Excavation induced cast iron pipeline failure – a numerical study

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Engineering works in many European city centres might be complicated because of the rich history of the area. Modern construction works should take into account not only the existing, often historical and fragile buildings that could be impacted by the work, but the underground infrastructure as well. Historical water and gas pipelines, district heating or sewage pipe are often still in use, while their technical state can sometimes remain unknown. Moreover, even the localisation of these pipelines can be imprecise because there are frequent documentation absences, e.g. especially in cities damaged during the World War II. Therefore every engineer working in a dense urban area with long history should assess the impact of modern construction works on the existing infrastructure.

An example of how an existing pipeline can be impacted by a modern construction was described in [7]. In 2013 a water pipeline placed more than 50 years ago below one of the Gdańsk intersections was damaged. In its vicinity several construction works were held at the time, and the street above the pipe was used as an access road to another construction site. The pipe was made of rigid and brittle grey cast iron and connected with shallow bell and spigot joints. The possible cause of failure was linked to an unsecured excavation performed next to the pipe and the resulting large soil displacements that damaged the pipe joint. That assumption is in accordance with several studies [3, 4, 5].

In this paper a similar scenario was modelled numerically using the Finite Element Method (FEM) in order to study how an unsecured excavation can impact the soil surrounding an underground pipeline and the pipeline itself.

An underground pipe can fail in a number of ways and the failure can be caused by different factors [4]. Here it was assumed that the failure would be linked with large soil displacements around the pipe that could lead to pipe element disjoining through axial pullout, excessive rotation of the pipe elements at the joint or bell material crack.

PROBLEM DESCRIPTION

Pipe – soil interactions in 2D are typically modelled in the plane perpendicular to the pipeline axis. But since in this paper the focus was put on the impact of an unsecured excavation, it was decided to investigate a plane perpendicular to the excavation that is placed along the pipe axis, see Figure 1. In every sim-

Table 1. Subsoil layer materials and its mechanical parameters

Soil symbol	M_0 MPa	γ_{sr} kN/m^3	γ_d kN/m^3	ν –	ϕ' °	c' kPa
Or - Peat	0.5	14.0	11.0	0.40	5.0	5.0
Or – Compacted mud / Peat	1.0	14.0	11.0	0.40	5.0	5.0
Or – Compacted mud	2.0	14.0	11.0	0.40	8.0	5.0
saOr	3.0	16.0	13.0	0.35	10.0	3.0
saclSi	5.0	18.0	14.0	0.35	15.0	10.0
orsiSa	10.0	18.0	14.0	0.35	20.0	3.0
siCl	20.0	21.0	17.0	0.35	15.0	30.0
FSa	30.0	20.0	16.0	0.30	30.0	0.0
MSa	50.0	20.0	16.0	0.30	35.0	0.0
Top layer and bedding layer	50.0	19.0	16.0	0.30	30.0	10.0

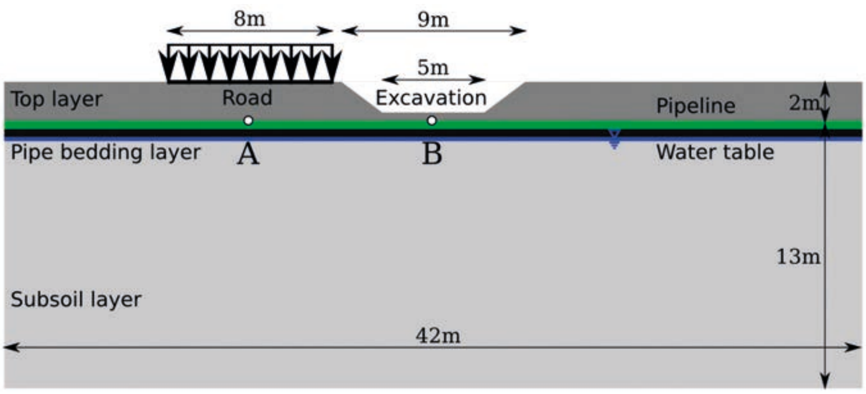

Figure 1. 2D geometry of the problem. Two points of interest, below the centerline of the road and the excavation centerline, were denoted A and B. The largest soil deformations occurred around these points

ulation the top layer and the pipe bedding remained the same, but different subsoil with different mechanical parameters was used, see Table 1. The mechanical parameters of the soils were based on the real soils in the Gdańsk area.

