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The Resonance Trap: Kinematic Collapse of R/C Frames Triggered by Shallow Top-Down Liquefaction in Near-Fault Zones

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Abstract: The conventional fixed-base seismic design paradigm suffers from fundamental limitations in predicting the response of structures situated on liquefaction-prone deposits in near-fault zones. Contrary to the common assumption that post-liquefaction soil softening acts beneficially as a natural base isolator, this study reveals a lethal anomaly known as a "double resonance trap." Employing a non-linear coupled Soil-Structure Interaction (SSI) numerical modeling approach—utilizing the Beam on Nonlinear Winkler Foundation (BNWF) framework and the PM4Sand bounding-surface plasticity material model—computational evaluations were conducted on specific stratigraphic profiles subjected to near-fault earthquake excitation. Simulation results demonstrate that the initiation of shallow (top-down) liquefaction at a depth of 5 meters triggers a period elongation phenomenon. Mechanically, this process shifts and concentrates inertial energy into extreme resonance spikes (reaching 7.5g to 9.0g) within the medium-to-long period range (T ≈ 1.1–1.3 s). Simultaneously, the loss of vertical bearing capacity induces asymmetric settlement, generating massive secondary P-Delta moments. This destructive interaction overwhelms the axial-flexural capacity of column base elements, causes premature plastic hinge failure, and drives the frame structure toward global kinematic collapse (with roof drift exceeding 6.0%). These analytical findings conclusively demonstrate that the generic design spectra of SNI 1726:2019 can lead to fatal under-design, underscoring the urgent need for integrated geotechnical-structural, site-specific design.
Keywords: Soil-Structure Interaction (SSI), Near-fault earthquake, Shallow liquefaction, Period elongation, Coupled kinematic collapse, P-Delta effect.

I. INTRODUCTION

Active strike-slip faults, such as the Palu-Koro fault system, represent one of the most potentially destructive seismic sources for civil infrastructure. Wave propagation characteristics within the near-fault zone are governed by the massive, instantaneous release of kinetic energy, which abruptly disrupts structural equilibrium. This phenomenon is fundamentally driven by two primary kinematic anomalies: forward rupture directivity and fling-step. Forward rupture directivity causes an accumulation of energy that reaches the site as a long-period velocity pulse, forcing the structure to absorb massive amounts of energy within just the first one or two cycles. Simultaneously, the fling-step phenomenon imposes a permanent static tectonic deformation, exerting a strong, asymmetric translational push on the foundation system [1] [2] [3] [4].

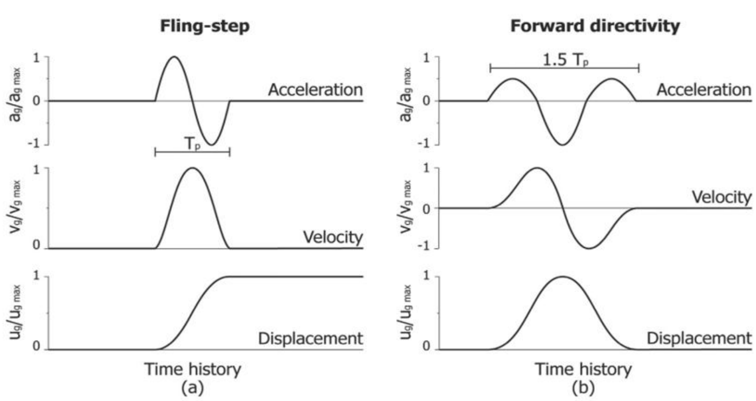

Fig. 1 Idealization of a sinusoidal pulse

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In the face of such extreme energy demands, the conventional paradigm for earthquake-resistant structural design—as embodied in contemporary standards—remains dominated by the fixed-base foundation dogma. This approach naively postulates that seismic energy is transmitted uniformly across the entire base of the building, without kinematic modification by the geotechnical profile. This postulate underpins the formulation of standard dynamic equations of motion:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{I\}\ddot{u}_g(t)$$

Where $[M]$ is the mass matrix, $[C]$ the damping matrix, $[K]$ the stiffness matrix, and $\ddot{u}_g(t)$ represents the ground acceleration vector, assumed to oscillate uniformly.

