4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1366

SIMPLIFIED PREDICTION FOR EARTHQUAKE INDUCED SETTLEMENTS OF GRANULAR SOILS

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ABSTRACT

The article presents a set of general relationships for permanent volumetric strain from cyclic loading. These relations can be used to predict earthquake induced settlements of granular soils.
The empirical relations predict volumetric strain of sands at the end of each loading cycle and apply to the following cases: drained or undrained conditions, isotropic initial stress state ($\sigma'_1=\sigma'_3$, e.g. free field) or anisotropic initial stress state ($\sigma'_1\neq\sigma'_3$, e.g. initial static shear), constant cyclic stress or constant cyclic shear.
The variables of the general relations are expressed in simple dimensionless mathematical forms with parameters directly related to the initial stress or strain state and density of the soil element.
The empirical relations apply to triaxial stress conditions, but extension to free field conditions is easily attained, through simlpe assumptions.
The empirical relations are based on statistical analysis of experimental data from drained cyclic triaxial tests.
The extension of empirical relations for prediction of settlements in case of undrained loading is realized with adequate transformation of formulation of the empirical relations for drained conditions. This transformation is based on the well established correlation between pore pressure build up in undrained conditions and (restrained) volumetric strain (Rowe,1962).
The accuracy of predictions is examined with a) comparison with experimental data from drained cyclic tests reported in relevant literature b) comparison of predicted volumetric strains with well established charts from other researchers (e.g.: Ishihara and Yoshimine (1992), Tokimatsu and Seed (1987)) and c) comparison with measured settlements from earthquake, at sites reported in literature.

Keywords: earthquake, settlements, volumetric strain, empirical relations, sands

INTRODUCTION

Densification of granular soils subjected to seismic loading is a well known phenomenon responsible for settlements of structures supported upon soil. This densification in case of dry soils takes place simultaneously with dynamic loading. In case of saturated soils the development of excess pore pressure from undrained cyclic loading does not allow initially the occurence of settlements. Indeed, settlements occur at post earthquake phase during the dissipation of induced excess pore pressures. The rate of these settlements depend on permeability characteristics of soil involved.

Although the importance of settlement calculation for the safe design of structures is obvious the usual practice is the omit of any cosideration, mainly due to lack of simple means for this. Indeed, for a simplified design, at present, the available means are limited to –anyway useful- charts from reported literature (Ishihara,1992,etc.).

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The scope of this work is the proposal of simple empirical relations for calculation of volumetric strains of sand from cyclic loading, applying to usual initial stress state of soil involved in geotechnical design.
More specifically, these relations apply to dry or saturated sands, constant stress or constant strain cyclic loading, free field stress state (that is absence of static shear) or stress state with initial shear.
The proposed relations result from drained cyclic triaxial tests (21 tests on fine Oosterschelde sand) and for this reason they apply initially to triaxial stress state. However, the extension to more general stress states through adequate assumptions is easily attained.

The proposed empirical relations provide the means for simplified computations of earthquake induced settlements involved in design of bearing capacity of foundations, thrust on retaining structures and so on. In addition, they can be used as reference for calibration of constitutive models aimed at the prediction of cyclic response of granular soil.

DESCRIPTION OF VOLUMETRIC STRAIN MODEL FOR SANDS

Data base for volumetric strain model on sands
The empirical relations for volumetric strain on sand resulted from adequate statistical fitting upon sufficient experimental data from drained cyclic triaxial tests on uniform sand:

- fine Oosterschelde sand with mean grain size d_{50}=0.17mm and uniformity coefficient C_u=1.40 (Lambe, 1979).

These tests are consolidated anisotropically in compression (CAD 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:

$p'_o=(\sigma'_1+2.\sigma'_3)/3$, $q_o=(\sigma'_1-\sigma'_3)/2$, $q_c=\sigma'_{1dc}/2$, $P=q_o/(p'_o.M)$, CSR= $\sigma'_{1dc}/(2\ .p'_o)$ or $\gamma_c(\%)$ (double amplitude cyclic strain)

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

Table 1. Range of initial parameters in drained cyclic triaxial tests on Oosterschelde sand

Test number	CSR	$\gamma_c(\%)$	p'_o/p_a	P	Initial void ratio e	d_{50} (mm)	Uniformity coefficient C_u
21	0.06 - 0.25	0.020-0.124	1.43-4.81	0.30-0.77	0.70-0.77	0.17	1.40

Development of volumetric strain on dry sands (drained loading)
Figure 1 shows in log-log scale the typical development of volumetric strain of sand when it is sheared cyclically in state of free drainage(continuous line) with number of loading cycles (data come from a typical CAD triaxial test with constant cyclic stress).
This behaviour can successfully be simulated from the following formula (dashed line):

$$\varepsilon_{VOL}(N) = \varepsilon_{VOL1} N^{C} \le \varepsilon_{VOL,\max} \quad (1)$$

Indeed the development of volumetric strain in the log-log scale is practically "linear" (that is exponential). In equation 1, ε_{VOL} is the volumetric strain (%), N is the number of cycles, c express the effect of loading cycles and $\varepsilon_{VOL,\max}$ the nominal upper limit of volumetric strain:

$$\varepsilon_{VOL,\max} = \frac{e_o - e_{\min}}{1 + e_o} \qquad (2)$$

relating to maximum relative density (DR(%)=100).
analytical prediction (just qualitative approach for better comparison with data) based on equation 1 is also included In Figure 1 with dashed line.

