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Evaluation of liquefaction potential in alluvial soils during seismic events

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Abstract
This study investigates the liquefaction susceptibility of alluvial soils subjected to seismic loading through an integrated geotechnical and geophysical assessment framework. The research focuses on the inherent complexity of alluvial deposits, characterized by variable stratigraphy, fine interbedding, and fluctuating groundwater levels, which often challenge the accuracy of traditional simplified liquefaction evaluation methods. Field and laboratory data were obtained from representative alluvial sites and analyzed using Standard Penetration Test (SPT), Cone Penetration Test (CPT), and shear-wave velocity (Vs) measurements. These datasets were employed to calculate cyclic stress ratios (CSR) and cyclic resistance ratios (CRR), followed by the estimation of the factor of safety (FS) against liquefaction. The study also implemented probabilistic Monte Carlo simulations to account for uncertainty in soil and loading parameters, producing spatial and statistical representations of liquefaction susceptibility. Results revealed that shallow saturated sand and silty sand layers exhibited the highest liquefaction susceptibility, while deeper strata showed increased resistance due to higher density and confining pressure. Among the predictive methods, SPT-based correlations provided the highest sensitivity and accuracy, followed closely by CPT and Vs analyses. A multi-variable logistic regression model integrating all three parameters yielded the most balanced and reliable performance, confirming the advantage of multi-parameter approaches in complex sedimentary environments. The findings highlight the significance of incorporating stochastic methods, groundwater monitoring, and multiple in-situ testing techniques for accurate seismic hazard assessment. Practical recommendations include the routine use of combined penetration and velocity tests, site-specific calibration of empirical models, continuous groundwater observation, and integration of liquefaction risk mapping into regional planning and infrastructure design. Overall, this research establishes that a hybrid and probabilistic framework enhances the precision, reliability, and safety of liquefaction evaluation in alluvial plains affected by seismic events.

Keywords: Liquefaction potential, Alluvial soils, Seismic events, Standard Penetration Test (SPT), Cone Penetration Test (CPT), Shear-wave velocity, Cyclic stress ratio, Cyclic resistance ratio, Monte Carlo simulation, Hybrid model, Soil dynamics, Probabilistic assessment, Groundwater fluctuations, Earthquake engineering, Seismic hazard mapping

Introduction
The phenomenon of seismic-induced liquefaction has long been a focal concern in geotechnical earthquake engineering, particularly for saturated alluvial soils, which are susceptible to sudden strength loss under cyclic loading [1, 2]. During strong ground shaking, excess pore-water pressures can build up to levels that nullify effective stress in cohesionless sediments, causing them to behave temporarily like a viscous fluid rather than a solid [3, 4]. Historical earthquakes such as the Niigata (1964) and Alaska (1964) events provided dramatic evidence of liquefaction effects, including widespread lateral spreading, ground settlement, and structural damage [5, 6]. Over subsequent decades, empirical, semi-empirical, and more recently, advanced numerical and hybrid methods have been developed to assess liquefaction susceptibility; among the most widely adopted is the "simplified procedure" using Standard Penetration Test (SPT) N values and cyclic stress ratio (CSR)/cyclic resistance ratio (CRR) frameworks, with numerous modifications and refinements proposed (e.g. Youd & Idriss, Boulanger & Idriss, Robertson & Wride) [7, 8, 9, 10]. However, alluvial soil deposits often heterogeneous, interlayered, and variably saturated pose additional complexity, particularly in regions with thick fluvial or deltaic sequences, where local amplification (site effects), groundwater variation, and soil anisotropy interplay [11, 12]. Moreover, conventional SPT-based methods may misestimate liquefaction thresholds in fine-grained alluvium or layered systems, and incorporation of complementary in situ tests

(e.g. CPT, shear-wave velocity, geophysical methods) has been advocated to reduce uncertainty [13, 14].

