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"Gheorghe Asachi" Technical University of Iasi, Romania

PLANNING OF TRENCHLESS REHABILITATION FOR WATER PIPELINES USING DIFFERENT PRESSURE LININGS

Anna Parka*, Emilia Kuliczkowska, Andrzej Kuliczkowski, Agata Zwierzchowska

Faculty of Environmental, Geomatic and Power Engineering, Kielce University of Technology,
Al. 1000-lecia Państwa Polskiego 7, 25-314 Kielce, Poland

Abstract

Trenchless renovation plays a key role in maintaining or improving the structural integrity and hydraulic capacity of water pipelines as well as water quality. It can be executed by installation of different pressure linings classified as A, B, C and D according to the European standards. This paper presents the model A-1.1 elaborated to verify whether renovation of water pipelines using specific pressure linings is feasible in given conditions. The model utilizes some AHP principles, however with a few modifications described later. It considers only 3 criteria suitable for subjective evaluation namely: water pipeline characteristics, safety constraints and further installation constraints. Another aspects associated with selection of pressure linings such as static and hydraulic requirements should be free of any subjective opinions and preferences. That is why a peer selection of pressure lining is highly recommended. In result, a decision maker gets an individual ranking of pressure linings. All linings are evaluated basing on the *FI* value calculated for each of them. Discrepancies in the *FI* values for these linings may not be significant but it is enough to choose the most appropriate lining. However, if the *fe* coefficient is assumed the *FI* value may be higher for chosen linings by at least 5%.

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1. Introduction

Water pipelines can be renewed using trenchless tecnologies presented e.g. by Boyd et al. (2000), Ellison et al. (2010), Kuliczkowski et al. (2019). In majority, a decision about renovation is made if only these pipelines show the evidence of structural degradation or unsatisfactory hydraulic capacity (EPA, 2013). However, a renovation of water pipelines may also be a good remedy for degradation of water quality resulting from infiltration of groundwater or soil migration into them. Moreover, it can help in reducing the amount of deposits or corrosion products at pipes' walls and preventing bacteria from further colonization of these pipelines (LeChevalier et al., 1993; Lehtola et al., 2006; Morton et al., 2005; Wingender and Flemming, 2011). The main problems associated with water of low quality, water quality variations or/and further challenges with biological stability of water were explained in details e.g. by Dohnalik and Wyrwał (2005), Jachimowski (2017), Manjie et al. (2016) or Prest et al. (2016). Some difficulties in maintaining the appropriate chlorine concentration in chosen distribution network were also described in literature, including by Virlan et al. (2021).

Although most technologies have been known for years the whole procedure associated with planning of trenchless renovation of water pipelines may be troublesome. It is because there are no unified standards elaborated for making a decision process far more feasible and rational while the number of models or strategies dedicated to selection of these pipelines for renovation or even replacement can lead to confusion. Another difficulty is that there are plenty variants available within trenchless technologies that

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* Author to whom all correspondence should be addressed: e-mail: ania.parka@interia.pl; Phone: +48 41 3424450; Fax: +48 41 3424450

produce different static and hydraulic effect. Nowadays the one can observe three opposite trends in it and try to find a solution amongst the models allowing for prediction of the optimal time for pipe replacement basing on the estimated failure rates for water pipelines and/or so called life – cycle cost analysis (Berardi et al., 2008; Jafar et al., 2010; Jayaram and Srinivasan, 2008; Khaled and Zayed, 2008; Sekar and Sinha, 2011; Silva et al., 2009) as well as survival functions (Herz, 1996; Reed, 2011), models focusing on the prioritization of water pipelines for repairs (Bałut et al., 2019) or just on managing emergencies within water supply system (Pagano et al., 2021).

There are also some models elaborated to help in selection of the most appropriate group of technologies (Aschilean and Giurca, 2018) or to assess the performance of a water supply system (El Chanati et al., 2016) or condition of individual water pipelines (Al-Barqawi and Zayed, 2008). Despite of many advantages the models themselves show one serious limitation, it means they do not allow to verify whether a water pipeline requires renovation using lining classified as A, B, C and D according to EN ISO 11295 or reconstruction. Except this, they do not take into consideration e.g. the impact of different linings on water quality or their predicted lifetime expectancy. The authors agree that planning of trenchless renovation of water pipelines should be started with selection of water pipelines for renovation followed by selection of appropriate pressure linings producing the required effect. A peer selection of these lining can be executed basing on 3 criteria, namely static, hydraulic and installation. At this stage a decision making process must be free of any subjective opinions and preferences.

A decision maker can use the model proposed earlier by Parka et al. (2020) for that purpose, however he will get the set of linings instead of the one. In order to find the most feasible and rational solution in given conditions the one should apply another methodology and criteria that may depend on individual preferences but will not affect the constructional safety of a renovated pipeline and its hydraulic characteristics. Carrying capacity of a single water distribution system before and after renovation can be assessed using Epanet 2.0. and methodology proposed by Gomes et al. (2020).

Being aware that water of high quality is today an emerging challenge the authors advise e.g. for extending the procedure of this selection and putting a greater emphasis on chemical safety of different materials used for trenchless renovation and their possible impact on human health. It is because some contaminants may leach from specific materials into water and produce side – effects. This fact was proven by independent tests conducted e.g. by Douglas et al. Młyńska et al. (2019), Morton et al. (2005), Musz et al. (2015), Rajasärkkä et al. (2016), Wąsowski et al. (2019) or van der Sloot (2000).

For instance, Douglas et al. (1996) showed that aggressive water having low alkalinity may significantly raise pH (from 7 to 12 after one week of testing), alkalinity and calcium content provided it is transported by pipelines with cement mortar coatings. He also revealed that the trace elements such as chromium, lead, zinc, nickel, arsenic, cadmium, vanadium or copper may also be released from protective cement mortar coating and got to potable water. Another tests conducted by van der Sloot (2000) led to conclusion that the above mentioned metals may leach from cement mortar coating depending on pH and time, during which a cement mortar stays in contact with potable water. Musz et al. (2015) also revealed a noticeable increase of benzene concentration in water resulting from its migration from PEHD pipes under turbulent flow conditions while Rajasärkkä et al. (2016) reported that a BPA (monomer bisphenol A) might leach from epoxy resins. Unfortunately, a general behavior of these resins in real conditions, including ageing process, remains unknown.

