Liquefaction Risk Microzonation for Low-Volume Road Networks

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The vulnerability of low-volume or low-cost roads to earthquakes in seismically active regions has not been given enough consideration. A simple, empirical approach to create a liquefaction risk map was developed. The proposed approach allows one to assess whether or not the soils at a given site will liquefy, and to determine the probability of liquefaction. The method is based on statistical studies of historical cases in which ground failures by liquefaction were or were not observed. The theoretical basis for this approach consists of a statistical risk model that was developed in 1983. Nine data sets from the Haicheng earthquake in 1975 and the Tangshan earthquake in 1976, and 46 data sets from earthquakes that were reported outside the country were used as input data in the development of the model. The approach was tested on liquefaction microzonations of Tienjin, where liquefaction of a large area occurred, and Sian, where an earthquake was predicted, for the purpose of local road network planning.

The vulnerability of low-volume or low-cost roads to earthquakes in seismically active regions has not been given enough consideration. A convenient method to quantitatively evaluate a site's liquefaction risk is needed in the process of planning and designing local road networks that cover a wide area. A simple, empirical approach to create a liquefaction risk map is represented.

Most current methods employ the peak horizontal accelerations of the ground surface as one of the inputs. However, great uncertainties and inaccuracies can result in the determination of peak horizontal accelerations. Therefore, the earthquake magnitude, M, and the epicenter distance, R, are used in the proposed methodology.

The probability of liquefaction as a quantitative risk index in the microzonation was defined to be a function of M, R, and SPT-values, N, with the consideration of total and effective overburden pressures, σ_v and σ_v', for a given depth point under the ground surface.

The calculation of liquefaction probability is based on a statistical risk model that was developed by the authors in 1983 (*1-4*). Nine case data sets from the Haicheng earthquake in 1975 and the Tangshan earthquake in 1976, and 46-case data sets from earthquakes that were reported outside the country were used as input data in the formulation of the model (*5-8*).

The proposed approach allows one to assess whether or not a given site or region will liquefy, and if liquefaction is possible, to assess the probability that it will occur. The method is based on statistical studies of historical liquefaction-induced failures.

The approach was tested on liquefaction microzonations of Tienjin and Sian, where earthquake-induced liquefaction had occurred or was predicted, for local road planning purposes.

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STATISTICAL MODEL

Consider an independent system with a randomly distributed capacity, C, to be subjected to an independent, randomly distributed demand, D. If the occurrence of liquefaction is considered to be such a system, soil resistance against liquefaction can be regarded as C, and seismic intensity can be regarded as D.

When the distributions of C and D are determined by a study of historical data, it can be assumed that two limits exist, α and β, that correspond to C and D, respectively. Therefore, a rational assumption can also be made that the event will surely occur whenever C is smaller than or equal to α, for $D = \beta$, or whenever D is greater than or equal to β, for $C = \alpha$. Therefore, two mutually exclusive and collectively exhaustive subevents exist, E_1 and E_2 (Figure 1), as follows:

$$E_1 = (C<\alpha \mid D = \beta);\ E_2 = (D>\beta \mid C = \alpha).$$

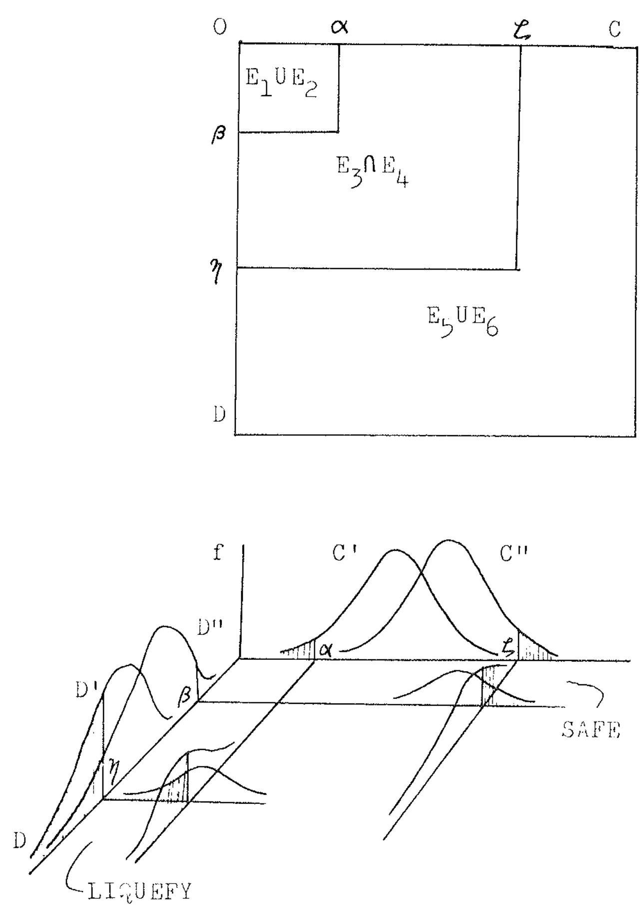

FIGURE 1 Concept of statistical risk model.

The occurrence of liquefaction, $E(L)$, is the union of E_1 and E_2, as follows:

$$E(L) = (E_1 \cup E_2).$$

This means that the soil system will liquefy by the occurrence of either or both E_1 and E_2.

The relation between α and β for certain occurrences of liquefaction has been derived for normal distributions of both C and D, as follows (*1-4*).

$$\alpha = m_c' + (\beta - m_D')\, \sigma_c' / \sigma_D'$$

in which m_c' and σ_c' are the respective mean and standard deviations of C for data sets of liquefaction, and m_D' and σ_D' are those of D.

If it can be similarly assumed that another set of bounds exists, ζ and η, such that liquefaction will not occur whenever C is greater than or equal to ζ, or D is smaller than or equal to η, the same relation between ζ and η for certain nonliquefaction is as follows:

$$\zeta = m_c'' + (\eta - m_D'')\, \sigma_c'' / \sigma_D''$$

in which m_c'' and σ_c'' are the respective mean and standard deviations of C for nonliquefaction data, and m_D'' and σ_D'' are those of D.

This is needed to estimate the probability of liquefaction for a point that falls in the area enclosed by the two boundaries (Figure 2). Consider a given point, $C = C^*$ and $D = D^*$, to be checked in the stochastic domain. According to the earlier equations, the variation limits of C^* and D^* should have the following form:

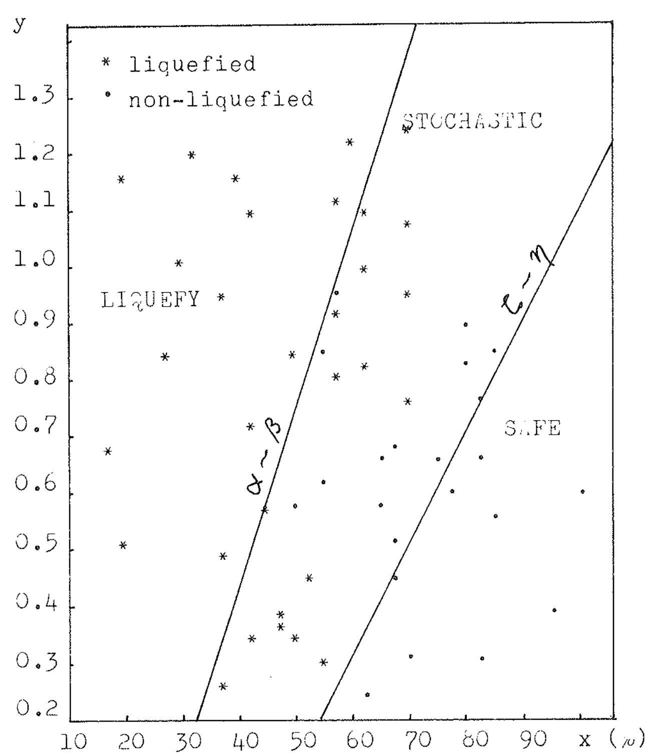

FIGURE 2 Data base and liquefaction limits of SPT-values.

