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The Unfavourable Impact of Street Traffic on Water Distribution Pipelines

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Abstract: This article analyses the relation between the failures that occurred in the water supply network and the road traffic in the city of Cluj-Napoca in Romania. The calculations in this case study were made using the Autodesk Robot Structural Analysis Professional 2011 software. In the case study, the following types of pipes were analysed: steel, gray cast iron, ductile cast iron and high density polyethylene (HDPE). While in most studies only a few sections of pipelines, several types of pipelines and certain mounting depths have been analysed, the case study presented analyses the entire water supply system of a city with a population of 324,576 inhabitants, whose water supply system has a length of 479 km. The results of the research are useful in the design phase of water distribution networks, so depending on the type of pipe material, the minimum depth of installation can be indicated, so as to avoid the failure of the pipes due to road traffic. From this perspective, similar studies could also be carried out regarding the negative influence of road traffic on sewerage networks, gas networks and heating networks.

Keywords: deterioration; pipeline breaking; pipe failure; street traffic; water distribution networks

1. Introduction

1.1. Context

The pipelines of water distribution systems must withstand ground loading, groundwater loading and road traffic loading. In this case, the pipeline is treated as a structure as well as a fluid transport pipe and it is designed to fulfil these two functions throughout its lifetime [1].

The frequency of breakage and failure of pipes in water distribution networks is increased over time mainly due to deterioration; when pipes deteriorate, the operation and maintenance costs typically increase, and the hydraulic network capacity and the quality of service decrease [2].

Al-Aghbar [3] stated that the four main reasons for the deterioration of the water distribution networks are:

- the aging of water distribution infrastructure due to environmental factors;
- inadequate preventive maintenance and asset management programmes;
- inappropriate funds and changed municipal priorities;
- lack of information and staff.

1.2. Literature Review

During the construction and service period, pipes must support pressures from soil and vehicle loads applied at the soil surface [4].

Xu et al. [5] conducted a study on the influence of road load on a reinforced concrete pipe with an inner diameter of 1400 mm, and the study showed that the unfavourable influence of road load depends on the pipe mounting depth.

Li et al. [6] conducted a study analysing the relationship between non-hydraulic factors and pipe failures. Thus, the following factors were taken into account: the type of material from which the pipes are made, the diameter of the pipeline and the types of materials used for the roads in the urban environment. The types of pipes used in the water distribution system were the following: galvanized pipes, glass fibre reinforced polymer (GFRP) pipes, polyethylene (PE), other plastics, ductile cast iron, gray cast iron, steel, multi-layer steel-plastic pipe and concrete pipes. Following the study, the authors concluded that most of the faults occur in the area of concreted roads, these failures being caused by road traffic.

Alzabeebee et al. [7] state that the scholarly literature does not provide clear conclusions about the effect of the pipe diameter and pipe mounting depth on the pipeline behaviour, and that most studies have focused on certain types of pipes, certain pipe diameters and certain pipe mounting depths. So they conducted a study on the effect of pipe diameter and pipe mounting depth; the study was conducted for rigid concrete pipes and flexible PVC pipes, and the traffic loads were considered to be those specified in BS 9295/2010 [8]. The study showed that the effect of road traffic loading becomes insignificant for a pipe mounting depth exceeding 2 m for concrete pipes and 3 m for PVC pipes, respectively.

Rajeev et al. [9] conducted a study on large diameter pipeline defects, and the study showed that most of the failures occurred in the case of steel pipes, cast iron pipes and ductile cast iron pipes. Among the causes of defects the authors identified corrosion, water pressure in pipelines, as well as road traffic.

Pislarasu et al. [10] presented a nomogram on establishing the thickness of the pipe wall in the case of steel pipes used in a water supply system, the pipes being mounted buried at depths of 1 m and 7 m and the pipes having a diameter between 500 mm and 1400 mm. The nomogram was drawn up for mobile loads, namely 10 t trucks, as well as for 30 t tracked vehicles.

In the paper [11], a graph on the minimum depth and maximum depth of the ductile iron pipe mounting is presented by a pipeline manufacturer. The graph is designed for pipes with a diameter of 700 mm and for pipes with a diameter of 2000 mm, and the recommended mounting depth is between 0.8 m and 7 m—the depth recommended according to the pipe diameter and the pipe nominal pressure.

1.3. Purpose and Contributions of the Paper

This study seeks to analyse the impact of street road traffic on water distribution network pipelines.

The necessity of this study results from the critical analysis of the scholarly literature on the impact of street road traffic on water distribution pipelines. Currently used water network failure patterns commonly take into account the characteristics of the pipes, but they often overlook the impact of road traffic. The need to make calculations about the impact of street traffic on pipelines in the local water supply systems arises from the fact that pipeline manufacturers usually indicate the minimum and maximum pipe mounting depths for only certain road traffic loads and for certain calculation hypotheses, and in practice, both road traffic loads and other calculation hypotheses can vary considerably.

The results of the research are useful on the one hand in the phase of water distribution networks design and on the other hand in the phase of water distribution networks exploitation.

2. Materials and Methods

2.1. Studied Area

This article analyses the relation between the failures in the water supply network and the road traffic in the case of the city of Cluj-Napoca, Romania. Following the field inventory of existing pipeline types, it was concluded that the water distribution network of the city of Cluj-Napoca has a length of 479 km and serves 324,576 inhabitants.

The paper represents a continuation of the research conducted by the authors within a doctoral thesis [12], as well as within a research grant [13].

Figure 1 shows the annual evolution of the number of failures in the water supply network of the city of Cluj-Napoca, by connecting pipes, by distribution pipes (DN 80–400 mm), by lanes (DN 400–600 mm) and by adductions (DN 600–1400 mm); the analysis period being the years 2002–2010.

