WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

VIBRATION SERVICEABILITY OF A TIMBER ARCH PEDESTRIAN BRIDGE CONSIDERING DETERIORATION OVER TIME

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ABSTRACT: The vibration serviceability of pedestrian bridges is an important indicator for ensuring safety and comfort of pedestrians while crossing a bridge. However, the research on the influence of localized decay of timber materials due to aging on the vibration serviceability is limited. Therefore, this study was aimed at assessing the influence of aging and localized decay of structural members on vibration serviceability, and a numerical analysis model was developed. The Young's modulus and degradation state of bridge members that have been in service for ~30 years were incorporated in the model. The vibration serviceability before and after degradation was considered using time-history response analysis with two models: a healthy and deteriorated condition models. As a result, the RMS (Root Mean square) values of response velocity were significantly higher during 2.2 Hz and 2.3 Hz (crowd walking), indicating an influence on vibration serviceability.

KEYWORDS: timber bridge, vibration serviceability, pedestrian bridge, local decay, glued laminated timber

1 – INTRODUCTION

As a maintenance and management indicator for pedestrian bridges, evaluating the vibration serviceability, including walking difficulty and discomfort, in addition to safety is important . The Japanese Technical Standards for Grade-Separated Crossing Facilities [1] has specified guidelines for the vertical vibrations of pedestrian bridges. According to these guidelines, the natural frequency of the main girder deflection vibration should be avoided in the range of 1.5–2.3 Hz. However, in many cases regarding aged timber pedestrian bridges, for the natural frequency beyond the human step frequencies of 1.5–2.3 Hz, the vibrations were described as "lightly hard to walk" or "extremely hard to walk" [2]. Therefore, this study was aimed at assessing the influence of aging and localized decay of structural members on vibration serviceability of timber pedestrian bridge.

In this study, the "Meoto Bridge," for which Young's modulus of both the decayed and newly constructed members are known, was focused. We proposed two models: a 3D solid model with Young's modulus of healthy members and a 3D solid model that considers localized decay. Time-history response analyses simulating pedestrian tests were conducted using numerical analysis models. By comparing the peak and root mean square (RMS) values of the walking response velocities were compared with the vibration serviceability evaluation criteria, and the vibration serviceability was evaluated. Furthermore, the impact of member decay on vibration serviceability was confirmed by comparing the vibration serviceability of the bridge in its healthy state with that in its deteriorated state, we confirmed the impact of member decay on vibration serviceability.

2 – TARGET BRIDGE

The target bridge, "Meoto Bridge," is situated in front of Meoto Cedar, a symbol of the Nibetsu National Forest, Akita Prefecture, Japan, and frequented by tourists and hikers. The bridge was rebuilt in December 2020. The previous bridge, constructed in 1994, was in service for approximately 30 years before being dismantled due to decay and deterioration.

Table 1. Outline of design of the Meoto bridge.

Design condition	
Load type	Pedestrian bridge
Structure consisting	Half through timber arch bridge (Type of two hinged arch)
Bridge length	23,000mm
Arch span length	20,000mm
Effective width	1500mm
Longitudinal siope	Level
Live load	Crowd load : 3.5kN/m^2
	Snow load：1.0kN/m^2
Materials	
Arch rib	Akita cedar glulam
Longitudinal girder	Akita cedar glulam
Floor girder	Akita cedar glulam
Deck	Akita ceda
Lateral bracing	Akita cedar glulam
Joint	SS400

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https://doi.org/10.52202/080513-0340

