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# Analytic Hierarchy Process is not a Suitable method for the Comprehensive Rating

Sai Nethra Betgeri

# ANALYTIC HIERARCHY PROCESS IS NOT A SUITABLE METHOD FOR THE COMPREHENSIVE RATING

by

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# ABSTRACT

The Pipeline Assessment and Certification Program (PACP) was developed by the National Association of Sewer Service Companies, the industry-accepted protocol for condition rating of sewer pipes in the US. The PACP method relies exclusively on visual inspections performed using Closed-Circuit Television (CCTV), where existing structural and operation and maintenance (O&M) defects are observed by certified operators. A limitation of the PACP method is that it does not use pipe characteristics, depth, soil type, surface conditions, pipe criticality, and capacity, nor the distribution of structural defects or history of preventative maintenance to determine the condition rating of the sewer pipe segment. Therefore, this research work addresses this limitation and develops a comprehensive rating model using Analytic Hierarchy Process(AHP) that incorporates pipe characteristics, environmental characteristics, and information about PACP structural score and PACP O&M score in hydraulic factors. Factors such as pipe age, pipe material, diameter, shape, depth, soil type, loading, type of carried waste, seismic zone, PACP structural score, and PACP O&M score are used. The results showed a below-average validity percentage because linear regression assumes a linear relationship between the input and output variables. Still, the actual relation between response and the predictor is not linear. Our proposed model is applied to the data received from the City of Shreveport, LA, which is currently under a Federal Consent Decree.

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## DEDICATION

This work is dedicated to my grandmother Sesharatnam Chekuri, my mother Dr. Naga Parameshwari Betgeri, and my sister Sai Seshu Betgeri who encouraged and supported me every step of the way during my studies, and I am forever grateful for their love and support.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Aging wastewater infrastructure is a growing source of concern for utilities all over the country. The US wastewater sector earned a worrying C- in the most recent Infrastructure Report Card(Report, 2021), an upgrade from the previous D score(USEPA, 2004). Over the next 25 years, $271 billion will be needed to run and manage these networks at the required level of operation. In addition, it is expected that demand for wastewater collection and treatment will increase by 23% by the end of the year 2032(ASCE, 2021). Sewer systems are made up of several parts that carry wastewater from residences and businesses to a treatment facility. In the United States, there are two types of wastewater networks: gravity lines and force mains. Gravity is usually the dominant force moving wastewater from its origin to its eventual treatment destination. This implies that no mechanical or electrical power is required to move the wastewater(Atalah and Ampadu, 2006). But force mains are used when wastewater moves from low-lying areas to higher altitudes through steep hills. They produce the necessary pressure to push wastewater up to higher elevations, and force mains rely on mechanical pumps or compressors situated in a lift station. Risk-based asset management entails recognizing the most critical properties to pursue the most effective course of action in rehabilitating and replacing these structures. Potential sewage pipe failures are eliminated by prioritizing infrastructure renewal with the highest probability of loss, resulting in increased economic, social, and environmental costs. CCTV (Closed-circuit television) crawler inspection is an industry go-to for pipe interior inspection.The Pipeline Assessment and Certification Program (PACP), established by the National Association of Sewer Service Companies, is the industry-accepted and used protocol for rating the condition of sewer pipes in the United States(DeBoda and Bayer, 2015). Since the initial development of the method, several updated versions exist, the most current one is PACP version 7.0.4, released on October 1, 2020(Version, 2021, DeBoda and Bayer, 2015, Kumar et al., 2020b, Kumar et al., 2020a, Kumar et al., 2018). PACP Ratings are listed in Table 1-1. Some utilities develop their in-house defect rating methods, but typically these are also some variations of the PACP method(Angkasuwansiri and Sinha, 2015).

**Table 1-1:** PACP ratings and description.

| PACP Ratings | Description |
|---|---|
| Defect rating 1 | Unlikely in the foreseeable future. |
| Defect rating 2 | Rehabilitate or replace in 20 years or more. |
| Defect rating 3 | Rehabilitate or replace in ten to twenty years. |
| Defect rating 4 | Rehabilitate or replace in five to ten years. |
| Defect rating 5 | Rehabilitate or replace in next five years |

The PACP method is entirely based on visual inspections utilizing closed-circuit television (CCTV), in which qualified operators examine existing structural and operation and maintenance (O&M) problems. A CCTV camera is mounted on an IBAK crawler with a 1000' cable which transmits the high-resolution images to an above-ground computer and display. Continuous video is recorded as the crawler carries the CCTV unit through the pipe. The crawler can be stopped at any time and the CCTV camera can be rotated and the area of interest "zoomed" to reveal fine details.The inner surface images of the pipe are recorded in real time for the period of the inspection and the videos are then analysed by the contractors immediately. The contractors make pipe assessment reports using the CCTV inspection and the inspectors calculates the final rating of a pipe using the industry accepted PACP protocol for all the pipe assessment reports. The overall Rating assessment is shown in Figure 1-1.