This assumption of absolute rigidity proves fundamentally flawed when applied to structures situated on liquefaction-prone alluvial deposits. In saturated, non-cohesive formations, repetitive cyclic loading triggers a rise in excess pore water pressure (Δ_u), drastically reducing soil shear strength in accordance with Terzaghi's effective stress principle:

$$\tau = (\sigma'_v - \Delta u) \tan \phi'$$

Where the ultimate shear stress (τ) decays to zero when the increase in pore water pressure equals the initial effective vertical stress (σ'_v).

When the excess pore water pressure ratio (r_u) reaches the critical threshold of 1.0, the base stiffness matrix $([K])$ degrades to near-zero. The fixed-base design paradigm is inherently blind to this post-liquefaction vertical deformation anomaly. In practice, the loss of soil bearing capacity triggers asymmetric foundation settlement, forcing the structure to accommodate differential settlement (Δ_v); this redistributes gravitational axial forces and generates destructive secondary moments due to the P-Delta $(P - \Delta)$ effect [5] [6].

In contemporary geotechnical engineering literature, a reductionist view frequently emerges, positing that post-liquefaction soil softening can benefit the superstructure. The degradation of soil shear modulus is perceived as acting like a natural base isolator, effectively cutting off the transmission of high-frequency inertial waves to the foundation level. However, this hypothesis conceals a critical research gap. This article presents an analytical proof to unravel the paradox, revealing that soil softening due to liquefaction—particularly in shallow surficial formations—does not necessarily save the structure. Instead, this anomaly induces a period elongation that shifts the inertial resonance peak toward the medium-to-long period range. This phenomenon creates a lethal resonance trap for mid-rise structures; when resonance coincides with the loss of vertical bearing capacity, it inevitably triggers a coupled differential collapse.

II. COMPUTATIONAL METHODOLOGY

The modeling architecture in this study was developed using a coupled numerical approach to replicate the transient interaction between the degradation of geotechnical capacity and the inelastic response of the superstructure. The entire dynamic integration scheme was executed using a finite element computational platform.

A. Constitutive Calibration of Liquefiable Soil Materials

The reliability of soil-structure interaction modeling in non-cohesive sedimentary formations depends heavily on the precision of the material constitutive model calibration. The hysteretic behavior and accumulation of plastic volumetric strain in sand deposits are modeled using the PM4Sand bounding-surface plasticity framework. To accurately capture the in-situ stress path, material parameter calibration is performed via two-dimensional single-element Direct Simple Shear (DSS) simulations under undrained conditions. These undrained conditions are computationally replicated using a constant-volume constraint method, wherein the sand's tendency to contract is restrained and translated into a reduction in effective vertical stress (σ'_v) [7].

In order to avoid manual calibration bias, an autonomous optimization algorithm based on bisection search is implemented to determine the contraction rate parameter (h_{po}). This algorithm is specifically designed to optimize the h_{po} value so that critical liquefaction conditions, represented by the excess pore water pressure ratio (r_u), can be achieved precisely.

$$r_u = 1 - \frac{\sigma'_v}{\sigma'_{v0}} \geq 0.95$$

Where σ'_v is the transient effective vertical stress and σ'_{v0} is the initial effective vertical stress. The algorithm enforces the boundary condition $r_u \geq 0.95$ such that it is reached exactly at the target of 15 loading cycles [8] [9].