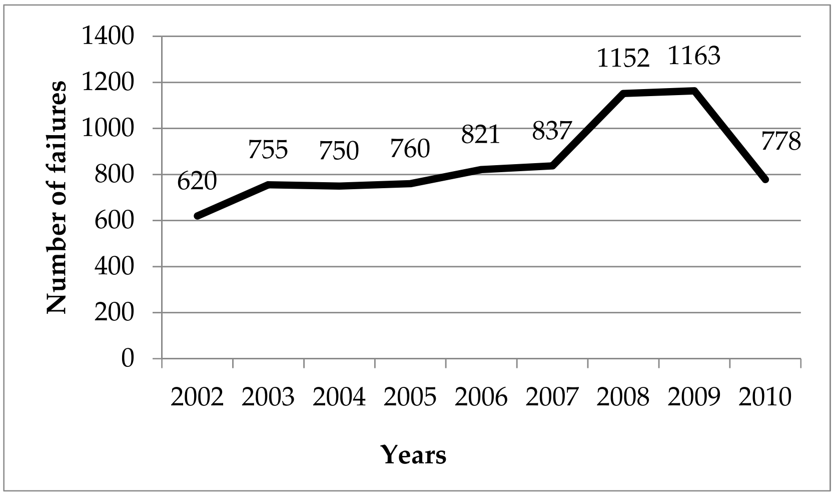
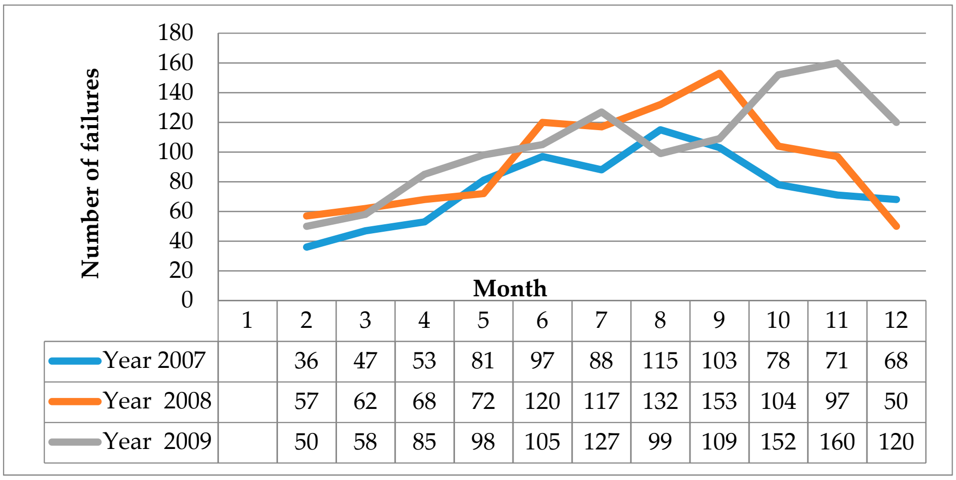


Figure 1. The annual evolution of the number of failures occurred in the water supply network of Cluj-Napoca during 2002–2010 [14].

An analysis of the data in Figure 1 reveals that the number of water supply network failures in the city of Cluj-Napoca increased by 37% in 2008 compared to 2007 and increased continuously until 2009. We mention that the road system in the city of Cluj-Napoca was rehabilitated and modernized during the period 2007–2009. Figure 1 shows that in 2010 the number of failures in the water supply network in Cluj-Napoca decreased, due to the fact that in 2009 the road system rehabilitation process was completed.

Figure 2 shows the monthly evolution of failures in the water supply network of the city of Cluj-Napoca for the period February 2007–December 2009.



	1	2	3	4	5	6	7	8	9	10	11	12
Year 2007		36	47	53	81	97	88	115	103	78	71	68
Year 2008		57	62	68	72	120	117	132	153	104	97	50
Year 2009		50	58	85	98	105	127	99	109	152	160	120

Figure 2. Monthly evolution of failures that occurred in the water supply network of Cluj-Napoca, February 2007–December 2009 [14].

Most pipelines for the water supply system of Cluj-Napoca are located under the road system, and repairs to the road system in Cluj-Napoca are usually carried out from April–December. Analysing the data in Figure 2, it can be noticed that the number of failures increased in the water supply system during the period from May to October, so there is a correlation between the number of failures in the water supply system of the city of Cluj-Napoca and the period to carry out repairs to the road system.

2.2. Materials

2.2.1. Materials Used for Building the Water Distribution Networks

Over time, several types of materials were used for making the pipes of the water supply systems. It began with the stone and wood, continued with prefabricated wooden items (staves), stone (masonry) and bricks (fitted in with lime and then with cement), lead and copper, and during the past 200 years, the iron was used, first in the form of cast iron and afterwards in the form of steel. In the 20th century, the plastics and composite materials industry developed [14–16].

The main materials currently used for water distribution networks are the following: steel, gray cast iron, ductile cast iron, asbestos cement, reinforced concrete, plastics, polyethylene (PE), glass fibre reinforced polymer (GFRP), and other materials [12–26].

A study of the pipeline types used for the 1.5 million km distribution network in The Netherlands, Belgium, Japan, South Africa, Spain, Switzerland, France, Norway, Australia, USA and Germany provides the following data on the share of pipeline types, which are presented in Table 1 [14].

Table 1. Share of water distribution pipelines depending on the pipe diameter and material type [14].

Pipe Diameter (mm)	Pipe Material					
	Plastics (%)	Concrete (%)	Asbestos Cement (%)	Cast Iron (%)	Steel (%)	Other Materials (%)
<200	29.2	0.1	24.7	40.6	4.4	1
200–400	17.9	0.4	15.2	56.6	4.6	5.3
>400	0	8.4	8.2	64.2	19.2	0

Following the analysis of data in Table 1, it can be noticed that one of the most used materials for building the water distribution networks was cast iron. Also, for pipes with a diameter under 400 mm, the plastics are ranked second place.

In the United States, the reason why cast iron was the most used material is because most of the water distribution system was built during the Second World War and good quality pipe materials were not quite available during the war. Due to this fact, a large number of cheaper and lower quality pipes [27] were used for the water distribution system.

This may also explain the increasing use of new materials, such as PVC and PE, for water distribution networks [22].

