A NEW SIMPLIFIED CRITERION FOR THE ASSESSMENT OF FIELD LIQUEFACTION POTENTIAL BASED ON DISSIPATED KINETIC ENERGY

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ABSTRACT :

A new energy based model for the evaluation of liquefaction in cohesionless soils has been proposed. In this model, the amount of the kinetic energy possessed by soil particles during shaking is considered in liquefaction potential assessment. A formulation procedure has been proceeded to reach a closed form relation which yields the maximum kinetic energy dissipated in the unit volume of liquefiable soil layer. Using a certain field liquefaction case histories catalog, acceptable performance of the kinetic energy model in the classification of liquefied and non-liquefied cases has been shown. The classification capabilities of the current model and the shear stress based model proposed by Seed and his colleagues have been compared. It has been found that, although the classification successfulness of the current model and initial form of the stress based method are comparable, additional studies and modifications, the same as those carried out for the initial form of stress method, may be required to improve the performance of the model.

KEYWORDS: Liquefaction, Kinetic Energy, Case Histories.

1. INTRODUCTION

Liquefaction is a disastrous type of failures observed during several past earthquakes. Loose saturated sand and silty sand deposits are the most susceptible geological units for this phenomenon when they are subjected to earthquake shaking. Studies for the reliable assessment of liquefaction potential in sites containing these susceptible soils have been considered by many researchers and consequently several methods have been developed to perform this task.

Simplified approaches for the quick evaluation of liquefaction occurrence in a specified site involve two main phases: (1) evaluation of the earthquake excitation induced on soil (earthquake demand) and, (2) estimation of the soil resistance developed against the excitation (soil capacity).

Seed and his colleagues (1971, 1982, 1983, and 1984) developed the most practical simplified liquefaction method when they introduced cyclic shear stress ratio, as earthquake demand, for expressing the cyclic liquefaction characteristic of granular soils under a level ground condition.

In this approach, in situ penetration tests such as standard penetration resistance (SPT) were supposed to be the best representative of soil liquefaction characteristics, because they indicate the important characteristics of the soil such as soil density, gradation, fabric, cementation, age, and stress history (Seed, 1979). In addition to this advantage, since great difficulties exist in obtaining undisturbed samples of sand deposits, many researchers have preferred to utilize in situ test indices.

Shear stress based model of Seed and his colleagues is capable to obtain a relatively reasonable classification between liquefied and non-liquefied case histories. Subsequent related studies have tried to modify this method in order to improve the efficiency of the classification.

Energy based liquefaction assessment methods have been recommended by the researchers (e.g. Davis and Berrill, 1982; Berrill and Davis, 1985; Law et al., 1990; Trifunac, 1995; Ostadan et al., 1998) who applied the amount of energy dissipated in soil during an earthquake, instead of the cyclic shear stress. They have argued that the use of energy concept could be more reasonable than cyclic stress or strain in liquefaction assessment since it considers both cyclic stress and strain histories. As simplified energy approaches, several relationships have been developed to yield the amount of the dissipated energy, named as energy demand, in soil deposits during earthquake. Scientific foundation of these methods can be categorized into three main divisions: (1) Methods which use Gutenberg and Richter (1956) relationship for the evaluation of the earthquake energy released in rupture source and consider geometrical and material attenuation laws for the waves travelling from source to site (Davis and Berrill, 1982; Berrill and Davis, 1985; Law et al., 1990; Trifunac, 1995), (2) Methods based on other seismological relationships for the direct estimation of the energy demand imparted at site (Trifunac, 1995), (3) Methods based on Arias intensity (Arias, 1970) concept (Kayen and Mitchell, 1997; Running, 1996).

The study presented herein introduces a new and simple energy demand relationship based on kinetic energy concept. Using a comprehensive and assured field liquefaction case histories database, it has been found that the amount of kinetic energy in the unit volume of the soil mass is a parameter which can reasonably classify liquefied and non-liquefied case histories.

