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2nd General Report for TC 203 Experimental characterization and analysis of soil behaviour under earthquake loads

2^e rapport général du TC 203 Caractérisation expérimentale et analyse du comportement des sols sous chargement sismique

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ABSTRACT: This General Report is addressed to resume and comment 32 papers mostly dealing with the characterization of natural and reconstituted soils under cyclic and dynamic loads reproducing earthquakes in field and laboratory tests, as well as in physical and numerical models. Predictive models are often assessed on the basis of good quality experimental data and field observations from post-earthquake damage reconnaissance are also accounted for. The papers have been grouped according to the engineering purpose of the relevant study, and highlight that the up-to-date technological innovations in geotechnical testing and analysis can nowadays provide a continuous and tangible improvement to the worldwide effort for seismic risk mitigation.

RÉSUMÉ: Ce Rapport général présente et synthétise les 32 articles portant essentiellement sur la caractérisation des sols naturels et reconstitués sous chargements cyclique et dynamique reproduisant les conditions d'un séisme dans des essais sur le terrain et en laboratoire, ainsi qu'en modélisation physique et numérique. Les modèles de prévision sont souvent évalués d'après la qualité des données expérimentales, mais aussi en tenant compte des observations sur le terrain après reconnaissance des dégâts dus au séisme. Les articles - regroupés en fonction de leur objectif - soulignent le fait qu'aujourd'hui les innovations technologiques les plus avancées dans le domaine des tests et des analyses géotechniques peuvent contribuer de façon tangible et continue aux efforts consentis au niveau mondial pour l'atténuation des risques sismiques.

KEYWORDS: earthquake, soil behaviour, cyclic loads, laboratory testing, physical models, field observations

1 INTRODUCTION

The 32 papers assigned to this session mainly deal with the characterization of natural and reconstituted soils under cyclic and dynamic loads reproducing earthquakes as well as other time-dependent phenomena. Most of them are based on the results of field and laboratory investigations, these latter including element and physical model tests. Predictive models are often assessed on the basis of good quality experimental data and field observations from post-earthquake damage reconnaissance are also accounted for. Following a traditional approach for earthquake geotechnical engineering, they will be shortly commented subdividing them into 5 sections, corresponding to relevant engineering issues:

- field and laboratory measurement of equivalent soil parameters (5 papers);
- measurement and modeling of cyclic degradation, strength and liquefaction (11 papers);
- liquefaction: empirical methods, field observations and countermeasures (7 papers);
- ground deformation and slope stability (6 papers);
- retaining structures (3 papers).

2 FIELD AND LABORATORY MEASUREMENT OF EQUIVALENT SOIL PARAMETERS

Gonzales et al. (Chile) analyze 'Correlations between the shear wave velocity profile and the response spectrum based on SASW tests' carried out on six medium stiff sites, where the $M_w=8.8$ Maule Earthquake (27.02.2010) was recorded. The Authors observe that in the three sites showing shear wave velocity inversions, the recorded response spectra are featured by multiple peaks, which would impose a design spectrum with a wider plateau. They also discuss the non-univocal correlation between peak spectral amplitudes and the equivalent velocity V_{S30} (Fig. 1). It is suggested by the writer to better assess the different roles of input motion and non-linear site amplification through seismic response analyses.

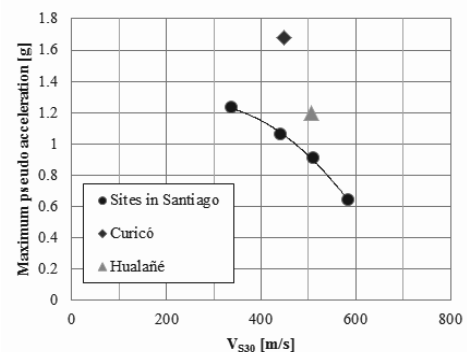


Figure 1. Peak spectral amplitudes versus V_{S30} (*Gonzales et al.*).

Zekkos et al. (USA) describe an up-to-date methodology for the 'In situ assessment of the nonlinear dynamic properties of Municipal Solid Waste' using mobile vibroseis shakers. Under incremental vertical static loads, small-strain crosshole and downhole tests were performed, along with sinusoidal horizontal loads with increasing amplitudes applied by the mobile shakers. The ground motions recorded by the geophones embedded in the waste were used to evaluate nonlinear stiffness of MSW throughout a wide shear strain range (0.0002% to 0.2%). The reduction curves of normalized shear modulus, G/G_{max} , were affected by waste grading and, to a lesser extent, by the increase of confining stress (Fig. 2). This latter induced a more linear behaviour, similarly to granular soils. It is expected that this powerful technique will provide interesting results even in terms of nonlinear in-situ damping.

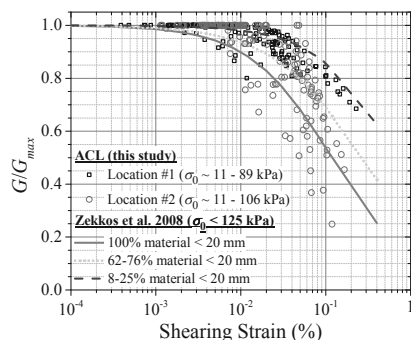


Figure 2. Modulus reduction curves of MSW (Zekkos et al.).

The paper by Liao et al. (USA) provides very useful laboratory test data on the ‘Normalized shear modulus of compacted gravel’ used for fills. Resonant Column and Torsional Shear (RCTS) tests were performed on large diameter specimens of poorly graded (PA) gravel and well-graded (WA) sandy gravel, both scalped at 19 mm particle size. The curves for the WA and PA samples (Fig. 3) fall in the ranges suggested by Seed et al. (1986) and Rollins et al. (1998) respectively, and are quite consistent with the stress-dependent curves suggested by Menq (2003) on the basis of the modified hyperbolic model formulated by Darendeli (2001). Once again, it is expected that similar considerations about the dependency on grading and stress state would hold for the damping-strain curves.