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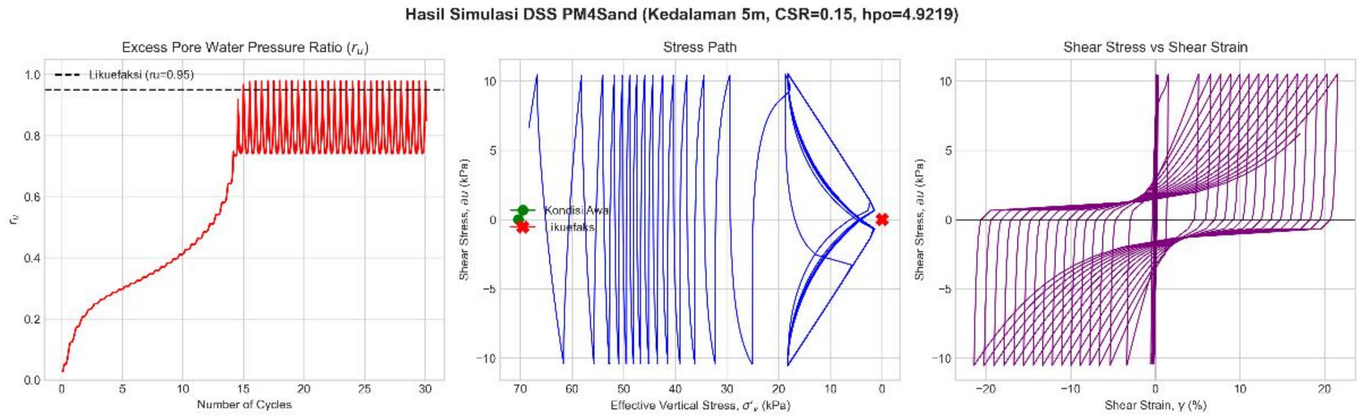

Fig. 2 DSS PM4Sand simulation results

B. *Soil-Structure Interaction Architecture (BNWF)*

Dynamic load transfer at the soil-structure interface is addressed by discretizing the soil medium into a series of independent, non-linear spring elements within the framework of the Beam on Nonlinear Winkler Foundation (BNWF) model. The interaction mechanism is formulated in terms of three orthogonal degrees of freedom: lateral resistance $(p-y)$, axial shaft friction $(t-z)$, and ultimate end bearing resistance $(q-z)$ [10] [11].

Instead of using static soil parameters, the stiffness matrix and ultimate capacity of this spring framework are subjected to transient degradation. Soil resistance parameters are directly reduced based on the evolution curve of the excess pore water pressure ratio (r_u)—derived from a 1D soil column analysis—thereby simulating the exponential loss of vertical bearing capacity associated with the occurrence of soil liquefaction.

