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Effects of earthquake-induced liquefaction: integrated research tools towards optimum reduction of society vulnerability

Effets de liquéfaction induite par des séismes: outils de recherche intégrés vers une réduction optimale de la vulnérabilité de la société

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ABSTRACT: Earthquake-induced liquefaction is widely recognised as a serious hazard threatening modern societies. Indeed, even if the death toll is usually smaller than with other seismic phenomena, such as tsunamis, the economic and social distress and the extent of post-earthquake recovery caused by liquefaction are often more severe. This paper describes the research carried out at the University of Coimbra, Portugal, with its international partners, focusing on the assessment and mitigation of earthquake-induced liquefaction hazards at different levels and using different tools to reduce more effectively society's vulnerability to this phenomenon. Element testing has been combined with centrifuge modelling to assess the basic soil behaviour and the actual mechanisms governing field performance of geotechnical structures. Numerical modelling is used to extend experimental findings and to predict more accurately liquefaction effects, so that the principles of performance-based design can be used in current design practice. New energy-based design approaches and innovative planning tools for transportation infrastructures considering liquefaction hazards at a macro scale have been developed, allowing for better consideration of liquefaction effects in informed decision-making.

RÉSUMÉ : La liquéfaction induite par des séismes constitue une menace pour les sociétés. En effet, même si les décès sont généralement inférieurs à ceux associés à d'autres phénomènes sismiques (raz de marée), les conséquences sociales, économiques et l'ampleur du recouvrement sont souvent plus graves. Cet article décrit les études menées à l'Université de Coimbra au Portugal avec ces partenaires internationaux, en soulignant l'évaluation et l'atténuation des risques de liquéfaction induits par les séismes à différents niveaux et en utilisant plusieurs outils pour réduire efficacement la vulnérabilité des sociétés. Des essais en laboratoire sont combinés avec des études en centrifugeuse pour évaluer le comportement du sol et les mécanismes réels qui régissent la performance des structures géotechniques. La modélisation numérique permet d'étendre les résultats expérimentaux et de mieux prévoir les effets de la liquéfaction, en légitimant l'utilisation des principes de la conception basée sur la performance dans les techniques courantes de conception. De nouvelles approches de conception basée sur l'énergie ou bien des outils de planification innovateurs pour les infrastructures de transport qui considèrent les risques macroéconomiques de la liquéfaction ont été élaborées. Ainsi, la prise de décisions peut considérer les effets de la liquéfaction.

KEYWORDS: earthquake-induced liquefaction, centrifuge modelling, element testing, numerical modelling, robust optimization.

1 INTRODUCTION

Earthquake-induced liquefaction has seriously affected society through the centuries, but its disruptive effects became more evident in the last few decades as modern societies are far less tolerant to failure and much more dependent on extensive and complex infrastructures. If the remarkable events that caused major destruction in Japan (Niigata) and USA (Alaska) in 1964 brought about a change in the attitude of researchers and practitioners towards liquefaction effects, recent events like those that have been striking Christchurch (New Zealand) since 2010 prove the extent and complexity of consequences that modern societies need to endure as a result of widespread liquefaction. In fact, even if the number of casualties is usually limited, the overall impact of liquefaction can be massive.

The consequences of Christchurch's seismic events prove the vast and multifaceted social and economic disruption caused by liquefaction. In fact, as shown by Potter et al (2015), amongst others, the impacts of these events affected individuals, environment and social networks and communities in many complex and interrelated ways: increased levels of depression

and anxiety, affecting especially children, economic problems resulting from property loss and insurance issues, loss of population and businesses, serious reduction in water quality and aquatic life due to the discharge of silt and untreated sewage into waterways, severe damage to historical buildings, amongst other. Important infrastructures, including railways, were seriously affected by these events. Thus, the fact that the number of people moving away from Christchurch (7000) largely exceeded the number of deaths (185) is unsurprising and a clear evidence of how much the society can be affected.

