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Seismic Safety Evaluation of Mechanically Stabilized Earth (MSE) Wall for Highway Construction

Muhammad Adi Ibrahim[1,*], **Yusep Muslih Purwana**[2]
[1] PT. Wijaya Karya (Persero) Tbk, Jakarta, Indonesia, 13440; muhammadadiibrahim@gmail.com
[2] Department of Civil Engineering, Sebelas Maret University, Surakarta, Indonesia, 57126; ymuslih@staff.uns.ac.id
***Correspondence**: muhammadadiibrahim@gmail.com

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ABSTRACT The usage of Mechanically Stabilized Earth (MSE) Walls has grown in popularity over the last few decades and has been widely used in many countries for highway construction, including Indonesia. As a country with a high risk against seismic hazards, a considerable stability analysis against earthquakes for construction must be conducted. This paper is directed to evaluate the static and seismic stability of MSE wall by adopting design criteria from SNI 8460:2017 using the pseudo-static approach with limit equilibrium method (LEM) and dynamic response approach with finite element method (FEM). Pseudo-static approach models an earthquake as a seismic coefficient, a one-way constant load, while dynamic response approach models an earthquake as ground motion, a fluctuating load which varies with time. In this study, stability analysis is performed by considering the three likeliest failure mechanisms in MSE Walls, i.e., base sliding, tensile overstress, and slope failure. The earthquake load is modelled based on 1000-year return period earthquake. Based on the analysis results, the most likely failure mechanism that may occur in the MSE wall is tensile overstress, while the least likely failure is base sliding. The analysis result also shows that the finite element method obtained higher safety factors compared to limit equilibrium for tensile overstress. However, for the remaining two failure mechanisms, the finite element method resulted in lower safety factors than limit equilibrium. Modelling seismic load as dynamic load have higher impacts on structure stability compared to pseudo-static. Although there are differences in the values of the safety factor obtained, the minimum safety factor required still complies for both methods.

KEYWORDS Mechanically Stabilized Earth Wall; Stability Analysis; Limit Equilibrium Method; Finite Element Method

1 INTRODUCTION

The continuous population growth has led to an increase in the number of goods required by the people, thereby leading to the need for appropriate distribution routes. One of the routes which is observed to have significant increment is in the use of land transportation. Construction of highway is expected to improve the distribution of goods. However, many obstacles are often encountered in highway construction, one of them being the limited construction area. Building retaining structure is one of the possible options in order to optimize the available area.

MSE (Mechanically Stabilized Earth) Wall is considered one of the excellent solutions for this problem. Due to its fast and relatively low-construction cost, this type of retaining wall has been widely used in many countries for highway construction, one of them being Indonesia. As a country with a high risk of seismic hazard, stability analysis against seismic load must be considered for construction of MSE wall. Previously, Mante et al. (2021) and Joseph et al. (2021) have conducted seismic analyses of this type of wall, focusing on its dynamic response against earthquakes using a variety of ground motion data. This paper focuses on MSE Wall seismic stability used for Highway structure by using pseudo-static and dynamic response analysis. Both analyses are performed using Geostudio Software, utilizing the SLOPE/W feature for limit equilibrium method pseudo-static analysis and the integrated SIGMA/W, QUAKE/W and SLOPE/W for finite element method dynamic response analysis. The stability performance requirement is adopted from SNI 8640:2017.

2 METHODOLOGY

The commonly used methods for seismic stability analysis are pseudo-static and dynamic response. The main difference between this method is from seismic load modelling. The pseudo-static analysis is a limit equilibrium method that includes additional seismic inertia forces in a conventional static slope stability analysis. Seismic coefficients are used as seismic load in this analysis, normally taken at 50% of peak ground accelerations (PGA). The illustration of seismic coefficient as a seismic load when calculating slope stability in pseudo-static analysis is displayed in Figure 1.

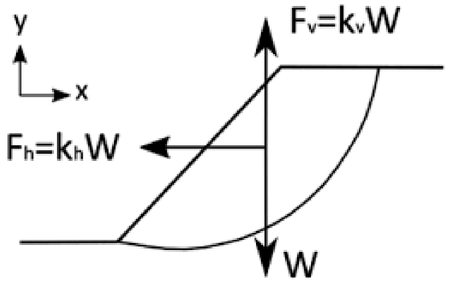


Figure 1. Pseudo-static analysis (Melo and Sharma, 2004)

Dynamic response method uses ground motion data for modelling seismic load. Ground motions (also referred to as earthquake records, accelerograms, or time histories) provide acceleration time histories of earthquake shaking, which are the fundamental observations used in seismology. One of the methods for obtaining ground motion data for seismic analysis is by using the response spectral matching method. This method is a process in which an original recorded earthquake response is modified such that its response spectrum matches the response spectrum on the observed site. The design response spectrum considers the site parameters across a range of periods and possibly multiple damping values to produce a scaled ground motion which is representative to the seismic load on the observed site. The illustration of scaling the original response spectrum with the designed target spectrum using the response spectral matching method is displayed in Figure 2.

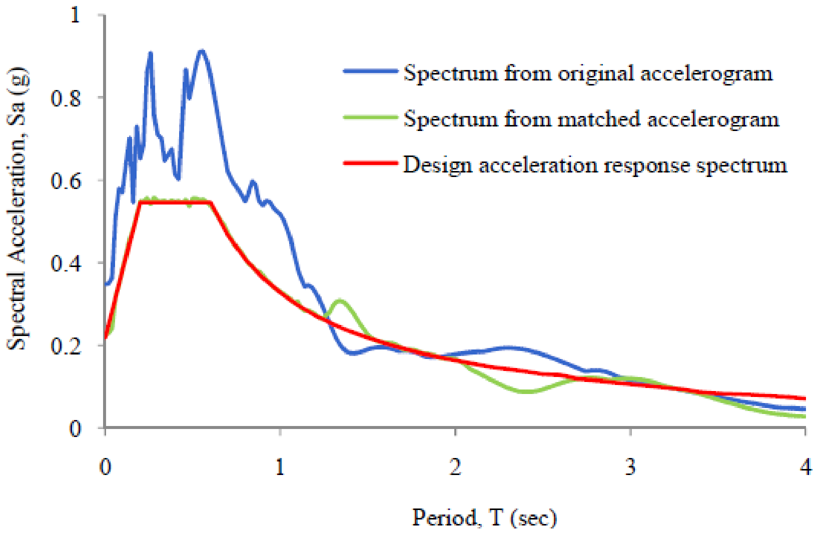


Figure 2. Spectral Matching Method (Sajed et al., 2020)