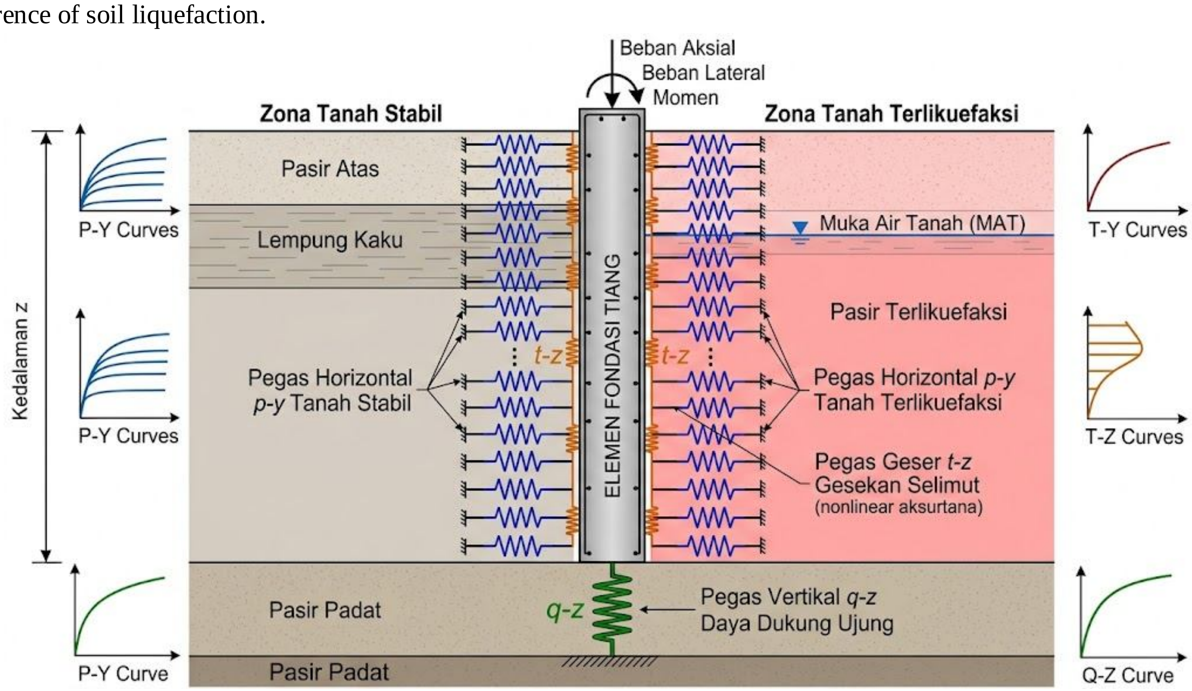

Fig. 3 Schematic of the BNWF method for foundation elements

C. *Fiber-Based Superstructure Modeling (Fiber Section)*

The building's lateral load-resisting system is represented by reinforced concrete frames discretized using displacement-based elements to capture the phenomenon of distributed plasticity. The section matrix is formulated using a fiber section integration approach that explicitly accounts for the non-linear stress-strain behavior of the constituent components.

Steel reinforcement is modeled using the Steel02 material to accommodate kinematic hardening and the Bauschinger effect, while the concrete section is represented by the Concrete02 material, which mechanically distinguishes between the strength of the confined core concrete and the behavior of the unconfined outer concrete cover (prone to spalling) [12].

$$M(x) = \int_A \sigma(\varepsilon, \dot{\varepsilon}) \cdot y \, dA \approx \sum_{i=1}^{n_{fiber}} \sigma_i \cdot y_i \cdot A_i$$

The above equation shows the integration of fiber-based cross-sectional moments that capture the inelastic stress excursions at each material layer.

Untuk mengevaluasi instabilitas global, transformasi matriks kekakuan elemen ke dalam koordinat global diformulasikan menggunakan metode P-Delta. Formulasi ini mutlak diperlukan untuk mendokumentasikan induksi momen sekunder destruktif yang lahir dari defleksi lateral ($P - \Delta$ makroskopis) dan eksentrisitas gaya aksial akibat amblesan diferensial fondasi (Δ_v) secara real-time.

To evaluate global instability, the transformation of the element stiffness matrix into global coordinates is formulated using the P-Delta method. This formulation is essential for capturing, in real-time, the induction of destructive secondary moments arising from lateral deflection (macroscopic $P - \Delta$) and axial force eccentricity caused by differential foundation settlement (Δ_v).

D. Near-Fault Seismic Loading Protocol

To mitigate uncertainty bias arising from record-to-record variability, a dynamic analysis (Non-Linear Time History Analysis) was performed using a suite of historical earthquake acceleration time-history records. The selection of records was strictly limited to earthquakes originating within 15 km of the fault rupture (near-fault zone) that exhibited directed velocity pulse characteristics [13].

To ensure a fair comparison of structural performance, all earthquake time-history records were linearly scaled (amplitude scaling) to an absolute target Peak Ground Acceleration (PGA) of 0.4g without altering their original frequency content. This extreme intensity was deliberately applied as a definitive trigger to ensure the immediate and massive onset of soil liquefaction during the initial stages of wave propagation. This condition forced the superstructure elements to operate well beyond their linear-elastic range, thereby isolating kinematic variables from soil softening effects—which serve as the primary governing parameter for structural collapse—for the purpose of analysis [14].

III.RESULTS: SITE RESPONSE DYNAMICS AND RESONANCE TRAPS

Evaluasi komputasional pada tapak RSUD Anutapura menyingkap anomali kinematik yang secara fundamental meruntuhkan asumsi konvensional terkait efek peredaman likuifaksi. Analisis elemen hingga menunjukkan bahwa mekanisme kegagalan di tapak ini secara spesifik dikendalikan oleh fenomena likuifaksi superfisial dangkal (*top-down*).

A. Inisiasi Likuifaksi Superfisial (Top-Down Liquefaction)

A computational evaluation of the Anutapura Regional General Hospital (RSUD) site reveals kinematic anomalies that fundamentally overturn conventional assumptions regarding the damping effects of liquefaction. Finite element analysis indicates that the failure mechanism at this site is specifically governed by the phenomenon of shallow, top-down liquefaction.

