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STRUCTURAL INTEGRITY OF WATER PIPELINES

1. INTRODUCTION

While analysing the failure frequency or reliability of water distribution systems it is an often practice to neglect structural integrity of water pipelines represented by theirs safety factor. This factor is also skipped in some rehabilitation strategies for water pipelines [7]. As long as the value of a safety factor remains unknown, it is hardly difficult to evaluate the remaining service life of water pipes. Consequently, it is not easy to predict in advance the optimal time for their rehabilitation or to select an appropriate technology for their rehabilitation if there is an urgent need for it.

This problem is of high importance since the failures of water pipelines are costly and disruptive not only to public utilities or water consumers but also to all these inhabitants occupying the affected areas. Of course, safety factors for water pipelines may significantly change during their exploitation since many factors have an impact on them. These factors were arranged into 17 points.

In order to verify the present value of the safety factor for a water pipeline it is necessary to run its field measurements involving site investigations and static calculations. Field measurements allows e.g. to:

a) verify whether a pipeline can be further exploited without undertaking any actions described in points b – d;

b) decide whether a pipeline should be replaced for a new one (in an open trench or trenchless);

c) verify whether a pipeline can be partially or fully rehabilitated using trenchless technologies

d) verify whether a pipeline can be non – structurally rehabilitated which is much cheaper solution comparing to partial or full rehabilitation;

The paper presents the scope of surveys typically undertaken during field measurements of water pipelines as well as the problems which an expert may face during static calculations.

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2. CAUSES OF CHANGES IN THE VALUES OF SAFETY FACTORS FOR WATER PIPELINES

Structural integrity of water pipelines depends on many factors. The most important factors are:

a) leak tightness of joints. Water that exfiltrates through open pipe joints to the surrounding soil causes destabilization of soil leading to negative changes in pipe bedding conditions;
b) defects observed in a pipeline due to its aging caused by physical, chemical or biological processes, including internal or external corrosion. Corrosion may be evenly distributed around the perimeter of a pipe or may form pits. Leaks from pipelines may occur as the consequence of these pits. Plastic pipes, for instance, show certain, time – dependent fragility. Ageing process also affects organic materials used for coatings such as jute and bitumen or for joint tightening such as hemp string or pitched string;
c) defects which correspond to the low quality of materials. These defects are observed in pipelines with certain material faults, insufficient corrosion protection from the inside, unequal wall thickness, etc. More defects are listed in [8];
d) defects which correspond to poor pipe installation. These defects may result from inappropriate pipe bedding (inadequate type of soil used for bedding or wrong bedding angle) or backfilling as well as from improperly made house service connections. Some defects may also occur as the consequence of wrong transportation or storage. For instance, stones or sharp objects remained in a backfill material may damage external protective coating of a steel pipeline or cause dents in the wall of a plastic pipeline;
e) changes in the values of traffic loads comparing to those assumed in a design project. Current traffic loads are higher than those assumed in the past however everything depends on time of their installation;
f) changes in the loads transmitted to a pipe due to road expansion – as the road expands, a pipe laid originally beyond the road may get under one of its lanes;
g) wrong calculations of a dynamic coefficient;
h) changes in a ground water table leading to dewatering of soil;
i) changes in a road surface. If a permeable road surface is replaced with an impermeable one, the ground below the road starts to drain. When drained ground shrinks the additional bending stresses are generated in pipes;
j) rebuilding of a road associated with installation of a new road surface. If an old road surface is removed, a pipeline may be overburdened by the loads generated by heavy vehicles;
k) installation or reinstallation of conduits in the closest surroundings of a water pipeline. Due to time – dependent rheological changes in the ground (took place after a few, a dozen or dozens of years), the loads transmitted directly to a pipe laid long time ago are lower comparing to those which occur just after backfilling. The value of these loads depends on e.g. type of soil, soil humidity, dynamic impacts. It also tends to rise if an excavated pipe is buried again;

l) loads generated by buildings located in the closest surroundings of a water pipeline. This case refers to a pipeline laid close to the foundations of buildings;
m) increase in the values of stresses generated in a pipe due to frozen soil provided a pipe is laid below a ground water table;
n) increase in the value of an operating pressure inside a pipeline, for example, due to its incrustation;
o) water hammer in a water pipeline;
p) stray electrical currents causing electrochemical corrosion of steel and iron pipelines;
q) another factors varying by regions including seismic impacts or mining damages.

