

Siti Nurlita FITRI  

Niken Silmi SURJANDARI 

Galuh CHRISMANINGWANG 

Bambang SETIAWAN 

Yusep Muslih PURWANA 

Brilliant Budi PRAKOSA 

Raden Harya Dananjaya Hesti INDRABASKARA

Sebelas Maret University, UNS Geoscience Research Group, Civil Engineering Department,
Indonesia

Nonlinear analysis for liquefaction simulation: implication of constitutive soil model

Keywords: liquefaction, DEEPSOIL, Lombok, Mandalika, strain

Introduction

Site-specific analysis of the response to seismic motion has been widely conducted using different methods. One of the approaches is nonlinear analysis, which provides the performance of the model through the dynamic loading and unloading process. During the process, several constitutive models are applied to produce dynamic properties, such as pore water pressure generation and strain–stress curves. Furthermore, one of the seismic event-induced liquefaction phenomena is also simulated from dynamic behavior output. The constitutive

model plays a significant role because the large-strain shear strength is generally considered unrestricted, leading to overestimated shear stress as shear strains increase (Chiu et al., 2012). This condition leads to overestimation and unrealistic predictions for the dynamic simulation.

The general nonlinear analysis for generating soil response is the DEEPSOIL program. This approach is also applied to validate the centrifuge test for the sloping ground in a one-dimensional site (Pervaiz et al., 2021). Moreover, liquefaction simulation was also conducted to simulate the Korea liquefaction case (Lee et al., 2025), estimate the lateral spreading in Indonesia (Fitri & Sawada, 2025b), and analyze near-fault motion (Tsai & Li, 2024). Modified Kondner–Zelasko (MKZ) and General Quadratic/Hyperbolic (GQ/H) are the constitutive models embedded in this software. MKZ utilizes a hyperbolic equation to fit normalized shear modulus reduction and damping curves to simulate hysteretic soil behavior (Matasović, 1993). Meanwhile, the GQ/H model can represent the soil's shear strength and small-strain nonlinear behavior (Groholski et al., 2015). However, it demonstrates that the computed site response highly depends on the implied shear strength in the soil model, particularly for porous soil sites. The constitutive model plays a significant role because the large-strain shear strength is generally considered unrestricted, leading to overestimated shear stress as shear strains increase (Carlton & Kaynia, 2017). This condition leads to overestimation and unrealistic predictions for the dynamic simulation. The soil response is highly nonlinear, and both model outputs are strongly correlated with a limited number of critical parameters, which leads to highly sensitive output.

The Lombok area is highly vulnerable to earthquake-induced liquefaction. The Mandalika circuit, as a site project, is dominated by sand in the subgrade with a high groundwater table and is susceptible to soil liquefaction. Several studies that simulated the liquefaction in this location provide cyclic tests and empirical assessments (Fitri & Sawada, 2025a). In addition to minimizing the hazard, several countermeasures have been proposed, such as site-specific assessment from microtremor data (Fitri et al., 2018; Taruna et al., 2024) and stone column mitigation (Sunarto et al., 2024). Fitri and Sawada (2024) described liquefaction analysis in Indonesia that has not been fully explored, especially regarding appropriate parameters for liquefaction assessment. Therefore, an accurate model of liquefaction behavior at the site produces a better mitigation strategy for disaster management. The modeling of nonlinear analysis should consider the appropriate constitutive model for simulating the liquefaction behavior of a particular site.

This study aims to generate a one-dimensional nonlinear analysis for simulating liquefaction behavior through two constitutive models in DEEPSOIL. The MKZ and GQ/H models are applied to yield the soil response from seismic motion data. The dynamic behavior from the analysis, such as pore water pressure ratio, strain ratio, and shear stress, is calculated in each layer of the ground to indicate the softening and failure of the ground. Several studies examining the comparison of similar constitutive models have been conducted in Southern California (Golkarfard et al., 2024), Southern Iran (Eskandarinejad et al., 2017), and South Korea (Shamsher et al., 2025), or compared with other constitutive models such as MKZ and PDMY02 (Demir, 2021). In addition, for liquefaction analysis, examinations of total stress and effective stress approaches to generate pore water pressure ratio have been conducted through this program without considering the different constitutive models (He et al., 2025). Although the approach is the same as that used for nonlinear site response analysis, this research was applied in Indonesia and focuses on seismic-induced liquefaction. This research is expected to provide an accurate constitutive model for the Lombok region to assess disaster mitigation actions comprehensively.

Material and methods

Research location

This research is located on Lombok Island, especially in the Mandalika circuit project. The detailed location is presented in Figure 1.

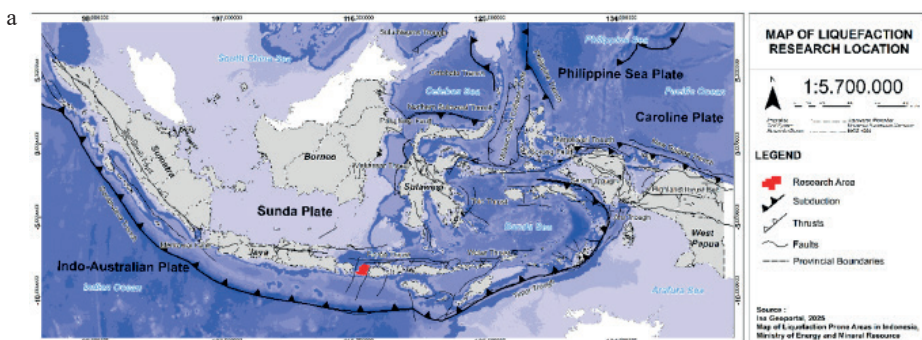


FIGURE 1. Research location in macroscale (a) and microscale (b)

Source: own work based on Ina-Geoportal maps (2025).

