DEVELOPMENT OF A CAUSAL LOOP DIAGRAM FOR BRIDGE RESILIENCE

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In recent years, the resilience assessment for bridges has drawn ample attention in the engineering and management community. It has been attempted to evaluate bridge resilience by developing a resilience matrix or single-measure index. However, existing studies overlooked the prevailing interdependency among various physical and social infrastructures. Moreover, the technical, organizational, social, and economic aspects of these infrastructures are of dynamic nature. Therefore, this study develops a causal loop diagram (CLD) of bridge resilience to explore and understand how other infrastructures and their dynamism influence bridge resilience. Total 21 bridge resilience factors are identified based on the literature review. Out of these, 14 bridge resilience factors are shortlisted by using the Delphi method. Along with these 14 shortlisted factors, four properties of resilience (robustness, rapidity, resourcefulness, redundancy) and four infrastructures (bridge, transportation network, other utility infrastructures, and governance system) are considered to develop CLD. Thus, eight causal loops are developed, validated, and presented for improving bridge resilience. Further, the proposed study can help to implement effective policies for improving urban resilience and developing a smart city digital twin (SCDT) system.

Keywords: bridge; resilience; causal loop diagram; Delphi method

INTRODUCTION

A bridge is one of the essential components of the ground transportation system. Recorded past literature indicates that comprehensive studies in the vision for bridge engineering and management cover several concepts such as sustainability, adaptability, safety, risk, transformation, etc. Further, these concepts implicit as main guidelines for action in improving bridge engineering and management domain. But still, the understanding of these concepts is not generalized and often uncertain as bridges all across the globe are vulnerable to various natural disasters, such as earthquakes, floods, tsunami, cyclones, etc. Bridge failures that occurred due to various disasters in the USA, Colombia, and China are reported and studied (Harik *et al.,* 1990, Wardhana and Hadipriono 2003, Diaz *et al.,* 2009, and Fu *et al.,* 2013). In India, a total of 3709 incidents of bridge damage and failure are reported due to natural disasters from 2001 to 2018 years. The above studies reveal that the bridge engineering and management domains are concerned with the effective response to natural disasters. Therefore, bridge owners should implement pre-disaster

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maintenance work to make bridges more robust and plan for post-disaster rapid recovery work.

Nowadays, the concept of resilience has been increasingly addressed in academic studies of bridge engineering and management domain (Banerjee *et al.,* 2019). Bridge resilience is defined as a "bridge's ability to maintain its functionality, social, and economic value against the disaster; and to plan the recovery activities to regain its original functionality, social and economic values within the shortest time" (Patel *et al.,* 2020). Banerjee *et al.,* (2019) presented a systematic and comprehensive literature review of bridge resilience assessment for single and multiple disasters. Ikpong and Bagchi (2015), Domaneschi and Martinelli (2016), Andrić and Lu (2017), Minaie and Moon (2017), and Patel *et al.,* (2020) used a qualitative approach to develop a simplified subjective procedure that can quickly estimate the resilience of multiple bridges. Thus, all these studies reveal that researchers have tried to develop a relevant resilience matrix or single-measure index for the bridge. Moreover, the previously mentioned studies also explore that they lack in considering the interdependency of bridge resilience on other infrastructures such as transportation networks, other utility infrastructures, and governance systems. Moreover, this interdependency can also involve several factors that can have dynamic behaviour. Therefore, this study seeks an opportunity to understand complex bridge resilience problems along with the interconnected infrastructures (transportation network, other utility infrastructures, and governance system).

In this connection, the current study sets the objectives: (1) to identify the factors that influence the bridge's resilience along with transportation network, other utility infrastructures, and governance network, and (2) to develop a causal loop diagram (CLD) for the bridge resilience. To achieve these objectives, the paper proceeds with the following sections. The paper first summarizes the CLD for its better understanding. Then, sections include the research methodology, data collection and analysis, and conclusions.

