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Assessment of Bridge Resilience Efficiency Using Data Envelopment Analysis

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Abstract

The assessment of resilience for bridges draws ample attention from bridge engineering and management community in recent years. Both qualitative and quantitative approaches are used to assess the resilience of the bridge. However, these approaches can be biased if they obtain bridge resilience scores without considering some essential variables such as age, design high flood level (HFL), and finish road level (FRL) of the bridge. Therefore, this study presents a methodology to measure the resilience efficiency of bridges using the data envelopment analysis (DEA).It computes the resilience efficiency of 12 bridges that are located across the Tapi river in Surat (India). For input and output variables of DEA model, variables like age, design high flood level (HFL), finish road level (FRL), and resilience score of the bridges are selected. Efficiency score was measured using a variable return to scale with an output-orientated Banker-Charnes-Cooper (BCC) formulation. A total of seven bridges out of twelve were observed inefficient as per this study. Asensitivity analysis is carried out to check the reliability of DEA model. Eventually, the finding of the study can be helpful to bridge owners for prioritizing the inefficient bridges to improve their resilience score.

Keywords:Bridge, Resilience, Efficiency, Data Envelopment Analysis, India.

1. Introduction

In the recent past, communities have experienced numerous devastating natural disasters, such as earthquakes, cyclones, floods, tsunamis, etc. Due to this, communities have suffered a lot of negative consequences, such as significant impacts on economic and services, and most importantly, the loss of human life. Owing to this, the concept of resilience attracted attention in the debates among disaster mitigation officials, practitioners, policymakers, and researchers. In this connection, Karamlou and Bocchini [1] stated that civil engineers and disaster mitigation officials haveborrowed the concept of resilience from ecological systems and communities [2] and redefine it for civil infrastructure. Moreover, several studies focused on the development of metrics and methods to assess the resilience of various civil infrastructures [1]. Among these civil infrastructures, the role of the bridge is to integrate social and economic aspects of any nation, as it is one of the essential components of transportation infrastructure.

For bridge resilience and its assessment process, a systematic and extensive review of literature is presented by Banerjee et al. [3]. They stated that most of the researchers used the analytical definition proposed by Cimellaro et al. [4], and Bocchini and Frangopol [5] to assess the resilience of the bridge. But, different from this analytical definition, some researchers [6-10] used the subjective judgment methods to propose a practical, simple, and decision-making procedure for computing the resilience of bridges. Thus, all this research on resilience assessment by the subjective judgment methods has its strength and limitations. But still, these all studies, due to its several limitations, fail to consider several other variables such as age, design high flood level (HFL), finish road level (FRL) of the bridge, etc.

Thus, in light of this gap, the current study aims to develop a framework to evaluate the resilience efficiency of the bridges against the variables like design high flood level (HFL), finish road level (FRL) of the bridge, etc. Then, the obtained resilience efficiency is used for prioritizing the bridge to improve its resilience score. A bridge resilience score is a numerical value that represents the ability of bridge functionality, social, and economic value against the uncertain event; and to plan the recovery activities to regain its original functionality, social and economic values within the shortest time [10].Further, it is obtained during the bridge resilience assessment process. For example, recently, Patel et al. [10] develop a three-level hierarchical structure called a bridge resilience measure matrix (BRMM). This BRMM has 16 variables that fulfil the characteristic of four properties and dimensions of resilience. Then, BRMM, along with multi-criteria decision-making (MCDM) techniques, were used to develop a novel methodology that can measure the resilience score of the bridge. However, variables like age, design HFL, and FRL, as mentioned

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earlier, failed to find a place in this BRMM because they lack the satisfaction level against the 16 variables that are selected during the questionnaire survey.

Thus, the present study uses a data envelopment analysis (DEA) to observe the efficiency of the bridge resilience score obtained by Patel et al. [10] against the other variables such as age, design HFL, and FRL that are not considered by them. But, before further discussing these different variables that are being considered for this study, it is better to gain an understanding of DEA application and methodologies. So, in the next section, a brief overview of DEA methodologies and framework determine for this study is explained.