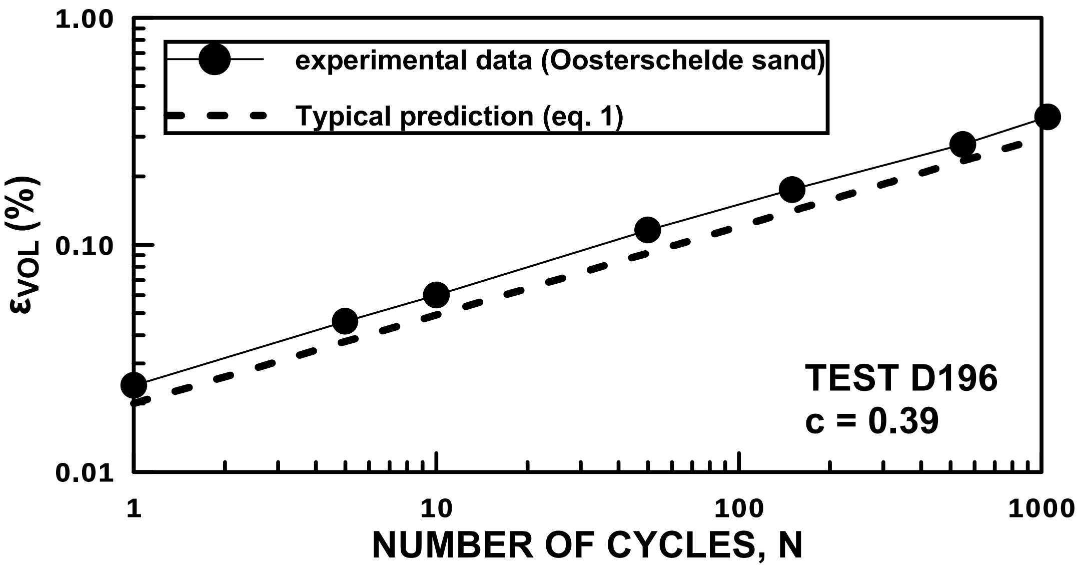

Figure 1. Typical development of volumetric strain with number of cycles

The volumetric strain at the end of 1st loading cycle ε_{VOL1} in equation 1 (either for constant stress or for constant strain) can be expressed (as it has been shown in previous research of the author (Egglezos (2004)) as simple product of exponential terms:

for constant stress: $$\varepsilon_{VOL1} = ACSR^{a1} \left(p'_o / p_a \right)^{a2} e^{a3} \frac{1-P}{1-(0.8P)^{a4}} \le \varepsilon_{VOL,\max} \qquad (3a)$$

for constant strain: $$\varepsilon_{VOL1} = B\gamma_C^{\,b1} e^{b3} \frac{1-P}{1-(0.8P)^{b4}} \le \varepsilon_{VOL,\max} \qquad (3b)$$

where, p_a is the atmospheric pressure for normalisation of units (p_a =100kPa).

It is worth noting that the above equations 3a and 3b are not arbitrary formulations of ε_{VOL1} but result from adequate simplification of strict analytical equations (Egglezos, 2004). These analytical formulae are based on Rowe's constitutive equation for volumetric strain (Rowe, 1962) and the hyperbolic model for τ-γ description (e.g. Duncan, (1970)). In addition, the variables of these formulae result directly from the initial stress and density state of soil.

Constants in equations 3a and 3b result from multivariable non-linear regression statistical analyses (StatSoft Inc., 1995) upon experimental data of Table 1. Indeed, the statistical analyses leads to a very good fitting of ε_{VOL1} formulae on experimental data. The values of these constants are presented in Table 2.
Exponent c, (in equation 1) which express the effect of number of loading cycles, in the case of excess pore pressure build up, can be expressed statistically (123 data, R=0.60) from initial state parameters as simple product of exponential terms (Egglezos (2004):

For constant stress: $c(CSR) = 1.07e^{1.58} CSR^{0.202} \exp(-0.521P)$ (4a)

For constant strain: $c(\gamma_c(\%)) = 0.833e^{1.295} \gamma_C^{0.060} \exp(-0.480P)$ (4b)

Table 2. Values of constants for application of the empirical relations

Constant stress CSR: No of data=21, R=0.921				
A	a1	a2	a3*	a4*
0.770	1.55	0.744	5.700	0.578
Constant shear γ_c(%): No of data=20, R=0.946				
B	b1	b2**	b3*	b4*
2.372	1.17, γ_c<1% 0.163, γ_c>1%	0.0	6.470	0.432

* Values of constants a3, b3 and a4, b4 are based on the relevant effect on excess pore pressure accumulation as it is explained in next paragraph.

** The effect of mean effective stress is negligible (b2=0.035) and for this reason it is omitted in equation 3a.

Although these formulae result from statistical analyses of undrained cyclic triaxial tests on sand, and describe the effect of cycles to excess pore pressure build up, it is assumed that can be used equivalently for the effect of loading cycles on volumetric strain accumulation. This is in agreement to Rowe's constitutive equation (eq.5) for linear relation of excess pore pressure and volumetric strain (eq. 6) as it is explained in next paragraph. It is worth noting that the limited range of c exponent from the available data from drained cyclic tests does not allow for a reliable statistical analysis of data.
Application of equations 4a and 4b to prediction of exponent c from experimental data leads to the following range of prediction ratio Rc (=$c_{predicted}/c_{measured}$): 0.85<Rc<1.15 either for constant stress or constant strain. These values justify the adoption of equations 4a and 4b for c-exponent calculation.