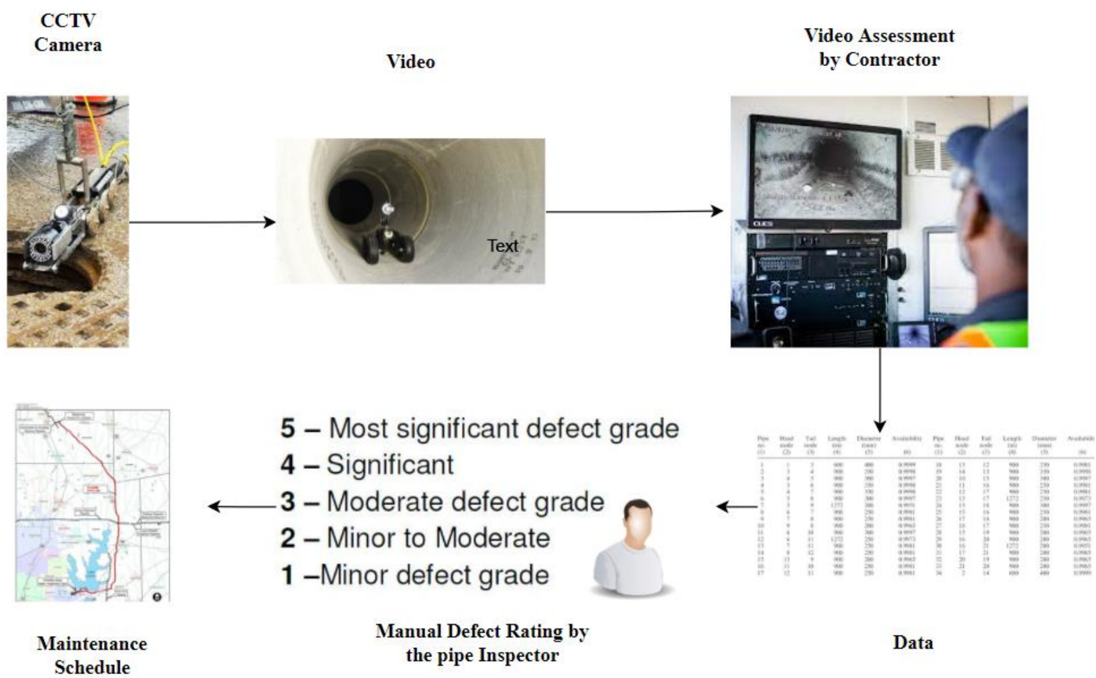


**Figure 1-1:** Overall video assessment

A limitation of the PACP method, according to Thornhill, is that it does not consider environmental characteristics such as depth, soil type, surface conditions, pipe criticality, and capacity, nor the distribution of structural defects or the history of preventative maintenance when determining the condition rating of a gravity sewer pipe segment. Some utilities create defect rating methods in-house, but these are mostly versions of the PACP method(PACP, 2021). Several studies address the need to incorporate physical, structural, operational, and environmental factors with visual pipe inspection data to evaluate the performance of wastewater collection systems better and developed many Overall Condition assessments for both machine learning and statistical models(Velayutham Kandasamy and Sinha, 2018, Ennaouri and Fuamba, 2013, Chughtai and Zayed, 2007, Tabesh and Madani, 2006, Yan and Vairavamoorthy, 2003, Vladeanu and Matthews, 2019a, Vladeanu and Matthews, 2019b, Sai Nethra Betgeri, 2021, Betgeri et al., 2022a, Betgeri et al., 2022b). In all the previous studies, pipe conditions from a structural, hydraulic, or operational perspective, or some combination of these, fail to consider a more comprehensive variety of parameters that affect pipe conditions(Opila and Attoh-Okine, 2011, Opila, 2011).

As a result, in addition to the PACP defect ratings, numerous other factors such as sewer pipe diameter, pipe material, burial depth, pipe bedding, load transfer, pipe joint type and material, surface loading, ground conditions, groundwater level, and soil type, type of waste carried, pipe age, sediment level, surcharge, and poor maintenance practices were assessed to provide a more precise assessment and these Rating, and it is listed for comprehensive Rating. Comprehensive Rating descriptions are listed in Table 1-2.

**Table 1-2:** Comprehensive ratings and description.

| Comprehensive Ratings | Description |
|---|---|
| Defect rating 1 | Reassess in ten years. |
| Defect rating 2 | Rehabilitate or replace in six to ten years. |
| Defect rating 3 | Rehabilitate or replace in three to five years. |
| Defect rating 4 | Rehabilitate or replace in zero to two years. |
| Defect rating 5 | Rehabilitate or replace immediately. |

A developed Pipe Overall Conditional Rating model (POCR) consists of several factors related to physical characteristics, external characteristics, and hydraulic characteristics to assess overall pipe rating using Analytic Hierarchy Process (AHP) to reduce the manual efforts to the inspector(Vladeanu and Matthews, 2019a). In addition, the AHP for decision-making is considered for prioritization in which many variables or criteria are considered. We have compared the final ratings obtained from the POCR model using AHP with Comprehensive ratings given by the inspector; the overall accuracy of the model was 9.32%.

## 1.2 Objective

The primary objective of this research is to build a Comprehensive Rating model upon the previous POCR version with exact factors related to physical characteristics, external characteristics, and hydraulic characteristics, which are used in actual comprehensive Rating to calculate the accurate predicted comprehensive Rating. The proposed model is designed to use 12 factors.

## 1.3 Thesis Organization

This Thesis is organized into four chapters: (1) Introduction; (2) Comprehensive Rating Model; (3) Results and Discussions (4) Conclusions, Limitations, and Recommendations.

Chapter 2 presents the methodology of the Comprehensive Rating model using the Analytic Hierarchy Process (AHP) method. A detailed description of the model's factors and the AHP method is provided.

Chapter 3 presents the results and discussions of the Comprehensive Rating model using the Analytic Hierarchy Process (AHP) method and model evaluation.

Chapter 4 presents some concluding remarks of the research presented in this Thesis, limitations of the model, and future work for improving the reliability and accuracy of the models presented.

# CHAPTER 2

# COMPREHENSIVE RATING METHODOLOGY

## 2.1 AHP Process

Saaty is the creator of the AHP system(Saaty, 1980). A commonly used decision-making approach uses a hierarchical structure to analyze problems and issues. The decision-maker is led by a series of small decision blocks that make up the core question to be examined. AHP Process is used to determine weights of all factors and criteria based upon factor importance.

In the following sections, a stepwise description of the AHP process is provided.

### 2.1.1 Hierarchical Structure

In the first step, the hierarchical structure of the model was developed, as shown in Figure 2-1. Factors that impact the worsening process of sewer pipes were selected based on an extensive literature review and grouped under three main criteria: physical characteristics, external characteristics, and hydraulic characteristics(Ennaouri and Fuamba, 2013).

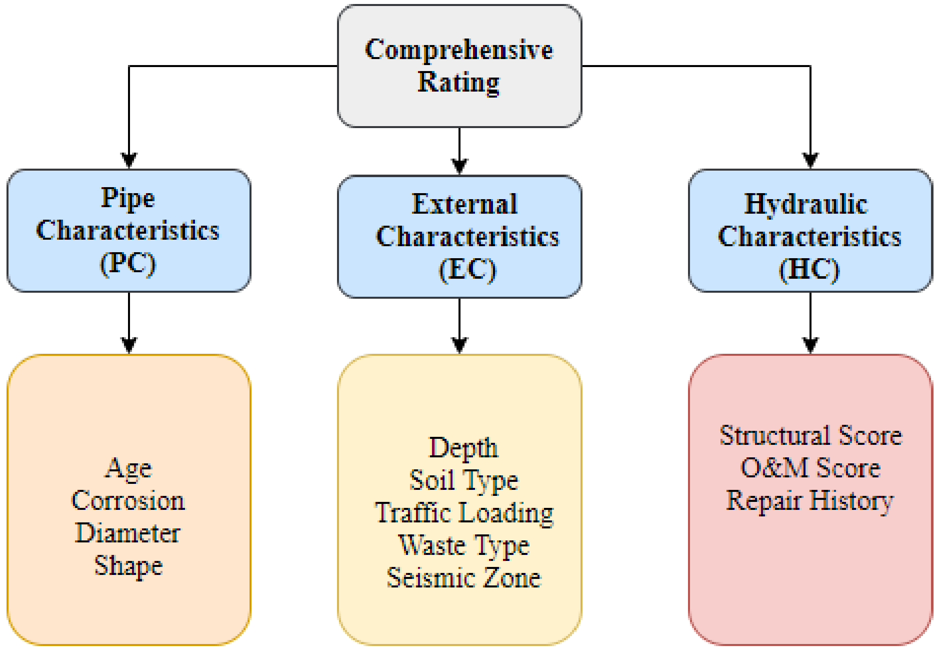


**Figure 2-1:** Hierarchical structure of characteristics.

The factors selected for Hydraulic characteristics in Comprehensive Rating are different from Hydraulic and Other Factors from POCR. Distribution of defects, flow/inflow, and pipe surcharge might affect the predicted comprehensive Rating because these factors were not considered in the actual comprehensive Rating. All the other Physical Characteristics, External Characteristics, Hydraulic Characteristics ratings were defined based on extensive information found in the literature. The factors summary is presented in Table 2-1.