Gray cast iron and ductile cast iron represent more than two-thirds of the length of existing water networks in Canada. Steel, polyvinyl chloride (PVC), high density polyethylene (HDPE), asbestos cement and concrete pressure pipe (CPP) are also used for Canada water pipelines [28].

As a result of the analysis carried out by the Romanian Water Association, 30% of the length of the water distribution networks in Romania was found to be represented by steel pipes (see Table 2) [29].

Table 2. Romanian water distribution pipelines [29].

Pipeline Material	Length (km)	Percent out of the Total Length (%)
Plastics	390	1
Concrete pressure pipe (CPP)	779	2
Gray cast iron	818	21
Steel	11,686	30
Asbestos cement	17,918	46

2.2.2. Road Traffic and Road Types inside Urban Areas

Among the main defects affecting the components of a water distribution network are also pipe cracks and breaks or other constituents. One of the causes that leads to these defects is represented by external loadings that affect the constituents of the network.

The occurrence of defects as a result of the action of external factors (road traffic, works, earthworks, etc.) leads to chained effects, which include:

- road structure damage;
- possible dangers to the lives and safety of citizens;
- interruptions of utility supply to the population and businesses;
- additional costs etc.

Nowadays, many streets and urban networks are undergoing rehabilitation and modernization processes. This is accompanied by an increase in the volume of road traffic and of the direct loading of vehicles. Consequently, the problem that arises is the avoidance of the occurrence of defects in the underground networks, caused by road traffic. At the same time, it is intended to optimize the process of modernization and rehabilitation of urban networks, so as to minimize the possibility of failure of the network constituents.

As a result, studying the unfavourable impact of street road traffic on water distribution pipelines and analysing possible solutions respond to the need of eliminating defects arising from the above-mentioned causes and affecting water distribution networks.

According to the Romanian laws [30], the streets are public roads inside the localities, arranged specifically for:

- vehicle and pedestrian circulation;
- placement of technical and municipal networks;
- ensuring access to adjacent buildings.

According to the Romanian laws [31,32], there are four categories of streets, having the geometrical characteristics of the standard cross-sectional profile presented in Table 3.

Table 3. Streets—geometrical constituents in cross-sectional profile [31,32].

Street Category	Number of Lanes	Lane Width (m)	Roadway Width (m)
I	6	3.50	21.00
II	4	3.50	14.00
III	2	3.00; 3.50	6.00; 7.00
IV	1	3.00; 3.50	3.00; 3.50

Obviously, the most intense traffic is in the case of the streets from the 1st category.

The main types of road structures that can be used for streets are:

- flexible road structures;
- rigid road structures;
- road structures with carved stone paving carpets;
- road structures with self-locking concrete paving carpets;
- road structures with crushed stone surface, macadam, penetrated macadam carpets;
- pavement of rough stone or cobble (recommended for streets in rural areas).

2.3. Methods

In this study, we are trying to determine the unitary stresses that take place in the walls of the pipelines of the water distribution networks, under the pressure of road traffic and filler earth.

The software used to run the computations in this case study was Autodesk Robot Structural Analysis Professional 2011 [33]. This is a program for calculation by finite element structures that includes a wide range of design codes of all types of metal and concrete structures, with the possibility of contemplating other structural materials [34].

Two basic hypotheses are considered in the calculation:

- pipeline in initial state, in ground free of groundwater;
- pipeline in running order, in ground with groundwater.

The general calculation model used in order to assess the loadings on the water distribution networks is presented in Figure 3.

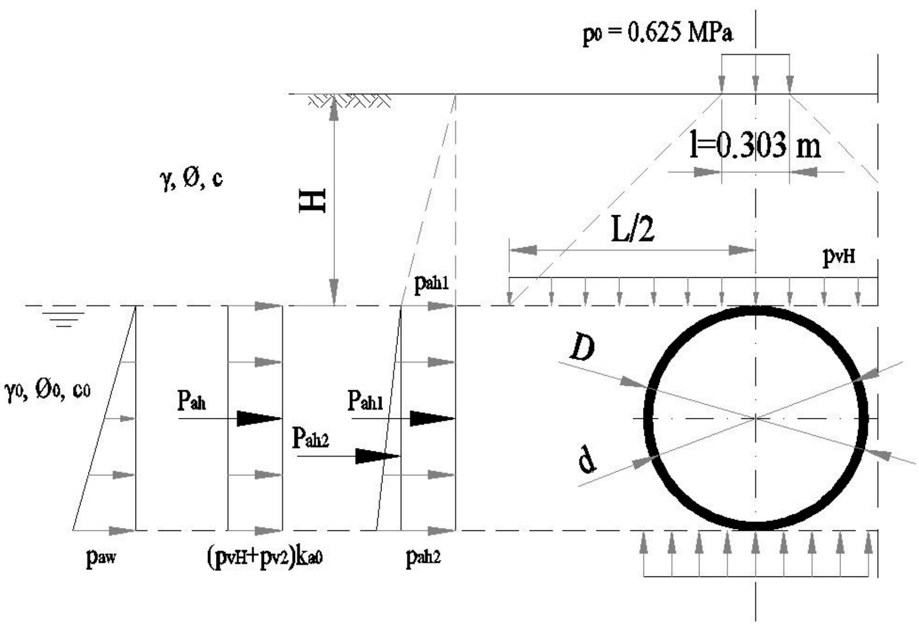


Figure 3. Pipeline loadings calculation model.

The meanings of the terms are the following:

p_0	uniformly distributed pressure from the standard semi-axle;
l	width of the indentation of the standard semi-axle (l = 303 mm);
H	pipe coverage thickness/overlay + road structure thickness;
L	distributed width of the indentation of the standard semi-axle;
D	outer pipe diameter;
γ	volumetric weight of the filler earth above the pipe/pipe overlay density;
Ø	internal friction angle of the filler earth above the pipe;
c	cohesion of the filler earth above the pipe;
ka, k_0	coefficient of lateral earth pressure;
γ_0	volumetric weight of the filler earth around the pipe;
$Ø_0$	internal friction angle of the filler earth around the pipe;
c_0	cohesion of the filler earth around the pipe;
pvH	uniformly distributed vertical pressure from the standard semi-axle at depth H and 45°;
pv2	uniformly distributed loading from the filler earth at depth H;
pah1, pah2	active compression of the earth on the pipe's height;
Pah1, Pah2, Pah	resultants of the active compression of earth on the pipe's height;
paw	underground water lateral pressure.

