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NUMERICAL ANALYSIS OF THE FLEXIBLE MANHOLE-SOIL INTERACTION IN MINING AREAS BASED ON THE LABORATORY TEST RESULTS

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Abstract: Horizontal soil strains, caused by underground mining, change the distribution and values of loads acting on a manhole. The result of a significantly unbalanced distribution of horizontal loads on a flexible manhole is the cross-sectional deflection, which causes passive soil pressure. These loads may damage manholes, leading to failures of the sewer system. The article employs numerical modelling to analyse the interaction between a flexible manhole and horizontally strained soil for the conditions of the performed laboratory tests. The numerical simulations were conducted with FLAC3D v.5.0. software, based on the finite difference method. The numerical analyses showed that in mining areas the cross-sectional deflection of flexible manhole risers depends on the horizontal soil strains, the ring stiffness of the risers and the foundation depths of manholes.

Keywords**:** *soil-structure interaction, soil deformation, sewer system, cross-sectional deflection, numerical modelling*

1. INTRODUCTION

Underground mining has a negative impact on utility networks, including manholes, which are indispensable and one of the main objects of sewer systems. Underground extraction causes deformations of the subsurface soil strata. The impact of continuous mining deformations of the soil on manholes is mainly manifested by the horizontal

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soil strains. These soil strains influence original horizontal loads and cause additional loads of manholes when compared with objects located in non-mining areas. It may result in significant deformation of its construction, especially the riser, being the basic element of a flexible manhole. The manholes discussed in the article are flexible (deformable) objects made of thermoplastic materials. Horizontal soil strains, in the immediate vicinity of the wall of a flexible manhole, are disturbed due to differences in the stiffness of the riser and the soil. Then, changes in the distribution and values of horizontal loads acting on the manhole riser occur. Under the impact of the unbalanced distribution of external horizontal loads, the horizontal cross-section of the riser is deflected, which, in turn, causes passive soil pressure.

In non-mining areas, the values of loads and deformations of manhole riser may be calculated based on (ASTM F1759-97, 2010; Cevallos Palacios 2006; Gartung et al. 1989; Petroff 1994; Steinfeld und Partner 1991). Only a few analytical and empirical works concerning the impact of mining deformations of the soil on manholes were conducted (Zięba 2014; Zięba and Kalisz 2019). Unlike analytical methods, which consider external loads acting on the manhole, the numerical model enables the analysis of the manhole-soil interaction. There is a lack of works concerning the numerical analyses of the interaction between a manhole and the soil in the areas influenced by underground mining. Numerical and analytical works that analyse the interaction between the objects of the underground utility network, located in mining areas, and the soil concern mainly pipelines, e.g., (Cheng et al. 2015; Kalisz and Zięba 2014; Xu et al. 2018; Zhang et al. 2015). The distribution and values of external loads acting on sewer pipelines and sewer manholes installed in mining areas are significantly different (Zięba and Kalisz 2019).

The article aims to analyse the interaction between a flexible manhole and horizontally strained soil with numerical modelling for the conditions of the conducted laboratory tests applying physical models of manhole risers. The results of laboratory tests and their analysis are discussed in detail in (Zięba and Kalisz 2020). The numerical model of the flexible manhole-soil interaction was developed with FLAC 3D v.5.0. software, based on the finite difference method. The numerical calculations analysed the dependence of the cross-sectional deflection u of thermoplastic manhole risers with various ring stiffnesses S on horizontal soil strains ε for various foundation depths h of the manhole. The results obtained with numerical calculations were analysed and compared with the results of laboratory tests, which were conducted in conditions similar to in-situ conditions.

2. IMPACT OF HORIZONTAL SOIL STRAINS ON FLEXIBLE MANHOLES

The typical impact of horizontal soil strains on a manhole caused by a single underground longwall mining can be divided into three stages, depending on the orientation of the mining edge, i.e., stage I – horizontal soil loosening (within tension zone), followed by stage II – horizontal soil compaction (within compression zone) and stage III – further horizontal soil loosening. The value of horizontal soil strains, caused by underground mining, is disturbed by the presence of a manhole. When the impact of horizontal soil strains on loads of a manhole is assessed, there are two characteristic directions to the mining edge taken into consideration, a perpendicular one (along axis x_2, Fig. 1) and a parallel one (along axis x_3, Fig. 1). Figure 1 shows the strain and stress state in the soil in the immediate vicinity of given places of the cross-section (A-A along axis x_2 and B-B along axis x_3) of the flexible manhole riser. There is a three-dimensional strain state in the soil in the immediate vicinity of a manhole: $\varepsilon_{11} \neq 0$, $\varepsilon_{22} \neq 0$, and $\varepsilon_{33} \neq 0$, where:

- ε – horizontal soil strain caused by mining extraction, perpendicular to the mining edge (Fig. 1),
- ε_{11} – horizontal soil strain along axis x_1 (Fig. 1),
- ε_{22} – horizontal soil strain in the immediate vicinity of the manhole along axis x_2 (Fig. 1) which value depends on the value of horizontal soil strains ε and the flexibility of a manhole riser,

