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Parametric Investigation of Lateral Spreading in Free-Face Ground Formations

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ABSTRACT

Liquefaction-induced lateral spreading can cause extensive damage and even failure to foundations and earthworks resting inside or in the vicinity of the affected ground. The current practice for the evaluation of the ground surface displacement due to lateral spreading, is to rely upon a number of published empirical relations which are based on statistical analysis of field measurements. As an alternative, aimed to overcome a number of objective limitations related to the interpretation of field data, this article employs a numerical investigation to explore the main parameters affecting the anticipated maximum ground surface displacement and to quantify their effect in the form of a simple analytical relation. To ensure the credibility of the numerical methodology, it has been thoroughly validated against nineteen (19) previously reported centrifuge experiments. Furthermore, the accuracy of the new relation is evaluated through a systematic comparison with the numerical predictions of ground surface displacement, as well as with field measurements from the data base of Youd et al. (2002).

INTRODUCTION

Lateral spreading of liquefied ground may occur in the case of even small free ground surface inclination or small topographic irregularities (e.g. river and lake banks). Recent earthquakes (e.g. Kobe 1995, Chi-Chi 1999, Nisqually 2001) have shown that this phenomenon is of significant practical importance for civil engineering structures (quay walls, bridge piers, etc) as it imposes considerable lateral loads and may lead to wide spread failures. The efficiency of the available methods for the design of such structures against lateral spreading depends greatly on our ability to estimate the anticipated lateral ground displacements and their distribution with depth.

Seven (7) empirical relationships have been located in the literature that can be used for the evaluation of the ground surface displacement due to lateral spreading near free-face topographic irregularities. These relationships can be roughly divided in two main categories, depending upon the type of parameters used to quantify the severity of seismic motion:

– those that rely on "seismological" parameters of the earthquake motion (e.g. earthquake magnitude M, epicentral distance R), such as Bardet et al. (1999, 2002), Rauch & Martin (2000), Youd et al. (2002), Zhang & Zhao (2005), Faris et al. (2006), and
– those that rely on "engineering" parameters (e.g. maximum acceleration, frequency), such as Shamoto et al. (1998) and Hamada (1999).

Note that the relationship of Hamada (1999) referenced above was originally developed for gently sloping ground but has been later found to provide equally accurate results in the case of free-face geometries as well (Valsamis, 2008).

Regardless of the variables used, all these relationships were derived from statistical analysis of field measurements. This approach has the definite advantage of fitting directly data obtained from actual events. However, it has also two basic disadvantages which may induce considerable uncertainty. The first is that, in the majority of case studies, crucial geotechnical and seismological parameters have not been directly measured and consequently had to be indirectly evaluated based on circumferential evidence. The second disadvantage is that, due to the unique nature of each case history, it is almost impossible to isolate the effect of each individual parameter affecting lateral spreading displacements and study it in a systematic manner.

To avoid the aforementioned objective limitations, this paper explores the potential of alternatively using a numerical investigation for identifying the key parameters affecting lateral spreading displacements and for quantifying their effect. The numerical methodology that is used for this purpose has been recently developed at N.T.U.A. with the aim to perform fully coupled, effective stress dynamic analysis of liquefaction related problems (Papadimitriou et al. 2001, Andrianopoulos et al. 2009, Karamitros 2009). To ensure the credibility of the predictions, the parametric analyses were preceded by an extensive validation of the numerical methodology against well documented centrifuge experiments of earthquake – induced lateral spreading. Furthermore, the accuracy of the proposed new relations is evaluated through comparison with measurements of ground surface displacements in centrifuge tests, as well as in field case studies.

NUMERICAL METHODOLOGY

The constitutive model which was employed for the numerical analyses is a bounding surface model with a vanished elastic region that incorporates the framework of Critical State Theory. It is based on a previously proposed model (Papadimitriou et al., 2001; Papadimitriou & Bouckovalas, 2002) which has been developed with the aim to simulate the cyclic behaviour of non-cohesive soils (sands and silts), under small-medium-large cyclic shear strain amplitude using a single set of soil-specific constants, irrespective of the initial stress and density conditions.

In its current form (Andrianopoulos 2006, Karamitros 2009) the model incorporates three (3) open cone-type surfaces with apex at the origin of stress space: (i) the Critical State surface at which deformation develops for fixed stresses and zero volumetric strain, (ii) the Bounding surface which locates the (ever-current) peak stress ratio states and (iii) the Dilatancy surface which dictates the sign of the plastic volumetric strain rate during loading. The foregoing constitutive model was incorporated in the code FLAC (Itasca, 1998) using the User Defined Model capability.

In the present study, the model constants have been calibrated on the basis of data from element laboratory tests performed on fine Nevada sand at relative densities of D_r = 40 & 60% and initial effective stresses between 40 and 160 kPa (Arulmoli et al, 1992). In particular, the laboratory data originate from resonant column tests, as well as, from cyclic direct simple shear and triaxial tests. Thus, they offer a quantitative description of various aspects of non-cohesive soil response under cyclic loading, such as shear-modulus degradation and damping increase with cyclic shear strain, liquefaction resistance and cyclic mobility.

