Sand liquefiability assessment by Flat Dilatometer Test (DMT)

Évaluation de la susceptibilité à la liquéfaction des sables par l'essai de dilatomètre (DMT)

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ABSTRACT

The aims of this paper are: (1) To summarize the available knowledge on the use of the flat dilatometer test (DMT) for evaluating sand liquefiability. (2) To formulate a new tentative correlation for evaluating the cyclic resistance ratio CRR from the DMT horizontal stress index K_D, to be used according to the "simplified procedure" (Seed & Idriss 1971). The proposed CRR-K_D correlation combines previous CRR-K_D curves with current correlations for evaluating CRR from CPT and SPT, translated using the relative density D_r as intermediate parameter.

RÉSUMÉ

Les objectifs de cet article sont: (1) Résumer la connaissance disponible sur l'emploi de l'essai de dilatomètre (DMT) pour évaluer la susceptibilité à la liquéfaction des sables. (2) Formuler une nouvelle corrélation préliminaire pour évaluer le rapport de résistance cyclique CRR de l'indice de tension horizontal K_D de DMT, pour être utilisé selon la "procédure simplifiée" (Seed & Idriss 1971). La corrélation CRR-K_D proposée combine des courbes CRR-K_D précédentes avec les corrélations courantes pour évaluer CRR de CPT et de SPT, traduites en utilisant la densité relative D_r comme paramètre intermédiaire.

1 INTRODUCTION

The "simplified procedure", introduced by Seed & Idriss (1971), is currently used as a standard of practice for evaluating the liquefaction resistance of soils. This method requires the calculation of two terms: (1) the seismic demand on a soil layer generated by the earthquake, or cyclic stress ratio CSR, and (2) the capacity of the soil to resist liquefaction, or cyclic resistance ratio CRR. If CSR is greater than CRR, liquefaction can occur.

The cyclic stress ratio CSR is calculated by the following equation (Seed & Idriss 1971):

$$\mathrm{CSR} = \tau_{av} / \sigma'_{vo} = 0.65\,(a_{max} / g)\,(\sigma_{vo} / \sigma'_{vo})\,r_d \qquad (1)$$

where τ_{av} = average cyclic shear stress, a_{max} = peak horizontal acceleration at ground surface generated by the earthquake, g = acceleration of gravity, σ_{vo} and σ'_{vo} = total and effective overburden stresses and r_d = stress reduction coefficient dependent on depth.

The 1996 NCEER and 1998 NCEER/NSF workshops (see summary report by Youd & Idriss 2001) reviewed the state-of-the-art of the Seed & Idriss (1971) "simplified procedure" and recommended the use of in situ tests for routine evaluation of the liquefaction resistance CRR. Criteria for various tests, notably the cone penetration test CPT and the standard penetration test SPT (both widely popular because of the extensive databases and past experience), were revised. As to evaluating CRR from laboratory or calibration chamber (CC) testing, the major obstacle is obtaining undisturbed samples, unless non-routine sampling techniques (e.g. ground freezing) are used. The adequacy of using reconstituted sand specimens, even "exactly" at the same "in situ density", is questionable (in situ fabric / cementation / aging affect significantly CRR), as noted by Porcino & Ghionna 2002.

This paper illustrates the potential of the flat dilatometer test (DMT) as an alternative or integration to other in situ tests in liquefaction studies. The available knowledge on sand liquefiability assessment by use of DMT is reviewed. A new tentative correlation for evaluating CRR from DMT, to be used according to the Seed & Idriss (1971) "simplified procedure", is formulated by combining previous DMT correlations with current methods based on CPT and SPT (supported by past experience), using the relative density D_r as intermediate parameter.

2 CURRENT METHODS FOR EVALUATING LIQUEFACTION RESISTANCE BY CPT AND SPT

The liquefaction resistance CRR is commonly evaluated from CPT or SPT by use of charts where CRR is plotted vs a normalized penetration resistance. The CRR curve separates two regions of the plot – "liquefaction" and "no liquefaction" – including data obtained at sites where surface effects of liquefaction were or were not observed in past earthquakes. Interpretations based on CPT are generally expressed in form of charts where CRR is plotted vs a dimensionless, normalized cone penetration resistance $q_{c1N} = (p_a / \sigma'_{vo})^n\,(q_c / p_a)$, where q_c = measured cone penetration resistance, p_a = reference pressure (1 atm in the same units of σ'_{vo}), n generally ≈ 0.5 to 1. The curve currently recommended for evaluating CRR from CPT (Youd & Idriss 2001, Robertson 2004) is the "CPT Clean Sand Base Curve" shown in Fig. 1. Criteria based on SPT are largely embodied in the "SPT Clean Sand Base Curve" shown in Fig. 2 (Youd & Idriss 2001), where CRR is plotted vs $(N_1)_{60}$ = SPT blowcount normalized to σ'_{vo} = 100 kPa and hammer energy ratio of 60%.