Since earthquake magnitude parameter is required to calculate the kinetic energy in the unit volume of the soil deposit, it is not needed to use the earthquake magnitude or duration adjustment which is commonly employed in the stress method in order to correlate laboratory harmonic and field random loading conditions. The results clearly demonstrate the capability of kinetic energy and its physical feature in liquefaction potential assessment.

2. KINETIC ENERGY MODEL

Kinetic energy is the energy of motion. It is defined as the work needed to accelerate a body from rest to its current velocity. The body maintains this kinetic energy unless its velocity changes. The kinetic energy of a vibrated mass is the energy it possesses during its shaking. In a vertically propagating wave condition, it is reasonable to assume that the energy is propagated vertically. For a level ground site condition subjected to a vertically propagating wave, instantaneous measure of the kinetic energy in a mass body can be given in a specified time t as:

$$\text{Instataneous Kinetic Energy} = \frac{1}{2} m_b v^2(t) \tag{2.1}$$

Where m_b = mass of body and $v(t)$ = instantaneous velocity of the mass body

Earthquake wave energy is attenuated due to traveling from the rupture source to a specified site. This attenuation occurs due to the intrinsic energy dissipation of the materials located between source to site and also geometrical spreading of wave propagation. Consequently, only a part of earthquake total energy reaches the site and a smaller part of the reached energy is dissipated in the potentially liquefied layer and the remaining part is passed on through the layer. The dissipated energy shakes the soil particles and each particle gets its own velocity, $v(t)_i$, dependant on the magnitude of the input excitation and interparticle interactions.

Let us consider a mass of materials comprised of particles subjected to a dynamic shaking. Since energy is a scalar variable, the instantaneous total kinetic energy of the system at a given time instance, t , is algebraic summation of the kinetic energy values possessed by each particle as follows:

$$\text{Instataneous Total Kinetic Energy} = \sum_{i=1}^{n} \frac{1}{2} m_i v(t)_i^{\,2} \tag{2.2}$$

Where $v(t)_i$ = velocity of each particle, m_i = particle mass, and n = number of particles.

In this study, it has been assumed that soil particles in a potentially liquefied soil layer constitute a mass system. According to Eqn. 2.2, the amount of total kinetic energy needed for a vibrating soil layer is time dependant. In other words, soil particles give different velocities at different time instances. Therefore, the amount of total kinetic energy varies during shaking and Eqn. 2.2 yields the total kinetic energy at a specific instance of shaking. From a conservative viewpoint, only maximum velocity of particles in the liquefiable layer during shaking ($v_{\max,liq}$) is considered in this study. In fact, it is assumed that the soil particles are constraint together and are vibrated uniformly with maximum velocity experienced by the liquefiable layer. Use of this assumption will reduce Eqn. 2.2 to the following equation which introduces the parameter Maximum Kinetic Energy (MKE) in the liquefiable layer:

$$\text{MKE (Maximum Kinetic Energy)} = \frac{1}{2} m v^2_{\max,liq} \tag{2.3}$$

Where $v_{\max,liq}$ = maximum particle velocity at the liquefiable layer and m = mass of liquefiable layer.

Since the values of peak ground velocity ($v_{\max,liq}$) were not directly recorded during past liquefaction case histories, an empirical seismologic relationship is used in order to correlate $v_{\max,liq}$ to the maximum acceleration of the liquefiable layer ($a_{\max,liq}$) and earthquake magnitude.

Because the peak horizontal velocity and acceleration of strong ground motion are usually caused by waves with different frequencies, the ratio of $v_{\max}$ to $a_{\max}$ is a measure of the frequency content of the motion. Therefore, it is rational to assume that $v_{\max}/a_{\max}$ is a function of earthquake magnitude and distance (McGuire, 1978).