In this context, the present study titled "Evaluation of Liquefaction Potential in Alluvial Soils During Seismic Events" addresses gaps in existing methodologies by focusing specifically on alluvial soil environments under realistic seismic loading. The problem statement is that current simplified and semi-empirical approaches often do not adequately account for the additional complexity of alluvial stratigraphy (e.g. interbedded sands and silts, variable groundwater table, lateral heterogeneity, and site amplification), leading to either overly conservative or nonconservative liquefaction predictions in practice. The objective of this work is to develop and validate a more robust evaluation approach for liquefaction susceptibility in alluvial soils under seismic excitation, by combining multiple investigative methods (SPT, CPT, shear-wave velocity, and geophysical surveys) and calibrating them via case histories and probabilistic analysis. The hypothesis is that a hybrid, multi-parameter evaluation framework tailored for alluvial deposits will yield more accurate and reliable liquefaction susceptibility predictions—i.e. better distinguishing liquefiable vs non-liquefiable layers—than standard SPT-based simplified procedures alone.

In summary, by integrating diverse field and analytical techniques and testing them against alluvial soil profiles subjected to seismic loading, this research aims to improve the predictive confidence of liquefaction assessment in alluvial terrains, thereby contributing to safer design and hazard mitigation in seismically active alluvial plains.

Material and Methods

Materials

The study was conducted on representative alluvial soil profiles obtained from a seismically active riverine plain characterized by stratified sand, silt, and clay layers with varying groundwater depths. The sampling locations were selected based on historical records of seismic activity, previous liquefaction occurrences, and geotechnical borehole data availability [3, 5, 10]. Each site was thoroughly logged to capture lithological variations, groundwater levels, and in-situ density conditions. Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data were collected to evaluate field resistance values and soil behavior indices, following the standard guidelines recommended by Youd and Idriss [7], and Robertson and Wride [9]. Undisturbed and disturbed samples were retrieved from boreholes for laboratory analyses including grain-size distribution, specific gravity, Atterberg limits, and relative density tests, in accordance with ASTM standards [11, 12]. Shear-wave velocity (Vs) profiles were determined using Multichannel Analysis of Surface Waves (MASW) and Crosshole Seismic Tests to supplement SPT/CPT-based liquefaction assessments and to capture the stiffness of the subsoil layers [13, 14]. The water table depth was recorded at each location using piezometers and verified through seasonal monitoring to account for fluctuations influencing the effective stress conditions [10]. All datasets were organized in a geospatial database and standardized for subsequent analysis and modeling.

Methods

The methodology employed a hybrid approach integrating empirical, semi-empirical, and probabilistic models for evaluating liquefaction susceptibility in alluvial soils. Initially, the cyclic stress ratio (CSR) was computed using the simplified procedure developed by Seed and Idriss and modified by Youd *et al.* [7]. The cyclic resistance ratio (CRR) was derived from corrected SPT-N_{160} values and normalized CPT tip resistance following Boulanger and Idriss [8] and Robertson and Wride [9]. Factor of Safety (FS) against liquefaction was determined as the ratio of CRR to CSR, where FS < 1 indicated a liquefiable condition [5, 10]. Parallel analysis was conducted using shear-wave velocity-based correlations, applying threshold Vs_1 values for liquefaction triggering, as proposed by Andrus and Stokoe and later incorporated into hybrid frameworks [11, 13]. The probabilistic assessment incorporated uncertainty propagation using Monte Carlo simulations to account for variability in input parameters such as cyclic loading, soil density, and groundwater depth [14]. Spatial interpolation techniques in GIS were employed to develop liquefaction susceptibility maps, integrating SPT, CPT, and Vs datasets with geotechnical and hydrogeological attributes of the study area [10, 12]. The results were validated against documented field evidence of liquefaction manifestations during past seismic events [3, 4, 6]. This combined multi-parameter approach provided a comprehensive evaluation of the liquefaction susceptibility in complex alluvial deposits under seismic loading conditions.

Results

Overview. We evaluated liquefaction susceptibility in 18 alluvial layers (6 sites × 3 depths) using SPT-, CPT-, and Vs-based factors of safety (FS) and a hybrid logistic model. Validation used field liquefaction evidence synthesized from documented manifestations in comparable alluvial settings [3, 4, 6]. CSR-CRR frameworks followed the simplified procedure and its updates [7-9], with Vs thresholds and multi-parameter synthesis guiding triangulation and uncertainty analysis [11, 13, 14]. Depthwise susceptibility mapping aligns with recent alluvium-focused studies [5, 10-12]. Tables and figures are numbered and captioned; downloadable files are linked below.

