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BURIED TRANSPORTATION STRUCTURES: FUZZY-MARKOV COMPUTATION CASE STUDY

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This paper will focus on how to improve buried structures' resilience and sustainability so that they hold up over time, withstand extreme weather events, and minimize the use of natural and financial resources. Generally, buried Transportation structures are those which have some portion of their elements and configuration dormant, such as culverts, bridges, and their foundation systems. These structures are a significant part of transportation networks and their related systems. These structures can be disrupted by extreme weather events such as seismic activities, extreme wind gusts, tornado, and tropical cyclones. Repairing the damage after such events can challenge resources and negatively impact the area's economy by disrupting traffic. Moreover, a common problem with buried structures is the lack of understanding about each individual structural element. Accordingly, as a part of this paper's focus, careful attention is given to such important structural integrity. Nevertheless, a number of Australian case studies were undertaken to further improve the buried structures' resilience and sustainability. To support this paper's aim a Fuzzy-Markov computation using a modified *FuzzyStatProb* for buried assets were also explored. The Fuzzy-Markov computation accurately identified the appropriate treatment regimes for selected bridges; which ultimately reduced the natural and financial resources usage.

Keywords: Resilience and sustainability, Fuzzy-Markov process.

1 INTRODUCTION

Universally, buried Transportation structures are those which some of their elements and configurations are concealed, more likely underground. These assets include bridges, where some of their structural elements are dormant (beneath the natural ground level), including columns, pillars, and so on. Such buried Transportation structures conventionally have their footing systems, along with their connections and joints, sealed under the *natural ground level*. Since all of these structures are an important part of the transportation network, their dormant and concealed components need to be regularly monitored and examined.

Although these components typically have low failure rates, when they fail the consequences can be quite severe. Their low rate of failure, coupled with the high cost of inspection and condition assessment contributes to the situation where there is a lack of data necessary to model the deterioration rates of these assets and subsequently to make rational decisions regarding their repair or renewal (Gharehbaghi and Georgy 2015). Nevertheless, inspections determine the maintenance requirements and subsequent maintenance regimes (Hurt and Schrock 2016). Gharehbaghi and Chenery (2017) noted that, while structural resilience includes sturdiness and regaining abilities (under extreme loads), sustainability on the other hand, involves the holistic integration of economic, social, and in particular environmental factors. They also noted, although structures are subject to conventional corrosion and rustis, they also can be disrupted by extreme weather events such as seismic activities. In addition, they also highlighted that efficient maintenance regimes for structures are paramount to prolong these asset's life span.

Since repairing the damage after extreme weather events can challenge resources and negatively impact and disrupt the general traffic, an understanding of buried assets and their individual structural elements is vital. Although, such investigations have been considered and examined widely, the aim of this paper is to provide a number of recent Australian case studies to further improve the buried structures resilience and sustainability. Numerous computation methods such as Artificial Neural Network (ANN), Genetic Algorithms (GA), and Bayesian Networks (BN) have been proposed for the measurement of the deterioration of buried assets, the most prominent approach has been the Markovian processes which will be used be explore the case studies. Lorenzo (2014) rightly highlighted that the Fuzzy-Markov process is one of the most effective computational methods for such structures. Such a proclamation is due to the Fuzzy-Markov process's ease of use and more importantly, accurately validating some of the more common considerations for the buried structures.

2 COMMON CONSIDERATIONS FOR THE BURIED STRUCTURES

Gharehbaghi and Sagoo (2016) argued that the primary consideration for buried Transportation structures consists of understanding how to improve resilience and sustainability of such assembly. Nevertheless, Hurt and Schrock (2016) highlighted that to successfully achieve this, a checklist needs to be developed and maintained that reemphasizes the importance of minimization of natural resource demands and environmental impacts. Such a checklist would highlight environmental mitigation and durability, along with identifying climate change risks and subsequent areas. On the other hand, Shi *et al.* (2012) noted that an essential factor to accomplish more sustainable buried structures also comprises comprehension of when buried structures are viable and appropriate. However, to achieve such an outcome capabilities of buried structures and their installed elements needs to be precisely identified and carefully validated. Fuzzy-Markov process provides an appropriate apparatus to accurately validate such considerations for buried structures.