In Romania, the standard vehicle axle load is 115 kN, as stated in Reference [35]. In the considered model, a local force representing a standard semi-axle load was applied. The real tyre-pavement contact surface is elliptical. However, the PD 177 standard [36] states that it may be considered circular, with a radius of 171 mm and an applied uniform load p_0 = 0.625 MPa. For model convenience, the contact surface was modelled as a 303 × 303 mm square, with the same applied load.

The pressure p_0 of the standard semi-axle was assessed by equivalence of the 57.5 kN concentrated force with the loading distributed on the contour of a square surface having the side l = 30.3 cm [36]. Thus it results p_0 = 0.625 MPa.

Considering that each layer of a road structure has a well-defined role, it has been studied how the road traffic loadings are distributed on the thickness of the road system. Thus, we made a calculation model consisting of a plate on elastic medium having the area of 1 m^2 and the deformability characteristics presented in Table 4, centrically and vertically stressed with a concentrated force F = 57.5 kN.

As this study focuses on the impact of street traffic on water distribution pipelines, a common flexible road structure, modelled as a multi-layer system, was considered (v. Table 4). The design of such non-rigid pavements may be carried out using an analytical method, which consists of analysing the state of stresses and strains in the configured pavement, under the standard semi-axle load, using the Burmister model for different cases of multi-layered systems [37].

The calculation model for the plate is presented in Figure 4.

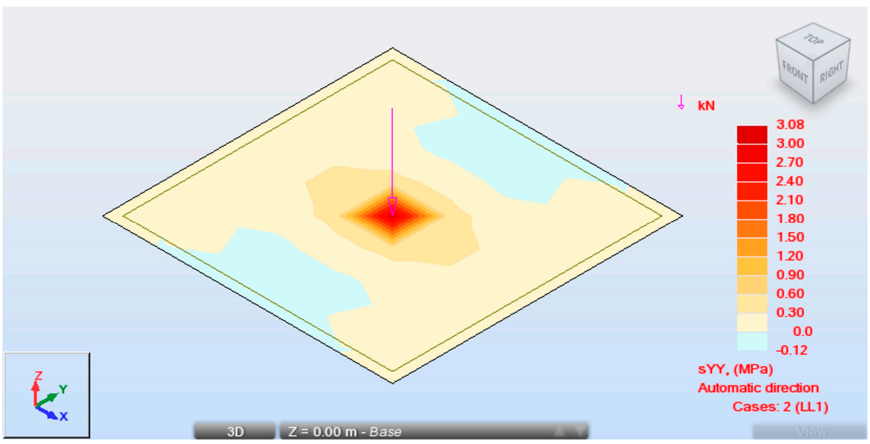


Figure 4. Plate calculation model.

Thus, a distribution of the stresses on the road structure thickness similar with the one presented in Figure 5 is obtained.

Table 4. Characteristics of the materials composing the flexible road structure.

Material	Dynamic Elasticity Modulus E (MPa)	Poisson's Ratio μ
Asphalt mixture-wearing course	3600	0.35
Asphalt mixture-binder course	3000	0.35
Asphalt mixture-base course	5000	0.35
Intermediate aggregate-optimal mixture	500	0.27
Ballast	300	0.27

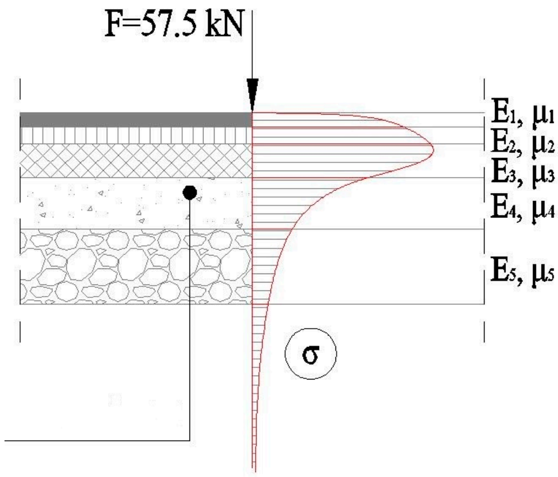


Figure 5. Distribution of stresses on the thickness of the road structure.

Considering a modernized street with a non-rigid road structure on the route of which water distribution networks are disposed, the distribution of road traffic loadings is therefore decreasing with the depth. The maximum values of stresses generated by road traffic are recorded at depths of 10–25 cm from the surface of the wear layer. Thus, the essential structural role of the base course in a road system is justified.

Numerous defects of underground public networks occur during and following repair, rehabilitation or street modernization works, due to the reduction of piping coverage and the heavy machinery used in road works [12].

Thus, it should be considered the situation where the piping coverage is reduced to the minimum and significant dynamic actions are recorded. According to European standards [38], it is recommended to multiply the characteristic values of actions with dynamic coefficients with values up to 2.

This study considers a distribution to 45° of the uniformly distributed load from the standard semi-axle through the filler earth above the pipelines; a hypothesis which includes cases where road works are being carried out on the streets in question.

If groundwater is present, when assessing the earth compression, we took into account the density of the earth in submerged state as well as the hydrostatic pressure of the groundwater. At the same time, assuming that the water supply pipes are functional and full, the filler earth is subjected to a stress by the pipe's walls. Thus, the earth compression is considered as passive.

The earth active compression ratios were assessed using the Rankine theory:

$$\mathrm{ka} = \mathrm{tg}^2(45^\circ - \varnothing/2), \tag{1}$$

$$\mathrm{ka}_0 = \mathrm{tg}^2(45^\circ - \varnothing_0/2), \tag{2}$$

Similarly, the ratios of the earth passive compression were assessed:

$$\mathrm{kp} = \mathrm{tg}^2(45^\circ - \varnothing/2), \tag{3}$$

$$\mathrm{kp}_0 = \mathrm{tg}^2(45^\circ - \varnothing_0/2), \tag{4}$$

As a result of the comparative study of the calculation hypotheses, it was concluded that the maximum loadings arise when the pipes are filled with water and the filler earth exerts passive pressure on the walls of the pipelines.

