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EMPIRICAL RELATIONS FOR EARTHQUAKE PORE PRESSURE BUILD-UP IN GRAVEL

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ABSTRACT

In terms of this paper a method is proposed for prediction of earthquake induced excess pore pressure in gravelly soils. Prediction is based on empirical relations initially developed for sands (Egglezos, 2004). The main idea is the introduction of an equivalent void ratio of clean sand (e_{es}) - in substitution of gravel nominal void ratio e_o - which leads to similar pore pressure build-up. This idea is based on the finding that pore pressure build-up from cyclic loading in gravel, (qualitatively at least) follows similar path to that of clean sand, but gravel at a given relative density and gravel content, develops excess pore pressure corresponding to a sand of higher density. The empirical relations applies to triaxial stress conditions, but extension to free field conditions is easily attained, through simlpe assumptions.

The procedure for the estimation of "equivalent void ratio" e_{es} is based upon statistical analysis of experimental data. These data originate from cyclic triaxial tests in gravel mixtures or natural gravels reported in relevant literature (e.g. Evans M.D., 1995, Kokusho, 1994 etc).

The accuracy of the proposed method is examined with comparison of predictions with published experimental data from cyclic tests on gravel. As a conclusion the proposed method for calculation of earthquake excess pore pressure in gravel a) is characterized of great simplicity, b) uses as input parameters the initial stress and density state of soil and c) agrees well with published experimental data from other researchers and d) can apply equally to gravelly sands (practically for gravel content GC≤65%) and sandy gravels (GC>65%).

Keywords: earthquake, pore pressure, gravel, empirical relations, liquefaction

INTRODUCTION

Excess pore pressure of granular soils under cyclic loading is a well known phenomenon which causes degradation of soil strength and increase of its deformability. This phenomenon is extremely obvious in cases that liquefaction occurs, because of its catastrophic nature upon human structures. For this reason, the study of undrained behavior of granular soils under cyclic loading, concentrates always increasing interest from researchers. This interest focuses mainly on sands, and, as a consequence, sand behavior nowadays is considered well documented. In addition, last decade an increasing interest for undrained behavior of gravelly soils under seismic loading is observed. This interest is justified from the fact that either many earth works are constructed from gravel (e.g. the main body of earth dams, foundation of pavements e.t.c.) or significant structures have to be founded upon gravel layers. Despite this fact, documentation of undrained behavior of gravel under seismic loading is far from being satisfactory. This is attributed mainly to the difficulty for performance of in situ and laboratory testing on gravel (due both to financial and technical limitations relating to the equipment and the grain size). For this reason the usual practice in geotechnical design -whenever

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gravelly soil is met- is the omit of any particular consideration for seismic conditions. Indeed, gravel is considered to be (and usually it is!) very resistant to seismic action. On the other hand, case histories reported in relevant literature (e.g. Valera J. et al., 1994) make reference of serious failures on gravelly soils as a result of earthquake action and indicate that previous consideration is no generally applicable.

The scope of this work is the extension of simple empirical relations for prediction of excess pore pressure on clean sands from cyclic loading (Egglezos, 2004) to gravelly soils. The evaluation of these empirical relations is based upon experimental data from 10 gravelly soils (data from 138 triaxial tests) collected from relevant literature. It is worth noting that experimental data from cyclic triaxial tests involved in this analysis are coming exclusively from in situ frozen samples, in order to reflect actual free field response in seismic loading (that is, no use of reconstituted samples is taken place). In addition, the results of analyzed tests have been corrected for membrane compliance effects, according to the authors of these data.

The proposed empirical relations provide the means for simplified computations of bearing capacity of foundations, thrush on retaining structures, slope stability and so on. In addition, they can be used as reference for calibration of constitutive models aimed at the prediction of cyclic response of gravel.

DESCRIPTION OF EXCESS PORE PRESSURE MODEL FOR SANDS

Data base for pore pressure model on sands

The empirical relations for excess pore pressure on sand resulted from adequate statistical fitting upon sufficient experimental data from cyclic triaxial tests on six non cohesive soils:

- fine Oosterschelde sand with mean grain size d_{50}=0.17mm and uniformity coefficient C_u=1.40 (Lambe, 1979).
- fine to medium (N.T.U.A. sand (from the historical bay of Marathonas), with d_{50}=0.25mm and C_u=1.70 (Egglezos, 2004).
- fine Nevada sand with d_{50}=0.100mm and C_u=1.41 (The earth Technology Co., 1993).
- fine Banding sand with d_{50}=0.190mm and C_u=1.50 (Dobry, 1983).
- fine Baskarp sand with d_{50}=0.17mm and C_u=1.40 (NGI, 1988).
- Silica Flour silt with d_{50}=0.02mm and C_u=6.25 (Sangseom, 1988).