The elastic ground (equivalent linear) model is used to model the behaviour of soil under the action of dynamic loading. The required soil parameters to utilize this model include shear modulus (G), modulus reduction (G/G_{max}), and damping variations with cyclic strains (D). For zonal embankment structure, the dynamic parameter of each material must be determined for more accurate results. Some equations to determine the dynamic properties of soil are developed based on parameter correlation. Maximum shear modulus (G_{max}) values for some soil classifications can be calculated using the pore value function based on the correlation between G_{max} and confining pressure (σ'_m) as displayed in equation (1).

$$G_{max} = A \times F(e) \times (\sigma'_m)^n \quad (1)$$

The summary of pore value function used in this analysis for each material are shown in Table 1**.**

Table 1. Pore value function for each material

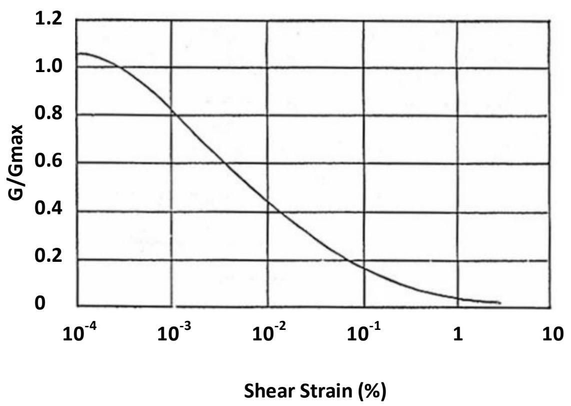
Researcher	A	F (e)	n	Material
Hardin - Black (1968)	3270	$(2.97 - e)^2 / (1+e)$	0.6	Fine-grained soil
Hardin – Richart (1963)	7000	$(2.17 - e)^2 / (1+e)$	0.5	Coarse-grained soil

Over the years, several researchers have presented a variation of shear modulus (G/G_{max}) and damping ratio (D) value based on its correlation with shear strain for various soil types. Rollins (1998) proposed equations (2) and (3) to determine the G/G_{max} dan D value for coarse-grained soil.

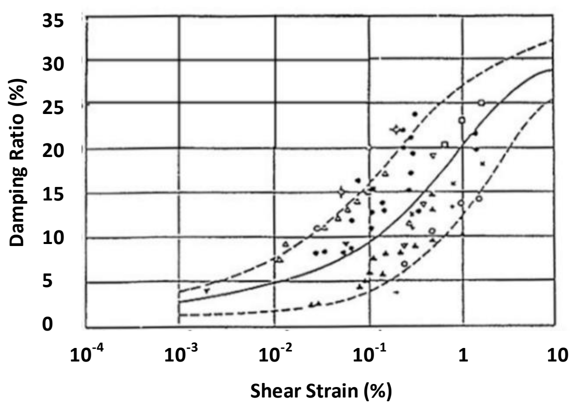
$$G/G_{max} = 1 / (1{,}2 + 16 \ (1+10^{-20\gamma})) \quad (2)$$

$$D = 0{,}8 + 18 \ (1+ 0{,}15 \ \gamma^{-0{,}9})^{-0{,}75} \quad (3)$$

Seed and Idriss (1970) has developed modulus and damping curves for fine-grained soil, which is displayed in Figure 3.



(a)



(b)

Figure 3. (a) Shear modulus and (b) damping ratio variation with shear strain for fine grained materials (Seed and Idriss, 1970)

MSE wall design requires safety conditions for several modes of failure. In this paper, the wall safety is analyzed based on its stability against external (base sliding), internal (Tensile overstress), and global/slope failure. Each illustration potential failure mechanism is displayed in Figure 4.

The design criteria used for this analysis are implemented from SNI 8640:2017. The code adopts seismic design criteria from several references, including FHWA-NJ-2005-002. According to SNI 8640:2017, the seismic load applied for highway retaining wall stability analysis is based on a 1000-year return period, which will be adopted to model the seismic load into seismic coefficient and scaled ground motion in this analysis. The minimum safety requirement for retaining wall design is displayed in Table 2.

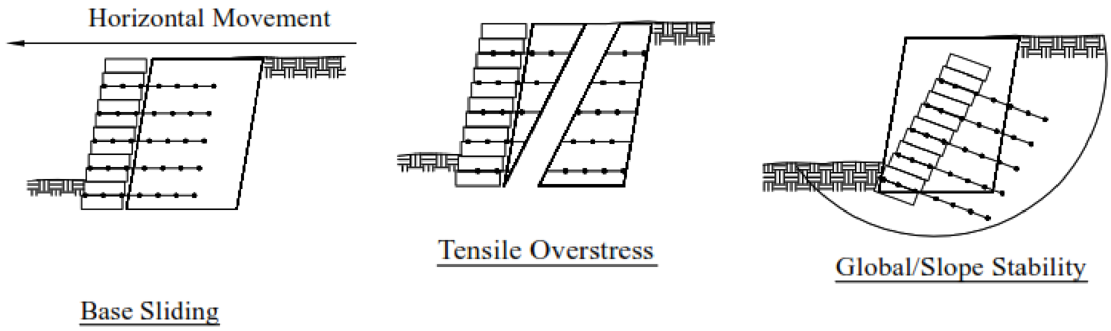


Figure 4. Potential failure mechanism for reinforced-soil wall (NCMA-2010)

Table 2. Minimum safety factor requirement for MSE wall based on SNI 8640:2017

Potential Failure Mechanism	Static	Seismic
Base Sliding (External Stability)	1.5	1.1
Tensile Overstress (Internal Stability)	1.5	1.1
Global / Slope Stability	1.3	1.1

3 INPUT DATA

3.1 MSE Wall

MSE wall as earth retaining structure in this analysis is made up of three main components: granular soil as the earthfill, geofabric material as reinforcement, and concrete blocks for the facing element. The long section of MSE wall used in this analysis is displayed in Figure 5, while the cross-section model is displayed in Figure 6.