Causal Loop Diagram (CLD)

The causal loop (also called feedback loop) is defined as the closed sequence of causes and effects or a closed path of transmission and return of information of a system (Richardson and Pugh 1981). Further, Richardson and Pugh (1981) stated that the purpose of the causal loop diagram (CLD) is to understand the pattern behaviour of system model and to discuss management policies for the same. An example of a simple causal loop diagram is shown in Fig 1, where A, B, C, and D represent the variables of any system, arrows describe the links between the variables. The signs (+ or −) along with arrows annotate the movement of variables in the same or opposite direction. To briefly understand Fig 1, one can say that variable-A is linked positively (+) to variable-B. This link indicates that the increase in variable-A makes the same amount of increment to variable-B, or the decrease in variable-A makes the same amount of variable-B reduction. Similarly, variable-B is linked positively with variable-C, and variable-D is also linked positively with variable-A. But, variable-C is linked negatively (−) with variable-D (Fig 1), which indicates that an increase in variable-C reduces variable-D or a decrease in variable-C makes an increment in variable-D.

Further, the negative sign annotated with a bracket in the middle of Fig 1 describes the type of causal or feedback loop. Generally, there are two types of causal loop diagrams: (1) a positive causal loop, also called a reinforcing loop, and (2) a negative causal loop, also called a balancing loop. The reinforcing loop is indicated with (+) sign in the bracket if there are an even number of negative causal links or if all the causal links are positive. The balancing loop is indicated with the (−) sign in the bracket if there are an odd number of negative causal links. The example shown in Fig 1 is a negative causal loop because it has only one negative causal link. One can refer to the procedure and guidelines presented by Richardson and Pugh (1981) and Kirkwood (1998) to create the causal or feedback loop diagram.

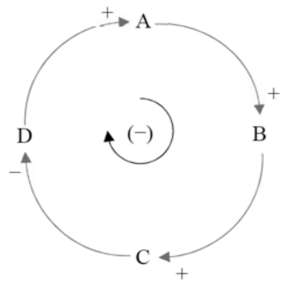

Fig 1: Illustration of the causal loop diagram (CLD)

METHOD

In light of the previous sections, the ensuing research methodology is implemented in two phases, and they are illustrated as follows.

In phase-1, dynamic factors that represent bridge resilience are identified and shortlisted using the Delphi technique. Delphi technique is a structured and interactive research technique used to obtain the judgment of a panel of independent experts on a specific topic (Hallowell and Gambatese 2010). Further, Hallowell and Gambatese (2010) stated that Delphi is more accurate than other conventional simple survey methods. Because it allows researchers to maintain significant control over bias responses obtained from qualified experts. Based on this, controlled responses obtained during multiple rounds can easily help to achieve consensus among the experts. Therefore, the Delphi technique generally consists of two or more rounds of questionnaire surveys. In the first round, experts respond to questions developed from the literature review and personal judgment, while each additional round depends on previous rounds' responses. Thus, the process is concluded after the acceptable result is reached (Hallowell and Gambatese 2010). Further, the guidelines to certified respondents as experts in a panel and performing the Delphi technique are predefined before the survey process begins (Hallowell and Gambatese 2010). Hallowell and Gambatese (2010) also recommended that one can modify these guidelines as per the requirement of their study. Therefore, to implement the Delphi technique, this study's guidelines are modified and described in Table 1. These modifications in criteria are as per the requirement of Indian bridge engineering and management. Thus, at the end of phase-1, the study identifies the dynamic bridge resilience factors.

Subsequently, in phase-2, the CLD is developed to understand the dynamic bridge resilience behaviour. For determining CLD, Sterman (2000) suggested to acquired existing knowledge about real-world systems through literature review and experts' judgments. A questionnaire survey is performed in this study to have the expert's knowledge in developing the CLD. Finally, the CLD is validated using the face validation technique, in which the structure of the CLD is empirically verified using expert judgment (Lucko and Rojas 2010).

DATA COLLECTION AND ANALYSIS

Data collection and analysis in both the phases of the research methodology are illustrated as follows.

