Application of Analytic Hierarchy Process to Retaining wall maintenance prioritization

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Abstract – *This paper proposes the application of the Analytic Hierarchy Process (AHP) in determining the relative weights of important maintenance decision-making factors in retaining wall management. Based on a pairwise comparison of the criteria (age, operating & maintenance condition, safety consequence & mobility consequence), weights are generated, which are used in computing a priority index for ranking the maintenance importance of the walls. These weighted factors are applied to 29 retaining wall structures in Tennessee, with maintenance priority ranking as output. This method provides transportation agencies with a simple but effective method of selecting the retaining wall for maintenance, given a limited budget. Sensitivity analyses are conducted to identify the factors that most significantly affect a chosen outcome variable of estimated repair cost – in a bid to validate the AHP model. Overall, the case study clearly demonstrates the applicability and practicality of the AHP-based method for maintenance prioritization of retaining wall structures.*

Key Words: Retaining Wall, Asset Management, AHP, Multicriteria Decision-Making, Operations & Maintenance.

1. INTRODUCTION

In the United States, most transportation agencies do not observe specific maintenance or rehabilitation regime for their retaining wall structures (Anderson et al., 2009; Kimmerling & Thompson, 2015). While other “primary” transportation infrastructure such as pavement and bridges have scheduled proactive inspection timeframes, this asset class is mostly ignored (Lawal, 2021). Without these inspection cycles, there is no way asset managers could identify distresses at an early stage to avert failure (Pettway & Sinkey, 1980). With this background, a few Departments of Transportation have started extending their risk-based asset management programs to include retaining walls (Tappenden & Skirrow, 2020; Thompson et al., 2016; Vessely et al., 2015).

However, with more asset classes to manage comes at the competing cost of maintenance prioritization (Frangopol & Liu, 2019). The limited annual maintenance budget most transportation agencies have is barely enough to cover the legacy assets in need of maintenance (Kulkarni & Miller, 2003). Yet, these agencies are compelled to simultaneously maintain other assets such as retaining walls which have been found to be equal contributors to safety and mobility along transportation highways (NCHRP Report 903). Therefore, it is an important issue for these agencies to find the best possible way they can allocate their maintenance budget, while having the most impact.

Due to the lack of historical data, there has not been a lot of research on retaining wall management as a transportation or geotechnical asset. Regardless, asset managers routinely have to make maintenance decision-making on pavement and bridges at the network level, considering the performance and other characteristics of the road sections (O’Reily & Perry, 2009; Wang et al., 2022). The performance of these assets and subsequent maintenance decision-making is premised on several factors and criteria (Niekamp et al., 2015; Lawal et al., 2017). Similarly, retaining walls along highway corridors can be modelled as a multi-factor and multi-criteria decision-making problem. Based on available literature, the factors worthy of consideration include structure age, condition rating, mobility consequence, etc. The goals of maintenance are to restore as many structures to the best possible conditions, and also to minimize overall agency maintenance costs while doing this (Lawal, 2022). These two important, yet seemingly contradictory goals could be achieved using a scientific process that can rationally rank the maintenance priority of the assets based on set criteria (Saaty, 1988).

Considering the qualitative nature of the relationship between each factor, determining the weight of each criterion and sub-criteria then becomes difficult. Analytic Hierarchy Process (AHP) comes in handy in demystifying the problems based on hierarchies and pairwise comparison (Saaty, 2008). This method has been widely adopted in several multicriteria decision-making problems with complicated structure, due to its relative simplicity (Ziara et al., 2002). Its application has been found in several infrastructure class from bridges (Dabous & Alkass, 2010) (Wakchaure et al., 2012) to pavements (Ramadhan et al., 1999) (Ahmed et al., 2017; Li et al., 2018), and has been used in this study to determine the weight of each factor, in a bid to arrive at a comprehensive ranking index for the prioritization of retaining wall maintenance.

2. OBJECTIVE

The goal of this study is to develop an AHP-based maintenance prioritization ranking index for retaining walls. A case study of retaining wall data collected in the State of Tennessee was used to demonstrate the applicability of the

AHP-theory. Certain pre-determined important factors were used as decision-making factors. These factors include retaining wall age, operations & maintenance (O&M) condition, mobility consequence, safety consequence. Hierarchies are then constructed based on these factors to determine the weight of each of the decision-making factors – cumulatively lending towards the prioritization ranking index. Sensitivity analysis is subsequently carried out in order to verify the accuracy and effectiveness of the weighting process.

