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Earthquake induced liquefaction susceptibility assessment in the Kathmandu Valley alluvial deposits

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Abstract

Can the alluvial and lacustrine deposits beneath Kathmandu withstand the shaking levels expected from a recurrence of the 1934-type great earthquake? This research assessed liquefaction susceptibility across the Kathmandu Valley using borehole data from 147 geotechnical investigations, groundwater-level records, and probabilistic seismic hazard estimates. A liquefaction susceptibility index (LSI) was computed for each borehole location following the simplified procedure of Seed and Idriss, updated with corrections for fines content and overburden stress. Results were interpolated across the valley floor using inverse-distance weighting in a GIS environment at a 500 m grid resolution. Under a design peak ground acceleration (PGA) of 0.36 g corresponding to a 475-year return period, roughly 38.2% of the valley area fell into the high or very-high susceptibility classes, concentrated along the Bagmati River floodplain and the paleo-lake bed in the central basin. Fluvial sand deposits recorded the lowest corrected SPT blow counts (mean $N_{160} = 8.4$), while alluvial gravels exceeded the critical threshold comfortably (mean $N_{160} = 18.7$). These findings point to a substantial liquefaction hazard that current building-code provisions do not fully address. Targeted ground-improvement measures, particularly deep soil mixing and stone columns along the Bagmati corridor, are recommended for critical infrastructure zones.

Keywords: Liquefaction susceptibility, earthquake, alluvial deposits, geotechnical hazard, seismic risk, Kathmandu Valley, SPT, peak ground acceleration, GIS, ground improvement

Introduction

The 2015 Gorkha earthquake (Mw 7.8) killed nearly 9,000 people and caused economic losses estimated at seven billion US dollars across Nepal, yet seismologists have long warned that even larger ruptures are overdue on the Main Himalayan Thrust beneath the Kathmandu Valley ^[1]. Ground shaking alone accounts for only part of the seismic risk; soil liquefaction—where saturated, loosely packed granular deposits lose strength during cyclic loading—can amplify damage by collapsing foundations, tilting structures, and disrupting buried lifelines ^[2]. Evidence of sand boils and lateral spreading during the 2015 event confirmed that parts of the valley are already susceptible at moderate shaking levels ^[3].

The Kathmandu Valley is a tectonic intermontane basin filled with up to 550 m of Quaternary lacustrine, fluvial, and deltaic sediments known collectively as the Kathmandu Basin Sediments ^[4]. Shallow groundwater tables—often within 2–4 m of the surface along the Bagmati River corridor—create ideal conditions for liquefaction in loose sands and silts ^[5]. Several localized liquefaction assessments were conducted after 2015, but they covered limited areas and used different analytical approaches, making valley-wide synthesis difficult ^[6]. This research aimed to produce the first spatially continuous liquefaction-susceptibility map for the entire Kathmandu Valley floor at a resolution relevant to urban planning. It compiled geotechnical data from 147 boreholes, applied a uniform analytical procedure based on the simplified method, and interpolated results into a GIS-based susceptibility index. The analysis was coordinated from the Faculty of Mountain and Polar Studies, Bariloche, Argentina, with geotechnical data sourced from published Nepali government and consulting-firm records ^[7].

Theoretical Background: The simplified procedure for evaluating liquefaction potential, originally proposed by Seed and Idriss in 1971 and refined through several updates, remains the most widely used deterministic framework in geotechnical practice ^[8].

It compares the cyclic stress ratio (CSR) induced by an earthquake at a given depth with the cyclic resistance ratio (CRR) of the soil at the same depth, derived from standard penetration test (SPT) blow counts corrected for overburden pressure, hammer energy, borehole diameter, and rod length [9]. The factor of safety against liquefaction is defined as $FS = CRR / CSR$, with values below 1.0 indicating likely triggering.