**Table 2-1:** Comprehensive ratings and description.

| Criteria | Factor | Data Type | Description |
|---|---|---|---|
| Physical Characteristics (PC) | Pipe age (years) | Numeric | The time between pipe installation and inspection year and aged pipes have more issues. |
| | Pipe material | String | The pipe material includes various types of material, such as ceramic, glass, fiberglass, many metals, concrete, and plastic. |
| | Diameter(mm) | Numeric | Nominal pipe diameter and smaller diameters are not easy to access. |
| | Shape | String | Typically pipe shapes are circular but depending upon the project, and shapes are changed. Circular shapes are easily accessed. |
| External Characteristics (EC) | Depth (feet) | Numeric | Higher-depth sewers are more challenging to access. |
| | Soil Type | String | Soil corrosiveness can impact the external pipe wall worsening mechanism. |
| | Loading | String | A pipe failure on or near a high traffic area can significantly increase delays and detour distances that negatively affect the social impact. |
| | Waste Type | String | Waste materials carried in a pipe can impact the pipe failure by blocking, corrosion, etc. |
| | Seismic Zone | String | Zones with higher seismic activities can negatively impact the structure. |
| Hydraulic Characteristics (HC) | Structural Score | Numeric | The score is given based upon the structure alignment. |
| | O & M Score | Numeric | The score is given based upon the operational and maintenance. |
| | Repair History | String | Pipes with more maintenance can impact the final Rating |

Under the physical characteristics (PC) criteria, the following factors are defined: pipe age, material, diameter, length, and shape. Accordingly, as the pipe material ages, the degradation process becomes more significant(Hawari et al., 2017). In the present study, larger diameter pipes are considered more prone to worsening than smaller diameters(Balmer and Meers, 1981). Finally, different geometrical shapes will result in varying levels of deposits and degradation patterns(Ennaouri and Fuamba, 2013). The factors' attributes and the assigned ratings of physical characteristics (PC) is presented in Table 2-2.

**Table 2-2:** Attributes factors rating for physical characteristics.

| Factor | Attribute | Ranking |
|---|---|---|
| Age (years) | <10 | 1 |
| | ≥10 and <25 | 2 |
| | ≥25 and <40 | 3 |
| | ≥40 and <50 | 4 |
| | ≥50 years | 5 |
| Corrosion Resistance | Plastic/GRP | 1 |
| | Clay | 2 |
| | NRCP/AC | 3 |
| | RCP | 4 |
| | Metallic | 5 |
| Diameter | >=49 | 1 |
| | >31 and <=48 | 2 |
| | >18 and <=30 | 3 |
| | >11 and <= 18 | 4 |
| | <=11 | 5 |
| Shape | Circular | 1 |
| | Oval | 2 |
| | Horseshoe | 3 |
| | Semielliptical | 4 |
| | Arch | 5 |

Under the external characteristics (EC) criteria, the following factors are defined: burial depth, soil type, loading, waste carried, and seismic zone. The deep burial of the pipe results in increased soil overburden on the pipe. Next, the soil type refers to the surrounding soil that comes in direct contact with the pipe, which can impact the external pipe wall worsening mechanism, mainly corrosive materials, hydrocarbons, etc., present in the soil(Hawari et al., 2017). Traffic loads include all pedestrian and vehicle traffic above and in the proximity of the pipe, which impacts the overall integrity of the pipe. The type of waste carried can potentially erode the internal pipe wall if highly corrosive. Including the seismic zone factor ensures that any possible effects of seismic activities on the overall condition of the pipe are considered in the model. The factors' attributes and the assigned ratings of external characteristics (EC) is presented in Table 2-3.

**Table 2-3:** Attributes factors rating for external characteristics.

| Factor | Attribute | Ranking |
|---|---|---|
| Depth | <= 10 Feet | 1 |
| | > 10 and <= 15 Feet | 2 |
| | > 15 and <= 20 Feet | 3 |
| | > 20 and <= 25 Feet | 4 |
| | > 25 Feet | 5 |
| Soil Type | Low corrosivity | 1 |
| | Low to moderate corrosivity | 2 |
| | Moderate corrosivity | 3 |
| | Moderate-to-high corrosivity | 4 |
| | High corrosivity | 5 |
| Loading | No traffic to very light traffic | 1 |
| | Light traffic | 2 |
| | Medium traffic | 3 |
| | Moderate to heavy traffic | 4 |
| | Heavy traffic | 5 |
| Waste Type | Mildly corrosive | 1 |
| | Mildly to Moderate corrosive | 2 |
| | Moderately corrosive | 3 |
| | Moderately to highly corrosive | 4 |
| | Highly corrosive | 5 |
| Seismic Zone | Zone 1 | 1 |
| | Zone 2 | 2 |
| | Zone 3 | 3 |
| | Zone 4 | 4 |
| | Zone 5 | 5 |

Under the hydraulic characteristics (HC) criteria, the following factors are defined: PACP structural, PACP operations and maintenance (O&M) defects, and repair history. The PACP structural and O&M defect scores are on a scale of 1–5. PACP structural scores gives the defect rating for infrastructure with 1 being the least severe and 5 being the most severe defect. PACP operational scores gives the defect rating for maintenance with 1 being the least severe and 5 being the most severe defect.The repair history gives information about the maintenance of pipes in the previous years. The factors' attributes and the assigned ratings of Hydraulic characteristics (HC) is presented in Table 2-4.

**Table 2-4:** Attributes factors rating for hydraulic characteristics.

| Factor | Attribute | Ranking |
|---|---|---|
| Structural Score | 1 | 1 |
| | 2 | 2 |
| | 3 | 3 |
| | 4 | 4 |
| | 5 | 5 |
| O & M Score | 1 | 1 |
| | 2 | 2 |
| | 3 | 3 |
| | 4 | 4 |
| | 5 | 5 |
| Repair History | No maintenance | 1 |
| | Minor maintenance | 2 |
| | Moderate maintenance | 3 |
| | Significant maintenance | 4 |
| | Extreme maintenance | 5 |

### 2.1.2 Expert Judgement

Expert judgment is utilized for obtaining the relative importance weights of the factors close to the evaluation criteria. The following question is asked: What is the relative importance of the first factor compared to the second factor concerned with influencing the criterion? The answer of the scale is rated between 1-9. The detailed description is shown in Table 2-5(Saaty, 1980).