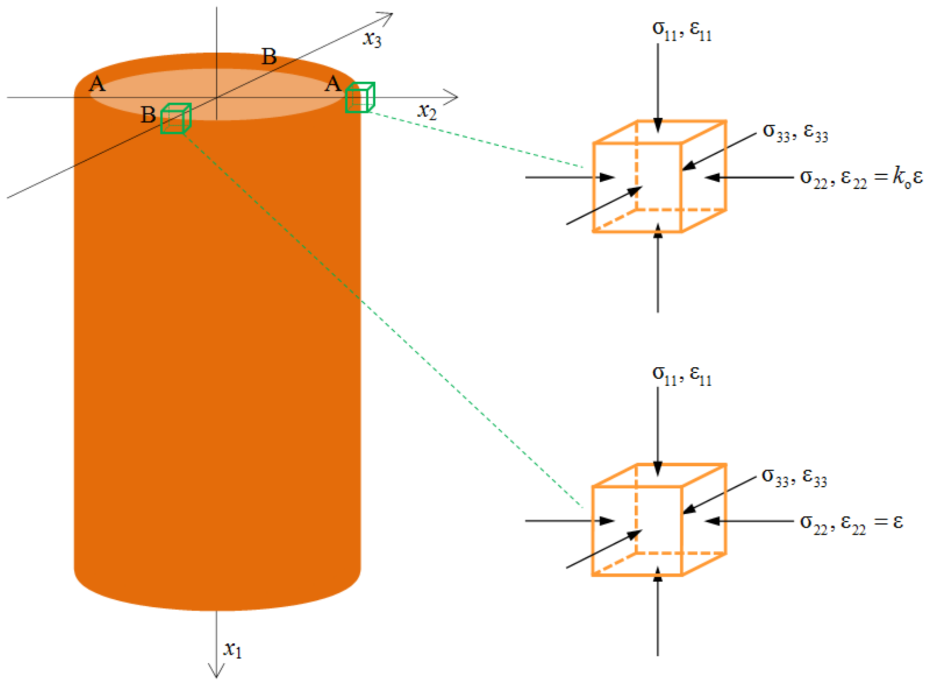

Fig. 1. Strain and stress state in the soil in the immediate vicinity of a flexible manhole riser along axes x_2 and x_3, where: k_o is a factor (Zięba and Kalisz 2019) of horizontal soil strain ε concentration

ε_{33} – horizontal soil strain in the immediate vicinity of the manhole along axis x_3 (Fig. 1) which value depends on the value of horizontal soil strains ε and the displacements of the wall of a flexible manhole, caused by the cross-sectional deflection of the riser under the impact of unbalanced loads.

In the initial stage: $\varepsilon_{11} = 0$, $\varepsilon_{22} = 0$, and $\varepsilon_{33} = 0$.

A change in the value of soil strains results in a change in the value of horizontal loads acting on the flexible manhole riser (Kalisz and Zięba 2014; Zięba and Kalisz 2019). The highest values of loads occur during the horizontal soil compaction. The value of stress σ_{22}^{z} in the soil for the horizontal soil compaction after its prior loosening acting on the riser along axis x_2 (Fig. 1) is a total of

$$\sigma_{22}^{z} = \sigma_{22}^{r} + \Delta\sigma_{22}^{z}, \tag{1}$$

where:

σ_{22}^{r} – value of stress in the soil after its horizontal loosening along axis x_2 (Fig. 1),

$\Delta\sigma_{22}^{z}$ – increase in stress in the soil along axis x_2 (Fig. 1) during horizontal compaction.

3. NUMERICAL MODEL OF THE FLEXIBLE MANHOLE-SOIL INTERACTION

The small model simulations fall short of accurately capturing actual conditions in mining regions, particularly concerning intricate phenomena like the flexible interaction between a manhole and the soil. However, in terms of speed, control, and cost, the small laboratory models are far superior. They offer a controlled setting for learning material properties, verifying numerical models, and testing theories. Laboratory models are especially helpful for evaluating failure modes, validating designs at the outset, and gaining basic knowledge that may be transferred to larger-scale systems or real-world scenarios. As a result, they are crucial instruments in the early phases of research, enabling targeted experimentation and quick iteration prior to advancing to more involved, difficult-to-fully-control and expensive field investigations.

The real, spatial numerical model of the interaction between a flexible manhole riser model and horizontally strained soil was developed using FLAC 3D v.5.0 software for the conditions of the conducted laboratory tests which results are discussed in detail in (Zięba and Kalisz 2020).

The results of numerical calculations are the values of the cross-sectional deflection u of the flexible manhole riser model. The values of the cross-sectional deflection u of the riser with various ring stiffnesses S depending on horizontal strains ε of the cohesionless soil (medium-grained sand) for various foundation depths h of a manhole were determined. The values of riser deflection were measured along axes x_2 and x_3 (Fig. 1). To develop a numerical model of the flexible manhole-soil interaction, the geometric model was discretized into elements, for which a numerical grid was generated. The elements are (Fig. 2): a model of a manhole riser, the soil and a test stand box, consisting of two mobile walls, two immobile ones and the bottom. In Figure 2, the mobile and the immobile walls of the test stand box are located along axis x_2 and axis x_3, respectively. Simultaneous movements of the mobile walls enabled simulation three stages of a typical impact of horizontal soil strains on the model of a flexible manhole riser, similar to the horizontal soil strains induced by mining activities, in the direction of the x_2 axis: stage I – horizontal soil loosening (tension, from $\varepsilon = 0$ mm/m to $\varepsilon \approx 12$ mm/m), stage II – horizontal soil compaction (compression, from $\varepsilon \approx 12$ mm/m to $\varepsilon \approx -12$ mm/m) and stage III – further horizontal soil loosening (tension, from $\varepsilon \approx -12$ mm/m to $\varepsilon \approx 0$ mm/m).