Table 1: Guidelines for Delphi method

Characteristics	Minimum requirement adopted in this study
Identifying potential experts	Experts must satisfy at least one of the following criteria: 1. Membership of IRC or IBC. 2. Known participation in similar expert-based studies. 3. Delegation and expert list of conferences, seminars, training, and other events.
Qualifying panellists as experts	Experts must satisfy at least three of the following criteria: 1. Invited to present at a conference, training program. 2. Member or chair of a nationally recognized committee, society, or council 3. At least five years of professional experience in designing, managing, and constructing bridges. 4. Advanced degree in civil engineering, structural engineering, CEM, or other related fields (minimum B.E./B. Tech.) 5. Professional registration such as Registered Engineer or Licensed Engineer 6. A primary or secondary writer of at least three peer-reviewed journal articles.
Number of panellists	10
Number of rounds	3
Feedback for each round	Round 1: Data from existing literature, personal judgment, interview with experts, or archived data (if available). Round 2: Median response from Round 1. Round 3: Median response from Round 2 and reasons for outlier responses.
Measuring consensus	Absolute deviation (median) (AD), coefficient of variance (CV), range of data

Note: B.E./B.Tech. = bachelor of civil engineering; CEM = construction engineering and management; IRC = Indian Road Congress; IBC = Indian Building Congress.

Phase-I

In the first phase of the study, first, factors essential for the bridge's resilience are identified through the literature review. These identified bridge resilience factors must fulfill the requirements of four properties of resilience (robustness, rapidity, resourcefulness, and redundancy). Then, a questionnaire survey is framed, and its evaluation is carry-out using the Delphi technique to shortlist these identified factors. Concerning the COVID-19 pandemic situation, google form and google meet tools are used to carry out the questionnaire survey in all Delphi technique rounds. Further, as mentioned in the research methodology section, this study modifies the selection criteria for selecting panellists (Table 1). Based on these criteria, a total of 10 experts are selected: four experts are from Surat Municipal Corporation (local government), three experts from Road and Building Department (state government), one expert is from Central Public Works Department (central government), and two experts are from the construction companies. Further, to emphasize on-field experience, at least five years of professional experience in the bridge's construction and maintenance is fixed as one criterion for selecting experts. The average work experience of these ten experts is found approximately 17 years.

In the first round of the Delphi method, based on the literature review and interviews with ten selected experts, 21 dynamic bridge resilience factors are identified and listed in Table 2. Further, out of these 21 factors, 20 are identified from the following previous studies: Freckleton *et al.,* (2012), Decò *et al.,* (2013), Dong and Frangopol (2016), Andrić and Lu (2017), Minaie and Moon (2017), Karamlou and Bocchini (2017), Vishwanath and Banerjee (2019), and Patel *et al.,* (2020). While one factor, namely 'Political Condition,' is recommended by the four experts. The political dispute may change the structure/staff of governance/ management/organizations. Further, these changes may delay the bridge's restoration/ maintenance work.

Table 2: List of bridge resilience factors

Resilience properties	Factors
Robustness	(F1) Bridge age, (F2) Bridge vulnerability, (F3) Severity of disaster, (F4) Average daily traffic, (F5) Load-carrying capacity of bridge, (F6) Deterioration rate of bridge, (F7) Bridge maintenance cost.
Rapidity	(F8) Area and region affected, (F9) Restoration time, (F10) Disaster preparedness, (F11) Type of bridge, (F12) Duration of procuring and tendering, (F13) Political condition.
Resourcefulness	(F14) Inspection techniques, (F15) Arrangement of funds, (F16) Automated planning and scheduling, (F17) Resources for network management, (F18) Access to fuel and energy.
Redundancy	(F19) Availability of backup contractor, (F20) Accessible material and equipment, (F21) Availability of funds.

In the second round of the survey, the outcome from the first round is presented to the experts. Subsequently, experts are asked to quantify the importance of the dynamic bridge resilience factors on a six-point Likert scale, where extremely unimportant = 1, unimportant = 2, somewhat-unimportant = 3, somewhat-important = 4, important = 5, and extremely important = 6. In this study, 'Neutral' is not considered for having convenient scores without cognitive efforts. Further, to judge whether experts have reached consensus to a certain extent, all required statical parameters such as absolute deviation (AD)-median, coefficient of variation (CV), and range of data are computed. The cut-off values for these statical parameters (AD, CV, and range of data) are based on study requirements (Patel and Jha 2017). Therefore, in this study, AD-median, CV, and the range of the data should be less than 1.00, 0.25, and 3, respectively. The opinions obtained in the second round of the Delphi method are then analysed, and the statical parameters outcomes are shown in Table 3. It shows that seven factors (highlighted with star sign) exceed the fixed limit of statical parameters. Therefore, these seven factors are eliminated from the final list. After that, Cronbach's alpha of the remaining 14 factors is computed to check the reliability and internal consistency. Hair *et al.,* (2014) advocated that Cronbach's alpha value should be greater than 0.7 to have better reliability and internal consistency among the factors. In the current study, Cronbach's alpha value is estimated to 0.82, which indicates that the remaining 14 factors have better reliability and internal consistency. Thus, at the end of the second round of the Delphi method, 14 bridge resilience factors are shortlisted.