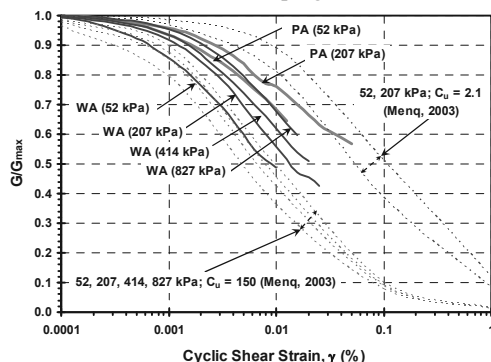


Figure 3. Modulus reduction curves of compacted gravels (Liao et al.).

Ray & Szilvgyi (Hungary), authors of the paper ‘Measuring and modeling the dynamic behavior of Danube Sands’, report and discuss results obtained by a RCTS device on hollow pluviated specimens of a typical alluvial sand. The equipment, originally developed by the first author in USA (Ray & Woods, 1987), was updated in Gyr University in order to be capable of loading at higher torques and measuring wider strain ranges, under non-isotropic confining stresses and irregular cyclic shear loads. The Authors mention, although not showing the comparisons, that such data were satisfactorily interpreted by the Ramberg-Osgood model with extended Masing criteria.

Sas et al (Poland) investigate ‘The behaviour of natural cohesive soils under dynamic excitations’, by RC tests on natural shallow samples of silty sand, subjected to stepwise consolidation stages. The normalized shear modulus-strain curves, however, appear excessively non-linear for some of the confining stress levels: this may be due to several experimental factors, including strain measurement resolution and/or effects of the consolidation procedure followed.

3 MEASUREMENT AND MODELLING OF CYCLIC DEGRADATION, STRENGTH AND LIQUEFACTION

3.1 Clean sands

Bolouri Bazaz & Bolouri Bazaz (Iran) present ‘An experimental approach to evaluate shear modulus and damping ratio of granular material’, a Standard Leighton Buzzard sand. Loose and dense dry specimens were prepared by air-pluviation in a

cubic Biaxial Testing (BT) device, able to apply independent variations of horizontal principal stresses by hydraulic actuators. Repeated sequences of cyclic loads with increasing peak stress ratios, R_{max} , showed that both dense and loose sand underwent progressive densification with the number of cycles. The stress-strain behaviour was featured by a kind of ‘elastic shakedown’, i.e. closed loops corresponding to steady shear modulus and damping ratio approaching zero (Fig. 4). At the highest stress ratio, soil behaviour turned to softening and dilatant, eventually leading to a ‘run away’ failure. The results encourage to an interpretation in terms of hardening plasticity models.

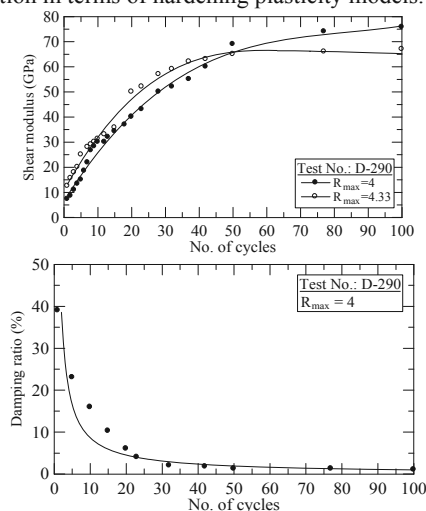


Figure 4. Cyclic evolution of modulus and damping for dry dense sand (Bazaz et al.).

A further interesting contribution from Iran is by Jafarzadeh & Zamanian, investigating the ‘Effect of stress anisotropy on cyclic behavior of dense sand with dynamic Hollow Cylinder apparatus’ (HC). Wet tamped specimens of uniform Babolsar sand were saturated and isotropically consolidated at the same effective stress, then subjected to constant amplitude shear loads corresponding to different ratios between torsional shear and deviator stress, i.e. to different degrees of stress-induced anisotropy. Results show that the angle α , representing stress anisotropy, does affect the excess pore water pressure ratio (Fig. 5a), but has no significant influence on the strain dependency of shear modulus (Fig. 5b) and damping ratio.

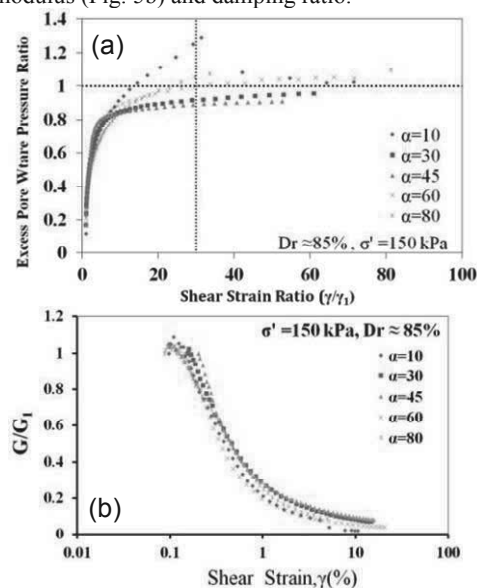


Figure 5. Effects of stress anisotropy on pore water pressure (a) and shear modulus (b) for saturated dense sand (Jafarzadeh & Zamanian).

Another study on the effects of loading pattern on cyclic behaviour of clean sands is provided by Coelho et al. (Portugal-

UK), in their ‘Challenges to the laboratory evaluation of field liquefaction resistance’. Air-pluviated specimens of uniform Coimbra sand were saturated, isotropically consolidated at the same effective stress, and subjected to undrained CTX tests with different loading patterns. Irregular axial loads including a singular higher amplitude cycle pointed out the significant influence of its location, in terms of current mean effective stress ratio, p'/p'_0 , on the number of cycles for the onset of liquefaction. Cyclic strength was greater under axial (UCT/V) than under radial (UCT/H) loading; also, multidirectional load patterns (UCT/HV) led to an even faster degradation than that observed in the unidirectional tests (Fig. 6).