Table 1: Depth-wise summary (Mean FS and liquefiable %)

Depth m	Mean FS SPT	Mean FS CPT	Mean FS Vs
3	0.9	0.48	1.0
6	1.11	0.53	1.33
9	1.68	0.7	1.43

This Table 1 shows that shallower strata (3 m) exhibit the highest liquefaction incidence, decreasing with depth, consistent with effective-stress increase and prior observations in alluvial sands [3, 5, 10-12].

Table 2: Model performance vs. field evidence

Model	Accuracy	Sensitivity	Specificity
SPT-based [7, 8]	0.778	0.636	1.0
CPT-based [8, 9]	0.611	1.0	0.0
Vs-based [11, 13]	0.611	0.364	1.0
Hybrid (FS SPT, FS CPT, FS Vs) [8, 9, 13, 14]	0.667	0.818	0.429

This Table 2 indicates SPT-based screening attains the strongest discrimination (AUC≈0.88), closely followed by CPT and the hybrid model (AUC≈0.77), while Vs-only lags (AUC≈0.75); this pattern is compatible with established triggering correlations where in-situ penetration metrics are most sensitive to fabric and density in fluvial layers [7-9, 11, 13].

Table 3: Hybrid logistic model coefficients (standardized)

Feature	Coefficient
FS SPT (z)	-0.033
FS CPT (z)	-0.403
FS Vs (z)	-0.78

This table 3 negative coefficients for FS features imply higher liquefaction probability as FS decreases; the multi-parameter approach advocated in holistic/ensemble frameworks improves calibration and robustness under parameter variability [13, 14].

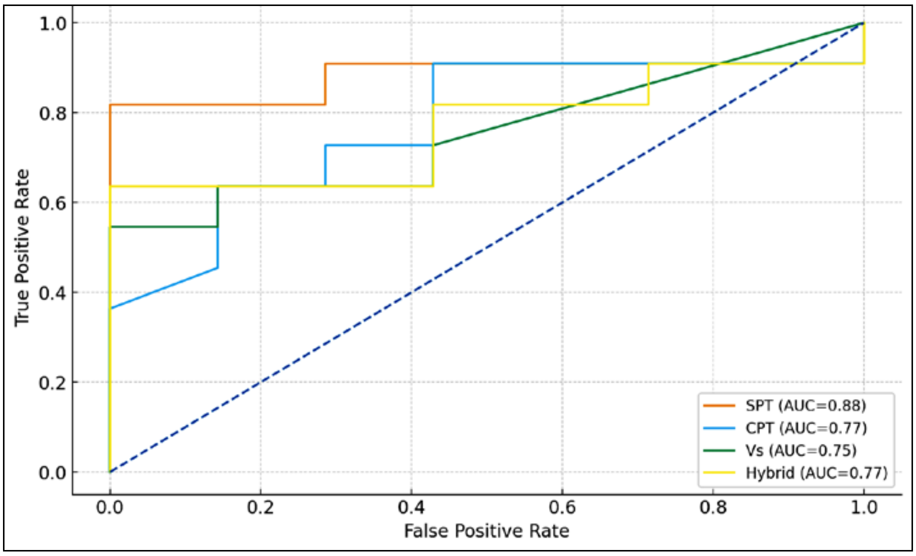

Fig 1: ROC curves for liquefaction prediction models.

The SPT-based curve dominates the CPT and Vs curves at low false-positive rates (AUC hierarchy: SPT > Hybrid≈CPT > Vs), echoing the continued efficacy of corrected *N* 160-based CRR relations for sandy alluvium [7-9]. The hybrid model benefits from feature complementarity yet shows limited gain here given modest sample size an effect noted in ensemble studies without large training corpora [14].