Another issue that cannot be neglected during the investment planning is predicted lifetime expectancy for different linings exploited in specific conditions. It is because it may have an impact on future renovation or replacement of pipelines. The rest factors that can help in building the subjective ranking of pressure linings are presented later in the text.

In their studies the authors concentrated on identifying the potentials of different pressure linings to restore or enhance structural and hydraulic capacity of water pipelines or to guarantee high water quality provided a condition of water supply system is well known. Basing on the findings coming from these studies (presented in section 2, point 2.1) they elaborated the model A–1.1, whose aim is to make a trenchless renovation planning far more profitable and rational comparing to the previous solutions. The model itself utilizes some AHP principles, however with a few modifications introduced by the authors of this paper.

The whole methodology as well as basic assumptions for modelling were described later in section 2, point 2.1 and 2.2. Contrary to the previous solutions (Adamović et al., 2007; Ban et al., 2020; Kwast-Kotlarek and Hełdak, 2019) the model allows to rank pressure linings, not technologies, depending on the proposed criteria. It is quite important since the manufacturers sometimes offer linings, which may produce different static effect within one technology. Besides the model considers the factors, which have been neglected so far, including the possible impact of different linings on water quality or predicted lifetime expectancy.

The proposed model was verified on chosen example, which is presented in details in section 2, point 2.3. Results coming from the case study are discussed in point 3 while further conclusions are given in section 4.

2. Material and methods

2.1. Data collection and basic assumptions for the model A-1.1

The authors analyzed different pressure linings including linings used for relining /sliplining, CIPP linings, woven hose linings, close fit linings and spray–applied linings mentioned e.g. in EPA (2013). At first, all linings were considered with respect to their mechanical properties, their impact on hydraulic characteristics of water pipelines and possibilities of their installation. This allowed to verify their potential for restoring or improving hydraulic or structural capacity of these pipelines. Depending on local conditions and water pipeline characteristics the authors obtained the subset of linings called R^{PL}, which included only these pressure linings $r_{x,y}$ out of the set R that satisfy 3 main criteria: strength $K1$, hydraulic $K2$ and installation $K3$ (Eq. 1). To avoid the real names of linings the authors used the abbreviation $r_{x,y}$, where x represents the specific group of linings used in technologies falling into the same family according to EN ISO 11295 while $\boldsymbol{y}$ represents the consecutive number assigned to a lining within this group.

$$R^{PL} = \left\{ r_{xy}:\ r_{xy} \in R;\ r_{xy} = f\,(K1, K2, K3) \right\} \tag{1}$$

Once it was done, the authors focused on recognizing the unit costs of trenchless renovation using specific linings, possible impact of different linings on water quality as well as their life time expectancy.

A peculiar attention was paid on identification some extra factors (poor bedding condition, soil movements in the closest surroundings of water pipelines, etc.) impeding the investment process in given conditions.

The authors also examined different water pipelines for defects affecting their load capacity and analyzed their failure frequency as well. The investigations covered 465 km of pipelines supplying the potable water for citizens of Kielce city, which vary by material of pipes, time of their exploitation and overall condition. Courtesy of local public utility the authors were able to determine the ILI Index for chosen sectors of water supply system and verify the costs associated with failure and leakage elimination. This allowed to recognize the condition of analyzed water pipelines as well as their potential for trenchless renovation.

Basing on the above findings the authors proposed the model A–1.1, which allows for verifying whether trenchless renovation of water pipelines using different pressure linings of diameter not greater than 3600 mm is technically and economically feasible in given conditions. The model was based on 2 fundamental principles saying that installation of linings must be executable in given conditions and must not disturb the hydraulic performance of a water supply system. All pipelines considered for renovation can be exploited in any possible conditions and made of any material, except of asbestos cement. However, the size of pipelines, pipe classes, materials as well as the condition under which these pipelines are exploited must remain unchanged along the renovated segment. Initial selection of pressure linings to be used for trenchless renovation of these pipelines can be done using the algorithm presented by Parka et al. (2020).

The proposed model also utilizes some principles of the AHP method just as previously did Al – Barqawi and Zayed (2008), Ginevicius et al. (2004), Chi-Shun et al. (2018), Imane et al. (2019) or Dinulescu and Bugheanu (2020) for different purposes, however it contains a few important modifications. In general, it facilitates the investment planning with respect to 3 extra decision criteria, namely: water pipeline characteristics $A^{(1)}$, safety constraints $B^{(1)}$ and specific installation constraints $C^{(1)}$. The sub–criteria associated with the above criteria were assumed as follows:

- age of water pipelines selected for renovation a_1, failure frequency for water pipelines a_2, affiliation of water pipelines to the previously defined zones depending on the infrastructural leakage index values a_3, exploitation efficiency of water pipelines expressed as the total investment costs required for their further exploitation prior to trenchless renovation a_4 as regards the first sub–criterion $A^{(1)}$;
- water quality and health safety b_1, structural safety b_2, local safety constraints b_3 as regards the second sub–criterion $B^{(1)}$;
- possible realization difficulties c_1, unit costs of renovation c_2, predicted life expectancy for different pressure linings c_3 and average time of installation c_4 as regards the third sub–criterion $C^{(1)}$.

Following the basic principles of a decision–making process typical to the AHP methodology the authors suggested to compare the established criteria and sub–criteria with each other to form so called pair–wise comparison matrices.

There should be 4 pair–wise comparison matrices at all – one for main criteria with respect to the goal $D^{(0)}$ and 3 for main criteria individually: $A^{(1)}$, $B^{(1)}$, $C^{(1)}$. These matrices may be obtained using the patterns given by Saaty (2008). The elements of such matrices are the equivalent of individual preferences of a decision maker. In order to set these preferences the one may use the fundamental scale of absolute numbers varying between 1 and 10. Once the matrices $D^{(0)}$, $A^{(1)}$, $B^{(1)}$, $C^{(1)}$ are built then the normalized pair–wise comparison matrices $D^{(0n)}$, $A^{(1n)}$, $B^{(1n)}$, $C^{(1n)}$ can be derived and the criteria weight vector W should be computed (Eq. 2).

$$\mathrm{W} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad \rightarrow \quad W^* = \begin{bmatrix} w_1^* \\ w_2^* \\ \vdots \\ w_n^* \end{bmatrix} \tag{2}$$

Possible deviation from consistency should be checked following instruction given in point 2.2. Finally, a decision maker can calculate so called feasibility index *FI* using the formula proposed by the authors (Eq. 13) and choose the most appropriate variant of trenchless technology and pressure lining for a single investment. The architecture of the A-1-1 model is presented in Fig. 1. The idea of a decision making process at the AHP – based stage shows Fig. 2. The feasibility index FI informs whether renovation of a single water pipeline using specific pressure lining is more or less reasonable comparing to the others. The ADW$_{ij}$ values for particular attributes given in Eqs. (12-13) can be obtained from subjective opinions and preferences of the experts. Examples of these values for each attribute defined are given in Appendix 1. Input variables required for proper estimation of ADW$_{ij}$ values can be obtained basing on actual field measurements, available exploitation data and technical information about pressure linings.

