UNIFORM CYCLES IN EARTHQUAKE MOTIONS

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SUMMARY

The actual irregular time histories produced by an earthquake can be represented by uniform amplitude cyclic stresses, although there may be a considerable amount of uncertainty associated with them. The available conversion procedures can be categorized as (1) the simple method - no consideration of the development of the pore-pressure and (2) pore-pressure development models (linear and non-linear). The simple method appears to be more appropriate. The use of a soil strength curve with a safety factor greater than 1.0 is inappropriate. The equivalent number of cycles corresponding to the horizontal accelerogram containing the maximum acceleration and stress level of 0.75 of the maximum acceleration can be used for a liquefaction study.

INTRODUCTION

An earthquake loading pattern is extremely irregular. Moreover, the earthquake time history of a future earthquake at a particular site is unknown. However, earthquake loading patterns are routinely idealized for practical applications and used to solve complicated problems analytically using very sophisticated theories and modeling techniques. This type of application gets very complicated in geotechnical problems, and the analytical results need to be verified using laboratory experiments. It is extremely difficult and expensive to reproduce the desired earthquake time history on a soil specimen in the laboratory. Most of the soil laboratories do not have the required facilities. In many cases, laboratory investigations are carried out under uniform loading conditions to predict the in situ soil behavior under any dynamic loading, including earthquake loading conditions. Thus, for a meaningful evaluation it is very important to correlate the two loading conditions. After this conversion from irregular to uniform cycles, the soil specimen should show the same strength or deformation characteristics.

To convert an irregular earthquake loading to equivalent uniform cycles, two parameters need to be estimated, namely, the intensity of

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the uniform cyclic loading, S_L, and the corresponding number of eqivalent cycles, N_{eq}. For this conversion a specific soil strength curve is necessary. The soil strength curve can be described as a failure curve representing the relationship between the intensity of the applied uniform loading and the number of cycles required to cause the specimen to fail. For a soil strength curve, using Miner's (Ref. 1) damage rule, an N_{eq} value corresponding to a known S_L value can be estimated for a particular earthquake motion. This concept was developed by several researchers (Refs. 2,3,4) without considering the pore-pressure development in a saturated deposit during the application of the earthquake motion. Recently, Wer and Dobry (Ref. 5) proposed a conversion procedure considering the pore-pressure development during the application of the earthquake motion.

Before discussing the methods available for this conversion, the underlying assumptions in the conversion concept need to be thoroughly understood. These assumptions are: (1) The ground motion is uniform at all sites, i.e., the ground motion used for a particular site can also be used for other similar sites in the same general area; (2) the stress-time history induced by an earthquake at the depth of interest in the deposit is directly proportional to the acceleration recorded at or near the ground surface; and (3) for all soils, the laboratory liquefaction test data results can be represented by a single normalized curve relating stress ratio or stress level, S_L, to the number of cycles causing liquefaction. These assumptions are valid in most cases of liquefaction analysis and have been studied extensively in the literature (Refs. 2,4,6). The tectonic nature of earthquakes justifies the first assumption. The second assumption leads to the conclusion that N_{eq} calculated from the normalized acceleration-time history record and the the normalized shear stress-time history record are essentially the same. The third assumption will be discussed in detail later. For a liquefaction analysis, the following observation will simplify the problem considerably. The effect of the compression waves produced by an earthquake traveling upward through a saturated sand deposit is probably negligible. Thus, the vertical accelerogram need not be considered for a liquefaction study.

METHODS OF CONVERSIONS

Methods available to convert the irregular earthquake time history to equivalent uniform cycles can be broadly divided into two major categories: (1) The simple method; no consideration of pore-pressure, and (2) pore-pressure development models. The second approach could be further divided into two subgroups; (a) the linear pore-pressure development model, and (b) the non-linear pore-pressure development model.

The details of the conversion procedures for all the aforementioned

methods can not be described here due to lack of space. The conversion procedures using the simple method have been discussed extensively in the literature and do not need further discussion here. The concept behind the second approach considers the development of pore-pressure in a saturated deposit during the application of earthquake motion. When the dynamic shear stresses are applied to a saturated deposit, the pore-pressure, u, starts building up and when it reaches the effective stress value, σ', or when $R_u = u/\sigma' \geq 1.0$, the soil is considered to have initial liquefaction. In this approach, the way the pore-pressure develops in a cyclic stress controlled test is expected to control the conversion procedures. This is discussed in detail elsewhere (Ref. 5).

