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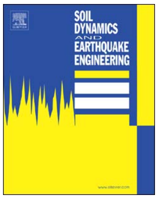

Evaluating liquefaction potential and lateral spreading in a probabilistic ground motion environment

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ABSTRACT

Liquefaction potential and lateral spreading are generally evaluated in engineering practice using deterministic procedures based on a design magnitude, M, and an associated Peak Ground Acceleration, PGA. In a probabilistic ground motion environment, a wide range of magnitudes contribute to the PGA. A common solution adopted to cope with the problems this poses for the deterministic approach is to select a single magnitude somewhat close to the maximum magnitude to represent the combined effects of all the magnitudes contributing to the hazard. However there is no measure of whether this approach is appropriate. Finn and Wightman (2007) [6] introduced a magnitude deaggregation method for evaluating liquefaction potential and showed that practice at that time was overly conservative for the code ground motions. This paper evaluates the performance of current practice for the proposed National Building Code for Canada, NBCC 2015 ground motions and extends the deaggregation method to the calculation of lateral spreading based on Youd's empirical equation (Youd et al., 2002) [11]. Some case histories of recent applications in school retrofit projects of the conventional approach and the deaggregation method are presented to highlight the difference in results.

1. Introduction

In current practice, the potential for liquefaction triggering is commonly assessed using the ‘simplified’ stress-based methodology (e.g., [9,10]). EERI published a monograph by Idriss and Boulanger [9] entitled “Soil Liquefaction during Earthquakes” which describes a global review of research and practice up to 2007 and made new recommendations for evaluating the triggering of liquefaction, which have been widely adopted in practice.

The evaluation of liquefaction potential involves comparing the seismic demand posed by the earthquake shaking to the capacity of the site to resist liquefaction. As described in Idriss and Boulanger [9], the capacity is expressed in terms of normalized penetration resistance measured by either the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT) or by shear wave velocity (V_s). The seismic demand is specified by the average Cyclic Stress Ratio, CSR.

The simplified method for estimating the average CSR caused by earthquake shaking is given by Eq. (1) (Seed and Idriss, 1971),

$$CSR = 0.65\frac{a_{\max}}{g}\frac{\sigma_{v0}}{\sigma'_{v0}}\frac{r_d}{MSF} \tag{1}$$

where a_{max}=peak ground surface acceleration, g=acceleration of gravity (in same units as a_{max}), σ_{vo} and σ_{vo}'=total and effective vertical stresses at the depth of interest, and r_d=depth reduction factor, and MSF is a Magnitude Scaling Factor which weights the contribution of the selected design magnitude to liquefaction potential relative to the reference magnitude M7.5. For M7.5, MSF=1.0. The MSF according to Youd et al. [10], Idriss and Boulanger [9] and a proposed update in Boulanger and Idriss [4] are shown in Fig. 1. It is clear that there has been a continuing significant reduction in MSF values over the last 15 years. Other things being equal, for low density soils, the Boulanger and Idriss [4] MSF will lead to much larger CSRs for earthquake magnitudes below M6.5 and could have significant impact on computed liquefaction hazard in areas of moderate earthquakes..

The simplified method for determining the cyclic stress ratio is deterministic. It is based on a known pair of parameters, a moment magnitude, M, and a_{max}. Therefore, the MSF for M can be applied directly in Eq. (1). However, if a probabilistic a_{max} is used, which is the result of the contributions of the many magnitudes affecting the site, what characteristic magnitude and hence what MSF should be used? In current practice a single magnitude is often selected which tends towards the maximum or mode magnitude expected and its weighting factor is used with the National Building Code for Canada, NBCC 2015 a_{max}. The use of maximum magnitude, as opposed to mode magnitude could lead to quite different assessments of liquefaction potential. In Vancouver prior to 2007, M7.3 was recommended for use. In 2007,

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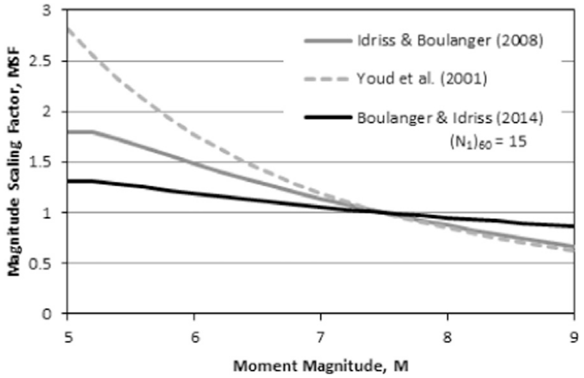

Fig. 1. Comparison of Youd et al. [10], Idriss and Boulanger [9] and Boulanger and Idriss [4] Magnitude Scaling Factors.

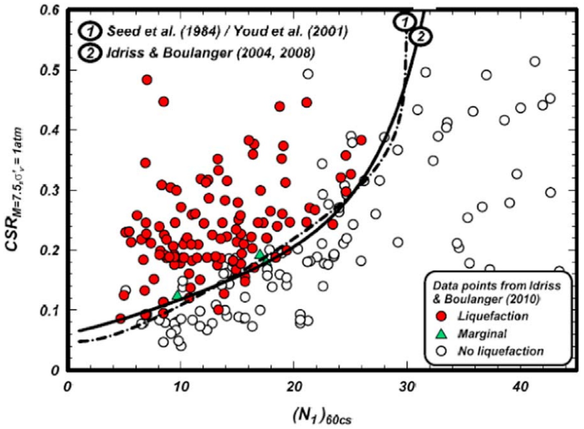

Fig. 2. Correlation of Cyclic Resistance Ratio (CSR), with normalized clean sand SPT-N, after Boulanger and Idriss [4].