In the third and final round of the Delphi method, experts are asked to look at the results and analysis the final list of bridge resilience dynamic factors. Further, experts are also asked to rate the statements accordingly again. Moreover, if a particular expert rating differs from the panellist, the expert is asked to explain. However, there is consensus among all the experts regarding the final list of bridge resilience factors. In brief, at the end of the first phase of the study, a list of 14 bridge resilience dynamic factors is finalized to develop a CLD.

Table 3: Results of statical parameters

Factor's code	AD (Median)	CV	Range of data	Factor's code	AD (Median)	CV	Range of data
F1	0.71	0.12	2.00	F12*	1.17	0.49	3.00
F2	0.67	0.13	2.00	F13	0.52	0.11	0.00
F3	0.82	0.16	2.00	F14	0.70	0.21	2.00
F4	0.74	0.23	2.00	F15	0.67	0.13	2.00
F5*	1.03	0.32	3.00	F16*	1.25	0.54	3.00
F6*	1.05	0.26	3.00	F17*	1.33	0.33	4.00
F7*	0.79	0.36	2.00	F18	0.32	0.06	1.00
F8	0.74	0.14	2.00	F19	0.74	0.15	2.00
F9	0.82	0.16	2.00	F20	0.42	0.07	1.00
F10	0.67	0.13	2.00	F21	0.52	0.09	1.00
F11*	0.95	0.41	3.00				

Note: * indicated that factors are eliminated from the study.

Name of F1, F2, F3, …., F21 are available in Table 2

Phase-II

In the second phase of the study, the CLD is first created based on the procedure and guidelines presented by Richardson and Pugh (1981) and Kirkwood (1998). For this, Vensim (PLE version) software is used. Then, a face validation technique is utilized to verify the CLD. For this, a questionnaire with a two-point scale of 0-1, in which 1=satisfied and 0=unsatisfied, is designed. The same ten bridge experts from the first phase of the study are selected for verification. Moreover, google form and google meet tools have been used to carry out the questionnaire survey. Thus, all ten experts responded 1, which means they are all satisfied with the structure of the CLD. Therefore, no modification is required, and CLD is considered reliable. The finalized CLD is shown in Fig 2. Subsequently, the finalized CLD is discussed with experts to understand the dynamic behaviour of the bridge resilience along with the transportation network, other utility infrastructures, and governance system. Thus, the bridge owners can use the Delphi technique to select the qualified experts of their region/area. Based on those selected experts, the bridge owners can modify/upgrade CLD and understand the resilience of any bridges located anywhere in the globe.

DISCUSSION

In the finalized CLD (Fig 2), eight causal loops are formed, and all are reinforcing loops as there are no negative links involved in them. These all loops are discussed as follow:

- Loop-1: Bridge resilience → Transportation network → Average daily traffic → Robustness

Loop-1 indicates the interconnection between the bridges and the transportation network, considering the average daily traffic. Decò *et al.,* (2013) have signified average daily traffic as the level of service (LOS) of the bridge. Further, Minaie and Moon (2017) have described the LOS of the transportation network or bridge as robustness. For illustration, flooding events can affect the road network functionality, which can also affect the bridge LOS or visa-versa. This situation can compromise the region's connectivity, accessibility to essential services, economic productivity, and logistics (Cartes *et al.,* 2020). Therefore, if the operation of the transportation network is affected, then the nature of the bridge resilience also changes.

