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Seismic Analysis of Double Unit Tunnel Form Building Subjected to Out-of-Plane Lateral Cyclic Loading

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Abstract

Most of the high-rise buildings for commercial and residential purposes in Malaysia are constructed using a tunnel formwork system. This type of building becomes a favor due to the fast construction and cost-effectiveness. However, the research on the behavior of Tunnel Form Building (TFB) under the seismic effect is still insufficient and requires further investigation. Therefore, the safety level of double unit TFB subjected to weak plane (out-of-plane) was investigated in this study. The TFB was designed using a non-seismic provision to represent an existing condominium building constructed in Selangor. Ten past earthquake records categorized as major, moderate, and low magnitudes were utilized. The behavior of the double unit TFB was analyzed using the Ruaumoko 2D program. The ultimate lateral load, displacement, pseudo-spectral acceleration (PSA), pseudo-spectral displacement (PSD), and mode shape of TFB were also analyzed. Based on the findings, most of the selected earthquake records exceeded the lateral capacity of TFB. The building experienced a major damage under 6.9 Richter scale of Imperial Valley, 7.3 Richter scale of San Joaquin Valley, and 7.9 Richter scale of Denali Earthquakes excitations. Therefore, these findings suggested if any similar magnitudes of unpredicted seismic events would occur in the future, significant damages may be experienced by the existing TFB in Malaysia.

Keywords: Safety; Weak; Earthquake; Tunnel Form Building; Significant Damage.

1. Introduction

Even though the Peninsular Malaysia has not been experiencing any major devastating earthquakes up to date, there is no promise that this country will permanently be safe from unpredicted seismic events in the future. The activation of an existing fault line in Peninsular Malaysia in Bukit Tinggi and Kuala Lumpur caused 22 seismic activities to be recorded from 2007 to 2009. This event may develop the potential near-field seismic source in the future [1]. Several moderate seismic activities have been recorded in the Sabah region, starting with the 6.0 Richter scale of the 2015 Ranau Earthquake. Figure 1 indicates that more frequent seismic activities had occurred within the last 20 years before the 2015 Ranau Earthquake [2, 3]. The magnitude of earthquakes gradually increased, and it is predicted by geologists that bigger earthquakes will occur in the future. Thus, a comprehensive research study should be performed as a preparation for unpredictable seismic events in the future.

The 2015 Ranau earthquake was caused by the reactivation of old fault lines due to the movement of three main tectonic plates, namely the Philippine Plate, the Pacific Plate, and the Eurasian Plate. The location of Sabah on the Southeastern Eurasian Plate bordered by the Philippine Plate had caused Sabah to receive a compression force, which was released through the interaction of those three major tectonic plates. Ranau tends to experience another earthquake

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tremor in the future depending on the rapid release of energy where seismic waves move in all directions around those three main plates [4].

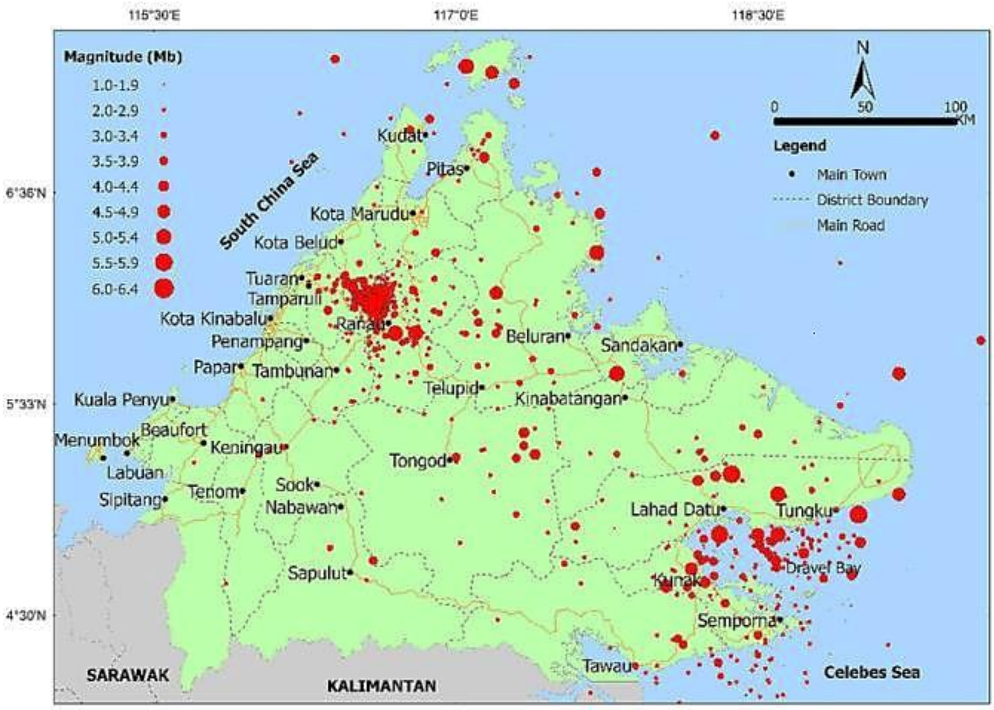


Figure 1. Past Earthquake records within 20 years prior to 2015 Ranau Earthquake [3]

Moreover, 90% of the existing buildings in Malaysia, either the Peninsular Malaysia or the East region, were designed and constructed without seismic load consideration [5]. The existing buildings in Malaysia will suffer from extensive damages under seismic above 5.5 magnitude in the future [6]. This will require an excessive strengthening and rehabilitation process if the predicted earthquake (greater than 5.5 Richter scale) occurs in Malaysia.

In Malaysia, the development of TFB is still active to accommodate the high population, especially in the Klang Valley, Selangor, Johor Bharu, and Penang. However, the safety level of TFB under seismic event is still questionable. Despite the fact, Malaysia experiences only minor to moderate seismic events due to near- and far-field earthquakes. The latest 6.2 magnitude of Sumatra earthquake that occurred on February 25, 2022, was evidence that Malaysia is no longer free from seismic impacts. On February 25, 2022, the occupants of high-rise buildings experienced shaking and sway motion due to this earthquake from West Sumatra, Indonesia.