It was assumed that the pipe geometry correspond to a standard DN400 pipe. This type of pipe consists of 6 m long elements that are connected with bell and spigot joints. The load q = 35 kPa applied on the road surface was supposed to model heavy loaded trucks passing to the nearby construction site (Kowalów and Mayer [1] suggest even higher load of 50 kPa for heavy traffic). Any dynamical effects linked to traffic or construction works were neglected in the study to simplify analysis.

NUMERICAL ANALYSIS

Numerical modelling of the buried pipe and the nearby unsecured excavation was focused on calculating soil displacements for different subsoil materials. The analysis was performed in plane-strain conditions using PLAXIS FEM code [6]. The mesh consisted of 15-node triangular finite elements. The soil was modelled with Coulomb-Mohr (CM) constitutive model. A more sophisticated model, such as Hardening Soil (HS) for example, would not enhance the results due to large strains induced in the simulations [8].

Since the 2D conditions actually model a 1 m thick slice of soil, whereas the pipe diameter was equal to 0.40 m, it was necessary to reduce the stiffness of the pipe. The implemented stiffness was reduced by a ratio of pipe-to-soil in 1 m section (i.e. 0,4); this assumption should actually be validated in the future 3D analysis.

Simulations were divided into two groups. The first group was used to find an extreme deflection value, meaning a situation with a perfectly soft pipe. In these simulations the soil displacements were largest and therefore the worst soil conditions were found. The second group of simulations incorporated a pipe with realistic stiffness for grey cast iron pipe: elastic modulus E = 100 GPa and Poisson's ratio ν = 0.3.

The soil stress history was induced by dividing each simulation into following steps:

- loading and unloading of the road surface with traffic (stress history emulation),
- soil displacement values reset to zero (reference point),
- excavation,
- traffic loading.

SIMULATION RESULTS

First group of simulations, where the pipe stiffness was equal to zero, lead to the largest displacements. It was decided to focus not on the total, but on the differential displacements, assuming that while the soil beneath the traffic loaded road would subside, the excavation floor might uplift. Figure 2 and Figure 3 present the absolute values of horizontal and vertical differential displacements respectively, calculated between two points A and B as denoted in the Figure 1.

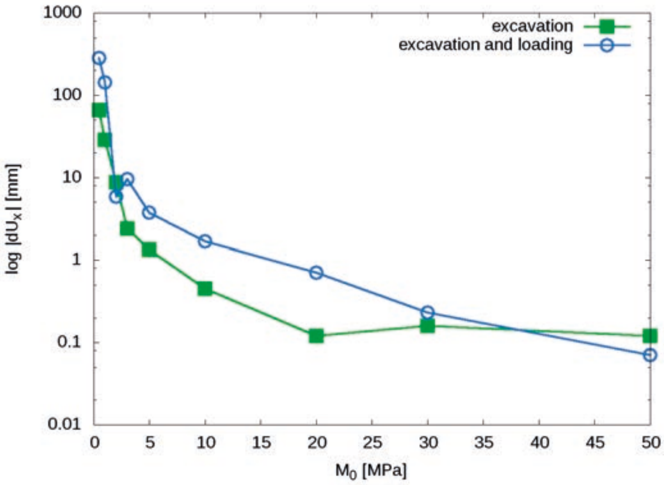

Figure 2. Upper-bound case (pipe with no stiffness) horizontal differential displacements | $U_x^A - U_x^B$ | plotted against subsoil oedometric modulus

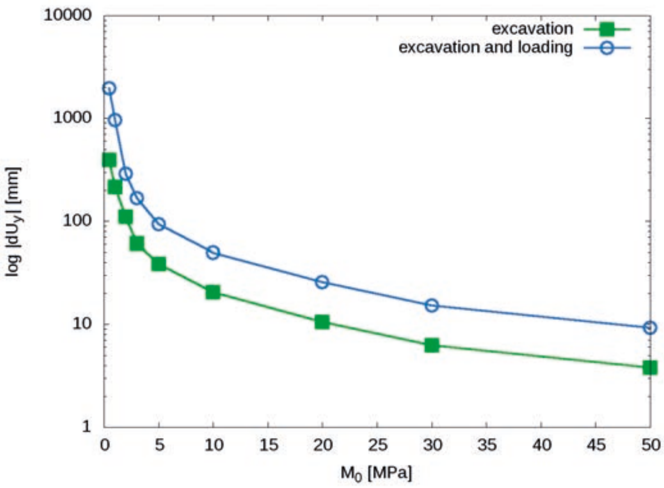

Figure 3. Upper-bound case (pipe with no stiffness) vertical differential displacements | $U_y^A - U_y^B$ | plotted against subsoil oedometric modulus

As expected, the analysis indicated the oedometric modulus M_0 is the most important parameter for soil settlements. Moreover, its value is correlated to values of the other mechanical parameters. As an example, in Figure 4 and Figure 5 the differential displacements are plotted as a function of the internal friction angle and show a similar trend (it is clear however that lower values of friction angle are correlated to lower oedometric modulus, which determines soil deformations).