Although the model A-1.1 incorporates the AHP – based procedure to find the most appropriate pressure lining, however it contains some modifications comparing to traditional solution. Most changes refer to the step 2 called the preference analysis, which is based on the findings coming from the survey research process.

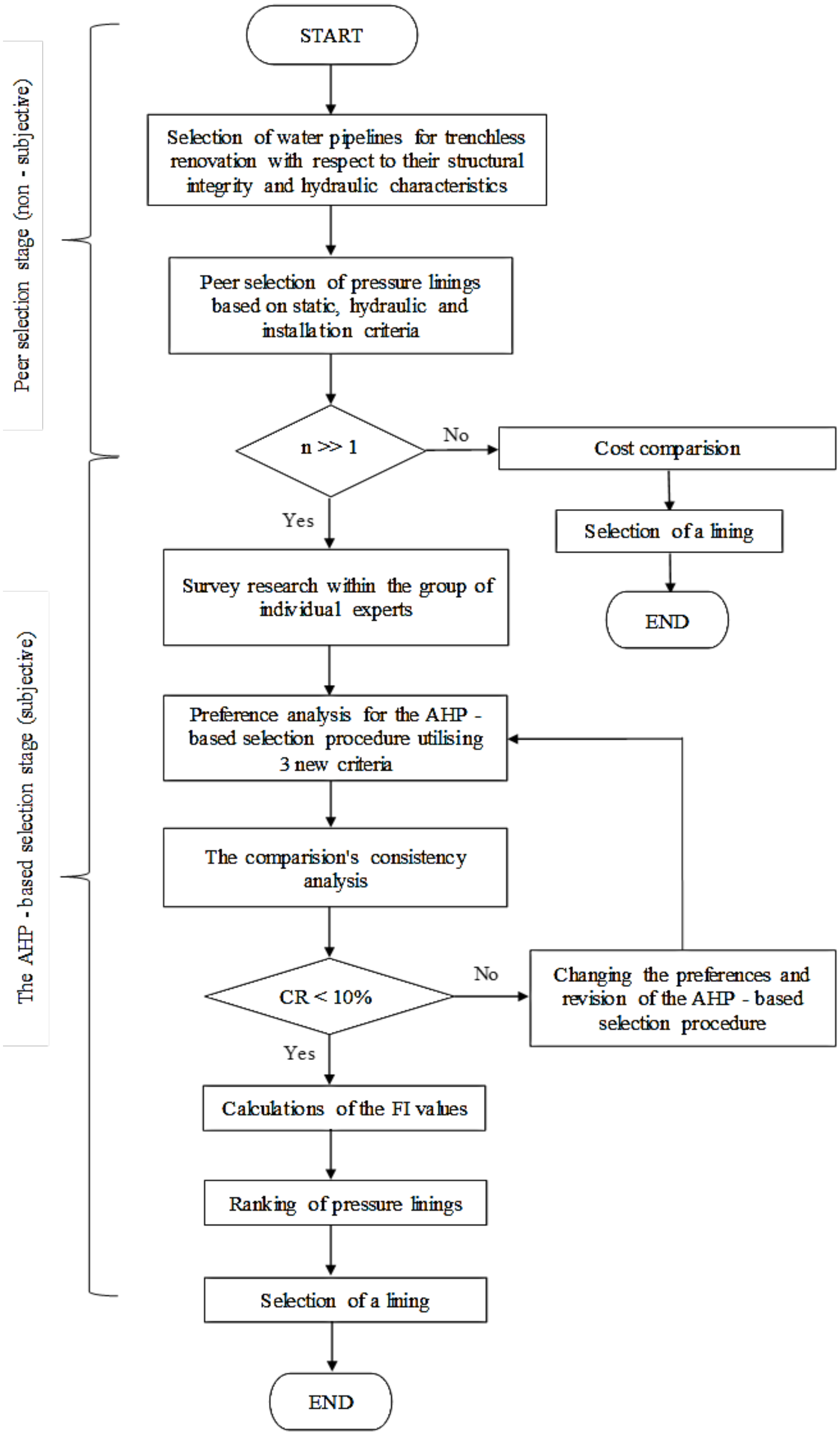

Fig. 1. The architecture of the A-1-1 model

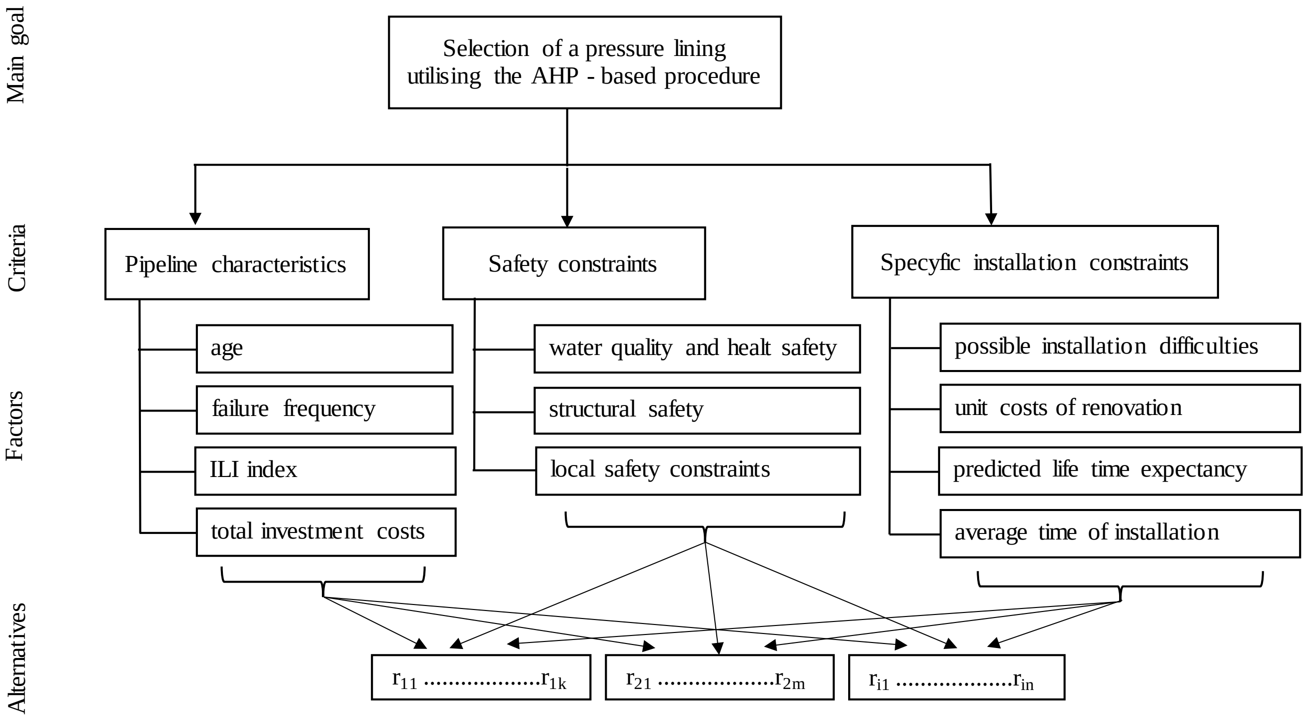

Fig. 2. The architecture of a decision making process at the AHP – based selection stage

For instance, the model A-1.1 allows to modify the final weights for main criteria it means the elements of a standard priority vector W known as w_1, w_2 … w_n into w_1^*, w_2^* … w_n^* by applying the factors f_1, f_2 … f_n and Eqs. (3-6). This eliminates the necessity of changing the preferences to build the new pair – wise comparison matrix and it is quite useful especially if there are more water pipelines having similar characteristics including similar failure frequency records or leakage pattern. In such a situation the f_1 value for the first criterion may equal 2.0 while f_2 and f_3 can be computed using (Eq. 6).

$$w_1^* = w_1 / f_1 = w_1 / 2.0 \qquad (3)$$

$$w_2^* = w_2 + f_2 \qquad (4)$$

$$w_3^* = w_3 + f_3 \qquad (5)$$

for

$$f_2 = f_3 = w_1^* /(n-1) = w_1 /\left(f_1 \cdot (n-1)\right) = w_1\left(2.0(n-1)\right) \qquad (6)$$

If the factor f_1 is assumed the priority weight w_1^* obtained for the first criterion is lower comparing to the original one w_1 computed basing on the conservative AHP principles explained e.g. by Ginevicius et al. (2004) or Saaty (2008). That means the first criterion shall play a smaller role in a decision–making process versus the second or third criterion. Since the factor f_2 and f_3 are also considered thus the priority weight for the second criterion w_2^* as well as the third criterion w_3^* shall be higher. Despite of such modifications the sum of elements w_1^*, w_2^*, w_3^* still equals 1.0.

The principal Eigen value λ_{max} can be obtained using conservative formula presented by Saaty (2008), however the elements such as w_1, w_2 and w_n can be replaced with w_1^*, w_2^*, w_3^* (Eq. 7). The above changes impose further modifications of the elements used to build the principle Eigen vector *W* and elements of so called pair – wise comparison matrices.

$$\lambda_{\max} \to \lambda_{\max}^* = \Sigma 1^{(1)} \cdot w_1^* + \Sigma 2^{(1)} \cdot w_2^* + ... \Sigma n^{(1)} \cdot w_n^* \qquad (7)$$

where: $\Sigma 1^{(1)}$, $\Sigma 2^{(2)}$ and $\Sigma n^{(n)}$ represents the sum of elements in a pair – wise comparison matrix.

If more experts with different opinions participate in a decision making process then the authors suggest to calculate the single expert weight *EW* (Eq. 8) and then EW^* (Eq. 9).

$$EW = 1 / (1 + 1/\alpha_1 + 1/\alpha_2 + 1/\alpha_3) \qquad (8)$$

where: $\alpha_1, \alpha_2, \alpha_3$ – coefficient assumed according to Table 1.