Linear Pore-Pressure Development Model

According to this approach, if the ratio $R_u = u/\sigma'$ is plotted against N/N_L, where N is the number of applied equivalent cycles, and N_L is the number of cycles required to cause initial liquefaction corresponding to a soil strength curve and a stress level, the relationship can be considered as linear; or

$$R_u = N/N_L \tag{1}$$

R_u is zero at the beginning of the earthquake motion. As each half cycle of the earthquake motion is applied, the R_u value would increase according to Eq. 1. For each half cycle the increment of R_u is $0.5 \times N_L$. Of course, the N_L values would be different for each stress level corresponding to that particular half cycle. Thus, considering each half cycle one at a time, the R_u value can be calculated. If the R_u value stays less than 1.0 for an entire given earthquake motion, the simple method and this method are identical; however, if R_u exceeds 1.0 before the end of the complete earthquake motion it creates a problem, and will be discussed later.

Non-linear Pore-Pressure Development Model

De Alba et. al., (Ref. 7) noted that Eq.1 is not linear but can be represented as

$$\frac{N}{N_L} = \left[\frac{1}{2}\,(1 - \cos \pi R_u)\right]^{\alpha} \tag{2}$$

in which α is a function of the soil properties and the test conditions. The average value of α was observed to be 0.7.

In this procedure, each half cycle is again considered one at a time, the increase in R_u value is estimated for that half cycle according

to Eq. 2, and the total R_u value at the end of the half cycle is calculated by adding this increment to the value at the beginning of the half cycle. Here, the location of the half cycle in the earthquake record is important, whereas in the linear case it is not.

COMPARISON OF SIMPLE AND PORE-PRESSURE MODEL

To compare these methods effectively, the particular soil strength curve used plays a very important part. Seed et. al., (Ref. 3) used different safety factors (SF) in defining soil strength curves. Seed et. al. proposed a soil strength curve considering simple shear test results. Then they used several safety factors with this curve. Most of their reported results are based on a soil strength curve with SF = 1.5. Simply stated, this means that the curve is developed for a condition where the acceleration required to cause failure in one cycle is equal to 1.5 times the maximum acceleration of the earthquake. The underlying assumption is that a conservative N_{eq} value would be obtained in this and might indirectly consider the uncertainty associated with the soil strength curve. This approach may not be appropriate. It may appear intuitively that N_{eq} calculated using a soil strength curve with SF = 1.5 would be higher than that of when SF = 1.0. But this is not necessarily correct and depends on many factors. Several researchers (Refs. 2, 3, 4, 5) used S_L = 0.65 x the maximum acceleration in their studies. Using S_L = 0.65, the equivalence of several stress levels are given in Table 1, corresponding to soil strength curves suggested by Seed et al. (Ref. 3)

Table 1 Conversion Factors, S_L = 0.65

Safety Factor = 1.0	Safety Factor = 1.5
1 cycle of 1.0 x a_{max} = 2.1 cycles	1 cycle of 1.0 x a_{max} = 3.0 cycles
1 cycle of 0.9 x a_{max} = 1.8 cycles	1 cycle of 0.9 x a_{max} = 2.4 cycles
1 cycle of 0.8 x a_{max} = 1.2 cycles	1 cycle of 0.8 x a_{max} = 1.7 cycles
1 cycle of 0.7 x a_{max} = 1.1 cycles	1 cycle of 0.7 x a_{max} = 1.2 cycles
1 cycle of 0.65 x a_{max} = 1.0 cycle	1 cylle of 0.65 x a_{max} = 1.0 cycle
1 cycle of 0.50 x a_{max} = 0.5 cycle	1 cycle of 0.5 x a_{max} = 0.2 cycle
1 cycle of 0.40 x a_{max} = 0.2 cycle	1 cycle of 0.4 x a_{max} = 0.04 cycle

