

HYBRID ANALYSIS OF LIQUEFACTION POTENTIAL AND SITE ATTENUATION EFFECTS USING EMPIRICAL AND NONLINEAR NUMERICAL APPROACHES: A CASE STUDY OF RSU ANUTAPURA DURING THE 2018 PALU EARTHQUAKE

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Abstract

The Palu earthquake of September 28, 2018 (M_w 7.5) triggered massive liquefaction that had a destructive impact on critical infrastructure, including the Anutapura General Hospital (RSU) Building. Conventional liquefaction potential evaluations generally rely on empirical procedures based on the Standard Penetration Test (SPT), which are effective in detecting early vulnerability (triggering). However, this method has a fundamental limitation because it is unable to generate dynamic surface acceleration time-histories for structural design. This research proposes an in-depth case study using a hybrid approach that combines empirical methods (Simplified Procedure) with 1D Non-Linear Site Response Analysis (NL-SRA). Computational modeling is developed in the OpenSees framework using the PressureDependMultiYield02 (PDMY02) constitutive model to simulate cyclic mobility and effective stress dissipation due to pore water pressure generation under undrained conditions. The analysis results on the soil profile of Anutapura General Hospital confirmed the occurrence of extreme liquefaction in shallow to medium sand layers (depth 5–31 m), which is characterized by a drastic decrease in the empirical Safety Factor (FS) to 0.49. Numerically, the NL-SRA model validates that the loss of shear stiffness in the liquefied layer triggers an attenuation (de-amplification) phenomenon of peak seismic acceleration at the surface, which is accompanied by an elongation of the dominant wave period. This study concludes that the integration of empirical methods and advanced non-linear constitutive models is absolutely necessary to capture the wave modification effects due to soil liquefaction, while producing realistic seismic demand as a precise basis for Soil-Structure Interaction (SSI) analysis.

Keywords: Liquefaction, Palu Earthquake, Anutapura General Hospital, Non-Linear Site Response, OpenSees, PDMY02, Seismic Attenuation.

1. Introduction

The M_w 7.5 tectonic earthquake that struck Palu on 28 September 2018 triggered a series of highly destructive geotechnical hazards. Ground shaking caused by strike-slip movement along the Palu-Koro Fault induced massive liquefaction and lateral spreading on a scale rarely observed in the history of modern earthquakes (Song et al., 2019). This phenomenon attracted significant attention from the global geotechnical community because flow liquefaction occurred on very gentle slopes, with gradients ranging from 1% to 2% (Watkinson & Hall, 2019; Kiyota et al., 2020).



Figure 1. Structural failure and foundation settlement of RSU Anutapura induced by post-liquefaction effects following the 2018 Palu Earthquake

One of the most severely affected critical infrastructures was RSU Anutapura, a vital medical facility in Palu. The multi-story reinforced concrete buildings within the hospital complex experienced partial structural failure to total collapse (GEER, 2019). Post-earthquake forensic investigations indicated that the observed damage was not solely governed by inertial forces generated by seismic shaking, but was primarily triggered by a sudden loss of foundation bearing capacity accompanied by extreme differential settlement resulting from the liquefaction of underlying sandy soil layers (Montgomery et al., 2021). The collapse of this essential facility underscores the urgent need for a comprehensive quantitative evaluation of the dynamic behavior of the subsurface soil profile at the site to support future mitigation measures and structural redesign.

To date, liquefaction vulnerability assessment in geotechnical engineering practice has generally been dominated by stress-based empirical approaches, commonly referred to as the Simplified Procedure. This method, which has been continuously refined through the latest revision by Idriss and Boulanger (Boulanger & Idriss, 2014), evaluates liquefaction potential based on the correlation between the cyclic stress ratio (CSR) and in-situ test data, particularly the Standard Penetration Test (SPT). This approach has proven to be highly practical and reliable for preliminary screening to determine whether a soil layer is likely to trigger liquefaction, commonly quantified using the Factor of Safety (FS).