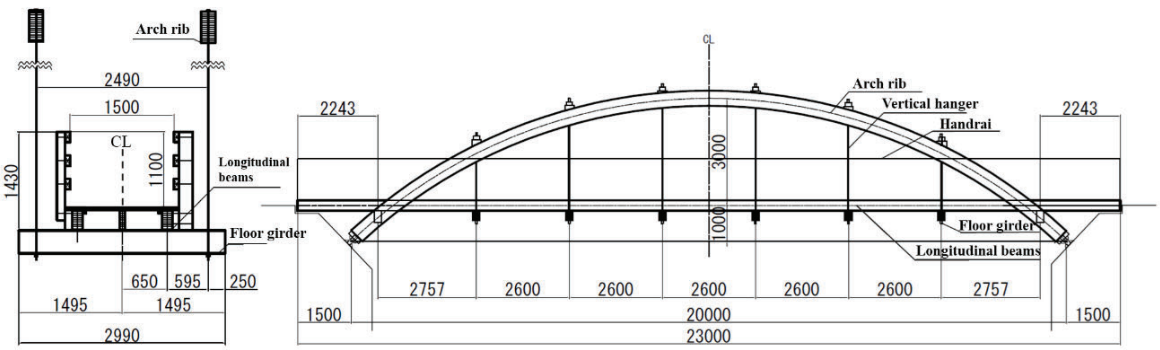


Figure 1. General drawing of Meoto bridge (Akita prefecture in Japan)

Figure 2. Meoto bridge (Akita prefecture in Japan)

After its removal, material tests were conducted on the structural members of the old bridge, including static bending tests, bending vibration tests, and stress wave transit time measurements, which showed the bending and axial Young's modulus [3]. For the current bridge, the Young's modulus of the members was measured in May 2021 using the stress-wave transit-time method. The design conditions are listed in Table 1, and a general drawing and the external appearance of the bridge are shown in Figs. 1 and 2, respectively.

3 – NUMERICAL MODEL

3.1 Condition of model

Numerical analysis was performed using the open-source FEM software Salome-Meca 2020.0.1 [4] with a 3D model of the targeted bridge. The FEM model was meshed with 1, 859, 486 tetrahedral elements, including 628,834 quadratic elements for the arch ribs and 1,230,652 primary elements for the other members. The ends of each arch rib were hinged at the midline cross-section. The lower faces of the longitudinal beams were constrained in the vertical and horizontal directions of the width of the bridge at both ends, while remaining free along the bridge axis (Fig. 3). Handrails were not modeled owing to their negligible structural influence. The arch ribs were considered as isotropic materials, whereas the other members were modeled as orthotropic materials. The Young's modulus of the healthy members (hereafter referred to as the “healthy condition”) were determined using measurements from the stress-wave transit-time method conducted in 2021 [5]. Young’s modulus of the old bridge (hereafter referred to as the “deteriorated condition”) were determined using measurements from the stress-wave transit-time method for removed members [3]. The Young's modulus of each member in healthy and deteriorated conditions are shown in Fig. 4.