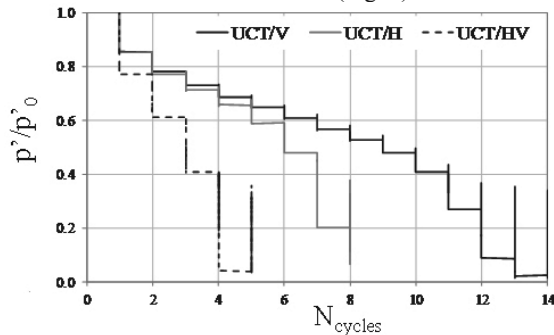


Figure 6. Comparison between liquefaction resistance under unidirectional and multidirectional loading (Coelho *et al.*).

Sze & Yang (Hong Kong) studied the ‘Cyclic loading behavior of saturated sand with different fabrics’ by comparing the failure modes of moist tamped (MT) and dry deposited (DD) loose specimens of uniform Toyoura sand. Undrained CTX tests were driven with different static shear stress ratio, α , showing different failure modes, varying from ‘cyclic mobility’ to ‘limited’ or ‘runaway’ deformation (Fig. 7). The mechanisms are viewed as dependent on both inherent anisotropy (expected to be higher for DD specimens) and the stress-induced fabric changes, in turn controlled by the combination between α and the cyclic stress ratio, $CSR = q_{cy}/(\sigma'_{1c} + \sigma'_{3c})$. The Authors conclude that fabric effects might be very significant, although they are inherently not accounted for in conventional design procedures, such as those based on liquefaction charts.

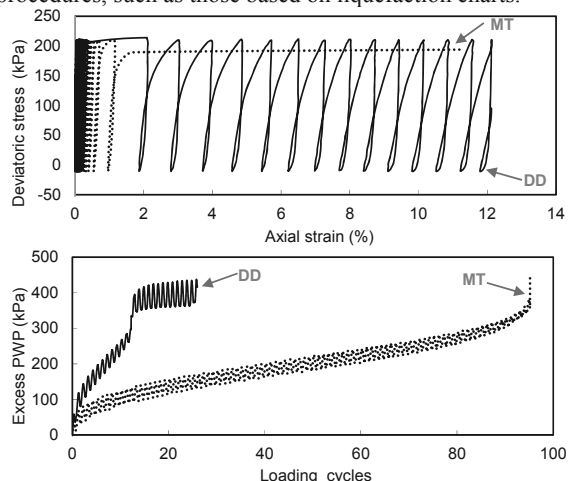


Figure 7. Limited (DD) vs. runaway (MT) deformation for $\alpha=0.1$, $CSR=0.11$ (Sze & Yang).

3.2 Silty sands

Mominul *et al.* (Bangladesh) investigate on ‘Dynamic properties and liquefaction potential of a sandy soil containing silt’ by means of undrained CTX tests on wet tamped specimens of dense silty sand. Results are reported in terms of strain dependent modulus and damping (indeed, well beyond the linear threshold strain), and cyclic resistance curves relevant to both pore pressure ratio and strain amplitude criteria are

compared. The ‘cyclic resistance ratio’ (i.e. CRR) was defined as the CSR value required to reach 5% double amplitude axial strain in 20 cycles: it was seen to decrease with non-plastic silt content increasing up to 30%, and to be nearly constant above this value (Fig. 8). It must be recalled that conventional empirical methods imply increasing the cyclic resistance ratio when plastic fines are present, but no correction for non-plastic fines is normally implemented.

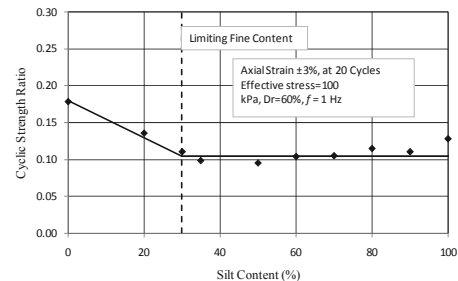


Figure 8. Variation of cyclic strength ratio with non-plastic silt content (Mominul *et al.*).

Noda & Hyodo (Japan) also investigate on ‘Effects of fines content on cyclic shear characteristics of sand-clay mixtures’ by mixing silica sand with a medium plasticity clay in different proportions, spanning from clean sand to clayey silt. By comparing undrained CTX tests on specimens compacted with different energy, it was again observed that the cyclic resistance ratio decreased with fines content, F_c , up to about 20% for dense mixtures, while the opposite trend was shown by the loose ones (Fig. 9). Specimens with plastic $F_c > 20\%$ had to be prepared by slurry pre-consolidation: they showed a rapid increase of the cyclic resistance ratio up to $F_c = 50\%$, beyond which the liquefaction strength asymptotically approached that of the clayey silt. Finally, the Authors interestingly suggest that with non-plastic $F_c < 20\%$, the dependency of cyclic resistance ratio on F_c at a given relative density is scaled out, if a properly defined ‘equivalent granular void ratio’ is adopted.

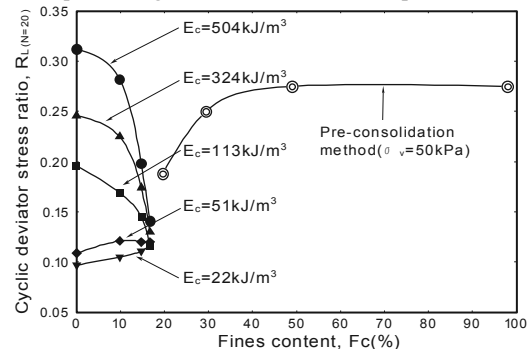


Figure 9. Variation of cyclic resistance ratio with non-plastic ($F_c < 20\%$) and plastic ($F_c > 20\%$) silt content (Noda & Hyodo).