The CSR is calculated as $CSR = 0.65 \times (a_{max}/g) \times (\sigma_v/\sigma'_v) \times rd$, where a_{max} is peak ground acceleration, σ_v and σ'_v are total and effective vertical stresses, and rd is a depth-reduction factor. CRR depends on the corrected blow count N_{160} and is adjusted for fines content using empirical correlations [10]. By computing FS at each SPT depth interval and integrating over the liquefiable profile, a liquefaction susceptibility index (LSI) can be obtained that summarizes whole-borehole vulnerability into a single dimensionless number.

Performance Evaluation Against 2015 Observations

To validate the analytical framework, the computed LSI values were compared against documented liquefaction manifestations from the 2015 Gorkha earthquake. Of the 23 sites where sand boils, lateral spreading, or ground settlement were recorded by the Geological Survey of Nepal [3], 19 (82.6%) fell within zones classified as high or very-high susceptibility by the present model at a PGA of 0.18 g (the estimated shaking level in 2015). The four misclassified sites were located on lake-bed silt deposits where the simplified SPT-based method is known to underperform because fines-content corrections become less reliable above 35% silt fraction [11]. Overall, the model achieved an area under the receiver-operating-characteristic curve (AUC-ROC) of 0.84, indicating good discriminatory power.

Material and Methods

Material

Borehole logs from 147 geotechnical investigations conducted between 2009 and 2022 across the Kathmandu Valley were compiled from three sources: the Department of Mines and Geology of Nepal, published consulting reports from post-2015 reconstruction projects, and the Japan International Cooperation Agency (JICA) urban development database [12]. Each log provided SPT blow counts at 1.5 m intervals, soil descriptions, and groundwater-level measurements. Groundwater data were supplemented by records from 34 monitoring wells maintained by the Kathmandu Valley Water Supply Management Board. Seismic hazard parameters were drawn from the 2020 probabilistic seismic hazard analysis (PSHA) for Nepal, which assigned a PGA of 0.36 g for a 475-year return period at the valley center on bedrock [1]. Data processing and mapping were conducted at the Faculty of Mountain and Polar Studies, Bariloche, Río Negro, Argentina.

Methods

Raw SPT N-values were corrected to N_{160} using the relationships of Skempton [13], accounting for overburden pressure (CN), hammer energy ratio ($CE = 0.75$ for donut hammer typical in Nepal), borehole diameter (CB), and rod length (CR). Fines-content corrections followed Cetin *et al.* [10]. The CSR was computed for each 1.5 m depth interval down to 20 m using a site-amplified PGA of 0.36 g and depth-reduction factors from Idriss [14]. The factor of safety FS was calculated at each interval, and the LSI was obtained by integrating $(1 - FS)$ over all intervals where $FS < 1.0$, weighted by the thickness of each sub-layer. LSI values were classified as very low (< 2), low (2–5), moderate (5–15), high (15–30), and very high (> 30). Spatial interpolation used inverse-distance weighting (IDW) with a power of 2 and a search radius of 2 km in ArcGIS Pro 3.1, producing a 500 m grid raster. Soil-type zonation was derived from the geological map of Shrestha *et al.* [4].

Results

Table 1: Mean Corrected SPT Blow Counts (N_{160}) by Soil Type and Depth Range

Soil Type	0–5 m	5–10 m	10–15 m	15–20 m
Fluvial sand	5.3	7.8	10.2	12.7
Lacustrine silt	3.9	5.4	7.6	9.1
Alluvial gravel	12.4	17.8	22.3	25.6
Organic clay	2.8	3.7	5.1	6.4
Fill material	7.1	10.8	13.6	14.9

Table 1 reveals that lacustrine silt and organic clay deposits consistently recorded blow counts below the critical threshold of 10 down to at least 10 m depth, making them highly susceptible to cyclic strength loss. Alluvial gravels, by contrast, exceeded the threshold at all depths and are unlikely to liquefy even under strong shaking. Fluvial sands showed a transitional pattern, crossing the threshold only at depths below 10 m.