3. FIELD MEASUREMENTS OF WATER PIPES

The purpose of field measurements of a water pipeline is to evaluate its structural integrity, especially its strength parameters as well as to verify its safety factor.

The scope of field measurements of a water pipeline varies depending on the specific features of pipes used for its installation. While analyzing a structural integrity of a pipeline, it is mandatory to consider e.g. material of a pipe, type of joints, installation conditions, depth of cover, type and values of loads transmitted to a pipe, soil parameters, factors responsible for internal and external corrosion of pipes, quality and temperature of water, hydraulic conditions inside a pipeline, possibility of water hammer occurrence, time of exploitation and other factors typical to a pipeline. The scope of field measurements of a water pipeline may involve, for instance:

- project analysis, examination of failure frequency of a pipeline, operating conditions, in which a pipeline is exploited, problems with exploitation which allow to set the details for field measurements;
- site investigations associated with pipe measurements including measurements of a pipe geometry, material measurements or measurements of strength parameters. It is also crucial for an expert to verify bedding conditions of a pipeline using point excavations as well as to verify its physical condition from the inside using CCTV inspection.
- verification of loads transmitted to a pipe followed by static calculations and determination of its safety factor;
- final decision whether a pipeline may be further exploited without its rehabilitation or whether a pipeline requires rehabilitation. If a pipeline requires rehabilitation it is obligatory to suggest appropriate technologies for that purpose.

To sum up, the expertise itself allow to make a decision whether a water pipeline:

- may be further exploited without undertaking any actions described below. Decision is made if the present value of a safety factor is higher than the required one and if a pipeline doesn’t suffer from processes causing deterioration its structural safety including external and internal corrosion;
- could be replaced for a new one in an open trench or replaced using trenchless technologies. Decision is made only if the present value of a safety factor is lower than the required one and if the hydraulic capacity of a pipeline is not sufficient or when hydraulic

capacity of a pipeline is sufficient but structural rehabilitation of a pipeline shows to be more expensive solution comparing to its replacement;

- could be partially or fully rehabilitated using trenchless technologies. Decision is made only if: the present value of a safety factor is lower than the required one, the hydraulic capacity of a pipeline is sufficient, replacement of a pipe in an open trench shows to be more expensive solution comparing to its partial or full rehabilitation by trenchless technologies;
- could be non – structurally rehabilitated. Decision is made only if: the present value of a safety factor is higher than the required one, pipeline suffers from corrosion, hydraulic capacity of a pipeline is sufficient, replacement of a pipeline for a new one shows to be more expensive solution comparing to its trenchless rehabilitation.

The following criteria should be considered before the final decision about trenchless rehabilitation is made: hydraulic capacity of a pipe required due to water supply demands; quality and temperature of transported water; leak tightness of pipes; localization of pipes and durability of the proposed materials. The analysis of these criteria may result in elimination of some technologies used for water pipe rehabilitation. For example, application possibility of cement mortar lining depends on concentration of sulfates and aggressive carbon dioxide in the water as well as its acid capacity.

4. PROBLEMS ASSOCIATED WITH STATIC CALCULATIONS OF WATER PIPELINES

4.1. Selection of appropriate load distribution scheme associated with soil impacts

Load calculations require assuming a proper load distribution scheme. The least advantageous conditions occur just after backfilling of a trench (Fig. 1a). As the time passes by (between installation and field measurements) the loads tend to change for more favorable. In case of rigid and tight pipelines exploited for a long time, the load distribution scheme should be assumed just like that given in Figure 1b.

a) b)

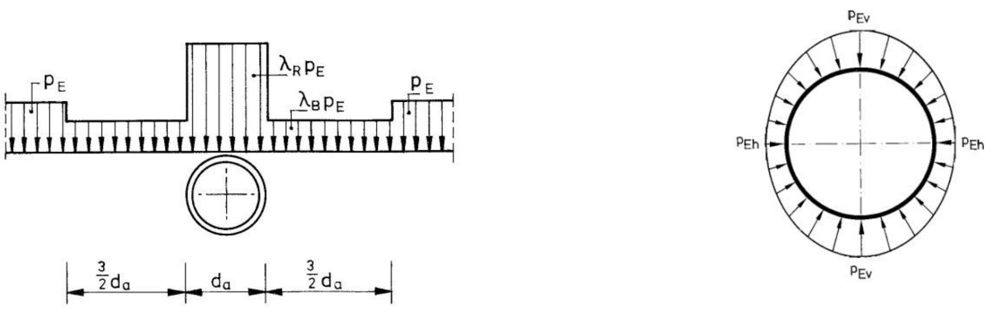

Fig. 1. Vertical loads acting on a rigid pipe: a) just after backfilling of a trench, b) after long time of exploitation provided rheological changes took place [5]