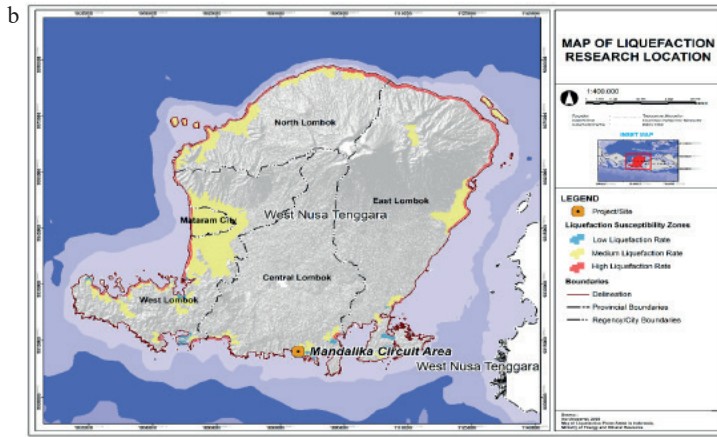


FIGURE 1. (cont.)

Regarding liquefaction susceptibility, the area is in the medium liquefaction risk zone based on the Indonesian liquefaction hazard map, which is layered in Figure 1. The site investigation was conducted using a standard penetration test (N-SPT) with five boreholes.

Soil properties

Sandy soil with a shallow groundwater table dominates the ground. Based on the site investigation, the five boreholes have different bedrock conditions, although all the properties are mixed with clay or silt. The groundwater level is generally 1.5 m, but in this analysis, the groundwater level is assumed to be 1 m deep for all boreholes. The bedrock condition is simulated at 20 m for BH1, BH2, and BH3, while at 10 m for BH4 and 17 m for BH5. To avoid misunderstanding, the unit weight of the soil is described as γ_s . Detailed information is presented in Table 1.

The soil properties that apply for the simulation are unit weight, shear wave velocity corresponding to the N-SPT value, and friction angle (ϕ). The relationship between shear wave velocity (V_s) and the SPT value (N_{60}) and initial effective vertical stress of the ground (σ'_{v0}) is described in Equation 1 (Brandenberg et al., 2010; Amalia et al., 2023):

$$\ln(V_s) = 4.045 + 0.096 \ln(N_{60}) + 0.236 \ln(\sigma'_{v0}). \quad (1)$$

This analysis computes the same layer consistency for the similar shear wave velocity values. Detailed N-values of SPT and V_s are also depicted in Figure 2.

TABLE 1. Soil properties for all borehole

BH1							
Depth	0–1 m	1–3 m	3–7 m	7–11 m	11–14 m	14–17 m	17–20 m
Soil type	sand		silty sand		sand		clayey sand
γ_s [$\text{kN}\cdot\text{m}^{-3}$]	16.2	16.2	16	17	18	18	18
V_s [$\text{m}\cdot\text{s}^{-1}$]	196	260	264	300	326	346	356
ϕ [°]	27	24	29	32	35	38	38
BH2							
Depth	0–1 m	1–4 m	4–6 m	6–9 m	9–14 m	14–18 m	18–20 m
Soil type	sand		silty sand			sand	
γ_s [$\text{kN}\cdot\text{m}^{-3}$]	17	17	18	18	16	16.8	17.8
V_s [$\text{m}\cdot\text{s}^{-1}$]	197	270	289	313	287	296	340
ϕ [°]	29.1	39.81	38	39	37	38.5	38.5
BH3							
Depth	0–1 m	1–2 m	2–4 m	4–5 m	5–7 m	7–17 m	17–20 m
Soil type	sand			silty sand			
γ_s [$\text{kN}\cdot\text{m}^{-3}$]	16	16.2	17.2	16	16	16	17.8
V_s [$\text{m}\cdot\text{s}^{-1}$]	216	222	270	252	234	248	355
ϕ [°]	22	22	32	35	35	38	39
BH4							
Depth	silty sand			sand		×	×
Soil type	0–1 m	1–3 m	3–5 m	×	8–10 m	×	×
γ_s [$\text{kN}\cdot\text{m}^{-3}$]	16	16.5	17	×	17.8	×	×
V_s [$\text{m}\cdot\text{s}^{-1}$]	208	210	251	×	340	×	×
ϕ [°]	27	28	31	×	35	×	×
BH5							
Depth	sand				gravelly sand		
Soil type	0–1 m	1–7 m	7–8 m	8–12 m	12–13 m	13–14 m	14–17 m
γ_s [$\text{kN}\cdot\text{m}^{-3}$]	16	17.5	16.2	16.2	17.5	17.5	18
V_s [$\text{m}\cdot\text{s}^{-1}$]	195	276	261	255	292	313	330
ϕ [°]	28	30	32	32	35	38	38

Source: own work.