2. Data Envelopment Analysis (DEA)

Data envelopment analysis (DEA) is a robust non-parametric linear programming mathematical approach to measure the efficiency of decision-making units (DMU's) [11-13]. The DEA determines relative efficiency, which is the ratio of weighted output to the weighted input. Thus, in this ratio, the DMU with the efficiency score equal to one is called as efficient DMUs. Otherwise, DMUs with the efficiency score between zero to one (i.e., $0 \leq$ efficiency score < 1) are called as inefficient DMUs. Then, the efficient DMUs make an efficient frontier, which incorporates the given input and output data. Further, efficiency measure quantifies in one way or other the distance to the efficient frontier.

DEA approach can mainly be classified into two models (1) constant return to scale (CRS)- Charnes-Cooper-Rhodes formulation (CCR) [14] and (2) variable return to scale (VRS)- Banker-Charnes-Cooper formulation (BCC) formulation [15]. Moreover, there are two types of orientation (1) input-oriented and (2) output-oriented in the DEA model, and it is on the evaluator to choose the orientation of the model [12].

Based on these formulations and orientation of DEA, some researchers have used DEA in bridge engineering and management domain. Wang et al. [16] used DEA along with the analytical hierarchy process and proposed a methodology to assess the bridge risk and decide the priority for maintenance management. Ozbek et al. [17] applied DEA to measure the efficiency of the counties of Virginia, USA, which consist of several bridges that need maintenance. Wakchaure and Jha [18] presented a method using the DEA, which was useful in selecting relevant bridges for maintenance management and enhance the efficiency of the bridge management system. Thus, all these studies comprehensively presented the implementation of the DEA concept to the cases in bridge engineering and management domain like bridge risk assessment, and maintenance management. Further, the syntheses of these studies [16-18] indicate that mostly four steps are used to determine the efficiency score. These are: (1) Deciding the decision-making units (DMU's), (2) Selecting the input and output variables for the DEA and running the DEA model, (3) Selecting an appropriate DEA model, and (4) Determining efficiency scores. These steps are also chosen for the present study, and they are briefly discussed as follows.

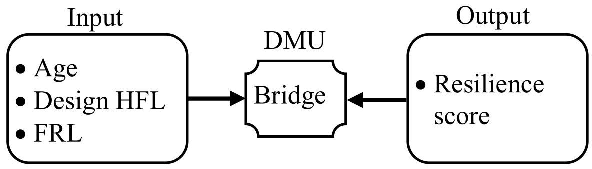

Fig. 1 Input and output variables for DEA model

Step 1: Deciding the decision-making unit (DMU's)

The first step is to decide the DMUs. The DMUs are compared with each other, so they must be homogeneous. In this regard, the DMU must be engaged with the same tasks under the same geographical condition and have the same objective [11-12]. In the present study, individual bridges are chosen as DMUs.

Step 2: Selecting the input and output variables for the DEA and running the DEA model

Once the DMUs are selected, input and output variables for each DMU are decided. In the DEA approach, it is necessary to specify both the input and output variables. In this study, variables that are selected as inputs and outputs must have an influence on the resilience of the bridge during DEA analysis. Thus, to ascertain the inputs and outputs, Ozbek et al. [12] stated that screening procedures along with the statistical or subjective judgment methods are used, thereby reducing the number to a realistic level. In this line, the selected input and output variables along with DMU for this study are shown in Fig. 1. The inputs variables are age, design high flood level (HFL), and finish road level (FRL) of the bridge. An increase in the age of the bridge can reduce the resilience score of the bridge [19]. Moreover, design HFL and FRL reduce when the high flood level increases. So, if the high flood level comes parallel to the design HFL and FRL of a bridge, then the bridge might be close to the traffic, and this affects the resilience score of the bridge. In contrast, the output variable is the resilience score of the bridge, and it is selected to determine its efficiency against the input variables.

Step 3: Selecting an appropriate DEA model

After the selection of inputs and outputs for DEA approach, it is essential to select the DEA model. This model selection depends on the application of the study. As mention in the previous step, the selected input variables, namely age, design HFL, and FRL can influence the output variable resilience score. However, the selected input variables have a non-constant return to scale property with respect to the resilience score. Becauseit is not clear that if the increase in age and reduction in design HFL and FRL of the bridge can have the same proportion of increase and decrease to the resilience score of a bridge. Owing to this, a VRS with output-oriented Banker-Charnes-Cooper formulation is selected for the current study. The mathematical form of VRS with output-oriented Banker-Charnes-Cooper formulation is given in Eq. (1-4) [13, 15].