However, empirical procedures have fundamental limitations when applied to the advanced design of critical infrastructure. The calculation of the FS value is limited to predicting the onset of liquefaction and fails to represent the post-liquefaction dynamic consequences on the soil–structure system (Cubrinovski et al., 2019). As excess pore water pressure builds up and the soil liquefies, a significant

degradation of shear stiffness occurs, which modifies the propagation of seismic waves from the bedrock to the ground surface. This phenomenon often results in attenuation of high-frequency accelerations and amplification of long-period waves (Kramer, 1996; Saenz et al., 2019).

Within the framework of Performance-Based Earthquake Engineering (PBEE), however, modern structural engineers can no longer rely solely on a binary “Safe/Liquefied” classification or an FS value. They critically require ground-surface acceleration time histories that explicitly incorporate the effects of soil plasticity and liquefaction. Such dynamic seismic demand is essential for modeling Soil–Structure Interaction (SSI) and for accurately evaluating structural damage, which cannot be adequately addressed by conventional empirical methods (Ulmer et al., 2021).

In response to this research gap, the present study aims to investigate in depth the dynamic behavior of the subsurface soil profile at RSU Anutapura under seismic loading specific to the 2018 Palu Earthquake. The principal novelty of this study lies in the implementation of a comprehensive hybrid framework that not only evaluates liquefaction susceptibility empirically, but also validates it mechanically through advanced one-dimensional nonlinear site response analysis (1D Nonlinear Site Response Analysis, NL-SRA). Unlike conventional equivalent-linear total stress analyses commonly used in commercial practice, the numerical modeling in this study was performed using the OpenSees computational framework based on effective stress principles. This approach explicitly models stress redistribution and the generation of excess pore water pressure under undrained conditions using advanced plasticity-based constitutive models (Elgamal et al., 2002; Yang et al., 2003).

The primary focus of this modeling framework was to quantitatively investigate how liquefaction of shallow sandy layers acts as a mechanical filter. The analysis examines how liquefied layers modify the characteristics of seismic waves—including amplitude, frequency content, and duration—as they propagate from the bedrock to the ground surface. The resulting surface acceleration time histories, incorporating these nonlinear plastic modifications, are expected to provide highly realistic and calibrated seismic demand records. Such outputs are essential as fundamental input for resilient structural design and Soil–Structure Interaction (SSI) analyses in liquefaction-prone areas of Palu in the future.

2. Method

The subsurface stratigraphic profile evaluated in this study was represented by a 32 m deep borehole located at RSU Anutapura, Palu. Based on in-situ Standard Penetration Test (SPT) data, the local hydrogeological conditions indicate a shallow groundwater table located at a depth of 3.0 m below the ground surface. Stratigraphic investigations identified Quaternary alluvial deposits predominantly composed of sandy and silty sand formations in a loose state. In particular, a highly critical zone was encountered from a depth of 5.0 m, characterized by very low penetration resistance, with N-SPT values

predominantly below 10 blows/ft ($N < 10$). A summary of the geotechnical parameters of the soil profile, used as input for both the empirical and numerical analyses, is presented in Table 1.

Table 1. Summary of Stratigraphy and Geotechnical Parameters of the RSU Anutapura Soil Profile

Depth (m)	Soil Description	N-SPT	γ (kN/m ³)	Status MAT
0,0 – 3,0	Stiff Sandy Clay	15 – 22	17,5	Dry
3,0 – 5,0	Medium Dense Sand	12 – 15	18,0	Saturated
5,0 – 9,0	Very Loose Sand	4 – 8	17,0	Saturated
9,0 – 31,0	Loose to Medium Dense Silty Sand	8 – 18	18,5	Saturated

As the dynamic excitation input for the model, this analysis employed the acceleration time-history record of the 28 September 2018 Palu Earthquake mainshock (Mw 7.5). The seismic record was baseline-corrected and frequency-filtered to remove noise contamination. This acceleration signal was applied as the bedrock input motion at the base of the computational model at a depth of 32 m. The characteristics of the bedrock acceleration time history used in this study are presented in Figure 2.

