Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

4-3-19

USE OF SHEAR-STRAIN ENERGY FOR LIQUEFACTION PREDICTION

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SUMMARY

This paper presents a procedure for evaluating the liquefaction potential of soil sites under earthquake loading. The procedure uses a nearly unique relation between the excess pore pressure response and the absorbed energy in sand. This makes the procedure relatively simple for design analysis purposes. The procedure will serve as a simple and rational alternative to existing methods for evaluating the liquefaction potential. Overall validity of the proposed procedure has been demonstrated through a case study.

INTRODUCTION

Liquefaction of cohesionless soils has been one of the primary reasons for the foundation soil failures during major earthquakes. A large number of studies have been made to clarify the mechanism of liquefaction and to develop procedures for predicting liquefaction potential. At present various numerical methods and design procedures are available for evaluating earthquake-induced liquefaction.

In spite of these recent developments further studies are needed to calibrate and improve existing methods. Assessment of the in situ soil conditions for use with these methods, for example, is an essential subject for further studies. Also, unified methods need to be developed for the assessment of the liquefaction potential under various types of loading, including earthquakes, storm waves, winds, blasts, and even static load.

The author is conducting a series of studies to develop a reasonably simple procedure for predicting the liquefaction potential against various types of loading. To accomplish this objective the author is looking into the possibility of using the relation between the residual pore-water pressure and the absorbed energy in sand during cyclic and dynamic loading, since this relation appears to be rather independent of stress paths and the type of loading.

This paper first presents the relation between the absorbed energy in sand and pore pressure responses and then a summary of the site-response analyses for quantifying the relation between the absorbed energy in various soil sites and major earthquake parameters. These are followed by a description of the proposed method and a summary of a case study.

PORE PRESSURE BEHAVIOR OF SAND

This paper proposes to represent the cyclic and liquefaction behavior of sand in terms of absorbed energy. There are several reasons why the absorbed energy can be a good parameter for representing the process of liquefaction. For example the absorbed energy in sand during cyclic loading must be closely related to its volume change for drained loading and to its pore pressure response behavior for undrained loading. During cyclic loading loose sands tend to decrease their volume, and this volume-decrease tendency causes an increase in pore pressures. Since the volume change of sand is the result of the plastic process that involves sliding and rearrangement of sand particles, the absorbed energy due to this plastic process must be a good measure of the volume change and the pore pressure response behavior of sand.

Only a few investigators, however, have studied the relation between the residual pore pressure and the absorbed energy in sand (Ref. 1 and Ref. 2). According to the results of an extensive cyclic tests performed by Towhata and Ishihara (Ref. 2), the excess pore pressure in sand is nearly independent of stress paths and loading types, but is dependent on the current stress level.

Preliminary results of our cyclic triaxial tests on clean sands also indicate similar conclusions. For a given sand density, the residual pore pressure is well related to the energy absorbed by the sand. This relation appears insensitive to the variation of cyclic wave forms and stress paths. Therefore, a nearly unique relation may be established for a given density of sand. Figure 1 presents tentative relations between the residual pore pressure and the absorbed energy in clean sands for three densities. Similar relations can also be established for soft clays to describe the process of pore pressure buildup and cyclic degradation (Ref. 3).

ENERGY ABSORPTION DURING AN EARTHQUAKE

From the discussions above, the residual pore pressure of sand during cyclic loading appears to be closely related to its absorbed energy. Therefore, the liquefaction potential of a soil site may be judged if the amount of absorbed energy can be estimated for a given design earthquake event. Therefore, we performed a series of site-response analyses a) to estimate the absorbed energy of various soil sites during major historical earthquakes and b) to relate this absorbed energy to the major parameters of an earthquake.

The site-response analyses involved 87 earthquake motions recorded at 20 Japanese strong-motion recording sites. These earthquake motions were selected from the compilation made by Mori and Crouse (Ref. 4). The earthquake magnitudes of the selected motions ranged from 5.1 to 7.9 and their peak accelerations ranged from 0.024g to 0.429g. These strong-motion sites involved various soil conditions (stiff shallow sites to deep, soft sites). The majority of these recording sites had records of SPT data that we could use to estimate the stiffness and damping parameters for our site-response analyses. Figure 2 demonstrates the estimated profiles of the small-strain shear moduli of these sites for our site-response analyses.

The site-response analyses identified two key parameters controlling the absorbed energy; the peak ground surface acceleration (a_{max}) and the magnitude of an earthquake (M). Although stiff sites tend to decrease the absorbed energy, its effect has been found to be relatively minor. Figure 3 summarizes the relations between a_{max} and the normalized maximum energy (E_{max}/σ_v) for all the cases studied. The normalized maximum energy (E_{max}/σ_v) represents the ratio between the maximum absorbed energy within a soil profile and the effective overburden stress at the depth of the occurrence of the maximum energy.

