Australian Earthquake Engineering Society
2024 National Conference, 21-23 November 2024
Adelaide, South Australia

Dynamic stability of ballasted and ballastless railway tracks

Hafsa Farooq[1], Sanjay Nimbalkar[2], Daichao Sheng[3]

[1]Ph.D. Candidate, School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, Sydney, NSW 2007, Australia. Email: HafsaFarooq@student.uts.edu.au

[2]Senior Lecturer, School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, Sydney, NSW 2007, Australia. Email: Sanjay.Nimbalkar@uts.edu.au (Corresponding author)

[3]Distinguished Professor, School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, Sydney, NSW 2007, Australia. Email: Daichao.Sheng@uts.edu.au

Abstract

Railway tracks require sufficient strength and durability to withstand dynamic forces. Withstanding these forces is important, as dynamic instability can lead to potential track failures. Railway embankments can undergo significant deformations due to dynamic loading resulting from seismic activity or high-speed trains. This article summarises the recent trends in the dynamic analysis for railway tracks and discusses the potential applications of computational models to capture the response of railway tracks due to dynamic excitations. The effectiveness of these models in achieving safe and reliable systems during earthquakes is also elaborated.

Keywords: dynamic forces, seismic instability, transport corridors, railway embankments, deformations.

1 Introduction

The railway track network is one of the most essential infrastructures in any country. It is imperative that these systems are designed to be safe, efficient, comfortable, and resilient against both train loads and natural disasters, including earthquakes. Railway tracks must exhibit sufficient strength to withstand seismic forces, as the potential for seismic instability can result in sliding or overturning failures, which may lead to catastrophic outcomes. To mitigate such failures, it is essential that tracks are designed and maintained in such a manner that they can counteract dynamic ground motion resulting from earthquakes. This requires careful consideration of factors such as track alignment, foundation stability, and the inclusion of advanced engineering techniques, such as performing advanced analysis and simulations to ensure the integrity of the railway system during and after an earthquake. Historical earthquake events have underscored the critical importance of maintaining track geometrical stability to ensure maximum safety (Esmaeili & Noghabi, 2013).

A range of approaches, including experimental, numerical, and analytical methods, has been employed to assess the impact of seismic loads on railway tracks. Among these, analytical models, particularly those based on the beam on elastic foundation (BoEF) approach, are often preferred due to their efficiency and cost-effectiveness. However, these models have traditionally concentrated on vertical responses, often overlooking the critical lateral effects that are paramount in seismic analysis. It is vital to consider lateral deformations resulting from seismic loads to avert track failures and maintain the safety and stability of railway systems.

Over the past century, research has focussed on addressing the issues relating to soil-structure interaction, with significant effort being directed towards developing methods for understanding soil structures during ground excitation (Hoseini et al., 2019). While protecting railway track networks from seismic damage has been recognised, only a few in-depth investigations have been conducted (Housner & Lili, 2002). For example, Sekine and Ishikawa (2005) performed experimental analysis to assess deformation in railway tracks caused by earthquakes, Nakamura et al. (2011) conducted shake table tests on a large-scale railway track model, Kumakura et al. (2010) observed that ballast in a railway track displaced from its original position during a large-scale earthquake, though no visible defects were noted on-site.

In addition to the experimental studies, analytical studies have also been conducted. For instance, Esmaeili and Noghabi (2013) examined the seismic behaviour of ballasted railway tracks by using a rheological model and reported deformations and internal forces developed within rails and sleepers during an earthquake. Hoseini et al. (2019) focussed on the soil-structure response using earthquake excitations on a rheological model. Additionally, Jiang et al. (2021) developed a train-track-bridge coupled model to compare responses with and without seismic excitation during a high-speed train operation concluding that the risk of derailment increases during an earthquake. Figure 1 illustrates the effect of an earthquake on a railway track.

This paper provides an overview of research methodologies aimed at enhancing the seismic resilience of railway tracks. It reviews various techniques used to understand the impact of earthquakes on railway structures, with particular emphasis on a developed model designed to capture the lateral response of railway tracks; an essential factor in assessing seismic stability. The paper underscores the critical need for continuous innovation and rigorous engineering practices to safeguard railway systems against seismic events.