**Table 2-5:** AHP importance scale

| Scale | Definition |
|---|---|
| 1 | Equally important |
| 2 | Slightly more important |
| 3 | Moderately more important |
| 4 | Moderately plus more important |
| 5 | Strongly more important |
| 6 | Strongly plus more important |
| 7 | Very strongly more important |
| 8 | Very very strongly more important |
| 9 | Extremely more important |

### 2.1.3 Pairwise Comparison Matrix

A pairwise comparison matrix is used for collecting the data at Step 2. The row components are compared to the column components, and if the criterion in row i is more important than the criterion in column j, then the value of the matrix element (i,j) is more than 1. Otherwise, the column component is more important than the row component. The diagonal elements are always 1. The (j,i) element is the reciprocal value of the (i,j) matrix element.

### 2.1.4 Weights of the factors

The Comparison matrix and the normalized eigenvector are computed to find the relative importance weights of the factors.

### 2.1.5 Consistency Index

A Consistency Index (CI) is evaluated to test the consistency of the responses by experts. The comparisons must be re-examined when the CI does not reach the desired level. The CI is calculated as shown in Eq 2-1.

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \qquad \textbf{Eq. 2-1}$$

$\lambda_{max}$ is the maximum eigenvalue of the comparison matrix.

n is the order of the matrix.

### 2.1.6 Consistency Ratio

A Consistency Ratio (CR) is calculated by dividing CI by the value for the set of judgments corresponding to the order of the matrix, called the Random Consistency Index (RCI), as shown in Eq 2-2.

$$CR = \frac{CI}{RCI} \qquad \textbf{Eq. 2-2}$$

The values of RCI have been pre-determined by Saaty, who calculated these values for large samples of random matrices of varying orders, as shown in Table 2-6. If CR is > 0.1, we need to revisit the comparison.

**Table 2-6:** Random consistency index for matrices of varying order

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RCI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 |

## 2.2 Comprehensive Rating Score

The subject matter expert (SME) is PACP certified and has experience of 10 years. With the SME help, the relative weight of physical characteristics ($W_{PC}$), the weight of external characteristics ($W_{EC}$), and the weight of hydraulic characteristics ($W_{HC}$) and the weight of each factor under this criterion has been determined.

Regression analysis is a statistical tool used for the investigation of relationships between variables. Usually, it helps in seeking the effect of one variable upon another, the impact of grades on performance. To explore such issues, the data should be assembled on the underlying variables of interest, and regression should be employed to estimate the quantitative effect of the causal variables upon the variable that they influence. Typically, the 'statistical significance' of the estimated relationships is assessed, which is the degree of confidence.

Regression analysis utilizes the relationship between multiple quantitative or qualitative variables to predict dependent variables' behavior based on the independent variables' behavior. The simplified model can be created from the equation shown in Eq 2-3 that the true relationship is close to the estimated relationship

$$\mathrm{Y}_i = \beta_0 + \beta_1 X_i + \varepsilon_i \qquad \textbf{Eq. 2-3}$$

$Y_i$ represents the value of the response variable in the $i^{th}$ trial.

$\beta_0$ and $\beta_1$ represents the regression parameters.

$X_i$ represents the value of the predictor variable in the $i^{th}$ trial.

$\varepsilon_i$ represents the random Error.

Multiple variables are used to predict the behavior of the response variable in multiple regression models. As a result, Eq 2-3 can be converted into an Eq 2-4

$$\mathrm{Y}_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots\ldots + \beta_p X_{ip} + \varepsilon_i \qquad \textbf{Eq. 2-4}$$

These weights, along with linear regression, are combined to obtain the final comprehensive rating scores (CRS), as shown from Eq 2-5 to Eq 2-8.

$$CRS = W_{PC}PC + W_{EC}cEC + W_{HC}HC \qquad \textbf{Eq. 2-5}$$

$$PC = \sum_{i=1}^{m}(w_i R_i) \qquad \textbf{Eq. 2-6}$$

$$EC = \sum_{j=1}^{n}(w_j R_j) \qquad \textbf{Eq. 2-7}$$

$$HC = \sum_{k=1}^{o}(w_k R_k) \qquad \textbf{Eq. 2-8}$$

$W_{PC}$ is the factor weight for overall PC criteria.

$W_{EC}$ is the factor weight for overall EC criteria.

$W_{HC}$ is the factor weight for overall HC criteria.

$w_i$ is each factor weights under the PC criteria

$w_j$ is each factor weights under the EC criteria.

$w_k$ is each factor weights under the HC criteria

$R_i$ is the $i^{th}$category factor rating under the PC criteria

$R_j$ is the $j^{th}$category factor rating under the EC criteria

$R_k$ is the $k^{th}$category factor rating under the HC criteria

$m$ is number of factors under the PC criteria

$n$ is number of factors under the EC criteria.

$o$ is number of factors under the HC criteria

The overall framework of the Comprehensive Rating Framework is shown in Figure 2-2.

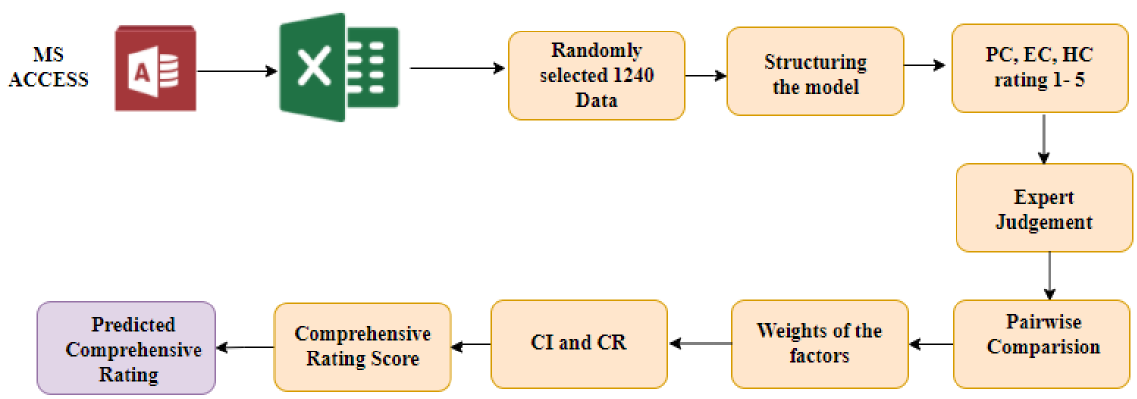


**Figure 2-2:** Comprehensive rating framework.

# CHAPTER 3

# RESULTS AND DISCUSSIONS

## 3.1 Case Study

A total of 3089 pipe segment data with a total length of approximately 198.9 miles with information such as pipe age, pipe material, diameter, depth, length, etc., is given MS ACCESS database from the Dept. of Engineering & Environmental Services, Shreveport, Louisiana Phase 3. The data contained information about pipe has an average age of 56 years. There was no information related to loading, soil type, seismic zone in the documents, and these ratings were defined based on extensive information found in Table 3-1. For this study, a pipe length of approximately 29.20 miles, totaling 1240 pipe segments randomly used, was selected. For data analysis, a centralized spreadsheet was created with data for each of the 1240 pipe segments containing all factors listed.