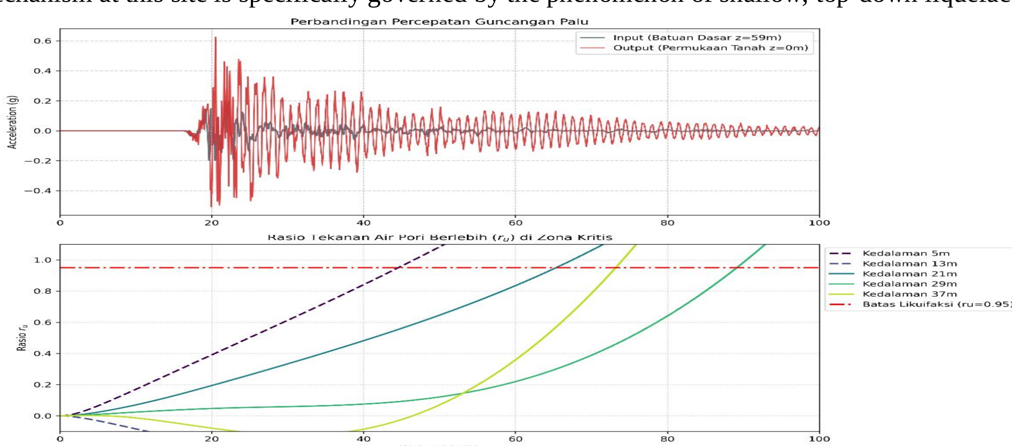

Fig. 4 Site response of Anutapura Regional General Hospital for the Palu earthquake

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B. Spectral Modification and Period Elongation

The liquefaction of the sand matrix at this shallow depth triggers a drastic loss of shear modulus—a phenomenon known in dynamic soil mechanics as soil softening. Contrary to the common view that this softening interrupts wave propagation much like a base isolator, visualization of the transformation into the frequency domain demonstrates that amplitude attenuation in the time domain does not actually eliminate seismic energy.

Conversely, this geotechnical mechanism mechanically modifies and shifts the earthquake's dominant frequency distribution. The spectral peak (S_{a-max}) consistently undergoes a period elongation phenomenon. Rather than being dissipated, the kinetic energy shifts from the high-frequency band toward the medium-to-long period range, becoming centralized and concentrated in the $T \approx 1.1$ s to 1.3 s interval.

To quantify stiffness degradation due to liquefaction at a depth of 5 meters, the reduced soil shear modulus (G) can be empirically approximated using the following equation:

$$G_{liq} \approx G_{max}\sqrt{1 - r_u}$$

Where $r_u \approx 1.0$ at a depth of 5 meters, the natural frequency of the soil deposit shifts massively toward longer periods.

C. Extreme Spectral Demands and Exceedance of Design Standards

This shift of energy into the 1.1 s to 1.3 s period range creates a highly lethal resonance trap for mid- to high-rise structures. Numerical data extraction reveals that the spectral acceleration demand (S_a) at the surface within this resonance band surges to extreme and uncontrolled levels.

During the near-fault El Centro earthquake excitation, recorded spectral acceleration reached an extreme 9g. Meanwhile, during the Kocaeli earthquake, acceleration demands peaked at 7.5g. These sharply surging inertial demands vastly exceeded the safety limits defined by the design spectrum envelope in SNI 1726:2019. This computational evidence demonstrates that conventional design standards are wholly inadequate for providing structural protection at a site with a stratigraphic profile like that of RSUD Anutapura, as the building is forced into dynamic resonance at intensities far exceeding the ductility capacity of its structural sections.