In Kota Kinabalu, 60.4% of the 250 existing government, residential, and commercial buildings have been identified as unsafe to be occupied [7]. Further investigations have been suggested to determine the behavior of each of the buildings using a simulation analysis subjected to local earthquake events. Thus, the present study was conducted to investigate the behavior of tunnel form building (TFB) using the ten past earthquake records.

Other than that, it is crucial for the Malaysian research teams to conduct unlimited research studies, especially for the existing high-rise buildings in this country. This is because this type of building is occupied by a high number of populations. If the earthquake strikes occur at this type of building, a huge number of injuries, fatalities, losses, and damages will be expected in the future. Currently, the seismic activities have become a significant fear among Malaysians due to the lack of seismic compressive plans and awareness to face the unpredicted devastating seismic events [8]. Hence, the present study was also conducted to investigate the safety level of the existing TFB in Malaysia subjected to major, moderate, and low magnitudes of seismic events.

2. Method

Figure 2 shows the flowchart of the methodology utilized in this study. The steps involved were modelling of TFB based on the existing practice in Malaysia for significant impacts from seismic load, creating the data input, running the Ruaumoko 2D program under the ten past earthquake records, and using Dynaplot to plot the data output obtained from the Ruaumoko 2D program. Finally, the lateral capacity of TFB subjected to Figueroa Mountain, Adelanto Station, Colton – Hospital Complex, Oroville, Mammoth Lakes, Ranau, Pacoima Dam, Imperial Valley, San Joaquin Valley, and Denali Earthquakes was analyzed to determine the safety level of the TFB under those seismic events. The existing TFB constructed in Malaysia was used to investigate its lateral capacity subjected to out-of-plane (weakest axis) lateral cyclic load.

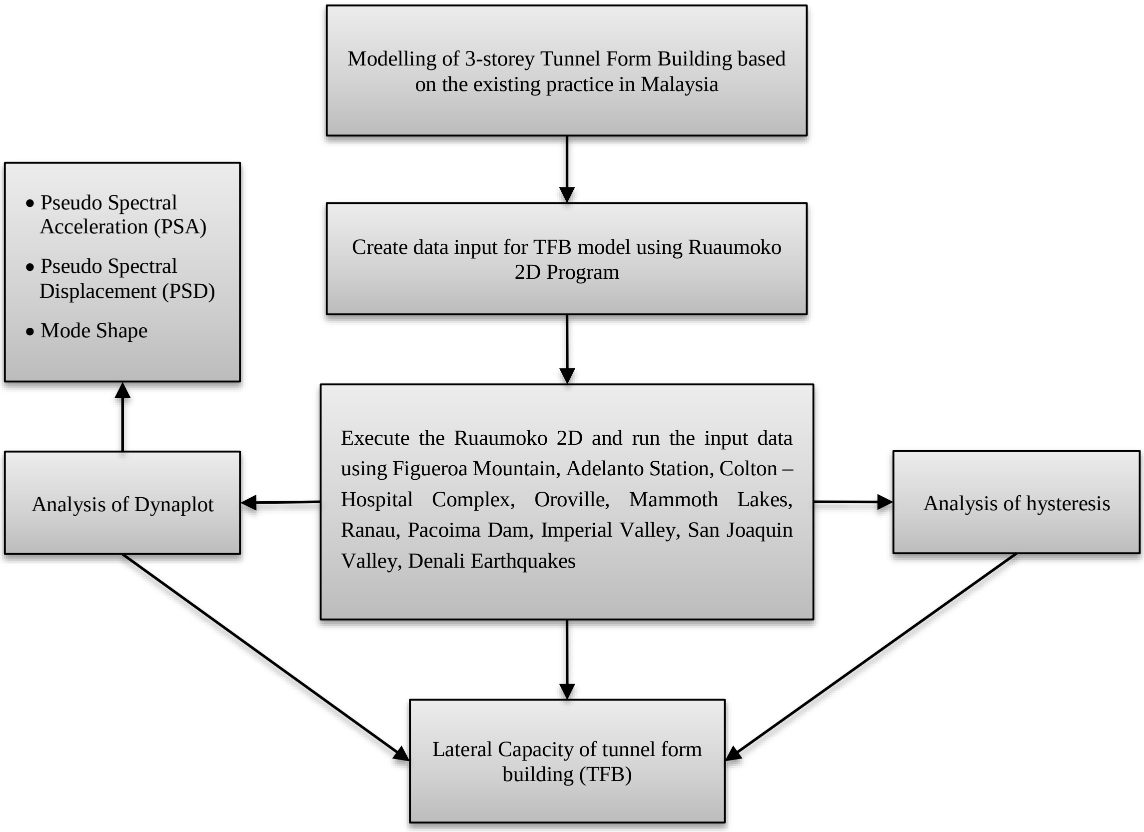


Figure 2. Flowchart of the research methodology

To obtain the exact lateral performance of TFB in Malaysia, the ten past earthquake records were used as shown in Table 1. Multilevel earthquake data all over the world were selected. The maximum lateral load and displacement were plotted and compared with the lateral capacity curve of TFB obtained from the experimental data [9].

Table 1. Past earthquake records used in this analytical study

Location	File name	Magnitude	Depth (kM)	Date	Classification
Figueroa Mountain, HLN	CIFIGHJL.EQP	3	19.2	18 Oct 2003	minor
Adelanto Station, HHZ	CIADOHHZ.EQP	3.9	16	27 Aug 2003	minor
Colton – Hospital Complex FF	BEARAFT.EQP	4.53	10	10 Feb 2001	Light
Oroville Airport	OROVILLE.EQP	4.79	10	2 Aug 1975	Light
Mammoth Lakes	MAMMOTH.EQP	5.7	6	26 May 1980	Moderate
Ranau, Sabah	KDM_HNE.EQF	6	10	5 June 2015	Moderate
Pacoima Dam	PACM942.EQS	6.7	18.2	17 Jan 1994	strong
Imperial Valley	EL40NSC.EQB	6.9	16	18 May 1949	strong
San Joaquin Valley	KERNSBA1952.EQP	7.3	16	21 July 1952	major
Denali, Alaska	DENALI.EQP	7.9	13	3 Nov 2022	major

3. Results and Discussion

3.1. Pseudo Spectral Acceleration

Spectral acceleration is the response measurement due to seismic load. In the present study, the data of pseudo-spectral acceleration (PSA) versus period for 0%, 2%, 5%, 10%, and 20% were plotted using Dynaplot. Figure 2 indicates the comparison of PSA values for all the ten past earthquake records selected in the analysis of seismic behavior of TFB subjected to out-of-plane lateral cyclic load. The acceleration values were found to decrease as the damping coefficient increased. This was because a huge damping energy absorbed by the TFB caused a reduction of movement from the earthquake event, as shown in Figure 3. Each building comprised a different capability absorption of energy released by the seismic event. To avoid devastating damages to reinforce the buildings, the absorption ability should be increased by developing a plastic deformation [10].