These tests are consolidated either isotropically (CIU tests: $\sigma'_1=\sigma'_3$) or anisotropically in compression (CAU tests $\sigma'_1>\sigma'_3$). Cyclic stress (double) amplitude σ'_{1dc} remained constant during testing.
The range of the initial stress and density parameters are presented in Table 1, as function of the following invariant magnitudes:

$$p'_o=(\sigma'_1+2.\sigma'_3)/3, \quad q_o=(\sigma'_1-\sigma'_3)/2, \quad q_c=\sigma'_{1dc}/2, \quad P=q_o/(p'_o.M), \quad CSR=\sigma'_{1dc}/(2.p'_o)$$

where, M denotes the slope of PTL line (e.g. Ishihara et al., (1975), Luong and Sidaner (1981)), which separates contractive from expansive behaviour in space q_o - p'_o.

Table 1. Range of initial parameters in the analyzed undrained cyclic triaxial tests on sand

Number of sand soils	Test number	CSR	p'_o/p_a	P	q_o/q_c	Void ratio e	d_{50} (mm)	Uniformity coefficient C_u
6	193	0.04 - 3.28	0.3 - 7.0	0.0-1.11	0.0-5.0	0.53-0.88	0.02-0.25	1.40-6.25

Excess pore pressure model on sands

Figure 1 shows in log-log scale the typical development of excess pore pressure of sand (continuous line) with number of cycles for cyclic loading (data come from a typical cyclic CIU triaxial test with

constant cyclic stress). This type of test simulates well free field conditions. It is observed that excess pore pressure development presents two characteristic stages.
At 1st stage the development of excess pore pressure in the log-log scale is practically "linear" (that is exponential). At the next stage a sharp increase in excess pore pressure accumulation is observed, which finally leads to liquefaction ($U_{max}= p'_o$).
For CIU conditions, the excess pore pressure U (or, equivalently, the normalised pore pressure ratio $RU=U/p'_o$) of experimental data, is successfully simulated from the following formulae (dashed line):

$$\mathrm{U(N)} = U_1 N^C \left[1 + 0.01\left(N / N_{1st} \right)^b \right] \leq U_{\max} \tag{1a}$$

$$\mathrm{RU(N)} = RU_1 N^C \left[1 + 0.01\left(N / N_{1st} \right)^b \right] \leq 1.0 \tag{1b}$$

In equations 1a and 1b, U is the excess pore pressure , N is the number of cycles, N_{1st} corresponds to the number of cycles for the end of 1st stage (relates to excess pore pressure U_{1st}), c express the effect of loading cycles at the 1st stage, b express the effect of loading cycles at the final (2nd) stage, U_1 is the excess pore pressure at the end of 1st cycle and U_{max} the upper limit in excess pore pressure (for CIU tests: $U_{max}= p'_o$) with value directly estimated from initial state parameters

$$U_{\max} = p'_o - q_o / M \tag{2}$$

and corresponds to stress state (q, p´) on PTL line for loading cycles $N=N_L$.
Figure 1 includes analytical prediction-dashed line (just qualitative approach for better comparison with data) based on equation 1.