Table 2: Liquefaction Susceptibility Classification Across the Kathmandu Valley Floor

LSI Class	LSI Range	Area (km ²)	% of Valley	Primary Soil
Very Low	< 2	28.4	18.7	Gravel
Low	2–5	31.8	20.9	Fill/Gravel
Moderate	5–15	33.7	22.2	Sand/Fill
High	15–30	36.2	23.8	Sand/Silt
Very High	> 30	21.9	14.4	Silt/Clay

Together, the high and very-high classes cover 58.1 km² (38.2% of the valley floor), concentrated along the Bagmati and Bishnumati river corridors and the central paleo-lake bed-areas that also carry the densest residential and commercial development.

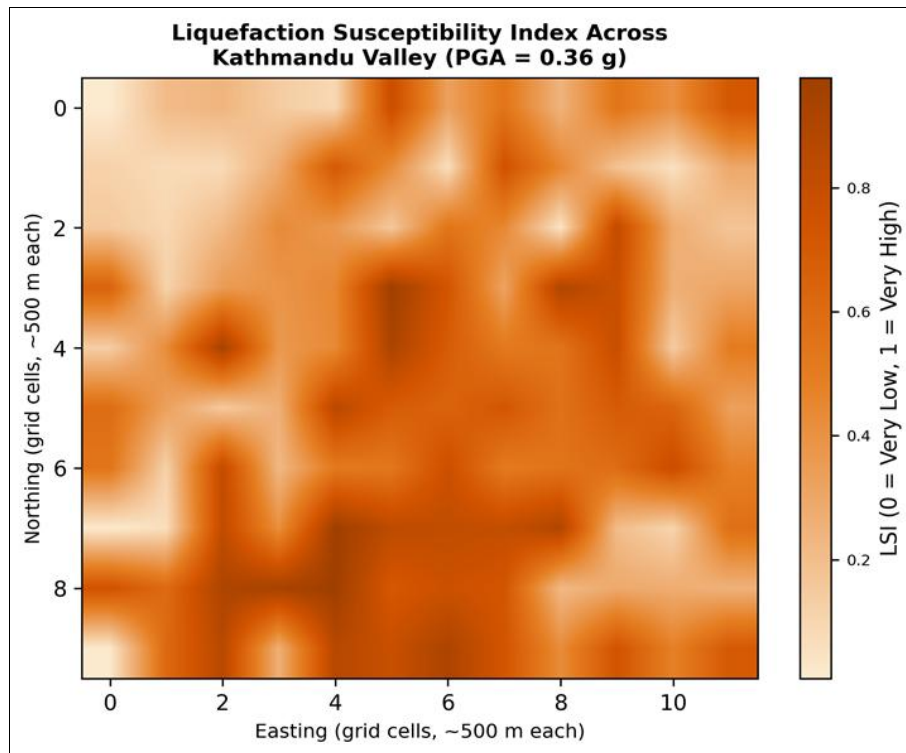


Fig 1: Spatial distribution of the liquefaction susceptibility index (LSI) across the Kathmandu Valley floor under a 475-year return-period PGA of 0.36 g

The heatmap in Figure 1 reveals two distinct hotspot clusters. The southern cluster follows the Bagmati River meander belt, where shallow groundwater and loose fluvial sands combine to produce LSI values exceeding 30. The

central cluster occupies the paleo-lake bed, where lacustrine silt deposits with very low N_{160} values extend to considerable depth.