**Table 3-1:** Presents the relevant data for the comprehensive rating score.

| Factor | Data Type | Source | Brief Description |
|---|---|---|---|
| Soil Type | Soil Data Information | (Projections) | Contains soil data for all US states |
| Traffic Load | Land Use data | (Traffic) | Land cover data can use to infer traffic loading |
| Seismic Zone | Seismic hazard map | (maps) | Presents seismic hazard maps and site-specific data |

## 3.2 AHP Results and Discussions

Once the experts' judgment weights were determined using the AHP method, the relative importance weights of factors affecting sewer pipe conditions were calculated. The ranking of the factors is determined using global weights. The global weights are obtained by multiplying the individual factor's relative importance weight with the criterion's weight under which it falls. The results in Table 3-2 will show the criteria weight, relative importance weight of each factor, global weights, and factors; the sum of all weights is 1. Table 3-3 will show the consistency ratio for all the factors. The consistency ratio of all the factors was less than 0.01. The judgment of this decision-maker is acceptable.

**Table 3-2:** Resulting weights of criteria and factors affecting sewer pipe condition.

| Criteria | Factors | Criteria Weight | Relative Importance Weight of Factor | Global Weights | Rank |
|---|---|---|---|---|---|
| **Pipe Characteristics** | | **0.38589** | | | |
| | Age | | 0.2781271 | 0.10732 | 3 |
| | Corrosion Resistance | | 0.5544271 | 0.21394 | 1 |
| | Diameter | | 0.0880052 | 0.03396 | 11 |
| | Shape | | 0.0794406 | 0.03065 | 12 |
| | | | **∑ = 1.0** | **0.38589** | |
| **External Characteristics** | | **0.39691** | | | |
| | Depth | | 0.1199432 | 0.04761 | 9 |
| | Soil Type | | 0.3214313 | 0.12758 | 2 |
| | Loading | | 0.181072 | 0.07187 | 7 |
| | Waste Type | | 0.1525865 | 0.06056 | 8 |
| | Seismic Zone | | 0.224967 | 0.08929 | 5 |
| | | | **∑ = 1.0** | **0.39691** | |
| **Hydraulic Characteristics** | | **0.21720** | | | |
| | Structural Score | | 0.452165 | 0.09821 | 4 |
| | O&M Score | | 0.344118 | 0.07474 | 6 |
| | Repair History | | 0.203717 | 0.04424 | 10 |
| | | | **∑ = 1.0** | **0.21720** | |

**Table 3-3:** Consistency index and consistency ratio.

<table>
<tr><th>Criteria</th><th>CI</th><th>CR</th><th>Factor</th><th>CI</th><th>CR</th></tr>
<tr><td rowspan="4">Pipe Characteristics</td><td rowspan="12">0.024</td><td rowspan="12">0.042</td><td>Age Grade</td><td rowspan="4">0.029</td><td rowspan="4">0.033</td></tr>
<tr><td>Corrosion Resistance</td></tr>
<tr><td>Diameter</td></tr>
<tr><td>Shape</td></tr>
<tr><td rowspan="5">External Characteristics</td><td>Depth</td><td rowspan="5">0.023</td><td rowspan="5">0.021</td></tr>
<tr><td>Soil Type</td></tr>
<tr><td>Loading</td></tr>
<tr><td>Waste Type</td></tr>
<tr><td>Seismic Zone</td></tr>
<tr><td rowspan="3">Hydraulic Characteristics</td><td>Structural Score</td><td rowspan="3">0.023</td><td rowspan="3">0.041</td></tr>
<tr><td>O & M Score</td></tr>
<tr><td>Repair History</td></tr>
</table>

### 3.3 Comprehensive Ratings Results and Discussions

The obtained Comprehensive rating scores for selected pipes calculated using Eq. 2-3 to Eq. 2-6 are presented in Table 3-4.

**Table 3-4:** Sample comprehensive rating score

| Pipe ID | Pipe Characteristics Score | External Conditions Score | Hydraulic & Other Factors Score | POCR Score |
|---|---|---|---|---|
| 925 | 2.0983 | 3.0964 | 3.3888 | 2.7748 |
| 197 | 4.3161 | 2.8565 | 1 | 3.0165 |
| 213 | 2.1860 | 2.8565 | 3.3888 | 2.7135 |
| 822 | 2.1860 | 2.9765 | 2.5925 | 2.5882 |

The CRS score of a sewer pipe is a measure of the overall deteriorated condition of the segment. Reaching a score of 5 involves the fact that all the 12 factors have a rating of 5. Suppose the majority of the 12 factors have a rating of 5, and a few have intermediate values of 2, 3, and 4; in that case, the Comprehensive rating score will be in the maximum interval. Therefore, to categorize each segment into a condition based on the segment's Comprehensive Rating score, the following method was implemented.

The top-ranked factor based on the AHP analysis is the Corrosion Resistance factor. For this study, the selection criterion is the type of material considered for the project. Based on the type of material, five cases were analyzed. In each one, all but the Corrosion Resistance factors were given the same Rating. First, all factors were set to 1; then all were provided a rating of 2, then a rating of 3, 4, and finally, all factors' ratings were set to 5.

This process aimed to obtain an approximate interval variability of the Comprehensive rating score based on the value of the factor ratings. The results are summarized in Table 3-5.

**Table 3-5:** Ratings based on comprehensive rating score for different pipe materials.

| Pipe Material | All 1's | All 2's | All 3's | All 4's | All 5's |
|---|---|---|---|---|---|
| Plastic/GRP | 2.259 | 2.586 | 2.912 | 3.237 | 3.563 |
| Clay | 2.365 | 2.849 | 3.333 | 3.818 | 4.343 |
| NRCP/AC | 2.438 | 2.969 | 3.500 | 4.031 | 4.562 |
| RCP | 2.657 | 3.188 | 3.719 | 4.250 | 4.781 |
| Metallic | 2.954 | 3.461 | 3.968 | 4.475 | 4.985 |

Clay pipe material scores are selected for our comprehensive rating results based on the pipe material used for our data, and results are summarized in Table 3-6, but if there are different pipe materials weighted average can be used to calculate the overall comprehensive rating.

**Table 3-6:** Final Ratings based on comprehensive score for our data

| Comprehensive Score Ranges | Comprehensive Rating |
|---|---|
| >= 2.365 and <2.849 | 1 |
| >= 2.849 and <3.333 | 2 |
| >= 3.333 and <3.818 | 3 |
| >= 3.818 and <4.343 | 4 |
| >=4.343 | 5 |

As a general guideline, pipes in comprehensive rating 1 do not require any further consideration as these pipes are in excellent condition and can be reassessed in ten years. These pipes in comprehensive rating 2 are in good condition and can be rehabilitated or replaced in six to ten years. These pipes are in fair condition for pipes in comprehensive rating 3 and can be rehabilitated or replaced in three to five years. These pipes are in poor condition for pipes in comprehensive rating 4 and can be rehabilitated or replaced in zero to two years. Finally, pipes in condition 5 are in the worst overall condition and require immediate attention.