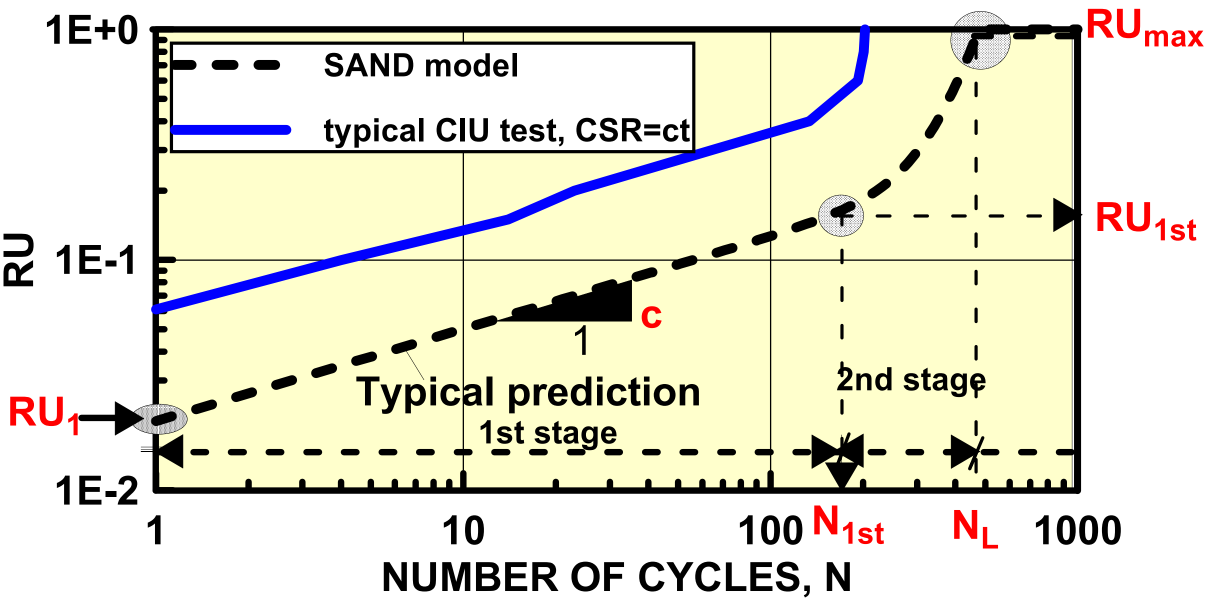

Figure 1. Typical excess pore pressure in granular soils

Previous research of the author (Egglezos (2004)) have shown that excess pore pressure U_1 (or equivalently RU_1) for CIU conditions can be expressed as simple product of exponential terms:

$$U_1 = A p_a CSR^{a1} \left(p'_o / p_a \right)^{a2} e^{a3} \leq U_{\max} \tag{3a}$$

$$RU_1 = A CSR^{a1} \left(p'_o / p_a \right)^{a2} e^{a3} \leq 1.0 \tag{3b}$$

where, p_a is the atmospheric pressure for normalisation of units. Constants in equations 3a and 3b result from multivariable non-linear regression statistical analysis (StatSoft Inc., 1995) upon experimental data of Table 1. Indeed, the statistical analysis leads to a very good fitting of experimental data (no of data=193, R=0.841) on U_1 formula, for the following values of constants: A=3.92, a1=1.58, a2=1.02, και a3=4. 70, and transforms general equations 3a and 3b as follows:

$$U_1 = 3.92 p_a CSR^{1.58} \left(p'_o / p_a \right)^{1.02} e^{4.70} \leq U_{max} \tag{4a}$$

$$RU_1 \approx 3.92 CSR^{1.58} e^{4.70} \leq 1.0 \tag{4b}$$

Exponents c and b, (in equations 1a and 1b) express the effect of number of loading cycles for the 1st and the 2nd stage respectively. Exponent c (for CIU state) can also be expressed statistically from initial state parameters (123 data, R=0.60) from the following formula:

$$c = 1.07 e^{1.58} CSR^{0.20} \tag{5}$$

while, the exponent b takes mean value 5.80 (typical range of b exponent: 4.80<b<6.80, but it can be easily calculated analytically through equations 1-5).

U_{1st} and N_{1st} are expressed with high accuracy as constant ratios of U_{max} and N_L respectively:

$$U_{1st} = \lambda \,.\, U_{max} \tag{6}$$

$$N_{1st} = \mu \,.\, N_L \tag{7}$$

Indeed, for triaxial conditions (CIU tests) factors λ and μ have practically constant values: λ=0.52 (range of experimental data : 0.50-0.55) and μ=0.54 (range of experimental data: 0.50-0.60).

It is worth noting that the proposed equations constitute a complete analytical frame for the description of excess pore pressure in sand. In addition the accuracy of the empirical relations has been well documented from previous works of the author (Egglezos, (2004), Egglezos (2006)), and is in good agreement with relevant works of other researchers (e.g. De Alba (1976), Seed et al. (1986)).

Application of pore pressure model for sands on gravel

Fig. 2 shows the typical development of excess pore pressure of gravel (fat continuous lines) with number of cycles.

In fig. 2a is also The analytical predictions are shown with fat dashed line. It is clear that excess pore pressure sand model can simulate well enough the excess pore pressure on gravel, (on the assumption that parameters U_1 and c are evaluated satisfactorily).

Fig.2a-2d shows (thin dashed lines) the application of sand model (equations 1-8) for prediction of excess pore pressure on gravel for the initial parameters (e_o, CSR, p'_o). It is eminent that direct application of equations 1-7 for sand model leads to systematic under-prediction of excess pore pressure in gravel. This under-prediction is ought to the combined effect of under-prediction of both parameters U_1 and c of sand model.