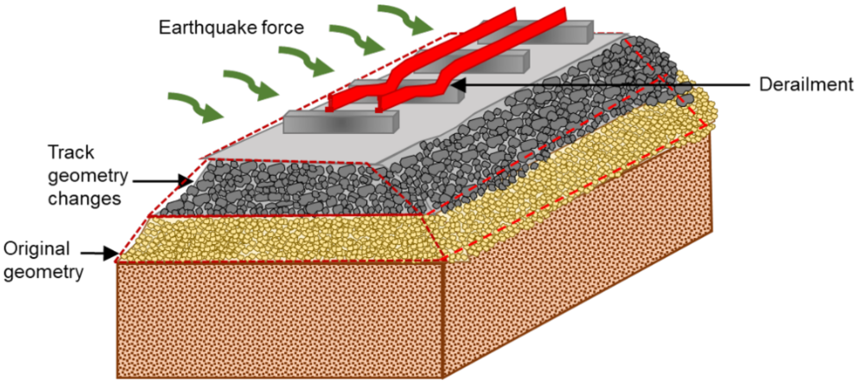

Figure 1 Effect of the earthquake on a railway track

2 Computational models from literature

Past investigations emphasise the importance of protecting railway tracks from earthquake damage (Esmaeili & Noghabi, 2013; Ghogre et al., 2022; Jiang et al., 2021). Several studies have assessed the seismic effects on railway tracks through various experimental methods, including shaking table tests (Nakamura et al., 2011), and analytical and numerical procedures (Esmaeili & Noghabi, 2013; Ghogre et al., 2022), to explore track responses during earthquakes. However, there is still a need for more advanced and accurate methods to improve seismic analysis, especially for investigating the long-term performance of railway tracks and soil-structure interactions during earthquakes.

Esmaeili and Noghabi (2013) developed a rheological model for seismic analysis of railway tracks, which was validated with shake table tests. The model simulated seismic excitation from the Kobe earthquake to evaluate deformations and internal forces in the track, considering different track lengths and varying peak ground acceleration (PGA) values. The varying PGA values were derived from the wavelet function provided by Suárez and Montejo (2005), based on the impulse response function, as shown in the following equation:

$$\psi = e^{-\zeta\Omega} \sin \Omega \tag{1}$$

where ζ and Ω represent decrement and time variation, respectively.

The study also found that, besides peak ground acceleration (PGA) values, the duration of strong motion (SMD) plays a significant role in affecting the structural and geometric integrity of railway tracks during and after an earthquake. Several approaches have been developed to estimate SMD. Trifunac and Brady (1975) defined significant duration for SMD as the time span between 5% and 95% of the Arias intensity. Arias (1970) introduced a ground motion parameter that quantifies the potential destructiveness of an earthquake. The Arias intensity is given by the following equation:

$$I_a = \frac{\pi}{2g} \int_0^{T_d} [a(t)^2] dt \tag{2}$$

where g is the acceleration due to gravity; $a(t)$ is the recorded acceleration; T_d is the duration of ground motion.

Esmaeili and Noghabi (2013) generated accelerograms to investigate the PGA effects on railway track. A 42 m track model was developed to evaluate longitudinal and lateral deflections. Figure 2 illustrates these deflections at PGA values of 0.4g and 0.8g. The plots indicate that higher PGA values lead to increased deflections in both longitudinal and lateral directions, with lateral deflections being more pronounced.