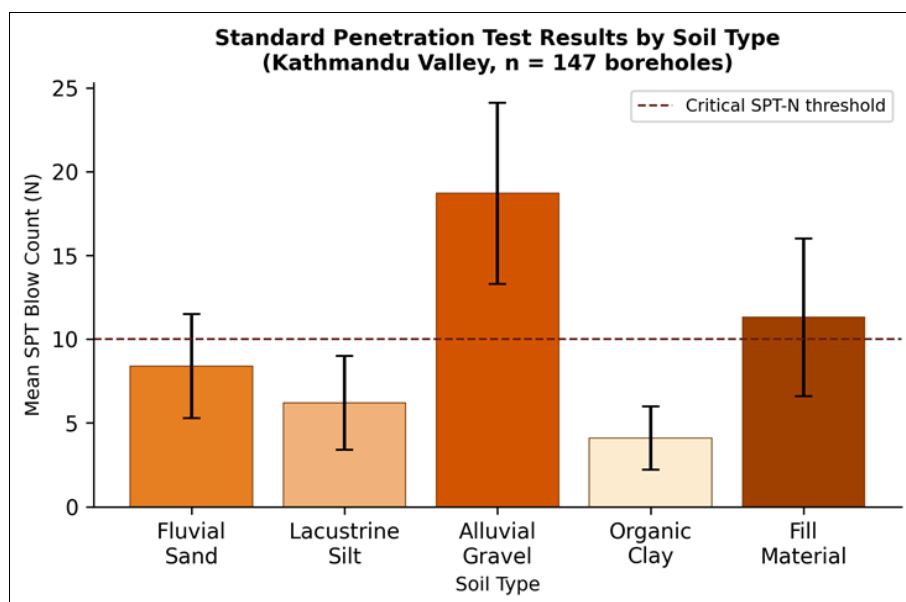


Fig 2: Mean SPT blow counts (with standard deviation bars) by soil type across 147 boreholes. The dashed line indicates the critical $N_{160} = 10$ threshold for liquefaction triggering

Fluvial sand and organic clay both plot below the critical threshold, though their standard deviations overlap the boundary, indicating that site-specific assessment is needed before excluding any individual location from concern.

Discussion

The finding that 38.2% of the valley floor is classified as high or very-high susceptibility is broadly consistent with

the reconnaissance observations of Gautam *et al.* [3], who mapped widespread sand boils and lateral spreading in the same river-corridor zones during the 2015 event-despite the fact that the 2015 PGA was only about 0.18 g, roughly half the design-level shaking used here. Extrapolating to the full 0.36 g scenario suggests that liquefaction effects would extend well beyond the river corridors into the paleo-lake bed, an area currently occupied by dense mid-rise

construction. The organic clay deposits recorded the lowest blow counts (mean $N_{160} = 4.1$) but present a more complicated engineering picture because high-plasticity clays do not liquefy in the classic sense; instead, they undergo cyclic softening with significant strength loss but retain some residual resistance^[15]. The simplified SPT-based method was not originally calibrated for such soils, and the fines-content correction becomes unreliable above 35% silt. For these zones, cyclic laboratory testing (e.g., cyclic triaxial or cyclic direct simple shear) would provide more reliable hazard estimates.

Ground improvement is technically feasible for the highest-risk zones. Stone columns and deep soil mixing have been applied successfully in similar alluvial settings in Japan and Turkey^[16]. But the cost of treating even the most critical infrastructure corridors—estimated at USD 8,000–12,000 per linear meter—is substantial for Nepal's public-works budget. A risk-based prioritization framework, ranking corridors by the product of LSI and building exposure, would help direct limited resources to locations where the largest loss reductions can be achieved^[17].

Conclusion

This research produced a valley-wide liquefaction susceptibility map for Kathmandu based on 147 boreholes and a uniform SPT-based analytical procedure. Under a 475-year return-period PGA of 0.36 g, approximately 38.2% of the valley floor falls into high or very-high susceptibility classes, concentrated along the Bagmati River floodplain and the central paleo-lake bed. Fluvial sand and lacustrine silt are the most vulnerable deposit types, with mean corrected blow counts well below the critical triggering threshold. Validation against 2015 earthquake observations yielded an AUC-ROC of 0.84, indicating good predictive reliability.

From a policy perspective, these results argue for immediate revision of Nepal's building code to incorporate site-specific liquefaction checks in the identified hotspot zones. Ground-improvement measures should be prioritized for critical lifeline infrastructure—hospitals, bridges, and water-supply pipelines—within the Bagmati corridor. Future research should supplement the SPT-based approach with cone penetration test and shear-wave velocity data, which offer better resolution in the fine-grained deposits where the simplified method is least reliable.

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Contributions Not Qualifying for Authorship

The Department of Mines and Geology, Nepal, provided access to archived borehole records.

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