To evaluate the overall capacity of the aforementioned numerical methodology to predict the relatively large displacements induced by lateral spreading it was systematically used to reproduce the results of several relevant centrifuge tests, summarized in Table 1. The above centrifuge tests cover a wide range of soil and earthquake parameters, such as relative density (D_r), maximum base acceleration (α_{max}) and thickness of the liquefiable soil layer.

Table 1. Summary of published centrifuge tests

Test name	Publication	Pore Pressure fluid	Type*	Dr (%)
Test 1	Taboada et al. (2002)	Viscous	FF (33.7^o)	45
Test 2	Taboada et al. (2002)	Viscous	FF (33.7^o)	45
SP-11	Dewoolkar et al. (2001)	Viscous	W (9m)	60
Model 2	Arulmoli et al. (1992)	Viscous	GS (2^o)	60
M2-1	Taboada & Dobry (1998)	Water	GS (2^o)	40-45
M2-2	Taboada & Dobry (1998)	Water	GS (1.94^o)	40-45
M2-3	Taboada & Dobry (1998)	Water	GS (2.18^o)	40-45
M2-4	Taboada & Dobry (1998)	Water	GS (2.07^o)	40-45
M2-5	Taboada & Dobry (1998)	Water	GS (2^o)	40-45
M2a-3	Taboada & Dobry (1998)	Water	GS (0.6^o)	40-45
M2a-4	Taboada & Dobry (1998)	Water	GS (0.6^o)	40-45
M2b-5	Taboada & Dobry (1998)	Water	GS (0.8^o)	40-45
M2c-6	Taboada & Dobry (1998)	Water	GS (3.95^o)	40-45
LAM1	Abdoun (1998)	Water	GS (2$^{oof\ the}$ numerical methodology)	40
LAM2	Abdoun (1998)	Water	GS (2^o)	40
L45V-2-10	Sharp et al (2003)	Viscous	GS (2^o)	45
L45V-4-10	Sharp et al (2003)	Viscous	GS (2^o)	45
L65V-2-10	Sharp et al (2003)	Viscous	GS (2^o)	65
L65V-4-10	Sharp et al (2003)	Viscous	GS (2^o)	65
L75V-2-10	Sharp et al (2003)	Viscous	GS (2^o)	75
L75V-4-10	Sharp et al (2003)	Viscous	GS (2^o)	75
Test name	amax (in base) (g)	Ncycle	Thick. Of liq. Layer (m)	Lateral ground disp (cm)
Test 1	0.20	20	10.0	191
Test 2	0.20	20	10.0	185
SP-11	0.20	9	9.0	4 (residual)
Model 2	0.23	22	10.0	50.7
M2-1	0.18	21.5	10.0	44.0
M2-2	0.23	22	10.0	47.0
M2-3	0.46	22.5	10.0	97.0
M2-4	0.19	22	10.0	61.0
M2-5	0.25	22	10.0	68.0
M2a-3	0.28	21.5	10.0	12.2
M2a-4	0.26	22	10.0	14.8
M2b-5	0.40	22.5	10.0	30.0
M2c-6	0.17	21.5	10.0	72.5
LAM1	0.30	40.5	6.0	80.0
LAM2	0.30	40.5	6.0	80.0
L45V-2-10	0.23	20	10.0	66.0
L45V-4-10	0.41	20	10.0	87.0
L65V-2-10	0.20	20	10.0	28.0
L65V-4-10	0.38	20	10.0	63.0
L75V-2-10	0.21	20	10.0	23.0
L75V-4-10	0.38	20	10.0	47.0

(*) FF: Free-face geometry and free-face angle
W: Flexible quay wall and height of quay wall (m)
GS: Gently sloping ground geometry and sloping ground angle

Note that only two of the experiments in Table 1 concern lateral spreading near free-face geometries (Taboada et al. 2002), while all the rest concern lateral spreading of gently sloping ground (Arulmoli et al 1992, Taboada & Dobry 1998, Sharp et al 2003, Abdoun 1998) or ground supported by a flexible quay wall (Dewoolkar et al. 2001). Still, it was considered appropriate to check the numerical methodology against all these different test types, as the underlying mechanism of lateral ground movements associated to each test type is essentially the same.

Fig. 1 shows the discretized profile which was used to simulate the tests by Taboada et al. (2002). It consists of 403 equal square elements, 1.0x1.0m in dimension, with the acceleration time history being applied at the external grid nodes as well as the base of the model in order to simulate the rigid box boundaries used during the centrifuge experiment.

The discretization used to simulate the gently sloping ground experiments utilized a grid of 220 elements, 1.0m x 1.0m in dimension, with the seismic excitation imposed as an acceleration time history at the base of the soil profiles. In this case, the lateral boundaries were tied to one-another in order to ensure that they will have the same horizontal displacements, simulating the boundary conditions imposed by the laminar box containers.

