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Preliminary Study of Different Joint Stiffness Ratio on Tunnel Internal Forces Subjected to Varying Seismic Wave Directions

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ABSTRACT

Earthquakes are natural disasters caused by Earth's crust movement, producing seismic waves in various directions. Even though underground structures tend to be more resistant to seismic waves than above-ground structures, these waves can still do a handful of damage to the structures, so maintenance must be done occasionally. In some cases, the waves can even cause failures due to a lack of attention to seismic effects. Research regarding seismic waves is developing, but topics revolving around its directions have yet to emerge. Hence, internal forces such as bending moment and normal force that occurred due to seismic waves from various directions on segmental tunnel linings are observed by using FLAC3D. Furthermore, the study also observed the results of using multiple joint stiffness ratios from 0.5, 1, and 1.5. Results show that using a more flexible joint is better suited for tunnels under dynamic load since the bending moment ratio from seismic impact increase as higher joint stiffness ratio was used. It is also concluded that the initial direction of seismic waves can impact tunnels differently. By comparing all the results, it can be seen that 2-directional waves cause the most damage to the tunnel structure.

1. INTRODUCTION

Earthquakes are natural disasters caused by Earth's crust movement, producing seismic waves in various directions. These waves propagate through the soil body and eventually reach the surface too. On the surface, the wave transforms into surface waves, and those waves are the ones that bring the most damage to surface structures. However, underground structures exist below the surface. Underground structures are known to be more resistant to seismic waves due to several factors. Despite this, seismic waves

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can still do a handful of damage to underground structures, which leads to occasional maintenance. In some cases, the waves can even cause failures due to a lack of attention to seismic effects.

Nobody can specifically estimate where the earthquake is going to be until the occurrence. The uncertainties that exist inside the soil body make it even more complicated to plan a specific seismic-resistant design for a tunnel. In this research, numerical analysis was done using a commercial program, FLAC3D, with the quasi-static method. This research aims to analyze internal forces such as bending moment and normal force that occurred due to various seismic wave directions on segmental tunnel linings. Furthermore, multiple joint stiffness ratios from 0.5, 1, and 1.5 were observed in those cases.

Limitations and assumptions were used while doing the research. The limitations faced were technical difficulties such as hardware competency, validation data, and time limitations. Assumptions were made to lessen the time consumed on each calculation and focus more on the main objectives.

2. RELATED LITERATURE

2.1 Quasi-static

Quasi-static is a method that simplifies theoretical and numerical methods in dynamic analysis and is commonly used in engineering field for designing structures (Ambrosio, 2001). The main concept of quasi-static method is applying a time-independent deformation profile on a model statically, which also led to assumption that there's no inertia force working. Seismic wave is considered as dynamic loading, hence it can be simulated using this method.

2.2. Joint Stiffness

Joint is one of the main components of a segmented tunnel which functions as a connector for segments. Joint can be made out of various materials which can have different stiffness value. There are few types of joint stiffness including normal stiffness, shear stiffness, rotational stiffness, axial stiffness, and radial stiffness. In this research, rotational stiffness is the research main subject while normal stiffness and shear stiffness are still considered. In numerical analysis, rotational joint stiffness can be simulated as springs. This joint stiffness is usually applied together with translational springs on nodes, so each node can have a total of 6 degree-of-freedoms (DOFs).

3. MODEL AND VALIDATION

As mentioned before, analysis was done using FLAC3D with a quasi-static method. The main object of the research is to observe internal forces occur on the segmented tunnel due to various joint stiffness ratio. In this research, the model was made in 3D with a global dimension of 120x100x40m as can be seen in Fig. 1. The soil material model is Mohr-Coulomb, while the tunnel material model is isotropic elastic. The model was created using parameters and assumptions applied in similar research of Do et al. (2015). Their model was used to validate this research model before doing analysis. Validation was done by comparing the internal forces of bending moment and normal force results.

Few parameter modifications were made to fit in the model and mind that every unit used is in The International System of Units (SI units). Fitted parameters are shown in Table 1. Note that the former research used a 2D model, while 3D model was implemented in this research so additional assumptions were applied.