3.3 Peculiar soils

Elmamlouk *et al.* (Egypt) analyze the ‘Liquefaction susceptibility of loose calcareous sand of Northern Coast in Egypt’ by means of undrained CTX tests on a poorly graded calcite-sand with apparently non-plastic fines content lower than 10%. Reconstituted specimens were prepared by tamping, appropriately using undercompaction technique (Ladd, 1978) to reach the target relative density $D_r = 40\%$ after consolidation. This calcareous sand showed greater cyclic strength (in terms of pore pressure ratio $r_u = 1.0$) compared to siliceous sands at the same D_r and σ'_c (Fig. 10). Particle crushing under cyclic loading was found to be insignificant for the range of σ'_c applied, resulting into a cyclic resistance ratio decreasing with confining pressure, apparently due to interlocking soil fabric.

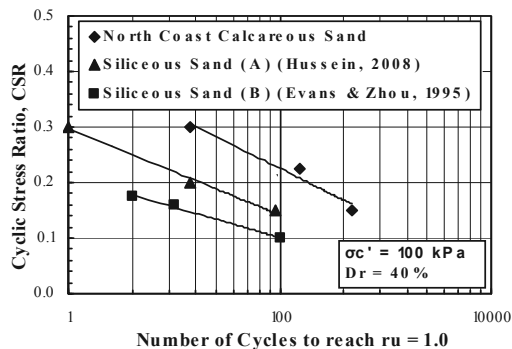


Figure 10. Liquefaction susceptibility of calcareous and siliceous sands (Elmamlouk *et al.*).

Another study on peculiar soils is presented by *Orense & Pender* (New Zealand) on 'Liquefaction characteristics of crushable pumice sand' which, like other volcanic soils, is poorly investigated in literature. Undrained CTX tests were performed on reconstituted specimens of uniform sand and undisturbed frozen samples of well-graded sandy silt. The effects of D_r and σ'_c on the liquefaction resistance were not as significant compared to that of hard-grained sands. Empirical liquefaction procedures derived for hard-grained soils were assessed by comparing the CRR (this time evaluated as CSR corresponding to 15 cycles) from the CTX tests on undisturbed specimens with those from cone penetration (CPT) and seismic dilatometer (sDMT) tests at the sampling sites. Due to particle breakage, the penetration-based methods did not agree well with the laboratory values, while that based on shear wave velocity (*Andrus & Stokoe*, 2000) showed better correlation (Fig. 11).

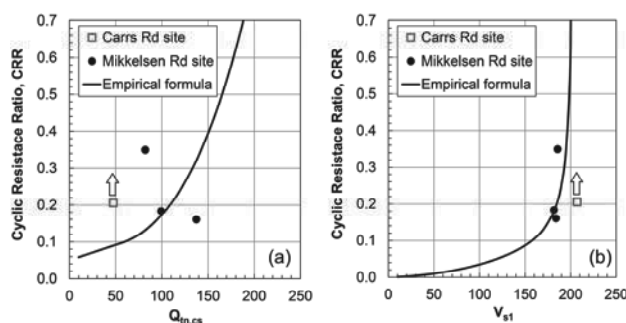


Figure 11. Comparison between CRR from CTX and those from CPT (a) and V_s (b) empirical methods (*Orense & Pender*).

Ahnberg et al. (Sweden) report a comprehensive study on 'Degradation of clay due to cyclic loadings and deformations' including CTX tests on many soft clays with variable frequency, highlighting that the cyclic overstrength was proportional to the logarithm of strain rate. They also mention that the cyclic resistance in terms of cyclic/static strength ratio increased with decreasing sensitivity and increasing organic content, although more specific correlations are not explicitly reported.

3.4 Analytical and physical modelling

Park & Ahn (South Korea) propose an interesting 'Accumulated stress based model for prediction of residual pore pressure'. The model uses a damage parameter, function of the cyclic stress ratio and of the length of the shear stress path, to transform the pore pressure model by *Seed et al.* (1975), which is instead based on the equivalent number of cycles. The formulation can be therefore incorporated in coupled effective stress analyses of dynamic transient motions in the time domain. The calibration procedure of the parameters, based on the cyclic resistance curves measured in stress-controlled cyclic tests, was successfully validated through comparisons with published and original laboratory test data on clean and silty sands (Fig. 12).

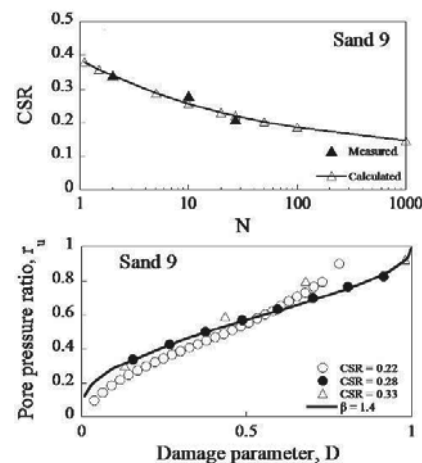


Figure 12. Comparison of measured and predicted cyclic resistance and pore pressures (*Park & Ahn*).

The paper 'Liquefaction impact revisited' by *Barends et al.* (Holland) reports laboratory tests on the variation of partial liquefaction with space and time. 1D (soil column) and 3D (cylindrical tub) models were filled with loose sand, respectively overlying and surrounded by a denser one, and instrumented to measure pore pressures and displacements under impact loads. When even partial liquefaction occurred, significant pore pressures arose also in the non-liquefied surroundings and slowly dissipated during the sedimentation of the liquefied mass (Fig. 13). The related porosity decrease was however small enough that the sand remained loose, and re-liquefaction was likely to occur due to subsequent new shaking.