2. NEED FOR INTEGRATED RESEARCH ON EARTHQUAKE-INDUCED LIQUEFACTION

Earthquake-induced liquefaction is a complex phenomenon causing massive consequences to modern societies. Design and decision-making should be able to incorporate liquefaction hazards at different levels and to use suitable tools to reduce more effectively society's vulnerability to this phenomenon. This requires the combination of different research tools and

approaches, in order to minimise the limitations and extend the benefits of each individual method. For example, element testing is usually the most effective method of assessing soil properties and carry out parametric experimental studies. Physical modelling, especially when carried out in a centrifuge, is a unique experimental tool for identifying the mechanisms governing real field performance of geotechnical structures and liquefaction effects. Despite the importance of detailed experimental characterisation, mitigation of liquefaction effects require complementary approaches, namely solid numerical tools able to accurately predict liquefiable ground-structure behaviour, comprehensive liquefaction interpretation frameworks able to deal with earthquake randomness and also decision support tools accounting for liquefaction hazards, which are particularly valuable for planning of large infrastructures, often more vulnerable to liquefaction effects. Effective reduction of society's vulnerability to earthquake-induced liquefaction depends strongly on the successful combination of these tools.

3. AN EXAMPLE OF COLLABORATIVE MULTI-STRATEGY RESEARCH ON LIQUEFACTION

This paper describes the research that has been carried out at the University of Coimbra, in Portugal, with international partners focusing on the assessment and mitigation of earthquake-induced liquefaction hazards using different tools and approaches. The research is based on the combination of experimental, numerical and planning tools selected in relation to the research objectives. For example, element testing is combined with innovative centrifuge and numerical modelling to enhance the ability to understand and predict earthquake-induced liquefaction effects, in adherence to the principles of performance-based design. Also, planning tools for transportation infrastructures considering liquefaction hazards at a macro scale, compatible with the detail level of data commonly available at the planning stage of large-scale infrastructures, have been developed. An overview on such a combination of distinct, yet integrated, research tools is presented herein.

3.1. Experimental tools

Experimental tools used included element testing of a local river and other selected sandy soils reconstituted with different relative densities, using variable strain ranges and loading/boundary conditions. Dynamic centrifuge modelling of shallow foundations built on liquefiable ground was also carried out at Cambridge University's Schofield Centre.

An extensive element testing program was performed on two different liquefiable air-pluviated sands, namely Coimbra and Hostun sands, to examine their behaviour under a wide range of strains and loading conditions. Figure 1.a illustrates the results of Bender Element (BE) tests performed on specimens of Houston sand, highlighting the dependence of stiffness on the current values of void ratio and mean effective stress. Within the medium to large strain range, the monotonic behaviour was observed through drained and undrained triaxial compression tests (DMTC and UMTC, respectively) carried out with increasing and decreasing mean stress ($p\uparrow$ and $p\downarrow$, respectively). Based on a state-parameter approach used in conjunction with the critical-state framework, the critical-state line (CSL) was predicted (Figure 1.b). A comparison with other data found in the literature suggests that the proposed CSL is independent of the sample preparation method and drainage conditions (Azeiteiro et al. 2017a). The stress-dilatancy behaviour of the sand can also be suitably predicted based on existing proposals, at least until the peak-stress-ratio state is reached.

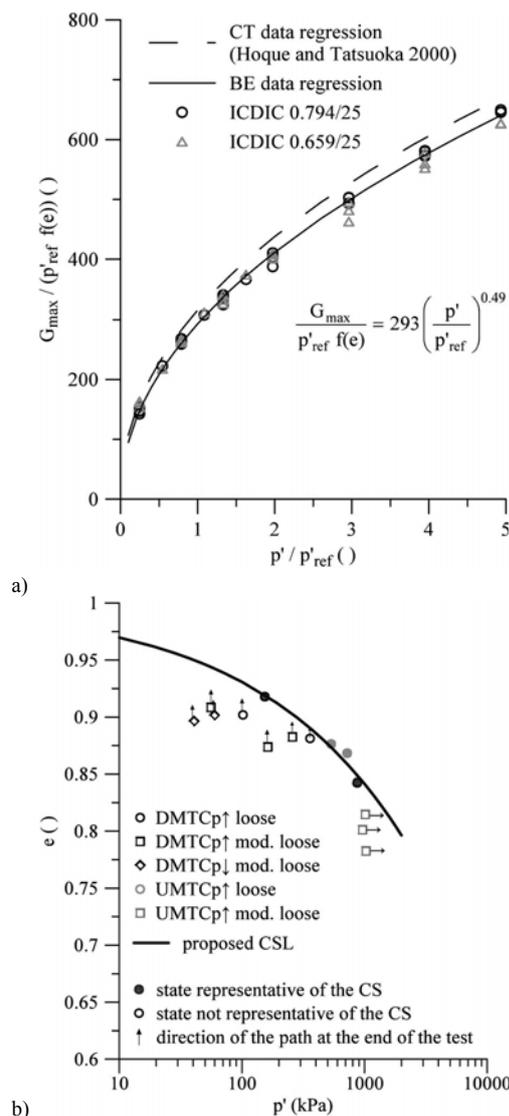


Figure 1. Test results on Hostun sand: a) Small-strain shear modulus - BE tests; b) Critical-state line - Triaxial tests (Azeiteiro et al 2017a)