Both the CPT and the SPT recommended CRR curves apply to magnitude 7.5 earthquakes. For magnitudes smaller or larger than 7.5, magnitude scaling factors should be applied (a recommended range is indicated in Youd & Idriss 2001).

3 THEORETICAL/EXPERIMENTAL BASE SUPPORTING THE USE OF DMT FOR ESTIMATING LIQUEFIABILITY

Marchetti (1982) and later studies (Robertson & Campanella 1986, Reyna & Chameau 1991) suggested that the horizontal stress index K_D from DMT ($K_D = (p_o - u_o) / \sigma'_{vo}$) is a suitable parameter to evaluate the liquefaction resistance of sands. Comparative studies have indicated that K_D is noticeably reactive to factors such as stress state/history (σ_h, OCR), pure prestraining, aging, cementation, structure – all increasing liquefaction resistance. Such factors are scarcely felt e.g. by q_c from CPT (see e.g. Huang & Ma 1994) and, in general, by cylindrical-conical probes. As noted by Robertson & Campanella (1986), it is not possible to separate the individual contribution of each factor on K_D. On the other hand, when K_D is low, none of the above fac-

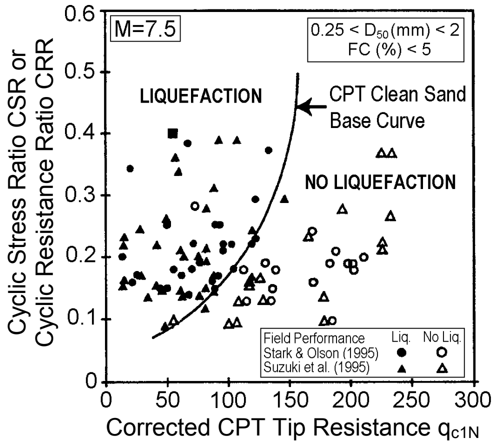


Fig. 1. Recommended curve for evaluating CRR from CPT (Youd & Idriss 2001)

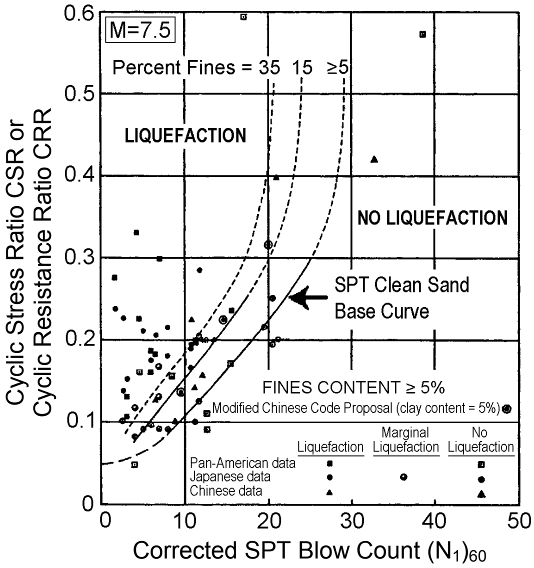


Fig. 2. Recommended curve for evaluating CRR from SPT (Youd & Idriss 2001)

tors is high, i.e. the sand is loose, uncemented, in a low σ_h environment and has little stress history. A sand under these conditions may liquefy or develop large strains under cyclic loading.

The most significant factors supporting the use of DMT for evaluating sand liquefiability are:

Sensitivity of DMT in monitoring soil densification

The high sensitivity of the DMT in monitoring densification, demonstrated by several studies (e.g. Schmertmann et al. 1986 and Jendeby 1992 found DMT ≈ twice more sensitive than CPT to densification), suggests that the DMT may also sense sand liquefiability. In fact a liquefiable sand may be viewed as a sort of "negatively compacted" sand, and it appears plausible that the DMT sensitivity holds both in the positive and negative range.