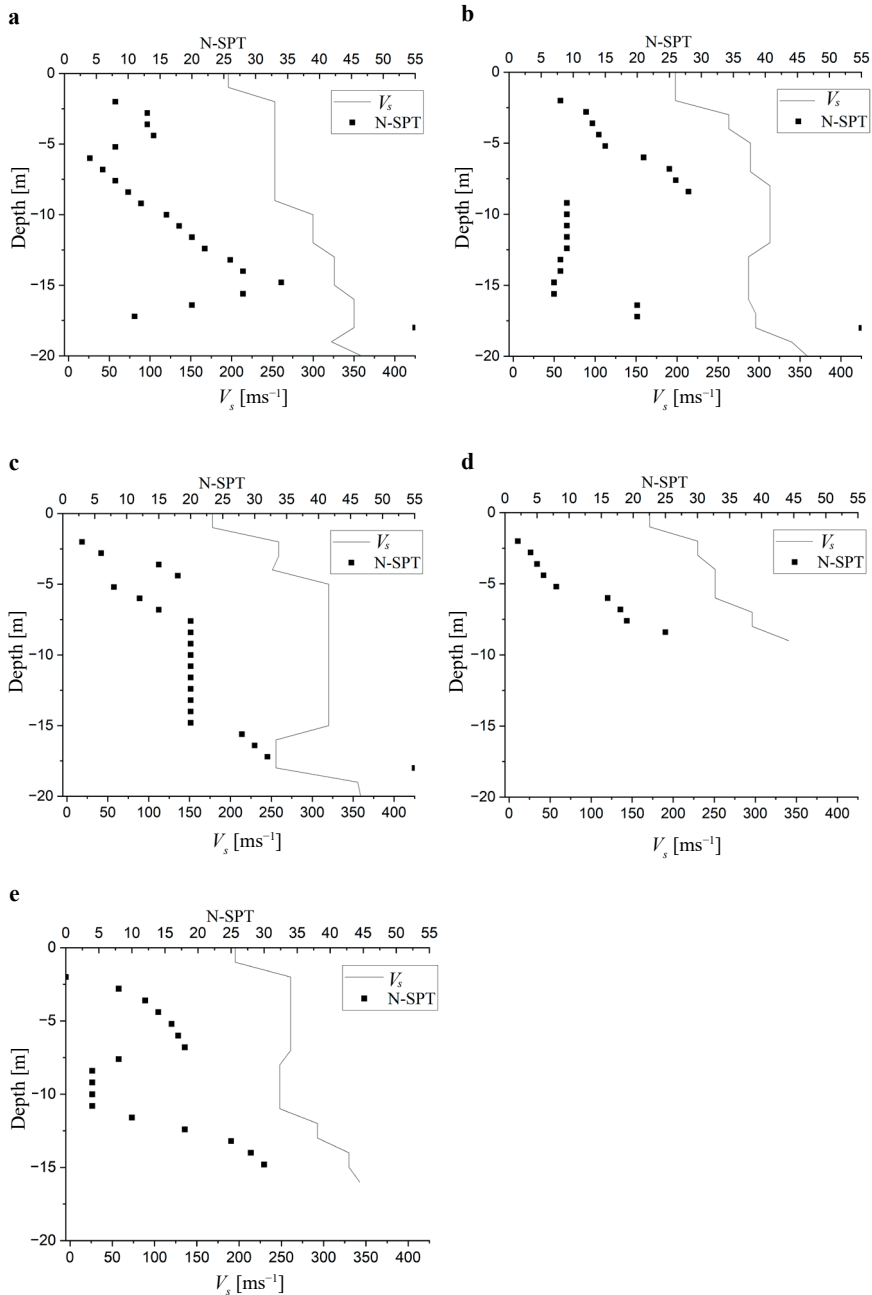


FIGURE 2. Results of standard penetration test (N-SPT) and shear wave velocity (V_s) test in designated boreholes: a – BH1, b – BH2, c – BH3, d – BH4, e – BH5

Source: own work.

DEEPSOIL model and assumption

In this study, the analysis of seismic behavior is based on site-specific response analysis through DEEPSOIL. This nonlinear calculation is applied to a one-dimensional model with input from the soil properties, using the seismic load from the Kobe earthquake ground motion. This is due to lack of real ground motion recorded at the location, although the area is highly impacted as a seismically prone site. The Kobe earthquake is embedded in DEEPSOIL and has been applied in several liquefaction cases in Indonesia, such as the 2018 Palu earthquake (Jalil et al., 2021; Hori et al., 2023) and the Yogyakarta airport project (Fitri & Pramana, 2025).

The dynamic properties of sand, such as soil properties, are estimated from Darendeli's empirical model (Stokoe et al., 2004). This approach is calculated to simulate cyclic loading behavior, such as loading and unloading, and yields the stress–strain loop connection. Moreover, Phillips and Hashash (2009) employed the damping factor (D) and modulus reduction (G/G_{\max}) for calibration and minimizing discrepancies between the targeted and resulting curves.

In general, numerous soil constitutive models for dynamic analysis have been proposed to account for the solid–liquid coupling phenomena in saturated sandy soils exposed to intense shaking, such as applying the effective stress method (Chiaradonna et al., 2018; Wang et al., 2014, 2021; Boccieri et al., 2024; Chen et al., 2024). Moreover, several constitutive models are available in DEEPSOIL for assessing the dynamic behavior of the ground. However, this research will apply two constitutive models for liquefaction analysis: General Quadratic/Hyperbolic (GQ/H) and Modified Kondner–Zelasko (MKZ). The detailed analysis, which focuses on shear strain and stress, is distinguished by the following approach.

Modified Kondner–Zelasko (MKZ)

The MKZ model is an upgrade from the hyperbolic approach model provided by Matasović and Vucetic (1993). This analysis applies β and s for fitting the shape of the curve where G_0 is the initial shear modulus, shear strength is τ , and shear strain is γ . The process ensures a stress–strain curve that complies with a user-specified shear strength at a specified strain while matching the analysis goal modulus-reduction (and related damping) curve over a selected strain range:

$$\tau = \frac{G_0 \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r} \right)^S}. \quad (2)$$

While in DEEPSOIL, the model is augmented by γ_r as confining pressure according to Hashash's and Park's theory (2001). The value is calculated by dividing the vertical effective stress (σ'_v) by the reference stress (σ_{ref}):

$$\gamma_r = \left(\frac{\sigma'_v}{\sigma_{\text{ref}}} \right)^b. \quad (3)$$

General Quadratic/Hyperbolic (GQ/H)