Finally, simulation of the flexible wall experiments required a grid of 309 elements, 1.0m x 1.0m in dimension. The applied excitation is a semi-sinusoidal time-history consisting of 9 main cycles with maximum acceleration of 0.2g. The lateral bounds during the centrifuge experiment were rigid and thus were simulated by applying the acceleration time history both in the base and the lateral boundaries of the grid.

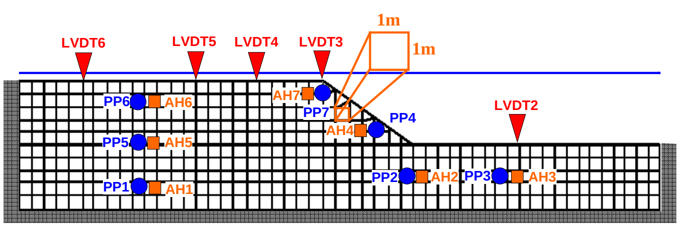

Fig. 1. Finite difference mesh used for the numerical simulation of centrifuge tests of Taboada et al. (2002) and associated instrumentation

The numerical predictions are compared to the centrifuge test measurements in Figs. 2 and 3. In more detail, Fig. 2 depicts a typical comparison between predicted and recorded time histories of horizontal displacement and horizontal acceleration for the centrifuge test of Taboada et al. (2002) Moreover, Fig. 3 compares the predicted and recorded maximum ground displacements from all centrifuge tests listed in Table 1. These comparisons show a reasonably good, qualitative but also quantitative, consistency. The slight tendency of the numerical predictions to exceed the recordings in Fig. 3 is attributed to the artificial restraint imposed by the latex membrane used to prevent leakage of the pore fluid through the walls of laminar box containers and thus no action was taken to calibrate the numerical algorithm towards an optimal fit.

A possible exception to the good overall agreement observed in Fig. 3 are the two points marked with a question mark, associated to experiments with small dominant excitation frequency (f=1Hz), where the numerical procedure conservatively overestimates the experimental values. The reason behind this discrepancy is not presently clear. Still, it is noteworthy that Taboada & Dobry (1998), who ran these experiments, also admit that the maximum measured displacements were 2.5 times less than the ones they expected theoretically.

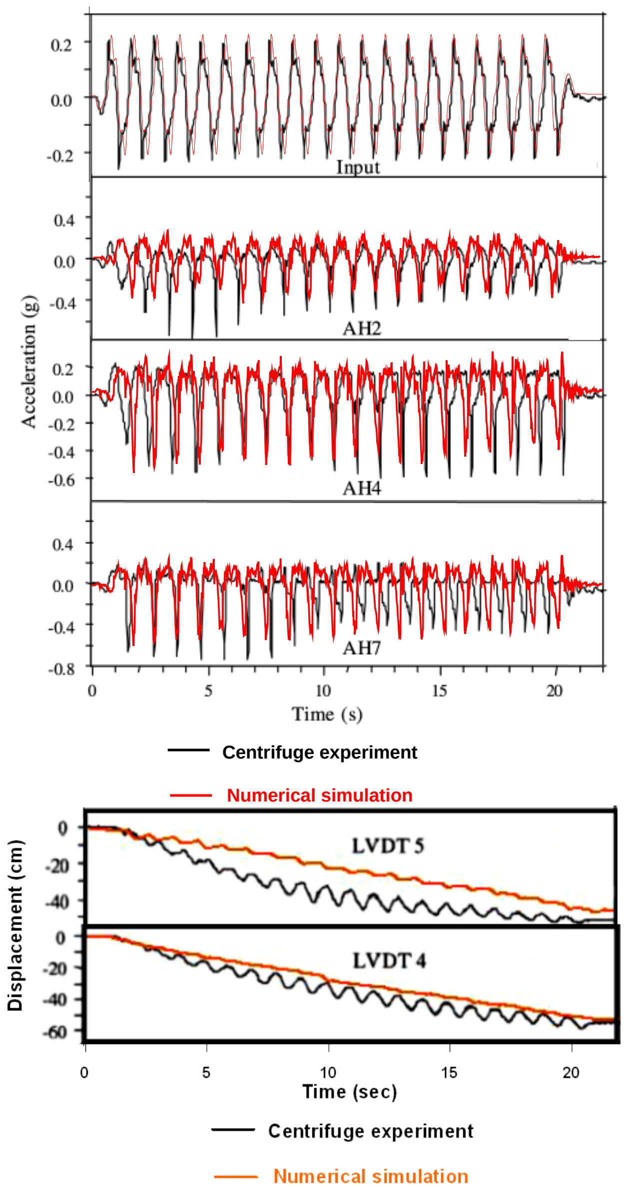

Fig. 2. Typical comparison between numerical predictions andexperimental results for the centrifuge test of Taboada et al. (2002)

PARAMETRIC ANALYSES

Using the numerical model described previously we performed a total of ninety three (93) parametric analyses with a wide range of variation of all input parameters, as shown in Table 2. The two different geometries that were examined are shown in Fig. 4: a uniform liquefiable soil layer (Fig. 4a) and a clay over sand, 2-layered geometry (Fig. 4b). The total liquefiable soil thickness ranged from $H_{tot,liq}$ = 4 to 10m, while the thickness of the non-liquefiable surface soil crust ranged from H_{crust}=0 to 5m. Note that, as shown in the figure, several researchers also define W as the ratio of the free-face height to the distance of the point of interest from the foot of the free-face.