Development of volumetric strain on saturated sands (undrained loading)
The extension of empirical relations in cases with restrained drainage (undrained loading) can be done according to Rowe's equation (Rowe, 1962) for description of volumetric strain

$$d\varepsilon_{vol} = dp'_o/K_t + A\, d\gamma^P = dp'_o/K_t + d\varepsilon_{vol}^P \quad (5)$$

where, ε_{vol}=total volumetric strain, p'_o=mean effective stress $(\sigma'_1 + 2\sigma'_3)/3$, γ^P=permanent shear strain, ε_{vol}^P= permanent volumetric strain, K_t=tangential Bulk Modulus

In case with restrained drainage during cyclic loading where $d\varepsilon_{vol}=0$, equation 5, transforms to:

$$d\varepsilon_{vol} = (d\sigma - dU)/K_t + d\varepsilon_{vol}^P = 0 \Leftrightarrow dU = K_t\, d\varepsilon_{vol}^P \quad (6)$$

From the above equation results direct relation of excess pore pressure and volumetric strain in undrained loading. This (restrained during cyclic loading) volumetric strain may produce post earthquake settlement when dissipation of excess pore pressure takes place.

For this reason it seems rational that formulae initially developed for prediction of excess pore pressure from cyclic loading (Egglezos, 2004, Egglezos (2007)) can offer a general pattern for prediction of post-earthquake volumetric strain.

a. CIU conditions (q_o=0) – constant stress
For CIU conditions and constant stress (which simulate well free field conditions) the excess pore pressure of sand after N cycles of cyclic loading can be expressed (according to previous research of the author (Egglezos, 2004, Egglezos, 2007)) as follows :

$$\mathrm{U(N)} = U_1 N^C \left[1 + 0.01 \left(N / N_{1st} \right)^b \right] \leq U_{max} \tag{7}$$

In equation 7, 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 of excess pore pressure accumulation (N_{1st} relates to excess pore pressure U_{1st}), c express the effect of loading cycles at the 1st stage of excess pore pressure accumulation (for $N<N_{1st}$), 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 directly estimated from initial state parameters: $U_{max} = p'_o - q_o / M$

For CIU tests $U_{max}= p'_o$ and corresponds to stress state (q, p′) on PTL line for loading cycles required for initial liquefaction ($N=N_L$).

U_{1st} and N_{1st} in granular soils are expressed with high accuracy as constant ratios of U_{max} and N_L respectively (Egglezos,2004,egglezos ,2007): $U_{1st} = 0.52\ U_{max}$, $N_{1st} = 0.54\ N_L$, while the exponent b can be taken with mean value 5.80 (typical range of b exponent from exact calculation: $4.80<b<6.80$, Egglezos,2004).

According to equation 7, volumetric strain in the case examined seems rational that could be expressed as:

$$\varepsilon_{\mathrm{VOL}}(\mathrm{N}) = \varepsilon_{VOL1} N^C \left[1 + 0.01 \left(N / N_{1st} \right)^b \right] \leq \varepsilon_{VOL,\max} \tag{8}$$

The above formula for post cyclic volumetric strain is modified adequately -comparing to that for drained loading- to account for the sharp increase of pore pressure after the first stage of excess pore pressure accumulation.

b. CIU conditions (q_o=0) – constant strain, CAU conditions (q_o>0) - constant stress or strain

In the above cases excess pore pressure is expressed (Egglezos,2004) as: $\mathrm{U(N)} = U_1 N^C \leq U_{max}$

This formulation for pore pressure is identical to that for volumetric strain in drained conditions. For this reason equation 1 : $\varepsilon_{\mathrm{VOL}}(\mathrm{N}) = \varepsilon_{VOL1} N^C \leq \varepsilon_{VOL,\max}$

is considered adequate for prediction of volumetric strain in the cases examined in this paragraph.

EVALUATION OF EMPIRICAL RELATIONS

The evaluation of the proposed empirical relations for volumetric strain of granular soils is based on the following applications:

Prediction of experimental data from drained cyclic tests

Figure 2 shows the application of empirical relations for calculation of volumetric strain in sands, from cyclic loading with constant shear strain of great amplitude (γ_c>1%). The experimenal data are coming from 4 drained cyclic torsional tests on Toyoura sand (Hyodo et al., 2002).

The basic initial parameters of the data are included in Table 3. In figure 2 experimental data are presented with continuous line while predictions (with use of equations 1, 3b and 4b) with dashed line. It is observed the relatively good fitting of predictions on experimental data. More specifically the prediction ratio $R\varepsilon_{VOL}$ ranges for number of cycles N=1-10 from 0.46 to 1.58 ($0.50<R\varepsilon_{VOL}<1.50$):

where, $R\varepsilon_{VOL} = \dfrac{\varepsilon_{VOL,predicted}}{\varepsilon_{VOL,measured}}$

In addition, figure 3 shows the application of empirical relations for calculation of volumetric strain in sands, from cyclic loading with constant shear stress. The experimental data are coming from 4 drained cyclic torsional tests on Ham River sand (Tsomokos, 2005).