Several researchers proposed magnitude dependence of $v_{\max}/a_{\max}$ to be implied by the attenuation relationships for $v_{\max}$ and $a_{\max}$ (Trifuac, 1976; Esteva and Villaverde, 1974; McGuire, 1974). While Trifunac (1976) proposed that $v_{\max}/a_{\max}$ in every site condition is equal to $\exp(0.622M - 0.0035M^2)$, in which M is earthquake magnitude, McGuire (1978) correlated this ratio to M and source-to-site distance R for the two types of site conditions: "Soil" and "Rock". He categorized strong ground motion records into these two classes. Soil site means that recording station was underlain by alluvium or other soft material greater than 10 meter thick. In contrast, rock site denotes on recording stations underlain by a thin veneer of alluvium. According to this categorization, McGuire (1978) proposed the following magnitude dependence empirical relation of $v_{\max}/a_{\max}$ ratio using recorded earthquake motions.

$$\frac{v_{\max}}{a_{\max}} = e^{0.4M} \qquad \text{rock sites}$$

$$\frac{v_{\max}}{a_{\max}} = e^{0.15M} \qquad \text{soil sites} \tag{2.4}$$

Where M denotes on magnitude of earthquake.

Substituting Eqn. 2.4 for soil sites in Eqn. 2.3, the following equation is obtained:

$$\text{MKE (Maximum Kinetic Energy)} = \frac{1}{2} m a_{\max,liq}^2 e^{0.3M} \tag{2.5}$$

It has been custom for the researchers to express dissipated energy in the unit volume of the soil mass. Dissipated energy in unit volume of the soil mass is known as dissipated energy density which is corresponding to the encircled area of the stress – strain loops constituted due to cyclic loading on soil. Thus, knowing that $m = \rho \times V$, in which ρ is the soil unit mass and V is the volume of the soil mass, maximum kinetic energy density (MKED) can be achieved from Eqn. 2.5 as follows:

$$\text{MKED (Maximum Kinetic Energy Density)} = \frac{1}{2} \rho a_{\max,liq}^2 e^{0.3M} \tag{2.6}$$

Where ρ is referred to the soil mass density.

As noted previously, $v_{\max,liq}$ and consequent $a_{\max,liq}$ denote on the maximum velocity and acceleration induced in the liquefiable layer, respectively. Since these parameters do not often exist in liquefaction case history catalogs, this parameter is substituted for the peak ground acceleration at the ground surface ($a_{\max}$) which is a widely used seismological parameter available in the current liquefaction case histories catalog. In the stress based method, a shear stress reduction factor is used (r_d). Seed and Idriss (1971) introduced the stress reduction factor r_d as a parameter describing the ratio of cyclic stresses for a flexible soil column to the cyclic stresses for a rigid soil column. Several subsequent studies have been performed to refine evaluation of this parameter.

Idriss (1999) extended the work of Golesorkhi (1989) and performed several hundred parametric site response analyses and concluded that for the most practical interest conditions, the parameter r_d could be obtained as a function of depth and earthquake magnitude (M). The following equation for r_d was derived to a depth of $z \leq 34m$ using those results (Idriss, 1999; Idriss and Boulanger, 2006):

$$Ln(r_d) = \alpha(z) + \beta(z)M \tag{2.7a}$$

$$\alpha(z) = -1.012 - 1.126\sin(\frac{z}{11.73} + 5.133) \tag{2.7b}$$

$$\beta(z) = 0.106 + 0.118\sin(\frac{z}{11.28} + 5.142) \tag{2.7c}$$

Where z and M refer to depth, in meters, and moment magnitude, respectively. Since uncertainty in r_d increases due to increasing depth, it has been recommended that these equations should only be applied for depth less than about 20m.

In the current study, this development have been used for the estimation of r_d in order to modify peak ground acceleration $a_{\max}$ at the ground surface and to obtain maximum acceleration in the liquefiable layer $a_{\max,liq}$. According to this concept, the following modification on $a_{\max}$ has been applied by acceleration reduction factor, r_d:

$$a_{\max,liq} = a_{\max}.r_d \tag{2.8}$$

Substituting (9) in (7) gives MKED as follows:

$$\text{MKED (Maximum Kinetic Energy Density)} = \frac{1}{2}\rho a_{\max}^2 e^{0.3M} r_d{}^2 \tag{2.9}$$