Sensitivity of DMT to prestraining

CC research on Ticino sand (Jamiolkowski & Lo Presti 1998, Fig. 3) has shown that K_D is much more sensitive to prestraining – one of the most difficult effects to detect by any method – than the penetration resistance (the increase in K_D caused by prestraining was found ≈ 3 to 7 times the increase in penetration resistance q_D). On the other hand, Jamiolkowski et al. (1985) had already observed that reliable predictions of liquefaction resistance of sand deposits of complex stress-strain history require the development of some new in situ device (other than CPT or SPT), more sensitive to the effects of past stress-strain histories.

Correlation K_D – Relative density

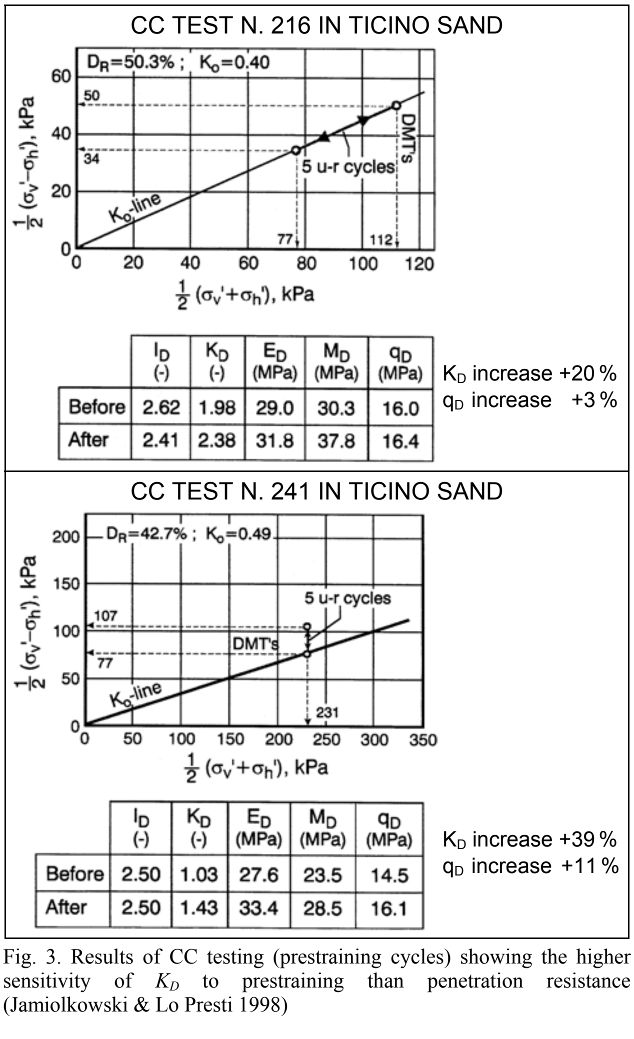
In NC uncemented sands, the relative density D_r can be derived from K_D according to the correlation by Reyna & Chameau (1991) shown in Fig. 4. This correlation has been confirmed by datapoints added by subsequent research, in particular by additional K_D-D_r datapoints (shaded areas in Fig. 4) obtained by Tanaka & Tanaka (1998) at the sites of Ohgishima and Kemigawa, where D_r was determined on high quality frozen samples.

Correlation K_D – In situ state parameter

The state parameter concept is an important step forward from the conventional relative density concept in characterizing soil behavior, combining the effects of both relative density and stress level in a rational way. The state parameter (vertical distance between the current state and the critical state line in the usual v - ln p' plot) governs the attitude of a sand to increase or decrease in volume when sheared, hence it is strongly related to liquefaction resistance. Recent research supports viewing K_D from DMT as an index reflecting the in situ state parameter ξ_o. Yu (2004) identified the average correlation K_D-ξ_o shown in Fig. 5 (study on four well-known reference sands). Clearly relations K_D-ξ_o as the one shown by Yu (2004) strongly encourage efforts to develop methods to assess liquefiability by DMT.