As an extended method from MKZ, the GQ/H method is a further approach that combines ultimate shear strength and modulus reduction factor with θ_τ as a parameter for fitting the curve, and maximum shear stress (τ_{max}):

$$\tau = \tau_{\text{max}} \left[\frac{1}{\theta_\tau} \left\{ 1 + \left(\frac{\gamma}{\gamma_r} \right) - \sqrt{\left\{ 1 + \frac{\gamma}{\gamma_r} \right\}^2 - 4\theta_\tau \frac{\gamma}{\gamma_r}} \right\} \right], \quad (4)$$

where θ_τ is calculated by the equation:

$$\theta_\tau = \theta_1 + \theta_2 x \frac{\theta_4 x \left(\frac{\gamma}{\gamma_r} \right)^{\theta_5}}{\theta_3^{\theta_5} \theta_4 x \left(\frac{\gamma}{\gamma_r} \right)^{\theta_5}}. \quad (5)$$

DEEPSOIL utilizes the MRDF (Phillips & Hashash, 2009) technique that improves the fit to damping behavior and modulus reduction. The correction factor is calculated as Equation 5. Parameters θ_1 , θ_4 , and θ_τ are employed to alter the large strain values according to the designated large strain shear strength and to maintain the modulus reduction curves derived from reference studies as much as possible. After generating the layered domain, the GQ/H curve fitting procedure generates the shear strength correction for the soil shear strength–shear strain graph and delivers the parameters θ_1 through θ_5 . All further detailed descriptions are provided in the DEEPSOIL user manual (DEEPSOIL, 2024).

Behavior reversal and hysteresis

In order to improve the simulation of cyclic strain calculation, the GQ/H model further specifies a thorough hysteresis formulation for including unloading and reloading approaches. The reaction to hysteretic stress is provided by Equation 6. The τ_{rev} and γ_{rev} are the point of reversal at stress and strain point, and τ acts as a reduction factor, and $G\gamma_{max}$ is the tangent modulus that associated with the particular γ_{max} :

$$\tau = F(\gamma_{max}) \left[-\frac{\tau_{max}}{\theta_{\tau}} \left\{ 1 + \frac{\gamma - \gamma_{rev}}{2\gamma_r} \right\} - \sqrt{1 + \left(\frac{\gamma - \gamma_{rev}}{2\gamma_r} \right)^2 - 4\theta_r \left(\frac{\gamma - \gamma_{rev}}{2\gamma_r} \right) - G\gamma_{max} (\gamma - \gamma_{rev})} \right] + G\gamma_{max} (\gamma - \gamma_{rev}) + \tau_{rev}. \quad (6)$$

Pore water pressure generation

The pore water pressure generation is calculated by Equation 7 and considers the Dobry–Matasovic (Dobry et al., 1982) model approaches when it is called normalized excess pore pressure (r_u) as u_n , a parameter for fitting the curve (p , s , and F), f is the dimensionality factor, N_c is the number of cycles, the shear strain reversal value is γ_c , and γ_{tvp} is the threshold for shear strain:

$$u_n = \frac{pfN_c F (\gamma_c - \gamma_{tvp})^S}{1 + fN_c F (\gamma_c - \gamma_{tvp})^S}. \quad (7)$$

The normalized excess pore water pressure ratio is also defined as the u_n parameter in the following equation:

$$r_u = \frac{u'}{\sigma'_v}, \quad (8)$$

where r_u is the pore water pressure ratio, u' is excess pore water pressure, and σ'_v is the effective vertical stress.

Results and discussion

Pore water pressure output

The output for r_u from each layer is presented in Figure 3 for all layers. All the results are included in two constitutive models, the MKZ and GQ/H models. The Darendeli model (Stokoe et al., n.d.) was employed to evaluate the modulus reduction and damping contours in this investigation for each layer, with the coefficient at rest (K_0) applied from Jacky's formula (Diaz-Segura, 2016). Different behaviors are depicted in all grounds since the model is on layered ground with varying soil properties. The r_u value occurs after 1 m depth because the modeling of the groundwater table is below 1 m depth.

In general, the MKZ and GQ/H results describe almost similar values in the several maximum ranges of r_u (BH1, BH2, BH3, BH5), although they have differences around the r_u under 0.5 (BH2, BH3, BH5). In addition, all the boreholes depict the deeper layer of the ground, and the values of the two constitutive models tend to be similar but have slight differences. The maximum value of r_u is in BH1 at 18 m, BH2 at 16 m, BH3 at 12 m, BH4 at 4 m, and BH5 at 10 m.

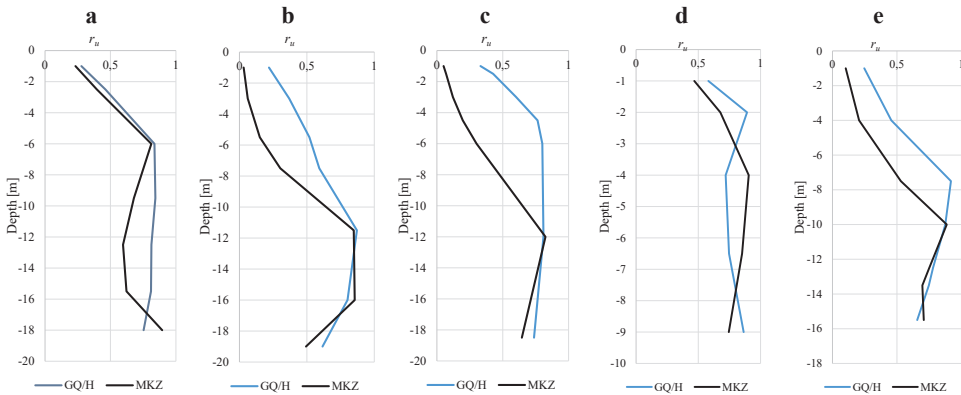


FIGURE 3. Pore water pressure generation from DEEPSOIL analysis: a – BH1, b – BH2, c – BH3, d – BH4, e – BH5

Source: own work.

