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Impact of Horizontal Soil Strains on Sewer Manholes and Pipelines within Mining Areas

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Abstract. The main purpose of the paper is to assess and compare the values of horizontal soil unit loads, acting on the construction of sewer manholes and pipelines within mining areas. The examples of failures of these building objects buried within mining areas are also presented. Flexible (e.g. thermoplastics) and rigid (e.g. concrete, reinforced concrete) objects are taken into account. The impact of mining extraction on sewer manholes and pipelines is mainly manifested by horizontal strains. Soil strains lead to additional loads acting on the construction of the objects, which are buried in the subsurface soil layer, during horizontal soil compaction and loosening. The horizontal strain in the subsurface soil layer within mining areas causes both considerable value changes in horizontal loads acting on the object walls and significant uneven load distribution in comparison to non-mining areas. It should be emphasised that these strains pose a threat to building objects, especially, during horizontal soil compaction. In the case of sewer manholes and pipelines, it is a reason for their failures and a lack of tightness, and changes in the cross-section shape of flexible objects. In the case of flexible manholes and pipelines made of thermoplastics, a deflection of construction elements can occur. The deflection of the elements should be limited to ensure the functionality of manholes. The additional loads should be considered when determining the foundation conditions of sewer manholes and pipelines within mining areas in order to aid their design, protection and resistance assessment to horizontal soil strains. The load values were determined for horizontal soil compaction and loosening caused by horizontal soil strains. For load determination in the case of flexible sewer manholes and pipelines, experimental test results were taken into account. The values of the determined external horizontal soil unit loads acting on the flexible and rigid object walls during horizontal soil compaction within mining areas vary a lot. The uneven distribution of horizontal soil loads is lower for flexible objects than rigid ones buried in the same soil conditions within mining areas. The differences between the values of horizontal soil unit loads, acting on the construction of flexible and rigid sewer manholes as well as pipelines, are also caused by the interaction between soil and these objects within mining areas.

1. Introduction
Mining exploitation causes deformations of the subsurface soil layer in which pipelines and sewer manholes are buried. Soil deformations lead to additional displacements and loads acting on the construction of the objects.

The impact of mining extraction on pipelines and sewer manholes is mainly manifested by horizontal strains. During horizontal soil compaction and loosening, horizontal strains cause both considerable value changes in horizontal loads acting on the object walls and significant uneven load distribution in comparison to non-mining areas. These strains pose a threat to objects, especially,
during horizontal soil compaction. The impact of horizontal soil strains can lead to the load-bearing capacity being exceeded and then, as a result, to failures in the affected areas taking place. The impact can also be a reason for an angular deviation and a lack of tightness between pipeline and sewer manhole elements, and changes in the cross-section shape of flexible objects.

The main purpose of the paper is to assess and compare the values of horizontal soil unit loads, acting on the construction of flexible and rigid pipelines and sewer manholes within mining areas during horizontal soil compaction and loosening. The additional loads should be considered when determining the foundation conditions of pipelines and sewer manholes within mining areas in order to aid their design, protection and resistance assessment to horizontal soil strains.

2. Impact of horizontal soil strains on pipelines and sewer manholes buried within mining areas

When the values of predicted horizontal strains in the subsurface soil layer are known, the foundation depth of pipelines and sewer manholes within mining areas can be determined. On this basis the values of additional horizontal soil unit loads, which do not occur within non-mining areas, are calculated [1,2,3,4,5]. These loads enable the determination of bending moment values acting on the object walls. What is more, they also enable the determination of the relative cross-section deflection of flexible objects [6,7] which is compared with permissible value.