To assess the behaviour of liquefiable sand under different conditions, torsional cyclic tests were carried out on a Hollow Cylinder Apparatus (HCA), where different and often more realistic cyclic loading and boundary conditions can be imposed to the sample. Figure 2 shows the response of a loose sample of Coimbra sand in a torsional cyclic test carried out with constant lateral stress, a condition accepted to represent sloping ground (Ishihara 1996). For the chosen cyclic stress ratio (0.175), some features of behaviour are similar to those observed in cyclic triaxial tests: the accumulation of cycles with moderate excess-pore-generation for intermediate values of p' (Figure 2.a) and the large increase in strain amplitude once liquefaction occurs (Figure 2.b). Yet, the stress-strain response does not show the build-up of residual strains after each cycle often observed in cyclic triaxial tests. Similar samples of Coimbra sand tested in the HCA under cyclic loading with restricted lateral strain showed distinct behaviour, highlighting the importance of the test boundary conditions (Araújo Santos 2015).

Centrifuge models of neighbouring shallow foundations built on liquefiable Hostun sand were also tested. In fact, buildings and infrastructures in urban areas are often closely built, rendering interaction effects a strong possibility. Thus, realistic physical modelling of liquefaction effects need to incorporate more than one foundation (Figure 3a).

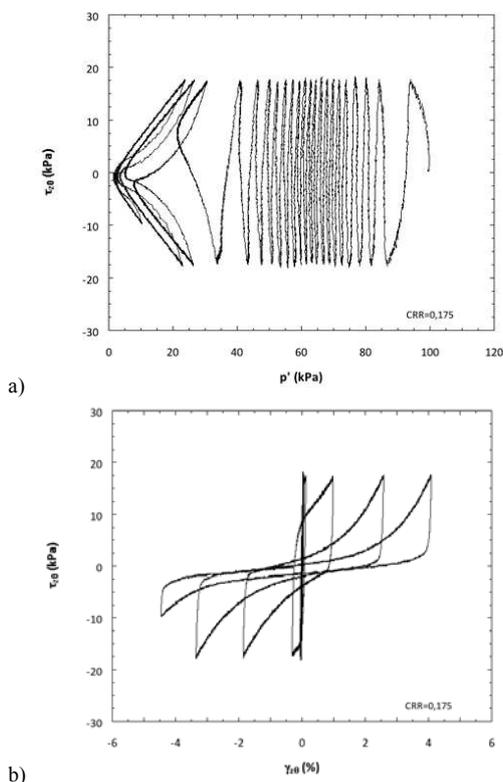


Figure 2. Results of a torsional cyclic test carried out at constant lateral stress on loose (40%-D_R) Coimbra sand (p'⁰=100 kPa and τ_{zθ}⁰=17.5 kPa): a) Stress-path; b) Stress-strain response (Araújo Santos 2015)