3. MULTICRITERIA DECISION-MAKING

The decision of which wall to maintain at a particular point in time is based on the prioritization ranking index of the wall. This index should reflect the relative importance of the wall, and why if required should be selected ahead of another. Therefore, the factors that have gone into the computation of this ranking should represent those that individually hold major importance. While there are several probable factors that contribute in varying degrees, it is impractical to include all of it in the hierarchical process. Thus, key criteria that were found through literature review have been shortlisted. The NCHRP Report 903 which provides an implementation guidance for transportation agencies implementing geotechnical asset management (GAM) developed a GAM planner tool. These factors which were retaining wall age, O&M condition, mobility consequence, and safety consequence correlated with the variables in the asset inventory of the GAM planner tool.

3.1 Retaining wall age

Structure age represents one of the most significant influencing factors for retaining wall maintenance decision-making, just like the other “primary” assets. Despite the lack of retaining wall historical data (construction and maintenance) in Tennessee, google earth pro historical imagery function was used in estimating the approximate age of all of the walls surveyed – which revealed that most of the walls were built over 20 years ago. As a stand-alone factor, it follows that barring any maintenance, the older structures would be closer to their design life and would need the most urgent attention. However, since age is not the only contributing factor to deterioration, this approach would not hold.

3.2 Operations & Maintenance condition

Based on the GAM planner tool, operating and maintenance condition, which in simple terms can be referred to as the condition rating of the structure is an important factor in maintenance prioritization. As defined in the tool and NCHRP report 903, the conditions are categorized into “1-New or Good”, “2-Minor Loss”, “3-Fair”, “4-Poor”, “5-Critical to Failed”. Considering the walls surveyed, the 1-4 rating scale has been used instead.

Table 1: O&M condition level definitions (NCHRP Report 903)

O&M Condition	Definition
1	New or Good
2	Minor Loss
3	Fair
4	Poor
5	Critical to Failed

3.3 Mobility consequence

Failure consequence that could affect mobility on adjourning highway is a very important factor to consider in maintenance decision-making. Those walls whose failure would seriously impact mobility would naturally be given priority over those with less. The GAM planner tool stipulates the different categories of “No Impact possible”, “Impact to shoulder possible”, “Impact to travel lane possible”, “Road closure possible: 1 day or less”, “Road closure possible: > 1 day”.

Table 2: Mobility consequence definitions (NCHRP Report 903)

Mobility consequence	Definition
1	No impact possible
2	Impact to shoulder possible
3	Impact to travel lane possible
4	Road closure possible, 1 day or less
5	Road closure possible, > 1 day

3.4 Safety consequence

Failure consequences of retaining walls that have safety implications towards the traveling public is a very significant metric that contributes to the maintenance prioritization decision-making of the assets. The categories of this factor as included in the GAM planner tool are: “No impact possible”, “Impact to shoulder possible”, “Impact to travel lane possible but avoidable”, “Vehicle damage possible”, “Fatality or injury possible”.

Table 3: Safety consequence definitions (NCHRP Report 903)

Safety consequence	Definition
1	No impact possible
2	Impact to shoulder possible
3	Impact to travel lane possible but avoidable
4	Vehicle damage possible
5	Fatality or injury possible

4. THE ANALYTIC HIERARCHY PROCESS

AHP was first developed and explored by Saaty (1980) as an objective mathematical and psychological weighting technique. Over the years, the technique has found its application in different transportation infrastructure multicriteria decision-making. However, specifically for retaining wall maintenance, it has not been really explored. The range of problems that could be solved using AHP spans across both objective and subjective evaluations. This is achieved through a systematic process including: a) development of a hierarchical structure; b) methodology for establishment of priorities, and c) ranking and overall consistency assessment.

4.1 Hierarchical structure

The first stage in the Analytic Hierarchy Process is the design of the hierarchies itself. This involves breaking down the whole problem structure into individual clusters – that forms a hierarchy. Each hierarchical level comprises of elements that in turn feed off into other sub-elements until the entire structure is decomposed completely. The goal of this approach would be to present the logical and mathematical interaction of the functional components that make up the problem. The flexibility and reliability offered by hierarchies make it difficult for the entire system to be affected by outside influence (Saaty, 1977). In the hierarchy model, the goal of the AHP is placed on the uppermost layer. This is followed by the criteria layer. In the case where there are sub-criteria, this represents the third layer. The alternatives are then placed at the bottom layer. A typical AHP hierarchy structure is shown in Fig. 1

4.2 Methodology for establishment of priorities

The second stage in the Analytic Hierarchy Process involves the establishment of an acceptable basis for priority settings. Through a pairwise comparison of each criterion, relative importance is determined. This is achieved using a 1-9 scale shown in Table 1.