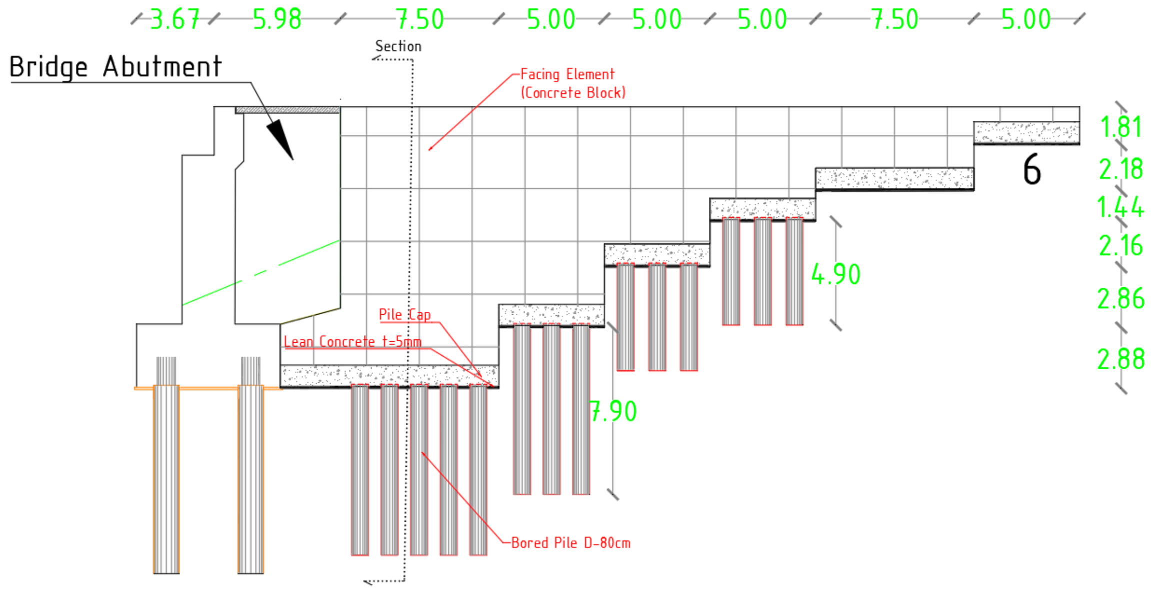


Figure 5. MSE wall long section

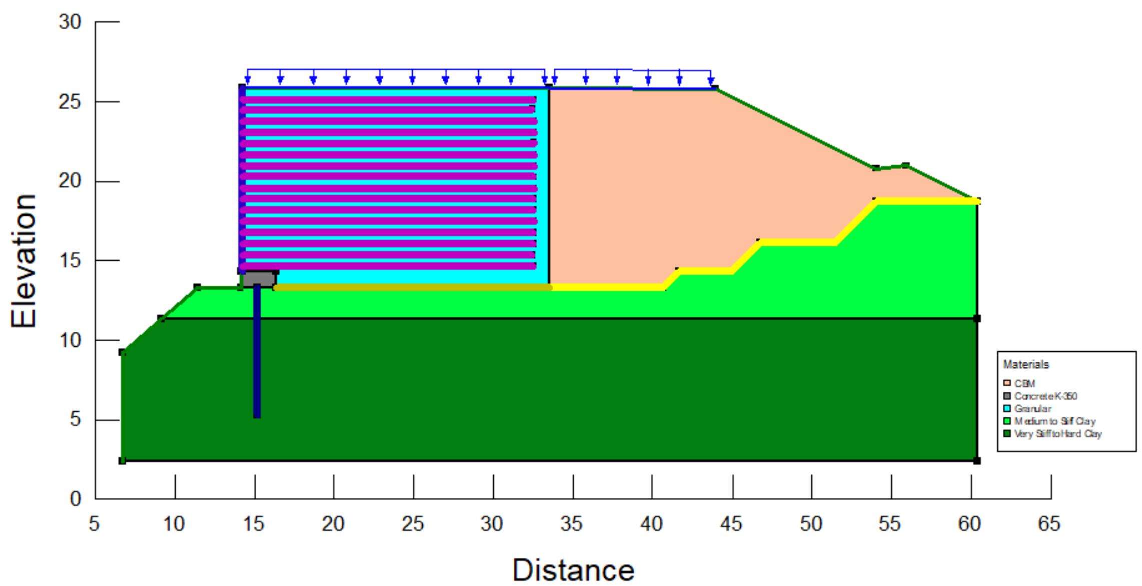


Figure 6. MSE wall stability analysis model

The facing element in this analysis is designed using precast concrete blocks. The material properties of facing element are displayed in Table 3. As for the embankment fill of MSE wall, granular material was used, while the rest of the embankment fill consist of clay. The base of the structure is created using K-350 concrete. Based on field investigation, the soil foundation consists of clay with various stiffness. The properties of each material is displayed in Table 4.

Table 3. Properties of facing element

Description	Value
Thickness (m)	0.15
f_c' (MPa)	10
Unit weight (kN/m^3)	24

Table 4. Properties of soil and foundation

Description	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	S_u kPa	ϕ (°)	E_s (kPa)	μ
Embankment						
CBM	15	16	50	-	10,000	0.30
Granular	16	17	-	37	30,000	0.30
Foundation						
Medium to stiff clay	17	18	115	-	26,929	0.30
Very stiff to hard clay	17	18	360	-	84,000	0.30
Others						
K-350 concrete	24	24	-	-	25,332,084	0.15

Geosynthetics are used for strengthening the MSE wall and base of embankment. Geogrid is used to reinforce the facing element while woven and non-woven geotextile were used at the base of the embankment. Geosynthetics used in the embankment are displayed in Table 5.

Table 5. Material properties of geofabric

Description	Geotextile		Geogrid
	Woven	Non-Woven	
Tensile Strength (kN/m)	200	12	50
Tensile Elongation (%)	10	10	6

Bored piles are used in this MSE wall structure to fulfill the bearing capacity requirements. The properties of piles used in this analysis are displayed in Table 6.