The basic initial parameters of experimental data are also included in Table 3. It is observed the relatively good fitting of predictions (from equations 1, 3a and 4a) on two cases (3a, 3d). In the other cases it is observed under-prediction for the initial cycles, while accuracy is improved with increasing number of cycles. The required CSR_{TX} for application of empirical relations refers to triaxial loading. For this reason reported CSR values (which refer to torsional shear) are transformed as follows:

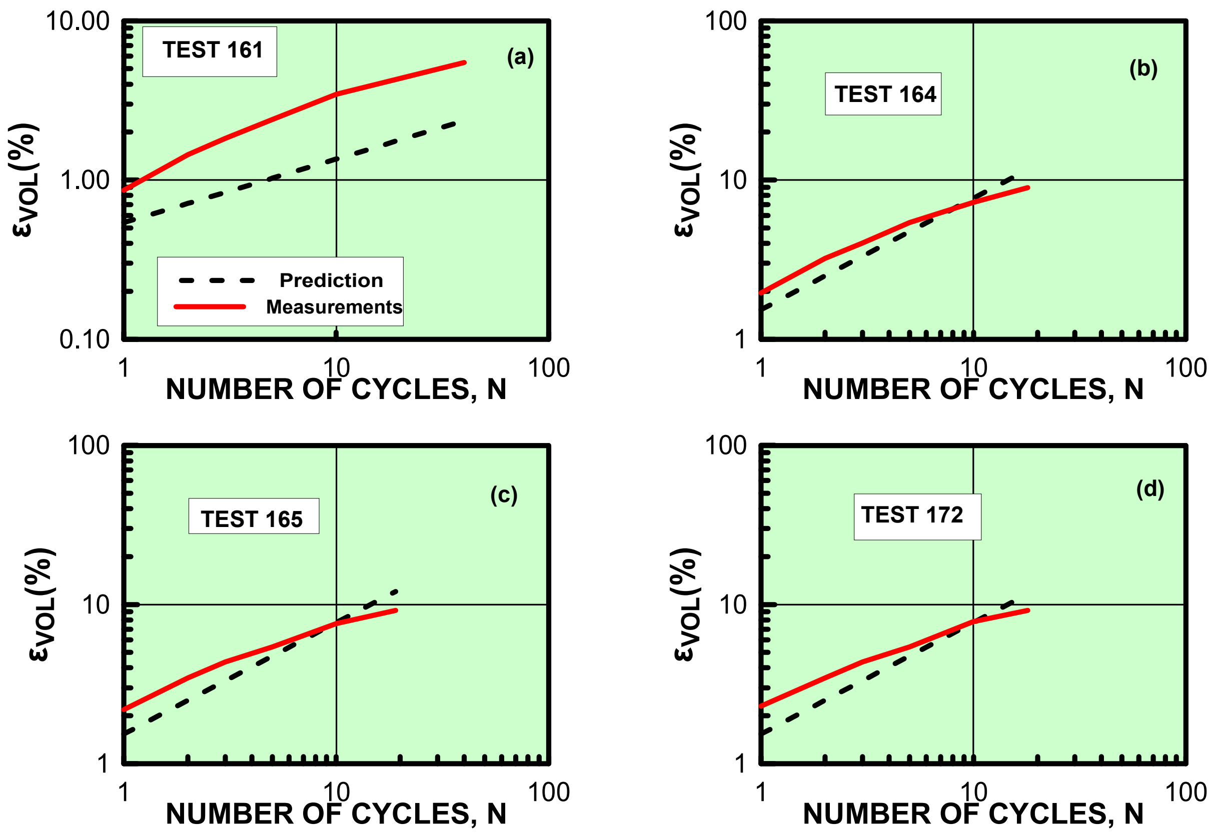

Figure 2. Prediction of volumetric strains of cyclic torsional tests in Toyoura sand

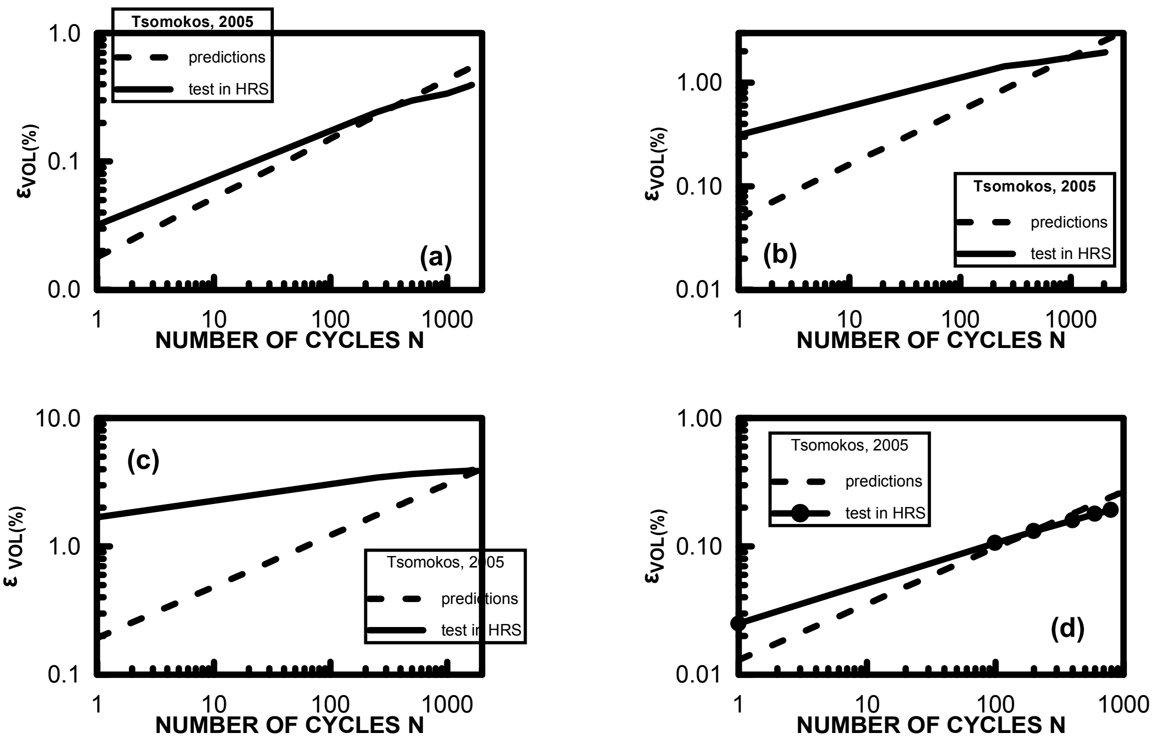

Figure 3. Prediction of volumetric strains of cyclic torsional tests in Ham River sand

$CSR_{TOR} = CSR_{TX}\ c_r$, where c_r is adequate correction factor for the stress state (e.g. Kastro (1975)). To be noted that experimental data used for evaluation of the empirical relations have not been used for the statistical evaluation of constants in equations 3a and 3b (type A prediction).