To evaluate the stress, we grouped the actions according to the following formula [39]:

$$\mathrm{Ed} = \gamma\mathrm{G}\cdot\mathrm{Gk} + \gamma\mathrm{P}\cdot\Phi\cdot\alpha\mathrm{P}\cdot\mathrm{Pk} + \alpha\mathrm{Q}\cdot(\gamma\mathrm{Q1}\cdot\mathrm{Qk1} + \gamma\mathrm{Q2}\cdot\mathrm{Qk2}), \tag{5}$$

where:

Ed	calculation value of the effect of the actions;
Gk	characteristic value of the permanent actions (own weight);
Pk	characteristic value of the temporary action of the road traffic;
Qk1	characteristic value of the permanent action from the earth filler;
Qk2	characteristic value of the permanent action from the earth compression;
γG	partial ratio for permanent actions (own weight); γG = 1.35;
γP	partial ratio for the temporary action of the road traffic; γP = 1.35;
γQ1	partial ratio for the permanent actions from the earth filler; γQ1 = 1.35;
γQ2	partial ratio for the permanent actions from the earth compression; γQ2 = 1.00;
Φ	dynamic ratio for the temporary action of the road traffic (see Table 5);
αP, αQ	heavy traffic loading factors; αP = αQ = 1.10.

Table 5. Adopted values of the dynamic ratio Φ.

H Pipe Coverage Thickness (m)	Dynamic Ratio Φ
≤0.50	2.00
0.60–0.90	1.80
1.00–1.50	1.50
1.60–3.00	1.20
>3.00	1.00

Thus the following formulas result for the groups of actions (see Table 6):

Table 6. Calculation formulas.

H Pipe Coverage Thickness (m)	Ed Calculation Formula
≤0.50	1.35·Gk + 3.00·Pk + 1.50·Qk1 + 1.10·Qk2
0.60–0.90	1.35·Gk + 2.65·Pk + 1.50·Qk1 + 1.10·Qk2
1.00–1.50	1.35·Gk + 2.20·Pk + 1.50·Qk1 + 1.10·Qk2
1.60–3.00	1.35·Gk + 1.80·Pk + 1.50·Qk1 + 1.10·Qk2
>3.00	1.35·Gk + 1.50·Pk + 1.50·Qk1 + 1.10·Qk2

The stresses were assessed for a selection of pipes used for water distribution networks covering a large range of materials and diameters, as follows:

- round steel pipes: Ø 48.3 × 2.6 mm; Ø 88.9 × 3.2 mm; Ø 114.3 × 4 mm; Ø 168.3 × 5 mm; Ø 244.5 × 6.3 mm; Ø 323.9 × 8 mm; Ø 406 × 8 mm; Ø 508 × 10 mm; Ø 610 × 12.5 mm;
- round (gray and ductile) cast iron pipes: Ø 222 × 11 mm; Ø 428 × 14 mm; Ø 634 × 17 mm; Ø 841 × 20.5 mm; Ø 1048 × 24 mm;
- high density polyethylene tubes (HDPE): Ø 20 × 2 mm; Ø 40 × 2.4 mm; Ø 75 × 4.5 mm; Ø 110 × 6.6 mm; Ø 160 × 9.5 mm; Ø 200 × 11.9 mm; Ø 250 × 14.8 mm; Ø 315 × 18.7 mm; Ø 400 × 23.7 mm.

The technical details regarding the geometrical and physical-mechanical characteristics of the building materials were taken from the catalogues provided by the manufacturers and authorized distributors of these items.

Stresses have been evaluated based on the laying depth of the constituents.

For the automated calculation of the stresses, a calculation model was chosen consisting of a continuous beam with a length of 10 m, supported on elastic supports arranged every 1 m along the pipe (see Figure 6), uniformly distributed by the assessed load calculations, both horizontally and vertically.

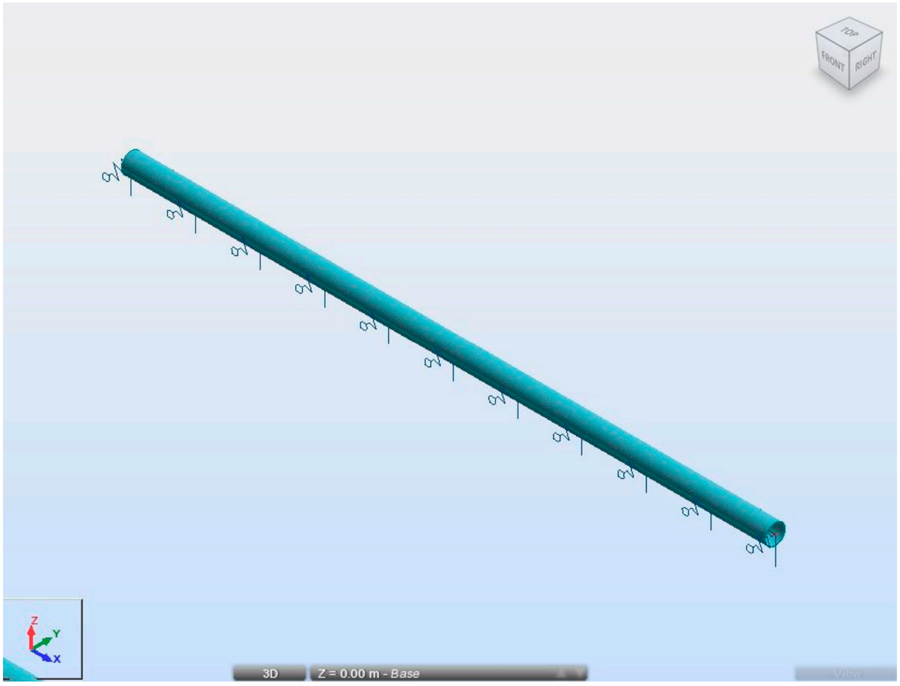


Figure 6. Calculation model for pipes.