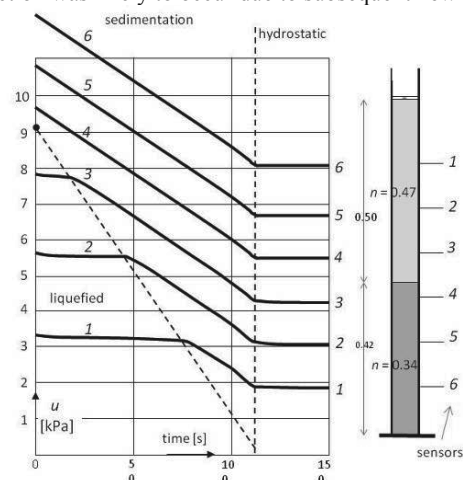


Figure 13. Typical pore pressure records after a full liquefying impact load (*Barends et al.*).

4 LIQUEFACTION: EMPIRICAL METHODS, FIELD OBSERVATIONS AND COUNTERMEASURES

4.1 Empirical methods

Katzenbach et al. (Germany) critically review the 'Recent developments in procedures for estimation of liquefaction potential of soils' in relation with Eurocode 8 (2010) as well as the methods described in the NCEER workshops (*Youd et al.* 2001). They discuss the main factors influencing the evaluation of CSR and CRR, claiming for more refinements and univocal approaches in terms of definition of screening criteria, stress reduction factor r_d , effects of fines content, magnitude scaling factor. They also suggest to introduce more details in EC8 about the use of penetration resistance and of V_s .

Wang et al. (China) discuss the 'Performance-based evaluation of saturated loess ground liquefaction' which supports recent updating of the seismic guidelines of Gansu

Province. The collapsible nature of such soils induced primarily to revise both stress- and strain-based criteria for CTX tests, adopting pore pressure ratio and strain thresholds more conservative than usual; thereafter, the Chinese code of practice rules for screening criteria and SPT-based method are amended. Considering the lower penetration strength of such soils, the reference SPT blowcount, N_0 , used for the evaluation of the critical value, N_{cr} , is reduced, in order to limit the degree of conservativeness of the empirical method.

4.2 Field observations

Yasuda (Japan) presents a comprehensive summary of 'Soil properties of liquefied soils in Tokyo Bay area by the 2011 Great East Japan earthquake', aka Tohoku Earthquake ($M_w=9.0$), which induced widespread liquefaction of reclaimed land. Cyclic TS tests with irregular loadings simulating the mainshock and a short-term aftershock allowed to explain the liquefaction of a silty sand in Urayasu City, which could not be otherwise justified on the basis of the relatively low peak ground acceleration, PGA, recorded (0.1-0.2g). Model tests on the same soil loaded with concrete blocks simulating road pavement could also show the mechanisms of sand eruption under static hydraulic gradient. 2D seismic response analyses in total stresses with significantly reduced stiffness for liquefied soils were carried out to try explaining the unusual heaving, buckling or thrust observed in some sites, which may have followed post-liquefaction sloshing. The results suggested that such phenomena might have occurred, due to the horizontal compressive strain of liquefied ground (Fig. 14). In the writer's opinion, analyses with advanced constitutive modeling might be helpful for a more objective interpretation.

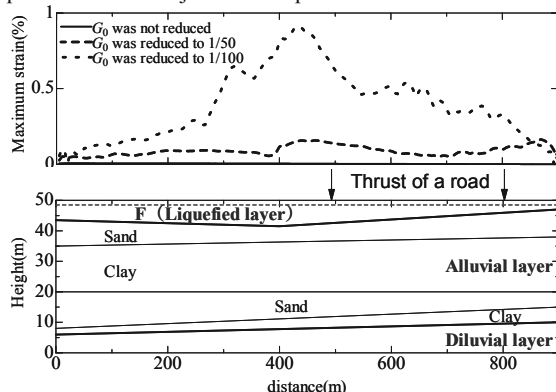


Figure 14. Seismic response analyses estimating the ground deformation phenomena (Yasuda).

As a matter of fact, effective stress analyses were adopted by Asaoka & Nakai (Japan) to interpret the phenomena occurred in Urayasu City, referring to the 'Dependency of non-uniform ground surface liquefaction damage on organization and slope of deep strata'. 1D and 2D coupled analyses with a hardening plasticity constitutive model were carried out using field tests data, focusing attention on the deep sloping clay deposits underlying the liquefied ground. The results showed that low-frequency amplification and localized shear strains might justify the non-uniform liquefaction observed at surface (Fig. 15).

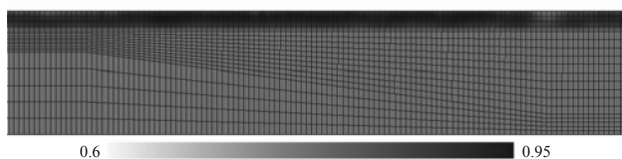


Figure 15. Predicted distribution of excess pore water pressure ratio (Asaoka & Nakai).

4.3 Countermeasures

Following again the lessons learned from the aforementioned Tohoku Earthquake, Nakamichi & Sato (Japan) investigate 'A

method of suppressing liquefaction using a solidification material and tension stiffeners' by means of CTX tests on Toyoura sand, prepared by wet tamping at $D_r=60\%$. The soil was added with different contents of Portland cement (C) and recycled Bassanite from waste plasterboard (B) as solidifying materials, and PVA (polyvinyl alcohol) fibers with an average length of 12.0 mm (F) as tension stiffener. Fig. 16 shows that the cyclic strength is more than doubled by a 2% cement addition and that a comparable improvement is obtained with $C=1\%$ plus either 5% of Bassanite or 1% PVA fibers.