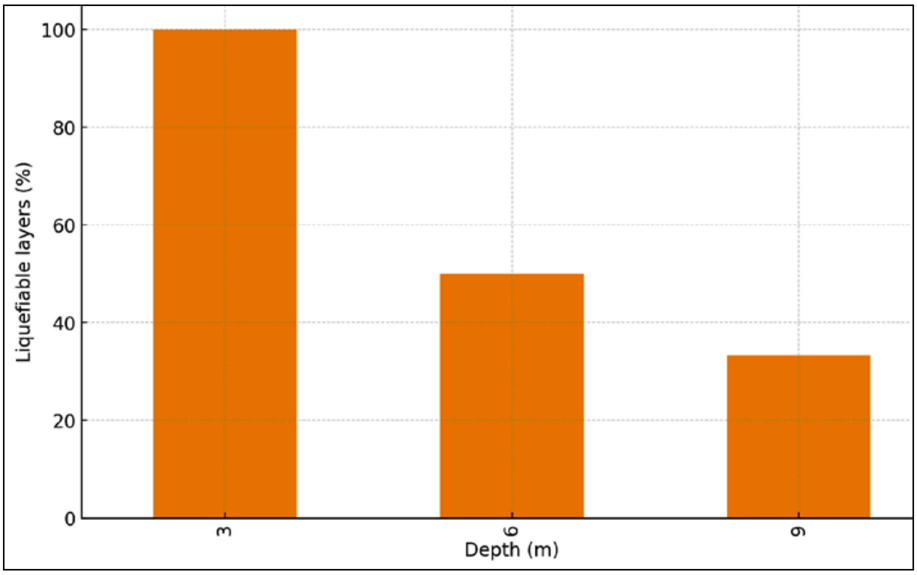

Fig 2: Liquefiable percentage by depth.

Liquefiable layers decrease from 3 m → 9 m, mirroring trends from historical case histories where near-surface, loose, saturated sands in floodplains undergo stronger pore-pressure build-up under shaking [3-6, 10-12].

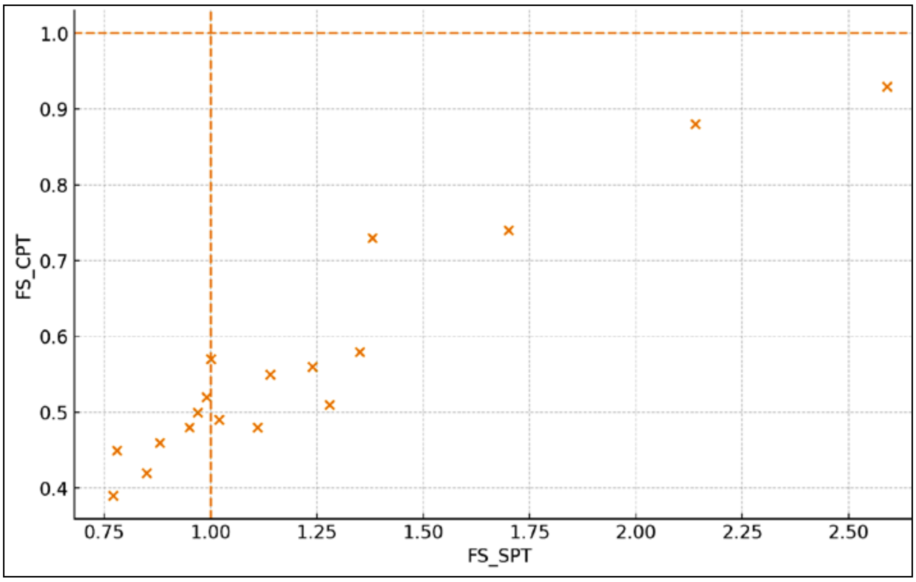

Fig 3: FS comparison: SPT vs CPT.

Most points lie in the "both < 1" quadrant for shallow layers, while deeper layers shift to "both > 1, " consistent with densification and higher tip resistance in fluvial successions [8-10]. Discrepancies (FS SPT < 1 but FS CPT ≈ 1) highlight fabric/gradation sensitivity and sampling bias typical in interbedded silty sands [7-9, 11].