Table 6. Properties of bored pile

Description	Value
Diameter (m)	0.80
f_c' (MPa)	30
Unit weight (kN/m^3)	24
Poisson ratio	0.15

3.2 Seismic Load and Traffic Load

According to SNI 8460:2017, the horizontal seismic coefficient utilized for pseudo-static analysis can be taken as 50% of peak ground acceleration (PGA). The PGA value is obtained from Indonesia Seismic Hazard Map 2017 (Irsyam et al., 2017) for 1000-year return period. Seismic coefficient also needs to consider the amplification factor based on site classification, which can be determined based on SNI 1726:2019. The seismic coefficient applied for pseudo-static analysis is presented in Table 7.

Table 7. Pseudo-static seismic coefficient

Description		Value
Site Class	(a)	D
PGA for 1000-years return period earthquake (g)	(b)	0.19
Amplification factor for D site class	(c)	1.4
Seismic coefficient (k_h)	50% × (b) × (c)	0.13

The seismic load model used to perform dynamic response analysis is taken from ground motion data. Ground motion data used in this analysis is scaled using the response spectrum obtained from Indonesia Seismic Hazard Map 2017 for the site. Amplification factors also need to be applied to the response spectrum parameters. The target response spectrum used for analysis is presented in Figure 7.

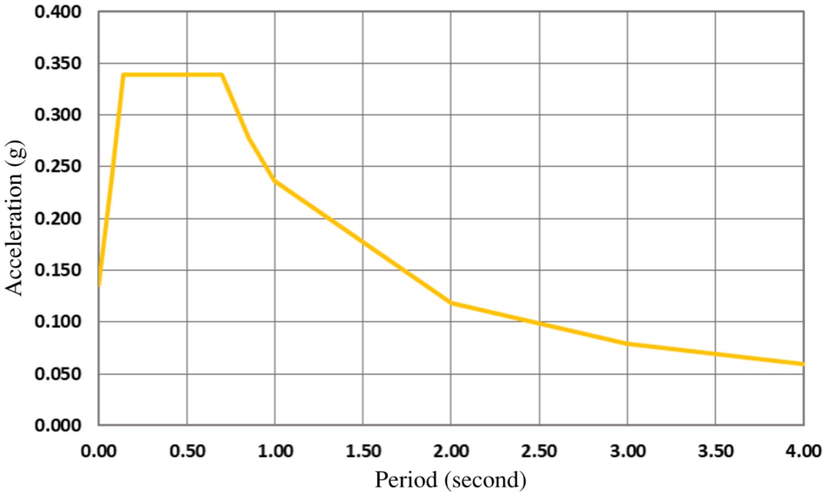


Figure 7. Target response spectrum of 1000-year return period earthquake based on SNI 1726:2019

The reference ground motion data used for this analysis is selected by the Probabilistic Seismic Hazard Analysis (PSHA) method which was developed by Cornell (1968). The analysis result is then applied to disaggregation analysis, a method that allows the identification of the seismic sources that makes dominant contributions to the hazard at a particular site (Bazurro and Cornell, 1999). According to the disaggregation result performed on the site, the controlling earthquake has magnitude range of 7.33-7.67 from a distance of 0-36 km. Hence, the ground motion data of the Kocaeli earthquake, Turkey, 1999, recorded in Goynuk Station, with a magnitude of 7.51 and a distance of approximately 31.74 km is selected as the seismic input due to its similarity of the disaggregation analysis result. The data is obtained from the Pacific Earthquake Engineering Research (PEER) Strong Ground Motion Database (https://peer.berkeley.edu/peer-strong-ground-motion-databases). The detail of the earthquake data is shown in Figures 8 and 9.

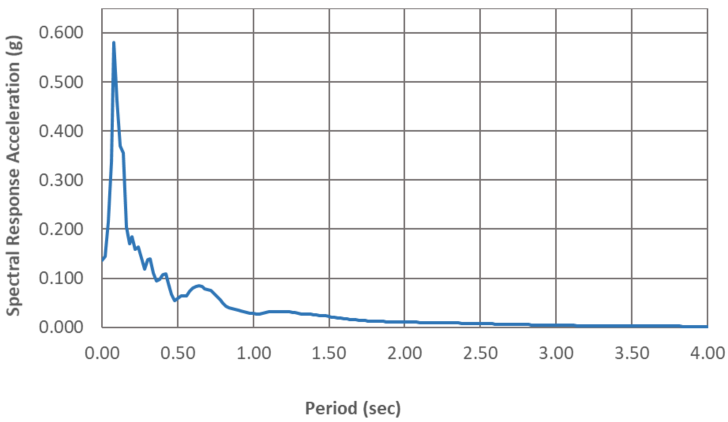


Figure 8. Response Spectrum of Kocaeli earthquake, Turkey, 1999

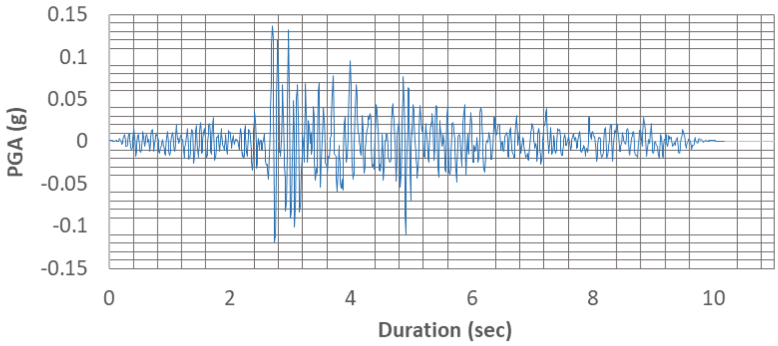


Figure 9. Accelerogram of Kocaeli earthquake, Turkey, 1999

The reference response spectrum is then scaled using spectral matching method with the reference response spectrum. The result of the spectral matching is a new scaled ground motion data which will be used for the seismic stability analysis. The figure of spectral matching is displayed in figure 10, while the scaled ground motion data is shown in Figure 11.