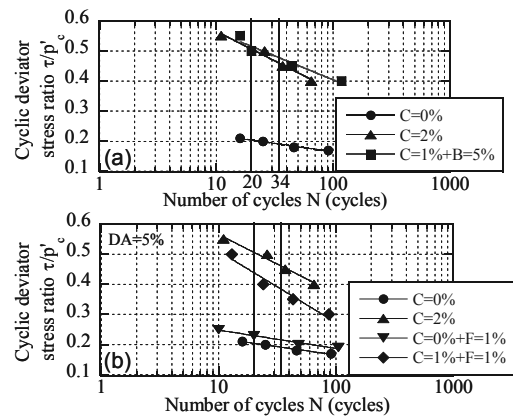


Figure 16. Cyclic strength of sand improved with different techniques (Nakamichi & Sato).

H. Takahashi *et al.* (Japan) present an 'Experimental study on lattice-shaped cement treatment method for liquefaction countermeasure', aimed to optimize the cost/effectiveness of cement-treated piles by comparing the behaviour of fixed-type and floating-type installations. These latter are not fixed to an underlying un-liquefiable stratum and therefore expected to be less effective. Pilot one-dimensional seismic response analyses with or without lateral constraints in the treated soil highlighted the basic confining mechanisms of the lattice-shaped grouting. A comprehensive centrifuge testing program on two series of models, consisting of floating-type grids without (A) and with surrounding fixed-type treatments (B), permitted to verify the increase of effectiveness with their depth in terms of reduction of pore pressure buildup and surface settlements (Fig. 17).

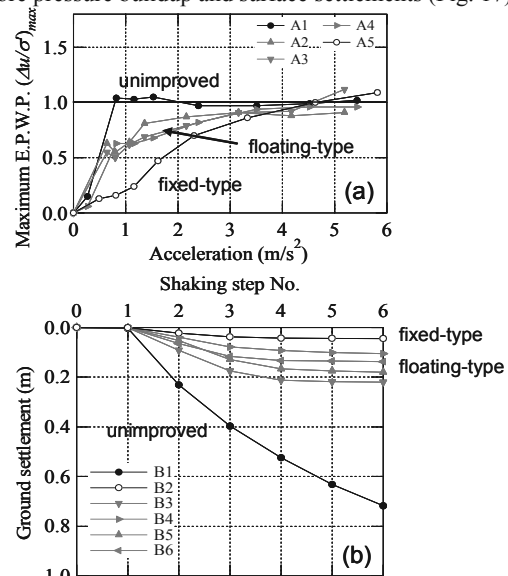


Figure 17. Reduction of pore pressure buildup (a) and settlement (b) in centrifuge tests on lattice-shaped treatments (H. Takahashi *et al.*).

N. Takahashi *et al.* (Japan), instead, investigate on 'Shaking model tests on mitigation of liquefaction-induced ground flow by new configuration of embedded columns' again of grouted soil. The performance of a regular triangular arrangement was

compared to that of an irregular configuration obtained by shifting square grids, thus preventing a straight flow passage of liquefied soil. Shaking table tests on sloping ground and quay wall models proved that the irregular pattern was more effective in reducing residual displacements in the treated soil volume; nevertheless, the ‘damming effect’ increased both downstream deformation in the sloping ground (Fig. 18a) and pore pressure in the treated backfill behind the quay wall (Fig. 18b).

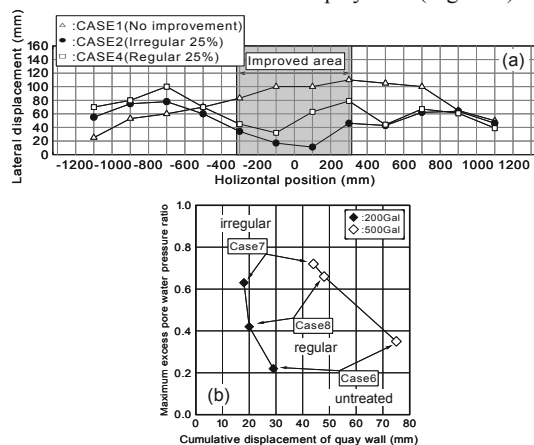


Figure 18. Lateral displacements and pore pressure buildup in shaking table tests on sloping ground (a) and quay wall (b) with columnar treatments (N. Takahashi et al.).

5 GROUND DEFORMATION AND SLOPE STABILITY

The paper by *Isoe & Ohtsuka* (Japan) reports a comprehensive ‘Study on long-term subsidence of soft clay due to 2007 Niigata Prefecture Chuetsu-Oki Earthquake’ ($M_w=6.8$). Pre-earthquake long-term settlements due to groundwater pumping at Kashiwazaki City were observed to significantly increase after the event. An accurate field (SPT) and laboratory (oedometer plus static and cyclic TX tests) investigation was carried out to calibrate the mechanical parameters of three soft to medium stiff clays, in order to carry out a coupled elasto-plastic FEM analysis of a 50m deep layering. The simulation of the shaking and post-earthquake behaviour allowed to predict pore water pressure increase and dissipation (Fig. 19), resulting in a long-term settlement as high as 25 cm in about 100 years.

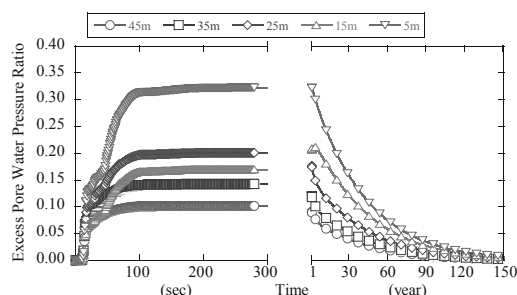


Figure 19. Pore pressure buildup and dissipation predicted by elasto-plastic simulation of earthquake-induced subsidence (Isoe & Ohtsuka).