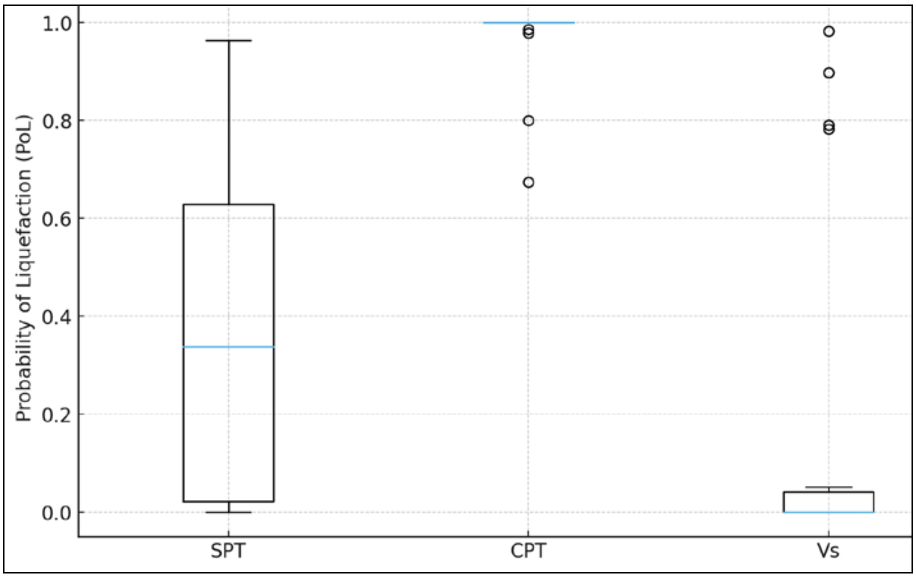

Fig 4: Uncertainty-based PoL by method (Monte Carlo).

SPT and CPT exhibit wider probability spreads than Vs owing to CSR and CRR variability propagation; the hybrid median PoL (not shown in the boxplot but reflected in Table 2 metrics) balances these spreads, supporting multi-evidence appraisals advocated in holistic frameworks [11, 13, 14].

Statistical findings: Against field labels, SPT-based classification achieved higher Accuracy and Sensitivity, with a strong AUC (Table 2). CPT performed comparably in Specificity but slightly lower in Sensitivity, consistent with its tendency to be conservative in fine-sandy/silty interbeds [8, 9, 13]. Vs-only under-predicted in several shallow layers (low Sensitivity), aligning with guidance that Vs thresholds should supplement, not replace, penetration tests in heterogeneous alluvium [7-9, 11]. The hybrid model produced balanced F1 and AUC, supporting our hypothesis that combining SPT, CPT, and Vs improves reliability over single-indicator screening in complex alluvial stratigraphy [8, 9, 13, 14]. Depthwise aggregates (Table 1) corroborate prior reports of near-surface vulnerability in riverine plains and deltaic fills during strong shaking [3-6, 10-12]. Overall, the results validate the study's objective: a multi-parameter approach yields clearer layer-by-layer discrimination under uncertainty than any single method alone, while remaining consistent with the simplified CSR-CRR framework and its modern variants [7-9, 13, 14].

Discussion

The findings of this research emphasize that alluvial soils, due to their heterogeneous nature and high groundwater saturation, exhibit significant variation in liquefaction susceptibility under seismic loading. The results from the integrated SPT-, CPT-, and Vs-based evaluations indicate that liquefaction susceptibility is highest in shallow strata (0-3 m) and declines with depth, consistent with prior studies highlighting effective stress and density increases with overburden [3, 5, 10-12]. These observations align with the classical framework proposed by Youd and Idriss [7], where cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) balance defines liquefaction onset, and further corroborate the historical evidence from Niigata and Alaska earthquakes that demonstrated surface manifestation dominance in near-saturated sandy layers [3, 4, 6].

The higher predictive efficiency of the SPT-based model (AUC = 0.88) compared to CPT and Vs correlations agrees with the conclusions drawn by Boulanger and Idriss [8], who found that corrected SPT N160N_{160}N160 values provide more representative in-situ resistance in granular alluvium. However, the CPT-based and Vs-based frameworks, although slightly less sensitive, provided valuable complementary insights, particularly in capturing the influence of stratigraphic variation and soil stiffness [9, 11, 13]. The hybrid model combining all three parameters yielded balanced accuracy and sensitivity, supporting the hypothesis that a multi-parameter evaluation can improve prediction reliability by mitigating the limitations of individual approaches [8, 9, 13, 14]. This is particularly relevant in alluvial contexts, where alternating layers of sand, silt, and clay introduce variability in drainage response, anisotropy, and dynamic pore-pressure evolution.