This under-prediction is attributed mainly to the nominal void ratio e_o of the gravel samples, given that parameters CSR and p'_o are partially independent of the material properties. Indeed, it is well documented (e.g. Kokusho et al., 1994) that void ratio of gravel composites for the same value of Dr is systematic lower from void ratio of clean sands. In Addition, gravel composites for the same Dr present decreasing void ratios (that is, higher cyclic resistance) for increasing GC (eg Evans, 1995). For that reason the introduction of an “equivalent void ratio of sand” e_{es} is attempted which applies in the excess pore pressure sand model and, leads to accurate prediction of excess pore pressure on gravel.

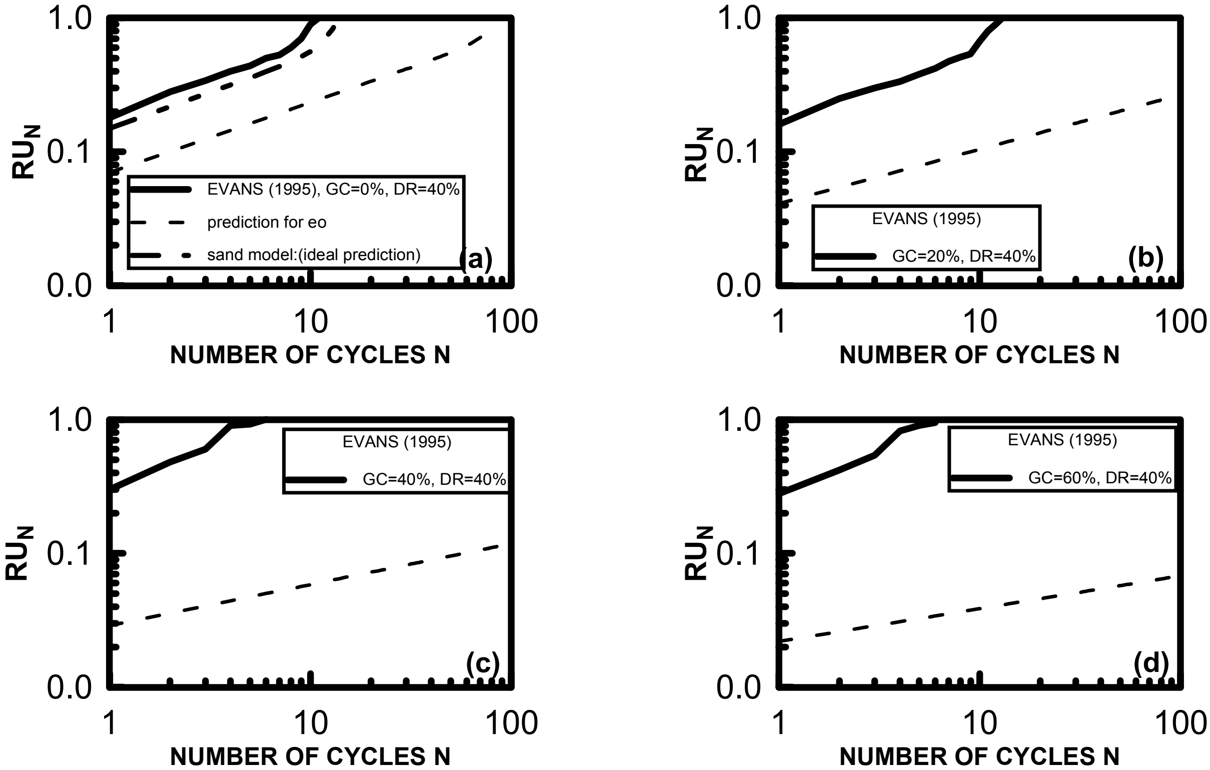

Figure 2. Application of sand model for prediction of excess pore pressure in gravel

The concept of equivalent void ratio e_{es}

This under-prediction is attributed mainly to the nominal void ratio e_o of the gravel samples, given that parameters CSR and p'_o are partially independent of the material properties. Indeed, it is well documented (e.g. Kokusho et al.(1994)) that void ratio of gravel composites for the same relative density DR is systematic lower from void ratio of clean sands.

In Addition, gravel composites for the same DR present decreasing void ratios (that is, higher cyclic resistance) for increasing gravel content (e.g. Evans). For that reason it is attempted the introduction of an “equivalent void ratio of sand” e_{es} which applies in the excess pore pressure sand model and leads to prediction of improved accuracy for excess pore pressure on gravel.