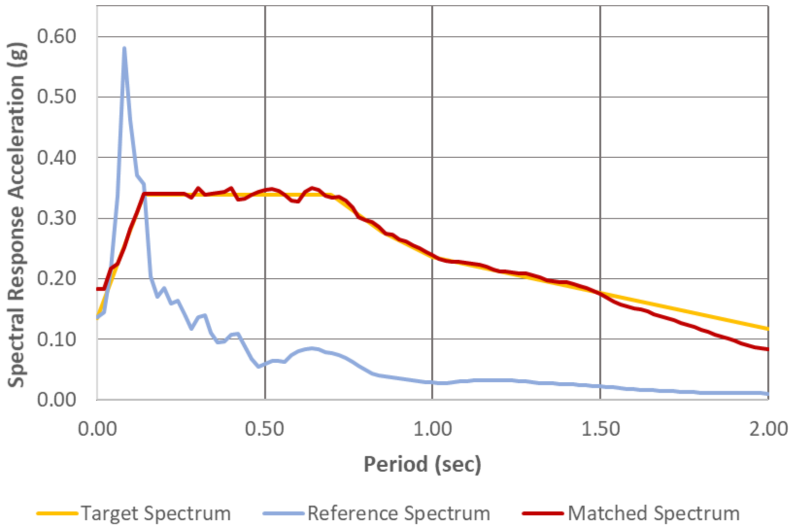


Figure 10. Spectral matching with 1000-year return period response spectrum

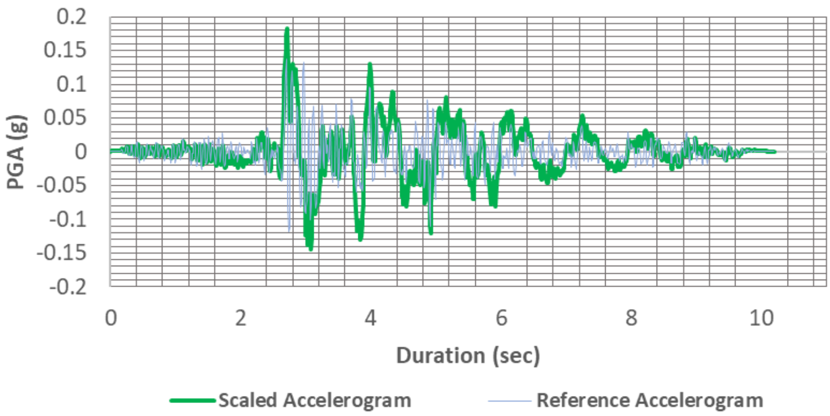


Figure 11. Scaled accelerogram using spectral matching

In addition to seismic load, traffic load must be added. For highway, in accordance to SNI 8460:2017, the recommended traffic load work is 15 kPa.

4 ANALYSIS AND RESULT

The static and seismic stability analysis results of the MSE wall using the limit equilibrium method for each failure mechanism is displayed in Figure 12 and 13. According to the analysis result, the most likely failure mechanism is the tensile overstress (lowest safety factor). However, the safety factor for all modes of failure still satisfies the minimum safety factor required. Recapitulation of safety factor result of the MSE wall using limit equilibrium method is displayed in Table 8.

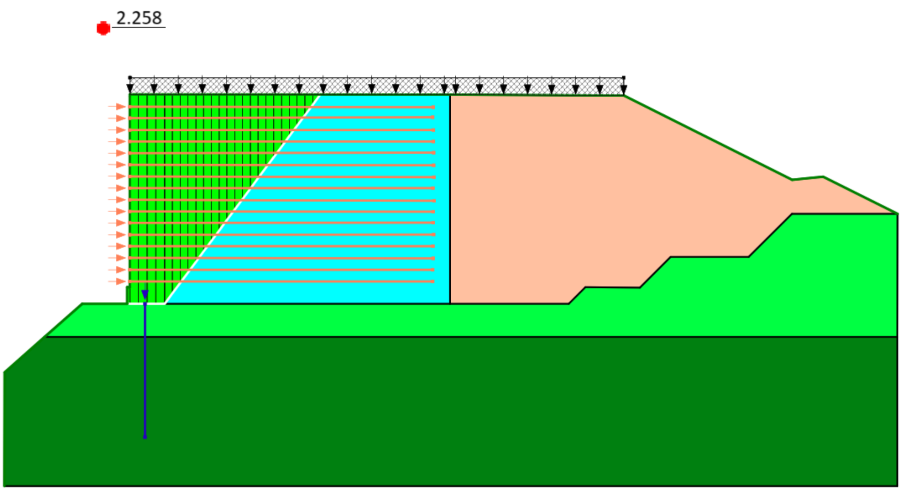
Table 8. MSE wall stability analysis result using limit equilibrium method

Potential Failure Mechanism	Static			Seismic		
	FS_{min}	FS_{Result}	Status	FS_{min}	FS_{Result}	Status
Base sliding	1.5	2.258	Satisfied	1.1	1.981	Satisfied
Tensile overstress	1.5	1.597	Satisfied	1.1	1.292	Satisfied
Global stability	1.3	2.207	Satisfied	1.1	1.801	Satisfied

The static and seismic stability analysis result of MSE wall using finite element method for each failure mechanism is displayed in Figure 14 and 15. The output from finite element analysis agrees with the limit equilibrium analysis, i.e., the most likely failure mode being tensile overstress and the least likely is base sliding. There are differences in magnitude of safety factor obtained. However, the safety factors acquired for all failure modes with both methods still complies with the required safety factor in the Indonesian National Code. Recapitulation of safety factor using finite element method is displayed in Table 9.