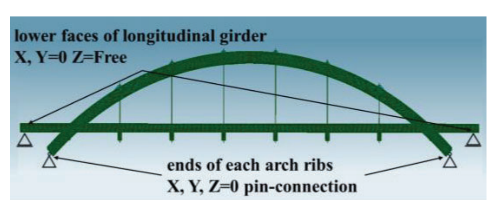


Figure 3. Boundary conditions of numerical model

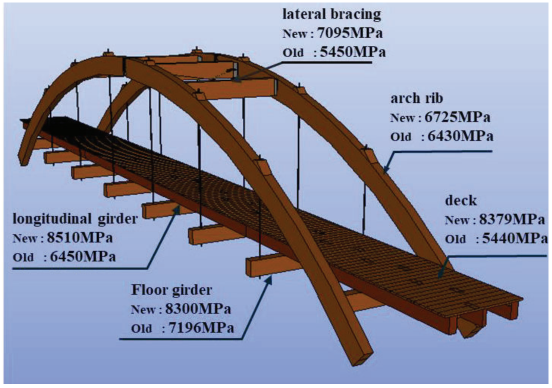


Figure 4. Young's modulus of each member

Figure 5. Determining locations of localized decay

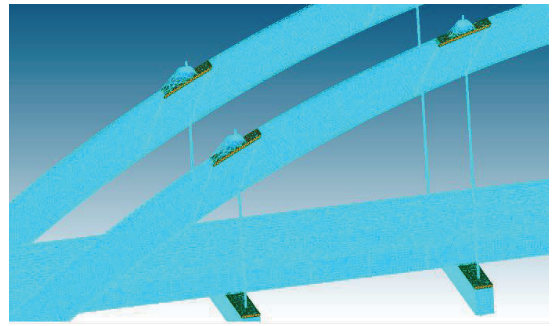


Figure 6. Details on the FEM model for decayed points

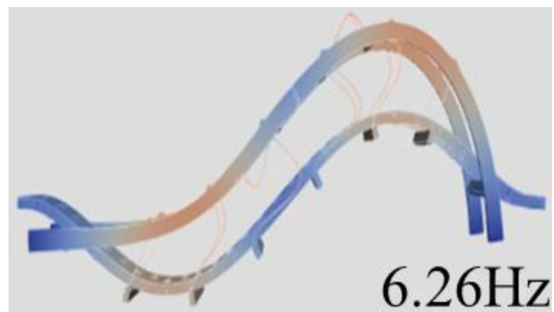


Figure 7. Vertically anti-symmetric 2 sin half-waves mode

3.2 Consideration of Localized Decay

In the old bridge, before its replacement, localized decay progressed in certain areas, resulting in cross-sectional losses. Therefore, in the numerical analysis model of the old bridge, the localized decay was represented by a significantly reduced Young's modulus in the affected areas. Partial cross-sectional losses were introduced at locations, such as the joints of longitudinal beams, ends of arch ribs, and contact areas between floor girders and longitudinal beams, identified through material tests [3]. The length, width, and thickness of the decayed areas were set to 1000, 200 or 150 (depending on the width of the member), and 30 mm (corresponding to the thickness of a single glulam lamina), respectively. Fig. 5 shows the localized decay areas where the numerical analysis model was applied.

4 – MODAL ANALYSIS

Modal analysis was conducted to calculate the natural frequency under healthy conditions and evaluate the validity of the numerical analysis model. The calculated results were compared with the measured natural frequency of the Meoto Bridge obtained through field measurements. The natural frequency was measured using tablet devices equipped with an accelerometer, and the measurements were conducted in the year following the determination of the Young's modulus of the bridge members [5].

According to the modal analysis results, the lowest vertical natural vibration mode was the vertically anti-symmetric 2 sin half-waves mode with a calculated natural frequency of 6.26 Hz. The measured natural frequency was 5.86 Hz, which resulted in a discrepancy of approximately 9%. This comparison confirmed the validity of the numerical analysis model. In addition, the natural frequency under deteriorating conditions, as determined by modal analysis, was found to be 4.78 Hz.

5 – TIME HISTORY RESPONSE ANALYSIS

The time-history response analysis simulating walking was conducted to examine the vibration serviceability during walking. The walking scenarios assumed were single walking (one person) and crowd walking (five people). The walking loads used in the analysis were periodic loads based on the cosine wave formula proposed by Kajikawa et al. [6].

$$f(t)= \alpha W \cos(2\pi f t) \tag{1}$$

where, α: impact factor, W: weight of the pedestrian, and f: walking frequency.

Generally, when considering human walking, the force is applied only downwards onto the floor surface. Therefore, we did not consider the load when the foot was off the floor, and calculations were performed using a half-cosine wave load.

The walking speed was based on typical human step frequencies of 1.7 Hz, 1.8 Hz, 2.0 Hz, 2.2 Hz, and 2.3 Hz, with a step interval of 70 cm. The pedestrian's weight was assumed to be 686 N. In the analysis, a modal damping coefficient of h=0.018 was applied. The outputs point of the vibration-response values are shown in Fig.8.

https://doi.org/10.52202/080513-0340

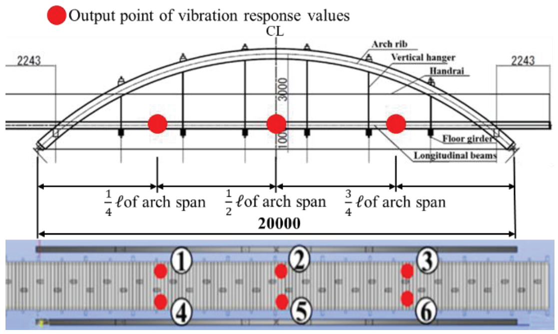
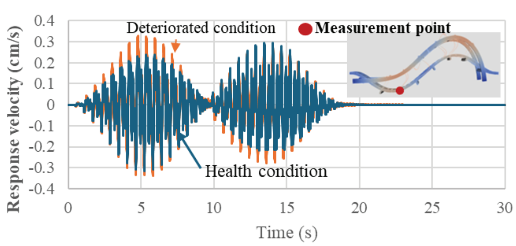