$$minimize\ A_0 = \sum_{i=1}^{m} v_i x_{i0} + \xi \quad subjected\ to \quad (1)$$

$$\sum_{i=1}^{m} v_i x_{io} - \sum_{j=1}^{n} u_j y_{jo} + \xi \geq 0 \quad (2)$$

$$\sum_{j=1}^{n} u_{j0} y_{j0} = 1 \quad (3)$$

$$u_j, v_i \geq \varepsilon \quad \forall_{i,j},\ \xi\ free\ in\ sign \quad (4)$$

Where A_0 = weighted sum of the inputs of DMU that is under consideration; p = number of DMUs in the data set;

n= number of outputs; m = number of inputs; y_{jr}, x_{ir}= known outputs and inputs of the o^{th} DMU and they are all positive; u_j, $v_i \geq 0$ = the variables (inputs and outputs) weights to be determined by the solution of this optimization problem; ε = positive non-Archimedean infinitesimal.

Step 4: Determining efficiency scores

Tim Collie developed a computer program known as Data Envelopment Analysis Program (DEAP) version 2.1 in a freeware program FORTRAN (programming language) [20]. So, in this study, the resilience efficiency scores of bridges are computed by using DEAP version 2.1.

3.Data Collection

The DEAP accepts variables in text format [20]. The prepared variable sheet is shown in Table 1. Out of these selected variables, data of the resilience scores (output variable) were considered form the study of Patel et al. [10]. Further, the data of age, design HFL, and FRL (input variables) were collected from the website of Surat Municipal Corporation (SMC) [21]. The data of input variables were also discussed with engineers working in the bridge cell department of SMC. This discussion was conducted with a telephonic interview using an open-ended, unstructured questionnaire. In this questionnaire, three questions were asked to validate the data available from the website. These three questions were (1) What is the year of bridge construction? (2) What is the design HFL of the bridge? and (3) What is the FRL of the bridge? Herein, age of bridges was measured from the period the year of bridge was constructed to the 2019 year. The reason for calculating it till the year 2019 was the resilience scores, as they were evaluated in year 2019.

Table 1. Input and output variables of DEA

Bridge name (DMU)	Age (years) (I^a)	Design HFL (m) (I^a)	FRL (m) (I^a)	Resilience Score (O^b)
1. Savijibhai Korat Bridge	18	15	19.66	0.60
2. Swami Dayanand Saraswati Bridge	7	16.51	22.08	0.65
3. Pandit Shyamji Krishna Varma Bridge (Old)	37	15	20.58	0.52
4. Pandit Shyamji Krishna Varma Bridge (New)	8	16.25	21.05	0.69
5. Dr. Shyama Prasad Murkhaji Bridge	7	15.75	20.66	0.61
6. Chandra SekharAzad Bridge	2	15.56	20.26	0.71
7. Nehru Bridge	43	11.52	15.71	0.53
8. Swami Vivekanand Bridge (Makkai Pool)	23	13.90	10.08	0.64
9. Sardar Patel Bridge [(New) Adajan to Athwa lines]	2	12	16.36	0.69
10. Sardar Patel Bridge (Old)	27	11.40	16.50	0.58
11. Sardar Patel Bridge [(New) Athwa lines to Adajan]	1	12	16.36	0.69
12. Pandit Dindayal Upadhyay Cable Stay Bridge	1	9.2	15.50	0.62

Note: [a]Input variable; [b]Output variable

4. Result and Discussion

The results observed from DEA model include resilience efficiency scores and peers. These are shown in column 2 and 3 of Table 2. The DMUs whose scores are equal to one are termed as efficient DMUs and the remaining as inefficient. Out of 12 DMUs, DMU 6 (Chandra Sekhar Azad Bridge), DMU 8 (Swami Vivekanand Bridge-Makkai Pool), DMU 9 (Sardar Patel Bridge-New Adajan to Athwa lines), DMU 11 (Sardar Patel Bridge-New Athwa lines to Adajan), and DMU 12 (Pandit Dindayal Upadhyay Cable Stay Bridge) are found as efficient DMUs since their resilience efficiency score are equal to one. In contrast, the remaining DMUs are found as inefficient due to having their resilience efficiency score less than one Further, the peers obtained in the outcome represent the DMU referring to the efficient DMUs along with its corresponding weights (presented in bracket). For example, DMU 1 with resiliency efficiency score of 0.849, refers to efficient DMU 6 and DMU 11 as peer with its weight 0.843 and 0.157 respectively.