## 3.4 Model Evaluation

Model evaluation is an essential step in the creation of a model. It aids in the selection of the best model to represent our data and the prediction of how well the chosen model performed for our data. For Classification predictions, there are four types of outcomes that occur there are True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN), and Accuracy, Precision, Recall and F1 score are calculated using Eq

3-1 to Eq 3-4, where True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN), Accuracy, Precision, Recall and F1 score is defined below.

TP - Predict an observation that belongs to one specific comprehensive Rating given that this observation belongs to this comprehensive Rating (Ex: Actual Comprehensive Rating is 1, and it predicts the Predicted Comprehensive Rating as 1).

TN - Predict an observation does not belong to one specific comprehensive Rating. It does not belong to that specific comprehensive Rating (Ex: Actual Comprehensive Rating is not 1, and it predicts the Predicted Comprehensive Rating as not 1( 2 or 3 or 4 or 5).

FP - Predict an observation that belongs to one specific comprehensive Rating, and it does belong to another comprehensive Rating (Ex: Actual Comprehensive Rating is 2 or 3 or 4 or 5, but it predicts the Predicted Comprehensive Rating as 1)

FN - Predict an observation that does not belong to one specific comprehensive Rating. It does belong to that comprehensive Rating (Ex: Actual Comprehensive Rating is 1, but it predicts the Predicted Comprehensive Rating as 2 or 3 or 4 or 5).

Accuracy - Percentage of correct predictions for the test data.

Precision - Ratio of correctly predicted positive observations to the predicted positive observations.

Recall - the ratio of correctly predicted positive observations to all observations in the actual class.

F1 score - Weighted average of Precision and Recall.

$$Accuracy = \left(\frac{TP + TN}{TP + TN + FP + FN}\right) * 100\% \quad \textbf{Eq. 3-1}$$

$$Precision = \frac{TP}{TP + FP} \quad \textbf{Eq. 3-2}$$

$$Recall = \frac{TP}{TP + FN} \quad \textbf{Eq. 3-3}$$

$$F1\ Score = \frac{2TP}{2TP + FP + FN} \quad \textbf{Eq. 3-4}$$

These True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN) outcomes are often plotted on a confusion matrix. A confusion matrix is a summary of prediction results on a classification problem. The correct and incorrect predictions are summarized with count values and broken down by each class, as shown in Table 3-7.

**Table 3-7:** Confusion matrix

| Predicted Comprehensive Rating | Actual Comprehensive Rating Count | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 22 | 44 | 50 | 68 | 30 |
| 2 | 39 | 36 | 58 | 81 | 46 |
| 3 | 46 | 66 | 38 | 95 | 24 |
| 4 | 33 | 75 | 66 | 44 | 32 |
| 5 | 30 | 54 | 65 | 78 | 20 |

Overall, the accuracy of our model predicted Comprehensive Rating with the actual Comprehensive Rating of the pipe segment reports was 12.90%. Since linear regression assumes a linear relationship between the input and output variables, it failed to fit the dataset properly because the relationship between response and the predictor is not linear. All the conclusions we drew became null and void and led towards the very low accuracy of the model. Table 3-8 shows the accuracy, precision, recall, and F1 score for 5 predicted Comprehensive ratings compared with the Actual Comprehensive Rating given by the inspector

**Table 3-8:** Accuracy, precision, recall, and F1 score

| Comprehensive Rating | Accuracy | Precision | Recall | F1 Score |
|---|---|---|---|---|
| 1 | 72.58% | 0.10 | 0.13 | 0.11 |
| 2 | 62.66% | 0.14 | 0.13 | 0.13 |
| 3 | 62.10% | 0.14 | 0.14 | 0.14 |
| 4 | 57.42% | 0.18 | 0.12 | 0.14 |
| 5 | 71.05% | 0.081 | 0.13 | 0.10 |

A few pipes were selected to compare actual comprehensive ratings to predicted comprehensive ratings. The comprehensive ratings vs. predicted comprehensive ratings were plotted to evaluate better the difference of both the ratings, as shown in Figure 3-1.

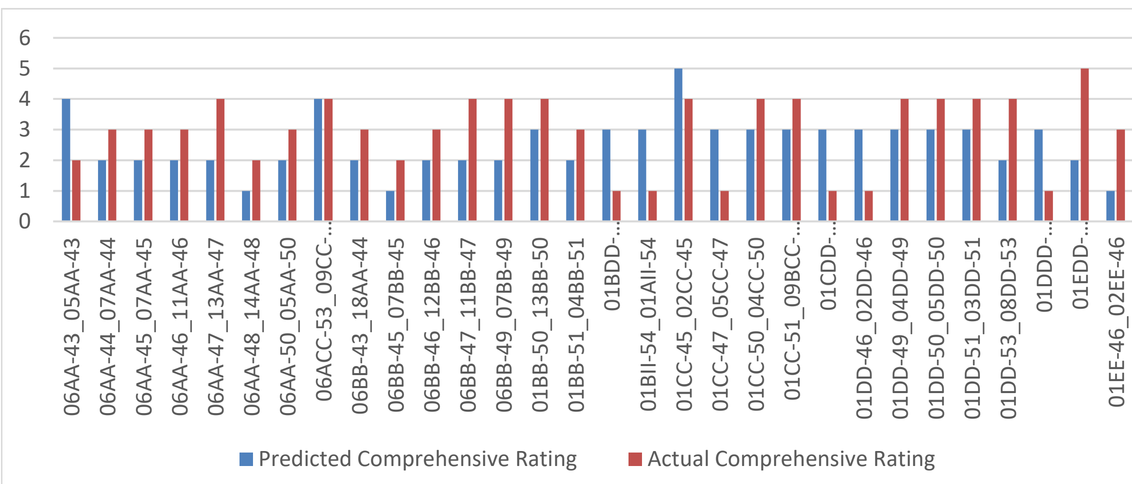


**Figure 3-1:** Rating comparison between actual comprehensive rating and predicted comprehensive rating for few selected pipes.

# CHAPTER 4

# CONCLUSION, LIMITATIONS, AND FUTURE WORK

## 4.1 Conclusion

AHP modeling has been used extensively to develop a model to predict the failure of sewer pipes. This study developed an AHP model for sewer pipe failure prediction models and calculated the overall pipe rating based on the pipe characteristics, external factors, and hydraulic and other factors in the sewer pipes in Shreveport in Louisiana, the United States. The comprehensive score was determined using a linear combination between the relative importance weights of all factors and their respective ratings. AHP was used to obtain the relative importance weights of all criteria. The predicted comprehensive Rating is compared with the actual comprehensive Rating, and this model showed us an accuracy of 12.90%, which is not satisfactory. Since the actual relation between response and the predictor is not linear, the accuracy of the model is very low. SME judgment can vary among different utilities. Because the CRS score is determined using a linear combination, any change in any of the factors will result in an obvious change of the outcome, a change that cannot be determined if it is statistically significant or not.