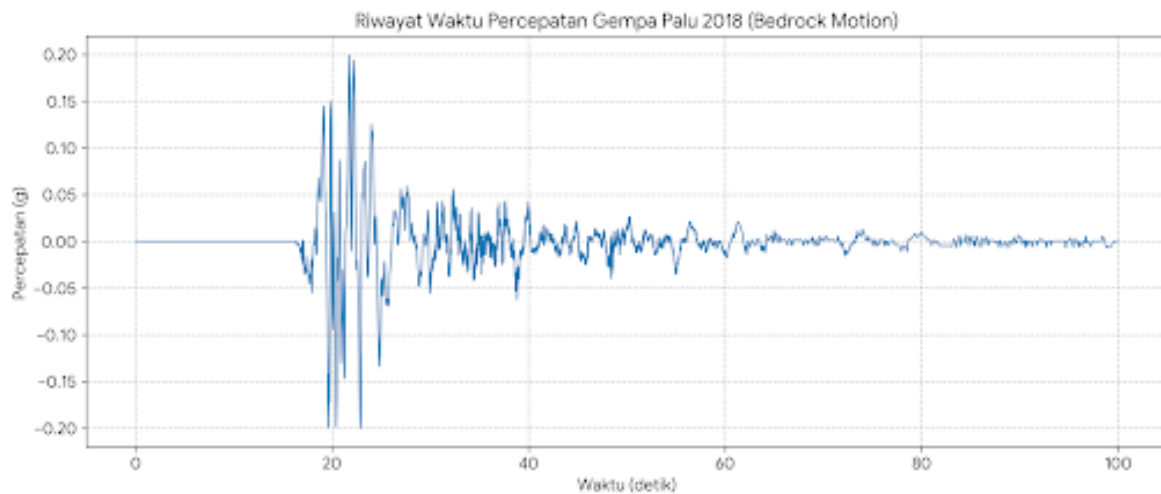


Figure 2. Acceleration time history of the bedrock input motion from the 2018 Palu Earthquake used in the one-dimensional site response analysis.

The initial stage of site vulnerability assessment was conducted using the stress-based empirical approach, widely known as the Simplified Procedure. This study adopted the updated formulation proposed by Idriss and Boulanger (Boulanger & Idriss, 2014) to evaluate Standard Penetration Test (SPT) data. The seismic demand that triggers liquefaction was quantified using the Cyclic Stress Ratio (CSR), which represents the equivalent average shear stress induced at a given depth during an earthquake. The CSR equation is expressed as follows:

$$CSR = 0,65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) \cdot rd$$

Where a_{max} is the peak ground acceleration at the surface (in units of (g)), g is the gravitational acceleration, σ_{v0} and σ'_{v0} are the total and effective vertical overburden stresses, respectively, at the depth of interest, and r_d is the depth-dependent shear stress reduction factor.

The capacity of the soil to resist cyclic loading is represented by the Cyclic Resistance Ratio (CRR). The CRR value for an earthquake with the reference magnitude of $M_w = 7.5$ and an effective overburden stress of 1 atm $CRR_{M=7.5;\sigma'=1}$ was calculated based on the SPT value corrected to the equivalent clean-sand resistance, $(N_1)_{60cs}$, using the following equation:

$$CRR_{M=7.5;\sigma'=1} = \exp \exp \left(\frac{(N_1)_{60cs}}{14,1} + \left(\frac{(N_1)_{60cs}}{126} \right)^2 + \left(\frac{(N_1)_{60cs}}{23,6} \right)^3 + \left(\frac{(N_1)_{60cs}}{25,4} \right)^4 - 2,8 \right)$$

The potential for liquefaction occurrence was evaluated by comparing the CRR and CSR values through the calculation of the Factor of Safety (FS), which incorporates the Magnitude Scaling Factor (MSF) to account for earthquake duration effects and the vertical overburden stress correction factor K_σ :

$$FS = \left(\frac{CRR_{M=7.5;\sigma'=1}}{CSR} \right) \cdot MSF \cdot K_\sigma$$

A soil layer is theoretically identified as susceptible to liquefaction when the calculated FS value is ≤ 1.0 . The results of this analytical evaluation were subsequently used as a baseline for validating the nonlinear site response numerical model.

To capture the realistic modification of seismic waves caused by liquefaction of shallow soil layers, this study modeled one-dimensional shear-wave propagation using one-dimensional Nonlinear Site Response Analysis (1D NL-SRA). This advanced computational simulation was performed using the OpenSees finite element framework (Mazzoni et al., 2006).