Table 5: Scale of relative importance (Saaty, 1980)

Intensity of importance	Definition
1	Equal importance
3	Weak or moderate importance of one over the other
5	Essential or strong importance
7	Very strong or Demonstrated importance
9	Absolute or Extreme importance
2,4,6,8	Intermediate values between two adjacent judgement values

The assignments and comparisons are done based on expert judgement and experience.

4.3 Ranking and overall consistency assessment

Based on the hierarchical structure and pairwise comparison, the importance of each criterion relative to the other is obtained. Considering the different indices used, the judgement matrix is normalized in order to give the relative importance. Due to the process of the pairwise comparison, it is possible for inconsistencies to be introduced, i.e., in the case of 3 criteria A, B, C, criterion A is more important than B, criterion B is more important than C, if criterion C is more important than A, this is mathematically impossible and thus an inconsistency arises.

Therefore, it is necessary to carry out a consistency check at the end of the pairwise comparison process in order to avoid contradictory results. While it is unlikely to obtain a perfect consistency, the smaller the consistency ratio (CR) is to 10%, the better. In order to obtain the consistency ratio (CR), a consistency index (CI) is calculated using Eq. 1 based on the maximum eigenvalue λ_{max}

$$CI = \frac{\lambda_{max}-n}{n-1}, n = 1, 2, ..., 9 \quad (1)$$

Consistency ratio is obtained by dividing the consistency index (CI) by the random consistency index (RI). RI is shown in Table 2.

$$CR = \frac{CI}{RI} \quad (2)$$

Table 4: The RI values

Elements	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.26	1.36	1.41	1.45

5. RESEARCH CASE STUDY

Twenty-nine retaining wall structures across the three main cities (Chattanooga, Knoxville, and Nashville) in Tennessee were selected from the Tennessee DOT report on rating and inventory of retaining walls. The four important factors earlier established were used in collecting and synthesizing the data, and aggregated as shown.

Table 6: Retaining wall data for case study

Wall	Retaining wall locations	Age	Weighted Overall Rating	O&M condition level	Safety Consequence	Mobility consequence
1	7244-7544 E Brainerd Chattanooga, TN	14	3.74	1	3	3
2	TN-153, Off Bonny Oaks Dr., Chattanooga, TN	21	2.1	3	3	2
3	308 Ashland Terrace, Chattanooga, TN	22	2.45	2	2	2
4	Northpoint Boulevard, Chattanooga, TN	13	2.91	2	3	2
5	Riverside Dr, Chattanooga, TN	27	2.21	3	3	3
6	Signal Mountain Rd, Chattanooga, TN	18	3.49	1	5	5
7	1727 Dayton Blvd, Chattanooga, TN	16	2.95	2	3	3
8	222 Baker Street, Chattanooga, TN	24	2.95	2	4	5
9	918-998 Cherokee Blvd, Chattanooga, TN	22	2.84	2	4	5
10	I-75 N, Chattanooga, TN	35	2.66	2	4	3
11	1201-1261 Dayton Blvd, Chattanooga, TN	27	2.97	2	4	4
12	I-75 S, Chattanooga, TN	36	2.43	2	4	3
13	US-11, Birmingham Hwy Cross Railway, Chattanooga, TN	38	1.85	3	2	2
14	6401 Lee Hwy	47	2.41	2	2	2
15	4177 Willard Dr	48	2.77	2	5	5