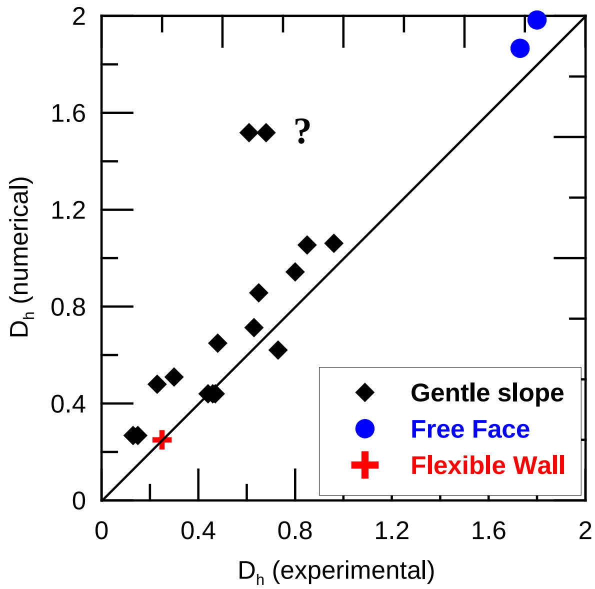

Fig. 3 Numerical prediction of lateral ground displacements versus centrifuge test measurements

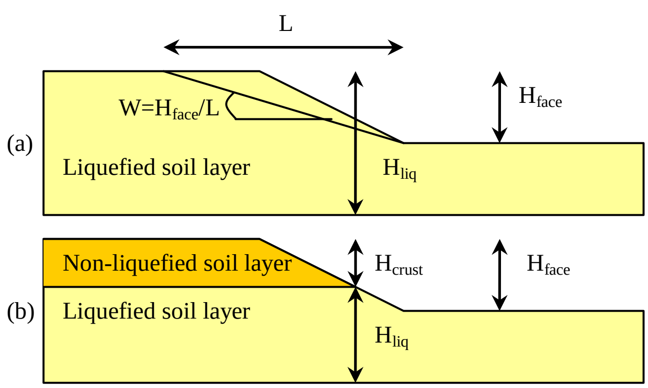

Fig. 4. Typical soil profiles used in the parametric analysis (a) uniform liquefiable soil layer and (b) 2-layered geometry (clay over sand)

Sixty-five (65) of the numerical analyses were performed with a sinusoidal acceleration time-history, consisting of 22 main cycles. The remaining twenty eight (28) analyses were performed with five real earthquake acceleration time-histories coming from the Aigio 1995, Greece earthquake, Kobe 1995 Japan earthquake (JMA N-S & E-W) and Lefkada 2003, Greece earthquake (TRANS & LONG). These earthquake time-histories were chosen because:

(a) they have very different acceleration time-history waveforms (e.g. Aigio 1995 earthquake has one main cycle of excitation, while the Lefkada 2003 earhtquake has almost 15 main cycles), and

(b) all have been associated with large ground failures and extensive liquefaction phenomena (Bouckovalas et al 1995, Bardet et al. 1995, Schiff 1998, Gazetas et al. 2005)

Table 2. Range of input parameters used for the parametric analyses

Parameter		Range of values	Reference value
Maximum horizontal base acceleration	a_{max}	0.04 to 0.82g	0.12 g
Predominant frequency of shaking	f	1 to 10Hz	2 Hz
Number of main excitation cycles	N_{cyc}	10 to 40	20
Relative density of liquefied layer	D_r	35% to 90%	45 %
Fines Content	FC	0% to 30%	0 %
Liquefied soil permeability	k	0.0021 to 0.105cm/sec	0.0021 cm/sec
Free-face height	H_{face}	3 to 10m	5m

STATISTICAL ANALYSIS OF NUMERICAL PREDICTIONS

Figure 5 shows the effect on predicted lateral ground displacements of all problem parameters examined herein, namely:

– 3 seismic excitation parameters: The maximum applied base acceleration a_{max}, the number of main cycles after initial liquefaction (N_{cyc}-N_L) and the dominant period T of the excitation. Equivalently the last two parameters may be substituted with the duration of the strong ground shaking after initial liquefaction t_d-t_L.
– 2 liquefied soil layer parameters: The relative density D_r, alternatively the corrected SPT blow count $(N_{1,60})_{cs}$, and the Fines Content FC
– 3 geometry parameters: The free-face ratio W, the free-face height H_{face} and the cumulative thickness of liquefied soil layers H_{Tot}.

Observe that permanent displacements show a marked increase with increasing a_{max}, t_d, H_{tot} and W, while they follow the opposite trend with increasing f, $(N_{1,60})_{cs}$, and FC.