The stratigraphic profile of RSU Anutapura was represented as a single soil column model with a thickness of 32 m extending to the engineering bedrock. Spatial discretization was carried out using Stabilized Single-Point quadrilateral (SSPquad) elements with a resolution of 1 m per element. This element size was selected to ensure that high-frequency shear waves could propagate without significant numerical damping (Kramer, 1996). To simulate the assumption of horizontally infinite soil extent, periodic boundary conditions were applied by constraining the degrees of freedom of nodes at the same elevation using the equalDOF command. This configuration mechanically constrained the model to undergo pure one-dimensional shear kinematics during upward propagation of seismic waves from the base of the column.

The principal novelty of this numerical modeling lies in the implementation of the PressureDependMultiYield02 (PDMY02) plasticity constitutive model to represent loose sandy soil

layers susceptible to liquefaction. PDMY02 is a multi-yield-surface plasticity material model specifically developed to simulate the dynamic response of cohesionless soils under cyclic loading (Elgamal et al., 2002; Yang et al., 2003).

This material model was selected because of its well-calibrated capability to accurately capture the fundamental mechanical behavior of Palu sand within an effective stress analysis framework. Unlike equivalent-linear modeling approaches, PDMY02 can simulate soil dilatancy, the progressive accumulation of shear strain leading to cyclic mobility, and explicitly compute the generation of excess pore water pressure under undrained conditions. When subjected to the seismic excitation of the 2018 Palu Earthquake, the computational model dynamically reduces effective stress and degrades the shear stiffness of the soil matrix to near zero, thereby reproducing extreme liquefaction conditions and wave attenuation effects in both physical and computational terms.

3. Results and Discussion

The initial vulnerability evaluation (triggering assessment) was conducted using the Simplified Procedure to obtain depth-dependent profiles of the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR). The results of the empirical analysis comparing seismic excitation demand with soil resistance capacity at RSU Anutapura are illustrated in Figure 3.

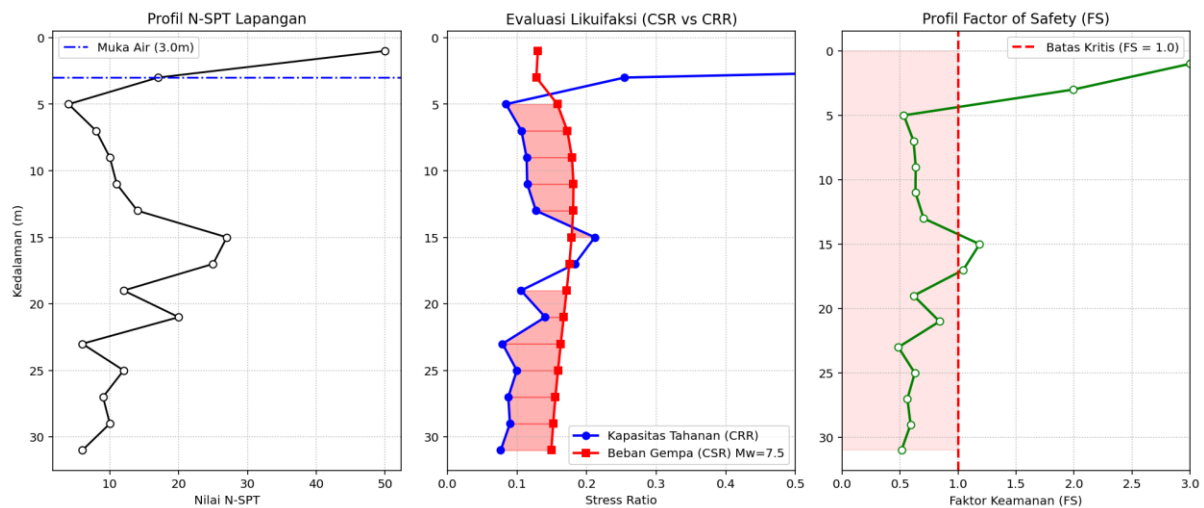


Figure 3. Depth profiles of the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR), together with the distribution of the Factor of Safety (FS), at RSU Anutapura.