These simulations lead to a conclusion that the soils with oedometric modulus $M_0 \leq 5$ MPa could cause differential settlements greater than 100 mm. Such values of displacements acting on rigid pipe elements could damage bell and spigot pipe joints. Therefore the second group of simulations was focused on these types of soils.

Simulations in the second group were performed with realistic values of pipe stiffness. The results agreed with the previous simulations. As expected, the soil displacement values were reduced by the existence of the stiff pipe, but still remained large. Exemplary results for a subsoil Or-Compacted mud (M_0 = 2 MPa) are presented below. First series of Figures 6 ÷ 8 represents the first stage of failure – the situation after excava-

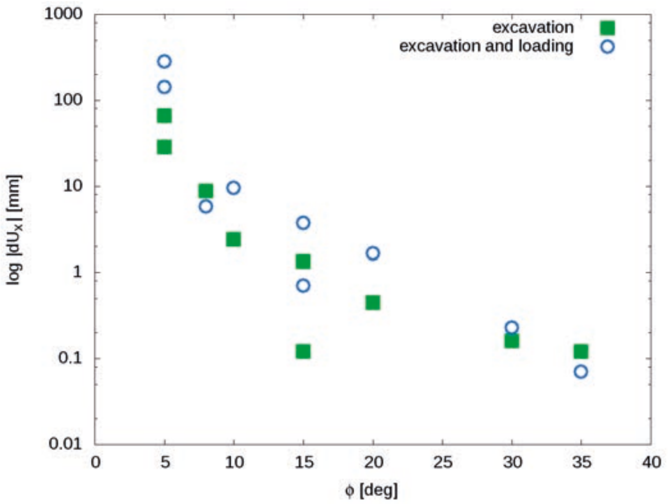

Figure 4. Upper-bound case (pipe with no stiffness) horizontal differential displacements $| U_x^A - U_x^B |$ plotted against subsoil internal friction angle

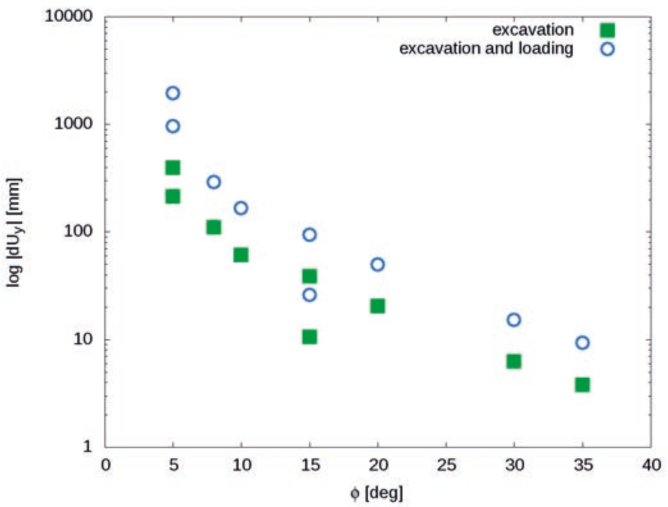

Figure 5. Upper-bound case (pipe with no stiffness) vertical differential displacements $| U_y^A - U_y^B |$ plotted against subsoil internal friction angle

tion, but without traffic loading. Figure 6 depicts a deformed mesh with indicated uplift caused by unloading the trench. Figure 7 and Figure 8 show detailed displacement fields divided into horizontal and vertical components.

The second failure phase – after applying the loading acting on the road, are presented in Figures 9 ÷ 11. Figure 9 presents a deformed mesh with clearly visible pipe deformation as a result of traffic load. Figure 10 and Figure 11 show detailed displacement fields divided into horizontal and vertical components.