Following the identification of the basic problem parameters, a statistical analysis of the numerical predictions was performed for the quantitative verification of their effect. For practical reasons, it was assumed that each problem parameter acts independently, so that the relation for the prediction of ground displacements can be written in product form.

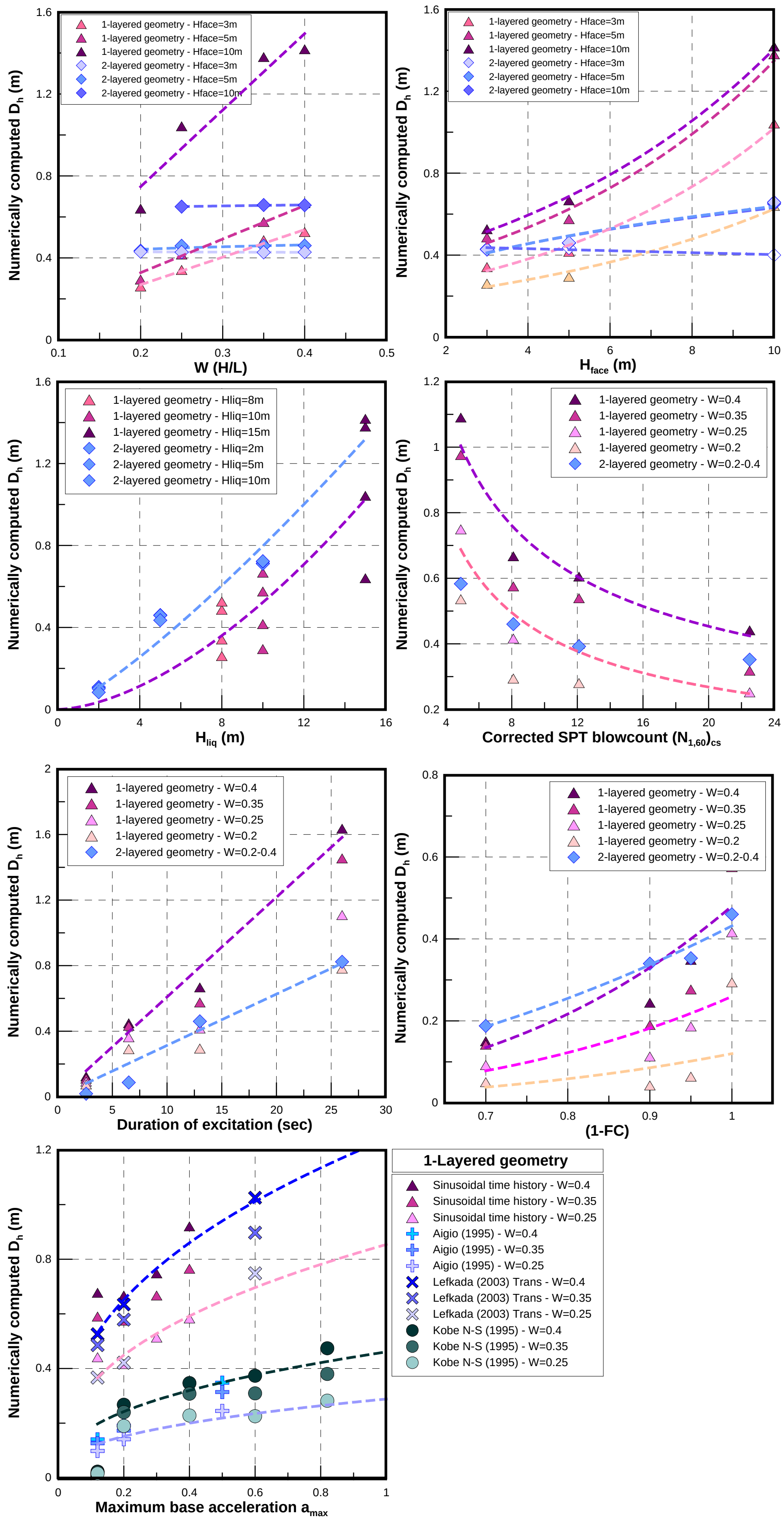

Fig. 5. Effect of basic problem parameters on ground surface displacement due to free-face lateral spreading

To improve the accuracy of the statistical analyses, care was taken to scale the values of the examined problem variables to comparable magnitudes. The statistical analysis was firstly applied to the numerical predictions which were obtained for a sinusoidal acceleration time-history, and led to the following relation:

$$D_h = d1\frac{W^{d2}\left(H_{face}\right)^{d3}\left(H_{liq}\right)^{d4}\left(a_{\max}\right)^{d5}\left(T_d\right)^{d7}\left(1-FC\right)^{d8}}{\left[\left(N_{1,60}\right)_{cs}\right]^{d6}} \tag{5}$$

with d1=0.029, d2=0.33, d3=0.604, d4=0.635, d5=0.437 d6=0.544, d7=1.147 and d8=9.056.

Note that the values of the constants in Eq. 5 are in fairly good agreement with the values resulting approximately from Fig. 5.