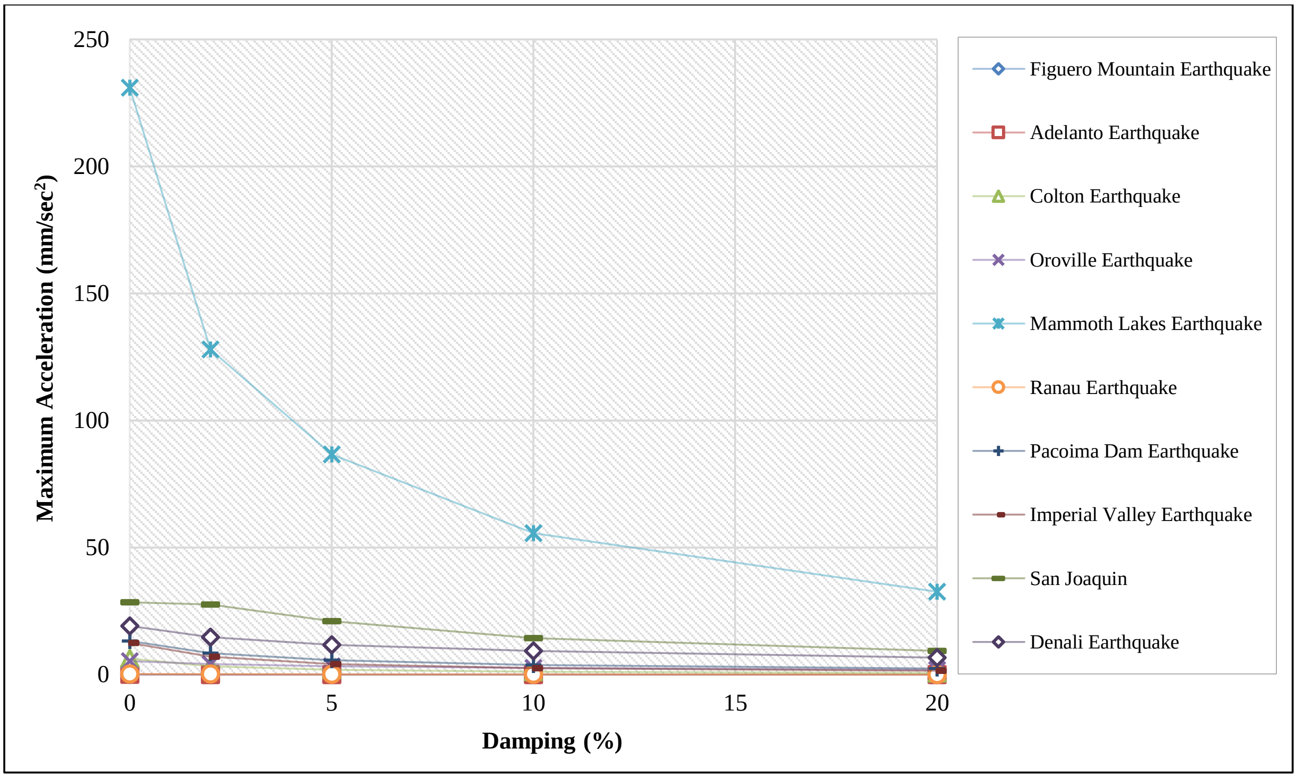


Figure 3. Comparison of maximum pseudo spectral acceleration (PSA) for 10 seismic events in Malaysia obtained at 0%, 2%, 5%, 10% and 20% damping

Based on tabulated data in Table 2, the maximum percentage difference for the spectral acceleration was obtained from the Colton Earthquake with 65.91%. Meanwhile, the lowest percentage difference was recorded from the San Joaquin Valley Earthquake with 22.81%. The damping coefficient was also affected by peak ground acceleration (PGA), epicenter, and depth of the earthquake and not only the magnitude. Each type of seismic event occurring at different spectral periods produced different effects to the reinforced concrete building [11].

Table 2. Percentage difference of damping coefficient for all selected past earthquake records used in this study obtained from pseudo spectral acceleration analysis

Location	Magnitude	Depth (km)	Classification	% Difference between 2% and 5% damping
Figueroa Mountain, HLN	3	19.2	minor	56.94
Adelanto Station, HHZ	3.9	16	minor	63.42
Colton – Hospital Complex FF	4.53	10	Light	65.91
Oroville Airport	4.79	10	Light	41.54
Mammoth Lakes	5.7	6	Moderate	62.36
Ranau, Sabah	6	10	Moderate	57.18
Pacoima Dam	6.7	18.2	strong	57.12
Imperial Valley	6.9	16	strong	63.01
San Joaquin Valley	7.3	16	major	22.81
Denali, Alaska	7.9	13	major	42.74

3.2. Pseudo Spectral Displacement

Figure 4 indicates the comparison of maximum pseudo-spectral displacement (PSD) for the selected seismic events utilized in this study obtained at 0, 2, 5, 10, and 20% damping. The plotted graph indicates the maximum ordinate from each spectrum recorded at different percentages of damping. This behavior reflected to the predominant period of the ground movement [12].