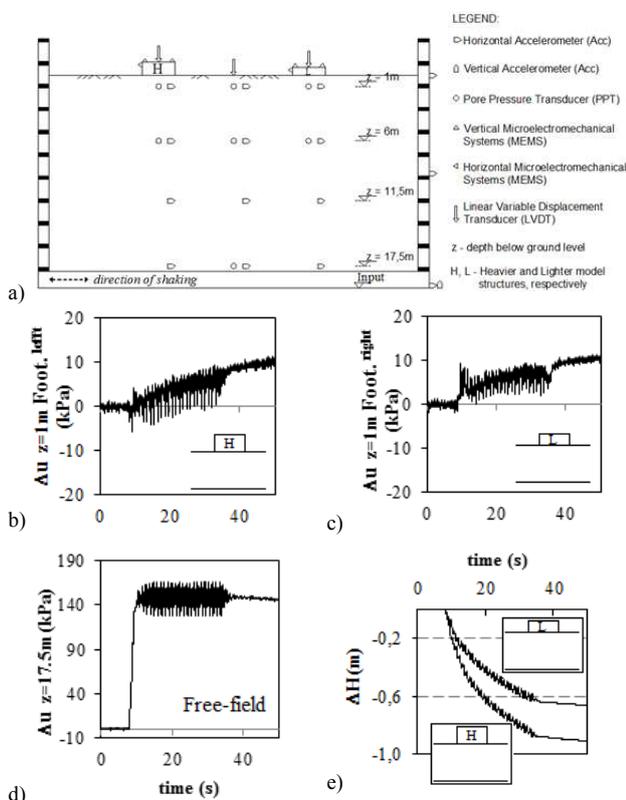


Figure 3. Centrifuge modelling of neighbouring shallow foundations built on liquefiable ground: a) model; b) excess-pore-pressure under heavier foundation H; c) excess-pore-pressure under lighter foundation L; d) excess-pore-pressure at the centre of the box; e) settlement of the foundations (Silva Marques et al 2014)

Figure 3 provides evidence of the excess-pore-pressure (epp) generation observed in the model and the settlements of the two shallow foundations resting on the liquefiable ground, during and after the seismic event. The pressures transmitted through the foundations basis, at prototype scale (50-g), were 58 kPa and 95 kPa for structures L and H, respectively. Firstly, it is clear that the epp build-up near the surface, under the shallow foundations (Figure 3b-c), is considerably slower than at deeper levels in the centre of the model (Figure 3d), where the influence of the shallow foundations is minor. However, epp dissipation starts soon after the end of the earthquake at the latter location, while epp keeps increasing under the shallow foundations. The heavier foundation (H) causes a more gradual variation of epp in its area of influence, while the lighter foundation (L) leads to a more irregular epp variation. Similar to what is shown in cases histories, settlements measured in the model for both shallow foundations are extremely large (Figure 3e). However, centrifuge test results show that settlements continue after the end of the earthquake. The influence that the neighbouring structures may have on each other will depend on the distance between them, their geometry and the pressure transmitted to the ground, detailed conclusions requiring solid numerical tools able to simulate the centrifuge model behaviour.

3.2. Numerical tools

Numerical tools have been used to expand the results of centrifuge modelling for variable field conditions, after calibrating soil models using element test results and validating the numerical analysis by simulating the observations obtained through physical modelling. Advanced numerical algorithms and soil models have been implemented on the bespoke finite element code (Grazina 2009) - UCGeocode2D -, which uses the full solid-fluid coupled formulation to compute pore pressures and soil movements due to seismic actions in order to simulate liquefaction phenomena. Numerical tools offer the largest potential for research findings to be transferred to the technical community and support the use of performance-based design in current earthquake geotechnical engineering design practice.

3.3. Innovative liquefaction analysis and planning tools

Reduction of society vulnerability to liquefaction effects requires the use of microscale design approaches for new constructions and for the retrofitting of existing critical infrastructure and the use of macroscale planning approaches for large new infrastructure developments.

Innovative liquefaction analysis focussing on the design of single buildings or infrastructure sections need to deal appropriately with earthquake randomness and unevenness. Indeed, there is limited benefit in producing detailed experimental data if the loading conditions employed in the tests (often with constant amplitude and frequency) are not representative of the real complex nature of seismic loading. Based on data from unconventional triaxial cyclic tests, Azeiteiro et al (2017b) suggest that the number of cycles required to the onset of liquefaction depends on the loading pattern followed in that particular test and not only on the magnitude of the imposed loading. Energy-based concepts were used to examine their ability to incorporate the irregularity of loading in the evaluation of field liquefaction potential. It was found that a unique relationship seems to exist between the normalised accumulation of dissipated energy per unit volume, ΔW/σ'₀, and the ratio of residual excess pore water pressure build-up, (r_u)_{res} (Figure 4). As the conclusions are similar for uniform or non-uniform loading, standard cyclic tests may be used for realistic evaluation of field liquefaction potential if interpreted using energy-based principles.