Figure 3 provides an empirical means to evaluate the maximum absorbed energy of a soil site from the peak ground surface acceleration and the magnitude of a given design earthquake.

PROPOSED PREDICTION METHOD

The results of this study may be summarized as the following empirical method for evaluating the liquefaction potential of a soil site during an earthquake:

1. Establish the design earthquake. For this step the peak acceleration (a_{max}) and the magnitude of the earthquake (M) are estimated either from an applicable design code or from a site-specific seismicity study.

2. Estimate the normalized maximum energy (E_{max}/σ_v) for the site from Fig. 3 by using the values for a_{max} and M.

3. Establish the soil profile. For this step the density profile of the cohesionless soils within the site is estimated from the geotechnical investigation data for the site. The present method calls for a relative density profile (D_r) at the site.

4. Estimate the pore pressures development at the site. The maximum amount of excess pore-water pressures that may develop at the site is obtained from Fig. 1 by using the values for E_{max}/σ_v and D_r.

Liquefaction may be considered to occur when the residual excess pore pressure ratio, estimated in Step 4, is 1.0.

EVALUATION OF PROPOSED METHOD

The overall validity of the proposed procedure has been examined by comparing a) the field performance of cohesionless soil sites in Japan during historical earthquakes and b) the predictions made by the proposed procedure. Table 1 summarizes typical results from this type of comparison. The predictions agree well with field observations. The "?" marks in our prediction indicate that liquefaction is marginally predicted. Results of similar comparisons are being compiled for more recent Japanese earthquakes and for Western U.S.A. earthquakes.

CONCLUDING COMMENTS

This study demonstrated the feasibility of establishing a relatively simple procedure for predicting the liquefaction potential of cohesionless sites against earthquakes. The procedure described in this paper is based primarily on Japanese earthquakes. Further studies are under way for Western U.S.A. earthquakes, for use with field soil test data such as SPT and CPT results, and for other types of loading such as blasts.

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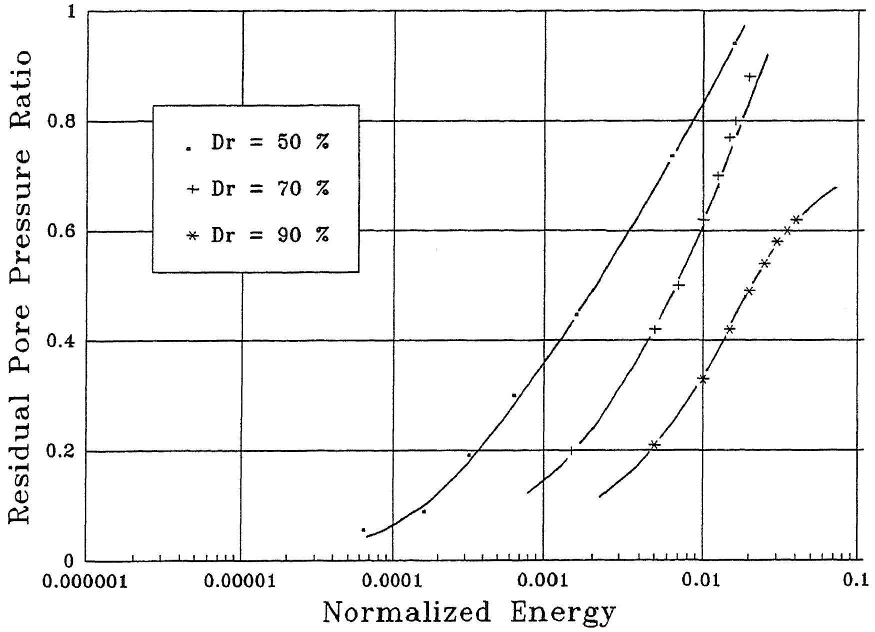