Based on Figure 3, it is explicitly observed that the seismic shear stress profile generated by the earthquake (the nearly vertical CSR curve, shown in red) substantially exceeds the inherent cyclic resistance capacity of the soil (the CRR curve, shown in blue). This pronounced deviation, where $CSR > CRR$, was detected persistently and extensively from the shallow depth of 5.0 m down to the base of the alluvial deposit at a depth of 31.0 m.

This critical condition is quantified by the Factor of Safety (FS), which drops drastically to values far below the theoretical safety threshold (FS

≤ 1.0). Within the depth range of 5–31 m, dominated by very loose to medium dense sand layers, the FS reaches a minimum value of 0.49. This reduction to less than half of the required resistance capacity indicates an extremely severe level of liquefaction susceptibility.

As an analytical conclusion of this empirical approach, the 26 m thick soil layer can be interpreted as highly susceptible to widespread liquefaction, with flow liquefaction expected under shaking comparable to the 2018 Palu Earthquake (Boulanger & Idriss, 2014). The confirmation of this extreme liquefaction zone supports the initial hypothesis regarding the loss of foundation bearing capacity at RSU Anutapura and provides a baseline for evaluating how this extensively liquefied layer modifies seismic wave propagation through subsequent nonlinear numerical analyses.

To validate and model the dynamic effects of the liquefied layers identified empirically, the one-dimensional NL-SRA was performed using the PDMY02 material model under undrained conditions. A comparison of the acceleration time histories between the wave motion injected at the bedrock and the motion reaching the ground surface is presented in Figure 4.

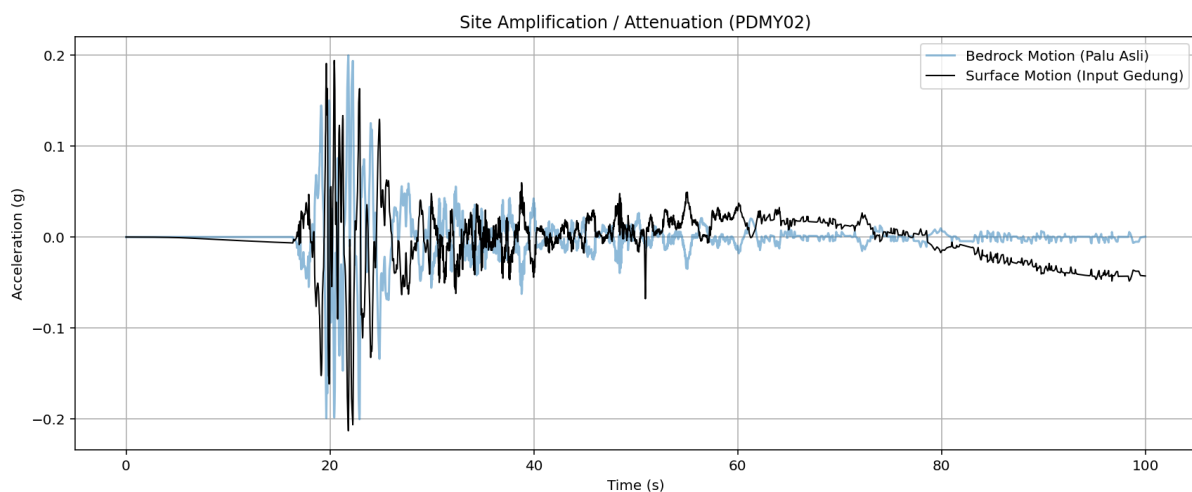


Figure 4. Comparison of seismic acceleration time histories between the bedrock input motion (lower blue curve) and the ground-surface response (upper black curve) at RSU Anutapura.

Based on Figure 4, a significant spatio-temporal transformation of the wave motion is observed as it propagates from the bedrock (32 m depth) to the ground surface. The seismic excitation at the bedrock (blue curve) exhibits high-frequency characteristics with closely spaced peak fluctuations, producing an input Peak Ground Acceleration (PGA) of 0.200 g.

As the wave penetrates the liquefied sandy layers, the acceleration record at the ground surface (black curve) shows a marginal amplification of peak amplitude to 0.213 g. However, the most fundamental seismic modification does not lie in the absolute PGA value, but rather in the transformation of the wave frequency characteristics.

