Abstract

Liquefaction of saturated clean sands caused by earthquake-induced shear stresses is responsible for severe damage to infrastructures worldwide. Structures built over marine, fluvial and alluvial deposits are susceptible to liquefaction hazards during earthquakes. Liquefaction could result in catastrophic failures, as evident from the infamous 1964 Niigata earthquake in the past and, more recently, during the 2021 Assam India and 2022 Java Indonesia earthquakes. The severe consequence of liquefaction necessitates the assessment of the triggering of liquefaction and estimating liquefaction-induced settlement as critical tasks for practising engineers.

Traditional deterministic approaches for assessing liquefaction hazards do not account for soil's lateral variability and uncertainties associated with earthquake loading. A machine learning-enabled method is developed for predicting the probability of liquefaction triggering and evaluating liquefaction-induced settlement of a 1 m thick layer at depth z (LIS_z) that accounts for these uncertainties. Cone penetration test (CPT) data from nine seismically vulnerable locations in India and scaled accelerograms are used to generate a big dataset. The CPTs are conducted at Mundra (Gujarat, 2 locations), Tezpur (Assam), Madanpur (Delhi), Madhepura (Bihar), Motihari (Bihar), Gorakhpur (Haryana), Rohtak (Haryana) and Polavaram (Andhra Pradesh). The selected locations reflect different earthquake zones per IS 1893 (Part 1 2016).

PDMY03 constitutive model is selected to capture the liquefaction and post-liquefaction behaviour of sands. A numerical calibration study using the cyclic simple shear test in OpenSEES determines the PDMY03 model parameters based on relative density interpreted from CPTs. Subsequently, the numerical soil column with PDMY03 constitutive model is verified against the VELACS experiment number 1.

The CPTs from nine locations are interpreted to quantify the soil's lateral variability in terms of relative density. Based on the relative density variations obtained from CPT, numerical soil columns are modelled in OpenSEES with Lysmer-Kuhlemeyer dashpot at the base. The dashpot accounts for the finite rigidity of the soil below the modelled/explored depth. The numerical soil column is subjected to selected 12 earthquake motions that are scaled to reflect the seismic vulnerability of the location.

A fully coupled (u-p) formulation captures the triggering of liquefaction and associated liquefaction-induced settlement. For liquefaction triggering, site response analyses with permeability 10^{-4} m/s (SRA_a) are conducted, and liquefaction is said to have been triggered if the excess pore pressure ratio reaches 0.98 or the single amplitude cyclic shear strain reaches 3 per cent. Similarly, site response analyses with permeability 10^{-2} m/s (SRA_b) are conducted to compute LIS_z.

The big dataset generated from numerical analyses (1,944 analyses) is used in machine learning algorithms to develop predictive models for the probability of liquefaction triggering (classification algorithms) and estimation of LIS_z (regression algorithms). Machine learning algorithms, namely logistic regression (for classification), multiple linear regression (for regression), k-nearest neighbours (for classification and regression), decision tree (for classification and regression), random forest (for classification and regression), support vector machines (for classification and regression) and XGBoost (for classification and regression), are employed, and their efficiency is evaluated using performance scores. The system/influencing variables considered in the current study are relative density at the depth of interest, relative density at the base of the numerical soil column, initial effective vertical stress at the depth of interest, peak acceleration and Arias intensity of the earthquake motion. It is observed that the XGBoost algorithm performs better than other considered algorithms and is adopted in the current study. Simple user interfaces are developed which predict the probability of liquefaction triggering and LIS_z based on these five system/influencing variables. The developed methodology is validated by plotting the predicted values against the actual values for the test set data.

These developed and calibrated algorithms can be used in professional practice for preliminary assessment before resorting to detailed investigation as long as the relative density and earthquake intensity fall within the range considered in this thesis.