Impact of horizontal soil strains on pipelines and manholes is considered in two directions: perpendicular (\(x_2\) - axis) and parallel (\(x_3\) - axis) to the exploitation edge as shown in figure 1 and figure 2. Horizontal strains in the subsurface soil layer cause changes in the value and distribution of external horizontal loads acting on pipeline and sewer manhole constructions. During soil loosening load values decrease and in non-cohesive soil active limit state occurs almost immediately in the case of rigid objects (figure 1, point 2 and figure 2, point 2). During soil compaction load values increase significantly (figure 1, point 3 and figure 2, point 3). Both during soil compaction and loosening in the zone immediately surrounding buried rigid and flexible objects the concentration of horizontal strains occurs [8] which can be characterised by a coefficient \(k_0\) (formula 3). If the values of horizontal strains in the subsurface soil layer are high, then, in the zone immediately surrounding buried objects with a little flexibility, passive limit state may even occur because of the concentration of these strains. In the case of flexible objects, the concentration is much lower than in the case of rigid ones but change in their cross-section shape occurs. Changes in the cross-section shape of flexible pipelines occur even within non-mining areas. This results from the flexibility of object walls made of thermoplastics.

During the installation of flexible objects into the ground, the initially well-compacted backfill of non-cohesive soil plays an essential role. It enables both proper load distribution and correct interaction between these objects and the surrounding soil. The creep of thermoplastics under load occurs and it causes the movement of object walls. In the case of thermoplastic sewer manholes, it results in active soil pressure and a small amount of load unevenness which causes little changes in their cross-section shape [2,9,10].

In figure 1 and figure 2 the changes in the distribution of external horizontal loads acting on rigid and flexible pipelines and manhole risers during horizontal soil compaction and loosening caused by mining impact are presented.
Figure 1. Changes in the distribution of external horizontal loads acting on flexible and rigid pipeline buried within mining area: 1) initial state ($\varepsilon = 0.0 \text{ mm/m}$), 2) horizontal soil loosening ($\varepsilon_{\text{max}}$), 3) horizontal soil compaction ($-\varepsilon_{\text{min}}$), 4) final state ($\varepsilon = 0.0 \text{ mm/m}$), where: $w_{\text{max}}$ - maximum subsidence, $r$ - radius of the range of main influences according to the Budryk-Knothe theory.
Figure 2. Changes in the distribution of external horizontal loads acting on flexible and rigid manhole riser buried within mining area: 1) initial state ($\varepsilon = 0.0$ mm/m), 2) horizontal soil loosening ($\varepsilon_{max}$), 3) horizontal soil compaction ($-\varepsilon_{min}$), 4) final state ($\varepsilon = 0.0$ mm/m), where: $w_{max}$ - maximum subsidence, $r$ - radius of the range of main influences according to the Budryk-Knothe theory.

3. Loads of flexible and rigid pipeline and manhole walls buried within mining areas

The values of additional external horizontal soil unit loads acting on flexible and rigid pipelines and manhole risers caused by the impact of horizontal soil strains were determined and compared below. The values of the bending moments acting on the pipeline and manhole walls depend on the differences between horizontal loads $\Delta p = p_{22} - p_{33}$, where $p_{22}$ and $p_{33}$ mean horizontal soil unit loads in the main directions, respectively, perpendicular and parallel to the exploitation edge. The values of horizontal soil unit load $p_{22}$ and $p_{33}$ acting on flexible and rigid pipeline and manhole walls during horizontal soil compaction were determined on the basis of the following formulas (1) [8] and (2) [11]...
where:

\[ p_{22} = \left[ \xi_z - (\xi_z - \xi_o) \left( 1 - \frac{k_o \varepsilon}{\varepsilon_{kr}} \right)^m \right] (\gamma z + q) \]  \hspace{1cm} (1)

\[ p_{33} = \left[ \xi_o + \nu (\xi_z - \xi_o) \left( 1 - \frac{k_o \varepsilon}{\varepsilon_{kr}} \right)^m \right] (\gamma z + q) + a_1 \varepsilon E_s' \]  \hspace{1cm} (2)

\[ \xi_z \] – the coefficient of lateral soil pressure when the passive limit state is reached,

\[ \xi_o \] – the coefficient of lateral soil pressure at rest,

\[ \varepsilon \] – the horizontal soil strain,

\[ \varepsilon_{kr} \] – the critical horizontal soil strain when the passive limit state is reached,