Load distribution schemes according to previously used methods, including method proposed by Marquardt, Voellmy or Wetzorke, should under no circumstances be assumed. The most appropriate methods for that purpose are described in [5,10]. It is also wrong to neglect the impact of lateral earth pressure on a pipe as it was done in Temporary Design Instructions for Wipro pipes [4].

4.2. Consideration of all factors having an impact on the traffic loads

It often happens that inappropriate values of traffic loads are assumed for static calculations. The wrong practice is to recommend (also in Poland) the Scandinavian method for design of plastic pipelines. This method was put in the disrepute e. g. in [3] mainly because of that the traffic loads are expressed here only as a function of cover depth while neglecting the impact of such factors as: total weight of a vehicle, pipe diameter or type of soil.

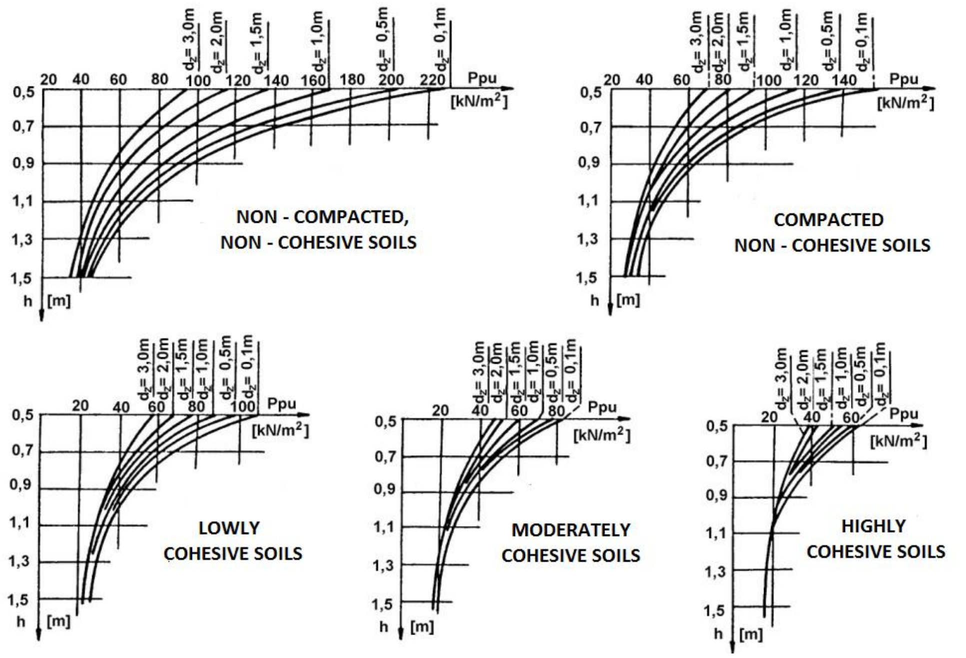

Fig. 2. Traffic loads generated by vehicle of 300 kN in weight for a cover depth of a pipe h between 0.5 and 1.5 m [5,6]

The factors neglected in Scandinavian method were taken into account in KA – 17 method created by the first author of this paper. The curves, which represent the relation between traffic load values and factors considered in KA – 17 method, are given e.g. in [5,6]. Figure 2 shows, for instance, the curves created for a vehicle of 300 kN in weight, different pipe diameters, different types of soils and a cover depth of a pipe varying between 0.5 – 1.5 m.

4.3. Discrepancies in the methodologies allowing for determination of a dynamic factor

A dynamic factor reflects the fact that dynamic traffic loads are transmitted through a soil to a pipe. There exist some different approaches to determining the values of this factor.