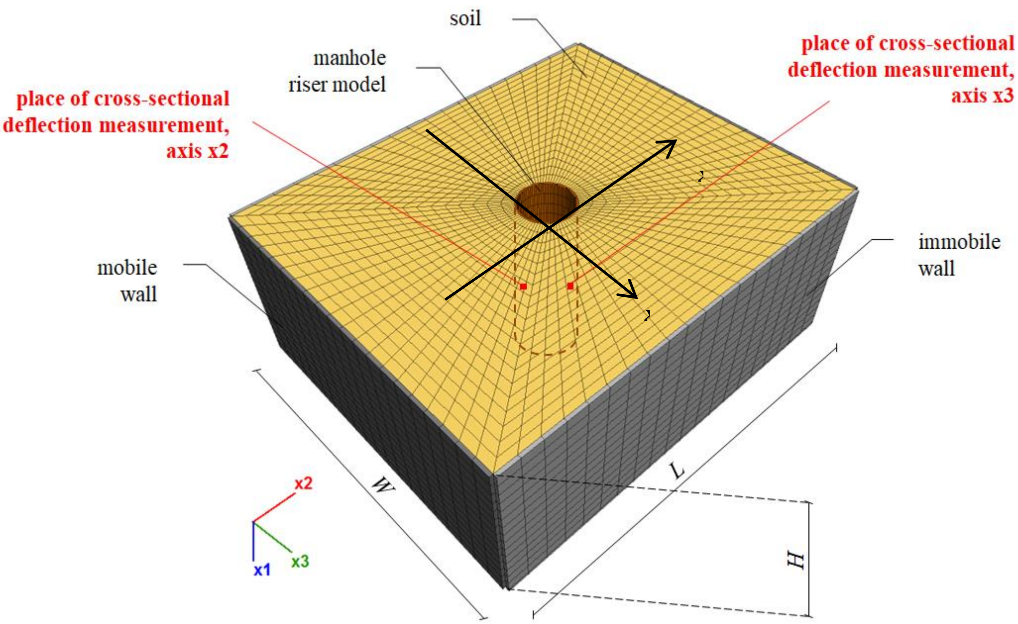

Fig. 2. Geometric model of the flexible manhole-soil interaction

The geometry of the elements was determined according to real dimensions (Fig. 3). The dimensions of the test stand box, filled with the soil, are (Fig. 2): length $L = 1.2$ m (along axis x_2), width $W = 1.0$ m (along axis x_3). The height of the box H (along axis x_1, Fig. 2), depending on the simulated foundation depth h of a flexible manhole (h = 0.5 m, h = 2.0 m and h = 4.0 m, that is σ_{11} = 10 kPa, σ_{11} = 40 kPa and σ_{11} = 80 kPa, respectively), was assumed to be: H = 0.5 m, H = 2.0 m and H = 4.0 m. For numerical calculations, models of a flexible manhole riser with ring stiffness class SN2 and SN4 (PN-EN ISO 9969:2008), of mean diameter d = 156.44 mm and d = 155.10 mm, respectively, and wall thickness s = 3.88 mm and s = 4.31 mm, respectively, were assumed. To minimise the impact of boundary conditions, the dimensions of the stand box were at least 5 times larger than the diameters of the manhole riser model, i.e., $L > 5d$ and $W > 5d$ (Fig. 2).

Fig. 3. Test stand box with a model of a flexible manhole riser in the soil (left) and a rigid steel plate which enables simulating vertical load on the soil (right)

To describe the mechanical behaviour of the soil, the elastic-perfectly plastic Mohr-Coulomb model was assumed. Mohr-Coulomb model is often chosen due to the availability of this model in computer programs, its simplicity and good understanding. At present, this constitutive model is still very common in practice to simulate the soil behaviour when considering the soil-pipeline interaction issues, despite its limitations (Robert 2017; Robert et al. 2015). Mohr–Coulomb model was used for numerical modelling of the issue of the interaction between a pipeline and the soil in non-mining areas (Abbas 2017; Feng 1999; Robert et al. 2015; Sarvanis and Karamanos 2017; Zhang, Xie et al. 2018; Zhang, Zhang et al. 2018) and mining areas (Cheng et al. 2015; Xu et al. 2018; Zhang et al. 2015). In Sabouni and El Naggar (2011) Mohr–Coulomb model was used to evaluate the effect of main parameters that impact the design of precast concrete manholes in non-mining areas. Assuming Mohr–Coulomb constitutive model for the soil requires attributing the following parameters (Itasca Consulting Group, Inc. 2013):

– shear modulus G and bulk modulus K

$$G = \frac{E}{2(1+\nu)}, \tag{2}$$

$$K = \frac{E}{3(1-2\nu)} \tag{3}$$

or Young's modulus E and Poisson's ratio ν

$$E = \frac{9KG}{3K+G}, \tag{4}$$

$$\nu = \frac{3K-2G}{2(3K+G)}, \tag{5}$$

– friction angle φ and dilation angle Ψ,
– cohesion c.

The elastic model was applied to describe the behaviour of a manhole made of unplasticized polyvinyl chloride (PVC-U) (Abbas 2017; Robert et al. 2015). The elastic model was also applied for the steel mobile and the immobile walls, and the steel bottom of the test stand box. The elastic constitutive model requires attributing two material constants for isotropic bodies: Young's modulus E and Poisson's ratio ν or shear modulus G and bulk modulus K.