16	6828 Northside Dr	17	3.74	1	4	4
17	US-27 N/Exit to Signal Mountain, Chattanooga, TN	6	3.9	1	4	4
18	US-27 S/Dayton Blvd Entrance, Chattanooga, TN	6	3.78	1	4	4
19	US-27 S/Near Manufacturers Road Exit, Chattanooga, TN	6	3.93	1	4	5
20	9303 E Brainerd Rd	15	3.75	1	3	3
21	6312 Fisk Ave, Chattanooga TN	16	3.32	1	4	3
22	1701-1899 Meharry Dr	45	2.4	2	2	2
23	US-27 N/Between Red Bank Exit and R.R. Olgiati Bridge, Chattanooga, TN	6	3.88	1	3	3
24	1301 Washington Avenue, Knoxville, TN	21	3.62	1	3	2
25	Hall of Fame Dr, Knoxville, TN	19	3.1	2	4	3
26	James White Pkwy, Knoxville, TN	31	2.59	2	4	5
27	N Broadway Ramp to I40, Knoxville, TN	15	2.16	3	4	5
28	Briley Pkwy, Nashville, TN	35	2.03	3	3	2
29	Elm Hill Pike, Nashville, TN	24	3.01	2	3	2

5.1 AHP weighting factor determination

In the hierarchical structure, the ultimate goal at the objective level is to compute a priority ranking index that would guide in retaining wall maintenance decision-making. The four important factors that are believed to affect this decision-making process, i.e., age, operating and maintenance condition, safety consequence, and mobility consequence form the criteria level. While the different retaining wall options available to be considered for maintenance are the alternatives. The hierarchical structure model is shown in Fig.

Based on expert judgement on retaining wall management, a comparison matrix of the criteria was formed. The pairwise comparison matrix, C is shown in Eq. 3

$$C = \begin{bmatrix} 1 & 1/5 & 1/5 & 1/3 \\ 5 & 1 & 3 & 4 \\ 5 & 1/3 & 1 & 1 \\ 3 & 1/4 & 1 & 1 \end{bmatrix} \tag{3}$$

We the compute the normalized pairwise matrix, C' as shown in Eq.

$$C' = \begin{bmatrix} 0.07143 & 0.1124 & 0.04 & 0.05 \\ 0.3571 & 0.5618 & 0.6319 & 0.5319 \\ 0.3571 & 0.1854 & 0.1923 & 0.1580 \\ 0.2143 & 0.1404 & 0.1923 & 0.16 \end{bmatrix} \tag{4}$$

The average of the normalized pairwise matrix then gives the factor weights represented by the vector, W

$$W = \begin{bmatrix} 0.0686 & 0.5319 & 0.2232 & 0.1762 \end{bmatrix} \tag{5}$$

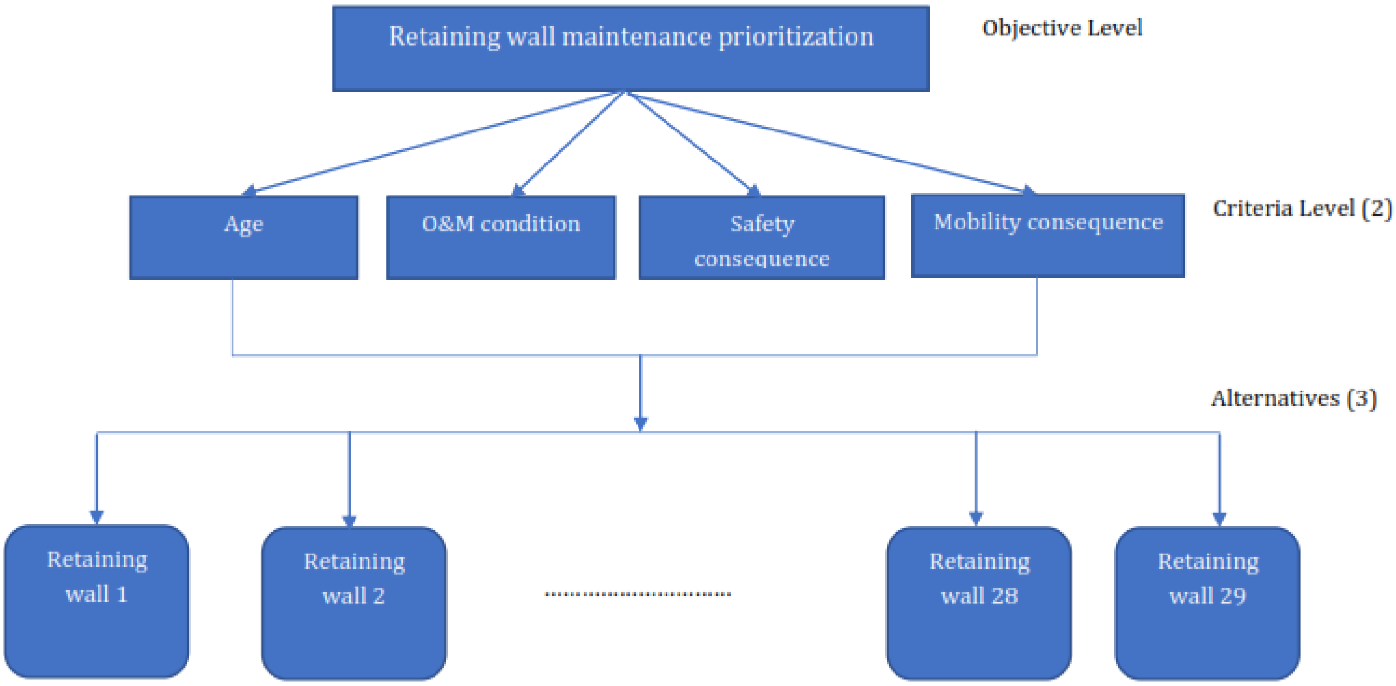
This is the weights of the factors age, O&M condition level, safety consequence, and mobility consequence, respectively. The maximum principal eigenvalue, λ_{max} is obtained as an average of the ratio of the weighted sum value and criteria weight. The weighted sum value is shown in equation below.