Therefore, increasing the number and the variability of experts can exactly tell the importance of the factors which might change the weights of the factors resulting in better accuracy. Secondly, adding the geometric location may change the weights of the factors, resulting in more accuracy. But finally, this model is not suggested as it requires manual effort from the inspectors to calculate the importance of factors for better accuracy, which might lead to human errors again.

## 4.2 Limitations and Future work

First, SME judgment can vary among different utilities, changing the relative importance of the factors. Firstly, for future research, the same experimental data and geographic location can be considered to determine the weights and improve the obtained results. Secondly, instead of Linear regression combined with AHP, the Sigmoid(non-linear) function combined with AHP might increase the accuracy. Thirdly, the same experimental data can be used for other classification algorithms to get more accurate results.

# APPENDIX A

# CALCULATION

## A.1 AHP Questionnaire

The purpose of this questionnaire is to ask you, as a subject matter expert in sewer pipe conditions, to perform a pairwise comparison between several factors and sub-factors. The aim of Section 1 of the questionnaire is to establish a weighted rating scale of physical characteristics, external characteristics, and hydraulic characteristics related to the worsening of sewer pipe conditions. Questions 1 through 4 are connected to establishing priorities among various factors and sub-factors as they relate to the condition of the sewer pipe. The scores presented in Table A-1 must be used for the pairwise comparison.

**Table A-1:** AHP importance scale

| Scale | Definition |
|---|---|
| 1 | Equally important |
| 2 | Slightly more important |
| 3 | Moderately more important |
| 4 | Moderately plus more important |
| 5 | Strongly more important |
| 6 | Strongly plus more important |
| 7 | Very strongly more important |
| 8 | Very very strongly more important |
| 9 | Extremely more important |

When performing the pairwise comparisons, compare the row component to the column component. For example, (Ex. 1), if Physical characteristics are extremely more important than External characteristics with respect to the condition of a sewer pipe, the importance for the Physical characteristics row would be a strong Importance of 5. Alternatively, if External characteristics are strongly more important than Physical characteristics with respect to the condition of a sewer pipe, the importance for the Physical characteristics would be the inverse of Strong Importance or 1/5 (see example in Table A-2 below).

**Table A-2:** Example pairwise comparison between two factors

| Condition of Sewer Pipe | Physical characteristics | External characteristics |
|---|---|---|
| Ex. 1: Physical characteristics | 1 | 5 |
| Ex. 2: External characteristics | 1 | 1/5 |

The following figures are presented as a reference for the questions. (see Figures A-1) for reference only.

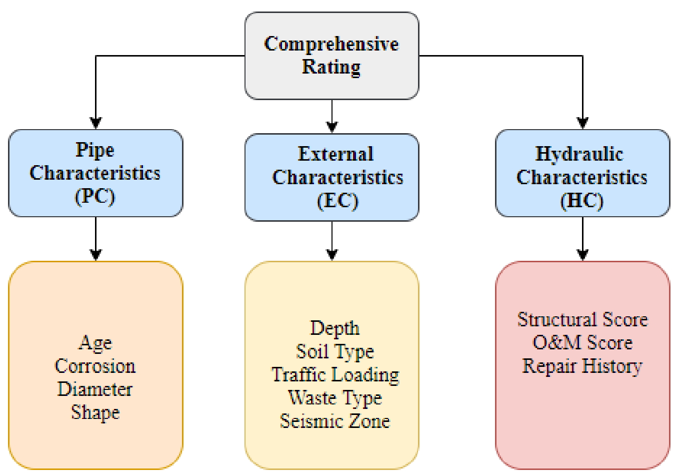


**Figure A-1:** Hierarchical structure

## SECTION: CONDITION OF PIPE SEGMENTS

1. What are the relative importance of physical characteristics, external conditions, and other factors relative to the overall condition of the sewer pipe?

| Condition | Physical Characteristics | External Characteristics | Hydraulic Characteristics |
|---|---|---|---|
| Physical characteristics | 1 | | |
| External Characteristic | | 1 | |
| Hydraulic Characteristic | | | 1 |

2. What is the relative importance of the age, corrosion resistance, diameter, and pipe shape relative to other physical characteristics?

| Physical Characteristics | Age | Corrosion Resistance | Diameter | Shape |
|---|---|---|---|---|
| Age | 1 | | | |
| Corrosion Resistance | | 1 | | |
| Diameter | | | 1 | |
| Shape | | | | 1 |

3. The relative importance of depth, soil type, loading, waste type, seismic zone, and groundwater relative to the other external characteristics?

| External Characteristics | Depth | Soil Type | Loading | Waste Type | Seismic Zone |
|---|---|---|---|---|---|
| Depth | 1 | | | | |
| Soil Type | | 1 | | | |
| Loading | | | 1 | | |
| Waste Type | | | | 1 | |
| Seismic Zone | | | | | 1 |

4. What is the relative importance of the PACP structural score, PACP O&M score, and repair history relative to other Hydraulic Characteristics?

| Hydraulic Characteristics | Structural Score | O&M Score | Repair History |
|---|---|---|---|
| Structural Score | 1 | | |
| O&M Score | | 1 | |
| Repair History | | | 1 |

**SUPPORTING INFORMATION FOR OVERALL CONDITION OF SEWER PIPE**

| FACTOR SCORE | PHYSICAL CHARACTERISTICS | | | |
|---|---|---|---|---|
| | **Pipe Age [yrs]** | **Corrosion Resistance** | **Diameter [inch]** | **Shape** |
| 1 | < 10 yrs | Reinforced Plastic Pipe, Polyvinyl Chloride, Vitrified clay pipe, Polyethylene | >=49 | Circular |
| 2 | ≥ 10 yrs and < 25 yrs | Cast Iron, Ductile Iron Pipe | >31 and <=48 | Oval |
| 3 | ≥ 25 yrs & < 40 yrs | Reinforced Concrete Pipe, concrete pipe (non-reinforcement), Concrete Segments | >18 and <=30 | Horseshoe |
| 4 | ≥ 40 yrs & < 50 yrs | Not Known | >11 and <= 18 | Semi-elliptic |
| 5 | ≥ 50 yrs | Other | <=11 | Arch |