EQUIVALENT VOID RATIO

Estimation of “equivalent void ratio of sand” from excess pore pressure model for sand

The analytical formulae of excess pore pressure sand model permits the evaluation of either parameter involved in equations 1-8 in terms of the other parameters. Specifically, the value of “equivalent void ratio of sand” e_{es}, for each test of gravel data base, can result from application of excess pore pressure sand model for $RU=RU_{1st}$ (equation 4b) :

$$e_{es} = \left(\frac{0.52}{3.92 CRR^{1.58} \left(0.54 N_L\right)^{c\left(e_{eq}\right)}} \right)^{(1/4.70)} \tag{8}$$

The value of exponent c in the above equation is calculated from equation 5 with use of an "equivalent void ratio, e_{eq}" where:

$$e_{eq} = 1.0 - 0.5DR(\%)/100 \tag{9}$$

$$c(e_{eq}) = 1.07CRR^{0.202}e_{eq}^{1.584} \tag{10}$$

This value of e_{eq} corresponds to a typical void ratio of uniform sand with e_{max}=1.00, e_{min}=0.50 and of relative density DR equal to that of gravelly soil under examination.
For the (anyway limited) available values of the exponent c, the above assumption seems quite rational, since 0.92<Rc<1.05, where ratio Rc refers to the ratio of measured c from experimental data to $c(e_{eq})$ from equation 10.

Cyclic resistance of gravels (CRR)
The evaluation of e_{es} parameter from equation 8 in the previous paragraph requires first the calculation of CRR of gravel.

CRR can be expressed particularly accurately from empirical relation resulting from statistical fitting on available data from gravel tests, in terms of the following parameters:
number of (uniform) cycles N(M) as function of the seismic magnitude M, nominal void ratio e_o and gravel content GC from the results of a usual geotechnical exploration.

In this work, the term gravel content corresponds to the fraction of soil with grain size greater than 2.0 mm.

From literature survey sufficient number of experimental data were collected, from cyclic triaxial CIU tests on 10 gravelly soils. The range of the initial stress and density parameters of experimental data are presented in Table 2.

It is obvious that ranging of data parameters permits the performance of reliable statistical analysis on the total sample collected, and deduction of valid conclusions, as well.

Table 2. Range of initial parameters in the undrained cyclic triaxial tests on gravel

Number of gravelly soils	Test number	CRR	p'_o/p_a	Number of cycles for RU=1.0 (N_L)	GC(%)	Void ratio e_o	DR (%)	D_{50} (mm)	C_u
10	138	0.10-2.36	0.5-5.0	1-258	0-100	0.20-0.91	20-80	0.40-27.0	2-39

Statistical multivariable regression analysis leads to a very good fitting of experimental data (no of data =93, R=0.875) on the following formula for CRR calculation:

$$CRR = 0.190e_o^{-0.90}N_L^{-0.457}EXP(0.312GC(\%)/100) \tag{11}$$

The accuracy of equation 11 for prediction of CRR is evaluated in figs 3-5.

Fig 3 shows the effect of nominal void ratio e_o on normalised CRR value for the effect of gravel content GC and number of cycles.