$$\alpha\ (\beta = D^*) \leq C^* \leq \zeta\ (\eta = D^*);\ \eta\ (\zeta = C^*) \leq D^* \leq \beta\ (\alpha = C^*)$$

The probability of the occurrence of the two independent events can be expressed by the following forms, respectively (Figure 3).

$$p(E_3) = \int_{C^*}^{\zeta} f(C \mid D = D^*)\, dC \Big/ \int_{\alpha}^{\zeta} f(C \mid D = D^*)\, dC;\ p(E_4) = \int_{\eta}^{D^*} f(D \mid C = C^*)\, dD \Big/ \int_{\eta}^{\beta} f(D \mid C = C^*)\, dD$$

Therefore, the probability that the soil system is likely to fail is expressed as follows:

$$p(C^*, D^*) = p(E_3 \cap E_4) \text{ or}$$
$$p(C^*, D^*) = (a - b)(c - d)/(a - c)/(b - d)$$

in which a, b, c, and d are normal cumulative functions of C^* and D^*.

The probability that a given soil layer or an area of ground will wholly liquefy can be expressed as follows, based on Morgan's theory:

$$P_L = 1 - (1 - p_1)(1 - p_2) \ldots\ldots (1 - p_i)$$

in which i is the number of calculated points in a volume of soil.

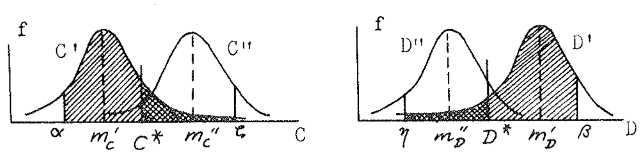

FIGURE 3 Liquefaction probabilities of events E_3 and E_4.

PRELIMINARY MICROZONING IN A REGION

It has been proven that the historical data of both functions, which consist of M and R, and N-values are normal distributions (*1, 4*). The statistics of the historical data sets that were used to formulate the statistical model are listed in the following table.

Parameters	*Liquefied*	*Nonliquefied*
Mean of $x = 210[N/(\sigma_v' + 70)]^{1/2}$(%)	44.0372	65.3290
Standard deviation of x(%)	11.6451	17.0256
Mean of $y = (M/R)^{1/2}\sigma_v/\sigma_v'$	0.7341	0.6141
Standard deviation of y	0.3916	0.3317

The critical limits of N for liquefaction, Ncr', and for nonliquefaction, Ncr'', have been derived as follows:

$$Ncr' = [(M/R)^{1/2}\sigma_v/\sigma_v' + 0.75]^2(\sigma_v' + 70)/39.69$$

$$Ncr'' = [(M/R)^{1/2}\sigma_v/\sigma_v' + 0.66]^2(\sigma_v' + 70)/17.64$$

where

M is the Richter scale value of the seismic event, R is in km, and σ_v and σ_v' are in kN/m^2.

This procedure, which is outlined in Figure 4, given sufficient consideration of the geological conditions at the site, is applicable to the process of a low-cost road network planning as a tool to determine preliminary microzones within a large area.