Table 9. MSE wall stability analysis result using finite element method

Potential Failure Mechanism	Static			Seismic		
	FS_{min}	FS_{Result}	Status	FS_{min}	FS_{Result}	Status
Base sliding	1.5	3.013	Satisfied	1.1	2.288	Satisfied
Tensile overstress	1.5	1.567	Satisfied	1.1	1.192	Satisfied
Global stability	1.3	1.843	Satisfied	1.1	1.435	Satisfied



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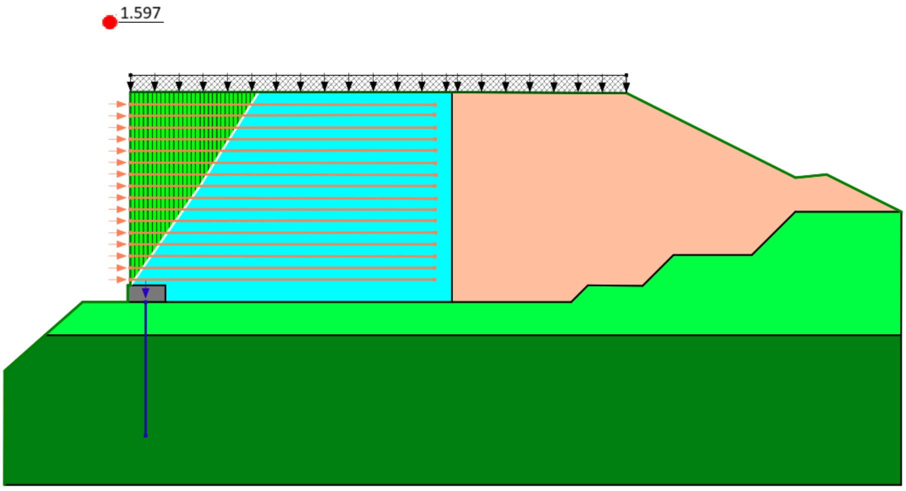

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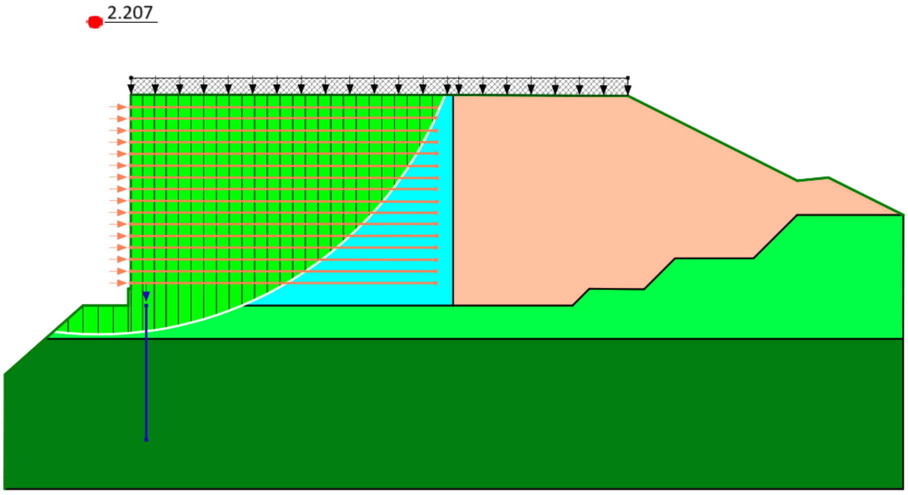
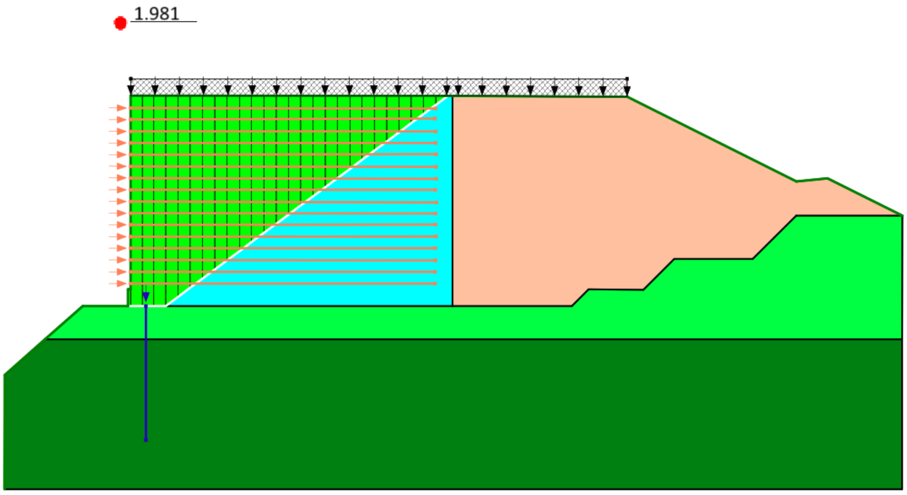


(c)

Figure 12. Static stability analysis result of MSE wall using limit equilibrium method for: (a) base sliding (b) tensile overstress (c) global stability



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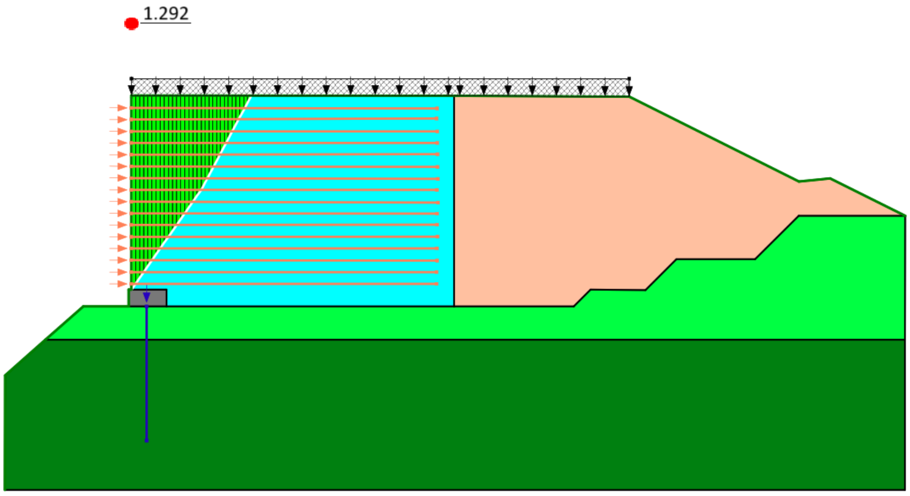