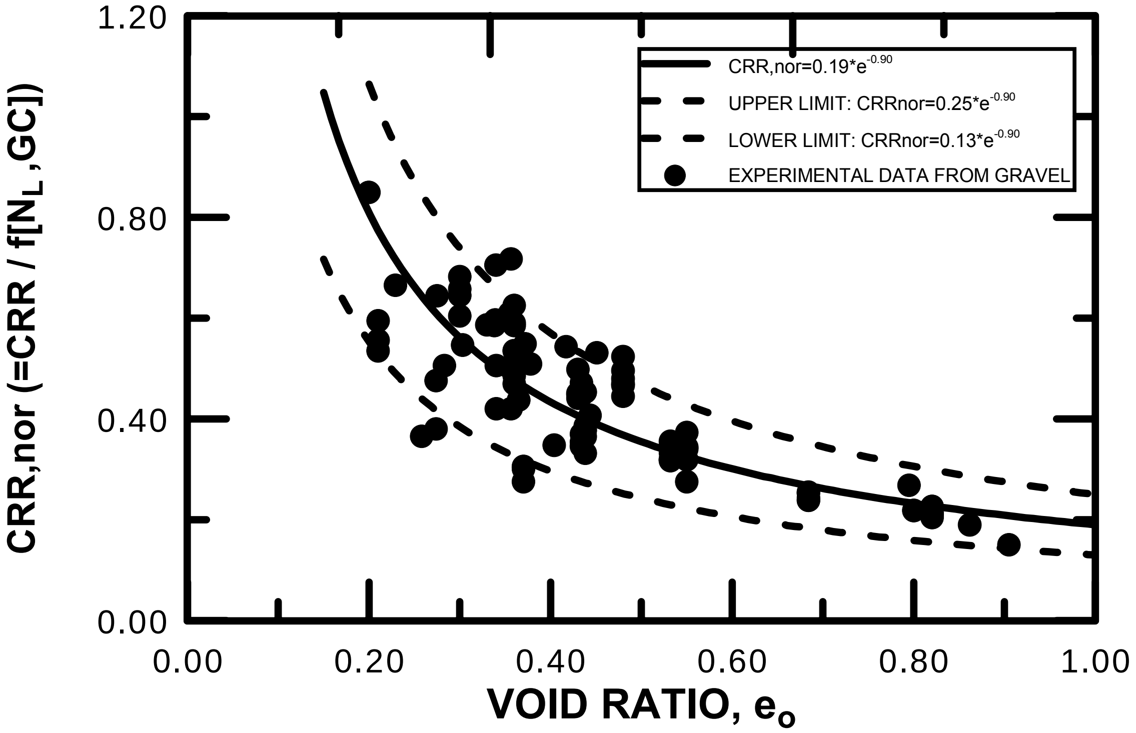

Figure 3. Empirical relation for prediction of CRR in gravel in relation to void ratio e_o

Fig 4 shows the prediction ratio RCRR (predicted CRR / measured CRR) vs measured CRR. It is obvious that great majority of predictions ranges ±30% from measurements.

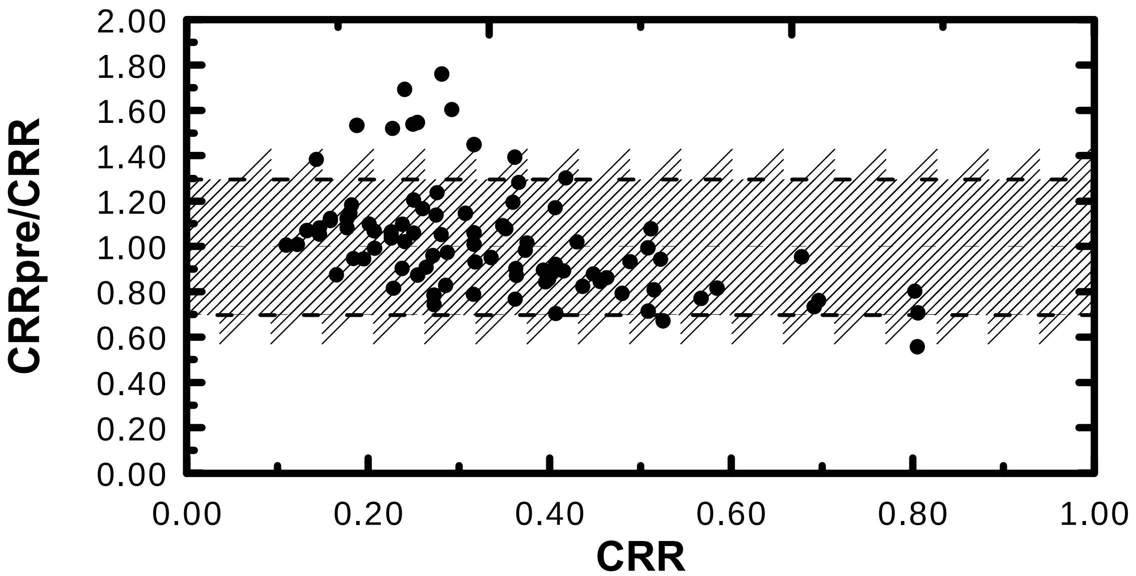

Figure 4. Comparison of predicted and measured CRR in gravel

In addition, the evaluation of equation 11 is presented in fig. 5 where, CRR predictions are directly compared to experimental data from cyclic triaxial CIU tests on gravels (Evans (1995), Kokusho (1994), Siddiqi (1984), Konno (1994)).