M7.0 was suggested. Do these suggested magnitudes represent adequately the combined effects of the many different magnitudes contributing to the probabilistic PGA? The answer to this question is not just a matter of opinion or judgement but can be demonstrated directly by three independent methods. First is a probabilistic seismic hazard analysis for which the magnitudes are weighted by the relative contributions they make to the PGA and hence to the liquefaction potential before a hazard analysis is conducted. This is known as the weighted magnitude method and was first proposed by Idriss [8]. An example of its application in practice has been described in Finn and Wightman [6]. However, for completeness, a brief description is given below. The second procedure is based on a magnitude-distance deaggregation for the specified site hazard level of PGA (usually with a 2% exceedance rate in 50 years), and the third is to use the mean magnitude with the PGA. All of these procedures can be applied in the same way irrespective of how the Cyclic Resistance Ratio, CRR, is specified. For this study, the CRR will be computed using the Idriss and Boulanger [9] procedure, with the appropriate modifications from Boulanger and Idriss [4]. The resistance is specified by $(N1)_{60cs}$ as shown in Fig. 2, from Boulanger and Idriss [4]. The CRR is calculated for each site condition using Eq. (2), from Boulanger and Idriss [4].

$$CRR_{\sigma'=1atm}=\exp\left[\frac{(N_1)_{60,cs}}{14.1}+\left(\frac{(N_1)_{60,cs}}{126}\right)^2-\left(\frac{(N_1)_{60,cs}}{23.6}\right)^3+\left(\frac{(N_1)_{60,cs}}{25.4}\right)^4-2.8\right] \tag{2}$$

.

2. Weighted magnitude probabilistic analysis

The weighted magnitude probabilistic analysis approach was first proposed by Idriss [8] and was worked out in detail by Finn and Wightman [6]. Before conducting a seismic hazard analysis for a site, all magnitudes are weighted according to their contribution to liquefaction as represented by the magnitude scaling factors. The weighting factors are the inverse of the MSF. It is convenient to use the scaling factors that are related to the reference baseline magnitude of M7.5 as no further scaling for magnitude is required when evaluating liquefaction potential. The result of the hazard analysis is a liquefaction resistance curve, which for a given return period gives the appropriate acceleration to use with M7.5 to get the correct Factor of Safety (FS). An example from Finn and Wightman [6] is shown in Fig. 3. At that time the scaling factors used in practice were those recommended by Youd et al. [10] and the computed seismic hazard for Vancouver was given in NBCC 2005 as 0.46 g. It can be seen from Fig. 3 that the acceleration for assessing liquefaction potential in Vancouver for an exceedance rate of 2% in 50 years is 0.30 g for M7.5, and not the full probabilistic acceleration 0.46 g given for Site Class C in NBCC 2005. The weighted magnitude method requires access to a seismic hazard analysis program and results in a somewhat more complicated analysis. Therefore, the Weighted Magnitude Probabilistic Analysis is omitted from the remainder of this study. The deaggregation and mean magnitude methods are easy to implement because the magnitude-distance deaggregation and the mean magnitude are available from the Geological Survey of Canada, GSC. Finn and Wightman [6] showed that all three methods gave the same results..

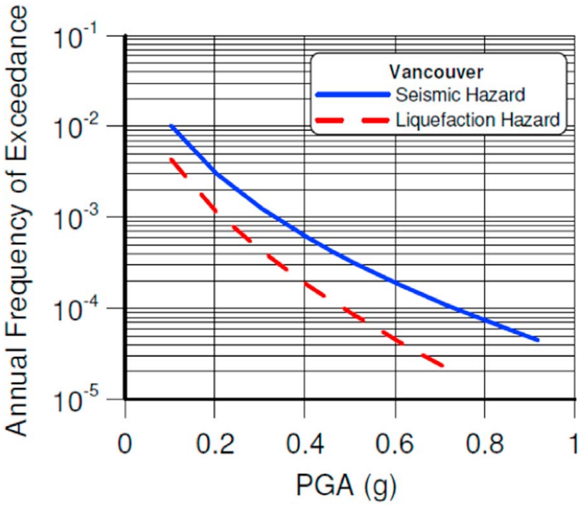

Fig. 3. Liquefaction hazard curve derived for M7.5 by the Idriss [8] weighted.magnitude hazard analysis (after Finn and Wightman [6]).

As the Weighted Magnitude Probabilistic Analysis requires access to a seismic hazard analysis program and results in a somewhat more complicated analysis, it is omitted from the remainder of this study.

3. Magnitude deaggregation method

The seismic demand in the simplified method is based on peak ground acceleration, a_{max}. Boulanger et al. [3] describes the estimation of a_{max} as follows: "*The formal assessment of liquefaction at a site using the simplified procedure should be based on the a_{max} that is estimated to develop in the absence of soil softening or liquefaction.*" The probabilistic a_{max} for Canadian locations with a 2% probability of exceedance is given in NBCC 2015 for a large number of locations and can be determined for a specific site not listed by running a seismic hazard analysis.

The deaggregation method is presented here for Site Class C the reference site class in the NBCC 2015. For Site Classes D and E the same procedure is applicable once the relevant, a_{max}, has been determined either by direct hazard analysis or more conveniently by using the period dependent site amplification factors in NBCC 2015 to