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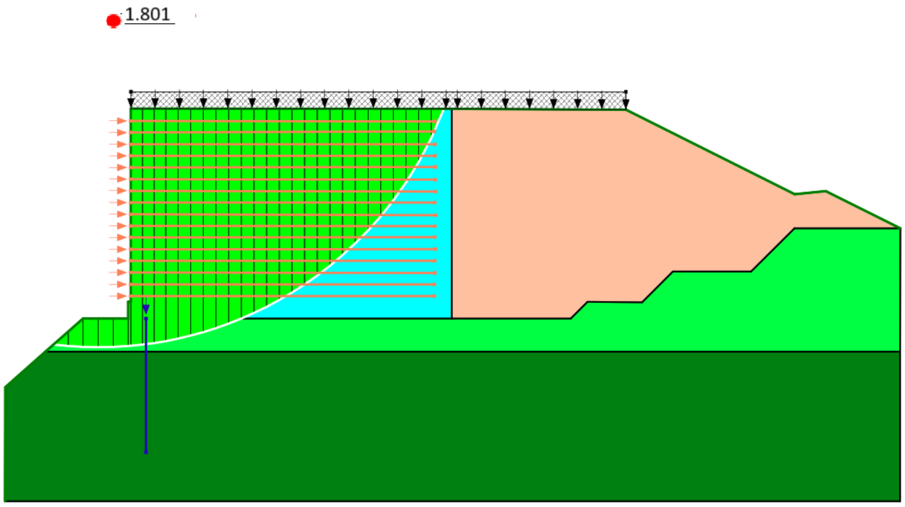

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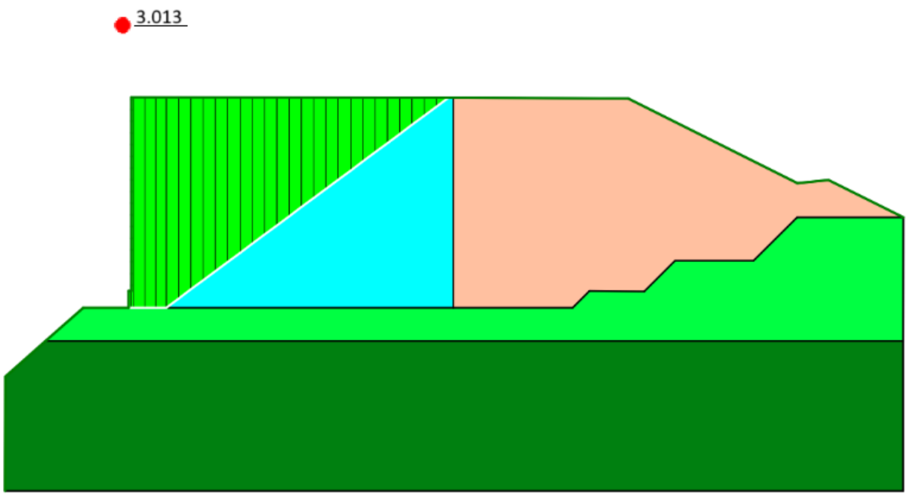
Figure 13. Seismic stability analysis result of MSE wall using limit equilibrium method for: (a) base sliding (b) tensile overstress (c) global stability



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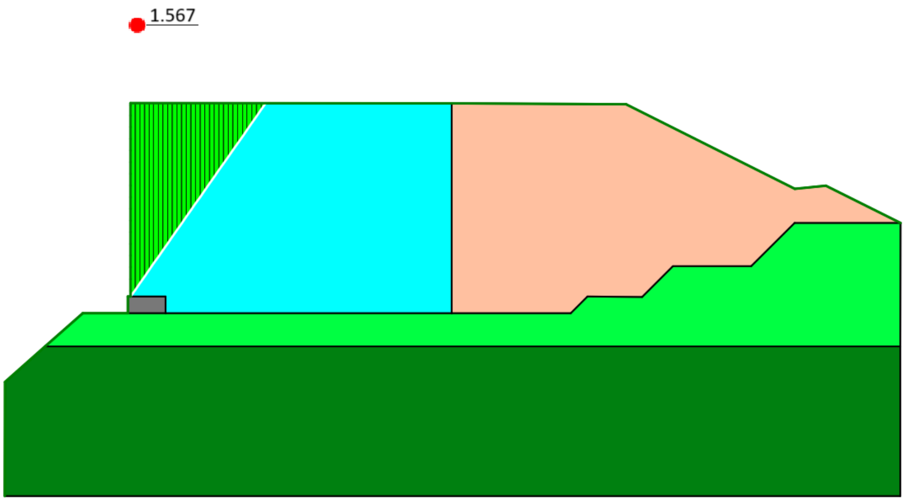

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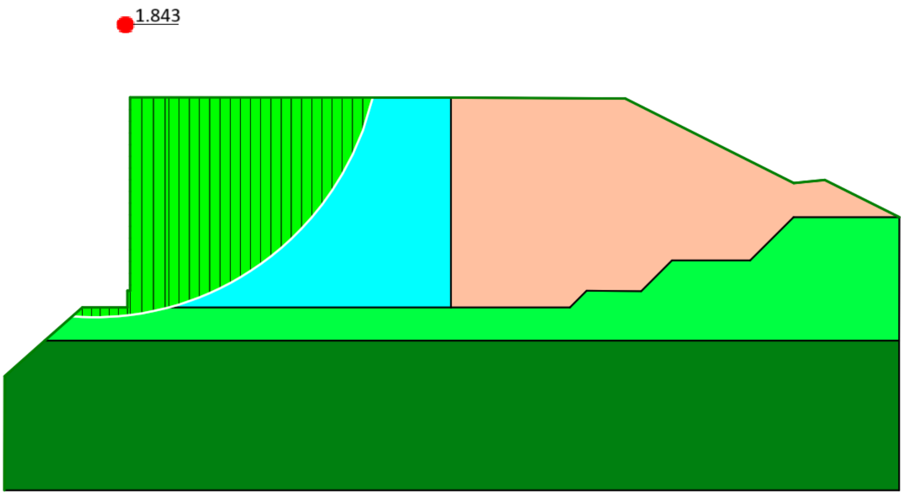
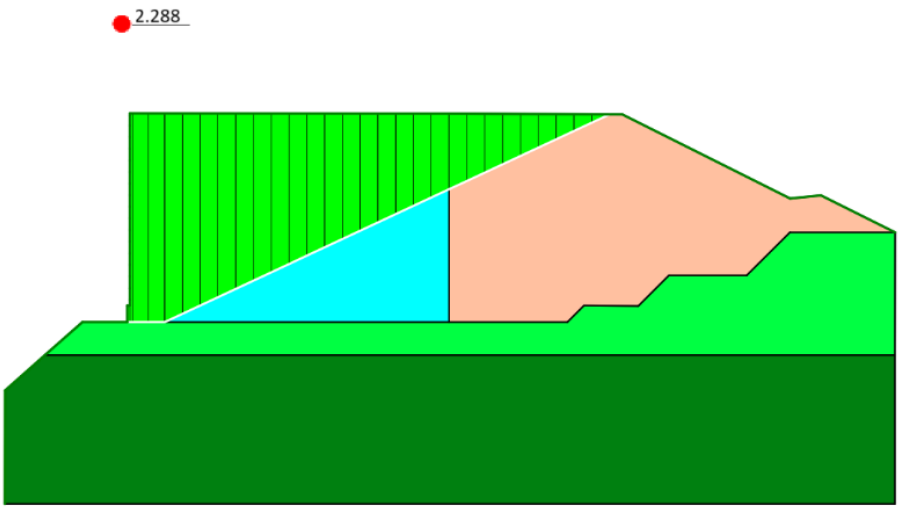