This study only focuses on modeling liquefaction simulation based on pore water pressure (r_u) generation without any supporting data from the physical laboratory tests. Based on the centrifuge analysis (Groholski et al., 2016), the MKZ typically generates the r_u effectively at a moderate level of liquefaction but lacks prediction accuracy under full liquefaction conditions. Furthermore, Raza and Ahmad implied

that $r_u \geq 0.9$ indicates complete liquefaction condition while marginal liquefaction is $0.8 \leq r_u \leq 0.9$ (Raza & Ahmad, 2024). Based on the results, the smaller the value of r_u from the MKZ approach, the larger the gap between the two constitutive models. This means that in the no liquefaction to marginal liquefaction conditions, the MKZ predicts less safe results than GQ/H. This threshold also combines with the strain value to predict the real phase of the liquefied soil layer more accurately.

GQ/H ignores the multiple, occasionally subjective processes frequently required to calibrate MKZ for strength under high stresses in cyclic loading. This condition leads to a more straightforward and transparent model calibration and more dependable output for crucial liquefaction situations. In addition, some studies also declare that similar degradation indicators for modulus and strength are included in the GQ/H model, which can more accurately represent large-strain shear strength than MKZ (Mei, 2018; Di Buccio & Pagliaroli, 2020).

Shear stress and strain relation

Due to the large gap between the two constitutive models in the r_u output, especially at shallow depths, the hysteresis loops (relation between stress and strain) are focused on the -5 m depth in all boreholes. This depth is chosen because the r_u value tends to be under 0.8 at this particular depth except in BH4, which means it is not in the full liquefaction condition. All the results are shown in Figure 4.

All the boreholes present a similar behavior in that strain results from MKZ tend to be smaller than GQ/H, although the values were reversed under conditions of full liquefaction (BH4). This output is appropriate for the study that proved MKZ underestimates the rate of shear strength degradation at high pore water pressures and the loss of cyclic stiffness, but it may be overestimated at large strains. Meanwhile, the GQ/H approach improves estimates of how soil deteriorates before and after the first phase of liquefaction by providing more realistic hysteresis that appropriately represents the significant decrease in cyclic resistance and energy dissipation (Shamsher et al., 2025).

The liquefaction analysis is not only about predicting the behavior of the excess pore water pressure ratio (r_u), but also the output for shear and strain of the modeling. The combination of the failure process in the soil due to strain stress, especially in shear force, is considered. The maximum r_u value in each borehole with the MKZ model is described in Figure 5.

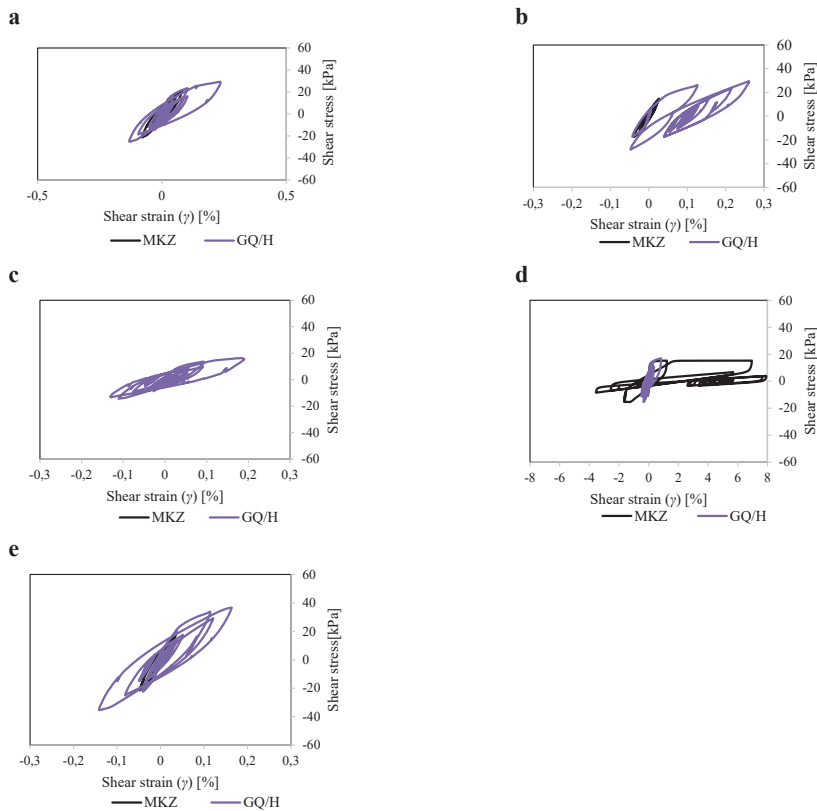


FIGURE 4. Shear stress and shear strain relation output in depth of -5 m: a – BH1, b – BH2, c – BH3, d – BH4, e – BH5

Source: own work.

The strain output shows that the peak of r_u does not always produce the maximum strain ratio. However, the pore water pressure of the MKZ model is lower than of GQ/H because the degradation model considers a reduction in soil material stiffness at each time step. For a more accurate simulation, Chiaradonna et al. (2015) suggested that the recalculation of stiffness and soil strength during the post-cyclic consolidation phase should be considered, as should the dissipation and redistribution of excess pore pressure inside a soil deposit.