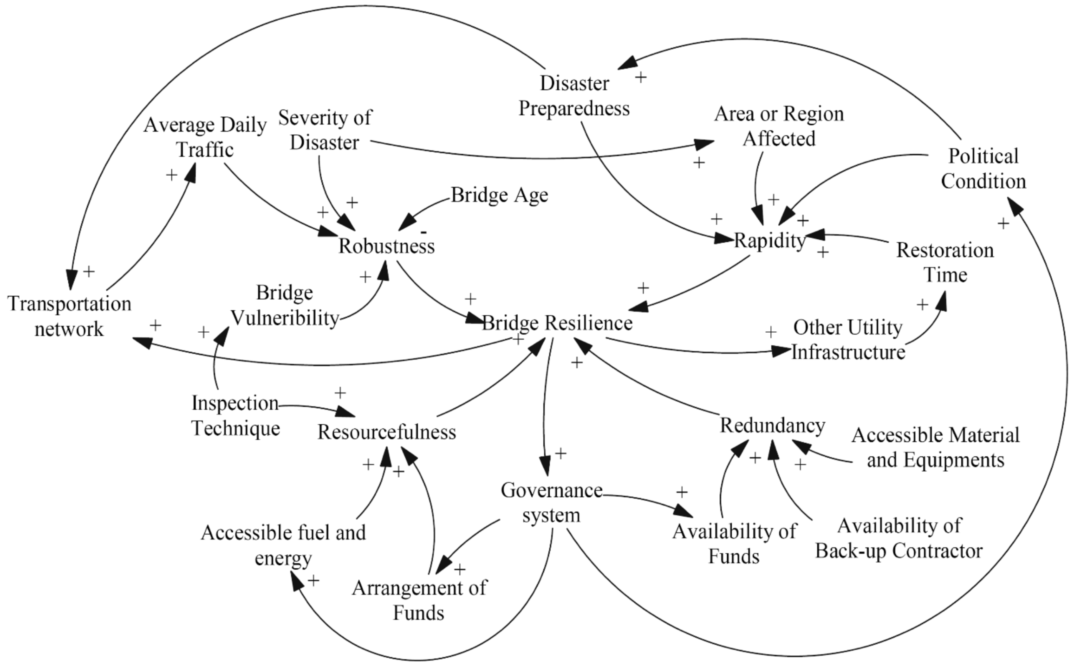

Fig 2: Causal loop diagram of bridge resilience

- Loop-2: Bridge resilience → Other utility infrastructure → Restoration time → Rapidity

Loop-2 indicates the interconnection between the bridge resilience and the other utility infrastructures such as liquefied petroleum gas line, water pipeline, communication cable line, etc. Thus, the loop represents the effect on the restoration time of the bridge due to the other utilities' infrastructure restoration time or vice versa. In this regard, Minaie and Moon (2017) advocated that the utility infrastructures and bridge owners should stay interconnected to have early restoration time after the disaster.

- Loop-3: Bridge resilience → Governance system → Political condition → Rapidity

Loop-3 represents the interconnection between the bridge resilience and governance system, considering the political condition. During the Delphi, procedure experts recommended that the political situation significantly impact the recovery phase of the bridge. As changes in the structure/staff of governance, management, or organizations due to the political condition may delay the restoration/maintenance work of the bridge. Moreover, the dispute in the political situation would also interrupt the recovery process of the bridge and road network. Thus, the political condition represents the dynamic nature as it is hard and uncertain to describe the political situation during and after the disaster.

- Loop-4: Bridge resilience → Governance system → Accessible fuel and energy → Resourcefulness

Loop-4 describes the interconnection and dynamic nature between the bridge resilience and governance system, considering fuel and energy resources. Freckleton *et al.,* (2012) stated that limited access to fuel and energy would deteriorate the ability of the road network and the bridge. Moreover, it would increase the impact of the destabilizing event on the resilience of the bridge. Thus, access to fuel and energy has a dynamic nature as it is based on governance policies, which can affect bridge resilience.