As stated previously, there is a difference in the direction of vertical displacements below the road and below the excavation, see Figure 11. Soil settlements exceed 90 mm below the road centreline, are close to 0 mm at the edge of the excavation near to the road and finally reach 60 mm of uplift on the other side of the excavation. Such differences occurring around points placed less than 15 m from each other could lead either to stress increase in the pipe joint material and possibly fracturing of the bell, or to disjoining of the pipe elements through rotation. Conversely, in Figure 10 we observe smaller horizontal displacements of the soil, in the range of 10 mm. Horizontal soil

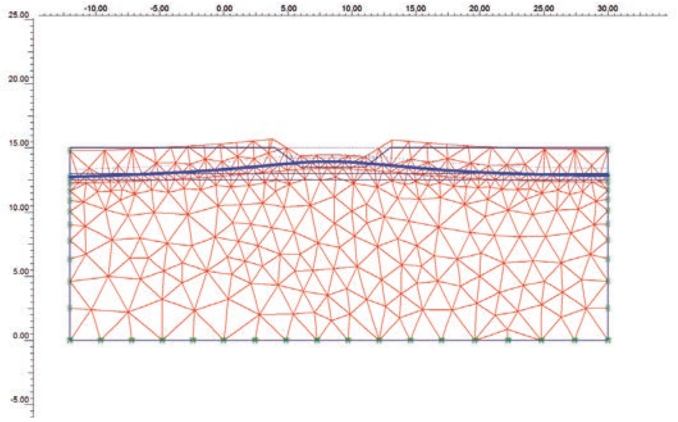

Figure 6. Deformed mesh after excavation (scaled up 10 times)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa)

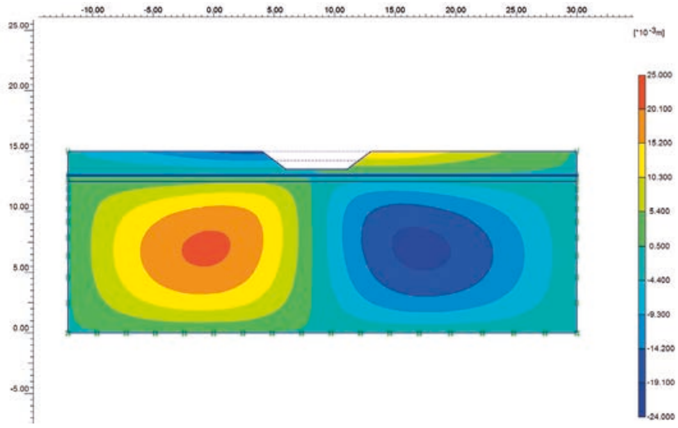

Figure 7. Horizontal soil displacements map (excavation unloading)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa)

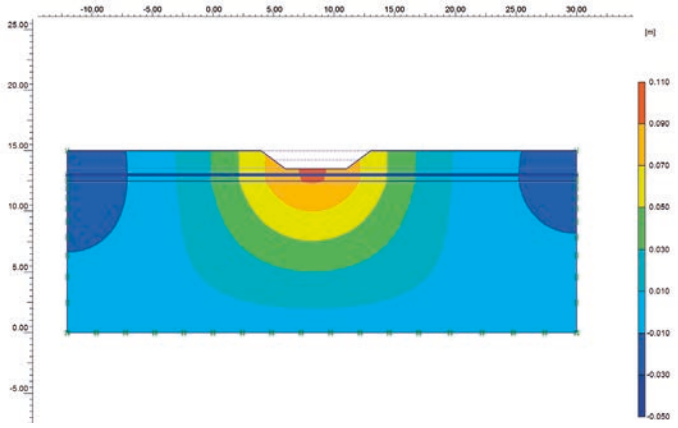

Figure 8. Vertical soil displacements map (excavation unloading)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa).

displacements around the pipe theoretically could lead to pipe joint failure by disjoining of the pipe elements, even though soil displacements are not identical with pipe displacements. Nevertheless, that kind of failure was reported in Gdańsk in 2013 [7].

The simulation results for soft soils show a potential risk connected to soil displacements around the pipes. It should be mentioned, that stiff and brittle pipes, especially corroded ones, could fail due to soil displacements in the range of centimetres [2, 7].

The vertical and horizontal soil displacements combined might cause a rotation of pipe elements out of the axis of the pipeline. While in the discussed case the pipes were made of brittle grey cast iron and equipped with shallow joints, modern, more ductile spheroidal cast iron pipes with deeper joints can sustain deflections smaller than 4° [2]. Therefore it is safe to assume that the limit for the older pipes would be lower. It was estimated the rotations for soft soils with oedometric modulus values lower than 5 MPa were in the range of 1 ÷ 2°, which signifies a potential risk.