Following the authors recommendations, the single expert weight *EW* shall depend on 3 coefficients, namely: α_1, which reflects the experts' experience, α_2, which is the function of *CR* parameter obtained for given criteria and α_3, which reflects the type of an expert (internal or external). The values of these coefficients are given in Table 1. For $k = 1 \dots n$ experts and $m = 1 \dots M$ pair-wise comparison matrices the EW^* value can be calculated (Eq. 9) provided the single expert weight *EW* value is known.

$$EW^* = (1/M) \cdot \sum_{m=1}^{M} EW \qquad (9)$$

Table 1. Suggested values for $\alpha_1, \alpha_2, \alpha_3$ coefficient

Coefficient	***Suggested value***
α_1	5 if less than 10 years of experience 8 if more than 10 but less than 20 years of experience 10 if more than 20 years of experience
α_2	5 if CR value is nearly 10% 6 if CR value is between 9 and 10% 8 if CR value is between 8 and 9% 9 if CR value is between 7 and 8% 10 if CR value is less than 7%
α_3	5 in case of internal expert 10 in case of external expert

If a normalization process is applied then a decision maker gets the EW^{**} value (Eq. 10).

$$EW^{**} = EW \cdot 1 / \sum_{k=1}^{n} EW^{*} \tag{10}$$

The final weight w_i' for each criteria can be calculated using (Eq. 11), in which w_i represents the original weigh for a criterion obtained according to the conservative AHP principles and EW^{**} represents the single expert weight after the normalization process.

$$w_i' = \sum_{i=1}^{n} w_i \cdot EW^{**} \tag{11}$$

The final selection of a pressure lining can be done provided the *FI* value (Eq. 12) is computed basing on the average decomposed weight of a factor ADW_{ij} and its attribute value AV_{ij}. The AV_{ij} parameter represents different effect of attributes defined within each sub–categories. Responders are asked to assign the AV_{ij} values for each sub–categories using the scale from 0 to 10. If a responder wants to promote a single variant he may increase the basic number of AV_{ij} parameter by a maximum of 2.0 and then multiply it by appropriate average decomposed weight calculated for a single sub–category. The final *FI* value may vary between 0 – 10. The alternative with the highest *FI* value is considered as the most feasible one in given conditions.

$$FI = \sum_{i=1}^{..} \sum_{j=1}^{...} ADW_{ij} \cdot AV_{ij} \tag{12}$$

However, some pressure linings show better mechanical properties comparing to the others including higher modulus of elasticity or higher tensile or flexural strength. Thus, it is possible to get a thinner lining with adequate ring stiffness instead of a thicker one, which may impact negatively on the hydraulic characteristics of a water pipeline selected for renovation. If a decision maker wants to promote a lining giving better mechanical properties he may do this by assuming so called structural factor f_e, which may vary between 1.1 and 2.0. Following the authors' suggestions the factor f_e shall only be applicable to structural constraints. In consequence, the final value of *FI* index should be calculated using Eq. (13) instead of Eq. (12).