Furthermore, Gharehbaghi and Rahmani (2017) also underlined the importance of materials selection and usage as a part of structural Resilience and Sustainability. The structural Resilience and Sustainability is paramount for stable buried Transportation structures (Stewart *et al.* 2011). Such material application would further strengthen the buried structures against extreme weather events such as seismic activities, extreme wind gusts, tornado, tropical cyclones, and so on. Accordingly, the buried Transportation structures resilience and sustainability are paramount factors to ensure these assets retain their structural integrity and therefore their life-span is prolonged. For Australia, tropical cyclones are common phenomenon and spread throughout the northern, north-east and north-west coast regions. Accordingly, this paper will examine a number of case studies in Australia to further improve the buried structures' resilience and sustainability.

3 AUSTRALIAN CASE STUDIES

Four bridges (including their structural elements) were selected as the basis of the case studies to further investigate the buried structures resilience and sustainability. These four sites are within the state of New South Wales (NSW). These sites all faced extreme wind gusts which were part of the category 4 Cyclone Debbie which occurred in 2017 and was the strongest tropical cyclone since 2015 (Tropical Cyclone Marcia). Cyclone Debbie had the highest wind speed of 195 km/h and wind gusts of 250 km/h. It affected Queensland, New South Wales, and New Zealand. The location of the four bridges and the actual Cyclone Debbie are presented in Figure 1.

As can be seen from an overview of the bridges in Figure 1, bridge NE-12-BBK2 was closest to the NSW and the Queensland border. In addition, this bridge was also closest to Cyclone Debbie's radius and subsequently would have faced more force and thus additional damage.

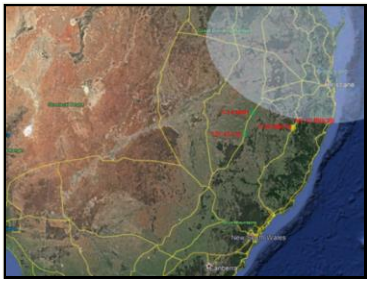
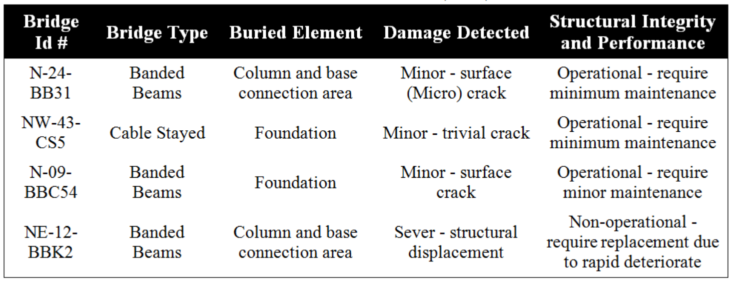


Figure 1. Represents overview of Cyclone Debbie and the four case studies.

Although, various damages were quite visible, however, appropriate Structural Health Monitoring (SHM) method was utilized as the basis of determining the level of impairment for each bridge. As noted, only one of the bridges required significant repair due to considerable structural damage. NE-12-BBK2 a Banded Beam Bridge sustained severe structural displacement at its base. The damage was centered on the connecting point of the third column base and its foundation system. The damage to the other three bridges was minimized and thus enabled them to be in-use. Nonetheless, to further validate the damage to these buried Transportation structures a detailed Fuzzy-Markov computation was carried out. The overview of this analysis is provided below in Table 1.

Table 1. Overview of the four Australian (NSW) case studies.