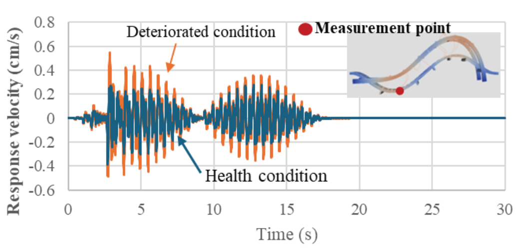
Figure 8. Output point of vibration response values

Figs. 9 and 10 show the velocity waveforms obtained from the time-history response analysis at Measurement point 1. Measurement points 1 corresponds to the antinode of the vertically anti-symmetric 2 sin half-waves mode, where the largest vibration response is expected to occur.

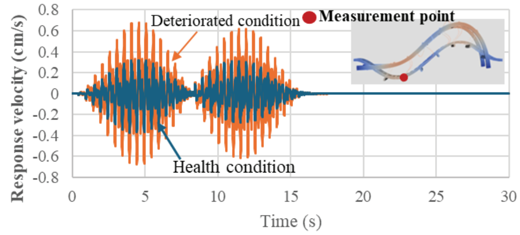
First, the single walking behaviors were examined (Fig. 9). At 1.7 Hz and 1.8 Hz, no significant increase was observed in the velocity amplitude. However, at 2.2 Hz and 2.3 Hz, the velocity amplitude increased significantly in the deteriorated condition. Factors contributing to this phenomenon were comprehensively considered in conjunction with the results of crowd walking. Additionally, no significant difference was observed in the shape of the vibration waveform between the healthy and deteriorated conditions.