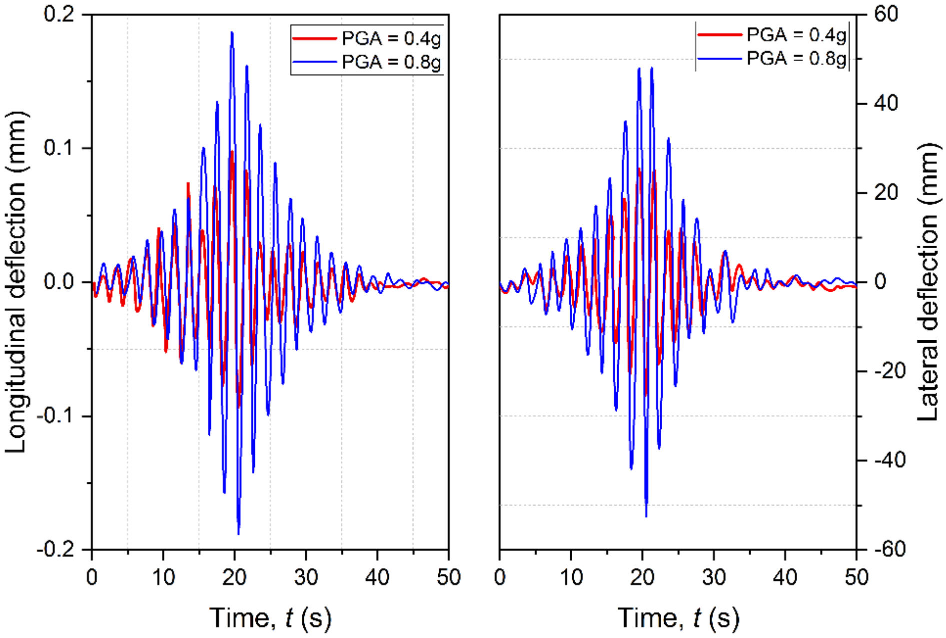

Figure 2 Deflections in a railway track modified after Esmaeili and Noghabi (2013)

Jiang et al. (2021) compared the efficiency of a developed coupled model with a conventional simply supported bridge model under seismic excitation. The coupled model, designed to significantly reduce computational effort, was tested through six earthquake ground motion simulations, such as the 1940 El Centro earthquake (Mexico & USA), 1979 Imperial Valley earthquake (Mexico), 1980 Trinidad earthquake (West Indies), 1989 Loma Prieta earthquake (USA), 1994 Northridge earthquake (USA) and 1995 Kobe earthquake (Japan). Across different earthquake scenarios, including vertical ground motions, the coupled model effectively captured the dynamic responses of the train-track-bridge system. The study concluded that higher seismic acceleration amplitudes result in increased car-body acceleration, wheel-rail forces, and wheel load reduction ratios.

Ghogre et al. (2022) highlighted the importance of understanding the lateral seismic response of railway tracks, an area that has relatively been less explored. The study focuses on analysing seismic responses in the lateral direction using various analytical models. The findings revealed that the seismic response is most pronounced in the central region of the track, with a rapid decrease in response observed beyond this area. Zhou et al. (2023) developed a simplified model for high-speed railway track bridges, which enhanced computational efficiency, reduced complexity and decreased calculation time in seismic response evaluations. Peng et al. (2024) introduced a method for assessing railway track smoothness after an earthquake, highlighting its crucial role in safe train operations. They established a logarithmic linear relationship between track irregularity and train speed, providing a practical method for determining a safe train speed threshold post-earthquake.

3 Methodology and results

The lateral response of railway tracks is a critical factor in seismic analysis, as it directly impacts the stability and safety of the rail infrastructure during and after seismic events. While much focus has traditionally been placed on vertical responses, lateral deformations, particularly those induced by seismic forces, pose significant risks, including track buckling, derailment, and permanent geometry changes. Understanding and accurately predicting lateral track behaviour under seismic loads is essential for designing railway systems that can withstand such dynamic forces and maintain operational integrity.

A viscoelastic rheological model is developed to simulate the behaviour of a ballasted railway track under dynamic conditions. This model characterises the track layers as a system of discrete masses connected by elastic springs (k_v and k_h) and viscous dampers (c_v and c_h) vertically and horizontally, as shown in Figure 3. It effectively captures the mechanical properties of the track. Seismic forces and train-induced vibrations are integrated into the model through dynamic equations of motion, which consider both vertical and lateral displacements under impacted loading. This comprehensive approach highlights the significance of lateral stability in seismic scenarios. The numerical framework allows for the precise simulation of the track time-dependent responses to the combined effects of seismic and train-induced loads, ensuring an accurate assessment of track behaviour under these complex conditions. Such numerical predictions are particularly valuable for identifying critical scenarios where lateral deformations may exceed safety thresholds, potentially leading to track instability or failure.