In the formula given as Eq. (13) the parameters such as $ADW_{11} \ldots ADW_{14}$ represents the average decomposed weights for sub–criteria defined within the criterion $A^{(1)}$ called 'water pipeline characteristics', the parameters such as $ADW_{21} \ldots ADW_{23}$ represents the average decomposed weights for sub–criteria defined within the second criterion $B^{(1)}$ called 'safety constraints' while the parameters such as $ADW_{31} \ldots ADW_{34}$ represents the average decomposed weights for sub–criteria defined within the third criterion $C^{(1)}$ called 'installation constraints'. The parameters such as $AV_{11} \ldots AV_{14}$, then $AV_{21} \ldots AV_{23}$ and finally $AV_{31} \ldots AV_{34}$ represents the attribute values for sub–criteria defined within the above criteria.

$$\begin{aligned} FI = {} & ADW_{11} \cdot AV_{11} + \ldots + ADW_{14} \cdot AV_{14} + ADW_{21} + fe \cdot \\ & \cdot \left[ADW_{22} \cdot AV22\right] + ADW_{23} \cdot AV_{23} + ADW_{31} \cdot AV_{31} + \ldots + \\ & ADW_{34} \cdot AV_{34} \end{aligned} \tag{13}$$

The above equation is a revised formula suitable for selection of pressure linings not technologies.

2.2. Procedure description

Step 1: Obtaining the pair–wise comparison matrices and normalized comparison matrices, assigning priorities and establishing the priority vector basing on the AHP principles. The first pair–wise comparison matrix called $D^{(0)}$ is built for $n=3$ criteria with respect to the goal. Similar matrices called $A^{(1)}$, $B^{(1)}$ and $C^{(1)}$ can then be built for each criteria individually as specified before. The next step is to calculate so called normalized comparison matrix for main criteria with respect to the goal $D^{(0,n)}$ and then 3 matrices for all criteria individually $A^{(1n)}$, $B^{(1n)}$ and $C^{(1n)}$. The priority vector *W*, consisting of *n* elements called w_1, w_2 … w_n , may be computed using Eq. (2). The principal Eigen value λ_{max} should be then calculated using Eq. (7).

Step 2: Consistency analysis. This step involves calculation of *CI* index (Eq. 14), which depends on the principal Eigen value λ_{max} or λ_{max}^{*} and number of elements *n* being compared to build a matrix as well as *CR* parameter (Eq. 20), which is the ratio between *CI* value and so called random index *RI* assumed according to Saaty (2008).

$$CI = \left(\lambda_{\max} - 1\right)/\left(n - 1\right) \quad (14)$$

$$CR = CI / RI \quad (15)$$

Step 3: Calculating the Decomposed Priority Weights. The decomposed priority weights for all sub–criteria are calculated according to the AHP principles known from the literature. However, different experts may have different opinions on a decision–making process and show different preferences. Thus the authors recommend to calculate the single expert weight *EW* (Eq. 8) and then EW^* (Eq. 9). If a normalization process is applied then a decision maker should also calculate the EW^{**} value (Eq. 10). The final weight w_i' for each criteria can be calculated using Eq. (11).

Step 4: Final selection of trenchless renovation technology using specific pressure lining. The last step is to select such a variant of trenchless renovation technology using a specific pressure lining, which will be the best one for a single investment. This can be done basing on the *FI* values calculated basing on Eq. (12) or its revised form (Eq. 13).

Step 5: Final decision. Decision can be made on the basis of *FI* value representing the recommended renovation by using appropriate pressure lining $r_{x,y}$. The *FI* values and its interpretation are as follows: 0–4: rehabilitation using lining $r_{x,y}$ is slightly recommended; 4–6: rehabilitation using lining $r_{x,y}$ is a good choice; 6–8: rehabilitation using lining $r_{x,y}$ is a very good choice; 8–10: rehabilitation using lining r_{xy} is an excellent choice.

2.3. Case study

In this case study the authors analyzed a 300 m long water pipeline made of cast iron pipes DN 350 mm and exploited for 22 years. The pipeline was laid under the asphalt pavement adapted to heavy traffic and in non – corrosive soils. Any ground movements in its closest surroundings were not expected. Due to unsatisfactory condition the pipeline required an immediate renovation using semi – structural pressure lining classified as B according to EN ISO 11295. The failure frequency factor based on 5–year observations was 1.32 failure/km×a.

The pipeline itself was assigned to the III zone according to the Infrastructure Leakage Index value (ILI =2.58). As regards the Exploitation Efficiency Index value for given pipeline there was an increase by 20–25% observed within the past years before renovation. There were no changes in the route direction registered as well as there were no house connections made along the route. The total number of armature installed on the route was 4. An additional protection from external corrosion was not required. An access to the pipeline was not limited or restricted.

Peer selection revealed that there were 4 different pressure linings suitable for renovation of the above pipeline, namely: $r_{2,1}$—a CIPP lining, $r_{3,6}$—a WHL lining (woven hose lining), $r_{4,1}$—a close fit lining and $r_{5,10}$ —a spray – on lining. Depending on the type of a lining a local repair had to be executed.

The results obtained by a single expert:

Step 1: Peer selection of pressure linings and calculation of their wall thicknesses. A decision maker was asked to consider four pressure linings used for trenchless renovation as it was stated before. Key parameters of these linings as well as specific details for their installation are given in Table 2.

Step 2 and 3. Obtaining the pair-wise comparison matrices, assigning priorities, establishing the priority vector and consistency analysis. Results of calculations for main criteria are collected in Table 2 while for sub – criteria are presented in Table 3, 4, 5 and 6.