Bridge Id #	Bridge Type	Buried Element	Damage Detected	Structural Integrity and Performance
N-24-BB31	Banded Beams	Column and base connection area	Minor - surface (Micro) crack	Operational - require minimum maintenance
NW-43-CS5	Cable Stayed	Foundation	Minor - trivial crack	Operational - require minimum maintenance
N-09-BBC54	Banded Beams	Foundation	Minor - surface crack	Operational - require minor maintenance
NE-12-BBK2	Banded Beams	Column and base connection area	Sever - structural displacement	Non-operational - require replacement due to rapid deteriorate

4 FUZZY-MARKOV COMPUTATION (OVERVIEW) FOR THE CASE STUDIES

Traditionally, the Fuzzy-Markov technique uses the condition of the asset in a distinct manner in a few discrete states (Anastassiou 2016). Nonetheless, this technique utilizes Computational Theorem and Discrete Mathematics to predict the transition of the asset from one state to the next (Gharehbaghi 2016). Figure 2 represents the schematics of this technique. As shown in Figure 2, stage 1 prescribes the algorithm development to determine the deterioration rates, and stage 2 imposes specific state of high, intermediate, and low. While these states are based on predicted asset conditions, the general algorithm developed further validates and filters these states. As Gharehbaghi (2006) argued, the Fuzzy-Markov computation, specifically complements the complexities of the Buried Transportation Structures. This is supported by Chmielowski (2016) who demonstrated that the computation needs the ability to be flexible and adaptable when computing to prolong the asset's life.

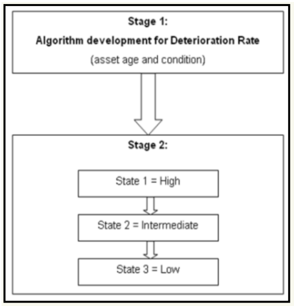


Figure 2. Fuzzy-Markov for buried Asset - Schematics (Gharehbaghi 2006).

Such an approach is fundamental to effectively validate the irregular variables such as design life, rate of use, maintenance and rehabilitation regimes and so on, of the Buried Transportation Structures. Appropriately, the Fuzzy-Markov computation (modified *FuzzyStatProb*) was used for the analysis of the four case studies. This process was selected (buried structures) since there was a probability of inaccurate inspection regimes and data acquisitions. The primary data was sourced from “updated records” along with the “validated and verified archives.” These specific records were maintained by the relevant transportation authorities, such as Transport for NSW, and were also summarized as a part of the "preliminary condition assessment". In addition, the encapsulated data was then grouped into specific categories (discussed below) for advance measurement and evaluation processing. The finalized data was next collaborated into the *algorithm sequencing* for pre-modeling purposes. The deterioration process was then modeled based on *fuzzy rule*, using the Markov method. Subsequently, this process was applied each time via two definite stages:

- Stage one: As a part of the input, this involved the design of fuzzy rule-based algorithm for the deterioration rate of specific *time steps* from asset’s age and condition. As already noted, the deterioration rate was thus finalized using SHM method.
- Stage two: As a part of the procedure stage, the condition rating of the asset was defined based on present conditions and deterioration rate. In other words, the deterioration process of an asset gradually moved from a high (good) state to lower condition states.

The process was then formulated to reflect what happens in reality where the condition of an asset can only be in transition between two or three states (as per Figure 2). Moreover, the Fuzzy-Markov computation for the Case Studies was carefully developed along with their guidelines. These are shown in Figure 3 and Table 2. While Figure 3 portrays the interaction between "each stage and state", Table 2 on the other hand represents the commentary for all the case studies. Whereas S1 (commencement of the segmentation) and S2 are the primary Fuzzy Markov fields, $S2^{-1}$ to $S2^{-3}$ are the secondary and ultimately the *taxonomy grounding*. Moreover, the taxonomy fields represent the 'sorting process' through the connecting lines as a part of the actual chain mechanism. Correspondingly, all the nodes were part of this chain system. The model ultimately uses a simple language to describe the existing problems, identify objects, and verify the main elements of such objects. Moreover, such objects consist of the specific elements including Stage 1, and so on. The Fuzzy-Markov computation was a complex model which also determined the interaction between elements. Nonetheless, the Fuzzy-Markov computation model also possessed multiple solutions, and thus allowed for the best solution to be selected. Based on the best outcome, a new strategy was then issued to the actual Buried Transportation Structures. Nevertheless, upon successful Fuzzy-Markov computation, a holistic inspection, maintenance and rehabilitation regimes were carefully developed. These regimes included:

- Cumulative waiting time's distributions were calculated using ANNs to observe effects.
- As the basis of Structural resilience, specific matrices for age-dependent transition probability were compiled using conditional survival probabilities in the various structural states.
- As the basis of Structural sustainability, environmental and economic schemes were then determined for each structure (for schemes of inspection, intervention and failure phases).
- Scheduled inspection and maintenance intervals were then calculated to reduce the overall cost to a minimum.
- Warning signs were also formulated for immediate intervention when the structural integrity of the asset was compromised.