Comments on evaluating liquefiability by CPT and SPT

Theoretical and experimental research (e.g. Sladen 1989, Yu & Mitchell 1998) has demonstrated that the correlation q_c-state parameter for CPT is not unique (as according to Been et al. 1987), but strongly dependent on the stress level. Sladen (1989) showed that ignoring the non-unicity of the correlation q_c-state parameter in design can lead, in some cases, to catastrophic consequences (e.g. the Nerlerk subsea liquefaction flow slides). In view of the possibility of large errors in CRR estimated from q_c, Sladen (1989) concluded that, while the CPT is ideal for providing a qualitative profile of sand deposits, future research should be



	I_D (-)	K_D (-)	E_D (MPa)	M_D (MPa)	q_D (MPa)
Before	2.62	1.98	29.0	30.3	16.0
After	2.41	2.38	31.8	37.8	16.4

	I_D (-)	K_D (-)	E_D (MPa)	M_D (MPa)	q_D (MPa)
Before	2.50	1.03	27.6	23.5	14.5
After	2.50	1.43	33.4	28.5	16.1

Fig. 3. Results of CC testing (prestraining cycles) showing the higher sensitivity of K_D to prestraining than penetration resistance (Jamiolkowski & Lo Presti 1998)

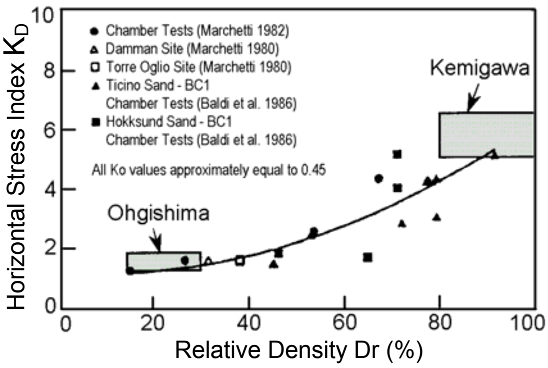


Fig. 4. Correlation K_D-D_r for NC uncemented sands (Reyna & Chameau 1991), also including Ohgishima and Kemigawa datapoints obtained by Tanaka & Tanaka (1998) on high quality frozen samples

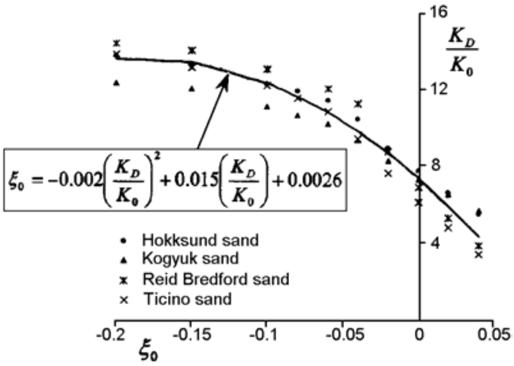


Fig. 5. Average correlation K_D - in situ state parameter ξ_o (Yu 2004)

probably directed towards other tools. Robertson & Wride (1998) warned that CRR evaluated by CPT (preferred to SPT, due to the poor repeatability) may be adequate for low-risk, small-scale projects, while for medium- to high-risk projects they recommended to estimate CRR by more than one method. Accordingly, the 1996 and 1998 NCEER workshops (Youd & Idriss 2001) concluded that, where possible, two or more tests should be used for a more reliable evaluation of CRR.

Comments on evaluating liquefiability by V_s measurements

The NCEER workshops (Youd & Idriss 2001) list the shear wave velocity V_s as a possible quantity to assess sand liquefiability. The seismic dilatometer SDMT, currently in use in the last years, provides V_s measurements, hence offers the possibility to estimate CRR from V_s. However, in the authors' opinion, methods for evaluating CRR from K_D should be preferred, since K_D is more sensitive than V_s to factors such as stress history and aging, which greatly increase the liquefaction resistance.

4 SUMMARY OF EXISTING CRR-K_D CORRELATIONS

Fig. 6 summarizes the various correlations developed to estimate CRR from K_D, expressed in form of CRR-K_D boundary curves separating possible "liquefaction" and "no liquefaction" regions. The central CRR-K_D curve by Reyna & Chameau (1991) supersedes the previous ones (Marchetti 1982, Robertson & Campanella 1986), as it includes liquefaction field performance datapoints (Imperial Valley, South California).