The contact plane (discontinuity) (Duriez and Vincens 2015; Itasca Consulting Group, Inc. 2013; Maji et al. 2016) was defined between the test stand box (its walls and bottom) and the soil. The interface is characterized by Coulomb sliding and has the properties of friction, normal and shear stiffnesses.

Table 1 presents the parameters of the models assumed for numerical calculations for the soil, the manhole riser model and the test stand box, as well as the interface type elements of the contact surface.

The assumed boundary conditions of the model were: 0.0 displacement velocity in the nodes of the numerical grid in all three directions of the two immobile walls and the bottom of the test stand box. Moreover, the two mobile walls could move only along axis x_2, following Figs. 2 and 3. By moving the mobile walls of the box simultaneously apart and together, it was possible to simulate horizontal soil strains. Given stages of the impact of horizontal soil strains on a manhole riser were determined by setting velocity vectors on the mobile walls of the box, the values of which were evaluated based on the results of the conducted laboratory tests (Zięba and Kalisz 2020).

All the analyses of the interaction between a flexible manhole and the soil were conducted in the three-dimensional state of stress and strain. The calculations assumed that the initial stress in the soil is caused by its specific weight. Further calculations simulated the stages of a typical impact of horizontal soil strains (tension and compression) on a flexible manhole riser.

Table 1. parameters of the models and the contact plane assumed for numerical calculations

Element	Parameter	Symbol	Value	Unit
Soil	bulk density	ρ	2.00	g/cm^3
	Young's modulus	*E*	10 (Abbas, 2017; Nirmala & Rajkumar, 2016)	MPa
	Poisson's ratio	ν	0.20 (Jiang & Zhang, 2012)	–
	friction angle	φ	34 (U.S. Department of the Interior Bureau of Reclamation 2014)	degrees
	dilation angle	Ψ	0 (Feng 1999; U.S. Department of the Interior Bureau of Reclamation 2014; Zhang et al. 2015)	degrees
	cohesion	*c*	0.0	kPa
Manhole riser	density	ρ	1.40 (Plastic Pipe and Fittings Association, 2008)	g/cm^3
	Young's modulus	*E*	3000 (Plastic Pipe and Fittings Association, 2008)	MPa
	Poisson's ratio	ν	0.40 (Nirmala and Rajkumar 2016; Plastic Pipe and Fittings Association, 2008)	–
Test stand box	density	ρ	7.86 (Itasca Consulting Group, Inc. 2013)	g/cm^3
	shear modulus	*G*	81.4 (Itasca Consulting Group, Inc., 2013)	GPa
	bulk modulus	*K*	167.0 (Itasca Consulting Group Inc. 2013)	GPa
Contact plane	normal stiffness	k_n	$1{\cdot}10^{10}$ (Itasca Consulting Group, Inc. 2013)	Pa/m
	shear stiffness	k_s	$1{\cdot}10^{9}$ (Itasca Consulting Group, Inc. 2013)	Pa/m
	friction angle	φ	15 (Itasca Consulting Group, Inc. 2013)	degrees

4. RESULTS OF NUMERICAL MODELLING, ANALYSIS AND DISCUSSION

The numerical simulations modelled the results of conducted laboratory tests of the impact of horizontal soil compaction after prior horizontal soil loosening, on the cross-sectional deflection *u* of the flexible manhole riser. Table 2 presents exemplary results of numerical calculations for flexible manholes with a specified ring stiffness class of the riser SN2 and SN4 for various foundation depths *h*, i.e., *h* = 0.5 m, *h* = 2.0 m, and *h* = 4.0 m.

Table 2. Values of cross-sectional deflection *u* of the flexible manhole risers

Results obtained with	Manhole foundation depth *h* [m]	Cross-sectional deflection *u* of the flexible manhole riser			
		SN2		SN4	
		axis x_2 [mm]	axis x_3 [mm]	axis x_2 [mm]	axis x_3 [mm]
FLAC 3D	0.5	–1.16	1.30	–1.17	1.10
Laboratory tests		–1.36	1.41	–1.02	1.04
FLAC 3D	2.0	–2.39	2.03	–1.84	1.57
Laboratory tests		–2.09	2.08	–1.87	1.80
FLAC 3D	4.0	–2.91	2.67	–2.42	2.05
Laboratory tests		–2.51	2.51	–2.09	2.07

Figures 4 and 5 present the values of cross-sectional deflection of the flexible manhole riser models with a ring stiffness class SN2 and SN4 for various foundation depths *h*, i.e., *h* = 0.5 m, *h* = 2.0 m, and *h* = 4.0 m, obtained from the laboratory tests and the numerical calculations.