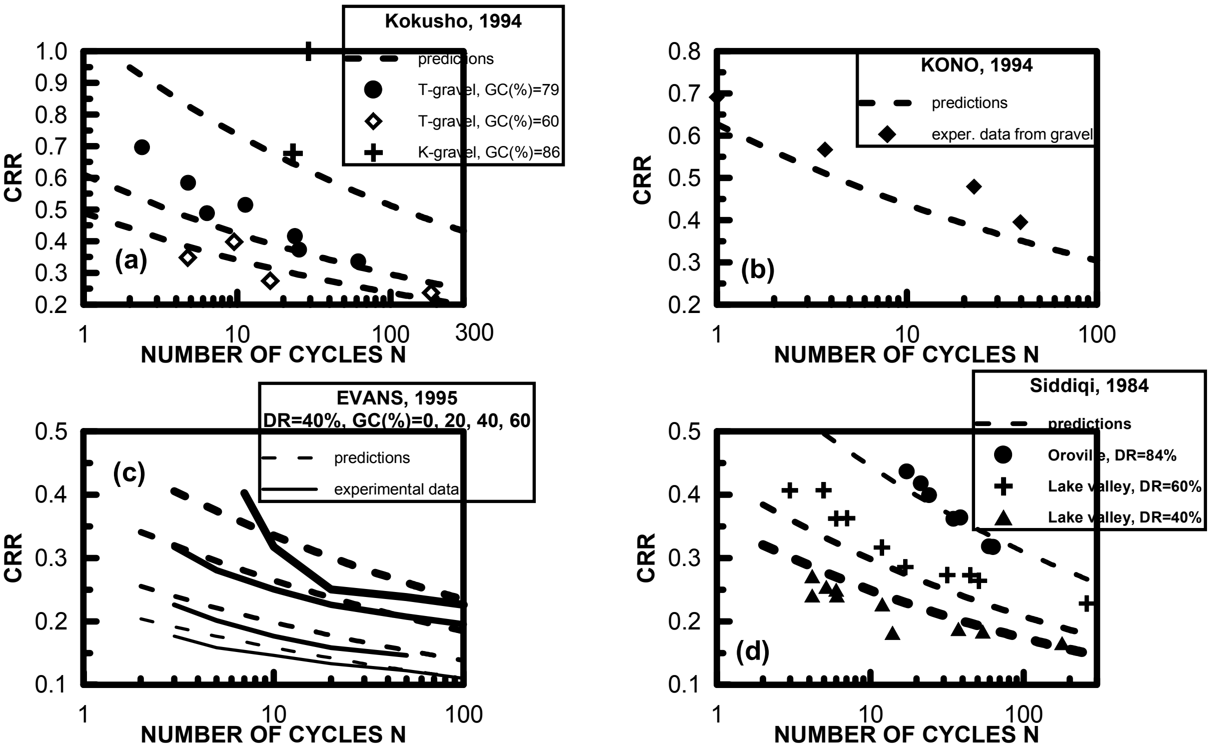

Figure 5. Empirical relations for prediction of CRR in gravel

To be noted that the calculated CRR from equation 11 refers to triaxial loading. The relevant value for free field condition CRR_{ff} is obtained from the following transformation:

$$CRR_{ff} = 0.90 \ CRR \ c_r, \qquad (12)$$

where c_r is adequate correction factor for the stress state (e.g. Kastro (1975)).

Empirical relation for calculation of equivalent void ratio (e_{es})

The estimated values of e_{es} through equation 8, for every test in the available data base from gravel tests, can be approached with high accuracy from the following empirical equation, resulting from statistical analysis of available experimental data (82 data, R=0.991):

$$e_{es} = 0.614 e_o^{-0.093} CRR^{-0.395} N_L^{-0.114} EXP\left(-0.013 GC(\%)/100\right) \qquad (13)$$

Application of equivalent void ratio (e_{es}) in prediction of undrained behavior of gravel

The application of e_{es} in prediction of excess pore pressure in gravel includes the following steps:

1. Calculation of CRR value for a) given number of (equivalent uniform) cycles N as function of the earthquake magnitude, b) nominal void ratio e_o and c) gravel content GC from usual grain size analyses, from empirical equation 11. To be noted that generally CRR#CSR for the problem under examination.

2. Calculation of e_{es} void ratio from empirical equation 13.

3. Application of e_{es} value, from the previous step, to empirical equations 1- 8, for calculation of excess pore pressure.