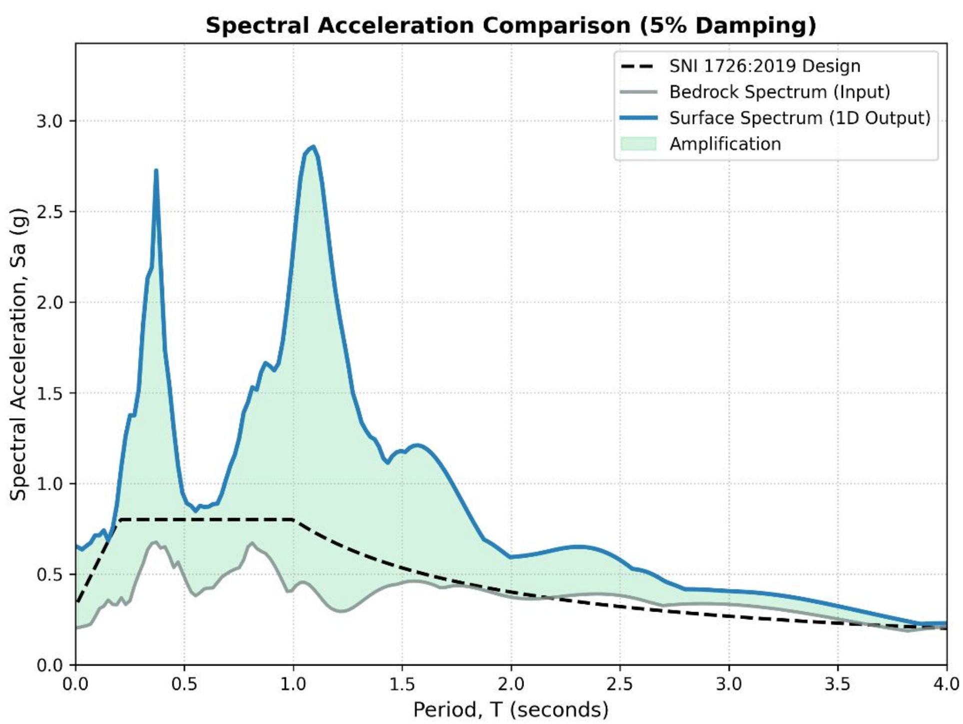

Fig. 5 RSUD Anutapura earthquake spectrum for the Palu earthquake

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IV. DISCUSSION: COUPLED KINEMATIC COLLAPSE

The structural implications of the resonance trap triggered by shallow liquefaction at the Anutapura Regional General Hospital site proved catastrophic for the reinforced concrete portal frames. The structure was forced into dynamic resonance, which combined destructively with the instantaneous loss of vertical bearing capacity in the shallow foundations. This destructive interaction revealed a coupled kinematic collapse phenomenon that conventional fixed-base design methods had failed to predict.

A. Differential Settlement and P-Delta Effect Induction

When the soil matrix undergoes a radical loss of shear modulus, foundation elements experience a drastic mechanical reduction in dynamic end-bearing resistance $(q-z)$ and shaft friction $(t-z)$. This loss of vertical resisting force equilibrium triggers severe asymmetric differential settlement between supports under the impact of dynamic excitation. Such differential settlement (Δ_v) directly disrupts the building's initial gravitational balance, precipitating an extreme redistribution of axial forces (P) among the columns.

Furthermore, this kinematic distortion resulting from gravitational eccentricity exponentially amplifies the secondary moments in the portal elements. This increase in destructive secondary moments can be quantified using the following formulation:

$$M_{sekunder} = P \cdot \Delta_v$$

Where the axial load eccentricity (P) resulting from asymmetric differential settlement (Δ_v) induces a secondary bending moment $(M_{secondary})$ acting independently of the pure lateral inertial force.

B. Plastic Hinge Capacity Degradation due to Axial-Flexural Loading

This surge in $P-\Delta$ secondary moments imposes a double penalty on the superstructure. Extraction of the moment-curvature hysteresis curves for the plastic hinge element at the column base demonstrates a radical deviation from the ideal yield envelope behavior.

The recorded hysteresis curve exhibits exponential decay beyond the peak flexural capacity point, confirming the early onset of section softening. This local failure stems not merely from reinforcement detailing deficiencies or a lack of conventional lateral ductility, but rather from axial-flexural kinematic demands. The base plastic hinge is forced into the inelastic domain, undergoing destructive curvature that ruptures the section before seismic inertial energy peaks—an anomaly driven entirely by differential foundation settlement in the substructure.

