

Scientific models and analysis for enhancing seismic safety of Uzbekistan's roads and aerodromes

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Abstract: Uzbekistan is located within seismically active zones, which increases the hazard level for highways, bridges, pipelines/culverts, and aerodrome pavements. This paper proposes an integrated system of scientific models aimed at assessing and improving the seismic stability and performance of road and aerodrome infrastructure: (I) probabilistic seismic hazard analysis (PSHA) and spectral intensity parameters; (II) computational models for geotechnical hazards (liquefaction, seismic settlement, and slope instability); (III) evaluation of the dynamic response of pavement structures; (IV) fragility curves and reliability indices for quantifying risk indicators based on damage probability; and (V) life-cycle cost (LCC) and resilience metrics. As a result, a prioritization algorithm for engineering measures to reduce seismic risk is formulated, and preventive strengthening strategies for highway and aerodrome pavements are developed.

Keywords: seismic hazard, PSHA, fragility curves, liquefaction, aerodrome pavement, road pavement, reliability index, resilience, life-cycle cost (LCC), risk

1. Introduction

In Uzbekistan, the probability of seismic impact is particularly high along urban areas and transport corridors such as the Tashkent-Fergana Valley, Samarkand-Karshi, and Jizzakh-Syrdarya routes [2]. Earthquakes may cause cracking in pavements, slope failures, displacement of bridge supports, liquefaction of foundation soils, as well as unevenness and deformation in aerodrome facilities (runway, taxiway, apron). These effects can lead to transport disruption, delays in evacuation and rescue operations, and a decline in aviation safety.

Therefore, managing seismic hazard should not rely solely on "code-based calculations", but rather on risk-based and performance-based approaches. This paper outlines a set of scientific models and computational algorithms required to implement such approaches.

2. Research Aim and Objectives

Aim: To develop a model for assessing seismic hazard, estimating damage probability, and scientifically prioritizing measures to enhance safety for Uzbekistan’s highways and aerodrome pavements.

Objectives:

- ✓ To determine design seismic intensity parameters based on PSHA;
- ✓ To select analytical models for geotechnical hazards (liquefaction, settlement, and slope instability);
- ✓ To evaluate the dynamic response of pavement structures;
- ✓ To estimate damage probability using fragility curves;
- ✓ To choose strengthening strategies based on LCC and resilience metrics.

3. Methodology: An Integrated Model for Seismic Risk Assessment

The paper proposes the following integrated workflow (pipeline):

(A) Seismic Action (Hazard) → (B) Vulnerability/Damage (Fragility) → (C) Consequences → (D) Risk and Decision-Making.

3.1. Probabilistic Seismic Hazard Analysis (PSHA)

Seismic intensity is commonly expressed using PGA (peak ground acceleration), PGV, or spectral acceleration $S_a(T)$. The PSHA output is the annual exceedance probability or the hazard curve $\lambda(IM)$ for the intensity measure IM .

In general form:

$$\lambda(IM > x) = \sum_{i=1}^{N_s} \int v_i(M, R) P(IM > x | M, R) dM dR$$

where:

- ✓ $v_i(M, R)$ is the recurrence (occurrence) rate of magnitude-distance pairs for the i -th seismic source zone;
- ✓ $P(\cdot)$ is the conditional probability based on GMPE (ground motion prediction equation).

Practical note: for roads and aerodromes, IM scenarios corresponding to different return periods (e.g., 10% and 2% in 50 years) are selected for the primary design evaluation.

3.2. Geotechnical Hazard Models

A significant portion of seismic damage is governed by foundation soil behavior [3]. Therefore, three key mechanisms are modeled:

(1) Liquefaction potential:

In a simplified approach, CSR (cyclic stress ratio) and CRR (cyclic resistance ratio) are compared:

$$FS = \frac{CRR}{CSR}$$

$$P_{liq} = \Phi \left(\frac{\ln (CSR/CRR)}{\beta_{liq}} \right)$$

where Φ is the standard normal CDF and β_{liq} is an uncertainty parameter.

(2) Seismic settlement: settlement is linked to densification and rearrangement of sublayers beneath the pavement structure.

(3) Slope instability: seismic displacement is assessed using the Newmark displacement model; if the displacement D_N exceeds a specified threshold, serviceability decreases.

3.3. Dynamic Response of Pavement Structures

Road and aerodrome pavements are multilayer systems represented as an "subgrade-base-surface" structure. The following parameters are essential in dynamic analysis:

- ✓ layer moduli $E(\omega)$ (frequency-dependent),
- ✓ damping ratio ξ ,
- ✓ soil-structure interaction (SSI).