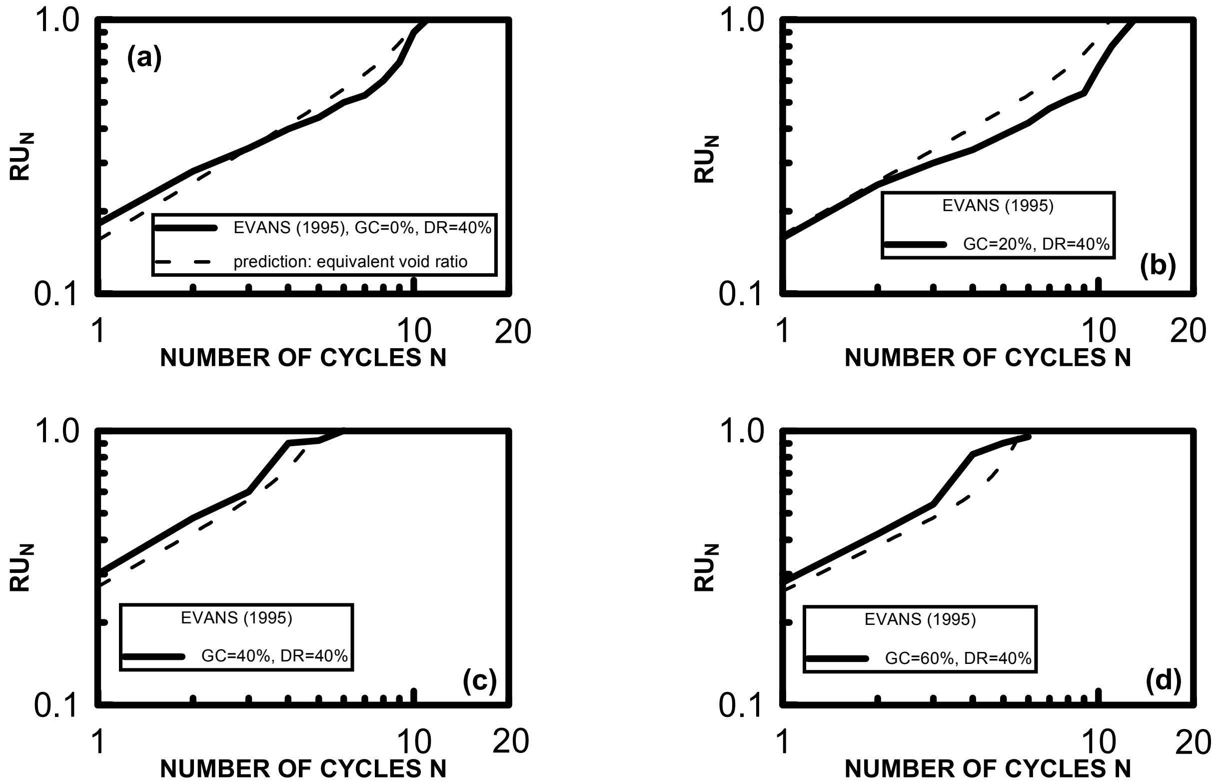

Figure 6. Application of "e_{es} void ratio" for prediction of excess pore pressure in gravel

The evaluation of e_{es} method on prediction of excess pore pressure in gravelly soils is examined in fig. 6. Fig 6 shows the application of e_{es} on prediction of excess pore pressure on gravel composites (Evans, 1995), for ranging gravel content (GC(%) = 0%, 20%, 40% and 60% respectively). The continuous line refer to experimental data, while, the analytical predictions are shown with dashed line. It is clear that prediction is particularly satisfactory. This fact indicates strongly that excess pore pressure sand model can simulate well enough the excess pore pressure on gravel.

CONCLUSIONS

The major conclusions of this research are the following:

(a) For the present time no other empirical relation for simplified calculation of excess pore pressure on gravel is referred on reported literature.

(b) Geotechnical designers as a rule omit calculation of excess pore pressure in granular soils (and consequently the decreased shear strength of soil) because of lack of simplified methods (with exception cases where danger of liquefaction hazard is eminent).

(c) The proposed empirical relations for prediction of excess pore pressure on sands can also apply in case of gravelly soils (equally to gravelly sands and sandy gravels).

(d) The proposed model is characterized of great mathematical simplicity and permits the estimation of either parameter involved in terms of the other parameters (e.g. CRR vs N_L, RU vs N e.t.c.).

(e) The parameters of the empirical relations result directly from the initial stress and density state of soil under examination.

(f) The application of the proposed model, for prediction of undrained behavior of gravel, is based on empirical formula for CRR of gravelly soils. This formula results statistically from analysis of 93 data, with R=0.875, in terms of basic parameters as: nominal void ratio e_o, number of cycles for initial liquefaction N_L and gravel content GC.

(g) The application of nominal void ratio e_o of gravel in the empirical relations for excess pore pressure leads to systematic under-prediction of pore pressures RU developed from cyclic loading
(h) Subtitution of nominal void ratio e_o by an "equivalent void ratio of sand" e_{es} can improve particularly the accuracy of predictions.
(i) Void ratio e_{es} is estimated statistically from analysis of 83 data, with R=0.991, in terms of basic parameters as: nominal void ratio e_o, CRR, N_L and gravel content GC.
(j) The accuracy of the proposed method is tested with application on the available experimental data for prediction of a) RU vs N and b) CRR vs N. Comparison of predictions and measurements is particularly good.

As main conclusion that "equivalent void ratio of sand" e_{es} can be used for simplified calculation in geotechnical design as well as in calibration of numerical codes for prediction of undrained dynamic behavior of gravelly soil. Of course, extension of data base in future, with additional experimental data from cyclic tests on gravel, could further improve the accuracy of prediction.

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