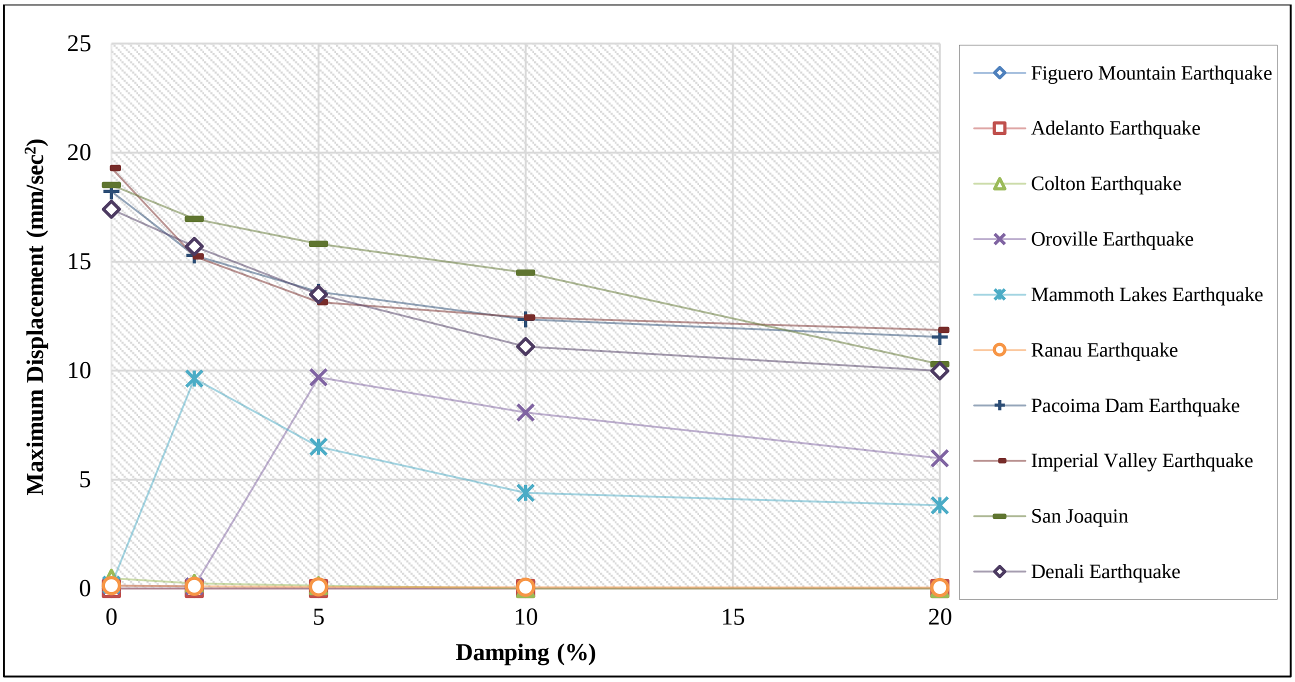


Figure 4. Comparison of maximum pseudo spectral displacement (PSD) for 10 seismic events in Malaysia obtained at 0%, 2%, 5%, 10% and 20% damping

To reduce the damages to the structures, the base isolation system, active dampers, passive dampers, mechanical energy dissipators, and fuse bars can be installed in the structures. By installing this equipment, the percentage of damping coefficient can be increased up to 20% and at the same time can reduce the lateral displacement of the structures. Among the various base isolators available, the most effective is the semi-active system to dissipate the seismic vibration released during the ground motion [13-16].

Table 3 shows the percentage difference of spectral displacement between 5% and 20% damping coefficients for each of the selected past earthquake records. The highest percentage different was obtained from the Colton Earthquake. Meanwhile, the lowest percentage difference was recorded by the Imperial Valley and Pacoima Dam Earthquakes. However, the maximum displacement seemed to decrease as the damping coefficient increased in all the selected earthquake records. It was observed that as the damping rate increased, the peak displacement differed, and the reduction of displacement was recorded at the increment of damping coefficient. The maximum displacement during the seismic event contributed unnecessary vibrations to the TFB thus leading to damages. To reduce the unnecessary vibrations, the stiffness should be increased.

Table 3. Percentage difference of damping coefficient for all selected past earthquake records used in this study obtained from pseudo spectral displacement analysis

Location	Magnitude	Depth (km)	Classification	% Difference between 2% and 5% damping
Figueroa Mountain, HLN	3	19.2	minor	44.58
Adelanto Station, HHZ	3.9	16	minor	65.67
Colton – Hospital Complex FF	4.53	10	Light	95.26
Oroville Airport	4.79	10	Light	38.29
Mammoth Lakes	5.7	6	Moderate	41.32
Ranau, Sabah	6	10	Moderate	45.77
Pacoima Dam	6.7	18.2	strong	15.27
Imperial Valley	6.9	16	strong	9.74
San Joaquin Valley	7.3	16	major	34.89
Denali, Alaska	7.9	13	major	26.07

Therefore, these findings suggested that all the structures needed to be equipped with active or passive viscous dampers to reduce the structural damages and to reduce the lateral displacement. It also can be summarized that the prototype building with bigger lateral displacement exceeding 0.03 m would collapse and would not survive under these earthquakes. Therefore, it is crucial to control the acceleration level for the TFB for damage reduction during the earthquake excitation.

3.3. Performance of Tunnel Form Building under Multi Level of Earthquake

The survivability of double unit TFB subjected to multilevel seismic events namely great, major, strong, moderate, light, and minor earthquake is indicated in Figure 5. From the analysis, San Joaquin Valley, Imperial Valley, Pacoima Dam, Ranau, Mammoth Lake, and Oroville Earthquakes exceeded the lateral capacity curve of TFB. Meanwhile, Denali, Colton, Adelanto Station, and Figuero Mountain Earthquakes lied on the lateral capacity curve.