\[ k_o \] – the coefficient of soil strain concentration,

\[ m \] – the coefficient which for non-cohesive soil amounts to, on average, \( m = 3.1 \),

\[ \gamma \] – the bulk unit weight of soil,

\[ z \] – the foundation depth of the analysed object cross-section,

\[ q \] – the surface loads,

\[ \nu \] – Poisson's ratio,

\[ E_s' \] – the secant modulus of horizontal soil reaction,

\[ a_1 \] – the coefficient of the relative cross-section deflection of flexible object, \( \alpha_1 = \left( \Delta d / d \right) \varepsilon \),

\[ d \] – the mean diameter of object cross-section.

The coefficient values of the relative cross-section deflection of the analysed flexible pipeline and manhole riser \( \alpha_1 \) were determined based on the results of laboratory tests [11,7]. These tests concerned the determination of the relationship between the increment of the relative cross-section deflection of flexible object model and the increment of horizontal soil strain. The \( \alpha_1 \) coefficient value depends mainly on the circumferential stiffness of the object and also on the properties and compaction of non-cohesive soil. For the rigid pipeline and manhole riser it amounts to \( \alpha_1 = 0 \). For the flexible pipeline and manhole riser with a circumferential stiffness of 8 kN/m² it amounts to \( \alpha_1 = 1.30 \) and \( \alpha_1 = 0.85 \) respectively.

The coefficient value of soil strain concentration \( k_o \) for the flexible pipeline and manhole riser was determined based on the formula (3)

\[ k_o = \frac{n + 1}{n - 1} - \frac{2a_1}{n - 1} \]  \hspace{1cm} (3)

where \( n \) means the multiple of object diameter \( d \).

For the rigid pipeline and manhole it amounts to \( n = 5 \) [8], so the coefficient \( k_o \) amounts to 1.5. For the flexible pipeline and manhole riser with a circumferential stiffness of 8 kN/m² during horizontal soil compaction the coefficient value of soil strain concentration \( k_o \), determined on the basis of the formula (3), amounts to \( k_o = 0.85 \) and \( k_o = 1.08 \) respectively.

The concentration of horizontal soil strains in the zone immediately surrounding rigid and flexible pipeline during soil compaction is schematically presented in figure 3.
In table 1 the values of external horizontal soil unit loads \( (p_{22} \text{ and } p_{33}) \) and their differences \( (\Delta p) \), acting on the cross-section of flexible and rigid pipeline and manhole walls during soil compaction, are presented. It was assumed that both the flexible and rigid pipeline and manhole riser analysed were installed in the same soil conditions, which means that these objects were buried to the same depth and subjected to the same values of horizontal soil strain. The soil unit loads acting on the analysed pipeline and manhole walls were determined for a foundation depth of \( z = 4.0 \text{ m} \) and horizontal soil strain of 6 mm/m (III category of mining area in Poland). The level of groundwater did not reach the bottom of manhole and pipeline. The values of horizontal soil unit loads \( p_{22} \text{ and } p_{33} \) were determined for the same compacted non-cohesive soil with the bulk density of soil \( \gamma = 20 \text{ kN/m}^3 \), the secant modulus of horizontal soil reaction \( E_s = 1.5 \text{ MPa} \) [3], the angle of internal friction \( \varphi = 30^\circ \) and the surface loads \( q = 5.0 \text{ kPa} \).

**Table 1. Values of external horizontal soil unit loads acting on flexible and rigid pipeline and manhole walls during soil compaction**