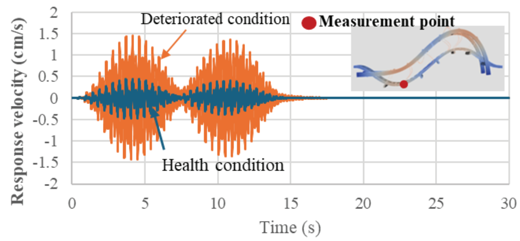
a) Velocity Response at 1.7 Hz



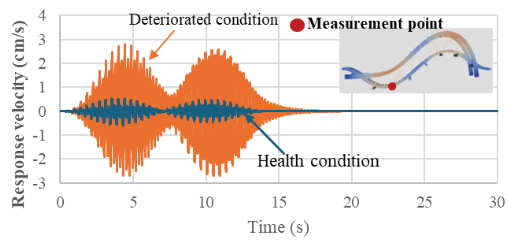
b) Velocity Response at 1.8 Hz



c) Velocity Response at 2.0 Hz



d) Velocity Response at 2.2 Hz

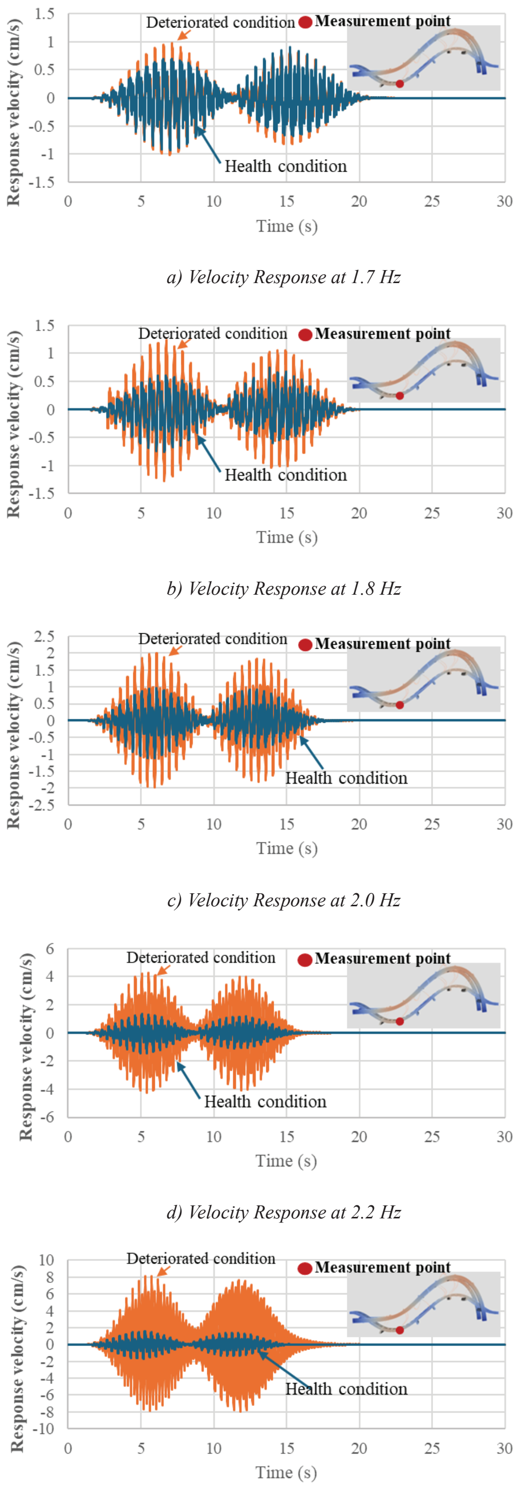


e) Velocity Response at 2.3 Hz

Figure 9. Comparison of velocity response between healthy and deterioration conditions (single walking)

Next, we discuss crowd walking (Fig.10). Similar to single walking, no significant increase was observed in amplitude at frequencies up to 1.7 Hz and 1.8 Hz during crowd walking. However, at 2.2 Hz and 2.3 Hz, the velocity amplitude increases significantly in the deteriorated condition.

According to results of both single and crowd walking, the reduction in stiffness owing to the decrease in Young's modulus or localized decay does not directly contribute to the increase in amplitude. However, when the natural frequency decreases and falls within the frequency range of double or triple that of the human step frequency, double-wavelength resonance [7] may occur, leading to an increase in amplitude.



a) Velocity Response at 1.7 Hz

b) Velocity Response at 1.8 Hz

c) Velocity Response at 2.0 Hz

d) Velocity Response at 2.2 Hz

e) Velocity Response at 2.3 Hz

Figure 10. Comparison of velocity response between healthy and deterioration conditions (crowd walking)

6 – VIBRATION SERVICEABILITY ASSESSMENT

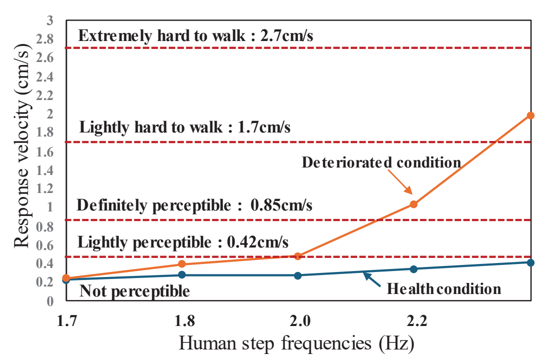
The vibration serviceability of pedestrian bridges is determined based on human vibration perception, with threshold values set according to the peak and root mean square (RMS) response velocities during walking. According to the category-specific thresholds proposed by Kobori et al. [8], when the RMS response velocity exceeds 1.7 cm/s or the peak velocity exceeds 2.4 cm/s, walking is considered "lightly hard to walk, " indicating an impact on pedestrian comfort. In this study, the vibration serviceability was evaluated for both healthy and deteriorated conditions based on these thresholds and categories. The category-specific thresholds proposed by Kobori et al [8] are listed in Table 2.

Table 2. Category-specific thresholds of vibration serviceability.

No.	content of category	lower limit (cm/s)	
		Peak value	RMS Value
0	Not perceptible	-	-
1	Lightly perceptible	0.6	0.42
2	Definitely perceptible	1.2	0.85
3	Lightly hard to walk	2.4	1.7
4	Extremely hard to walk	3.8	2.7

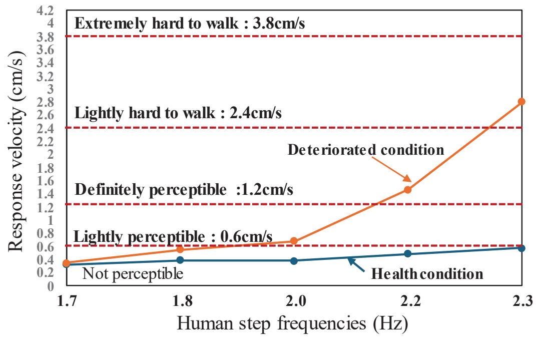
The peak velocity (V_{peak}) and root mean square (RMS) velocity (V_{RMS}) were calculated from the velocity response waveforms obtained through the time-history response analysis. When the velocity waveform can be approximated as a sine wave, the RMS velocity V_{RMS} can be estimated by multiplying the peak velocity V_{peak} by $\frac{1}{\sqrt{2}}$ [9].