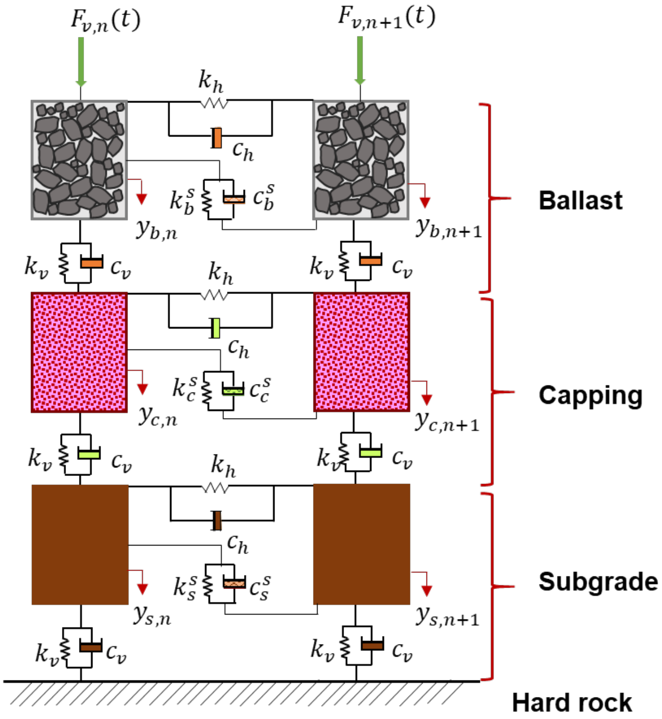

Figure 3 Viscoelastic rheological model

The model provides a crucial framework for understanding how different track parameters influence lateral responses, which is particularly important in seismic analysis. During an earthquake, the lateral forces acting on railway tracks can cause significant displacements, putting at risk the track stability and safety. A study by Farooq et al. (2024) has shown that higher axle loads lead to increased lateral displacement, indicating that tracks in seismically active regions must be designed to withstand not only vertical but also substantial lateral forces. Axle loads can cause substantial lateral displacement, and when combined with seismic forces, this can amplify the risk of track misalignment or failure. Controlling train speeds during seismic events may help mitigate lateral displacement, thereby reducing the risk of track failure. It is observed that the lateral displacement in the top layer of the railway track increases with an increase in the train speed. Table 1 includes the increasing lateral displacement due to the increasing train speed and the displacement ratio relative to 70 km/h. The displacement ratio is evaluated using Equation 3.

$$D_R = \frac{S_h}{S_o} \tag{3}$$

where S_h is the lateral displacement; S_o is the initial lateral displacement.

The input parameters for the viscoelastic model are mentioned in Table 2. Furthermore, the reduction in lateral displacement with increased capping thickness highlights the critical role of substructure design in enhancing seismic resilience, as shown in Figure 4. The displacement ratio shows a similar trend to the lateral displacements, providing valuable insights to practising engineers regarding variations at a nominal train speed of 70 km/h. A well-designed ballast and capping layer can effectively absorb and dampen seismic energy, minimising lateral movements that could otherwise result in track misalignment or failure.

Table 1 Lateral displacements in a railway track due to increasing train speed.

Train speed, V (km/h)	**Lateral displacement, S_h (mm)**	**Displacement Ratio (Relative to 70 km/h)**
70	3.9	1.00
150	4.6	1.18
200	5	1.28

Table 2 Input parameters for the viscoelastic track model

Property	**Symbol**	**Unit**	**Value**
Ballast			
Elastic modulus	E_{b}	MPa	250
Poisson’s ratio	υ_{b}	–	0.4
Shear stiffness	k_{b}^{s}	MN/m	1

Shear damping	c_{b}^{s}	kNs/m	80
Density	ρ_{b}	kg/m^3	1900
Thickness	h_{b}	m	0.35
Capping			
Elastic modulus	E_{c}	MPa	120
Poisson’s ratio	υ_{c}	–	0.4
Shear stiffness	k_{c}^{s}	MN/m	476
Shear damping	c_{c}^{s}	kNs/m	80
Density	ρ_{c}	kg/m^3	1920
Thickness	h_{c}	m	0.15
Subgrade			
Elastic modulus	E_{s}	MPa	20
Poisson’s ratio	υ_{s}	–	0.4
Shear stiffness	k_{s}^{s}	MN/m	1600
Shear damping	c_{s}^{s}	kNs/m	80
Density	ρ_{s}	kg/m^3	1920
Thickness	h_{s}	m	3