3. Results and Discussions

3.1. Results

In this study, assessments were made on the loadings occurring in the water distribution pipes subject to heavy road traffic. The case study was conducted for heavy traffic conditions in Romania.

The following types of pipes were analysed: steel pipes, gray cast iron pipes, ductile cast iron pipes and high density polyethylene (HDPE) pipes.

3.1.1. Steel Pipes

The resistance calculation for the steel pipes was made considering the types of round pipes presented in Table 7, having the corresponding geometric and physical-mechanical characteristics.

In Table 8, we presented the data used for calculations relating to Ø 48.3 × 2.6 mm steel pipes, the pipelines being located on a street open to heavy road traffic, the pipe being filled with water, in a ground with underground water.

Table 7. Steel pipes [40–43].

No.	Outer Diameter (mm)	Wall Thickness (mm)	Elastic Modulus E (MPa)	Shear Modulus G (MPa)	Poisson's Ratio μ	Specific Weight (kN/m^3)	Yield Point (MPa)
1	48.3	2.6	210,000	80,800	0.30	78.5	235
2	88.9	3.2	210,000	80,800	0.30	78.5	235
3	114.3	4.0	210,000	80,800	0.30	78.5	235
4	168.3	5.0	210,000	80,800	0.30	78.5	235
5	244.5	6.3	210,000	80,800	0.30	78.5	235
6	323.9	8.0	210,000	80,800	0.30	78.5	235
7	406	8.0	210,000	80,800	0.30	78.5	235
8	508	10.0	210,000	80,800	0.30	78.5	235
9	610	12.5	210,000	80,800	0.30	78.5	235

Table 8. Action assessment—characteristic values for Ø 48.3 × 2.6 mm steel pipe.

No.	Description	Symbol	Value	M.U.
1	Uniformly distributed pressure—standard semi-axle	p_0	625	kN/m^2
2	Indentation width	l	0.303	m
3	Pipe coverage thickness	H	0.3	m
4	Width of distributed indentation	L	0.903	m
5	Pipe outer diameter	D	0.0483	m
6	Overload volume weight	γ	23	kN/m^3
7	Internal friction angle	Ø	21.7	°
8	Cohesion	c	3.3	kPa
9	Active compression ratio	ka	0.461	
10	Filler volumetric weight	γ_0	19	kN/m^3
11	Internal friction angle	$Ø_0$	25	°
12	Cohesion	c_0	0	kPa
13	Passive compression ratio	kp_0	2.464	
14	Uniformly distributed pressure	pvH	70.37	kN/m^2
15	Uniformly distributed loading—standard semi-axle	pv1	63.5	kN/m
16	Overload	pv2	6.9	kN/m
17	Total vertical loadings	pv	70	kN/m
18	Upper earth compression	pah1	−1.35	kN/m^2
19	Lower earth compression	pah2	18.28	kN/m^2
20	Earth compression	Pah1	0.0	kN/m
21	Earth compression	Pah2	0.4	kN/m
22	Earth compression—overload	Pah	9.2	kN/m
23	Earth compression—total	Pah, total	9.6	kN/m
24	Water volumetric weight	γw	10	kN/m^3
25	Porosity	n	0.33	
26	Volumetric weight of the solid filler framework	γs	26	kN/m^3
27	Volumetric weight of the filler in submersed water conditions	γ'_0	10.72	kN/m^3

In Table 8:

- lines 6–8 refers to overlay;
- lines 10–12 refers to earth around the pipe;
- lines 18–23 refers to lateral earth pressure.

The data are entered in a similar way for the other types of pipes.

The results of the calculations for the steel pipes are presented in Table 9.

According to the results presented in Table 9, in the case of steel pipes mounted under roads subject to heavy traffic, the following conclusions can be drawn:

- 48.3 × 2.6 mm pipes and 88.9 × 3.2 mm pipes have inappropriate behaviour when placed under roads subject to heavy traffic;
- 114.3 × 4 mm pipes behave properly when placed under roads subject to heavy traffic, if they are placed underneath filler earth with heights ranging from 0.9 m to 2 m;
- 168.3 × 5 mm pipes behave properly when placed under roads subject to heavy traffic, if they are placed underneath filler earth with heights ranging from 0.3 m to 6 m;
- 244.5 × 6.3 mm pipes, 323.9 × 8 mm pipes, 406 × 8 mm pipes, 508 × 10 mm pipes and 610 × 12.5 mm pipes behave properly when placed under roads subject to heavy traffic.

Table 9. Results of the calculations for steel pipes.

No.	Coverage Thickness (m)	Steel Pipes (A = Accepted/N = Not Recommended) Dimensions (mm)								
		48.3 × 2.6	88.9 × 3.2	114.3 × 4	168.3 × 5	244.5 × 6.3	323.9 × 8	406 × 8	508 × 10	610 × 12.5
1	0.30	N	N	N	A	A	A	A	A	A
2	0.40	N	N	N	A	A	A	A	A	A
3	0.50	N	N	N	A	A	A	A	A	A
4	0.60	N	N	N	A	A	A	A	A	A
5	0.70	N	N	N	A	A	A	A	A	A
6	0.80	N	N	N	A	A	A	A	A	A
7	0.90	N	N	A	A	A	A	A	A	A
8	1.00	N	N	A	A	A	A	A	A	A
9	1.10	N	N	A	A	A	A	A	A	A
10	1.20	N	N	A	A	A	A	A	A	A
11	1.30	N	N	A	A	A	A	A	A	A
12	1.40	N	N	A	A	A	A	A	A	A
13	1.50	N	N	A	A	A	A	A	A	A
14	1.60	N	N	A	A	A	A	A	A	A
15	1.70	N	N	A	A	A	A	A	A	A
16	1.80	N	N	A	A	A	A	A	A	A
17	1.90	N	N	A	A	A	A	A	A	A
18	2.00	N	N	A	A	A	A	A	A	A
19	3.00	N	N	N	A	A	A	A	A	A
20	4.00	N	N	N	A	A	A	A	A	A
21	5.00	N	N	N	A	A	A	A	A	A
22	6.00	N	N	N	A	A	A	A	A	A
23	7.00	N	N	N	N	A	A	A	A	A
24	8.00	N	N	N	N	A	A	A	A	A

The meaning of the notations used in Table 9 are the following:

- A = accepted; the calculations carried out show that the pipes are resistant to road traffic stresses;
- N = not recommended; the calculations carried out show that the pipes are not resistant to road traffic stresses.