Table 1 Fitted parameters

Property	Parameter	Value
Soil	Young's modulus, E	7.00E+07
	Poisson's ratio, v	0.3
	Density, γ	1700
	Lateral pressure	0.5
	Cohesion, c	5000
Tunnel	Young's modulus, E	3.50E+10
	Poisson's ratio, v	0.2
	Density, γ	2400
	Moment inertia	0.00225

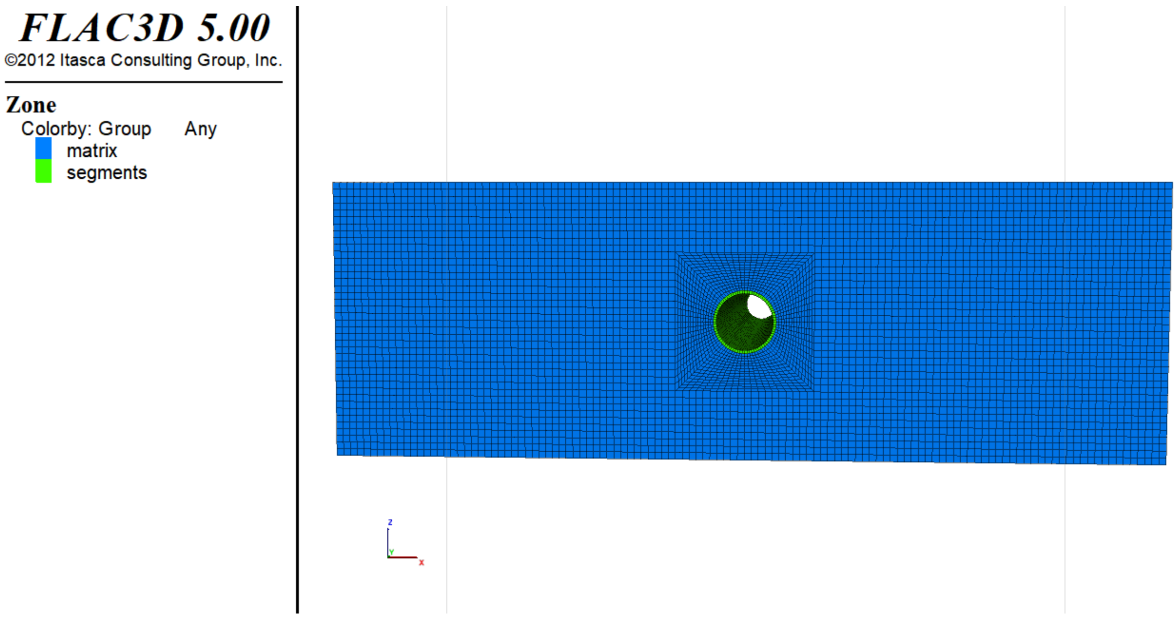

Fig. 1 Research initial model

Table 2 Result comparison

Model	Max. Bending Moment (kNm)	Max. Normal Force (kN)	Significance Level	
			Bending Moment (%)	Normal Force (%)
Do et al., 2015	156.00	1036.80	3.17	1.11
FLAC3D	160.94	1025.30		