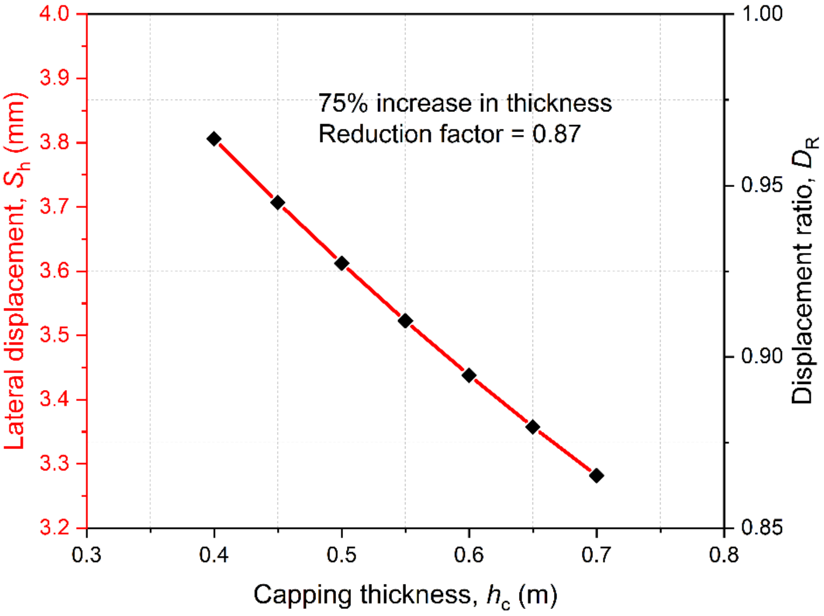

Figure 4 Variation of lateral displacement with capping thickness

4 Applications of computational models

The computational models developed for railway tracks have several critical applications in evaluating seismic responses. The rheological model by Esmaeili and Noghabi (2013) simulated the three-dimensional seismic behaviour of railway tracks. The model has been validated against shake table tests. This model can calibrate other seismic models, ensuring they accurately reflect real-world conditions. The model highlights how seismic forces, particularly in lateral directions, can impact the serviceability of railway tracks post-earthquake, showing that lateral deflections increase significantly with higher PGA values, potentially limiting track usability. Additionally, the model predicts the likelihood of rail buckling under different seismic intensities, even at low PGAs, which is crucial for maintaining the structural integrity and safety of the railway track. By identifying potential weaknesses and areas susceptible to seismic damage, the model aids in improving track design for seismic resilience and facilitates targeted maintenance for enhanced safety and durability.

An efficient and reliable tool for simulating seismic responses of a train-track bridge was presented by Jiang et al. (2021). The model not only accurately captured seismic behaviour but and significantly reduced computational time compared to conventional methods. The study reveals that increasing earthquake acceleration amplitude has a linear impact on car-body acceleration, wheel-rail force, and wheel load reduction. While this research primarily focuses on vertical responses, the model can be extended to investigate longitudinal and lateral seismic effects on train-track-bridge systems. In addition, Peng et al. (2024) assessed post-earthquake track smoothness using ground motion intensity indicators. The model employed a straightforward, calculable method to establish the relationship between track smoothness and speed, effectively determining track irregularity and its impact on train operations.

The proposed model by Farooq et al. (2024) can prove useful for designing a railway track that can withstand seismic forces. Insights into the effects of increased granular layer thicknesses on reducing lateral displacement can guide the design of more resilient track substructures, particularly in earthquake-prone areas. This is crucial for preventing track deformation, which could lead to derailments or infrastructure damage. The model by Farooq et al. (2024) also aids in assessing the risk of track failure during seismic events and in planning mitigation strategies. Implementing varying train speeds as part of an emergency response plan could further reduce the risk of lateral displacement and track failure in seismically active regions.

Moreover, the findings underscore the need for new guidelines and standards for the design and maintenance of ballasted railway tracks in seismically active areas. Regulatory bodies can use these insights to ensure that railway infrastructure is built to withstand seismic forces, ultimately enhancing the safety, reliability, and resilience of railway systems in the face of seismic events.