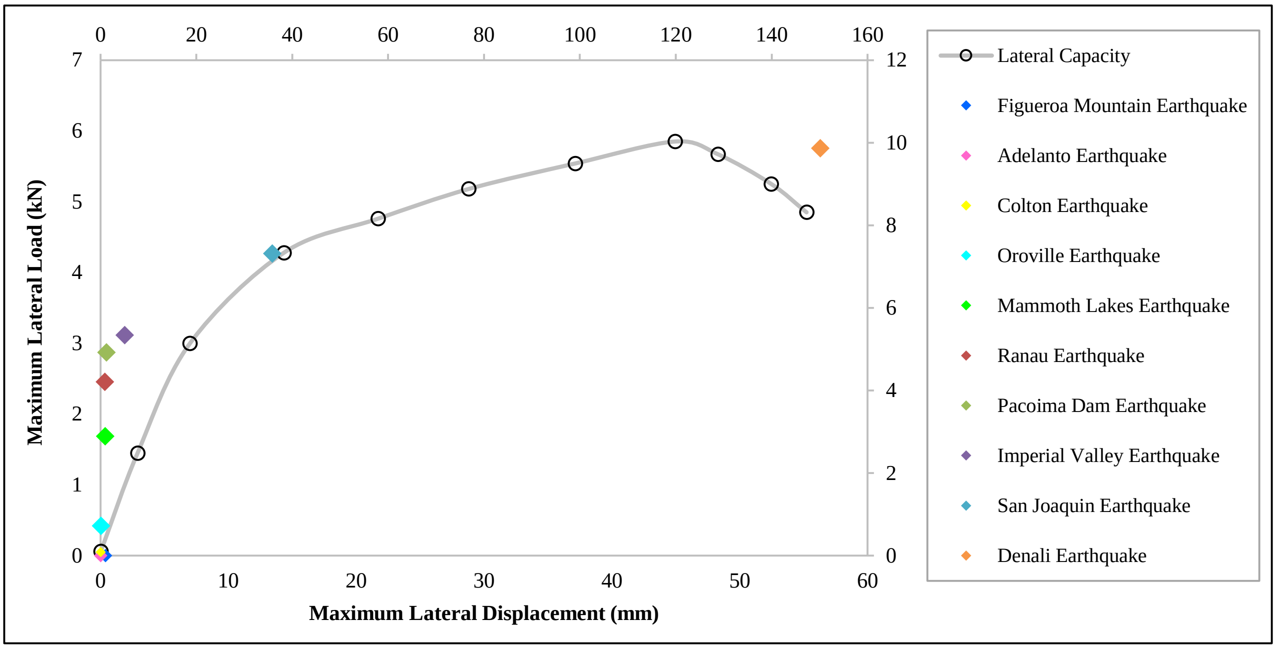
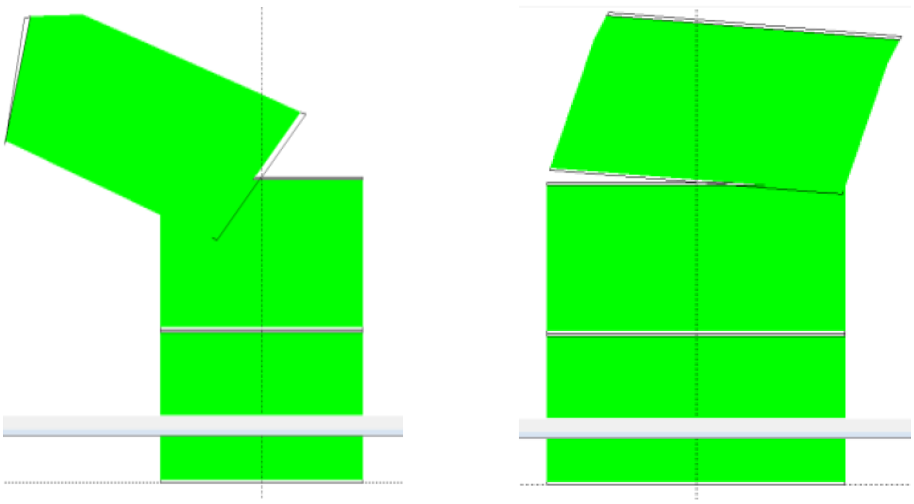


Figure 5. Survivability prediction of Tunnel Form building subjected to out-of-plane lateral cyclic load

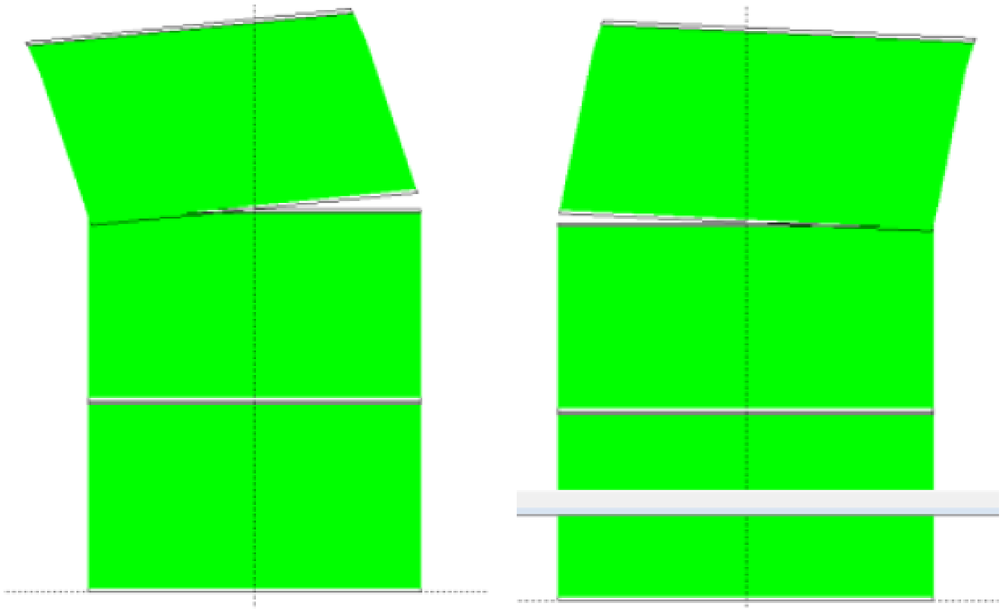
Based on this analysis, if the similar characteristics of earthquake activity occurred in the future, most all the existing TFB constructed using BS8110 code of practice in this country will suffer significant damages. Frequent seismic events from neighbouring countries have contributed to the significant impacts on the historical ground movement data and development of fault line in Malaysia [14, 17-24]. Hence, before a devastating seismic event hits Malaysia, a suitable plan for managing the seismic risks should be executed.