3.1.2. Cast Iron Pipes

The resistance calculation for cast iron pipes was made for both gray cast iron pipes and ductile cast iron pipes. The round pipe types presented in Tables 10 and 11 with the corresponding geometric and physical-mechanical characteristics were considered. The results of the calculations for the cast iron pipes are presented in Table 12.

Table 10. Gray cast iron pipes [44,45].

No.	Outer Diameter (mm)	Wall Thickness (mm)	Elastic Modulus E (MPa)	Shear Modulus G (MPa)	Poisson's Ratio μ	Specific Weight (kN/m^3)	Yield Point (MPa)
1	222	11.0	110,000	44,700	0.23	70.5	130
2	428	14.0	110,000	44,700	0.23	70.5	130
3	634	17.0	110,000	44,700	0.23	70.5	130
4	841	20.5	110,000	44,700	0.23	70.5	130
5	1048	24.0	110,000	44,700	0.23	70.5	130

Table 11. Ductile cast iron pipes [46,47].

No.	Outer Diameter (mm)	Wall Thickness (mm)	Elastic Modulus E (MPa)	Shear Modulus G (MPa)	Poisson's Ratio μ	Specific Weight (kN/m^3)	Yield Point (MPa)
1	222	11.0	170,000	69,100	0.23	70.5	200
2	428	14.0	170,000	69,100	0.23	70.5	200
3	634	17.0	170,000	69,100	0.23	70.5	200
4	841	20.5	170,000	69,100	0.23	70.5	200
5	1048	24.0	170,000	69,100	0.23	70.5	200

Table 12. Results of the calculations for the cast iron pipes.

No.	Coverage Thickness (m)	Gray/Ductile Cast Iron Pipes (A = Accepted/N = Not Recommended)				
		Dimensions (mm)				
		222 × 11	428 × 14	634 × 17	841 × 20.5	1048 × 24
1	0.30	A	A	A	A	A
2	0.40	A	A	A	A	A
3	0.50	A	A	A	A	A
4	0.60	A	A	A	A	A
5	0.70	A	A	A	A	A
6	0.80	A	A	A	A	A
7	0.90	A	A	A	A	A
8	1.00	A	A	A	A	A
9	1.10	A	A	A	A	A
10	1.20	A	A	A	A	A
11	1.30	A	A	A	A	A
12	1.40	A	A	A	A	A
13	1.50	A	A	A	A	A
14	1.60	A	A	A	A	A
15	1.70	A	A	A	A	A
16	1.80	A	A	A	A	A
17	1.90	A	A	A	A	A
18	2.00	A	A	A	A	A
19	3.00	A	A	A	A	A
20	4.00	A	A	A	A	A
21	5.00	A	A	A	A	A
22	6.00	A	A	A	A	A
23	7.00	A	A	A	A	A
24	8.00	A	A	A	A	A

According to the results presented in Table 12, the cast iron pipes of 222 × 11 mm, 428 × 14 mm, 634 × 17 mm, 841 × 20.5 mm and 1048 × 24 mm mounted under roads subject to heavy traffic behaved properly.

3.1.3. High Density Polyethylene (HDPE) Pipes

The resistance calculation for high density polyethylene (HDPE) pipes was made considering the pipe types presented in Table 13 with the corresponding geometric and physical-mechanical characteristics.

Table 13. HDPE pipes [48].

No.	Outer Diameter (mm)	Wall Thickness (mm)	Elastic Modulus E (MPa)	Shear Modulus G (MPa)	Poisson's Ratio μ	Specific Weight (kN/m^3)	Yield Point (MPa)
1	20	2.0	700	310	0.42	9.5	25
2	40	2.4	700	310	0.42	9.5	25
3	75	4.5	700	310	0.42	9.5	25
4	110	6.6	700	310	0.42	9.5	25
5	160	9.5	700	310	0.42	9.5	25
6	200	11.9	700	310	0.42	9.5	25
7	250	14.8	700	310	0.42	9.5	25
8	315	18.7	700	310	0.42	9.5	25
9	400	23.7	700	310	0.42	9.5	25

The results of the calculations for the HDPE pipes are presented in Table 14.

Table 14. Results of the calculations for the HDPE pipes.

No.	Coverage Thickness (m)	HDPE Pipes (A = Accepted/N = Not Recommended)								
		Dimensions (mm)								
		20 × 2	40 × 2.4	75 × 4.5	110 × 6.6	160 × 9.5	200 × 11.9	250 × 14.8	315 × 18.7	400 × 23.7
1	0.30	N	N	N	N	N	N	N	A	A
2	0.40	N	N	N	N	N	N	N	A	A
3	0.50	N	N	N	N	N	N	N	A	A
4	0.60	N	N	N	N	N	N	A	A	A
5	0.70	N	N	N	N	N	N	A	A	A
6	0.80	N	N	N	N	N	N	A	A	A
7	0.90	N	N	N	N	N	N	A	A	A
8	1.00	N	N	N	N	N	N	A	A	A
9	1.10	N	N	N	N	N	N	A	A	A
10	1.20	N	N	N	N	N	N	A	A	A
11	1.30	N	N	N	N	N	N	A	A	A
12	1.40	N	N	N	N	N	N	A	A	A
13	1.50	N	N	N	N	N	N	A	A	A
14	1.60	N	N	N	N	N	N	A	A	A
15	1.70	N	N	N	N	N	N	A	A	A
16	1.80	N	N	N	N	N	N	A	A	A
17	1.90	N	N	N	N	N	N	A	A	A
18	2.00	N	N	N	N	N	N	A	A	A
19	3.00	N	N	N	N	N	N	N	A	A
20	4.00	N	N	N	N	N	N	N	A	A
21	5.00	N	N	N	N	N	N	N	A	A
22	6.00	N	N	N	N	N	N	N	N	A
23	7.00	N	N	N	N	N	N	N	N	A
24	8.00	N	N	N	N	N	N	N	N	A