| Foundation depth \( z \) [m] | Flexible pipeline | Rigid pipeline | Flexible manhole | Rigid manhole |
|------------------------------|------------------|--------------|-----------------|-------------|
| \( p_{22} \) [kPa] | \( p_{11} \) [kPa] | \( \Delta p \) [kPa] | \( p_{22} \) [kPa] | \( p_{11} \) [kPa] | \( \Delta p \) [kPa] | \( p_{22} \) [kPa] | \( p_{33} \) [kPa] | \( \Delta p \) [kPa] |
| 1.0  | 39.1 | 25.0 | 14.1 | 53.3 | 25.0 | 28.3 | 44.6 | 30.6 | 14.0 |
| 1.5  | 54.7 | 35.0 | 19.7 | 74.7 | 35.0 | 39.7 | 62.4 | 39.8 | 22.6 |
| 2.0  | 70.4 | 45.0 | 25.4 | 96.0 | 45.0 | 51.0 | 80.2 | 49.0 | 31.3 |
| 2.5  | 86.0 | 55.0 | 31.0 | 117.4 | 55.0 | 62.4 | 98.1 | 58.2 | 39.9 |
| 3.0  | 101.6 | 65.0 | 36.6 | 138.7 | 65.0 | 73.7 | 115.9 | 67.4 | 48.6 |
| 3.5  | 117.3 | 75.0 | 42.3 | 160.0 | 75.0 | 85.0 | 133.7 | 76.5 | 57.2 |
| 4.0  | 132.9 | 85.0 | 47.9 | 181.4 | 85.0 | 96.4 | 151.6 | 85.7 | 65.9 |
Based on comparisons between the values of external horizontal soil unit loads during horizontal soil compaction caused by mining impact in table 1 it can be stated that:

- the values of horizontal soil unit loads acting on both flexible and rigid manhole walls are higher in a perpendicular direction to the mining exploitation edge \( (p_{22}) \) than in a parallel direction to the edge \( (p_{33}) \),
- the extreme values of the differences between horizontal soil unit loads \( (\Delta p) \) are lower in the case of flexible sewer manholes than in the case of rigid ones by approximately 50% for a foundation depth of \( z = 1.0 \) m and 30% for a foundation depth of \( z = 4.0 \) m,
- the values of horizontal soil unit loads \( (p_{22}) \) acting on both flexible and rigid pipeline walls are higher in comparison with the values of vertical soil unit loads \( (p_{11}) \) which depend on the bulk unit weight of soil and the foundation depth of the object,
- the extreme values of the differences between horizontal soil unit loads \( (p_{22}) \) and vertical soil unit loads \( (p_{11}) \) for flexible and rigid pipeline equal to approximately 50%.

The values of horizontal soil unit loads \( p_{22} \) and \( p_{33} \) acting on flexible pipeline and manhole walls during horizontal soil loosening were determined on the basis of the following formulas (4) [8] and (5)

\[
p_{22} = \left[ \xi_r + (\xi_o - \xi_r) \left( 1 - \frac{k_o \xi}{\epsilon_{cr}} \right) \right] \left( \gamma z + q \right)
\]

\[
p_{33} = \left[ \xi_o - \nu (\xi_o - \xi_r) \left( 1 + \left( 1 - \frac{k_o \xi}{\epsilon_{cr}} \right)^m \right) \right] \left( \gamma z + q \right)
\]

where:

- \( \xi_r \) – the coefficient of lateral soil pressure when the active limit state is reached,
- \( \epsilon_{cr} \) – the critical horizontal soil strain when the active limit state is reached,
- \( c \) – the coefficient which for non-cohesive soil amounts to, on average, \( c = 3.8 \).

For the flexible pipeline and manhole riser with a circumferential stiffness of 8 kN/m² during horizontal soil loosening the \( \alpha_1 \) coefficient amounts to \( \alpha_1 = 1.05 \) and \( \alpha_1 = 0.33 \) respectively and the \( k_o \) coefficient amounts to \( k_o = 0.98 \) and \( k_o = 1.34 \) respectively. For horizontal soil strain of 6 mm/m the values of external horizontal soil unit loads acting on flexible and rigid pipeline and manhole walls during soil loosening reach the values of the active limit state. Exemplary values of external horizontal soil unit loads acting on flexible and rigid pipeline and manhole walls for horizontal soil strain of \( \varepsilon = 1 \) mm/m (before the active limit state is reached) during soil loosening are presented in table 2.