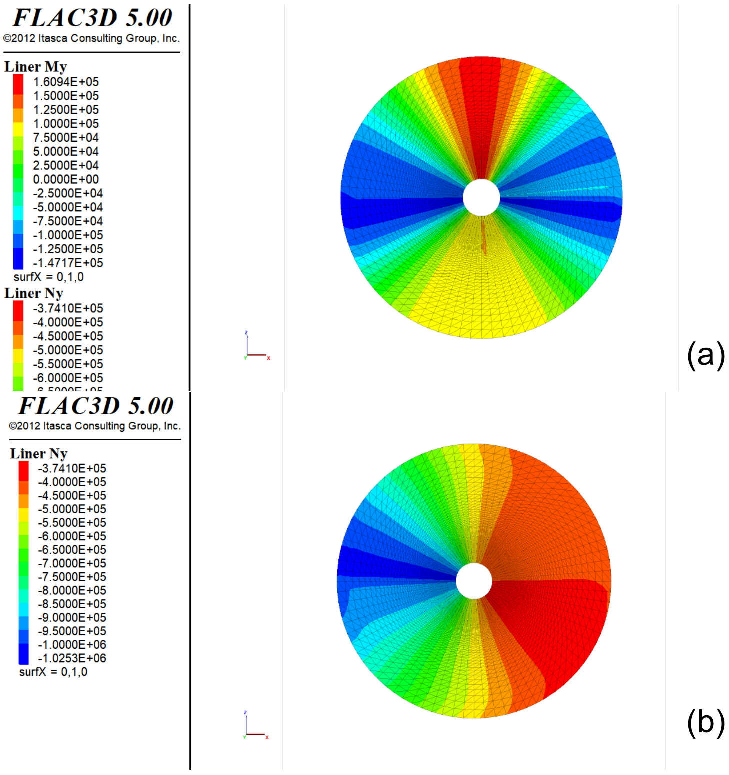

Fig. 2 Internal forces occurred on fitted model; (a) bending moment (b) normal force

Based on the validation results on Table 2, it was proven that the confidence level between this research model and similar research was more than 95% since the significance level is less than 5% which means the results are considered accurate to the reference. With that being said, the model can be used for further analysis.

4. ANALYSIS AND RESULT

After the model was validated, the research could be done. In this research, rotational joint stiffness ratios of 0.5, 1, and 1.5 were observed on various seismic wave propagations. Three seismic conditions are observed for each joint stiffness ratio: horizontal loading, vertical loading, and combined loading. The results of the analysis on all cases can be seen in Table 3 and the plotted results are shown in Fig. 3. The internal force ratio is the ratio of maximum and minimum value of each internal force.

Table 3 Analysis results

Rotational Joint Stiffness Ratio	**Loading Type**	**Max. Bending Moment (Nm)**	**Max. Normal Force (N)**	**Max./Min. Ratio**	
				Bending Moment	**Normal Force**
0.5	Horizontal Load	160940	1025300	1.00	1.01
	Vertical Load	405610	3736100	1.00	1.00
	Combined Load	468820	3756700	1.00	1.00

1.0	Horizontal Load	119690	1031100	1.34	1.00
	Vertical Load	286760	3690200	1.41	1.01
	Combined Load	357010	3737400	1.31	1.01
1.5	Horizontal Load	95141	1034300	1.69	1.00
	Vertical Load	217690	3675600	1.86	1.02
	Combined Load	282760	3717300	1.66	1.01