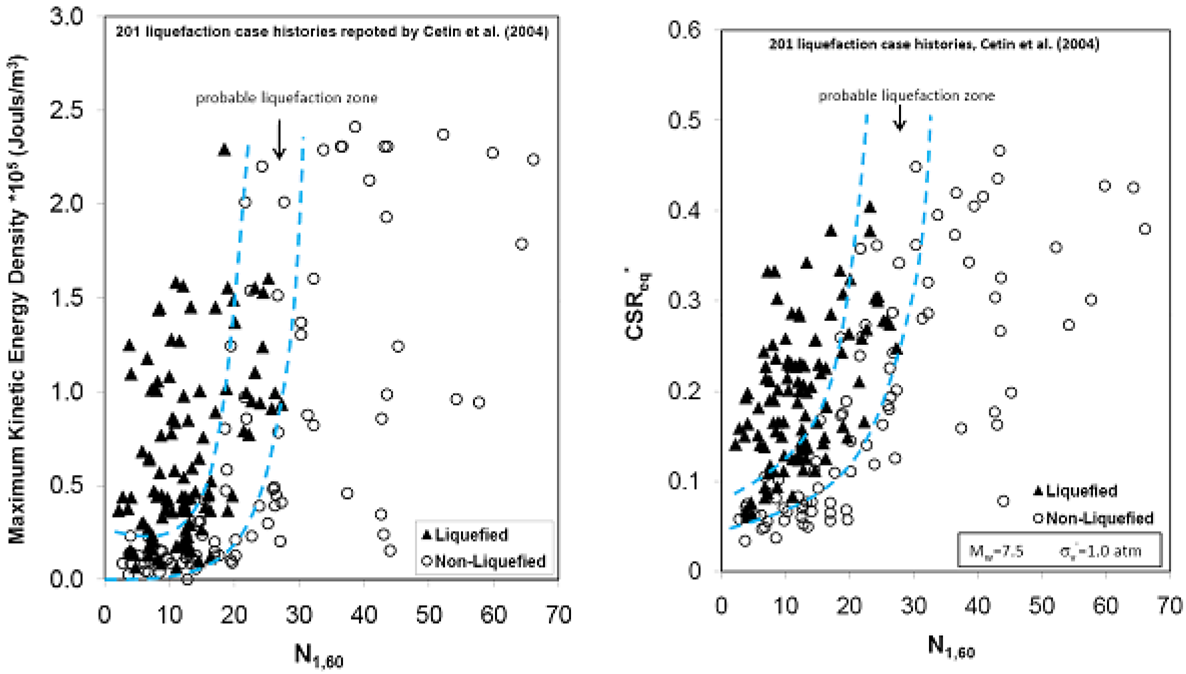
Dimension of the MKED is of $Jouls/m^3$ or Pa. Eqn. 2.9 describes the amount of the energy dissipated at the unit volume of the liquefiable layer. This is introduced as a new kinetic energy based demand for liquefaction potential assessment. In this equation once magnitude of earthquake or peak ground horizontal acceleration are increased, the likelihood of liquefaction triggering is consequently increased.

3. LIQUEFACTION CASE HISTORIES DATABASE

The performance of each earthquake demand model can be evaluated using liquefaction field data. In order to do this task for the current energy demand model, an assured database of liquefaction case histories, previously reported by Cetin et al. (2004), has been employed. The database contains 201 field data of liquefied and non-liquefied cases observed during past major earthquakes including the data used by Seed et al. (1984) and also new liquefaction data after 1984. Cetin et al. (2004) selected these 201 data among approximately 450 liquefaction (or non-liquefaction) field case histories via a judgment system established on the basis of quality and uncertainty of data. The database involves 90 case histories of the 126 case histories which were initially used by Seed et al. (1984) in their original work. Cetin et al. (2004) reevaluated Seed et al. (1984) data in term of peak horizontal ground acceleration (a_{max}) and corrected SPT values ($N_{1,60}$). All case histories are free-field and level ground cases in which initial shear stresses due to soil and structure interaction or large ground slope (more than 3%) are zero. More details of this liquefaction catalog can be found in the Cetin et al. (2004) comprehensive work.