Some interesting observations can be made from Table 1. When $S_L \geq 0.65$, the conversion factors corresponding to SF = 1.5 are greater than when SF = 1.0. However, for $S_L < 0.65$, a completely opposite behavior can be observed. Thus, the number of peaks in the earthquake motion less than $0.65 \times a_{max}$ is important. In fact, Wer and Dobry (Ref. 5) and Hochaimi and Haldar (Ref. 8) observed higher N_{eq} for SF = 1.0 than for SF = 1.5 in most recorded earthquakes. Moreover, the safety factor plays a very important role when pore-pressure development models are used and when R_u becomes greater than 1.0 before the end of the earthquake motion. In this case, according to Seed et. al.'s soil strength curves, N_{eq} values would be 2.1, 6.0, and 35 cycles, for SF = 1.0, 1.5, and 2.0, respectively for any earthquake motion. For $R_u > 1.0$, N_{eq} value attains a limiting value. This drastic difference in N_{eq} values for different safety factors would not occur if $R_u \leq 1.0$. These observations lead to two conclusions: (1) the safety factor need not be used in a soil strength curve in estimating N_{eq} values, and (2) the pore-pressure development models, linear or nonlinear, are inappropriate in converting irregular earthquake motions to uniform cyclic motions, particularly when $R_u > 1.0$.

The uncertainty in the soil strength curve can be considered by taking the original soil strength curve and assuming spreads in it, as was done by Lee and Chan (Ref. 2) and Haldar and Tang (Ref. 6).

More detailed discussion can not be made here due to lack of space, but will be addressed during the presentation. However, some important observations on the conversion procedures need some mention here. It is observed that the effect of the uncertainty in the soil strength curve on N_{eq} values is minimum if $S_L = 0.75 \times a_{max}$ is selected. Thus, by simply changing the stress level from 0.65 to 0.75, the uncertainty in the soil strength curve can be reduced significantly.

As mentioned earlier, only the horizontal acceleration-time history records of earthquake shaking are necessary to calculate the value of N_{eq} in three different ways:

1. By considering the accelerogram which contains the maximum acceleration a_{max}.

2. By considering the accelerogram which contains the weaker component in terms of the maximum acceleration, and

3. By considering the accelerogram which gives the maximum value of N_{eq}. To study this alternative, the values of N_{eq} corresponding to the two horizontal time histories are computed for each earthquake. The

larger of the two values is identified as $(N_{eq})_{max}$.

The relationship between N_{eq} and earthquake magnitude M, expressed in Richter's scale, can be developed for all three approaches. As expected, the $(N_{eq})_{max}$ versus M curve lies above the other curves. However, the difference is not significant. It seems reasonable that since a_{max} is the main design input parameter in the evaluation of liquefaction potential or similar problems, it is perhaps satisfactory to compute N_{eq} considering the accelerogram containing the maximum acceleration.

According to Haldar and Tang, a statistical relationship between N_{eq} and earthquake magnitude, M, can be developed using $S_L = 0.75 \times a_{max}$ and using the soil strength curve with SF = 1.0. The concept behind this relationship is that it has been shown that larger magnitude earthquakes are associated with a longer duration of earth shaking. Since the number of equivalent uniform cycles varies with the duration of earthquake shaking, it is expected that some kind of correlation would exist between N_{eq} and the earthquake magnitude. Haldar and Tang (Ref. 6) expressed the relationship as:

$$E(N_{eq}|M=m) = 106.08 - 36.42\ m + 3.312\ m^2 \quad ; \quad m \geq 5.0 \qquad (3)$$

and the corresponding variance, $Var(N_{eq}|M) = 29.05$. For M = 7.0, the uncertainty in the estimation of N_{eq}, in terms of coefficient of variation is about 0.40. This uncertainty is significant and should be considered in any probabilistic formulation.

CONCLUSION

The applicability of equivalent uniform stress cycles in soil dynamics to the study of soil behavior during and after an earthquake has been studied. It is observed that the simple method, without considering the pore-pressue development, is more appropriate to convert the irregular earthquake motions to equivalent uniform cyclic motions. The use of a soil strength curve with a safety factor greater than 1.0 is inappropriate. The pore-pressure development models, linear or nonlinear, are inappropriate particularly when R_u value is greater than one. When the intensity of uniform stresses is selected to be 75% of the maximum stress, the variation or uncertainty in the normalized soil strength curve has a minimum effect on the value of the N_{eq} versus M relationship. Thus, $S_L = 0.75$ is suggested to be used for such conversion. A statistical relationship between N_{eq} and the earthquake magnitude is suggested here, based on results obtained from earthquake time histories recorded at or near the ground surface. N_{eq} could be estimated adequately by considering the component of excitation containing the peak acceleration. The uncertainty in the estimation of N_{eq} is significant and should be

considered in any probabilistic formulation.

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