3.4. Deformation Behaviour of Tunnel Form Building

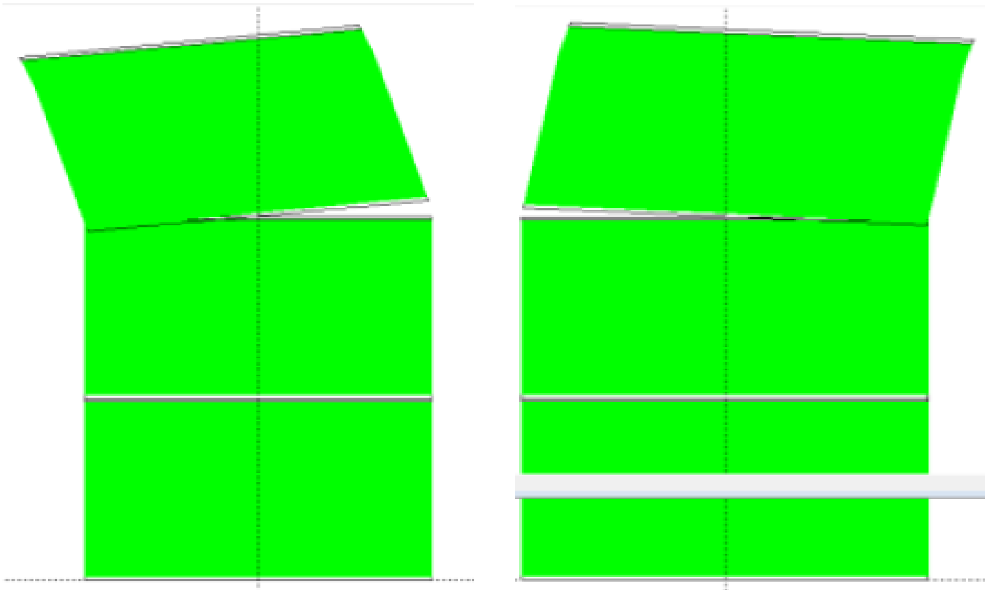
The deformation of TFB was investigated using Dynaplot Program in Ruaumoko 2D program as shown in Figure 6. It was measured from the yielding point of TFB when a seismic excitation was applied. Based on the mode shape, the critical damage was recorded at the upper level of TFB after experiencing 7.9 Richter scale of 2002 Denali Earthquake event. Mostly, the TFB suffered a failure at the node 4 recorded at the top floor of the TFB. Mode shape is the combination of complex motions obtained from the TFB during seismic events. It depends on the building height, axial stiffness, flexural stiffness, and rotational flexibility. The application of bracing system and additional shear wall may reduce the sway motion (mode shape) rate of the TFB.