| Foundation depth \( z \) [m] | pipeline | manhole |
|-------------------------------|----------|---------|
| \( p_{22} \) [kPa] | \( p_{11} \) [kPa] | \( \Delta p \) [kPa] | \( p_{22} \) [kPa] | \( p_{11} \) [kPa] | \( \Delta p \) [kPa] | \( p_{22} \) [kPa] | \( p_{33} \) [kPa] | \( \Delta p \) [kPa] | \( p_{22} \) [kPa] | \( p_{33} \) [kPa] | \( \Delta p \) [kPa] |
| 1.0   | 8.6     | 25.0    | -16.4 | 7.8     | 25.0    | -17.2 | 8.0     | 10.6    | -2.5 | 7.8     | 10.7    | -2.9 |
| 1.5   | 12.0    | 35.0    | -23.0 | 11.0    | 35.0    | -24.0 | 11.2    | 14.8    | -3.6 | 11.0    | 15.0    | -4.0 |
| 2.0   | 15.4    | 45.0    | -29.6 | 14.1    | 45.0    | -30.9 | 14.4    | 19.0    | -4.6 | 14.1    | 19.3    | -5.2 |
| 2.5   | 18.9    | 55.0    | -36.1 | 17.3    | 55.0    | -37.7 | 17.6    | 23.2    | -5.6 | 17.3    | 23.6    | -6.3 |
| 3.0   | 22.3    | 65.0    | -42.7 | 20.4    | 65.0    | -44.6 | 20.8    | 27.4    | -6.6 | 20.4    | 27.9    | -7.5 |
| 3.5   | 25.7    | 75.0    | -49.3 | 23.5    | 75.0    | -51.5 | 24.0    | 31.7    | -7.6 | 23.5    | 32.2    | -8.6 |
| 4.0   | 29.2    | 85.0    | -55.8 | 26.7    | 85.0    | -58.3 | 27.2    | 35.9    | -8.6 | 26.7    | 36.5    | -9.8 |
Based on comparisons between the values of external horizontal soil unit loads during horizontal soil loosening caused by mining impact in table 2 it can be stated that:

- the values of horizontal soil unit loads acting on both flexible and rigid manhole walls are lower in a perpendicular direction to the mining exploitation edge ($p_{33}$) than in a parallel direction to the edge ($p_{22}$),
- the extreme values of the differences between horizontal soil unit loads ($\Delta p$) are lower in the case of flexible sewer manholes than in the case of rigid ones by approximately 12%,
- the values of horizontal soil unit loads ($p_{22}$) acting on both flexible and rigid pipeline walls are lower in comparison with the values of vertical soil unit loads ($p_{11}$),
- the extreme values of the differences between horizontal soil unit loads ($p_{22}$) and vertical soil unit loads ($p_{11}$) for flexible and rigid pipelines equal to approximately 4%.

In figure 4 the examples of failures of rigid pipelines buried within mining areas are presented.

![Image of pipeline failures](image)

**Figure 4.** Failures of pipelines

4. Conclusions
Impact of underground mining exploitation causes changes in primary foundation conditions of objects in the subsurface soil layer. The impact of mining extraction on pipelines and sewer manholes is mainly manifested by horizontal strains which lead to additional displacements and loads acting on their construction. The horizontal strains in the subsurface soil layer within mining areas cause both considerable value changes in horizontal loads acting on pipeline and manhole walls and significant uneven radial load distribution in comparison to non-mining areas. These loads should be considered when determining the foundation conditions of objects within mining areas in order to aid their design, protection and resistance assessment to horizontal soil strains. The impact of horizontal soil strains can lead to failures and it can also be a reason for changes in the cross-section shape of flexible objects.

The values of the determined external horizontal soil unit loads acting on the walls of flexible and rigid pipelines and sewer manholes during horizontal soil compaction within mining areas vary a lot. The uneven distribution of horizontal radial soil unit loads is lower for flexible objects than rigid ones buried in the same soil conditions within mining areas. This is connected with the flexibility of objects and their interaction with the soil.

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