- Loop-5: Bridge resilience → Governance system → Arrangement of funds → Resourcefulness

Loop-5 is similar to loop-4 as it describes the interconnection and dynamic nature between the bridge resilience and governance system considering the arrangement of funds. Patel *et al.,* (2020) described arrangements of funds under resourcefulness because the adjustment in the financial budget by bridge owner is required if there is a strain in the available budget. Thus, these factors describe the dynamic nature of resourcefulness of the bridge resilience. The arrangement of the financial budget might change every year, and it depends on the requirement of the restoration/ maintenance of bridges.

- Loop-6: Bridge resilience → Governance system → Availability of funds → Redundancy

Loop-6 indicates the interdependency of the bridge resilience and governance system, considering the availability of funds. Patel *et al.,* (2020) describe the availability of funds factor as the redundancy to bridge resilience as it limits the options for repair and reconstruction work. Thus, the factors have a dynamic nature to the redundancy of the bridge resilience as the availability of the fund for maintenance might vary every year.

- Loop-7: Bridge resilience → Governance system → Political condition → Disaster preparedness → Rapidity

Loop-7 is the extension of loop 3, as the disaster preparedness factor is added to loop-3. Minaie and Moon (2017), Andrić and Lu (2017), and Patel *et al.,* (2020) stated that bridge owners conduct educational programs, schedule tests, and drill programs for the preparedness faster recovery from disaster. Further, this disaster preparedness program is interdependent on the political situation and governance policies. Therefore, a dispute in the political condition or delay due to the governance system would affect the disaster preparedness program by the bridge owner and eventually impact the recovery of the bridge.

- Loop-8: Bridge resilience → Governance system → Political condition → Disaster preparedness → Transportation network → Average daily traffic → Robustness

Loop-8 represents the interconnection between the bridge, ground transportation network, and governance system considering political conditions, disaster preparedness, and average daily traffic factors. This loop indicates the behaviour of the governance system to plan, manage, and maintain the physical condition of bridges along with the transportation network. Further, the loop also indicates the functionality of commerce and services for a particular region or highway. Thus, this loop is vital as it represents the dynamic relationships of three different infrastructures consider in this study.

Thus, the proposed CLD includes a sufficient number of factors and their relationships to present the reality of bridge resilience interdependency with the other infrastructures. Based on the discussion of all the eight loops, it is clear that they represent a dynamic nature of bridge resilience. Further, this dynamic nature can provide some implications for bridge owners to improve or create a resilience policy scenario. However, improving or creating a bridge resilience policy is a complicated and uncertain process. To overcome it, bridge owners must use system dynamic approach (SDA) as its simulation process can provide twice the result with half the effort to improve or create policy scenarios. Thus, based on SDA, more implications can be provided to bridge owners about building comprehensive bridge resilience.

CONCLUSIONS

This study develops and presents a causal loop diagram (CLD) to represent the dynamic nature of bridge resilience considering the interdependence of transportation networks, other utility infrastructures, and governance systems. To do so, the Delphi technique is utilized to identify and shortlist the dynamic factors of bridge resilience. In the first round of the Delphi technique, 21 factors are identified from the literature review and expert knowledge. Then, in the second round, absolute deviation (AD)-median, coefficient of variation (CV), and range of data are computed. The limit for AD-median, CV, and range of data should be less than 1.00, 0.25, and 3, respectively. Based on these statistical parameter limits, seven factors are eliminated from this study. Then, the Cronbach's alpha of the remaining 14 factors is estimated to 0.82, and it indicated that the remaining factors have better reliability and internal consistency. Finally, in the third round, the experts agree to the second round's results, so 14 dynamic bridge resilience factors are shortlisted and finalized.

Along with these14 shortlisted factors, four properties of resilience (robustness, rapidity, resourcefulness, and redundancy) and four infrastructures (bridge, transportation network, utility infrastructures, and governance system) are considered to develop a CLD. Eight loops are identified from the finalized CLD, and they all represent the dynamic nature of bridge resilience. Moreover, the CLD also indicates the importance of considering transportation networks, utility infrastructures, and governance systems while computing bridge resilience.

The study is only limited to the factors related to bridge resilience. Further study can use the simulation tools to study this dynamic nature of bridge resilience. As it can be helpful to predict and determines the changes in bridge resilience over time. Moreover, studies could use this CLD to propose a measure or methodology of governance policies for bridge resilience. The current research is a part of developing the smart city digital twin (SCDT) system.

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