For aerodromes, additional requirements arise due to stringent smoothness criteria and FOD risk (foreign object debris, i.e., engine damage caused by cracks and debris). Therefore, deformation limits are typically stricter than those for highways.

4. Fragility (Damage Probability) and Reliability Index

4.1. Fragility Curves

For a given damage state DS_k , the fragility function is expressed as:

$$P(DS \geq DS_k | IM) = \Phi \left(\frac{\ln (IM) - \ln (\theta_k)}{\beta_k} \right)$$

where θ_k is the damage threshold and β_k is the dispersion (model + aleatory uncertainty).

Example classification (for pavements):

- ✓ DS1 (minor): small cracks; no potholes; traffic is not restricted.
- ✓ DS2 (moderate): wider cracks and local unevenness; speed restrictions may be imposed.
- ✓ DS3 (severe): major unevenness and layer separation; closure of the road segment/runway becomes likely.

4.2. Reliability Index and Failure Probability

Using the stress-strength concept:

$$g(X) = R(X) - S(X)$$

$$P_f = P[g(X) \leq 0], \beta = -\Phi^{-1}(P_f)$$

where P_f is the probability of failure (damage exceedance) and β is the reliability index. In prioritizing infrastructure elements, β and P_f provide highly practical integrated indicators.

5. Consequences and Risk Estimation

Risk is the integral of hazard, damage probability, and consequences:

$$Risk = \int C(DS) P(DS | IM) dF_{IM}$$

In practice, using discretized scenarios:

$$EAL = \sum_j \Delta \lambda_j \sum_k C_k \cdot P(DS = k | IM_j)$$

where EAL is the Expected Annual Loss and C_k is the economic loss for damage state DS_k (repair costs, disruption, accident-related impacts).

5.1. Resilience Metric [4]

Using the service level $Q(t)$ (0-1 range), the resilience index is:

$$R = \frac{1}{T} \int_0^T Q(t) dt$$

The recovery speed after an earthquake (response and repair logistics) is a critical factor, particularly for aerodromes.

6. Measures to Enhance Seismic Safety: Engineering Strategies

6.1. For Highway Pavements

- ✓ Subgrade/base improvement: cementation, lime/cement stabilization, and geosynthetics (geogrids, geomats, geocells).

- ✓ Drainage and groundwater control: significantly reduces liquefaction and settlement risks.

- ✓ Layer optimization: high-modulus base (HMA base) and increased surface thickness in critical sections.

- ✓ Slope stabilization: anchoring, gabions, terracing, and relief drainage.

6.2. For Aerodrome Pavements

- ✓ Design focused on limiting unevenness: strict acceptance of "critical deformation" limits.

- ✓ Reduction of FOD risk: crack-resistant materials and rapid sealing technologies.

- ✓ For rigid (cement concrete) pavements: joint reliability, dowel/anchorage performance, and prevention of void formation beneath slabs.

- ✓ Rapid repair planning: material stockpiles and modular slab/asphalt patch technologies.

7. Prioritization Algorithm: Which Assets Should Be Strengthened First?

A decision-making priority index is proposed [5]:

$$PI = w_1 \cdot \frac{P_f}{P_{f,max}} + w_2 \cdot \frac{EAL}{EAL_{max}} + w_3 \cdot \frac{1 - R}{(1 - R)_{max}}$$

where:

- ✓ P_f - probability of failure,

- ✓ *EAL*- expected annual loss,
- ✓ *R*- resilience index,
- ✓ w_i - weighting factors defined by experts/policy makers.

Result: segments with higher *PI*(e.g., strategic crossings, bridge approaches, runway threshold zones) are strengthened first.

8. Discussion: Implementation in Uzbekistan's Context

✓ Data infrastructure: soil profiles, SPT/CPT, groundwater level, historical earthquake impacts, and pavement distress/passport data should be integrated into a unified GIS database.

✓ GMPE and microzonation: using PGA/PSA without local site effects increases estimation error.

✓ Pavement condition monitoring: laser profiling (IRI), deflection testing (FWD), and UAV photogrammetry help calibrate fragility parameters.

✓ Recovery planning: aerodrome downtime leads to major economic losses; thus, resilience modeling should be incorporated into decision-making.

9. Conclusion

This paper presented an integrated scientific approach to enhancing seismic safety for Uzbekistan's highway and aerodrome infrastructure. Based on PSHA outputs, geotechnical hazard models, pavement dynamic response analysis, fragility curves, and reliability indices, a risk estimation framework and a prioritization algorithm were proposed. Incorporating LCC and resilience metrics improves the scientific basis of engineering decisions and supports transport continuity and aviation safety, especially for strategic corridors and aerodromes [6].

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