In respect to this resilience efficiency score and peers, DMU 6isreferred five times as peers by the DMUs 1, 2, 3, 4, and 5 with its corresponding weight 0.843, 1, 0.843, 1, and 1 respectively. The summation of DMU 6 peer weights (i.e. 0.843+1+0.843+1+ 1) is 4.686. Apart from that, DMU 11 is also referred by five DMUs as peers, but summation of DMU 11 peer weights is 2.726. So, based on the summation of peer's weight, DMU 6 is ranked as the first DMU. Similarly, the remaining ranking of efficient DMUs is also considered. In inefficient DMUs, resilience efficiency scores are used for the ranking. But, DMU 5 and 10 obtained the

Table 2. Results of DEA

Bridge name (DMU)	Resilience efficiency score	Peers	Rank
1. Savijibhai Korat Bridge	0.849	6 (0.843), 11 (0.157)	10
2. Swami Dayanand Saraswati Bridge	0.915	6 (1.000)	7
3. Pandit Shyamji Krishna Varma Bridge (Old)	0.736	11 (0.157), 6 (0.843)	12
4. Pandit Shyamji Krishna Varma Bridge (New)	0.972	6 (1.000)	6
5. Dr. Shyama Prasad Murkhaji Bridge	0.859	6 (1.000)	8
6. Chandra Sekhar Azad Bridge	1.000	6	1
7. Nehru Bridge	0.791	8 (0.073), 11 (0.706), 12 (0.221)	11
8. Swami Vivekanand Bridge (Makkai Pool)	1.000	8	4
9. Sardar Patel Bridge [(New) Adajan to Athwa lines]	1.000	11 (1.000)	5
10. Sardar Patel Bridge (Old)	0.859	11 (0.786), 12 (0.214)	9
11. Sardar Patel Bridge [(New) Athwa lines to Adajan]	1.000	11	2
12. Pandit Dindayal Upadhyay Cable Stay Bridge	1.000	12	3

same resilience efficiency score. In this case, DMU 5 is given eight rank because it refers to only one efficient DMU as peer (column 3 of Table 2).In contrast,DMU10is given the ninth rank, as it refers to two efficient DMUs as peer (column 3 of Table 2). Thus, the efficiency score, along with the peer, are used to rank the DMUs. The rank of all the DMUs are shown in column 4 of Table 2.

Overall, the result suggests that DMUs 1, 2, 3, 4, 5, 7, and 10 are found inefficient, so they are prioritized for improving their resilience scores. Other side, DMUs 1, 2, 4, and 5 have got low priority for improving resilience scores based on the study by Patel et al. [10]. Overall, the study indicates that a bridge having less score on efficiency should be given priority for improving their resilience scores. Thus, to improve this resilience score, Patel et al. [10] illustrated that bridge owners should utilize advance resources, enhance preparedness of disaster management planning, and coordinate with other concerned infrastructure owners, disaster management teams, and transportation agencies. Preparedness of disaster management planning can reduce uncertainty level of occurring consequences due to the disaster. Moreover, using advanced resources and coordination with other infrastructures owners can helpto expedite faster recovery in functions of the bridge and managing transportation networks. In this line, bridge owners should use advanced resources such as building information modeling (BIM), finite modeling, and wireless sensing techniques to analyze and improve the bridge's structural health condition. Intelligent transportation and advanced traveler information systems can be used to manage transportation network during the disaster.

5. Sensitivity Analysis

According to the DEA application, a bridge (DMU) can become efficient if it achieves exceptionally better results in terms of one input but performs below average in terms of other inputs. So, it is reliable to test the inputs selected in this study on the efficiency score by using sensitivity analysis (SA). In SA, the DEA results are tested by eliminating an input or output variable from the DEA model and then determine the DEA result again [11]. So, based on this Ramanathan [11] procedure, the present study employs SA to test the impact of removing input variables on resilience efficiency scores. In this line, all the inputs variables in the framework are eliminated one by one, and then the formulation selected for the DEA model (steps 3 and 4 in section 2) were rerun.