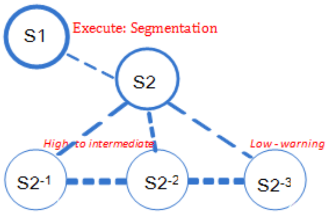
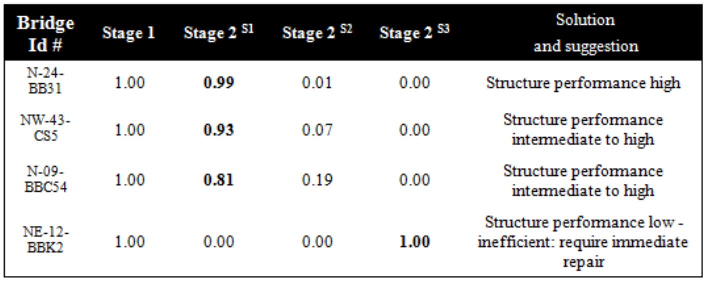


Figure 3. Shows the simplified Fuzzy-Markov computation model.

Table 2. Represents the guidelines of the Fuzzy-Markov computation model.



Bridge Id #	Stage 1	Stage 2 ^{S1}	Stage 2 ^{S2}	Stage 2 ^{S3}	Solution and suggestion
N-24-BB31	1.00	**0.99**	0.01	0.00	Structure performance high
NW-43-CS5	1.00	**0.93**	0.07	0.00	Structure performance intermediate to high
N-09-BBC54	1.00	**0.81**	0.19	0.00	Structure performance intermediate to high
NE-12-BBK2	1.00	0.00	0.00	**1.00**	Structure performance low - inefficient: require immediate repair

Finally, the Fuzzy-Markov computation process validated that, while assets N-24-BB31 and NW-43-CS5 were deemed totally safe and operational however, minimum maintenance was required. On the other hand, although N-09-BBC54 was operational, it needed minor maintenance. Conversely, it was established that the asset NE-12-BBK2 was in total despair and thus required immediate replacement. As a result, these four Australian case studies clearly highlighted the significance of the Fuzzy-Markov process to further improve the buried structures' resilience and sustainability through better identification and thus proper treatment recommendation for such assets. Such resilience and sustainability mechanisms were the outcome of transition probability, using conditional survival possibilities along with early warning signs for prematurely interventions. Accordingly, Fuzzy-Markov process highlighted the structural resilience and sustainability of the four case studies and in-turn specific maintenance regimes were also developed to further prolong these asset's lives. Ultimately, while to ensure

Structural resilience matrices for age-dependent probability was accumulated, to warrant sustainability, environmental and economic schemes were then determined for each bridge. Such an outcome would eventually lead to minimizing the use of natural and financial resources.

5 CONCLUSIONS

The aim of this paper was to review strategies for the improvements of the buried transportation structures' resilience and sustainability. To achieve this, four different types of bridges (including their structural elements) were selected all within the state of NSW, Australia. All of these bridges were subject to Cyclone Debbie, which occurred in 2017. These four bridges were selected since as they each showed different signs of structural damage. Nevertheless, to support this paper's aim, a Fuzzy-Markov process for buried assets was also explored. The examination of the Fuzzy-Markov process for four case studies validated the advantage of such computational process to further augment the buried structures' resilience and sustainability. As already noted, such improvements were through superior identification using Fuzzy-Markov processes and thus the appropriate treatment was recommended for the assets; which in-turn would ultimately point to curtailing the use of natural and financial resources. Consequently, the utilization of the Fuzzy-Markov computation, precisely distinguished the most suitable rehabilitation regimes for the said bridges. Ultimately, the instituted Fuzzy-Markov computation led to reduction of the resources required for the purpose of the four bridge's rehabilitation regimes.

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