Review of the numerical predictions for the non-sinusoidal excitations revealed one simple way to extend Eq. 5 from sinusoidal to actual seismic motions is to substitute the maximum acceleration a_{max} with the mean acceleration of the motion a_{mean}, defined as

$$a_{mean} = \frac{1}{t_d}\int_0^{t_d}\left|a(t)\right| dt \tag{6}$$

where t_d is the duration of shaking.

Taking further into account that, for the sinusoidal seismic motion, a_{mean} =0.63 a_{max}, Eq. 5 is finally modified to:

$$D_h = 0.035\frac{W^{0.33}\left(H_{face}\right)^{0.6}\left(H_{liq}\right)^{0.64}\left(a_{mean}\right)^{0.44}\left(T_d\right)^{1.15}\left(1-FC\right)^{9.06}}{\left[\left(N_{1,60}\right)_{cs}\right]^{0.54}} \tag{7}$$

Note that, for the non-sinusoidal excitations used in this study, it was found that a_{mean} = (0.10 ÷ 0.63) a_{max}, while the respective mean value for strong earthquakes was computed as a_{mean}= 0.50 a_{max}.

A one-to-one comparison of all numerical predictions with the respective displacement values obtained from Eq. 7 is shown in Fig. 6, while the relative error of the analytical predictions is plotted against each problem parameter in Fig. 7. In that way, it was found that 95% of the estimated ground surface displacements varied between 50 and 200% of the computed values, without any significant bias with respect to any problem parameter. In addition, the correlation coefficient R^2 is 72% and the mean deviation for the relation is ±25% of the mean.

COMPARISON WITH FIELD AND EXPERIMENTAL MEASUREMENTS

To build confidence upon the accuracy of the proposed relationship, it was further checked against displacement measurements from the database of case histories created by Youd et al. (2002).

Before proceeding with this comparison it is necessary to clarify that the aforementioned database does not provide specific information on the parameters used by the proposed relations to describe the prevailing soil conditions (e.g. D_r or N_{SPT} of the liquefied soil) and the applied seismic excitation (e.g. a_{max} or t_d). Thus, the following assumptions were adopted in order to estimate these missing data, conscious of the additional uncertainty that they will introduce to the comparisons with the proposed relation:

(a) The corrected SPT value for the liquefiable soils was taken as $(N_{1,60})_{cs}$=7. This is a reasonable mean value, since Youd et al. (2002) considered only liquefiable soils with $(N_{1,60})$<15.

(b) The maximum base acceleration a_{max} was computed from the provided moment magnitude M_S and epicentral distance R based on the attenuation relationship of Sabetta & Pugliese (1987):

$$\log a_{\max} = 0.31\times M_S - \log[R^2 + 5.8^2]^{1/2} + 0.17\times S - 1.56 \tag{8}$$

The soil factor S in the above relation was taken as equal to 1, corresponding to soil conditions (as opposed to 0 for rock conditions).

(c) As noted in previous paragraphs the mean acceleration a_{mean} has been computed as 50% of the maximum acceleration a_{max}, a somewhat conservative value representative of common strong earthquakes.

(d) The height of the free-face H_{face} was arbitrarily chosen as one third of the thickness T_{15} of the potentially liquefiable soil layers with $(N_{1,60})$<15. The maximum free-face height used in this way was 5.6m.

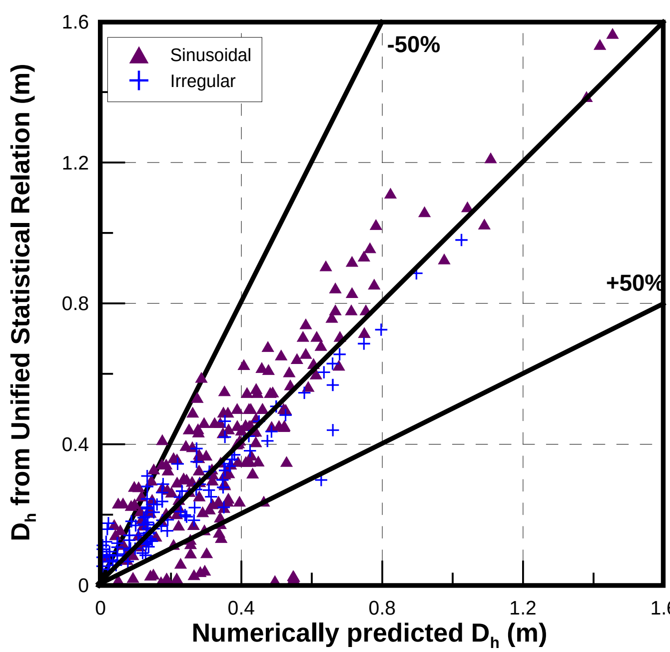

Fig. 6. Comparison between analytically computed (Eq. 7) and numerically predicted ground surface displacements