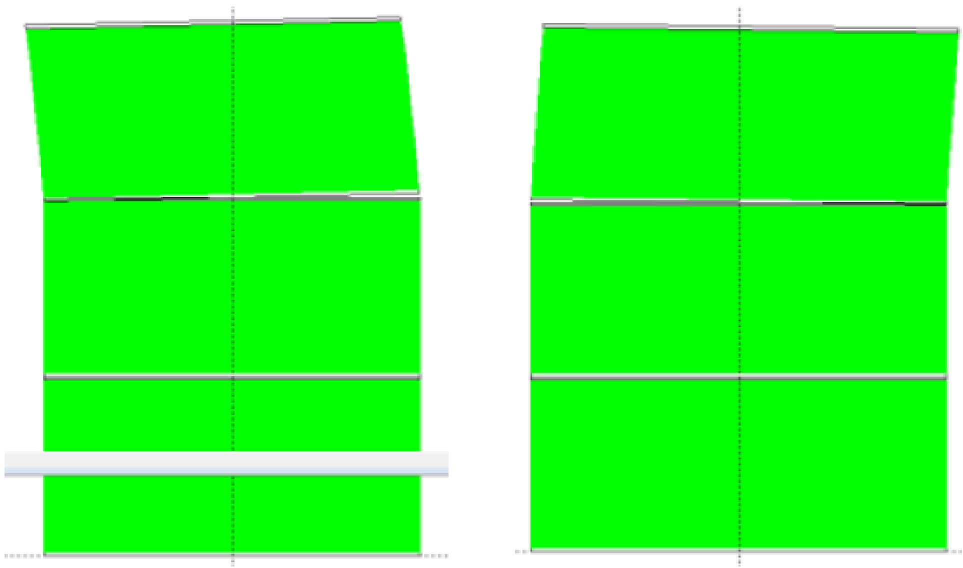
(a) Denali Earthquake



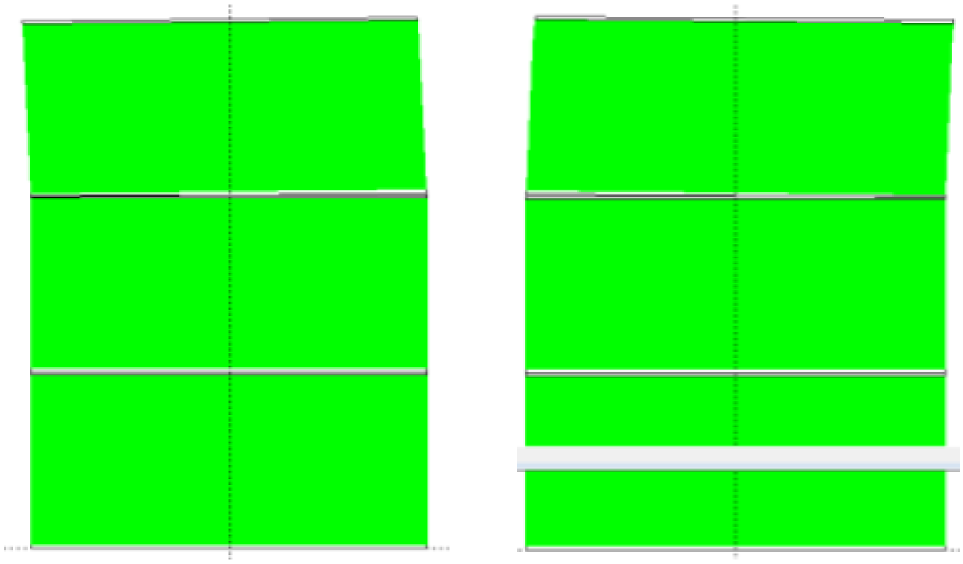
(b) Imperial Earthquake



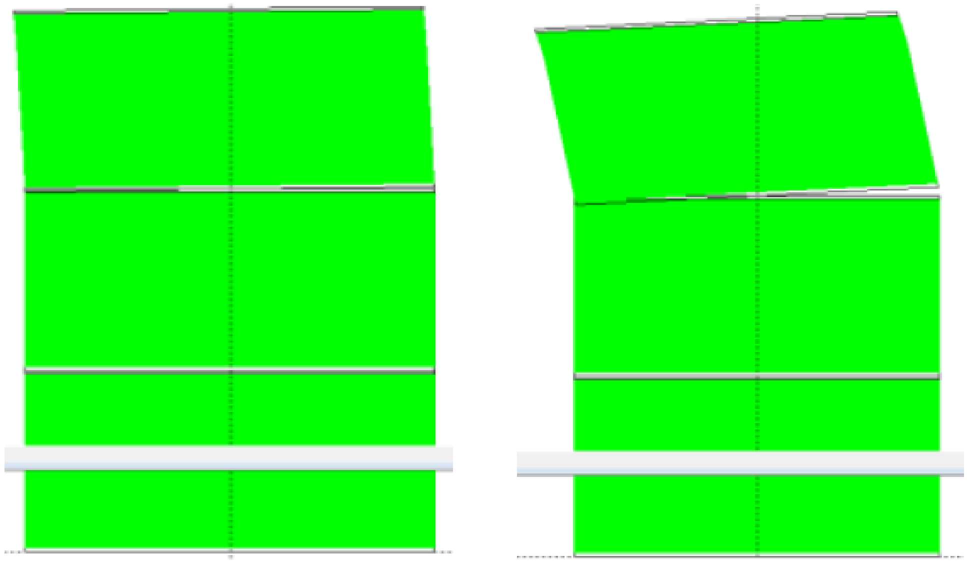
(c) San Joaquin Earthquake



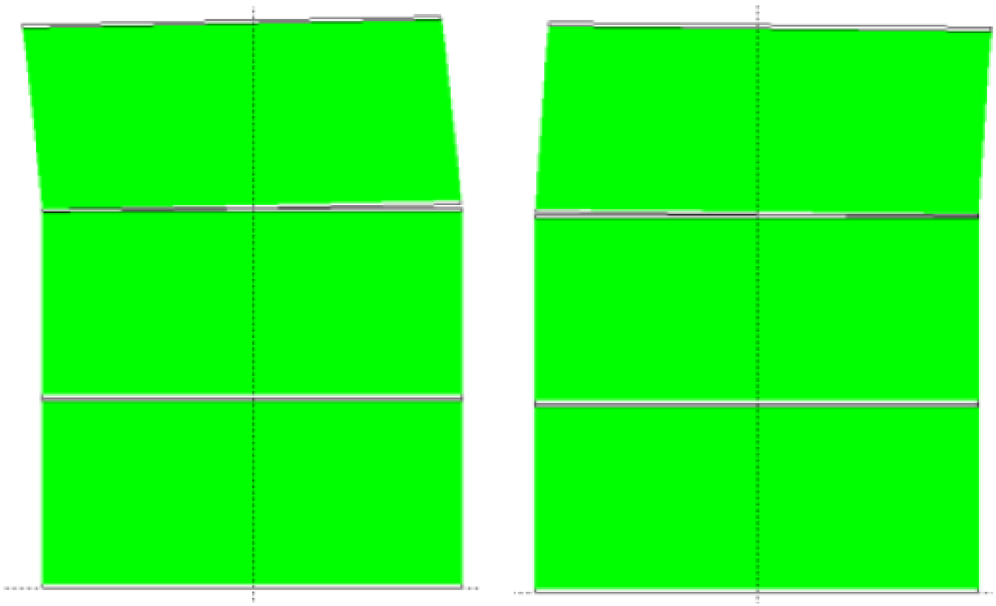
(d) Pacoima Dam Earthquake



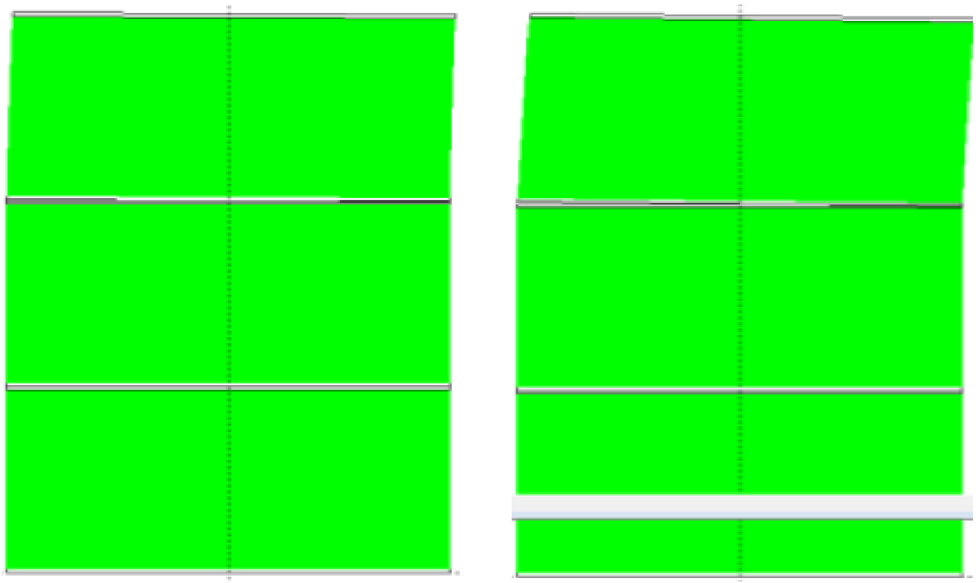
(e) Ranau Earthquake



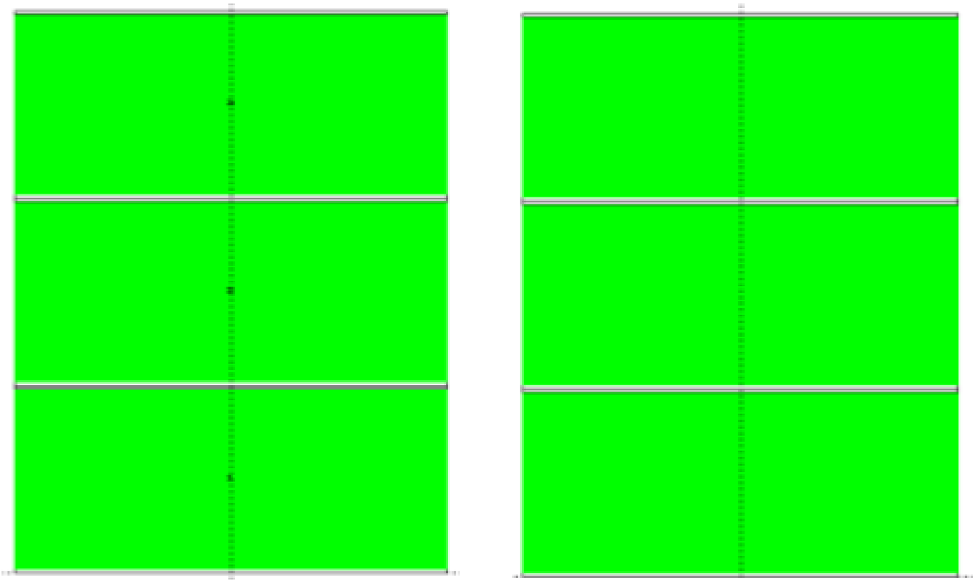
(f) Mammoth Lakes Earthquake



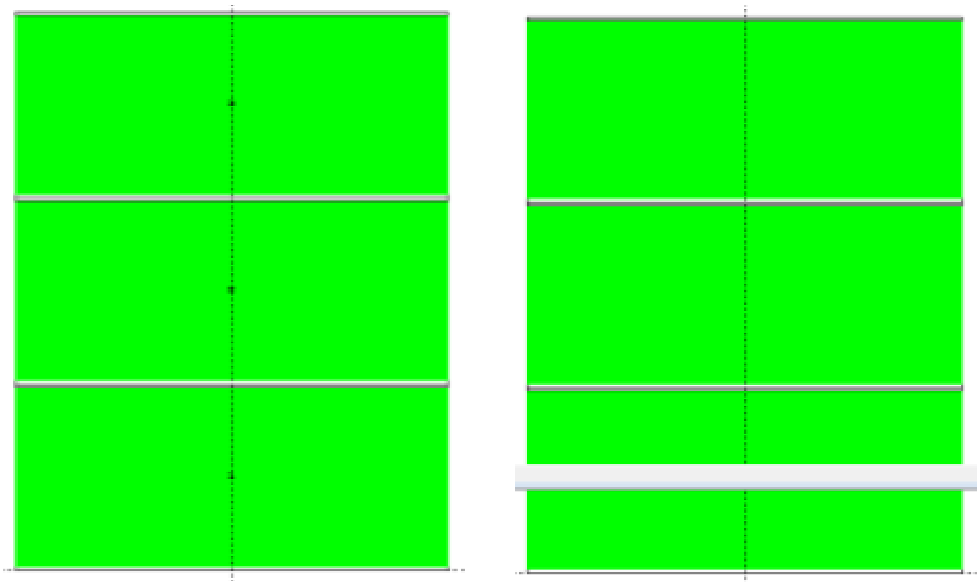
(g) Oroville Earthquake



(h) Colton Earthquake



(i) Adelanto Earthquake



(j) Figueroa Mountain Earthquake

Figure 6. Mode shape for (a) Denali, (b) Imperial, (c) San Joaquin, (d) Pacoima Dam, (e) Ranau, (f) Mammoth Lakes, (g) Oroville, (h) Colton, (i) Adelanto and (j) Figueroa Mountain Earthquakes

A similar deformation pattern was observed for the Imperial Valley, San Joaquin Valley, Pacoima Dam, Mammoth Lakes, Oroville, and Colton earthquakes. The top floor level indicated some deformation due to the ground movement. Those models were exposed to several excitations in 20 seconds. The failure was recorded at 9.87 kN of maximum lateral load with 150 mm maximum displacement for Denali Earthquake event. Meanwhile, for the Imperial Valley earthquake, the mode shape was recorded at 5.34 kN of maximum lateral load with 5.03 mm of maximum displacement point. Under the Mammoth Lakes Earthquake, the recorded maximum lateral load and displacement were 2.89 kN and 0.953 mm, respectively. Based on the mode shape analysis, no major deformation was recorded for the TFB when subjected to the Adelanto Station and Figuero Mountain earthquakes.

4. Conclusion