Tsai et al. (Taiwan-USA) propose a simplified procedure for a slope stability ‘Pseudo static analysis considering strength softening in saturated clays during earthquakes’. They update and combine well-established approaches for estimation of the shear strain amplitude and the equivalent number of uniform strain cycles from the peak ground acceleration and other seismological and site parameters. On such a basis, the strength softening can be evaluated and implemented in post-earthquake pseudo-static stability analysis. The method was applied to predict the post-seismic reduction of safety in an embankment at Berryman Reservoir (USA), as well as for the interpretation of the observed damage induced by the 1999 Kocaeli

earthquake (Turkey) at the Carrefour shopping center, which cannot be explained without a strength reduction (Fig. 20).

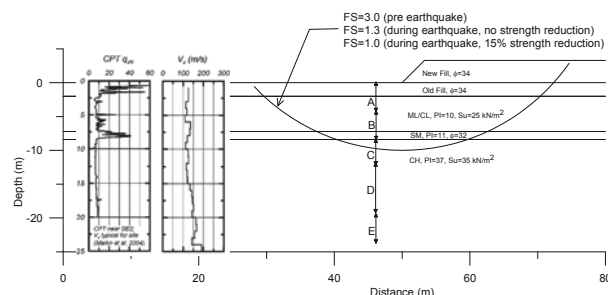


Figure 20. Stability analyses at Carrefour shopping center (Tsai et al.).

Fotopoulou & Pitilakis (Greece) present a ‘Reliability analysis of empirical predictive models for earthquake-induced sliding displacements of slopes’, comparing the predictions of:

- the coupled Bray & Travasarou (2007) stick-slip model (B&T), based on a single ground motion parameter, i.e. $S_a(1.5T_s)$, being T_s the degraded soil natural period;
- the decoupled Rathje & Antonakos (2011) model (R&A), based on two ground motion parameters (PGA, PGV or their equivalent values for soft slopes);
- the classical Newmark (1965) rigid block model (N).

The Authors assumed as reference displacements the results of 2D elasto-plastic FEM analyses for ideal sand and clayey slopes, with different accelerograms as input motion. It was verified that the approximation increased with the degree of definition of the input motion, being the B&T model (1 parameter) conservative, but with more dispersion, while the R&A (2 parameters) and the N (full time history) models under-predicted, although with less scatter, the FDM results (Fig. 21). Also, the reliability seemed overall better for the sand slopes. Such interesting benchmark claims for further comparisons on well-documented case studies.

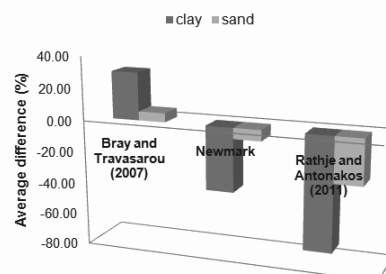


Figure 21. Median displacements predicted with simplified models vs. the corresponding FDM results (Fotopoulou & Pitilakis).

Abe et al. (Japan) present an ‘Analytical study of seismic slope behavior in a large-scale shaking table model test using FEM and MPM’, investigating on two steep model test slopes constituted by sand-bentonite mixtures. A homogenous and a layered model with a weak sloping layer were shaken with irregular or regular time histories, showing rotational or planar failure mechanisms, respectively. Blind numerical predictions of the former model test by nonlinear multiple spring FEM analysis could not capture the observed failure mechanism (Fig. 22 a-b), which was conversely well-predicted by the Material Point Method (MPM), able to simulate progressive failure due to strain-softening (Fig. 22c). The latter approach was also effective to predict the observed shear failure mechanism and displacements exhibited by the layered model.

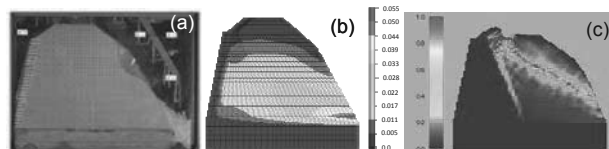


Figure 22. Observed failure (a) and contours of maximum shear strain predicted by FEM (b) and MPM (c) analyses (Abe et al.).

Two more case studies of failure mechanisms occurring along soft-stiff soil interfaces, although not relevant to earthquake loads, are described by *Rangel-Núñez et al.* (Mexico) and *Johansson et al.* (Norway).

The first paper describes a 'Pioneer application of a dynamic penetrometer and boroscope in archeological prospecting' of a heterogeneous fill covering a tuff pyramid, showing deformation and cracking induced by man-made excavation and environmental processes. FEM analyses proved the existence of a mechanism of plastic/creep sliding along the underlying tuff.

The second contribution investigates the 'Impact of blast vibrations on the release of quick clay slides' through empirical attenuation laws of PGV and numerical simulations of rock blasts near quick clay deposits. Cyclic loading contour diagrams based on CTX tests were used for simplified estimates of threshold vibration velocities inducing local slope failure.

6 RETAINING STRUCTURES

Otani et al. (Japan) describe a comprehensive 'Investigation of Reinforced Earth in the 2011 off the Pacific coast of Tohoku Earthquake', presenting damage statistics as well as detailed site-specific surveys. Only 4 out of the 1419 surveyed walls showed full collapse mechanisms (Fig. 23), attributed to: (a) inadequate drainage and earthfill material, (b) slippage on soft foundation soil, (c) scouring (bottom erosion) due to the wash away of an adjacent levee by the tsunami, and (d) weakness of strip-panels connections due to prior frost-heave.