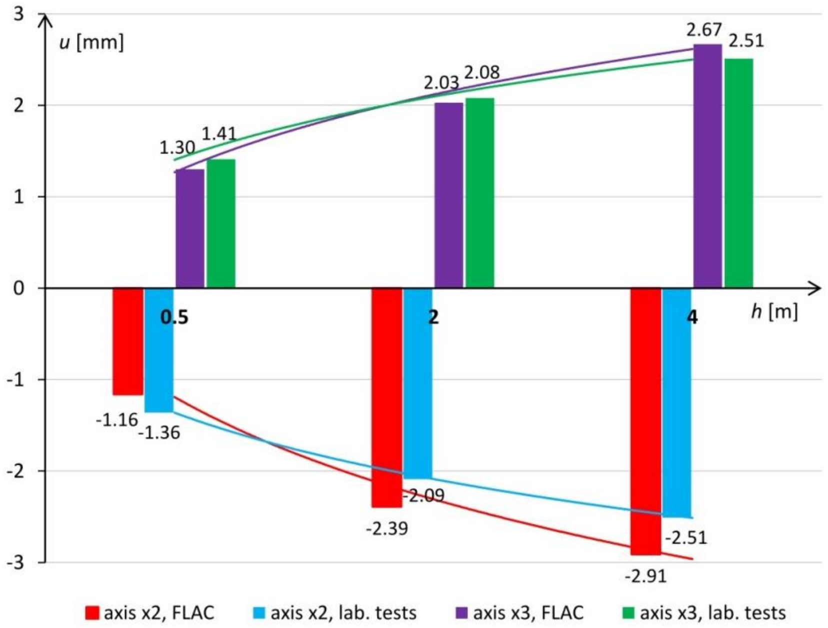

Fig. 4. Values of cross-sectional deflection *u* of the flexible manhole risers with a ring stiffness class SN2 for various foundation depths *h*

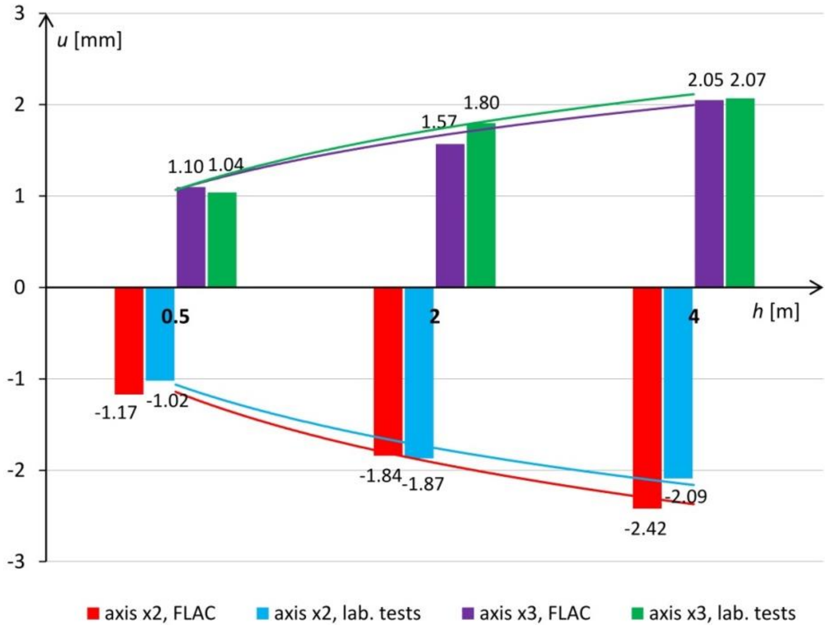

Fig. 5. Values of cross-sectional deflection *u* of the flexible manhole risers with a ring stiffness class SN4 for various foundation depths *h*

Based on the results (Table 2) obtained with numerical calculations and comparing them with the laboratory test results of the impact of horizontal soil strains on the cross-sectional deflection of a flexible manhole riser, it may be stated that:

1. The difference in the values of cross-sectional deflection of a flexible manhole along axes x_2 and x_3 for extreme horizontal compression strains of the soil falls within the range of approximately 1–16%. The obtained results of numerical calculations are quite similar to the laboratory test results for horizontal soil compaction after prior horizontal soil loosening.
2. The obtained results show that the assumptions made for the developed numerical model were correct. The results also confirm the possibility of employing the finite difference method to solve problems of the interaction between a flexible manhole and the horizontally strained soil with the Mohr-Coulomb model for the soil and an elastic model for a manhole.

Figures 6–9 present selected visualisations of the results of numerical simulations, which are the maps of displacements along axes x_2 and x_3 during horizontal soil compaction after its prior horizontal loosening. The visualisations refer to the flexible manhole risers with a ring stiffness class SN2 and SN4 at the foundation depths h = 2.0 m and h = 4.0 m.

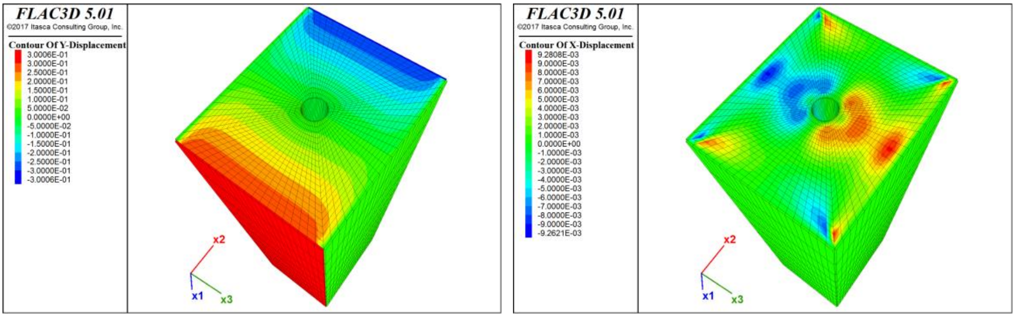

Fig. 6. Maps of displacements for horizontal soil compaction, directions: x_2 (left) and x_3 (right) – SN2, h = 4.0 m – values of cross-sectional deflection of manhole riser: –2.91 mm (axis x_2) and 2.67 mm (axis x_3)