The study covers the numerical analysis through modeling soil properties in Indonesia to obtain the liquefaction behavior of the ground. Although the cyclic load does not fully represent the actual seismic motion, the behavior of the softening soil is expected to be the basic threshold for disaster management in the Lombok region. The two constitutive models offer benefits and drawbacks

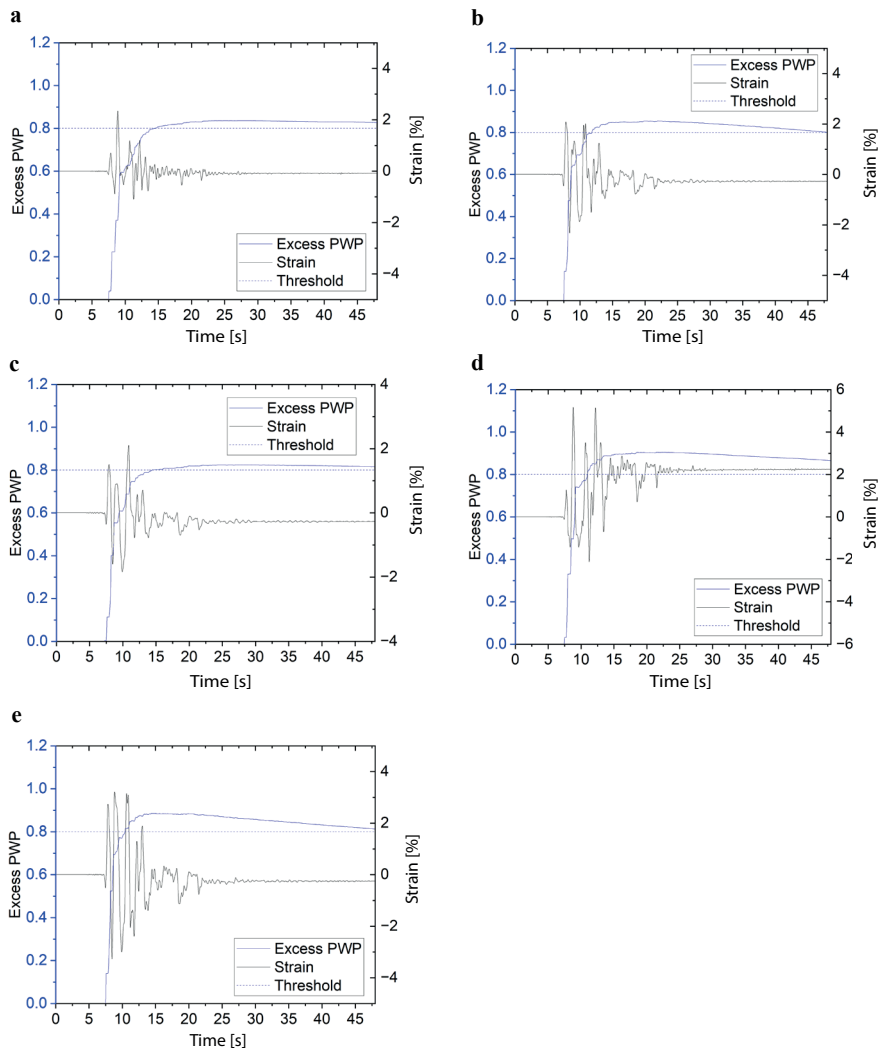


FIGURE 5. Relationship among excess pore water pressure ratio (r_u) and strain in the DEEPSOIL model: a – BH1, b – BH2, c – BH3, d – BH4, e – BH5

Source: own work.

to the output that a geotechnical expert should consider in engineering practices. In addition, laboratory physical testing, such as centrifuge and 1 g shaking table tests, is necessary for future study because these tests can replicate the soil model and specific site profiles, allowing for advanced validation of the MKZ and GQ/H constitutive models.

Conclusions

This research conducted the liquefaction behavior analysis through two constitutive models, namely the MKZ and GQ/H models. The pore water pressure ratio, shear stress, and strain ratio under seismic conditions were simulated based on DEEPSOIL. The major conclusion is the following:

1. From the investigation of pore water pressure ratio (r_u) from each borehole, the similar data shows that in the condition of full liquefaction, the MKZ tends to simulate the smaller value rather than the GQ/H model but has the opposite output when in a state of marginal liquefaction. Although at the maximum point, two models offer almost the same value in every borehole.
2. The output of shear strain ratio and shear stress in marginal liquefaction is the main reason MKZ underestimates the stress-strain value. All boreholes indicate that the GQ/H simulates a better estimation of the middle liquefaction situation for both the r_u and strain approaches. The realistic hysteresis as a dynamic property effect is investigated by GQ/H, which appropriately represents the significant decrease in cyclic loading.
3. The relationship between the shear strain ratio, pore water pressure ratio (r_u), and seismic time leads to a pattern in which the maximum r_u does not always provide the most significant strain ratio at a particular time. The combination of dynamic properties should be considered to assess liquefaction behavior comprehensively.

Acknowledgments

This research is funded by a Research Group Grant from Sebelas Maret University with contract 371/UN27.22/PT.01.03/2025. All the authors express their gratitude for this program.

References

- Amalia, K. P., Ismanti, S., & Saputra, A. (2023). Liquefaction potential evaluation in Toba crater Indonesia. *International Journal of GEOMATE*, 25(110), 123–131. <https://doi.org/10.21660/2023.110.3990>
- Bocciari, G., Gaudio, D., & Conti, R. (2024). An uncoupled approach for estimating seismic-induced pore water pressures in liquefiable sandy soils. *Computers and Geotechnics*, 170, 106266. <https://doi.org/https://doi.org/10.1016/j.compgeo.2024.106266>