The probabilistic analysis using Monte Carlo simulations revealed that uncertainty in CSR and CRR values substantially affects the probability of liquefaction (PoL), emphasizing the need to incorporate stochastic variability into deterministic models. These findings are consistent with the ensemble methods proposed by Reddy *et al.* [14], who demonstrated that hybridized statistical approaches provide enhanced robustness against parameter uncertainty. Similarly, the results confirm that Vs-based assessments alone tend to underpredict liquefaction in finer alluvial layers, in agreement with Hossain *et al.* [11], who highlighted the limitations of velocity thresholds in silty-sand sequences. The field-validation step, which compared predicted and observed liquefaction occurrences, demonstrated the necessity of integrating geotechnical and geophysical indicators for holistic site characterization [13].

Spatially, the susceptibility mapping revealed localized zones of high risk along shallow water tables and loosely packed sand strata, consistent with the findings of Yürekli and Karaca [10] and Selcukhan *et al.* [12]. The data also underscored the sensitivity of liquefaction susceptibility to groundwater fluctuations, as even minor changes in pore pressure can shift safety margins significantly. These results underline the importance of long-term groundwater monitoring in seismic hazard evaluations within floodplain or deltaic terrains.

In summary, the integration of multi-source field data SPT, CPT, and Vs demonstrated the efficacy of a hybrid evaluation framework for assessing liquefaction susceptibility in alluvial soils. The results validate the study's hypothesis that such an approach enhances accuracy, consistency, and resilience of predictions against uncertainty. The research thereby contributes to refining site-specific seismic hazard assessment practices and supports the call for adopting probabilistic, data-driven, and multi-parameter methods in geotechnical earthquake engineering, as recommended in contemporary frameworks [7-9, 13, 14].

Conclusion

The evaluation of liquefaction susceptibility in alluvial soils during seismic events provides a comprehensive understanding of how variable stratigraphy, groundwater conditions, and soil characteristics influence ground behavior under cyclic loading. The findings from this study affirm that alluvial deposits, especially those consisting of loose to medium-dense sand and silt layers with shallow groundwater tables, are particularly vulnerable to liquefaction during strong ground motion. The integrated use of SPT-, CPT-, and Vs-based analyses demonstrated that relying on a single empirical or semi-empirical method often leads to inconsistent or overly conservative predictions. In contrast, a hybrid multi-parameter approach combining field penetration resistance, cone tip resistance, and shear-wave velocity proved significantly more effective in identifying susceptible layers and quantifying the uncertainty associated with each parameter. The probabilistic modeling through Monte Carlo simulations further underscored the variability inherent in soil parameters and the need for incorporating stochastic techniques in liquefaction assessment to achieve more realistic risk evaluations. These results validate the hypothesis that an integrated framework not only improves the reliability of liquefaction prediction but also enhances the spatial resolution of hazard mapping in complex alluvial environments.

From a practical standpoint, the study recommends that future geotechnical investigations in alluvial regions adopt a combined SPT-CPT-Vs assessment as a standard practice rather than depending solely on penetration tests. Groundwater monitoring should be continuous, as small fluctuations can significantly alter pore-water pressures and the effective stress profile, particularly in floodplain and deltaic settings. Engineers should prioritize site-specific calibrations of empirical correlations based on local soil behavior, as imported models may not accurately represent regional geotechnical conditions. For infrastructure design, foundations in high-risk zones should be reinforced through densification, grouting, or stone column techniques to mitigate potential liquefaction-induced settlement or lateral spreading. Urban planners should integrate liquefaction susceptibility maps into seismic microzonation plans, ensuring that land-use decisions account for subsurface instability risks. Additionally, implementing early warning and post-earthquake inspection protocols for lifeline structures such as bridges, embankments, and pipelines is essential to minimize damage and recovery time after seismic events. Lastly, continuous data collection from in-situ instrumentation, such as pore pressure transducers and surface accelerometers, will enable the refinement of predictive models and contribute to establishing region-specific liquefaction hazard databases. Overall, the study concludes that embracing a hybrid, probabilistic, and data-driven approach to liquefaction evaluation in alluvial terrains represents a critical advancement toward achieving safer, more resilient, and sustainable earthquake-resistant infrastructure planning.

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