The out-of-plane lateral cyclic load acts directly on the shear wall, or known as the weak axis. Thus, it is crucial to investigate the capacity of TFB designed using a non-code of practice to represent the existing high-rise buildings in Malaysia that use the Industrialized Building System (IBS) method, which is widely used in this country.

Based on the analyzed data obtained from this study, the TFB was predicted to experience major damages under a 6.9 Richter scale for the Imperial Valley, a 7.3 Richter scale for the San Joaquin Valley, and a 7.9 Richter scale for the Denali Earthquakes excitations. The TFB exposed to the 6.7 Richter scale of the Pacoima Earthquake, the 6 Richter scale of Ranau, the 5.7 Richter scale of Mammoth Lake, the 4.79 Richter scale of Oroville, the 4.53 Richter scale of Colton, the 3.9 Richter scale of Adelanto Station, and the 3 Richter scale of the Figuero Earthquakes experienced severe to minor damages.

Under a weak axis excitation, it is recommended for all the existing high-rise buildings in Malaysia, which were designed and constructed using BS8110 (non-seismic code), be strengthened to face unpredicted earthquake events in the future. Those structures might not be able to sustain under devastating earthquake excitations. At least, the strengthening approach can provide adequate time for the occupants to save their lives from the collapse of the TFB during any seismic waves.

5. Declarations

5.1. Author Contributions

Conceptualization, S.A. and A.A.; methodology, S.A. and A.A.; software, S.A. and A.A.; analysis, S.A. and A.A.; writing—original draft preparation, S.A.; writing—review and editing, S.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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