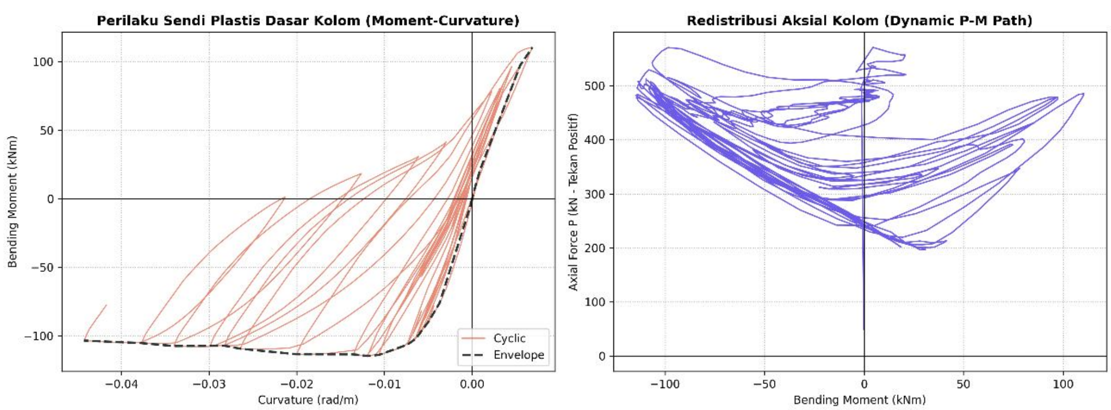

Fig. 6 Plastic hinge behavior and column axial force redistribution

C. Global Collapse (Kinematic Pushover)

The inability of vertical elements to maintain equilibrium following the formation of plastic hinges mechanically drives the structure into a kinematic pushover state. An evaluation of macroscopic stability, represented by the evolution of the Roof Drift Ratio (RDR), confirms the mathematical certainty of this global collapse.

Time-history records dynamically confirm that the RDR parameter surged uncontrollably beyond the absolute physical collapse limit of 6.0% (0.06 rad). Exceeding this "Collapse Prevention" performance threshold provides empirical evidence that the building had completely lost its lateral tangent stiffness.

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Ultimately, the structure collapsed under its own weight following the failure of its foundation supports—challenging the conventional design dogma that often assumes buildings collapse solely due to the impact of excessive lateral shaking.

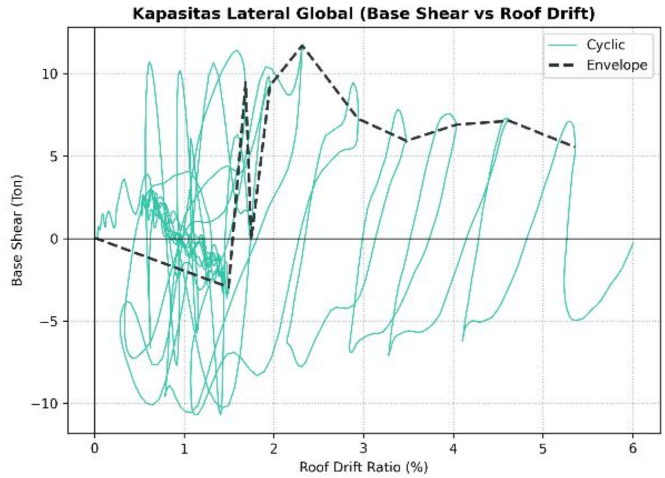

Fig. 7 Global lateral capacity and roof displacement

V. CONCLUSION

A coupled computational investigation focused on the specific site of Anutapura Regional General Hospital (RSUD Anutapura) has definitively exposed a fatal flaw in the fixed-base seismic design paradigm. The study validates that soil softening resulting from shallow, superficial liquefaction does not always benefit the structure by acting as a natural base isolator; instead, it can manifest as a lethal "double resonance trap."

First, a spectral trap is created when the liquefaction of subsurface soil at a depth of 5 meters triggers a period-elongation anomaly, mechanically shifting and focusing near-fault seismic inertial energy into an extreme resonance spike within the medium-to-long period range ($T \approx 1.1 - 1.3$ seconds). Second, a gravity trap is simultaneously activated when the loss of vertical load-bearing capacity triggers asymmetric subsidence, generating a massive secondary P-Delta moment that prematurely ruptures the plastic hinges at the base of the columns.

This destructive combination of coupled kinematic collapse utterly invalidates the protective capacity of the generic design spectrum envelope in SNI 1726:2019. Conventional probabilistic design is shown to suffer from a fatal degree of under-design, as it fails to anticipate extreme spectral demands and the axial-flexural kinematic effects resulting from geotechnical support deformation.