With respect to this, the study performs three experiments to conduct SA, where the variable age of the bridge is removed from the analysis in experiment 1. Similarly, experiments 2 and 3 eliminate variables FRL and design HFL of the bridge, respectively, from the analysis. Table 3 displays the result of all the experiments. The second column of Table 3 display the original efficiency score for each DMU of the framework. Meanwhile, third to fifth columns of Table 3represent the resilience efficiency scores for experiments from 1 to 3.

The result of SA observed some minor reduction in the resilience efficiency score of DMUs 3, 7, and 10. Thus, the result of experiment-3 indicates that design HFL is the

Table 3. Results of sensitivity analysis

Bridge name (DMU)	Original resilience efficiency score	Exp. 1[a] resilience efficiency score	Exp. 2[b] resilience efficiency score	Exp. 3[c] resilience efficiency score
1. Savijibhai Korat Bridge	0.849	0.849	0.849	0.849
2. Swami Dayanand Saraswati Bridge	0.915	0.915	0.915	0.915
3. Pandit Shyamji Krishna Varma Bridge (Old)	0.736	0.736	0.736	0.732
4. Pandit Shyamji Krishna Varma Bridge (New)	0.972	0.972	0.972	0.972
5. Dr. Shyama Prasad Murkhaji Bridge	0.859	0.859	0.859	0.859
6. Chandra Sekhar Azad Bridge	1.000	1.000	1.000	1.000
7. Nehru Bridge	0.790	0.790	0.782	0.774
8. Swami Vivekanand Bridge (Makkai Pool)	1.000	1.000	1.000	1.000
9. Sardar Patel Bridge [(New) Adajan to Athwa lines]	1.000	1.000	1.000	1.000
10. Sardar Patel Bridge (Old)	0.859	0.859	0.859	0.840
11. Sardar Patel Bridge [(New) Athwa lines to Adajan]	1.000	1.000	1.000	1.000
12. Pandit Dindayal Upadhyay Cable Stay Bridge	1.000	1.000	1.000	1.000

Note: [a]Experiment 1; [b]Experiment 2; [c]Experiment 3

sensitive variables to DMUs3 and 10. Further, the results of experiment-2 and 3 indicate that FRL and design HFL both are sensitive variables to DMU 7. Overall, the rest of the findings of all three experiments are same as discussed in the previous section, where DMUs 1, 2, 3, 4, 5, 7, and 10 are observed inefficient. Thus, the study can help bridge owners in prioritizing a particular bridge that has high resilience score; but, still, it is inefficient against the other variables that not considered during the evaluation of the resilience score of the bridge.

6. Summary and Conclusions

This study evaluatesthe resilience efficiency of bridges through a DEA model. The main aim is to use this resilience efficiency score to prioritize the bridges for improving its resilience score. For this, the study considered 12 bridges located across the Tapi river in Surat (India) as the DMUs. Then a VRS with output-oriented Banker-Charnes-Cooper (BCC) formulation is used in DEA model. The variables like age, design HFL, and FRL of bridge are considered as inputs, while the resilience score of the bridge is considered as the output in the DEA model. A computer program DEAP is used to compute the resilience efficiency score of the bridges.

From the evaluation of DEA model, DMUs 6, 8, 9, 11, and 12 are observed as efficient DMUs, while DMUs 1, 2, 3, 4, 5, 7, and 10 are found as inefficient DMUs. Then SA is applied for validating the reliability of the DEA model. In SA, each input variable is eliminated one by one, and then the formulation selected for the DEA model is rerun. The result of SA observed that input variable FRL is sensitive to the resilience efficiency score of DMUs 3 and 10. At the same time, both FRL and design HFL are sensitive to the resilience efficiency score of DMU 7. Thus, results of the study suggest to prioritize DMUs 1, 2, 3, 4, 5, 7, and 10 for improving their resilience scores.

Overall, the study can be helpful tothe bridge owners to identify a bridge that has a high resilience score, but it is not efficient against the age, design HFL, and FRL of the bridge. Further research can include area, load-carrying capacity, and deterioration rate of bridge, as they are not considered due to unavailability of the data. Moreover, bridges of other cities (regions) can also be incorporated to make its more extensive work. Thus, the proposed framework is simple to assess the resilience efficiency of the bridge. Moreover, it is also logical and useful in decision-making to improve the resilience score of bridges.

Disclosures

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