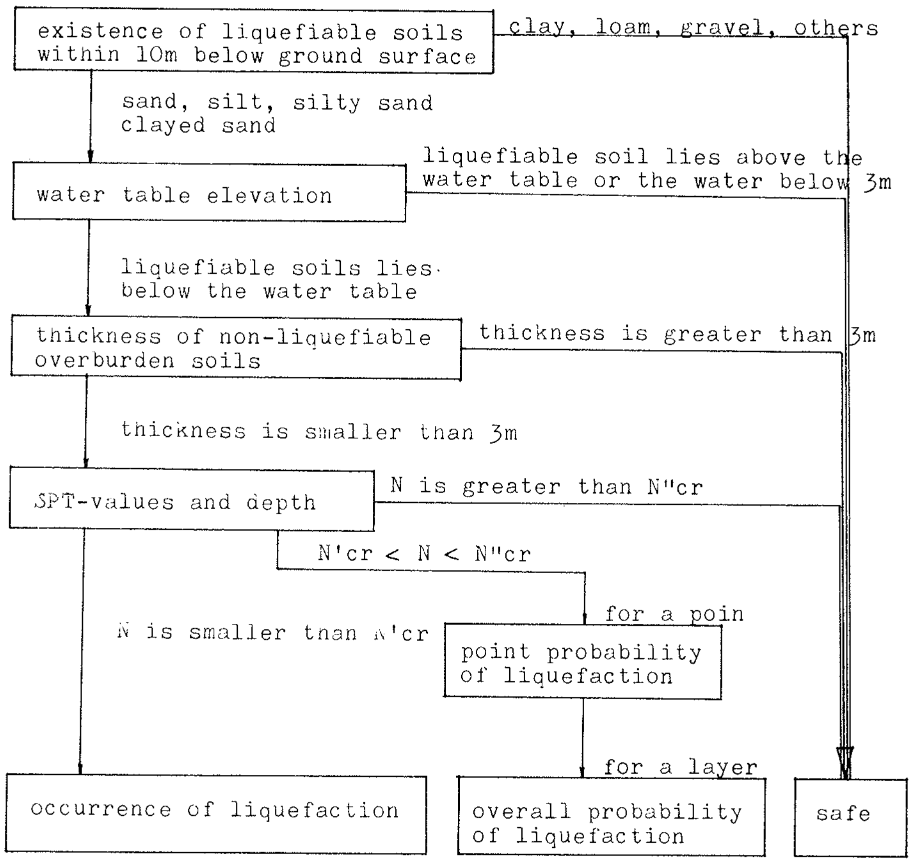

FIGURE 4 Preliminary liquefaction microzonation procedure.

LIQUEFACTION RISK ASSESSMENT IN DETAIL

As was previously mentioned, the liquefaction probability can be evaluated for any given point in the soil and for any given volume or area of a site. The following parameters were obtained in this study:

$a = \Phi\,(4.048y - 0.087)$
$b = \Phi\,(0.085x - 3.782)$
$c = \Phi\,(2.554y - 1.874)$
$d = \Phi\,(0.050x - 3.557)$

where

Φ = the standard normal distribution function,
$x = 210\,[N/(\sigma_v' + 70)]^{1/2}$, and
$y = (M/R)^{1/2}\sigma_v/\sigma_v'$.

The numerical model mentioned earlier has been programmed to microzone the liquefaction risk in a large region.

Examples

Liquefaction risk microzonation by use of the proposed approach was conducted in an analysis of seismic hazards in the Tangshan-Tienjin region. It was also conducted to check the seismic hazards of a local road network in the Wei River valley (Sian region) where an earthquake of a magnitude greater than 6 has been forecasted.

As shown in Figure 5, the two limits of SPT-values for liquefaction risk analysis vary with the epicenter distance under certain geological conditions in the Tienjin region.

A liquefaction risk microzonation map showing geological boundaries and isograms of *Ncr'* and *Ncr"* was created for the Sian region, as shown in Figure 6. Field investigations were conducted to determine whether or not subsurface conditions conducive to liquefaction existed within 10 m of the ground

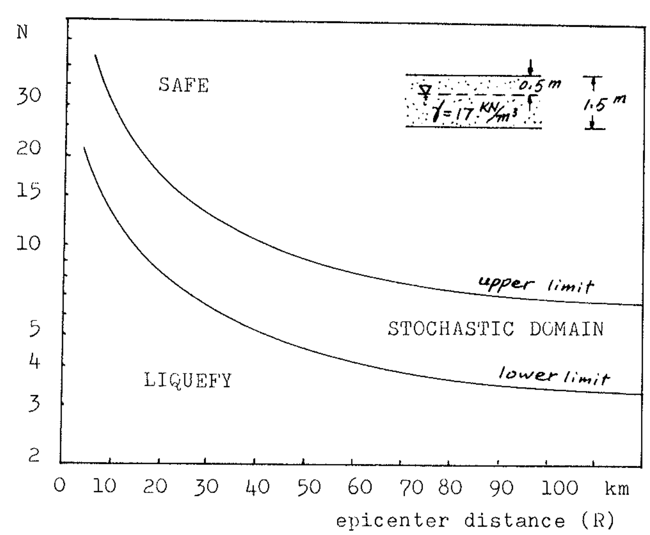

FIGURE 5 Liquefaction limits versus epicenter distance in Tienjin.