5 TRANSLATION OF CRR-CPT AND CRR-SPT CORRELATIONS INTO CRR-K_D CORRELATIONS USING D_r AS INTERMEDIATE PARAMETER

The specific contribution of this paper is to supplement the existing knowledge on evaluation of CRR by DMT, summarized in Fig. 6. Such supplement consists in additional CRR-K_D curves derived from current methods for evaluating CRR by CPT and SPT (supported by extensive field performance databases). The CRR curves recommended for CPT and SPT are translated into "equivalent" CRR-K_D curves, using the relative density D_r as intermediate parameter. The procedure is the following:

1) Evaluate D_r corresponding to the values of q_{c1N} for the "CPT Clean Sand Base Curve" in Fig. 1 using various D_r-q_c correlations (Baldi et al. 1986, Jamiolkowski et al. 1985).
2) Evaluate D_r corresponding to the values of $(N_1)_{60}$ for the "SPT Clean Sand Base Curve" in Fig. 2 using the D_r-N_{SPT} correlation by Gibbs & Holtz (1957), assuming a range of σ'_{vo} values relevant to common liquefaction conditions (depths ≈ 5 to 15 m, water table close to ground surface).
3) Estimate the values of K_D corresponding to the above calculated values of D_r using the K_D-D_r correlation by Reyna & Chameau (1991) shown in Fig. 4.
4) Plot the CRR-K_D curves derived from CPT and SPT (Fig. 6).

It could be observed that the above procedure basically relies on estimation of D_r from CPT and SPT, which, as widely recognized, is affected by many uncertainties. For this reason D_r was evaluated by more than one method, e.g. for the CPT two different D_r-q_c correlations recommended for current practice (Lunne et al. 1997) were used. As pointed out before, more rational interpretations would require the use of the in situ state parameter, rather than D_r. On the other hand, such interpretations are not sufficiently well-established at present. However, since the aim of this study was to locate a possible *range* of CRR-K_D curves, the results obtained may be considered adequate as a first approach. Fig. 6 shows that the CRR-K_D curves derived from the CRR curves recommended for CPT and SPT plot in a relatively narrow range, very close to the Reyna & Chameau (1991) curve.

A tentative conservative average CRR-K_D curve is proposed (bold line in Fig. 6), approximated by the following equation:

$$\mathrm{CRR} = 0.0107\,K_D^3 - 0.0741\,K_D^2 + 0.2169\,K_D - 0.1306 \qquad (2)$$

Fig. 6 could be used in the same way as other methods based on the Seed & Idriss (1971) procedure: (1) Enter K_D in Fig. 6 (or Eq. 2) to evaluate CRR. (2) Compare CRR with the cyclic stress ratio CSR generated by the earthquake calculated by Eq. 1.

The proposed CRR-K_D curve applies to magnitude M = 7.5 earthquakes. For magnitudes other than 7.5, magnitude scaling factors should be applied (possibly the same ranges recommended in Youd & Idriss 2001). Of course the method proposed for evaluating CRR by DMT is affected by the same restrictions which apply, in general, to the Seed & Idriss (1971) procedure (level to gently sloping ground, limited depth range, clean sand).

A preliminary verification of the proposed CRR-K_D curve is shown in Fig. 7, which includes liquefaction field performance datapoints obtained at various sites after the Loma Prieta 1989