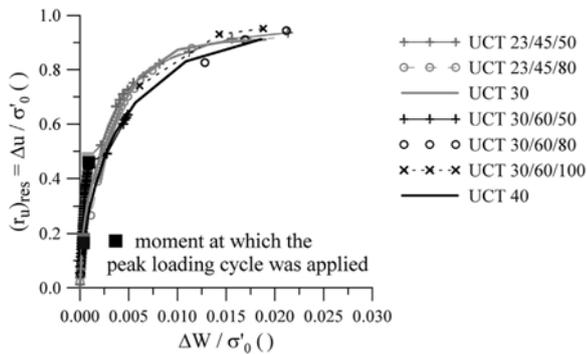


Figure 4. Residual pore water pressure build-up versus accumulation of dissipated energy per unit volume (Azeiteiro et al 2017b)

However, for large new infrastructure developments, which are often more vulnerable to liquefaction effects, the detailed design of sections has limited value during the early planning stages. This is worrying, as poor decision at an early stage can significantly increase the construction costs, the vulnerability and/or the exposure of the infrastructure to natural hazards. Therefore, decision support tools accounting for liquefaction and other natural hazards based on coarse information usually available at this stage can significantly improve the effectiveness of decision-making.

Taking into account that decisions in planning for transport infrastructure are the result of complex technical, political, and societal concerns, and usually involve large costs and limited public funding, an application of a simulated annealing algorithm to solve an integrated approach to high-speed rail (HSR) planning was developed (Costa et al 2016a). The algorithm proved able to successfully address the complexities imposed by real-world problems and offer a valuable tool for soundly-supported decision-making including multiple criteria.

Costa et al (2016b) present an application of the tool for the optimum selection of a corridor for the new Portuguese HSR at a planning stage, which substantially affects the construction costs. The formulation used includes the different components of the construction costs, the geometric constraints and connection conditions, in addition to the so-called natural barriers, namely protected land use and waterbodies. The obtained alignment (Figure 5) minimizes the construction costs, while complying with location, geometry, and land-use restrictions, showing its ability to systematically study trade-off opportunities and support decision making in similar planning problems. Robust solutions aiming at including the effects of natural hazards (e.g. earthquake-induced liquefaction), result in different optimum alignments that may have larger construction costs but should perform better during catastrophic events, allowing for enhanced informed decision making.

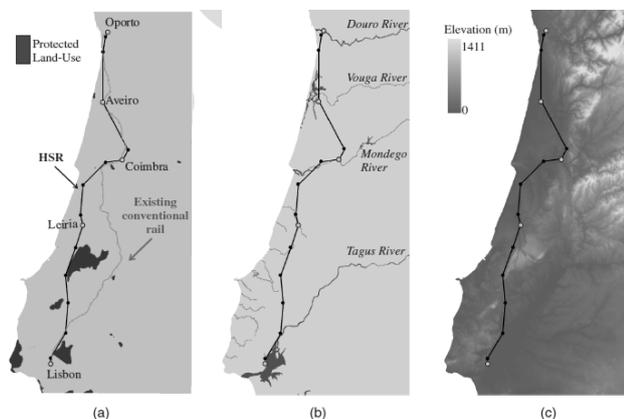


Figure 5. Plan view of HSR optimum alignment overlaid on the case study maps: (a) land use; (b) rivers; (c) elevation (Costa et al 2016b)

4. CONCLUSIONS

Earthquake-induced liquefaction is widely recognised as a serious hazard threatening modern societies, which are very reliant on extensive liquefaction-susceptible infrastructures and much less tolerant with failure. Recent events continue to prove that even if the death toll is usually smaller than with other seismic phenomena, such as tsunamis, the negative consequences of liquefaction on the natural, built, social and economic environments, as well as the extent of post-earthquake recovery are often more severe.

This paper describes the research carried out at the University of Coimbra, Portugal, with its international partners, focusing on the assessment and mitigation of earthquake-induced liquefaction hazards at different levels and using different tools. Element testing has been combined with centrifuge modelling to assess the basic soil behaviour and the actual mechanisms governing field performance of geotechnical structures. Numerical modelling is used to extend experimental findings and to predict more accurately liquefaction effects, so that the principles of performance-based design can be used in current design practice. New energy-based design approaches dealing with the irregularity of realistic earthquake loading and innovative planning tools for transportation infrastructures considering liquefaction and other natural hazards at a macro scale compatible with the detail of data available at this stage have been developed, allowing for better consideration of liquefaction effects in informed decision-making.

The research outcome demonstrates that society's vulnerability to the effects of earthquake-induced liquefaction is a serious issue that can only be effectively dealt with through the combination of different and frequently sophisticated experimental, numerical, analytical and planning tools selected according to the level of analysis and the specific problem under consideration.

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