The formula popularized by the old standards mentioned e.g. in [1] allows to calculate its values for a pipe laid not deeper than 1.0 m below the ground surface. As regards pipes laid deeper than 1.0 m, these standards suggested to assume the dynamic factor equals 1.0. Scandinavian method, for instance, recommends the dynamic factor equals 1.75, however this factor decreases with cover depth of a pipe reaching the value of 1.0 at the depth of 6.0 m. Both assumptions are inconsistent with physical laws since a dynamic factor does not depend on the cover depth of a pipe. Dynamic factors given e.g. in Swiss standards or German standards ATV-DVWK-A127 are independent from the cover depth of a pipe. Swiss standards suggest to assume the dynamic factor equals 1.3 while German standards vary its value depending on the total weigh of a vehicle. Dynamic factors recommended by German standards are: 1.2 for heavy vehicles, 1.4 for vehicles of average weight and 1.5 for light vehicles. Site measurements into dynamic factors, which were conducted in France, confirmed in majority the assumptions given in German standards since the value of a dynamic factor depends significantly on total weight of a vehicle as well as its speed. In case of uneven surfaces, the dynamic factor may reach the values higher than 2.0 [2].

4.4. Relieving impact of a road surface

Traffic loads are transmitted to a pipe through a road surface and soil respectively. Minor or major part of these loads is absorbed by road surface depending on its type while the rest part acts directly on a pipe. Relieving coefficient, which informs what part of traffic loads are transmitted to a pipe, can be taken from the graph given in Figure 3.

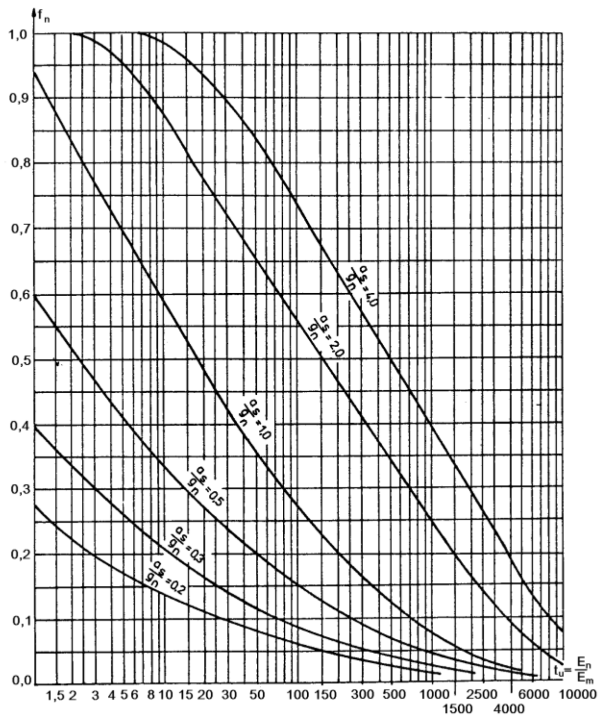

Fig. 3. The relieving coefficient f_n expressed as a function of ratios $\frac{E_n}{E_m}$ and $\frac{a_s}{g_n}$ *[5,6]*

Elasticity coefficient E_n can be assumed according to [1]. In case of improved ground surfaces it changes between 50 and 200 MPa while for improved rigid road surfaces made of concrete it reaches approximately the value of 15 000 MPa. Deformation modulus of a soil E_m is determined as a function of compaction index Is = 100%. Its values may change between 10 and 40 MPa depending on the types of soil.

Parameter a_s can be calculated from the following formula:

$$a_s = \sqrt{\frac{s_p \cdot d_p}{\pi}} \tag{1}$$

where:

s_p, d_p – width and length of the area through which a wheel has a contact with a road surface [m]

In case of vehicle whose weight is 300 kN, parameters s_p and d_p equal 0.6 m and 0.2 m respectively. Parameter g_n means the thickness of a road surface.

According to Figure 3, relieving factor may reach the value lower than 0.1 for concrete surfaces whose elasticity coefficient E_n is high. In that case, more than 90% of traffic loads are absorbed by road surface. So, if an expert neglects relieving impact of a road surface he will always get higher values of traffic loads for the analysis of structural integrity of a pipe.

4.5. Ring bending tensile stresses in a pipe wall

Due to soil and traffic loads both bending moments and axial forces are generated in the cross sections of a pipe wall. These bending moments cause tensile and compression stresses σ_r^z and σ_s^z respectively, which are shown in Fig. 4.