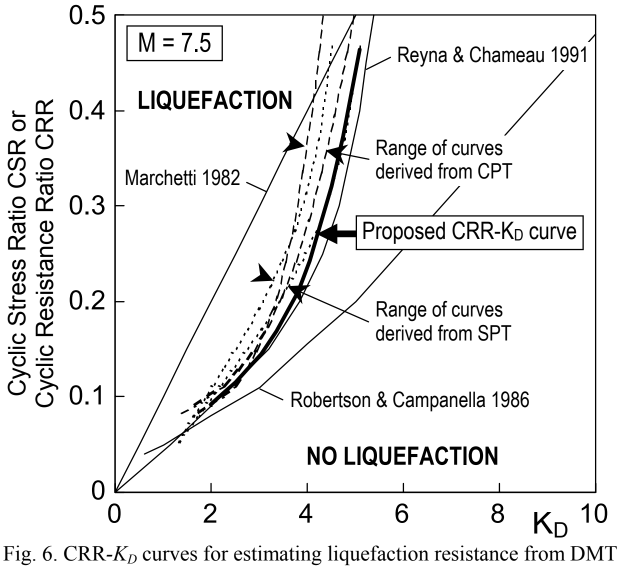


Fig. 6. CRR-K_D curves for estimating liquefaction resistance from DMT

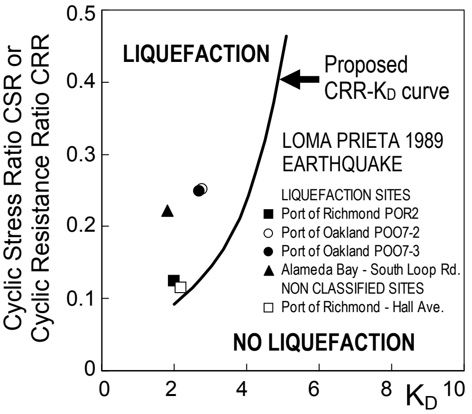


Fig. 7. Comparison of proposed CRR-K_D curve and Loma Prieta 1989 earthquake liquefaction datapoints (Mitchell et al. 1994)

earthquake ($M = 7.1$), in the San Francisco Bay region (to the authors' knowledge, one of the few documented liquefaction cases with DMT data). The CSR-K_D datapoints in Fig. 7 were calculated based on data contained in the report by Mitchell et al. (1994), which includes the results of DMTs performed after the earthquake at several locations where soil liquefaction had occurred (mostly in hydraulic sandfills), along with data on soil stratigraphy, water table, depths of soil layers likely to have liquefied, a_{max} estimated or measured from strong motions recordings. Fig. 7 shows that the datapoints obtained at sites where liquefaction had occurred are correctly located in the "liquefaction" side of the plot. One datapoint relevant to a site non classified as "liquefaction" or "non-liquefaction" site by Mitchell et al. (1994) plots very close to the proposed CRR-K_D boundary curve.

6 TENTATIVE IDENTIFICATION OF MINIMUM "NO LIQUEFACTION" K_D VALUES

In many everyday problems, a full seismic liquefaction analysis can be avoided if the soil is clearly liquefiable or non liquefiable. Guidelines of this type would be practically helpful to engineers. A tentative identification of minimum values of K_D for which a clean sand (natural or sandfill) is adequately safe against liquefaction (M = 7.5 earthquakes) is indicated in TC16 (2001):

– Non seismic areas: $K_D > 1.7$
– Low seismicity areas ($a_{max}/g = 0.15$): $K_D > 4.2$
– Medium seismicity areas ($a_{max}/g = 0.25$): $K_D > 5.0$
– High seismicity areas ($a_{max}/g = 0.35$): $K_D > 5.5$

The above values of K_D were identified based on the Reyna & Chameau (1991) CRR-K_D curve. As to non seismic areas, Marchetti (1997) indicated: (1) For $K_D > 1.7$ liquefaction is definitely not a problem. (2) For $K_D < 1.3$ (unless sporadic/isolated) liquefaction is definitely a problem, soil improvement is required. (3) For $1.3 < K_D < 1.7$ additional study is necessary. (Various studies have indicated that the Zelazny Most Tailing Dam in Poland, in a non seismic region, having typically $K_D = 1.5$, is marginally safe against liquefaction. Yet such dam is standing, possibly it would be definitely safe for say $K_D = 1.7$).

From comparison with the proposed CRR-K_D curve shown in Fig. 6, the above values of K_D appear reasonably conservative.

7 CONCLUSIONS

The DMT offers an alternative to current methods for estimating the liquefaction resistance of sands from CPT or SPT. Theoretical and experimental research over the last 20 years has shown that the horizontal stress index K_D from DMT is noticeably reactive to factors that greatly increase liquefaction resistance, such as past stress-strain history, aging, cementation and structure. On the other hand, such factors are scarcely felt by other tests (e.g. by q_c from CPT). The available experience supports viewing K_D as a suitable parameter to assess sand liquefiability.

A tentative correlation is proposed for evaluating the cyclic resistance ratio CRR from K_D according to the "simplified procedure" (Seed & Idriss 1971), by combining previous CRR-K_D correlations with the vast experience that has led to today used methods for evaluating CRR from CPT and SPT, using the relative density as intermediate parameter. A preliminary verification of the proposed method was obtained from comparison with field performance datapoints obtained at liquefaction sites investigated after the Loma Prieta 1989 earthquake (Mitchell et al. 1994). Obviously considerable additional verification is needed.

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