Table 3. initial parameters in cyclic CID torsional tests (evaluation of the empirical relations)

Drained cyclic torsional tests in Toyoura sand (constant shear)					
Test	**p´$_o$(kPa)**	**γ_c(%)**	**e$_o$**	**P**	**PI**
161	98	6	0.76	-	NP
164	98	6	0.89	-	NP
165	70	6	0.89	-	NP
172	134	6	0.89	-	NP
Drained cyclic torsional tests in Ham River sand (constant stress)					
Test	**p´$_o$(kPa)**	**CSR**	**e$_o$**	**P**	**PI**
HRS-1	130	0.144	0.715	-	NP
HRS-2	130	0.292	0.704	-	NP
HRS-3	130	0.371	0.708	-	NP
HRS-4	130	0.128	0.702	-	NP

Comparison with literature curves for volumetric strain of sands

i) Figure 4 shows application of the proposed empirical relations for prediction of cyclic stress CSR required for development of predetermined values of volumetric strain (ε_{VOL}= 0.1%, 0.2%, 0.5% and 1% respectively).

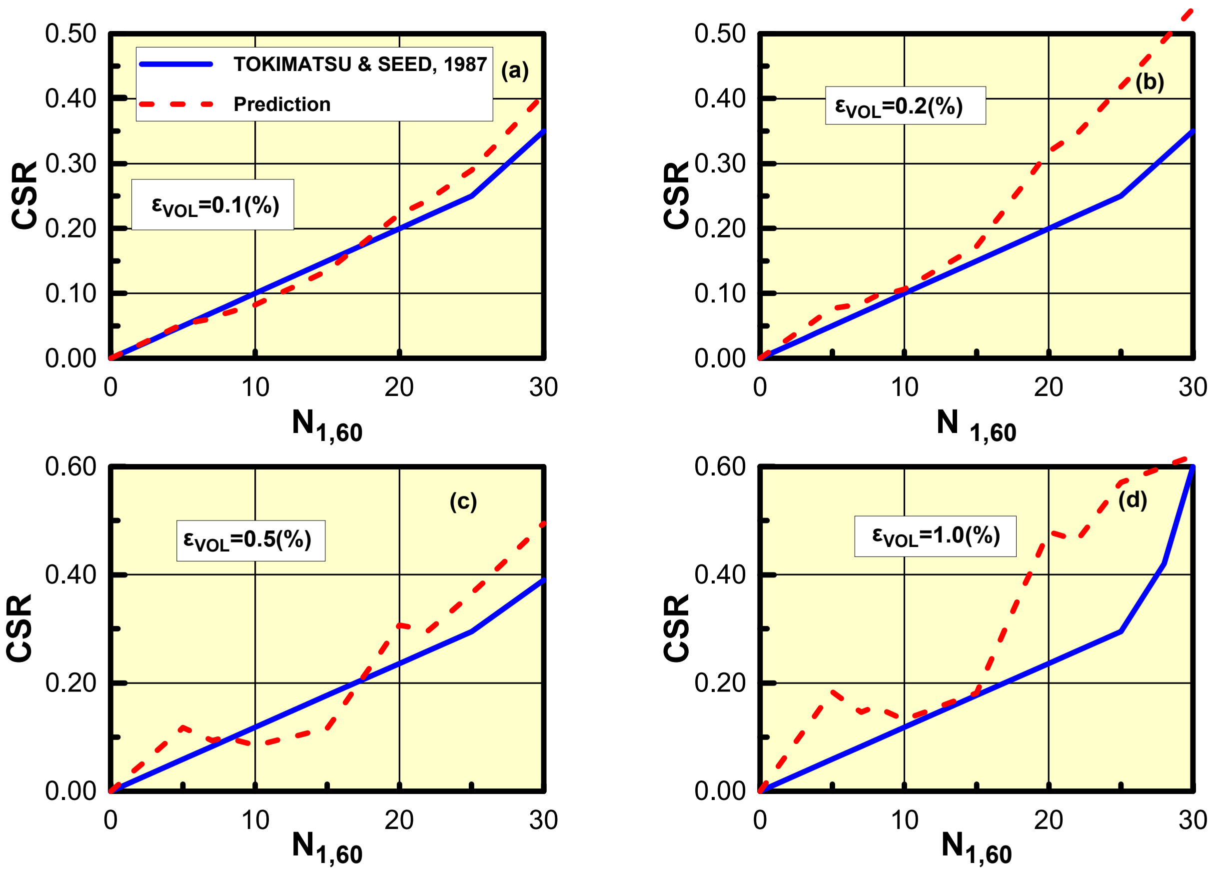

Figure 4. Comparison of empirical relations with Tokimatsu and Seed curves (1987)

The continuous lines correspond to reported values of required CSR for a M=7.5 earthquake (for development of given volumetric values) as function of SPT blows (Tokimatsu & Seed, (1987)).