According to the results presented in Table 14, in the case of high density polyethylene (HDPE) pipes mounted under roads subject to heavy traffic, the following conclusions can be drawn:

- 20 × 2 mm, 40 × 2.4 mm, 75 × 4.5 mm, 110 × 6.6 mm, 160 × 9.5 mm and 200 × 11.9 mm pipes behave inappropriately when placed under roads subject to heavy traffic;
- 250 × 14.8 mm pipes behave properly when placed under roads subject to heavy traffic, if they are placed underneath filler earth with heights ranging from 0.6 m to 2 m;
- 315 × 18.7 mm pipes behave properly when placed under roads subject to heavy traffic, if they are placed underneath filler earth with heights ranging from 0.3 m to 5 m;
- 400 × 23.7 mm pipes behave properly when placed under roads subject to heavy traffic.

3.2. Discussions

Analysing the results of the calculations, it is noticed that heavy road traffic primarily affects pipes having a small nominal diameter, namely pipes having a nominal diameter of up to 300 mm.

Also, for the analysed case study, namely the water supply system of the city of Cluj-Napoca in Romania, it was found out that out of the total number of failures, more than 95% were related to the water connecting pipes and distribution pipes.

As pipes have to satisfy both hydraulic requirements and road traffic resistance requirements simultaneously, we recommend that in the case of pipes with a nominal diameter of less than 300 mm, the resistance to road traffic loading should also be checked. Obviously, if the pipes do not withstand the load of the road traffic, then for the same nominal pipe diameter we can choose a pipe with a thicker wall, so that it can withstand the load of the road traffic.

The selection of pipes with a larger wall thickness leads to a reduction in pipe section and obviously to increased pressure losses. As a result of increased pressure losses, it may be necessary for some pipe sections to choose larger diameter pipes.

Analysing the failures that occurred in the water supply system of the city of Cluj-Napoca, it should be noted that the failures due to road traffic occur as a rule:

- on streets with intense road traffic;

- on streets where heavy road traffic has been deviated;
- on the roads where road repair works have been carried out;
- on old piping sections.

Failures to the water supply systems of localities due to the unfavourable influence of road traffic lead to higher pipeline repair costs, increased water losses, and water losses can also determine damages to other utility networks.

In this context, we recommend that in the Romanian technical regulations regarding the design, operation and rehabilitation of water supply systems, to introduce the obligation to analyze the influence of road traffic on the water supply system pipelines. This obvious analysis can be made on the basis of analytical calculations as presented in this paper, either by submitting documents from pipeline manufacturers with regard to the minimum and the maximum mounting depths at which pipelines can be fitted, depending on the type of material and depending on the loads resulting from road traffic.

We recommend that technical regulations in Romania should also comprise the obligation that, besides the technical expertise of the roads, the technical expertise of water networks, sewerage networks, methane gas networks and heating networks be conducted in the following cases:

- on the streets where heavy traffic is to be deviated;
- on the streets where road repair and modernization works will be carried out.

Following the expertise of utility networks, a number of conclusions can be drawn, for example:

- the maximum tonnage of the means of transport that will be able to travel on a certain street;
- the determination of the working technology for road infrastructure rehabilitation, namely the type of construction equipment to be used, the weight of the construction equipment, and the type of means of transport to be used;
- the need to replace utility networks along with the modernization of roads;
- the protection measures that need to be taken to protect utility networks.

Applying these measures will ultimately lead to:

- a reduction in the number of failures of utility networks;
- a reduction in the cost of repairs to utility networks;
- an increase in the safety of the utility networks;
- a reduction in the water losses related to the drinkable water distribution system in the localities.

Although the case study has been conducted for heavy road traffic conditions in Romania, Autodesk Robot Structural Analysis Professional 2011 software allows changing the calculation hypotheses so that calculations can be made for other road traffic loads as well as for different materials used for building the water distribution networks.

4. Conclusions

Based on this study, it is found that street road traffic exerts a certain influence on the constituents of the water distribution networks, depending on the building materials and the geometric configurations of the constituents, capable of generating defects of the water distribution networks. Therefore, preventive measures are recommended to avoid such situations.

Based on the results obtained from the analytical calculation, we noticed that heavy road traffic primarily affects the pipes with a small nominal diameter, i.e., pipes with a nominal diameter of up to 300 mm. In this context, we recommend that for pipelines with a nominal diameter of up to 300 mm located on roads with heavy road traffic, to carry out a verification of the strength of these pipelines for loads caused by heavy road traffic.

Obviously, if the pipes do not withstand the load of the road traffic, than for the same nominal pipe diameter we can choose a pipe with a thicker wall, so that it can withstand the load of the road traffic. The selection of pipes with a larger wall thickness leads to a reduction in pipe section and obviously to increased pressure losses. As a result of increased pressure losses, it may be necessary for some pipe sections to be necessary to choose larger diameter pipes.

The results of the research are useful in the design phase of water distribution networks, so depending on the type of pipe material, the minimum mounting depth can be indicated, so as to avoid the failure of the pipes due to road traffic.

The proposed method leads to the avoidance of failures in water distribution networks due to the unfavourable action of road traffic, so this method is a proactive method that is preferable to the reactive practice of rehabilitation of water distribution networks, i.e., after a failure.

During the phase of water distribution networks exploitation, the areas where street traffic can lead to water pipeline network failures can be established.

From this perspective, we are considering writing an article on the effect of dynamic loads and vibrations due to heavy road traffic on water distribution networks.

In the future, similar studies could also be conducted, regarding the negative influence of road traffic on sewerage networks, gas networks and thermal networks.

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