Figs.11 and 12 presents the vibration serviceability evaluation for single and crowd walking, respectively, under both healthy and deteriorated conditions.



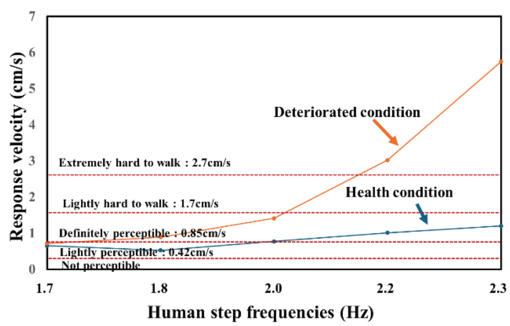
a) Vibration Serviceability of RMS Value

https://doi.org/10.52202/080513-0340

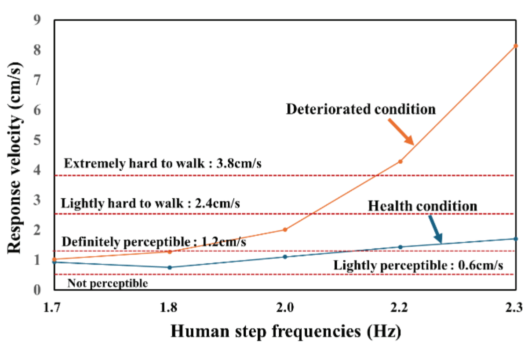


b) Vibration Serviceability of Peak Value

Figure 11. Comparison of vibration serviceability between healthy and deteriorated conditions (single walking).



a) Vibration Serviceability of RMS Value



b) Vibration Serviceability of Peak Value

Figure 12. Comparison of vibration serviceability between healthy and deteriorated conditions (crowd walking).

When evaluating the vibration serviceability during single (Fig.11) and crowd walking (Fiig.12), for walking paces of 1.7Hz, 1.8Hz, and 2.0Hz, the velocity response after deterioration exhibited slightly higher values compared to the healthy condition. However, these results did not indicate any significant issues with vibration serviceability that would make it "lightly hard to walk." In contrast, for a walking pace of 2.3Hz, where double-span resonance is likely to occur, the results indicated vibration serviceability issues that make walking "lightly hard to walk."

Thus a decrease in Young's modulus and a reduction in the overall bridge stiffness owing to localized decay do not directly impair vibration serviceability under normal conditions. Instead, double-wavelength resonance, which occurs when the natural frequency is two or three times the human step frequency, has the most significant impact on vibration serviceability. Therefore, for pedestrian bridges and other structures where vibration serviceability is a critical concern, regularly measuringe the natural frequency and assessing whether it falls within the frequency range of double or triple the human-step frequency is important. This study suggests that such evaluations are essential to maintain adequate vibration serviceability.

7 – SUMMARY

This study, was aimed at assessing the influence of aging and localized decay of structural members on vibration serviceability. The vibration serviceability before and after degradation was considered using a time history response analysis with two models.
According to the results of the modal and time-history response analysis results the reduction in Young's modulus and localized decay do not directly impair vibration serviceability. However, the occurrence of double-wavelength resonance when the natural frequency coincides with double or triple the human step frequency, most significantly affects the vibration serviceability.
Therefore, regularly measuring the natural frequency of pedestrian bridges, where vibration serviceability is a critical concern, and assessing whether it falls within the frequency range of double or triple the human step frequency is important.
These results can be used to design maintenance strategies of old timber bridges and deciding the structures in which the conventional materials can be replaced with timber.
In future, further detailed investigations will be conducted to determine whether localized decay concentrated in specific areas affects the velocity waveform.

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ACKNOWLEDGEMENT

This study was supported by JSPS KAKENHI Grant Number JP23K03983.

https://doi.org/10.52202/080513-0340