozostałych materiałów

(LECA i TDA) jest widoczne w wypadku szerokiego wykopu. W tego typu wykopie wprowadzenie warstw z materiałów LBMs skutkuje także znaczną redukcją naprężeń pionowych na całej szerokości wykopu. Zmniejszenie obciążeń rury (naprężeń pionowych w gruncie w strefie nad rurą) wywołane wprowadzeniem warstw z materiałów LBMs skutkuje także zmniejszeniem wartości momentów zginających M_z i siłnormalnych N_x w pierścieniu rurowym. W konsekwencji zmniejszeniu ulegają także naprężenia w ściance rury. Redukcyjny wpływ tych warstw jest najbardziej widoczny w wypadku wąskiego wykopu i warstwy EPS. W wykopie szerokim największa redukcja naprężeń wystąpiła przy wprowadzeniu warstwy LECA. Wyznaczone w analizie numerycznej wartości naprężeń w pierścieniu rurowym układu rur-grunt nie przekraczają wartości dopuszczalnej (dla PE80 σ_{dop} = 6,4 MPa). Opisane powyżej zróżnicowanie efektów zastosowania materiałów LBMs w zakresie ugięć rur i ich wytężenia jest trudne do jednoznacznego skomentowania. Wynika to z faktu, że na interakcję analizowanych rur PEHD z gruntem wpływa jednocześnie wiele czynników. Uzyskanie bardziej jednoznacznej oceny efektów stosowania w wykopach warstw z materiałów LBMs wymaga poszerzenia zakresów analizy o rury większych średnic, ułożonych w wykopach o większej głębokości.

Received: 2023-04-14, Revised: 2023-05-28