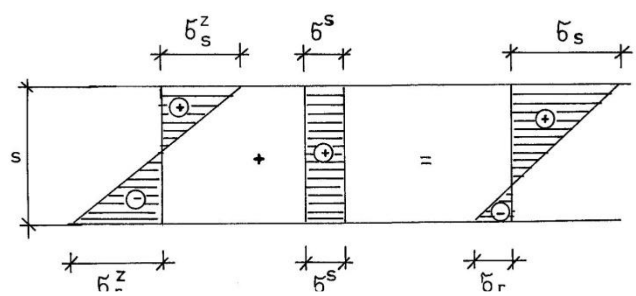

Fig.4. Stresses due to bending and axial tensioning of a pipe cross section and total stresses being the sum of these two

Except this, some compression stresses σ^s (evenly distributed) occur in a wall as a result of axial force. If these stresses are summed up, the one gets the final stresses typical to eccentric load. Such stresses usually occur in a pipe before exploitation starts, when a pipe is out of water.

The wrong practice is to take into consideration only bending stresses caused by bending moments while neglecting compression stresses due to longitudinal axial force. The result is that, these stresses are inappropriately calculated. The most serious mistake is to ignore them completely and design a water pipe considering only tensile stresses due to internal water pressure.

In case of a water pipe stress analysis it is crucial to aggregate both types of stresses, it means stresses due to internal water pressure and stresses due to external loads shown in Fig. 4.

5. SUMMARY

Safety evaluation of water pipelines is possible only after field measurements which require point excavations of pipelines along its route. Field measurements themselves allow to calculate the present value of a safety factor as well as to estimate remaining service life of pipelines. Consequently, they allow to verify whether a pipe rehabilitation is necessary.

Sometimes a decision about pipe rehabilitation is made without conducting field measurements. This runs the risk the pipeline, which should not be rehabilitated, will be selected for rehabilitation and vice versa. The lack of field measurements may also result in selection of inappropriate rehabilitation technology – instead of a non structural rehabilitation technology, the one proposes structural rehabilitation technology and vice versa. Such wrong decision may lead to underloading of a pipeline making it vulnerable to failure or its overloading generating higher investments costs.

REFERENCES

[1] Kuliczkowski A.: Design of buried water and sewer pipes, script no 161, Publisher: Kielce University of Technology, Kielce, 1988, p. 287.

[2] Kuliczkowski A., Sewer pipe design, Script no 356, Publisher: Kielce University of Technology, Kielce, 2000, p. 290.

[3] Kuliczkowski A., Kuliczkowska E.: Traffic loads transmitted to sewer pipes, Informacja Instal, 2000, no 5, pp. 38 – 41.

[4] Kuliczkowski A., Sewer pipes, vol. 1. Material properties, monograph no 28, Publisher: Kielce University of Technology: Kielce, 2001, p. 261.

[5] Kuliczkowski A.: Sewer pipe design, vol. 2., monograph no 42, Publisher: Kielce University of Technology, Kielce, 2004, s. 507.

[6] Kuliczkowski A., Kuliczkowska E., Parka A.: The loadings due to traffic considered in design of trenchless rehabilitation of sewage pipes, In Proc. No-Dig Conf., NASTT, Toronto, Ontario, Canada, Paper D-3-02, 2009, pp.1 – 10.

[7] Kuliczkowski A., Kuliczkowska E.: Rehabilitation strategies for water pipelines, Gaz, Woda i Technika Sanitarna, 2010, no 2, pp. 26 – 29.

[8] Kuliczkowski A.: Trenchless technologies in environmental engineering, Publisher: Seidel – Przywecki, Warszawa, 2010, p. 735

[9] Kuliczkowski A.: Durability of material solutions used for installation and rehabilitation of sewer pipes, Instal, 2014, no 3, pp. 54 - 56

[10] Madryas C., Kolonko A., Wysocki L.: Sewer pipes, Publisher: Wrocław University of Technology, Wrocław, 2002, p. 377

ABSTRACT:

Basing on the experience gained from field measurements of water pipelines made of different materials, 17 common factors have been identified, which cause the changes in their safety factors. Both general purpose and scope of field measurements were explained as well as their role in making a decision whether a pipeline could be further exploited or it should be rehabilitated. Except this, 5 common problems with verification of structural integrity of water pipelines were discussed, including: selection of appropriate scheme of load distribution, calculation of traffic loads with respect to several factors affecting their values, assumption of appropriate dynamic factor, assumption of relieving factor which reflects the possible decrease in traffic load values depending on the type of a road surface and finally proper calculations of stresses in the walls of water pipelines.