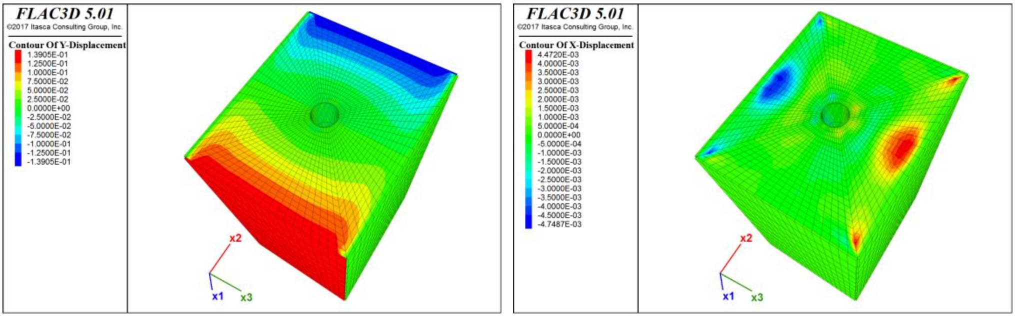

Fig. 7. Maps of displacements for horizontal soil compaction, directions: x_2 (left) and x_3 (right) – SN2, h = 2.0 m – values of cross-sectional deflection of manhole riser: –2.39 mm (axis x_2) and 2.03 mm (axis x_3)

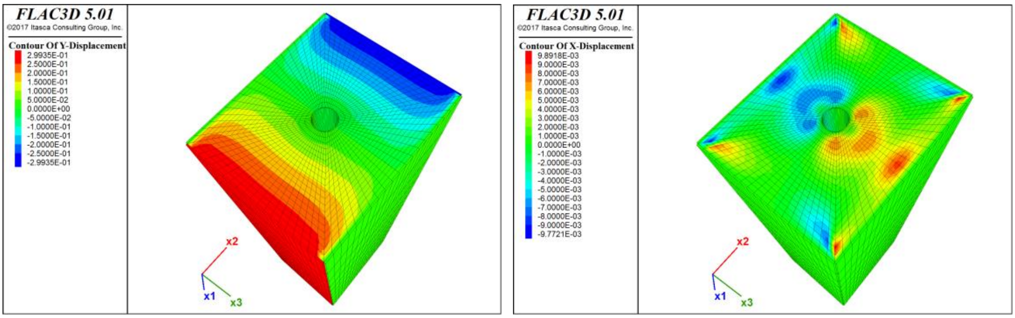

Fig. 8. Maps of displacements for horizontal soil compaction, directions: x_2 (left) and x_3 (right) – SN4, h = 4.0 m – values of cross-sectional deflection of manhole riser: –2.42 mm (axis x_2) and 2.05 mm (axis x_3)

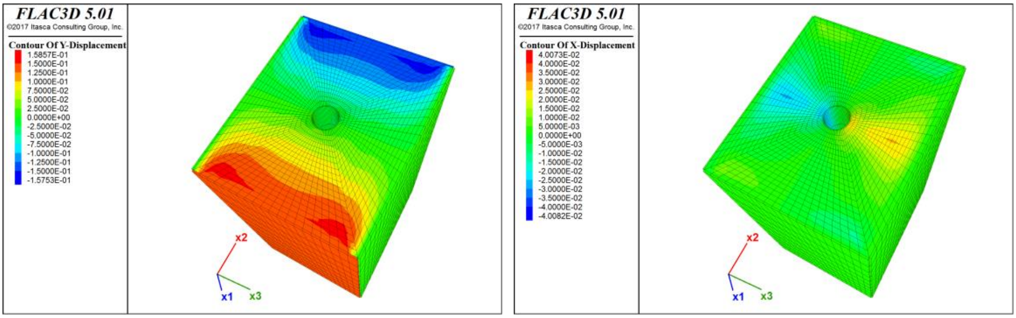

Fig. 9. Maps of displacements for horizontal soil compaction, directions: x_2 (left) and x_3 (right) – SN4, h = 2.0 m – values of cross-sectional deflection of manhole riser: –1.84 mm (axis x_2) and 1.57 mm (axis x_3)

The laboratory tests were conducted on physical models in conditions as close as possible to in-situ ones. Manhole models were made of real material used for the construction of riser pipes with real ring stiffness. These models were placed in compacted sand layers, the soil most often used for backfilling plastic manholes. The vertical load was also analogous to the real manhole depth of 2 m and 4 m in sewage systems. The real horizontal soil strain values in mining areas were applied. The relative deflection u of the horizontal cross-section of the riser pipe depends on the ring stiffness class (regardless of its diameter), the foundation depth of the manhole and the soil properties. To use the results of laboratory tests for the analysis in real conditions, model similarity criteria were determined based on the method of dimensional analysis using the Buckingham's π theorem [19–21]. The function of the riser pipe deflection taking into account the similarity criteria is

$$u = \frac{\Delta d}{d} = f\left(\frac{S}{\sigma_{11}}, I_D, \varphi, \varepsilon\right). \tag{6}$$

The model similarity criteria resulting from the equation (6) can be written in the form

$$\begin{gathered} u^n = u^m \quad or \quad \frac{\Delta^n d}{d^n} = \frac{\Delta d^m}{d^m}, \\ \frac{S^n}{\sigma_{11}^n} = \frac{S^m}{\sigma_{11}^m}, \\ I_D^n = I_D^m, \\ \varphi^n = \varphi^m, \\ \varepsilon^n = \varepsilon^m, \end{gathered} \quad . \tag{7}$$

where: S – ring stiffness of a riser pipe, σ_{11} – vertical stress in the soil (Fig. 1), I_D – density index of the soil, φ – angle of shearing resistance of the soil. The indexes "n" and "m" refer to the natural scale size and the model size, respectively. The ring stiffness classes of the riser models are the same as the riser stiffness classes used for the construction of manholes made of thermoplastics, i.e., $S_n = S_m$. This means that the results obtained can be used to estimate the riser deflection with larger diameters but with the same ring stiffness class in a natural scale.