Fig.1 Relation between Pore Pressure and Absorbed Energy

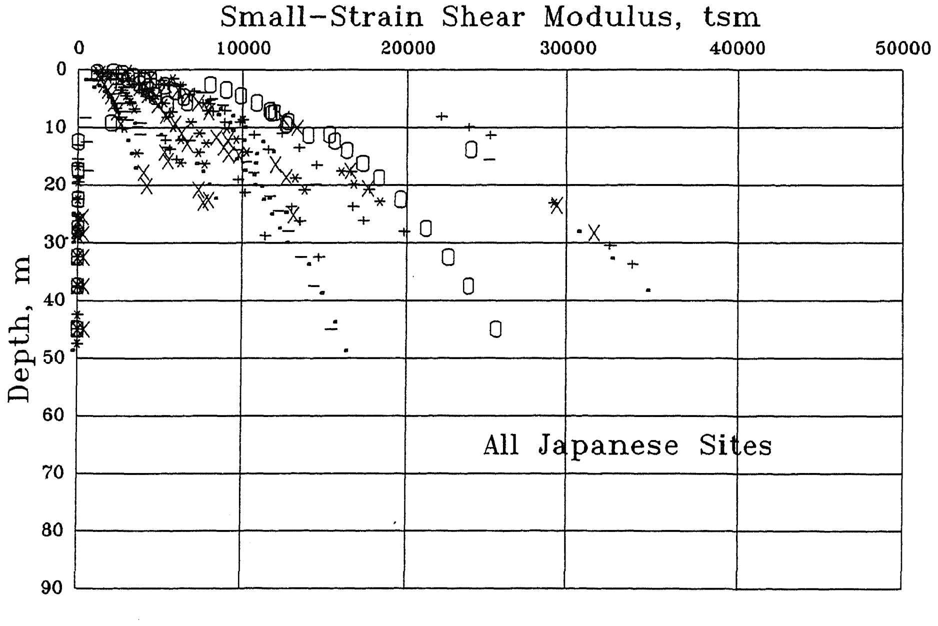

Fig.2 Stiffness Profiles of Japanese Soil Sites

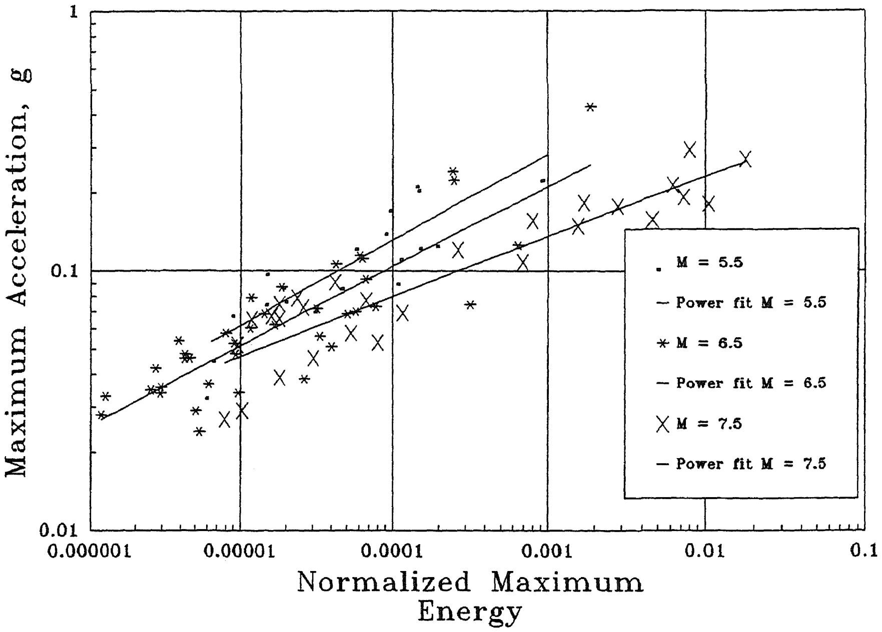

Fig.3 Relation between Acceleration and Absorbed Energy

E.Q.	Date	M	Site	Dr	Acc.	Obser.	Prediction
Niigata	1802	6.6	Niigata	53	0.12g	No Liq.	No Liq.
	1802	6.6	Niigata	64	0.12g	No Liq.	No Liq.
Niigata	1887	6.1	Niigata	53	0.08g	No Liq.	No Liq.
	1887	6.1	Niigata	64	0.08g	No Liq.	No Liq.
Mino Owari	1891	8.4	Ogaki	65	0.35g	Liq.	Liq.
	1891	8.4	Ginan W.	55	0.35g	Liq.	Liq.
	1891	8.4	Unuma	75	0.35g	No Liq.	No Liq.
	1891	8.4	Ogase P.	72	0.35g	Liq.	Liq.
Tohnankai	1944	8.3	Komei	40	0.08g	Liq.	?
	1944	8.3	Meiko St	30	0.08g	Liq.	?
Fukui	1948	7.2	Takaya	72	0.30g	Liq.	Liq.
	1948	7.2	Takaya	90	0.30g	No Liq.	No Liq.
	1948	7.2	Shonenji	40	0.30g	Liq.	Liq.
	1948	7.2	Agr. U.	50	0.30g	Liq.	Liq.
Niigata	1964	7.5	Niigata	53	0.16g	Liq.	No Liq.
	1964	7.5	Niigata	70	0.16g	Liq.	No Liq.
	1964	7.5	Niigata	64	0.16g	No Liq.	No Liq.
	1964	7.5	Niigata	53	0.16g	No Liq.	No Liq.
Tokachioki	1968	7.8	Hachinohe	78	0.21g	No Liq.	No Liq.
	1968	7.8	Hachinohe	58	0.21g	Liq.	No Liq.
	1968	7.8	Hachinohe	80	0.21g	No Liq.	No Liq.
	1968	7.8	Hachinohe	55	0.18g	Liq.	No Liq.

Table 1 Observed and Predicted Liquefaction Potential