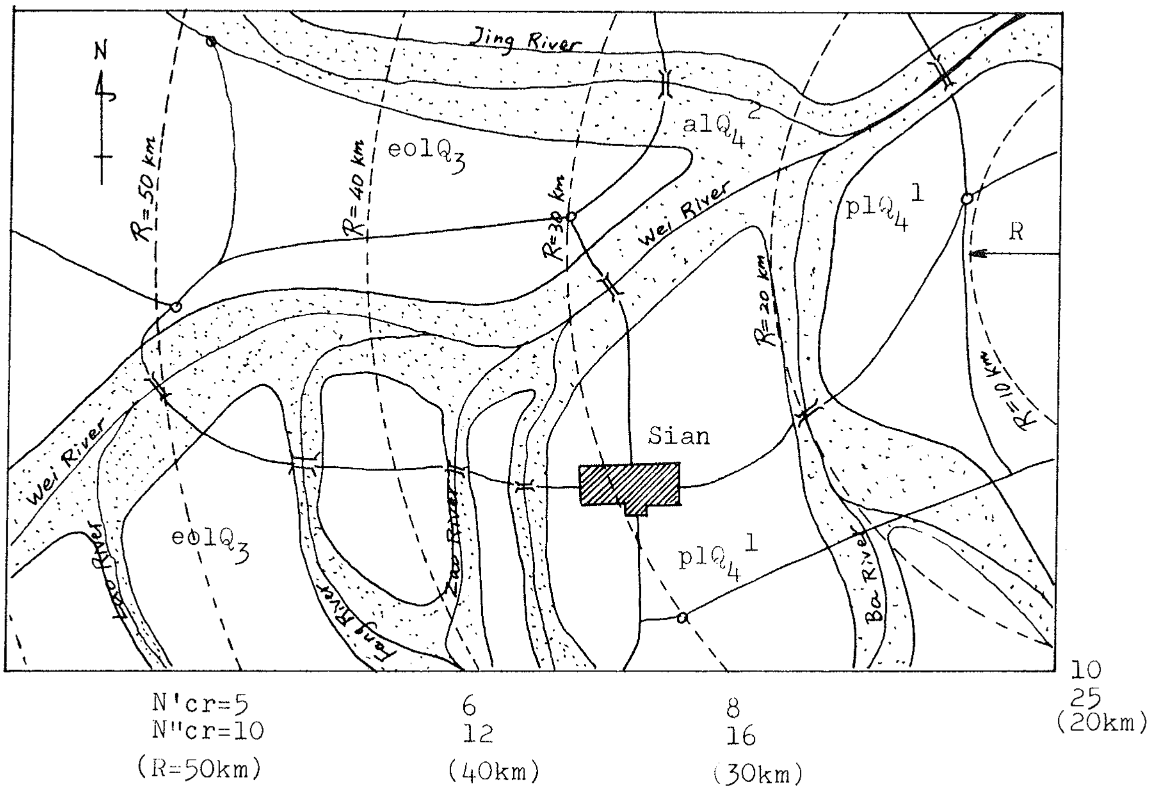

FIGURE 6 Liquefaction risk map of Sian region.

surface in the region to be microzoned. It was found that they were mainly distributed in the soils shown as al Q_4^2 in Figure 6. The second step was to determine if these deposits were below the water table. The SPT-values were also determined. The predicted epicenter is about 30 km from downtown Sian.

CONCLUSIONS

The methodology presented for liquefaction risk microzonation of a given region in which a local road network exists or is planned is based on the statistical risk model. This model was derived from 55 data sets of historical cases. Because of the convenience of this approach, it is applicable to the planning and seismic checking of local low-volume and low-cost roads.

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