- Brandenberg, S. J., Bellana, N., & Shantz, T. (2010). Shear wave velocity as function of standard penetration test resistance and vertical effective stress at California bridge sites. *Soil Dynamics and Earthquake Engineering*, 30(10), 1026–1035. <https://doi.org/10.1016/j.soildyn.2010.04.014>
- Carlton, B., & Kaynia, A. M. (2017). Nonlinear site response model with improved damping and strain softening. In *Proceedings of 16th World Conference on Earthquake Engineering, Santiago, Chile*. Paper 0721. <http://wcee.nicee.org/wcee/article/16WCEE/WCEE2017-721.pdf>
- Chen, G., Qin, Y., Wu, Q., Gu, X., & Juang, C. H. (2024). A Unified Model of Cyclic Shear–Volume Coupling and Excess Pore Water Pressure Generation for Sandy Soils under Various Cyclic Loading Patterns. *Journal of Geotechnical and Geoenvironmental Engineering*, 150(9), 4024075. <https://doi.org/10.1061/JGGEFK.GTENG-12247>
- Chiaradonna, A., Tropeano, G., d’Onofrio, A., & Silvestri, F. (2018). Development of a simplified model for pore water pressure build-up induced by cyclic loading. *Bulletin of Earthquake Engineering*, 16(9), 3627–3652. <https://doi.org/10.1007/s10518-018-0354-4>
- Chiaradonna, A., Tropeano, G., d’Onofrio, A., Silvestri, F., & Park, D. (2015, November 1-4). *Application of a simplified model for the prediction of pore pressure build-up in sandy soils subjected to seismic loading*. 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand. https://secure.tcc.co.nz/ei/images/ICEGE15%20Papers/Chiaradonna%20189.00_.pdf
- Chiu, P., Pradel, D. E., Kwok, A. O. L., & Stewart, J. P. (2008). Seismic response analyses for the silicon valley rapid transit project. In *Geotechnical Earthquake Engineering and Soil Dynamics IV* (pp. 1–10). ASCE Library. [https://doi.org/10.1061/40975\(318\)210](https://doi.org/10.1061/40975(318)210)
- DEEPSOIL (2024). *A nonlinear and equivalent linear seismic site response of 1-D soil columns*. User manual. Board of Trustees of University of Illinois at Urbana. https://deepsoil.cee.illinois.edu/Files/DEEPSOIL_User_Manual_v7.pdf
- Demir, S. (2021). Numerical assessment of the performance of different constitutive models used to predict liquefiable soil behavior. *International Advanced Researches and Engineering Journal*, 5(2), 260–267. <https://doi.org/10.35860/iarej.871429>
- Di Buccio, F., & Pagliaroli, A. (2020). Numerical modelling of seismic site response at large strains: a parametric study. *American Journal of Civil Engineering*, 8(5), 117–127. <https://hdl.handle.net/11564/736424>
- Diaz-Segura, E. G. (2016). The coefficient of earth pressure at rest. *Electronic Journal of Geotechnical Engineering*, 21(5). [https://doi.org/10.1016/0148-9062\(94\)90690-4](https://doi.org/10.1016/0148-9062(94)90690-4)
- Dobry, R., Ladd, R. S., Yokel, F. Y., Chung, R. M., & Powell, D. (1982). *Prediction of pore water pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method: Building science series*. National Bureau of Standards, US Department of Commerce, US Governmental Printing Office.
- Eskandarinejad, A., Jahanandish, M., & Zafarani, H. (2017). Divergence between nonlinear and equivalent-linear 1D site response analyses for different V_S realizations of typical clay sites. *Pure and Applied Geophysics*, 174(10), 3955–3978. <https://doi.org/10.1007/s00024-017-1586-y>

- Fitri, S. N., & Pramana, I. M. W. (2025). Non-linear seismic response for liquefaction analysis: pore water pressure and strain ratio approach. *Scientific Review Engineering and Environmental Sciences*, 34(3). <https://doi.org/10.22630/srees.10426>
- Fitri, S. N., & Sawada, K. (2024). Evaluation and opportunities for soil liquefaction vulnerability research: Lesson learned from Japan for Indonesia-A bibliometric analysis. In *Proceedings of the 2024 11th International Conference on Geomatics in Civil Engineering* (pp. 14–29). Springer Nature Singapore. https://doi.org/10.1007/978-3-031-68624-5_2
- Fitri, S. N., & Sawada, K. (2025a). Comprehensive assessment for liquefaction vulnerability in Indonesia: empirical and element simulation approaches. *Civil Engineering Journal*, 11(1), 326-345. <https://doi.org/10.28991/CEJ-2025-011-01-019>
- Fitri, S. N., & Sawada, K. (2025b). Soil liquefaction induces lateral spreading estimation based on site-specific response analysis. In S. A. Kristiawan, K. C. Tsai, M. Shahin, A. R. M. Sam & P. D. Hai (Eds.), *Proceedings of the 6th International Conference on Rehabilitation and Maintenance in Civil Engineering* (Vol. 2, pp. 255–266). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-4694-4_26
- Fitri, S. N., Soemitro, R. A. A., Warnana, D. D., & Sutra, N. (2018). Application of microtremor HVSR method for preliminary assessment of seismic site effect in Ngipik landfill, Gresik. *MATEC Web of Conferences*, 195, 03017. <https://doi.org/10.1051/mateconf/201819503017>
- Golkarfard, H., Ravichandran, N., Sedaghat, A., Saketh Jella, V., & Andrus, R. (2024, February 25-28). *Effects of different soil constitutive models on nonlinear seismic site response analysis using DEEPSOIL for the Blue Ridge and Piedmont Regions, South Carolina*. Geo-Congress 2024, Vancouver, British Columbia, Canada. <https://doi.org/10.1061/9780784485316.028>
- Groholski, D. R., Hashash, Y. M., Kim, B., Musgrove, M., Harmon, J., & Stewart, J. P. (2016). Simplified model for small-strain nonlinearity and strength in 1D seismic site response analysis. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(9), 04016042. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001496](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001496)
- Groholski, D. R., Hashash, Y. M. A., Musgrove, M., Harmon, J., & Kim, B. (2015, November 1-4). *Evaluation of 1-D non-linear site response analysis using a general quadratic/hyperbolic strength-controlled constitutive model*. 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand. <https://secure.tcc.co.nz/ei/images/ICEGE15%20Papers/Hashash%20269.00.pdf>
- Hashash, Y. M. A., Park, D. (2001). Non-linear one-dimensional seismic ground motion propagation in the Mississippi Embayment. *Engineering Geology*, 62(1–3), 185-206.
- He, H., Miao, Y., & Wang, S. (2025). Reproducing nonlinear ground response and pore pressure variations using in-situ soil properties. *Soil Dynamics and Earthquake Engineering*, 194, 109380. <https://doi.org/https://doi.org/10.1016/j.soildyn.2025.109380>
- Hori, R., Inoue, K., Ikeda, T., & Kiyota, T. (2023). Analytical study on ground behavior during the 2018 Sulawesi earthquake, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 1244(1), 012035. <https://doi.org/10.1088/1755-1315/1244/1/012035>
- Jalil, A., Fathani, T. F., Satyarno, I., & Wilopo, W. (2021). Nonlinear site response analysis approach to investigate the effect of pore water pressure on liquefaction in Palu. *IOP Conference Series: Earth and Environmental Science*, 871(1), 012053. <https://doi.org/10.1088/1755-1315/871/1/012053>