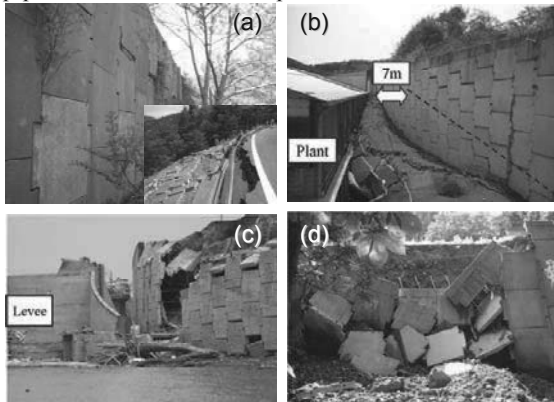


Figure 23. Observed failure (a) and contours of maximum shear strain predicted by FEM (b) and MPM (c) analyses (*Abe et al.*).

Watanabe & Koseki (Japan) propose a 'Seismic design of retaining wall considering the dynamic response characteristic'. The purpose was to predict displacements of railway-supporting gravity walls more accurately than following the previous standard procedure, based on a pseudo-static approach relying on a 'constant energy law'. The new design method applies the Newmark (1965) model considering the combination of sliding and overturning modes, defined by the yield surface of bearing capacity in terms of horizontal force – moment relationship. The approach predicted displacements and rotations in fair agreement with those recorded in shaking table tests (Fig. 24) and observed on a damaged railway cantilever wall after the 1995 Hyogo-ken nambu earthquake. In 2012 the proposed method was therefore adopted in the new performance-based design Japanese standard for railway retaining structures.

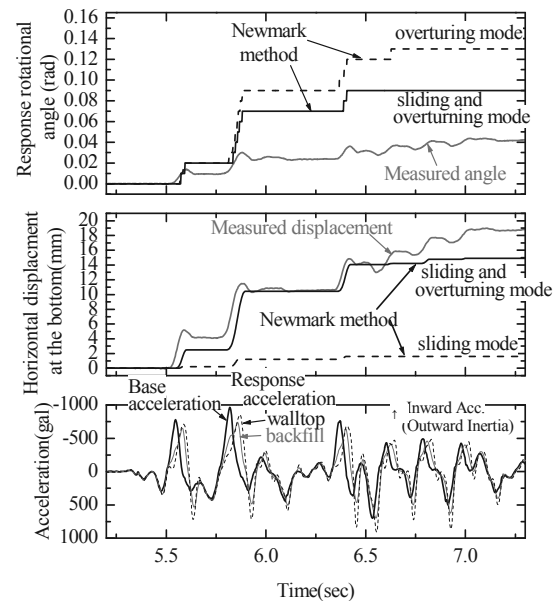


Figure 24. Wall response in shaking table tests vs. predictions by Newmark analyses with different failure modes (*Watanabe & Koseki*).

Xiao et al. (USA) investigate on 'Seismic responses of geogrid reinforced wall with Tire Derived Aggregates (TDA) backfill using reduced-scale shake table test'. This lightweight deformable recycled material was preliminarily characterized by laboratory large scale tests, then used to build a geogrid reinforced wall model overlying a thin sand layer resting on the table floor. The model, shaken by a Loma Prieta earthquake record, showed negligible relative base displacements while those at the top were characterized by significant elastic rebound (Fig. 25), not predictable by the rigid block model. Notwithstanding the limitations of both the scaling laws and the rigid base conditions, the Authors are encouraged to try FEM analyses for reliable interpretation of test data.

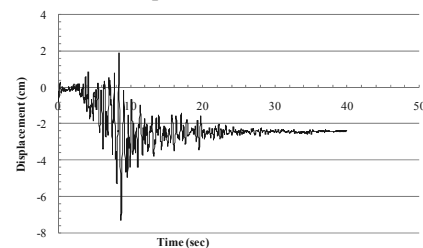


Figure 25. Top displacement recorded in a shaking table test on TDA geogrid reinforced wall (*Xiao et al.*).

7 DISCUSSION AND CONCLUSION

All the contributions to this Technical Session were perfectly aligned with the main conference theme: 'Challenges and innovations' are a strong commitment for earthquake geotechnical engineering.

From the bulk of the papers presented, it is apparent that advanced experimental techniques for cyclic and dynamic testing on soils are getting increasingly widespread in all countries. Some national scientific communities are progressively bridging the gap with the traditionally leading countries, U.S. and Japan above all, taking profit of their well-established expertise.

The writer wishes to address some final comments as well as suggestions for discussion and future research developments.

Field testing: practice in earthquake geotechnical engineering is achieving increasingly beneficial contributions from geophysics, especially in non-invasive techniques, such as surface wave methods. More effort should be devoted to in-situ

measurement of damping and characterization on hard-to-sample materials, such as gravels and MSW.

Laboratory testing: a four decades experience in CTX and RCTS tests makes such techniques well-established. However, non-conventional equipments (HC, BT) as well as multi-directional and irregular loading patterns can highlight some specific aspects of cyclic stress-strain behaviour and strength, which have traditionally been over-simplified.

Liquefaction assessment: while the classification of failure criteria and mechanisms in element tests is still debated, attention must be paid on the engineering applicability or extension of empirical methods on peculiar soils, e.g. focusing on the effects on fabric, non-plastic vs. plastic fines, crushable grains and so on. Sequences of multiple earthquake loads are a further challenge.

Physical and numerical modeling: their combination has an immense value for the understanding of complex mechanisms, calibration of design procedures and advanced models, and optimization of mitigation technologies.

Innovative materials: recycled materials (e.g. waste, PVA fibers, TDA) are increasingly used in element and model tests, with satisfying performances as sustainable techniques for soil reinforcement or lightweight fills.

Case studies: the damage scenario induced by a strong-motion earthquake, although dramatic, is still the most representative investigation 'laboratory'. Post-earthquake reconnaissance always provides new addresses for future research and suggests improvements for the codes of practice.

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