5 Summary and conclusion

Research on mitigating earthquake impacts on railway tracks has led to the development of various analytical models to enhance track resilience and safety during earthquakes. The development of various computational models marks a significant advancement in understanding and mitigating the seismic risks to railway infrastructure. By providing tools that are both accurate and computationally efficient, past studies contribute to more resilient railway designs and better-informed maintenance strategies. The ability to predict the effects of seismic events on track stability, particularly in terms of lateral deflections and rail buckling, is crucial for ensuring the structural integrity and safety of railway systems. However, the complexities of seismic events and their varying impacts on different types of railway structures indicate a rising need for further research in this field. Extending these models to account for more variables, such as varying soil conditions, different track types, and more complex seismic scenarios, will enhance their applicability and effectiveness. Therefore, advanced research is essential to ensure the ongoing safety and durability of railway networks in earthquake-prone regions.

The findings underscore the importance of designing railway tracks that can withstand both vertical and lateral forces, particularly in earthquake-prone areas. Measures such as maintaining train speeds during seismic events and optimising the design of ballast and capping layers can significantly enhance seismic resilience. Ultimately, this research contributes to safer and more reliable railway systems, guiding the development of infrastructure that can endure the challenges posed by seismic activity.

References

Arias, A. (1970). A measure of earthquake intensity. *Seismic design for nuclear plants*, 438-483.

Esmaeili, M., & Noghabi, H. H. (2013). Investigating Seismic Behavior of Ballasted Railway Track in Earthquake Excitation Using Finite-Element Model in Three-Dimensional Space. *Journal of Transportation Engineering*, *139*(7), 697-708. https://doi.org/10.1061/(asce)te.1943-5436.0000535

Farooq, H., Nimbalkar, S., Punetha, P., & Sheng, D. (2024). Viscoelastic Rheological Modelling of the Lateral Dynamic Response of Ballasted Railway Tracks. *Transportation Infrastructure Geotechnology*. https://doi.org/10.1007/s40515-024-00428-0

Ghogre, A., Phadke, H., & Jaiswal, O. (2022). Seismic Analysis of Railway Track. Seismic Analysis of Railway Track. In Symposium in Earthquake Engineering 589-607. Singapore: Springer Nature Singapore.

Hoseini, S. S., Ghanbari, A., & Davoodi, M. (2019). A New Approach in Equivalent Spring-Dashpot Method for Seismic Soil-Structure Interaction Analysis of Long Bridges Including Non-uniform Excitations. *Transportation Infrastructure Geotechnology*, *6*(3), 165-188. https://doi.org/10.1007/s40515-019-00076-9

Housner, G., & Lili, X. (2002). Report on the great Tangshan earthquake of 1967. *Chapter*, *1*, 1-60.

Jiang, L., Zhou, T., Liu, X., Xiang, P., & Zhang, Y. (2021). An Efficient Model for Train-Track-Bridge-Coupled System under Seismic Excitation. *Shock and Vibration*, *2021(1)*, 9924507.

Kumakura, T., Ishii, H., & Konishi, T. (2010). Seismic assessment of ballasted tracks in large-scale earthquakes. *JR East Technical Review*, *17*.

Nakamura, T., Sekine, E., & Shirae, Y. (2011). Assessment of Aseismic Performance of Ballasted Track with Large-scale Shaking Table Tests. *Quarterly Report of RTRI*, *52*(3), 156-162. https://doi.org/10.2219/rtriqr.52.156

Peng, D., Zu, L., Zhou, W., Liu, R., Jiang, L., Yu, J., & Liu, S. (2024). Study on quantitative indicators of seismic-induced track geometric irregularity in high-speed railway bridge based on train operation performance. Structures,

Sekine, E., & Ishikawa, T. (2005). Deformation characteristics of ballasted track during earthquake. *RTRI Rep. Japan*, *19*(2), 23-28.

Suárez, L. E., & Montejo, L. A. (2005). Generation of artificial earthquakes via the wavelet transform. *International Journal of Solids and Structures*, *42*(21-22), 5905-5919.

Trifunac, M. D., & Brady, A. G. (1975). A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America*, *65*(3), 581-626.

Zhou, T., Jiang, L., Liu, X., Xiang, P., Lai, Z., & Zhang, Y. (2023). An efficient simplified model for high-speed railway simply supported bridge under earthquakes. *Structure and Infrastructure Engineering*, *19*(12), 1811-1825. https://doi.org/10.1080/15732479.2022.2058562