Prediction of required CSR value is obtained from empirical equations 8 and 3a:

$$CSR_{TX} = \left[\varepsilon_{VOL}(N) / \left\{ 0.77 e_{eq}^{5.70} \left(\frac{p'_o}{p_a} \right)^{0.774} N^c \left(1 + 0.01 \left(\frac{N}{N_{1st}} \right)^{5.80} \right) \right\} \right]^{(1/1.55)} \quad (9)$$

The application is based in the following assumptions:

1. Void ratio required for the application (e_{eq}) is obtained as function of relative density DR_{eq} for assumed margin values e_{max}=1.0 and e_{min}=0.5 which consist typical void ratio limits for uniform clean sand: **e_{eq}=1-0.5*Dr_{eq}**
2. The relative density Dr_{eq} has been obtained as function of SPT blows N_{160} (Bowles,1995):

N_{160}	5	10	15	20	22	25	28	30	32	35
Dr_{eq}	0.10	0.30	0.46	0.60	0.63	0.68	0.74	0.78	0.81	0.85

3. For magnitude M=7.5 earthquake the number of equivalent uniform cycles is **N_{eq}(M)=16**
4. Initial effective vertical stress: **p'_o=100 kPa**.
5. the required value for c-exponent in equation 3a is obtained iteratively through equations 4a and 9.

To be noted that the calculated CSR_{TX} from equation 9 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, where c_r is adequate correction factor for the stress state (e.g. Kastro (1975)). Practically, for the specific application: CSR_{TX}=2.0 CSR_{ff}.

From inspection of chart it is observed a satisfactory fitting of predictions (dashed lines) with reported values of CSR_{ff} (continuous lines) particularly for volumetric strain ranging 0.1-0.5%.

ii) Figure 5 shows application of the proposed empirical relations for prediction of volumetric strain from cyclic loading of constant shear strain at different levels of relative densities **(Dr=45%, 60% και 80%)**, for an M=7.5 earthquake.

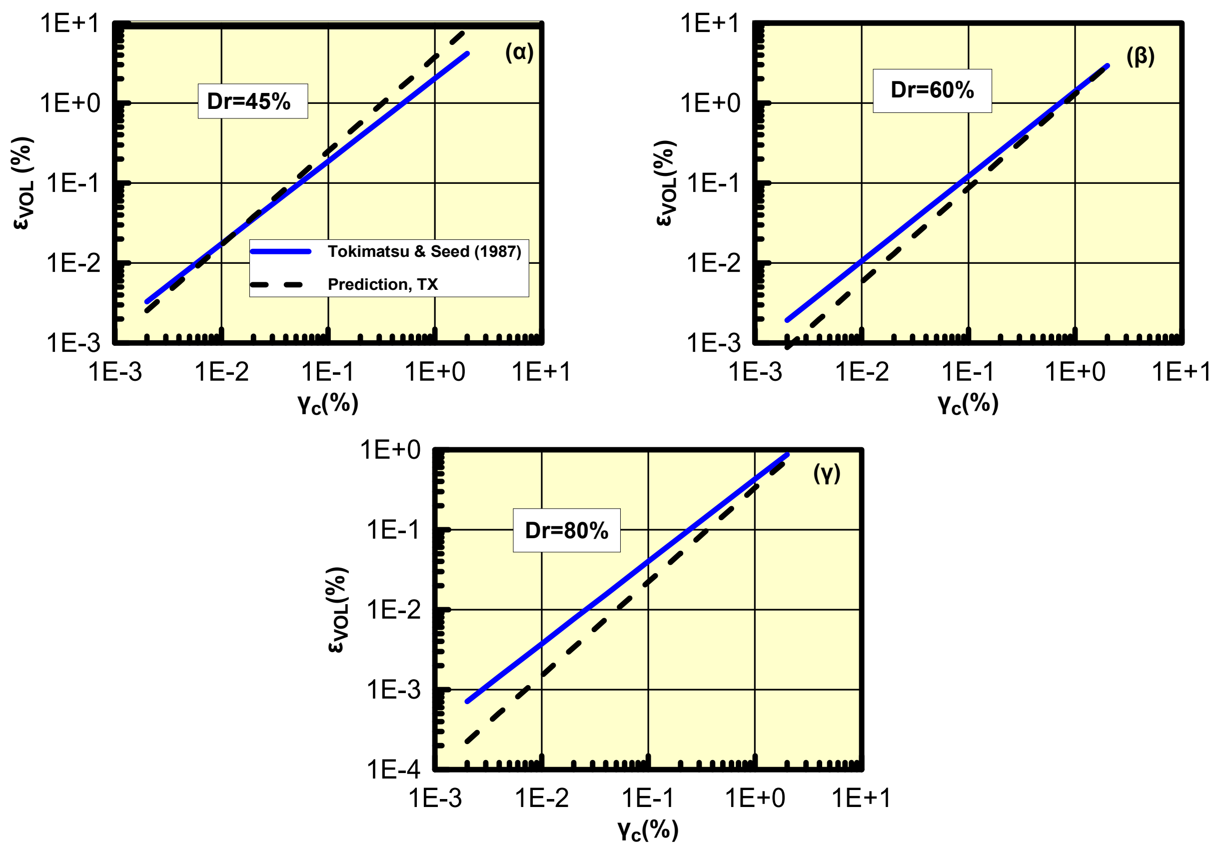

Figure 5. Comparison of empirical relations with Tokimatsu and Seed curves (1987)