(c)

Figure 14. Static stability analysis result of MSE wall using Finite Element Method for each Failure Mechanism (a) base sliding (b) tensile overstress (c) global / slope failure



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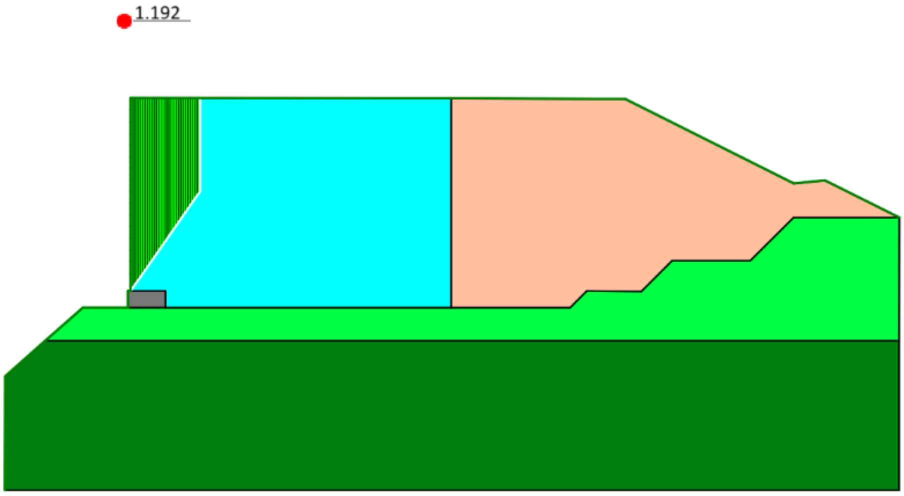

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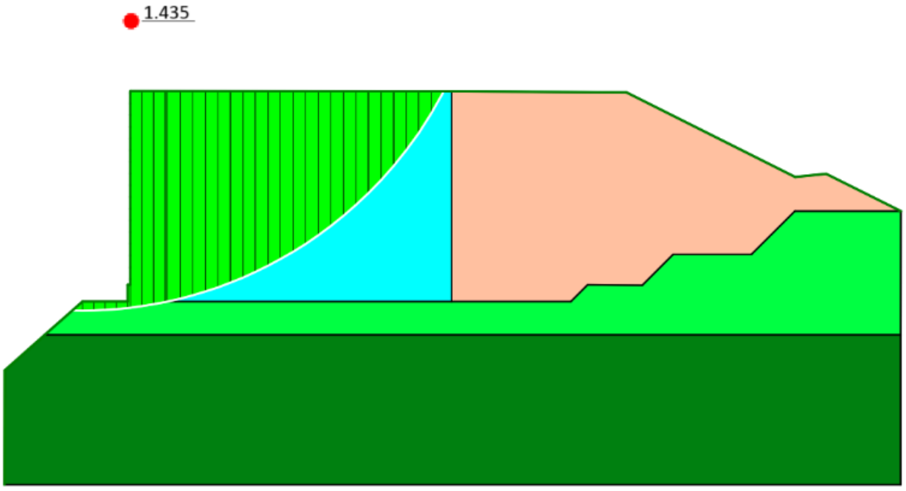

(c)

Figure 15. Static stability analysis result of MSE wall using Finite Element Method for each Failure Mechanism (a) base sliding (b) tensile overstress (c) global / slope failure

Comparison of stability analysis results between limit equilibrium method (LEM) and finite element method (FEM) is displayed in table 10.

Table 10. Comparison of analysis result between LEM and FEM

Potential Failure Mechanism	FS_{static}	$FS_{seismic}$	$FS_{reduction}$
Limit equilibrium			
Base sliding	2.258	1.981	12.27%
Tensile overstress	1.597	1.292	19.10%
Global stability	2.207	1.801	18.40%
Finite element			
Base sliding	3.013	2.288	24.06%
Tensile overstress	1.567	1.192	23.93%
Global stability	1.843	1.435	22.14%

Modelling seismic load as accelerogram suggested that earthquakes have higher impacts on structure stability compared to seismic coefficient, based on seismic safety factor reduction of each method, indicating that the result of the conventional pseudo-static method may underestimate the effect of earthquake against the MSE Wall Stability. Although there are some differences in the obtained safety factors for both methods, the minimum safety factors required still complies with the Indonesian National Standard.

5 CONCLUSION

The conclusion from the analyses conducted are stated as follows:

1. Both limit equilibrium and finite element analysis agrees that tensile overstress is the most likely failure mode for the MSE wall in this case study. Although the safety factors obtained varied between the two method for all failure modes, the required safety factors in Indonesian National Standard are still met.
2. Modelling seismic load as dynamic load has higher impact than pseudo static in terms of safety factor reduction (24% vs. 12%). Although this may give indication that pseudo-static method may be less conservative than dynamic loading, it should be noted that the safety factor obtained by finite element is higher than limit equilibrium. It is suggested that engineers have to conduct both LEM and FEM analysis to ensure safety.

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