- Lee, Y. G., Pervaiz, U., Park, D., Kim, B., & Han, J. T. (2025). Assessment of liquefaction potential using simplified method and one-dimensional effective stress ground response analysis during 2017 Pohang earthquake in South Korea: A case study. *Soil Dynamics and Earthquake Engineering*, 196, 109463. <https://doi.org/10.1016/j.soildyn.2025.109463>
- Matasović, N. (1993). *Seismic response of composite horizontally-layered soil deposits* (doctoral dissertation). University of California. <https://www.researchgate.net/publication/34090029>
- Matasović, N., & Vucetic, M. (1993). Cyclic characterization of liquefiable sands. *Journal of Geotechnical Engineering*, 119(11), 1805–1822. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1993\)119:11\(1805\)](https://doi.org/10.1061/(ASCE)0733-9410(1993)119:11(1805))
- Mei, X. (2018). *Pore pressure generation and liquefaction analysis using nonlinear, effective stress-based site response analysis* (doctoral dissertation). University of Illinois at Urbana-Champaign. <http://hdl.handle.net/2142/102927>
- Pervaiz, U., Park, D., Hashash, Y., & Xing, G. (2021). Testing performance of pore pressure models implemented in one-dimensional site response analysis program against centrifuge test data measured in mildly sloping ground. *Soil Dynamics and Earthquake Engineering*, 149, 106867. <https://doi.org/10.1016/j.soildyn.2021.106867>
- Phillips, C., & Hashash, Y. M. (2009). Damping formulation for nonlinear 1D site response analyses. *Soil Dynamics and Earthquake Engineering*, 29(7), 1143–1158. <https://doi.org/10.1016/j.soildyn.2009.01.004>
- Raza, H., & Ahmad, N. (2024). Assessment of seismic liquefaction hazard and ground response in subduction zone: a 1D non-linear effective stress approach. *Engineering Research Express*, 6(4), 045121. <https://doi.org/10.1088/2631-8695/ad980a>
- Shamsher, S., Won, M. S., Park, Y. C., Park, Y. H., & Sayed, M. A. (2025). Effect of nonlinear constitutive Models on seismic site response of soft reclaimed soil deposits. *Journal of Marine Science and Engineering*, 13(7), 1333. <https://doi.org/10.3390/jmse13071333>
- Stokoe, K. H., Darendeli, M. B., Gilbert, R. B., Menq, F. Y., & Choi, W. K. (n.d.). *Development of a new family of normalized modulus reduction and material damping curves*. https://apps.peer.berkeley.edu/lifelines/Workshop304/pdf/Stokoe_PlenaryPaper.pdf
- Sunarto, S., Setyono, E., Darmawan, A. A., & Ondang, K. K. (2024). Liquefaction potential and soil bearing capacity improvement with stone column case study. *AIP Conference Proceedings*, 2927(1), 030009. <https://doi.org/10.1063/5.0193689>
- Taruna, R. M., Septiadhi, A., Sungkono, Mase, L. Z., & Mashuri. (2024). Preliminary assessment of liquefaction vulnerability using microtremor analysis in North Lombok. *Journal of Physics: Conference Series*, 2866(1), 012061. <https://doi.org/10.1088/1742-6596/2866/1/012061>
- Tsai, C. C., & Li, P. C. (2024). Quantifying near-fault motion effects on soil liquefaction through effective stress site response analysis. *Soil Dynamics and Earthquake Engineering*, 183, 108779. <https://doi.org/10.1016/j.soildyn.2024.108779>
- Wang, R., Cao, W., Xue, L., & Zhang, J. M. (2021). An anisotropic plasticity model incorporating fabric evolution for monotonic and cyclic behavior of sand. *Acta Geotechnica*, 16(1), 43–65. <https://doi.org/10.1007/s11440-020-00984-y>

Wang, R., Zhang, J. M., & Wang, G. (2014). A unified plasticity model for large post-liquefaction shear deformation of sand. *Computers and Geotechnics*, 59, 54–66. <https://doi.org/10.1016/j.compgeo.2014.02.008>

Summary

Nonlinear analysis for liquefaction simulation: implication of constitutive soil model. The nonlinear analysis for assessing the cyclic behavior of a specific location is widely applied to minimize geohazards, especially soil liquefaction. The Mandalika circuit project in the Lombok area is highly prone to earthquakes and is located on sand as the subgrade. The high soil liquefaction susceptibility leads to a comprehensive assessment by implementing the appropriate soil constitutive model. One-dimensional nonlinear analysis with two constitutive models, Modified Kondner–Zelasko (MKZ) and General Quadratic/Hyperbolic (GQ/H), provided by the DEEPSOIL program, is examined to generate the dynamic behavior aimed at by this research. Five boreholes from SPT data are conducted as part of the soil investigation data. Based on the pore water pressure, the MKZ and GQ/H in the maximum value (full liquefaction condition) are almost similar in output. However, in other situations, they show the opposite result. The GQ/H predicts a more realistic simulation in the low and medium liquefaction cases, which presents the most significant correlation between strain ratio and shear stress results in all sites. For an accurate evaluation of liquefaction behavior, the combination of dynamic features from an appropriate constitutive model should be considered to simulate the liquefaction behavior of sand.