The continuous lines correspond to reported values of Tokimatsu and Seed curves (1987) for volumetric strain of dry sands while dashed lines refer to proposed empirical relations (equations 1, 3b and 4b). The void ratio required for empirical relations is obtained as it was explained in case I of this paragraph.
From inspection of figure 5 it is observed a satisfactory fitting of predictions with Tokimatsu curves (continuous lines) with prediction ratio ranging $0.40<R\varepsilon_{VOL}<2.0$ for $0.01\%\leq\gamma_c\leq1\%$.

iii) Comparison with Ishihara and Yoshimine chart for calculation of volumetric strain of saturated sands for constant stress cyclic loading:. Figure 6 shows application of the empirical relations for prediction of volumetric strain as function of safety factor against liquefaction FSL. The continuous curves correspond to volumetric strain from application of the empirical relations for densities DR=50% and DR=90% and earthquakes with magnitudes, M=6 (Neq=6), M=7 (Neq=12) and M=8 (Neq=20). The void ratio is obtained as it was explained in case I of this paragraph. In the same figure are included, with dashed line, Ishihara & Yoshimine curves for the relevant densities. Generally there is good agreement of the two kind of curves. However it is worth noting that empirical relations are more detailed as they take account not only for soil density (as it happens to Ishihara & Yoshimine charts) but in addition for the earthquake magnitude (through the effect of number of equivalent cycles).

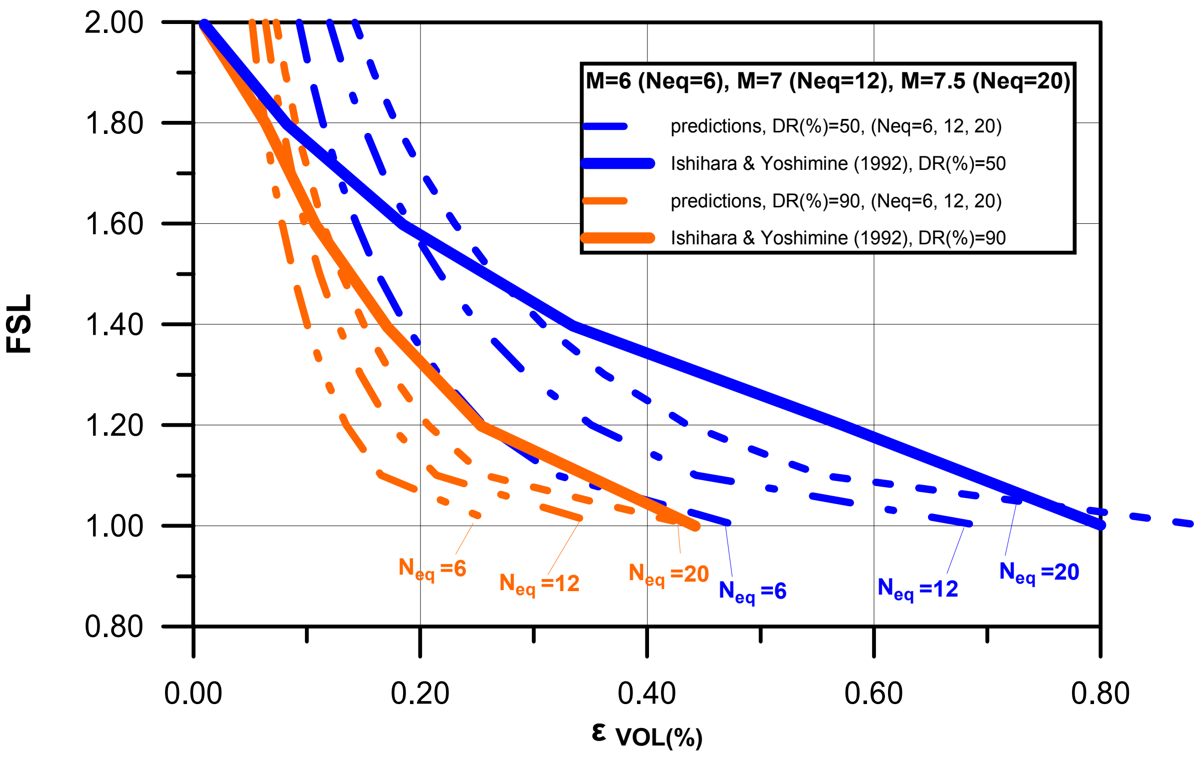

Figure 6. Application of empirical relations for prediction of volumetric strain in saturated sands – comparison with Ishihara & Yoshimine chart (1992)

Prediction of settlements – comparison with measured settlements in case histories
This paragraph comprises comparison between predictions from the proposed empirical relations and measured settlements.

i) Settlement prediction of saturated sand in Marina district of San Francisco from Loma Prieta earthquake (Kramer, 1995). Prediction is based on equations 1, 3b and 4b. In addition, multidirectional effect of the shaking has been taken in account by doubling the calculated ε_{VOL}. Analytically, the required steps for calculation of settlements are included in Table 4.

Table 4. Settlement of dry sand deposit due to San Fernando earthquake: (M=6.6, N_{eq}=9).