| FACTOR SCORE | EXTERNAL CHARACTERISTICS | | | | | |
|---|---|---|---|---|---|---|
| | **Depth [feet]** | **Soil Type** | **Loading** | **Waste Type** | **Seismic Zone*** | **Groundwater** |
| 1 | 10 Feet | Granular (Crushed Stone/Gra vel) | No/Very Light Traffic | Mildly Corrosive | Zone 1 | Low |
| 2 | 10 and <= 15 | Coarse Grained (Gravelly | Light Traffic | Mildly to Moderately Corrosive | Zone 2 | Low to Moderate |
| 3 | 15 and <= 20 Feet | Silty/Clay ey Gravels | Medium Traffic | Moderately Corrosive | Zone 3 | Moderate |
| 4 | 20 and <= 25 Feet | Fine Grained (Sands/Sil ts) | Moderat e to Heavy Traffic | Moderately to Highly Corrosive | Zone 4 | Moderate to High |
| 5 | 25 Feet | Inorganic Silts/Clay s | Heavy Traffic | Highly Corrosive | Zone 5 | High |

| FACTOR SCORE | HYDRAULIC CHARACTERISTICS | | |
|---|---|---|---|
| | **Structural Score** | **O&M Score** | **Repair History** |
| 1 | 1 | 1 | No maintenance |
| 2 | 2 | 2 | Minor maintenance |
| 3 | 3 | 3 | Moderate maintenance |
| 4 | 4 | 4 | Significant maintenance |
| 5 | 5 | 5 | Extreme maintenance |

*Based on 2017 USGS Seismic Maps:

Seismic Zone 1: ND, MN, WI, MI, IA, NE, FL, South LA, TX, Northeast MT, West KS, OK (except Central)

Seismic Zone 2: NY, PA, OH, WV, VA, East NC, MD, DC, South GA, South AL, South MS, North LA, Southwest AR, Central OK, East KS, North IL, North IN, North KY, North and West MO, North TX, East CO, East NM, South SD, North NE

Seismic Zone 3: Parts of East SC, AR, and MO, Parts of South IL, Parts of West KY and TN, North of VT, Central WA, Large part of OR and NV, Central AK, Central CA, Parts of NM, AZ, Co, and TN.

Seismic Zone 4: Parts of West WA, OR, CA, NV, WY, and MT, Parts of East SC, AR and MO, Parts of South IL, Parts of West KY and TN, Parts of MT, West WY, East ID, Central UT

Seismic Zone 5: West and East CA, West NV, West WA, West OR, HI, South AK

## A.2 Example calculation of relative weights and consistency ratio

This appendix presents an example calculation of the Relative weights and Consistency Ratio (CR) with random values.

**Step 1. Pairwise comparison**

Each entry of the upper diagonal is based on where the row component is evaluated against the column component based on the following questions: What are the relative importance of physical characteristics, external conditions, and other factors relative to the overall condition of the sewer pipe? As shown in Table B-1

**Table A-3:** Example pairwise comparison between two factors

| | Physical Characteristics | External Characteristics | Hydraulic Characteristics |
|---|---|---|---|
| Physical Characteristics | **1** | 3 | 9 |
| External Characteristics | 0.333 | **1** | 6 |
| Hydraulic Characteristics | 0.111 | 0.167 | **1** |
| **Σ** | **1.444** | **4.167** | **16** |

**Step 2. Normalization**

The next step is to normalize the matrix by calculating the sum of all the column components and then dividing each individual column component by the sum of the column components. As a result, a new matrix is obtained. For example, the first component of the first row is obtained as $\frac{1}{1.444} = 0.6923$. For this matrix, the sum of all rows is calculated, and the average value of the rows is also computed, as shown in Table A-4.

**Table A-4:** Normalized matrix

| | Physical Characteristics | External Characteristics | Hydraulic Characteristics | Row Average |
|---|---|---|---|---|
| Physical Characteristics | 0.6923 | 0.7200 | 0.5625 | **0.6583** |
| External Characteristics | 0.2308 | 0.2400 | 0.3750 | **0.2819** |
| Hydraulic Characteristics | 0.0769 | 0.0400 | 0.0625 | **0.0598** |
| **Σ** | **1** | **1** | **1** | **1** |

**Step 3: Relative weights calculation**

The next step is to calculate relative weights. Relative weights are calculated using the Pair wise Comparison[P] * average of each criterion[F] using the matrix multiplication. As a result, new matrix (W) is obtained.

$$W = \begin{bmatrix} 1 & 3 & 9 \\ 0.33 & 1 & 6 \\ 0.11 & 0.167 & 1 \end{bmatrix} * \begin{bmatrix} 0.6583 \\ 0.2819 \\ 0.0598 \end{bmatrix}$$

$$W = \begin{bmatrix} 2.0423 \\ 0.86020 \\ 0.17990 \end{bmatrix}$$

**Step 4. Consistency Index (CI) calculation**

Next step is to calculate consistency index. First step is to calculate the consistency vector and $\lambda_{max}$ is calculated using the average of consistency vectors.

$$C = \text{Consistency vector} = \begin{bmatrix} \frac{W1}{F1} \\ \frac{W2}{F2} \\ \frac{W3}{F3} \end{bmatrix} = \begin{bmatrix} \frac{2.0423}{0.6583} \\ \frac{0.86020}{0.2819} \\ \frac{0.17990}{0.0598} \end{bmatrix} = \begin{bmatrix} 3.1025 \\ 3.0512 \\ 3.0086 \end{bmatrix}$$

$$\lambda_{max} = \frac{3.1025 + 3.0512 + 3.0086}{3} = 3.0541$$

The Consistency Index is calculated as the next step as presented in Eq. A-1.

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad \textbf{Eq. A-1}$$

Then

$$CI = \frac{3.0541 - 3}{2} = 0.0270$$

**Step 5. Calculation of the Consistency Ratio (CR.)**

The *CR* is calculated as presented in.

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad \textbf{Eq. A-2}$$

Where *RCI* is found in Table 5 and is 0.58 in this case, the value of *CR* is:

$$CR = \frac{0.0270}{0.58} = 0.046$$

The *CR* is less than 0.1, meaning that the judgment of this decision-maker is acceptable.

### A.3 Example calculation of Comprehensive Rating

This appendix presents an example calculation of the final Rating with the weights obtained in Table A-5.

$$CRS = W_{PC}PC + W_{EC}cEC + W_{HC}HC \quad \textbf{Eq. A-3}$$

$$PC = \sum_{i=1}^{m}(w_i R_i) \quad \textbf{Eq. A-4}$$

$$EC = \sum_{j=1}^{n}(w_j R_j) \quad \textbf{Eq. A-5}$$

$$HC = \sum_{k=1}^{o}(w_k R_k) \quad \textbf{Eq. A-6}$$

PC = (0.27813*4) + (0.55443*5) + (0.08801*5) + (0.07944*1) = 4.40411

EC = (0.11994*1) + (0.32143*4) + (0.18107*3) + (0.1529*3) + (0.22497*2) = 2.85657

HC = (0.45216*3) + (0.34411*3) + (0.20371*3) = 2.99994

CRS = (0.38589*4.40411) + (0.39691*2.85657) + (0.2172* 2.99994) = 3.4849

Comprehensive Rating of 3.4849 CRS is 3

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