While these findings provide an essential mechanistic synthesis regarding soil-structure interaction anomalies, the evaluation framework in this study is limited to a deterministic assessment using a single peak excitation intensity of 0.4g. As a roadmap for future research, this assessment framework will be upgraded to a probabilistic evaluation through the execution of Incremental Dynamic Analysis (IDA). This iterative dynamic analysis will be used to comprehensively construct seismic fragility curves and to evaluate the effectiveness of numerical retrofitting interventions—such as deep pile foundation substitution—in reducing site-specific structural vulnerability.

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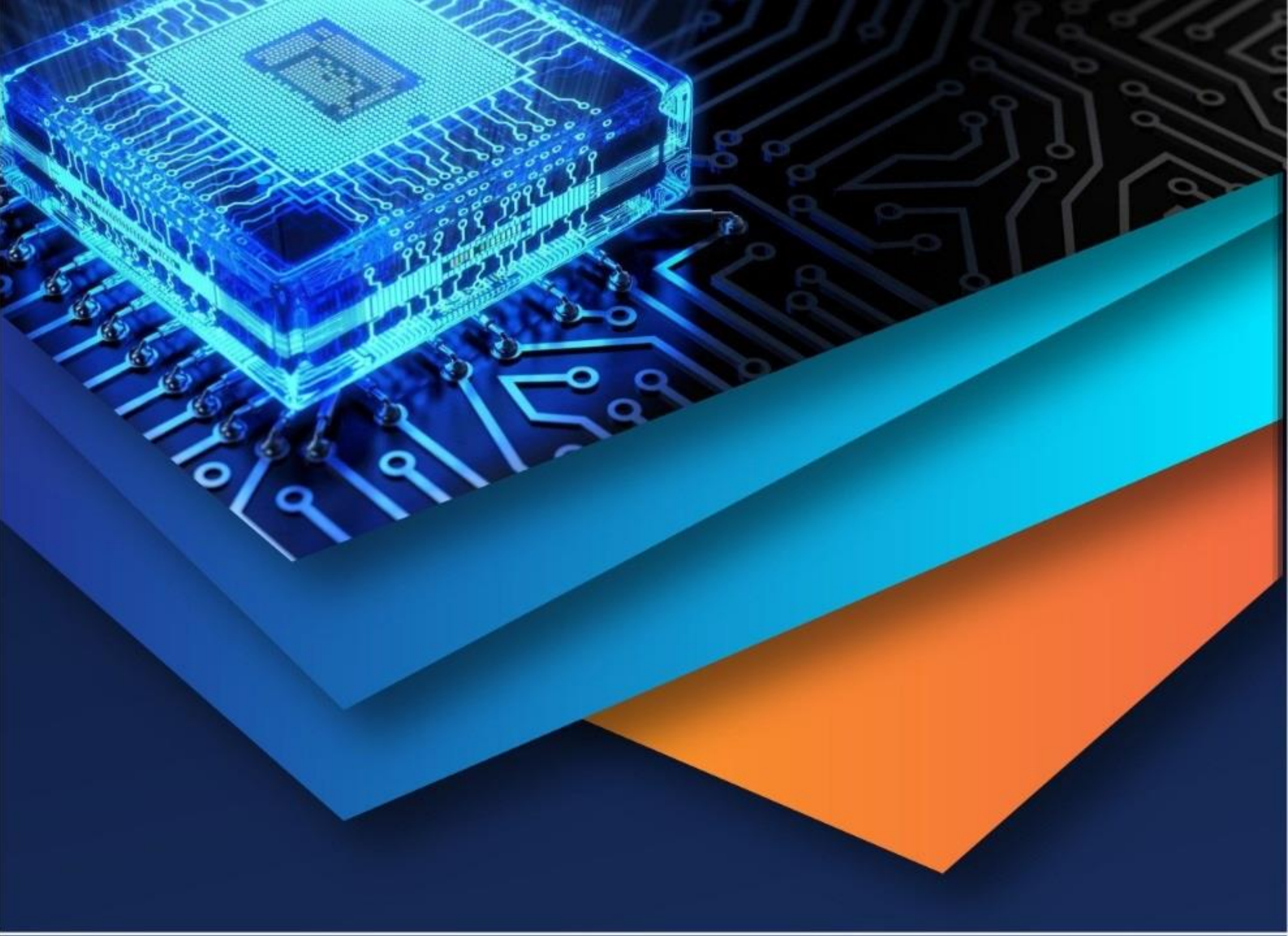

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