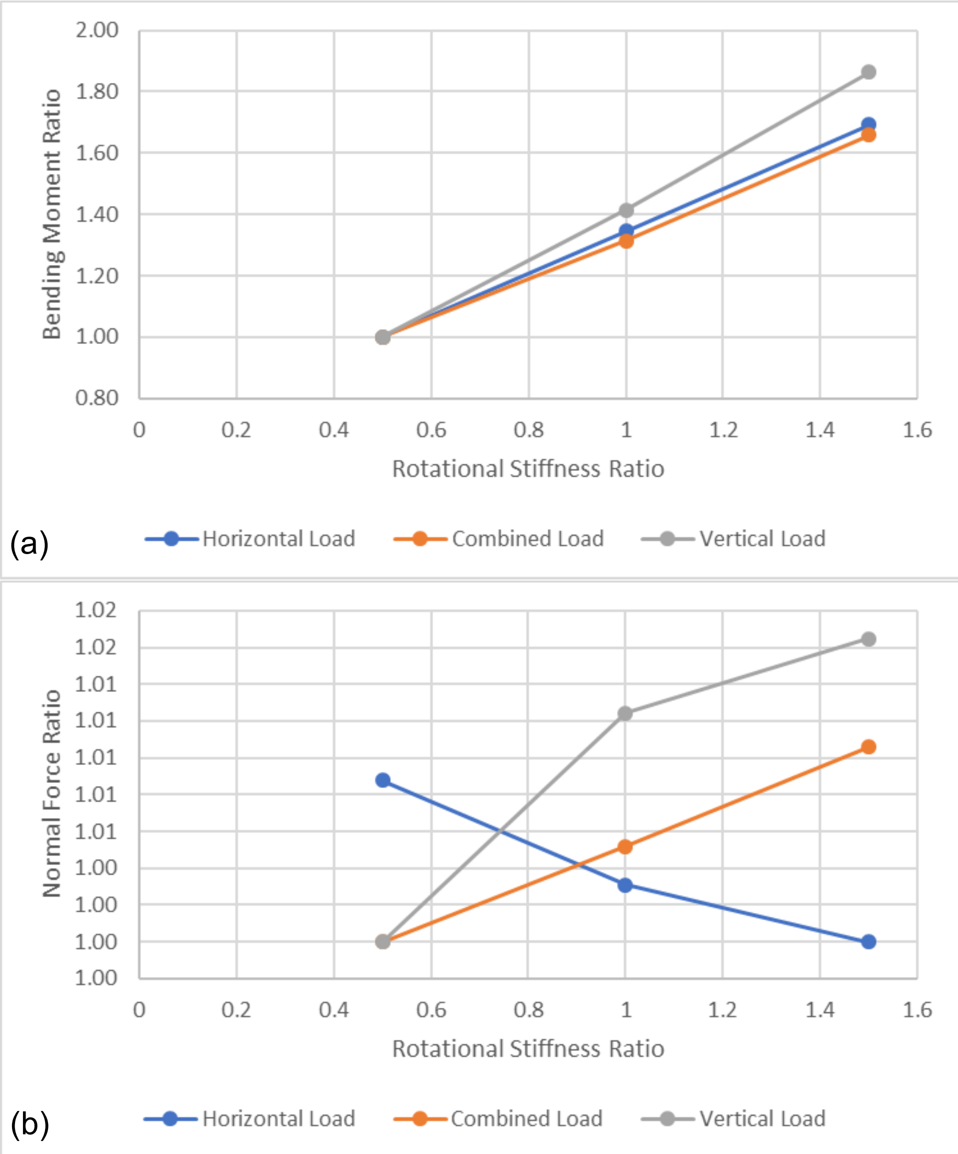

Fig. 3 Internal force ratio on various rotational stiffness; (a) bending moment (b) normal force

As seen from Fig. 3a, the bending moment ratio increases as the rotational stiffness gets bigger on every case. On the other side, the normal force ratio seems to decrease when dealing with horizontal seismic load, but tends to increase when dealing other loads as seen in Fig. 3b. The result trend is similar as the mentioned research reference.

5. CONCLUSION

Based on research done, it can be concluded that bending moment ratio increases when a bigger rotational stiffness ratio is used even though in normal force it depends on the applied load type. Hence, it is proven that a more flexible joint is more desirable to use for segmental tunnels since it lowers the bending moment ratio from the seismic impact. A joint can be considered flexible if its ratio is below 1, but note that its ideal flexibility may not be excessively flexible or rigid. Aside from that, it is shown that the initial direction of seismic occurrence can impact tunnels differently. Horizontal oriented seismic load typically produces lower bending moment and normal force than vertical oriented seismic load, approximately more than 2x. The combination of the two certainly would have more impact on both forces, as proven in the previous section.

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REFERENCES

Ambrosio, J.A.C. (2001), “Quasi-Static Behavior. In: Ambrosio, J.A.C. (eds) Crashworthiness”, International Centre for Mechanical Sciences, vol 423. Springer, Vienna. https://doi.org/10.1007/978-3-7091-2572-4_2

Do, N. A., Dias, D., Oreste, P., & Djeran-Maigre, I. (2013), “2D numerical investigation of segmental tunnel lining behavior”, Tunnelling and Underground Space Technology, **37**, 115-127.

Do, N. A., Dias, D., Oreste, P., & Djeran-Maigre, I. (2015), “2D numerical investigation of segmental tunnel lining under seismic loading”, Soil Dynamics and Earthquake Engineering, **72**, 66-76.

Itasca Consulting Group. (2012), “FLAC Fast Lagrangian Analysis of Continua, Version 5.0. User’s Manual”.

Lee, K. M., Hou, X. Y., Ge, X. W., & Tang, Y. (2001), “An analytical solution for a jointed shield-driven tunnel lining”, International journal for numerical and analytical methods in Geomechanics, **25**(4), 365-390.