The surface response curve (black) visually indicates a loss of high-frequency components, as evidenced by the dramatic increase in spacing between successive wave peaks (period elongation) and the smoother oscillatory shape associated with low-frequency content. This waveform transformation physically demonstrates the degradation of soil-matrix shear stiffness caused by effective stress dissipation during excess pore water pressure generation. Although no absolute de-amplification occurred in the peak PGA value, the softening of the soil layers consistently produced an isolation effect against high-frequency waves, a mechanical phenomenon commonly observed in liquefied loose sand deposits (Kramer, 1996; Cubrinovski et al., 2019).

The waveform transformation characterized by period elongation and the filtering of high-frequency components at the ground surface, as observed in the NL-SRA records, is a direct manifestation of plastic material degradation. From a fundamental soil mechanics perspective, this phenomenon is governed by Terzaghi's effective stress principle under undrained cyclic loading conditions.

When the saturated loose sand deposits at RSU Anutapura were subjected to the seismic excitation of the 2018 Palu Earthquake, the soil particles exhibited an inherent tendency toward volumetric contraction. However, because the pore water could not dissipate instantaneously under undrained conditions, this contractive tendency transferred stress from the soil skeleton to the pore fluid. As a result, excess pore water pressure Δ_u increased rapidly. As shaking continued, the pore pressure ratio $R_u = \frac{\Delta_u}{\sigma'_{v0}}$ rose sharply until reaching or approaching 1.0. At this critical state, the effective stress of the soil σ' was drastically reduced to near zero (Ishihara, 1993).

As a mechanical consequence of the loss of effective stress, the shear stiffness of the soil matrix G decreases dramatically. Theoretically, high-frequency shear waves require a sufficiently stiff medium to propagate efficiently. When the sand layers between depths of 5 and 31 m liquefy and lose their shear stiffness, this thick stratum effectively transforms into a viscous fluid-like medium. The transitional layer then acts as a shear isolation base that filters high-frequency shear-wave propagation from the bedrock through a low-pass filtering mechanism (Kramer, 1996; Elgamal et al., 2002).

Therefore, the seismic energy that reaches the ground surface is dominated by low-frequency waves, manifested as long-period oscillations (period elongation) in the surface acceleration time history. This mechanical interpretation confirms that the absolute PGA value alone cannot adequately represent seismic hazard in liquefied soils; rather, the shift in frequency content (period elongation) becomes the more critical parameter because it may induce resonance in medium- to long-period structures such as the buildings of RSU Anutapura (Cubrinovski et al., 2019).

4. Conclusion

Based on the in-depth case study of seismic vulnerability and site response at RSU Anutapura following the 2018 Palu Earthquake, this study draws the following principal conclusions:

1. Empirical Confirmation of Extreme Vulnerability: The Simplified Procedure successfully identified and confirmed the presence of a massive liquefaction hazard zone within the soil profile of RSU Anutapura. Sand deposits in very loose to medium dense conditions at shallow to intermediate depths (5–31 m) exhibited extreme susceptibility to seismic excitation, which was the primary trigger for the loss of foundation bearing capacity at the site.
2. Validation of Undrained Behavior as a Seismic Filter: Advanced numerical modeling through one-dimensional Nonlinear Site Response Analysis (1D NL-SRA), using the PDMY02 constitutive model, proved highly effective in simulating the plastic behavior of Palu sand under undrained conditions. The analysis mechanically confirmed that liquefaction of shallow layers induced by excess pore water pressure buildup acted as a natural seismic filter (shear isolator), reducing the propagation capacity of shear waves toward the ground surface.
3. Waveform Modification and Significance for Structural Input: As a consequence of shear stiffness degradation within the liquefied layers, seismic waveforms were significantly modified through attenuation of high-frequency components and the onset of period elongation. The resulting modified surface acceleration time histories represent a critical seismic demand that cannot be captured using conventional empirical methods alone. Extraction of these dynamic time histories constitutes a key output of the proposed hybrid framework, providing highly realistic input motions for future structural vulnerability assessments and advanced Soil–Structure Interaction (SSI) analyses.

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