4. RESULTS AND DISCUSSION

Based on the mentioned case histories of observed and recorded field – behavior during earthquakes, Maximum Kinetic Energy Density (MKED) per each liquefied and non-liquefied cases has been calculated and plotted versus $N_{1,60}$. FIG. 1(a and b) illustrates performance of the presented kinetic energy model and stress based method, respectively. A relatively satisfactory performance is clearly seen for this model in compare with stress based method, since it has classified liquefied and non-liquefied case histories with an acceptable degree of accuracy. it is noted that CSR^{*}_{eq} is a modified CSR for earthquake magnitude and effective overburden stress based on the recommendations indicated by Cetin et al. (2004).



(a) Kinetic Energy Model (b) Stress Based Model

Figure 1 Performance of the proposed and stress based model

The stress based method is established upon observations of earthquakes with $M = 7.5$ and therefore the effects of magnitude is not considered in the original formulation of CSR. The concept of the equivalent number of cycles and its corresponding laboratory studies has been employed to determine liquefaction potential at other earthquake magnitudes. In contrast, the kinetic energy model directly uses the magnitude of earthquake in its formulation. Thus, the use of laboratory cyclic tests data for deriving correlation curves between harmonic and earthquake random loading conditions (duration weighting factor) is not required in this method.

As can be seen in the FIG. 1(a), the kinetic energy model works satisfactorily for the range of chart in which $N_{1,60}$ and kinetic energy density values are over than 15 and $25\, kJouls/m^3$, respectively.

The unsuccessful classification of the current model at the low values of kinetic energy may be due to the limitations involved in the model formulation. A brief discussion on probable causes of the mentioned unsuccessful classification is presented in the following.

Kinetic energy density values obtained from Eqn. 2.9 does not reflect the effects of liquefiable soil characteristics. It has been assumed in the current study that $N_{1,60}$ values substantially reflect the influence of soil relative density and effective vertical stress (Gibbs and Holtz, 1957; Law et al., 1990). This limiting assumption may affect the model to obtain unsuccessful classification in the MKED values lower than $25\, kJouls/m^3$. The MKED values located in this region of the chart correspond to the case histories having low earthquake magnitude or high source-to-site distance. It should be noted that, in the MKED formulation procedure, v_{max}/a_{max} ratios in liquefaction sites have only been dependant to earthquake magnitude, according to the previous studies of researchers. However, a closer look at the physical feature of this ratio reveals that it may dependent on the characteristics of site soil as well as earthquake source-to-site distance. Therefore, a more accurate evaluation of the v_{max}/a_{max} may improve performance of the model.

Another limitation which may affect the performance of the model is the procedure (stress reduction factor) used to convert maximum particle acceleration in the liquefiable layer to the peak ground acceleration recorded at the ground surface. This conversion has been applied because of the lack of data for liquefaction case histories in liquefiable layer. Such limitation is also observed in the stress based method.

The kinetic energy demand model presented herein is a basic form of a knowledge introducing the use of kinetic energy concept for liquefaction potential assessment. With no doubt, reasonable modifications are required in order to reach to a more successful classification in the low part of the chart.

5. CONCLUSIONS

A new criterion for the quick assessment of field liquefaction potential is presented based on kinetic energy concept. It is suggested that in a horizontally soil layer subjected to earthquake motion, the kinetic energy possessed by soil particles is a key parameter which can classify liquefied and non-liquefied case histories in an acceptable degree of accuracy. This suggestion has been verified using 201 certain field liquefaction case histories. It has been found that the kinetic energy demand model works satisfactory except for the low values of kinetic energy which correspond to the cases having low earthquake magnitude or high source-to-site distance. Additional studies and refinements, the same as those carried out for the stress based liquefaction method, will increase classification performance at the low values of kinetic energy. It is suggested that the parameter of peak velocity to peak acceleration ratio at the ground surface should be evaluated more accurate in order to improve the performance of the kinetic energy model.

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