Step 4: Obtaining the Decomposed Priority Weights. Basing on the results obtained in steps 1…4 the authors computed the values of decomposed priority weights (Table 7).

Step 5: Calculation of the FI values for alternative variants of pressure linings. The FI values were calculated using Eq. (12). The results of these calculations are presented in Table 8. Similar calculations as those presented in steps 1…5 were repeated provided coefficients f_1, f_2 and f_3 are taken into consideration. The results of these calculation are presented in Table 9, 10 and 11.

Table 2. Key parameters of linings and specific details for their installation

Lining	*Wall thickness t [mm]*	*Stiffness factor E·I [N·mm^2]*	*By-pass system required*	*Local repair or replacement required*	*Unit costs [Euro/m]*	*Predicted lifetime expectancy in given conditions [years]*	*Average time for installation [hours]*
$r_{2,1}$	9.0	34931.3	yes	no	250	40-50	12-24
$r_{3,6}$	7.5	49007.8	yes	no	270	40-50	12-24
$r_{4,1}$	12.0	21600.0	yes	no	440	50	up to 24
$r_{5,10}$	6.9	53382.7	no	yes	189	70	up to 10

Table 3. Results of calculations for main criteria

Main criteria	*A*	*B*	*C*	*W$_i$*	*CI*	*CR (%)*
A	**1.000**	0.333	5.000	0.2674	0.020	0.040
B	3.000	**1.000**	9.000	0.6689		
C	0.200	0.111	**1.000**	0.0637		
SUM	**4.200**	**1.444**	**15.000**	**1.000**		

Table 4. Results of calculations for sub – categories defined within the criteria A

Sub – factors for criteria A	*a_1*	*a_2*	*a_3*	*a_4*	*W_i*	*CI*	*CR (%)*
a_1	**1.000**	0.200	0.143	0.111	0.0417	0.058	0.065
a_2	5.000	**1.000**	0.333	0.200	0.1330		
a_3	7.000	3.000	**1.000**	0.333	0.2676		
a_4	9.000	5.000	3.000	**1.000**	0.5577		
SUM	**22.000**	**9.200**	**4.476**	**1.644**	**1.0000**		

Table 5. Results of calculations for sub – categories defined within the criteria B

Sub – factors for criteria B	*b_1*	*b_2*	*b_3*	*W_i*	*CI*	*CR (%)*
b_1	**1.000**	0.200	0.333	0.1062	0.02	0.03
b_2	5.000	**1.000**	3.000	0.6333		
b_3	3.000	0.333	**1.000**	0.2605		
SUM	**9.000**	**1.533**	**4.333**	**1.0000**		

Table 6. Results of calculations for sub – factors defined within the criteria C

Sub – factors for criteria A	*c_1*	*c_2*	*c_3*	*c_4*	*W_i*	*CI*	*CR (%)*
c_1	**1.000**	3.000	9.000	6.000	0.5720	0.048	0.054
c_2	0.333	**1.000**	8.000	3.000	0.2719		
c_3	0.111	0.125	**1.000**	0.250	0.0417		
c_4	0.167	0.333	4.000	**1.000**	0.1144		
SUM	**1.611**	**4.458**	**22.000**	**10.250**	**1.0000**		

Table 7. Average decomposed weights for each sub – factor defined within criteria

Sub - factors	*Average weights for main criteria*	*Average sub – factors weights*	*Average decomposed weight*
Water pipeline characteristics	0.2674		
– age of water pipelines selected for rehabilitation ***a_1***		0.0417	0.0112
– failure frequency for water pipelines ***a_2***		0.1330	0.0356
– affiliation of water pipelines to the previously defined zones depending on the infrastructural leakage index values ***a_3***		0.2676	0.0716
– exploitation efficiency of water pipelines expressed as the total investment costs required for their further exploitation ***a_4***		0.5577	0.1491
E Safety constraints	0.6684		
– water quality and health safety ***b_1***		0.1062	0.0710
– structural safety ***b_2***		0.6333	0.4233
– local safety constraints ***b_3***		0.2605	0.1741
Installation constraints	0.0637		
– possible realization difficulties ***c_1***		0.5720	0.0364
– unit costs of rehabilitation ***c_2***		0.2719	0.0174
– predicted life expectancy for different pressure linings ***c_3***		0.0417	0.0027
– average time of installation ***c_4***		0.1144	0.0073

Table 8. The FI values for different pressure linings

Criterion	*Sub-factor*	*ADW_{ij}*	*AV_{ij} for a subfactor*				*ADW_{ij}·AV_{ij}*			
			$r_{2,1}$	$r_{3,6}$	$r_{4,1}$	$r_{5,10}$	$r_{2,1}$	$r_{3,6}$	$r_{4,1}$	$r_{5,10}$
A	a_1	0.0112	6	6	6	6	0.067	0.067	0.067	0.067
	a_2	0.0356	8	8	8	8	0.285	0.285	0.285	0.285
	a_3	0.0716	8	8	8	8	0.573	0.573	0.573	0.573
	a_4	0.1491	8	8	8	8	1.193	1.193	1.193	1.193
B	b_1	0.0710	10	10	6	10	0.710	0.710	0.426	0.710
	b_2	0.4233	6	6+2	7	2+2	2.540	3.386	2.963	1.693
	b_3	0.1741	7+2+1	7+2+1	7+2+1	7-2+1	1.741	1.741	1.741	1.045
C	c_1	0.0364	8	8	8	10	0.291	0.291	0.291	0.364
	c_2	0.0174	6	4	2	8	0.104	0.070	0.035	0.139
	c_3	0.0027	6	6	8	10	0.016	0.016	0.022	0.027
	c_4	0.0073	8	8	8	10	0.058	0.058	0.058	0.073
FI according to (Eq. 12)							7.578	8.390	7.654	6.169
FI according to (Eq. 13) for *fe*=1.4								9.744		

Table 9. The results of calculations for main criteria provided the factors f_1, f_2, f_3 were assumed

Main criteria	*A*	*B*	*C*	*W_i*	*CI*	*CR (%)*
A	**1.000**	0.152	1.248	0.135	0.020	0.040
B	6.562	**1.000**	4.995	0.738		
C	0.801	0.200	**1.000**	0.127		
SUM	**8.363**	**1.353**	**7.243**	**1.000**		

Table 10. Average decomposed weights for each sub – factor defined within criteria provided the factors f_1, f_2, f_3 were assumed

