

# Discussion: Cementation liquefaction remediation for existing buildings

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## Contribution by Felipe A. Villalobos

The authors present experimental results (Mitrani and Madabhushi, 2010) of great interest and importance for geotechnical earthquake engineers. Cementation techniques applied to loose and saturated soils under existing structures undergoing cyclic movement are assessed. Centrifuge test results using two different soil profiles are shown in terms of superstructure and soil settlements as well as in terms of excess pore pressures and acceleration amplification or attenuation. The authors conclude that cementation techniques are effective to reduce or avoid potential structural damage, caused by liquefied soil surrounding the ground improved, depending on the remediation depth and also on the liquefied depth.

This discussion comments on two issues. First, the authors use the term ‘structural settlements’ to refer to the sinking of the aluminium model used to simulate low-rise residential buildings. However, the term structural settlement is used in cases when a structural element fails within a building, causing the decrease in height of the building, which is not necessarily related to soil settlement. In other words, during an earthquake, for example, a reinforced concrete short column in the ground floor can fail severely by shear and compression. The concrete blows up and the vertical reinforced bars buckle, causing the descent of the structure leading to a structural settlement. For that reason, it is suggested to use the expression settlement of the structure or structure settlement.

The same occurs with the expression ‘structural accelerations’ that are used in Figures 11, 12 and 13, where not all of the accelerations correspond to the structure but also to accelerations on the base and in the soil.

The second issue is related to the selection of earthquakes and their sequence in testing. Two soil profiles without improvement and the same soil profiles with two different configurations of improvement are considered. The authors choose a sequence of seismic events in which the maximum acceleration increases from 0.1g to 0.48g. However, according to earthquake statistics (for example, data in United States Geological Survey (USGS, 2010), it is more likely to be the occurrence of a big shock (i.e. EQ4 but longer) followed by several aftershocks that are smaller

and shorter than the main one. The authors present references to support evidence of multiple earthquakes, but not the order. Therefore, it is unfortunate that information from EQ4, which is actually the most important earthquake to study (but longer), is not available to assess liquefaction in the presence of an improved soil. Therefore, the conclusion of adequate performance of this type of soil improvement should be restricted to earthquakes with maximum accelerations equal to or below 0.32g with durations shorter than 29 s, which correspond to 7.0 magnitude earthquakes according to Chang and Krinitzsky (1977) (see Table 3-2 in Kramer (1996)).

In addition, another point related to earthquake selection is the duration of the seismic event. The maximum input accelerations applied range from 0.1g to 0.48g, but the duration is almost the same for the earthquakes fired, from 27 to 30 s. In strong ground motions the duration can be as important as the acceleration amplitude in terms of structure damage, especially in liquefaction cases. In fact, a procedure to evaluate liquefaction potential developed by Seed and Idriss (1971) incorporated the duration of an earthquake in terms of equivalent cycles of ground motion. The number of cycles is correlated with the earthquake magnitude, which in turn can be correlated with the duration and acceleration amplitude according to the type of soil (in loose soils the seismic event should last slightly longer than in dense soils). For that reason it would be expected, for example, for a 0.25g earthquake to have a duration around twice that for a 0.13g earthquake. For instance, the earthquake EQ4 of 0.48g, not shown in the paper, should have a duration of around 2 min. There is also an effect of the type of fault rupture mechanism which can influence the earthquake duration. In general, for larger areas of interaction of seismic plates, it will take longer to release the accumulated energy. For that reason stronger earthquakes related to large magnitudes are likely to last longer than smaller seismic events.

## Authors’ reply

The following explanations are offered for the points raised by the discussor.

The first issue is the use in the paper of the term ‘structural settlement’ to refer to the settlement of the whole structure due to

failure of the foundation soil, rather than settlement of the structure caused by failure of individual structural elements. The authors feel that there is no ambiguity about the use of this term. It is explained in the paper that a very simple, single-degree-of-freedom frame structure is tested (Figure 1, Section 3.1). This structure is designed such that the frame walls will not undergo any failure during the earthquakes fired. This is because the focus of the paper is the geotechnical processes occurring in the foundation soil and the effect of these on the overall behaviour of the structure. In this context there should be no question that 'structural settlement' may be due to individual structural element failure. Similarly the authors feel that the term 'structural acceleration' clearly applies to the acceleration of the whole structure. However, in order to understand the structural accelerations, it is useful to compare them to the accelerations in the foundation soil and the input accelerations applied to the model. It is for the ease of this comparison that these accelerations are included in Figures 11, 12 and 13.

The second issue raised is the order and the choice of size of the earthquakes fired in the centrifuge tests. The authors appreciate the discussor's views on the selection of different earthquake magnitudes with respect to past occurrences of earthquakes. The order of the earthquakes is justified in Section 3.2. Once sand liquefies, its density and liquefaction resistance increases. Therefore the earthquakes in the centrifuge tests were fired in order of increasing size to try to minimise this effect on the sand behaviour, so that the results from different earthquakes could be compared easily. The sizes of the earthquakes fired were chosen to enable study of the performance of the remediation methods

when the soil does not liquefy and when liquefaction occurs to different depths. This was an area of particular interest in the research carried out. In addition, the centrifuge tests described in the paper were part of a larger research programme and the size and duration of the earthquakes were chosen to give consistency throughout. It was decided to only vary the magnitude of the earthquakes to reduce the number of variables. The authors agree that it may be a topic of interest to carry out further experiments in which the duration of the earthquakes is varied or stronger earthquakes are fired in different sequences.

#### REFERENCES

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