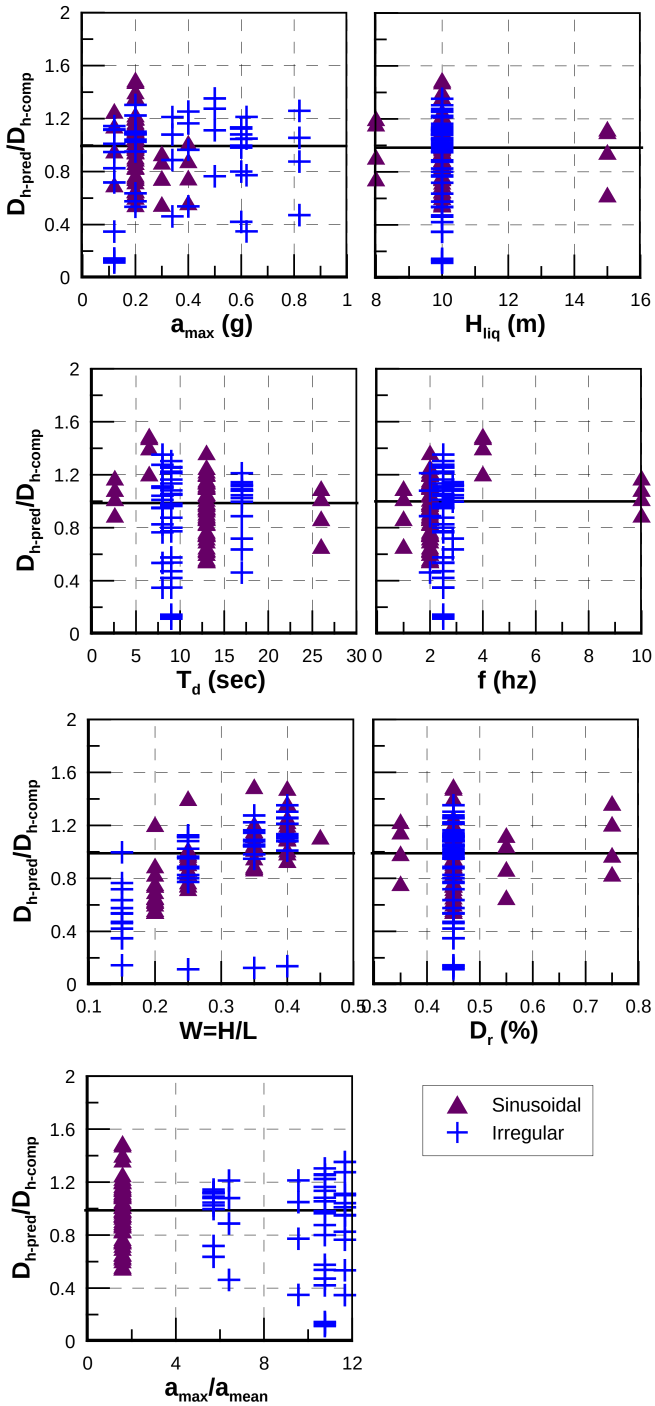

Fig. 7. Effect of various problem parameters on the scatter of ground surface displacements predictions

(e) The duration t_d for each seismic motion was derived from the reported seismic moment magnitude M_S , according to Chang & Krinitzky (1977):

$$t_d = 0.2859 e^{0.673 M_S} \tag{9}$$

Predicted ground surface displacements according to the proposed relation are compared to the field measurements in Fig. 8. Observe that Eq. 7, provides a reasonable average fit of the measurements, without any systematic bias. More specifically, 75% of the estimated displacements fall between 50 and 200% of the field measurements, while the mean deviation of the comparison is ±50% of the mean and the correlation coefficient is R^2 = 51%.

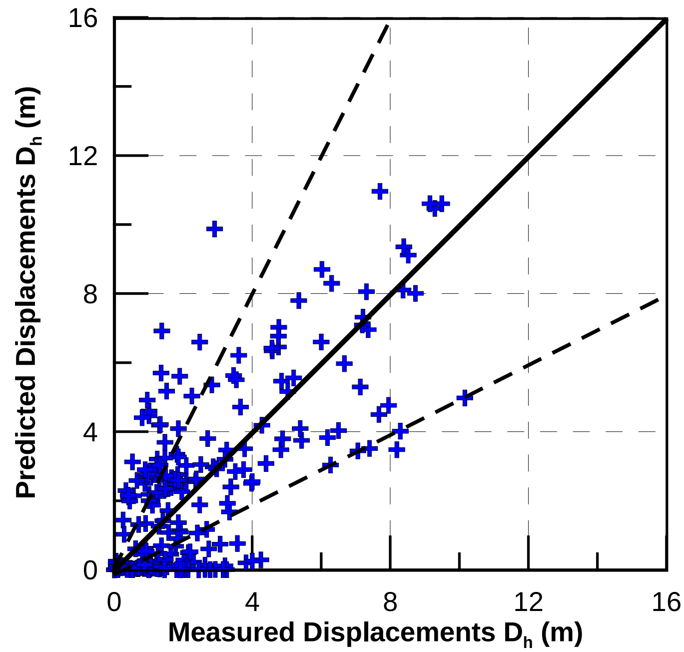

Fig. 8. Comparison between ground surface predictions (Eq. 7) and field measurements reported by Youd et al. (2002)

It is worth pointing that the above error margins are not very far from those of empirical relationships which were based directly on this database, despite that the latter are not subject to the additional uncertainty resulting from assumptions (a) to (e) above. For instance, in the empirical relationships of Barlett & Youd (1995), Bardet et al (1999) and Youd et al. (2002) 90% of the estimated displacements fall between the 50 and 200% prediction bounds while reported correlation coefficient were R^2 = 82.3%, 80.6% and 83.6% respectively.