Sub - factors	*Average weights for main criteria*	*Average sub – factors weights*	*Average decomposed weight*
Water pipeline characteristics	0.1350		
age of water pipelines selected for rehabilitation ***a_1***		0.0417	0.0056
failure frequency for water pipelines ***a_2***		0.1330	0.0180
affiliation of water pipelines to the previously defined zones depending on the infrastructural leakage index values ***a_3***		0.2676	0.0361
exploitation efficiency of water pipelines expressed as the total investment costs required for their further exploitation ***a_4***		0.5577	0.0753
E Safety constraints	0.7380		
water quality and health safety ***b_1***		0.1062	0.0784
structural safety ***b_2***		0.6333	0.4674
local safety constraints ***b_3***		0.2605	0.1922
Installation constraints	0.1270		
possible realization difficulties ***c_1***		0.5720	0.0726
unit costs of rehabilitation ***c_2***		0.2719	0.0345
predicted life expectancy for different pressure linings ***c_3***		0.0417	0.0053
average time of installation ***c_4***		0.1144	0.0145

Table 11. The FI values for different pressure linings calculated using the coefficients f_1, f_2, f_3

Criterion	*Sub-factor*	*ADW_{ij}*	*AV_{ij} for a subfactor*				*$ADW_{ij} \cdot AV_{ij}$*			
			$r_{2,1}$	$r_{3,6}$	$r_{4,1}$	$r_{5,10}$	$r_{2,1}$	$r_{3,6}$	$r_{4,1}$	$r_{5,10}$
A	a_1	0.0056	6	6	6	6	0.034	0.034	0.034	0.034
	a_2	0.0180	8	8	8	8	0.144	0.144	0.144	0.144
	a_3	0.0361	8	8	8	8	0.289	0.289	0.289	0.289
	a_4	0.0753	8	8	8	8	0.602	0.602	0.602	0.602
B	b_1	0.0784	10	10	6	10	0.784	0.784	0.4704	0.784
	b_2	0.4674	6	6+2	7	2+2	2.804	3.739	3.272	1.870
	b_3	0.1922	7+2+1	7+2+1	7+2+1	7-2+1	1.922	1.922	1.922	1.153
C	c_1	0.0726	8	8	8	10	0.581	0.581	0.581	0.726
	c_2	0.0345	6	4	2	8	0.207	0.138	0.069	0.276
	c_3	0.0053	6	6	8	10	0.032	0.032	0.0424	0.053
	c_4	0.0145	8	8	8	10	0.116	0.116	0.116	0.145
FI according to (Eq. 12)							7.512	8.379	7.5418	6.076
FI according to (Eq. 13) for *fe*=1.4								9.877		

3. Results and discussion

If a decision maker considers only basic structural, hydraulic and installation criteria for selection of pressure linings there is a risk that he will get a set of linings instead of the single one. It is because there are a lot of variants of pressure linings, which may provide similar benefits or show similar limitations. To facilitate future renovation planning for water pipelines, the authors developed the model A–1.1, in which a selection of linings is considered as a multi criteria decision – making problem.

The model A–1.1 utilizes some AHP principles, however it contains a few modifications described in details in the text. The proposed model was tested using data obtained for water distribution system exploited in Kielce city. Basing on the experts' opinions the authors calculated the following weights for main criteria: 0.2674 for 'water pipeline characteristics', 0.6684 for 'safety constraints' and 0.0637 for 'installation constraints'. The highest weight among all sub–criteria, it means 0.6333, was obtained for structural safety. In case of criterion called 'water pipeline characteristics' the highest weights, it means 0.5577 and 0.2676, were obtained for sub–criteria such as exploitation efficiency of a water pipeline and affiliation of a water pipeline to the previously defined zone according to *ILI* index. As regards criterion called 'installation constraints' the highest weights, it means 0.5720 and 0.2719, were obtained for sub–criteria such as possible realization difficulties and unit cost of renovation. These weights can change depending on the individual preferences of exerts participating in a decision–making process. In order to modify these weights the one can use the coefficients ***f_1*, *f_2*** and ***f_3*** or try to calculate the new pair – wise comparison matrices basing on the new set of preferences. However, the discrepancies in the results may not be significant if renovation is planned for a single water pipeline. What is more, the low discrepancies in the results shall be expected since peer selection is applied to reduce the amount of pressure linings. It is easy to notice if the results given in Tables 8, 11 and 14 are compared. Thus the correction factor *fe* was introduced for criterion B to modify the final *FI* value. Similar coefficients may be recommended for other criteria, especially if there are more water pipelines selected for renovation.

In the above case study the calculated *FI* values were as follows: 7.578 and 7.474 for the lining $r_{2,1}$, 8.390 and 8.136 for the lining $r_{3,6}$, 7.654 and 7.324 for the lining $r_{4,1}$, 6.169 and 6.580 for the lining $r_{5,10}$ depending on the variant (table 8 and 11). If the correction factor *fe* was applied then the *FI* value for lining $r_{3,6}$ changed from 8.390 to 9.744 and from 8.379 to 9.877 respectively. That means the *FI* value increased by 16.14 and 17.88% comparing to the results obtained using more conservative formula. It was possible since the above lining shows very good mechanical properties including very high stiffness factor. In result, all safety constraints are satisfied with high level of certainty. Although in all cases renovation is recommended (*FI*>5.0), the lining $r_{3,6}$ is far more preferable comparing to the others.

4. Conclusions

If a decision maker uses a traditional model based on 3 non – subjective criteria, namely: static, hydraulic and basic installation constraints he will get a set of linings instead of the one. In order to facilitate an investment planning and management process and to reduce the amount of possible alternatives the model A-1.1 based on 3 subjective criteria was elaborated. The model allows to build the ranking of pressure linings although the differences in the ***FI*** values may not be so large (not greater than 3.0).

Calculations revealed that the safety constraints (weight: 0.6689) are far more important comparing to installations constraints (weight: 0.0637), including possible installation difficulties or unit costs of renovation. It is an encouraging trend since most decisions associated with trenchless technologies were strongly dependent on economic aspects for years.

The results showed also the proposed model is consistent with realistic investment environment and may be implemented for future investment planning and management process. If it is necessary the expert weight can be calculated in order to reflect the expert's importance. In the nearest future the authors will test the PROMETEE method for selection of pressure linings used for trenchless renovation of water pipelines.