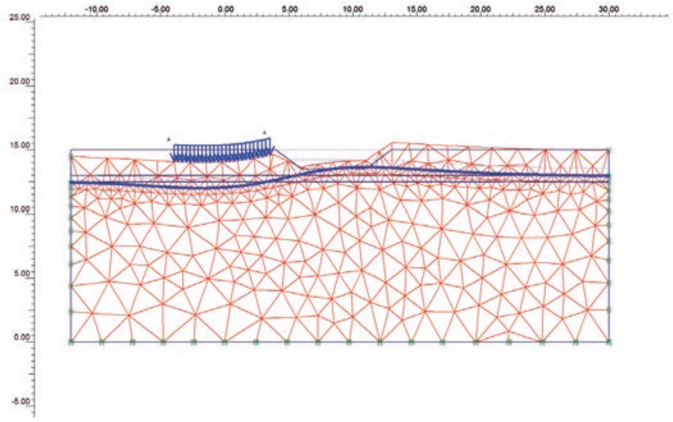

Figure 9. Deformed mesh after traffic loading (scaled up 10 times)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa)

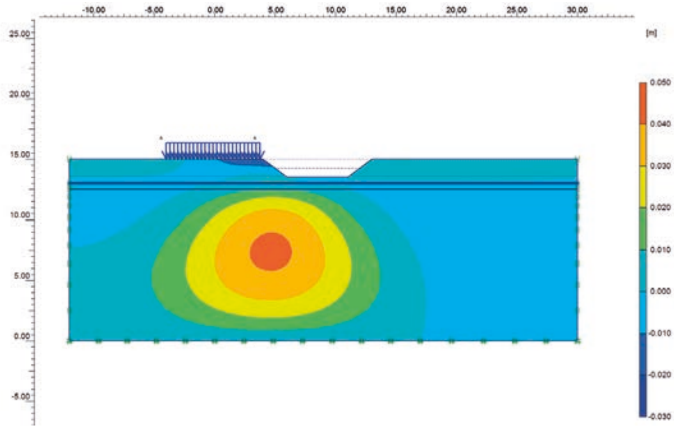

Figure 10. Horizontal soil displacements map (after traffic loading)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa)

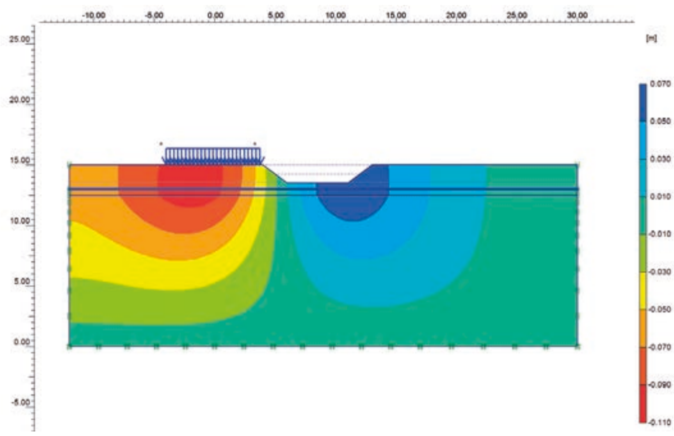

Figure 11: Vertical soil displacements map (after traffic loading)
Subsoil type: Or – Compacted mud (M_0 = 2 MPa)

CONCLUSIONS

Engineers performing works in dense urban areas with long history often face unexpected complications. The existing infrastructure can pose problems due to imprecise localisation, especially when the archival data are incomplete, uncertainty of its actual technical condition, or due to being subjected to situations not accounted for during its design (e.g. additional constructions in the area or much higher loads). In such environment engineering works should be performed with great care and attention to safety. In the Figure 12 and Figure 13 one can see effects of such unexpected circumstances acting together.

The focus of this paper was to study how an unsecured excavation leads to soil displacements in the area around underground pipeline. The influence of soil mechanical parameters on the resulting soil movements was shown, and the conditions that could most likely lead to pipe failure were highlighted. The worst conditions were observed where the subsoil layers consisted of the softest soils, with oedometric modulus values lower than 5 MPa.

This problem will be studied further in the future with a full 3D FEM analysis. Additional insight might be gained from

Figure 12. General view of Gdańsk 2013 real-life case of a pipe failure
in the vicinity of an unsecured excavation that inspired this study
Dotted lines indicate road edges while solid line indicates the axis of the pipeline

Figure 13. Close-up of the Gdańsk 2013 pipe failure area
Dotted lines indicate road edges while solid line indicates the axis of the pipeline

a Discrete Element modelling used to study the soil friction effects on the pipe elements and calculating the actual pipe displacements.

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