For further checking, the proposed relationship was compared against displacement measurements from the centrifuge experiment of Taboada et al. (2002). The comparison is shown in Figure 9 for four different positions with W ranging from 0.67 (33.3^o) to 0.18(10.4^o). It is clear that there is good agreement between the empirical relation estimation and the measured ground surface displacements, with only exception the measurement at the edge of the free-face where local ground instabilities may have increased measured displacements.

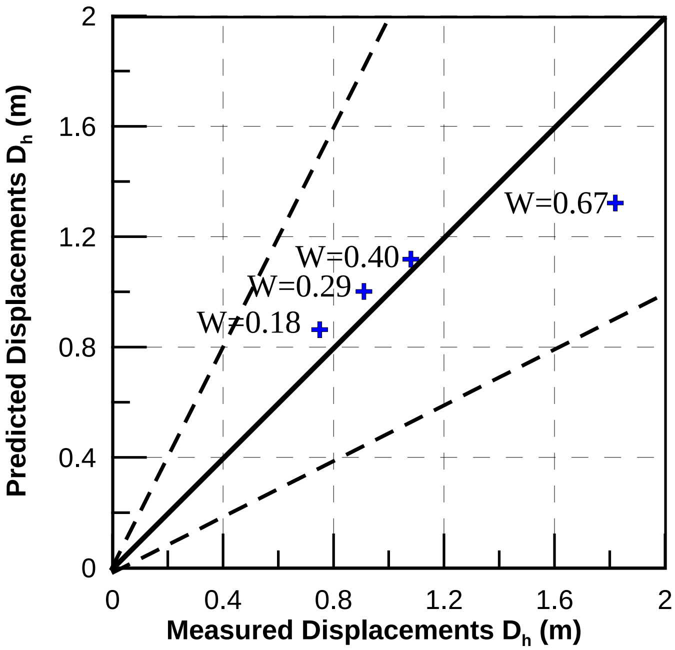

Fig. 9. Comparison between ground surface predictions (Eq. 7) and centrifuge measurements reported by Taboada et al. (2002)

CONCLUSION

In summary, a recently developed numerical methodology for the analysis of liquefaction related boundary value problems was employed in order to simulate lateral spreading of gently sloping ground, define the basic problem parameters and provide empirical relationships which quantify their effect. To ensure the validity of the analyses, a number of well documented centrifuge experiments were first reproduced and evaluated using the aforementioned numerical methodology. Furthermore, the final empirical relationship was one-to-one compared against results from one relevant centrifuge test, as well as from two hundred twenty eight (228) field measurements, collected and interpreted by Youd et al. (2002).
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The conclusions of practical interest resulted from this study are the following:

(a) The numerical analyses performed herein have shown that lateral spreading displacements of "free-face" ground surface irregularities:
- increase with increasing seismic acceleration a_{max}, duration of shaking t_d, cumulative thickness of liquefied soil layers H_{tot} and free-face ratio at the point of interest W, while they
- decrease with increasing predominant shaking frequency f, SPT blow count $(N_{1,60})_{cs}$, and fines content FC.

The vast majority of similar empirical relations used in practice today do not account for the complete set of the above effects.

(b) A statistical analysis of the predictions derived from a set of ninety-three (93) parametric numerical analyses led to a decoupled empirical relationship, where the effect of the above parameters is separately accounted for.

(c) Comparison to the numerical predictions has shown that, the new relation provides a reasonably accurate fit for ground surface displacements up to 1.50m, with
- 95% of the data points falling between the 50% and 200% prediction bounds, and
- ±25%. standard deviation from the mean,

(d) Good agreement is also observed when the empirical relationship is compared to the field measurements reported by Youd et al.(2002), despite the fact that a number of the input parameters required for the new relationship had to be indirectly estimated from the data reported by Youd et al..

(e) This objective limitation in the application of the new relation, addressed in conclusion (d) above, brings to the stage the need for better documented field measurements, as well as the need for more experimental studies (i.e. with centrifuge or large shaking table tests) where the soil and excitation conditions are adequately controlled.

(f) Although not directly related to the scope of this study, it is also worth noting that the numerical methodology employed herein (Papadimitriou et al. 2001, Andrianopoulos et al. 2009, Karamitros 2009) performed well in seventeen (17) out of the nineteen (19) centrifuge tests which were used for its validation, prior to the execution of the main set of parametric analyses.

ACKNOWLEDGEMENTS

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