The laboratory tests, conducted in conditions similar to in-situ conditions, can be applied as the basis to verify and calibrate numerical models of the interaction between a flexible manhole and horizontally strained soil. Based on small-scale laboratory test results, numerical analysis of the flexible manhole-soil interaction offers a potent tool for predicting the behaviour of these structures during underground movements caused by mining. While numerical analysis offers scalability, complexity, and efficiency in predicting real-world performance, small laboratory tests are essential in providing the material and behavioural data required for accurate simulations. Combining these techniques allows engineers to create infrastructure that is more robust and resilient, lowering the likelihood of failure in harsh settings like mine regions. However, to guarantee the most precise and useful results, ongoing attempts to improve models and confirm them through field research are crucial.

The obtained results of numerical simulations confirm that the developed numerical model is useful for modelling the issue of the flexible manhole-horizontally strained soil interaction. The results enable predictions of the impact of horizontal soil strains, caused by mining, on the cross-sectional deflection of a flexible manhole riser. It is important for the proper selection and safety of a manhole structure installed in mining areas. It results from the fact that horizontal soil compaction is the most unfavourable stage of the impact of mining deformations of the soil on manholes and is crucial for the determination of whether they can, and under what conditions, be applied in mining areas. The usefulness of the developed numerical model as a tool supporting design work at the stage of selecting the optimal manhole structure was demonstrated. The developed numerical model also allows for the assessment of the possibilities and conditions of using flexible sewage manholes in mining areas. This assessment consists of determining the foundation depth h of the flexible manhole with a specified ring stiffness S of the riser pipe for the predicted values of horizontal soil strains.

5. SUMMARY AND CONCLUSIONS

Horizontal compaction of the soil, caused by mining extraction, is crucial for the issue of the impact of horizontal soil strains on the loads acting on manholes made of thermoplastic materials. It causes a significant increase in the horizontal loads acting on a manhole, both perpendicular and parallel to the mining edge. There is a change in the distribution and the values of loads in the horizontal plane of the manhole riser. The effect of a significantly unbalanced distribution of horizontal loads on a flexible manhole is the cross-sectional deflection of its riser, additionally, the occurrence of passive soil pressure parallel to the mining edge. The values of the loads depend on horizontal soil strains caused by mining, the ring stiffness of the manhole riser and the foundation depth of the manhole.

Numerical methods may be applied to solve complex computational problems, e.g., associated with the impact of horizontal soil strains, caused by mining, on the cross-sectional deflection of a flexible manhole. One of the most important design criteria for flexible pipes is their cross-sectional deflection. The maximum value of cross-sectional deflection is determined based on the permissible value of strains in pipe wall and, if necessary, the pavement deflection in pipelines under road construction. Similar rules may be adopted for flexible sewer manholes when their function in the sewage system and their equipment are taken into account. For example, the cross-sectional deflection of the pumping station riser should be much smaller than the inspection chamber riser. With numerical modelling, the article analyses the interaction between a flexible manhole and horizontally strained soil for the conditions of the conducted laboratory tests. It was shown that the developed numerical model is a useful tool to support design works at the stage of selecting the optimal construction of a manhole in areas affected by soil movement. The developed numerical model is useful for the prediction of the impact of horizontal soil strains on the cross-sectional deflection of a flexible manhole riser. The numerical model enables the assessment of the possibility and the conditions of applying flexible manholes in mining areas. The assessment determines the foundation depth of a flexible manhole with specific ring stiffness of the riser for the predicted values of horizontal soil strains.

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REFERENCES

ABBAS B.J., 2017, *Parametric studies of reducing applied stress on buried PVC pipes using finite element*, Muthanna Journal of Engineering and Technology, Vol. 5, No. 2, 21–29. https://doi.org/10.18081/mjet/2017-5/21-29

ASTM F1759-97, 2010, *Standard practice for design of high-density polyethylene (HDPE) manholes for subsurface applications*, West Conshohocken, PA: ASTM International.

CEVALLOS PALACIOS J.L., 2006, *Análisis de desempeño de Tubería de Polietileno de alta densidad (HDPE) de Pared Estructurada usada como elevador de Pozo de Inspección (Manhole) de Aguas lluvias*, Doctoral dissertation, Escuela Superior Politécnica del Litoral (ESPOL), Facultad de Ingenería Mecánica y Ciencias de la Producción, http://web.nchu.edu.tw/pweb/users/feng/research/1462.pdf

CHENG G., LIU T., and WANG Y., 2015, *Study of deformation mechanism on the pipeline in steep longer distance seams mining*. In: P. Yarlagadda (Ed.), Proceedings of the 2015 4th International Conference on Sustainable Energy and Environmental Engineering: December 20–21, 2015, 44–48. Australia: Queensland University of Technology, https://doi.org/10.2991/icseee-15.2016.8

DURIEZ J. and VINCENS E., 2015, *Constitutive modelling of cohesionless soils and interfaces with various internal states: An elasto-plastic approach*, Computers and Geotechnics, Vol. 63, 33–45, https://doi.org/10.1016/j.compgeo.2014.08.001

FENG Z., 1999, *An application of constitutive modeling in FLAC for cohesionless soils*, Proceedings of 8th Conference on Current Researches in Geotechnical Engineering, 304–314. http://web.nchu.edu.tw/pweb/users/feng/research/1462.pdf

GARTUNG E., PRÜHS H., and HOCH A., 1989, *Design of vertical shafts in landfills. Sardinia 89*, Second International Landfill Symposium: "Landfill Concepts, Environmental Aspects, Lining Technology, Leachate Management, Industrial Waste and Combustion Residues Disposal", 9–13 October.