$$\begin{bmatrix} 0.0686 & 0.1064 & 0.04 & 0.06 & 0.2778 \\ 0.3430 & 0.5319 & 0.6696 & 0.7050 & 2.2496 \\ 0.3430 & 0.1755 & 0.2232 & 0.1763 & 0.9180 \\ 0.2058 & 0.1330 & 0.2232 & 0.18 & 0.7382 \end{bmatrix}$$

$$\begin{bmatrix} 4.0497 & 4.2289 & 4.1127 & 4.1884 \end{bmatrix}$$

λ_{max} is obtained as 4.1449. Consistency index, CI is given by Eq. 1. Therefore, using Table 2 of RI values, with n = 4, and given λ_{max} , CI is 0.0483. Consistency Ratio, CR, from Eq. 2 is then obtained as 0.0537. i.e., 0.0483/0.9.

Since 0.0537 < 0.1, the overall ranking is consistent and passes this logical test.



5.2 Weighting Application to Ranking

Based on the weights of the four factors, and the synthesized data, a priority ranking index is generated for all the twenty-nine retaining walls. Using the principles of normalization on the synthesized data, older retaining walls, retaining walls with the worst O&M condition, retaining walls with worst safety consequence, and retaining walls with worst mobility consequence are given highest preference. In Table, the summary of weighting together with the other factors computed in assessing consistency are shown. Overall, Table outputs the priority ranking index based on normalized data values from all four considered factors.

Factor weight	Age	O&M condition	Safety consequence	Mobility consequence	lambda max	CI	RI	CR
W	0.0686	0.531943805	0.223205423	0.176255182	4.145	0.0483	0.9	0.0537

Table 7: Factor weights and consistency check

The weights of each factor multiplied by the assigned value (normalized) is then summed for each retaining wall, and this gives a relative index (0-1) of the maintenance needs of the retaining walls, and which should be prioritized. The higher the priority index, the greater the need for maintenance relative to the other structures, and vice-versa. Finally, ranks are assigned to give a numerical importance to the priority of the walls for maintenance. This is further presented in Table.