Layer thickness (m)	σ´$_v$ (kPa)	N_{160}	Dr_{eq}	e_{eq}	$γ_c$(%)	c	$ε_{VOL,tx}$	$ε_{VOL,,max}$	ΔH(m)
1.5	12	9	0.45	0.7525	0.100	0.48	0.077742	0.146	0.002735
1.5	36	9	0.45	0.7525	0.160	0.49	0.13933	0.146	0.004748
3.0	72	9	0.45	0.7525	0.240	0.51	0.230652	0.146	0.015286
3.0	120	9	0.45	0.7525	0.280	0.51	0.279423	0.146	0.018318
3.0	168	9	0.45	0.7525	0.300	0.51	0.304481	0.146	0.019864
3.0	216	9	0.45	0.7525	0.260	0.51	0.254805	0.146	0.016792
PREDICTED SETTLEMENT OF DRY SAND DEPOSIT (m)									0.08
MEASURED SETTLEMENT (m)									0.07-0.10

ii) settlement of dry sand deposit from San Fernando earthquake San Fernando (Kramer, 1995). Prediction is based on equations 8, 3a and 4a. Analytically, the required steps for calculation of settlements are included in Table 5.

Table 5. Settlement calculation of saturated loose sand fill in Marina district of San Francisco (Loma Prieta earthquake(1989): M=6^3/$_4$, N_{eq}=10).

Layer thickness (m)	σ´$_v$ (kPa)	N_{160}	Dr_{eq}	e_{eq}	CSR_{ff}	CSR_{tx}	c	$ε_{VOL,tx}$	$ε_{VOL,,max}$	ΔH(m)
1	55	7.5	0.357	0.821	0.141	0.282	0.606	0.001815	0.176471	0.001815
1.8	67	11.4	0.426	0.786	0.165	0.330	0.585	0.002243	0.160526	0.004037
1.5	82	8.6	0.356	0.821	0.180	0.360	0.637	0.080883	0.176588	0.121325
1.7	96	18.7	0.508	0.745	0.186	0.372	0.550	0.001508	0.140661	0.002564
PREDICTED SETTLEMENT OF SATURATED LOOSE SAND FILL (m)										0.13
MEASURED SETTLEMENT (m)										0.12

iii) Prediction of settlement of the backfill in Lefkada Marina from the 14-8-2003 earthquake, M=6.4, N_{eq}=8 (Alexoudi et al. (2006), Anastasiadis et al.(2006), Gazetas et al. (2006)). The required geotechnical information for prediction is obtained from borehole section in the Marina area reported in literature (Anastasiadis,(2006)). Analytically, the required steps for calculation of settlements are included in Table 6.

Table 6. Settlement calculation of saturated loose NP soil layers in Marina district of Leukas island-Greece (Leukas earthquake(2003): M=6.4, N_{eq}=8).

Layer thickness (m)	σ´$_v$ (kPa)	N_{160}	Dr_{eq}	e_{eq}	CSR_{ff}	CSR_{tx}	c	$ε_{VOL,tx}$	$ε_{VOL,,max}$	ΔH(m)
1	9.5	65	0.94	0.527	0.387	0.774	0.369	4.72652 E-05	0.018204	4.73E-05
1	23.5	37	0.68	0.658	0.462	0.924	0.543	0.000637	0.095646	0.000637
2	37	8	0.31	0.843	0.573	1.147	0.840	0.009647	0.186538	0.019295
2	55	7	0.28	0.855	0.623	1.246	0.874	0.017273	0.191696	0.034546
1	68.5	23	0.48	0.757	0.634	1.269	0.722	0.007645	0.146315	0.007646
3	86.5	21	0.44	0.776	0.635	1.270	0.751	0.011223	0.155431	0.033669
4	118	18	0.39	0.800	0.617	1.235	0.785	0.017495	0.166914	0.069982
PREDICTED SETTLEMENT OF LOOSE NP SOIL LAYERS (m)										0.17
MEASURED SETTLEMENT (m)										0.10-0.20

In all the above case histories a particularly good agreement is observed between predictions and measurements. The required values for void ratio and relative density are obtained according to assumptions explained in previous paragraphs.

SYNOPSIS-CONCLUSIONS

The major conclusions of this research are the following:

(a) For the present time no other empirical relation for simplified calculation of volumetric strain in granular soils is referred on reported literature.
(b) Geotechnical designers, as a usual practice, omit calculation of volumetric strain in granular soils because of lack of simplified methods and absence of relevant provision in many national anti-seismic codes.
(c) The proposed empirical relations for prediction of volumetric strain on sands with adequate transformation (concept of "equivalent void ratio", Egglezos (2001), Egglezos(2007)) may also apply in case of gravely or silty soils.
(d) The proposed model predicts the accumulated volumetric strain at the end of each cycle of cyclic loading. It is characterized of great mathematical simplicity and permits the estimation of volumetric strain for different initial stress or strain states of soil (constant cyclic stress or shear, initial static shear or not, drained or undrained conditions e.t.c.).
(e) The parameters of the empirical relations result directly from the initial stress (or strain) and density state of soil under examination.
(f) The values of constants in the empirical relations result from statistical analysis of available experimental data for drained cyclic triaxial tests (21 tests on Oosterschelde sand).
(g) The extension of empirical relations to undrained conditions is achieved through the general constitutive relation between excess pore pressure and volumetric strain (Rowe, 1962).
(h) The accuracy of the proposed relations is tested with application on a) prediction of impartial experimental data from cyclic torsional tests on sand (type A prediction), b) comparison with well established charts from relevant literature for calculation of volumetric strains and c) calculation of post-earthquake settlements measured in a number of case histories. In all the above cases predictions agree particularly well with measurements.

Finally as main conclusion it has to be mentioned that the proposed empirical relations for volumetric strain can be used for simplified calculation of earthquake settlements in geotechnical design, as well as in calibration of numerical codes for prediction of dynamic behavior of granular soils. Of course, the extension of experimental data base in future, with additional data from cyclic tests, could further improve the accuracy of predictions.

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