Itasca Consulting Group, Inc., 2013, FLAC 3D v. 5.0. *User's Manual*.

JIANG Z.H. and ZHANG Y.X., 2012, *Second development of hardening soil constitutive model in FLAC3D*, Electronic Journal of Geotechnical Engineering, Vol. 17, 3429–3439.

KALISZ P. and ZIĘBA M., 2014, *Impact of mining exploitation on pipelines*, Acta Montanistica Slovaca, Vol. 19, No. 3, 111–117.

MAJI V.B., SOWMIYAA V.S., and ROBINSON R.G., 2016, *A simple analysis of reinforced soil using equivalent approach*, International Journal of Geosynthetics and Ground Engineering, Vol. 2, No. 2, 1–12, https://doi.org/10.1007/s40891-016-0055-5

NIRMALA R. and Rajkumar R., 2016, *Finite element analysis of buried UPVC pipe*, Indian Journal of Science and Technology, Vol. 9, No. 5, 1–5, https://doi.org/10.17485/ijst/2016/v9i5/87225

PETROFF L.J., 1994, *Design methodology for high density polyethylene manholes*. In: D. Eckstein (Ed.), *Buried Plastic Pipe Technology*, 2nd ed., Issue 1222, 52–65, https://doi.org/10.1520/stp12665s

Plastic Pipe and Fittings Association, 2008, *PVC piping systems for commercial and industrial applications. Design guide*.

PN-EN ISO 9969:2008, 2008, *Thermoplastic pipes. Determination of ring stiffness*, Polish Committee for Standardization (ed.).

ROBERT D.J., 2017, *A modified Mohr-Coulomb model to simulate the behavior of pipelines in unsaturated soils*, Computers and Geotechnics, Vol. 91, 146–160, https://doi.org/10.1016/j.compgeo.2017.07.004

ROBERT D.J., SOGA K., and Britto A., 2015, *Soil constitutive models to simulate pipeline-soil interaction behaviour*, Proceedings of the International Conference on Geotechnical Engineering (ICGE 2015), 10–11 August 2015, 347–350.

SABOUNI R. and EL NAGGAR M.H., 2011, *Circular precast concrete manholes: Numerical modeling*, Canadian Journal of Civil Engineering, Vol. 38, No. 8, 909–920, https://doi.org/10.1139/l11-059

SARVANIS G.C. and KARAMANOS S.A., 2017, *Analytical model for the strain analysis of continuous buried pipelines in geohazard areas*, Engineering Structures, Vol. 152, 57–69, https://doi.org/10.1016/j.engstruct.2017.08.060

Steinfeld und Partner, 1991, Report to Bauku – Germany from Grundbauingenieure Steinfeld und Partner, Erobaulaboratorium Hamburg.

U.S. Department of the Interior Bureau of Reclamation, 2014, Report DSO-14-02. *Reclamation Managing Water in the West. Verification of FLAC Mohr Coulomb model for granular materials under monotonic loading*, https://www.usbr.gov/ssle/damsafety/TechDev/DSOTechDev/DSO-14-02.pdf

XU P., ZHANG M., LIN Z., CAO Z., and CHANG X., 2018, *Additional Stress on a Buried Pipeline under the Influence of Coal Mining Subsidence*, Advances in Civil Engineering, 2018, https://doi.org/10.1155/2018/3245624

ZHANG J., LIANG Z., and HAN C.J., 2015, *Numerical modeling of mechanical behavior for buried steel pipelines crossing subsidence strata*, PLoS ONE, Vol. 10, No. 6, 1–16, https://doi.org/10.1371/journal.pone.0130459

ZHANG J., XIE R., and ZHANG H., 2018, *Mechanical response analysis of the buried pipeline due to adjacent foundation pit excavation*, Tunnelling and Underground Space Technology, Vol. 78, 135–145, https://doi.org/10.1016/j.tust.2018.04.026

ZHANG J., ZHANG L., and LIANG Z., 2018, *Buckling failure of a buried pipeline subjected to ground explosions*, Process Safety and Environmental Protection, Vol. 114, 36–47, https://doi.org/10.1016/j.psep.2017.11.017

ZIĘBA M., 2014, *Loads of sewer manholes within mining area*, Journal of Sustainable Mining, Vol. 13, No. 4, 34–39, https://doi.org/10.7424/jsm140407

ZIĘBA M. and KALISZ P., 2020, *Impact of horizontal soil strain on flexible manhole riser deflection based on laboratory test results*, Engineering Structures, 208, https://doi.org/10.1016/j.engstruct.2019.109921

ZIĘBA M. and KALISZ P., 2019, *Impact of horizontal soil strains on sewer manholes and pipelines within mining areas*, IOP Conference Series: Materials Science and Engineering, Vol. 471, No. 4, https://doi.org/10.1088/1757-899X/471/4/042025