Table 8: Priority index and ranking based on normalization of data

Wall	Age	O&M condition level	Safety consequence	Mobility consequence	Priority index	Priority Ranking
1	0.291667	0.333333333	0.6	0.6	0.436998012	27
2	0.4375	1	0.6	0.4	0.766379702	5
3	0.458333	0.666666667	0.4	0.4	0.545853091	20
4	0.270833	0.666666667	0.6	0.4	0.577632502	19
5	0.5625	1	0.6	0.6	0.810205187	3
6	0.375	0.333333333	1	1	0.602498553	15
7	0.333333	0.666666667	0.6	0.6	0.617170763	14
8	0.5	0.666666667	0.8	1	0.743746519	8
9	0.458333	0.666666667	0.8	1	0.740888369	9
10	0.729167	0.666666667	0.8	0.6	0.688964269	12
11	0.5625	0.666666667	0.8	0.8	0.712782707	10
12	0.75	0.666666667	0.8	0.6	0.690393343	11
13	0.791667	1	0.4	0.4	0.746032889	7
14	0.979167	0.666666667	0.4	0.4	0.581579961	17
15	1	0.666666667	1	1	0.822685398	2
16	0.354167	0.333333333	0.8	0.8	0.521177357	22
17	0.125	0.333333333	0.8	0.8	0.505457534	23
18	0.125	0.333333333	0.8	0.8	0.505457534	23
19	0.125	0.333333333	0.8	1	0.540708571	21
20	0.3125	0.333333333	0.6	0.6	0.438427086	26
21	0.333333	0.333333333	0.8	0.6	0.484497246	25
22	0.9375	0.666666667	0.4	0.4	0.578721811	18
23	0.125	0.333333333	0.6	0.6	0.425565413	28
24	0.4375	0.333333333	0.6	0.4	0.411750499	29
25	0.395833	0.666666667	0.8	0.6	0.666099072	13
26	0.645833	0.666666667	0.8	1	0.753750042	6
27	0.3125	1	0.8	1	0.908199447	1
28	0.729167	1	0.6	0.4	0.786386749	4
29	0.5	0.666666667	0.6	0.4	0.593352325	16

6. BENEFIT OF THE METHOD

Maintenance budget for Department of Transportation is greatly limited, despite the different transportation assets under their management jurisdiction. The attendant effect of this is some important assets not maintained at the most optimal time, leading to increased life-cycle cost. In recognition of this constraint, this AHP-based maintenance prioritization method for retaining walls offer managers a data-driven, yet, simple approach of timely prioritizing their maintenance and rehabilitation. With this system in place, available budget can be allocated to the structures based on priority index and overall relative rank.

7. STUDY LIMITATIONS

AHP operates on a subjective evaluation and pairwise comparison of criteria. Despite that this is mitigated through expert judgements and assessment, it's still an imperfect system based on the subjectivity. Two experts also are not likely to have the same exact assessment. This is a great limitation for the method. Nevertheless, it is greatly encouraged in future studies to incorporate multiple expert judgements in the process and compare the final outcomes. If the individual comparisons are consistent (which confirms the logic of the comparison), the final priority index and ranking should not be such that a wall ranked 1st through one expert's comparison is then ranked 15th through another's.

8. SENSITIVITY ANALYSIS

In this section, the results of the AHP-based maintenance prioritization are validated using sensitivity analysis. The goal of sensitivity analysis is to identify which contributing factor(s) has significant effect on the decision-making pertaining to retaining wall maintenance. This is tested against a target variable of estimated repair cost, which is provided in the Tennessee DOT report.

For the analysis, retaining wall age was set to 10 years, O&M condition to 3, safety consequence to 3 and mobility consequence to 3. The influence of each of the factors are tested on the estimated repair cost and is illustrated by the changing value of the cost. The time value of money is used in estimating the present value of the walls after t years

Original cost of wall * $(1+y)^t$, where y is the 30 years average inflation rate. The *y* value adopted for the project is 3.5% (Zarenski, 2021). The O&M condition level change had the most significant impact on the estimated repair cost. The O&M condition level were substituted with residual percentage and used in estimating the repair cost. Similarly, the safety and mobility consequence were varied to see their impact on the estimated cost of repair. Overall, the O&M condition level resulted in the most variation in the repair cost which validates the outcome of the weighting from the Analytic Hierarchy Process model.

Table 9: Assumption of Residual Percentage Based on Rating Score (NCMA, 2004)

Current Rating Score	Residual Percentage
4	80%
3	60%
2	40%
1	20%

9. CONCLUSIONS

This method has been widely applied to different multicriteria decision-making problems across different fields, including transportation infrastructure management like pavement and bridges. Given that retaining wall management is relatively new to most Transportation agencies, they typically do not have to plan for their maintenance, and thus there had not been a need for prioritization. As more highway agencies are moving to improved proactive management techniques, this approach for prioritizing retaining wall maintenance could not be timelier.

The AHP-based technique incorporated certain important potential maintenance related factors that could help give a quantitative relative importance of the walls – through a priority index and ranking for all of the considered walls. With the case-study validation using a total of four maintenance decision-making factors including age, operating and maintenance condition, safety consequence, and mobility consequence considered. A hierarchical structure model consisting of the goal, criteria, and retaining wall alternatives was developed followed by pairwise comparison and weighting of the important factors. With the factor weights, and the data normalized, the result is a retaining wall maintenance priority index and priority ranking.

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