Appendix 1

Table 12. Typical AV_{ij} values suggested to be assumed in the A – 1.1. model

Main decision criterion	***Factors defined within the criterion***	***Variants assigned to the factors***	***Score numbers assigned to each variant***
Criterion A: Water pipeline characteristics	age of water pipelines selected for rehabilitation, a_1	in case of water pipelines made of steel and cast iron:	
		$a_1 > 40$ years	10
		40 years $\geq a_1 \geq 31$ years	8
		31 years $> a_1 \geq 21$ years	6
		21 years $> a_1 \geq 10$ years	4
		in case of water pipelines made of materials different than the above mentioned ones;	2
		$a_1 \geq 21$ years	8
		21 years $> a_1 \geq 10$ years	5
		$a_1 < 10$ years	2
	failure frequency for water pipelines, a_2	very high failure frequency, it means $\lambda \geq 1.5$ failures/km×a	10
		high failure frequency: $1.0 < \lambda \leq 1.5$ failures/km×a	8
		increased failure frequency: $0.5 < \lambda \leq 1.0$ failures/km×a	6
		average failure frequency: $0.15 < \lambda \leq 0.5$ failures/km×a	4
		low failure frequency $\lambda \leq 0.15$ failures/km×a	2
	assignment of water pipelines to the appropriate zones depending on the infrastructural leakage index values (ILI values[1]), a_3	water pipeline can be assigned to the I zone according to the ILI value	10
		water pipeline can be assigned to the II zone according to the ILI value	9
			8

		water pipeline can be assigned to the III zone according to the ILI value affiliation water pipeline can be assigned to the IV zone according to the ILI value water pipeline can be assigned to the V zone according to the ILI value water pipeline can be assigned to the VI zone according to the ILI value	6 4 2
	exploitation efficiency index (EEI index) for water pipelines expressed as the total investment costs required for their further exploitation referred to the unit length of a pipeline equals 100 m, a_4	significant increase in the EEI was observed within the past years before planned renovation, it means by more than 25% the EEI value increased by 20 – 25% within the past years before planned renovation the EEI value increased by 15 – 20% within the past years before planned renovation the EEI value increased by 10 – 15% within the past years before planned renovation the EEI value increased by 0 – 10% within the past years before planned renovation	10 8 6 4 2
Criterion B Safety constraints	water quality and health safety, b_1	water quality and health safety is guaranteed without any restrictions and additional risks water quality and health safety can be guaranteed under certain circumstances unless there is a risk of migration of some compounds released from a lining material to drinking water; contamination of drinking water is possible depending on the disinfectant doses there is a possibility of migration of some organic or non organic compounds released from a lining material to drinking water possible impact of lining material on water quality is still under investigation it is not recommended to use a pressure lining in given conditions since water quality can be affected	10 8 6 4 2
	structural safety, b_2	pressure lining will withstand a host pipe fracture if any occurs unexpectedly after rehabilitation with a high level of certainty pressure lining will withstand a host pipe fracture if any occurs unexpectedly after rehabilitation with an average level of certainty pressure lining will withstand a host pipe fracture if any occurs unexpectedly after rehabilitation with a low level of certainty unexpected pipe fracture after rehabilitation is not a relevant because a pipeline is still in a good or very good condition pressure lining will not withstand a host pipe fracture if any occurs unexpectedly after rehabilitation a strong bond between a lining and a host pipe is not required	8 6 5 4 2 +2
	local safety constraints b_3	additional protection from external corrosion is not required; pipe is laid in non corrosive soil additional protection from external corrosion is still not required; pipe is laid in a mildly corrosive soil additional protection from external corrosion should considered since there is a risk of external corrosion or corrosion of small intensity; pipe is laid in a moderately corrosive soil additional protection from external corrosion should be applied since external corrosion of	7 6 5 4 3

		average intensity was detected; pipe is laid in a corrosive soil additional protection from external corrosion must be applied since external corrosion of high intensity was detected; pipe is laid in a highly corrosive soil there are no large defects observed in a pipeline construction that is why it does not have to be locally repaired or replaced larger defects observed in a pipeline construction must be repaired from the inside or outside (holes must be filled or supported) or pipe segment must be replaced pipe is laid in the area where ground movement does not occur pipe is laid in the area where ground movement occurs	+2 -2 +1 -1
Criterion C Installation constraints	realization difficulty, c_1	installation is of very low difficulty; there is no need for by – pass system, however its installation can reduce installation time and increase installation speed; the access to pipelines is not limited or restricted; no large scale disruption is expected since e.g. connections can be plugged, inspected and drilled open from the inside installation is of low difficulty; there is a need for by – pass system, however the access to pipelines is not limited or restricted; little disruption is expected since e.g. a few connections have to be excavated installation is of average difficulty; there is a need for by – pass system, however the access to pipelines is not limited or restricted; some disruption is expected since e.g. more connections have to be excavated installation is of high difficulty; there is a need for by – pass system and the access to pipelines is limited or restricted, much more disruption is expected since a lot of connections have to be excavated installation is of very high difficulty; there is a need for by – pass system and the access to pipelines is limited or restricted; large scale disruption is expected	10 8 6 4 2
	unit cost of rehabilitation, c_2	less than 150 Euro /m between 150 and 200 Euro/m between 201 – 250 Euro/m between 251 – 300 Euro/m more than 300 Euro/m lack of data	10 8 6 4 2 1
	predicted life expectancy for different pressure linings in given conditions, c_3	at least 50 years between 40 – 50 years between 30 – 40 years less than 30 years it is not recommended for pipes with residual life less than 20 years	10 8 6 4 1
	average time of installation, c_4	not longer than 10 hours not longer than 24 hours a few days	10 8 4

Additional comments:

if ILI > 3.5 then a water pipeline can be assigned to the I zone and its condition can be considered as extremely poor;

if 3.0 < ILI < 3.5 then then a water pipeline can be assigned to the II zone and its condition can be considered as very poor;

if 2.5 < ILI < 3.0 then a water pipeline can be assigned to the III zone and its condition can be considered as poor;

if 2.0 < ILI < 2.5 then a water pipeline can be assigned to the IV zone and its condition can be considered as average;

if 1.5 < ILI < 2.0 then a water pipeline can be assigned to the V zone and its condition can be considered as good;

if ILI < 1.5 then a water pipeline can be assigned to the VI zone and its condition can be considered as very good;

Stiffness factor is expressed as E×I, where E stands for modulus of elasticity of a lining and I stands for moment of inertia of its wall

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