Liquefaction potential of hydraulic fills

Liquéfaction potentielle de remblais hydrauliques

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ABSTRACT

A container terminal is under construction at the Port of Barcelona. The quay, 1.6 km long, is made of concrete caissons founded on granular rubble mounds. The natural soil is a sequence of normally consolidated fine-grained deltaic deposits that reach a thickness of over 60 m. The quay was backfilled with hydraulic fill dredged from the seabed soils in front of the caissons quay, deposited by a rainbowing technique. A failure of a section of the quay was attributed to the static liquefaction of the hydraulic fill. This failure prompted a field campaign to identify fill properties and its liquefaction potential. Standard and seismic CPTU´s and Marchetti dilatometer tests were performed as well as a programme of laboratory tests. Available indices to estimate liquefaction potential were calculated and compared. One of the relevant issues raised after the quay failure was the ability of preloading to eliminate the liquefaction potential of the fill. In situ tests were performed on the fill before and after a large scale preload test. Liquefaction indices at those two stages are compared showing, in some cases, a reduction of liquefaction potential after preloading.

RÉSUMÉ

Un terminal de containers est en construction dans le Port de Barcelone. Le quai, long de 1.6km, est composé de caissons de béton s'appuyant sur des monts de débris granulaires. Le sol naturel est une séquence de sol deltaïque de grain fin normalement consolidé qui atteint une épaisseur de plus de 60m. Le quai a été remblayé par un remblai hydraulique dragué depuis le fond marin pris en face du quai de caissons et déposé par une technique arc-en-ciel. Une rupture d'une portion du quai a été attribuée à la liquéfaction statique du remblai hydraulique. Cette rupture a donné lieu à une campagne sur site pour identifier les propriétés du remblai et son potentiel de liquéfaction. Des essais CPTUs standards et sismiques ainsi que des tests au dilatomètre de Marchetti et un programme d'essai de laboratoire ont été réalisés. Les indices disponibles pour estimer le potentiel de liquéfaction ont été calculés et comparés. Un des aboutissements importants soulevé après la rupture du quai est la capacité de précharge du remblai hydraulique pour éliminer son potentiel de liquéfaction. Des tests in situ ont été réalisés sur le remblai avant et après un test de précharge à grande échelle. Les indices de liquéfaction de ces deux étapes sont comparés et montrent dans certains cas une réduction du potentiel de liquéfaction après précharge.

Keywords : liquefaction, soft soil, hydraulic fill, in-situ tests.

1 INTRODUCTION

The enlargement of the Barcelona Harbour, currently under way, includes the construction of a new container terminal. The large area involved (1.6 km x 0.6 km) extends between a new quay and the original shoreline; the mooring area is sheltered by the erection of a new breakwater. The quay has been under construction since 2005; it is 1600 m long and it is divided in two phases. Concrete caissons are used to form the quay structure, 25 caissons for Phase I and 12 caissons for Phase II. Somewhat different designs are used for the caissons in the two Phases but all are 40 m long. Caissons were placed on top of granular rubble mounds constructed previously.

Figure 1 shows the emplacement of the quay and the locations of the two quay Phases. The construction sequence for the quay and storage area was as follows:

- Dredging of the natural soil from -8m to -25m depth. The length of dredged trench was 65 m.
- Construction of the rubble mound using granular materials.
- Emplacement and filling of the caissons on top of the levelled rubble mound and subsequent caisson filling.
- Construction of the caissons backfill using hydraulic fill.

A typical quay section is presented in Figure 2.

On January 1st 2007, the caissons forming about 600 m of the quay length of phase I slid forward (Figure 1). Sliding took place along the interface between the rubble mound and the caissons. At the time, the hydraulic fill elevation was about +2.5 m above mean sea level. Subsequent investigations revealed that it was highly likely that the liquefaction of the fill played a key role in the triggering of the incident. The failure itself is not discussed in this paper; here we focus in the analysis of the liquefaction potential of the hydraulic fill and how it can be reduced. This is a very important issue as some of the remaining material is to be left in place during the reconstruction of the quay. Also, it is unavoidable, in a harbour environment, to use again to some extent hydraulic fills in the reconstruction works.

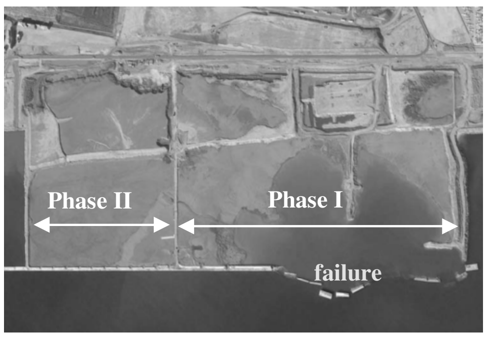

Figure 1. Aerial photo of phase I and II of the container terminal. Caisson failure partially affected Phase I (Courtesy of Barcelona Port Authority).

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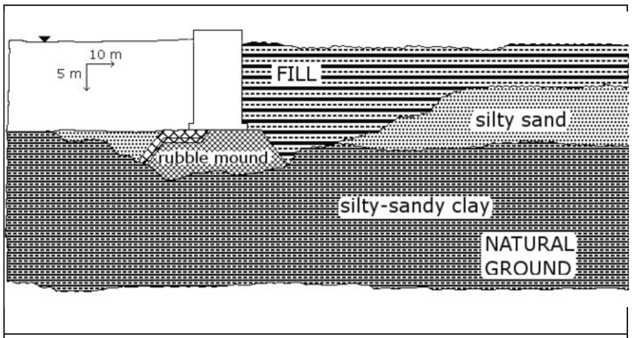

Figure 2. Cross section of caisson and backfill

In the paper, a number of liquefaction criteria are used and compared in the characterization of the hydraulic fill. It will be shown that some of those criteria did indicate a significant liquefaction risk.

As part of the ground improvement measures adopted to reduce subsequent settlements of the container area, an intensive preloading programme was undertaken, assisted by the installation, in some zones, of prefabricated vertical drains or gravel columns. In principle, preloading could also reduce the liquefaction potential of the hydraulic fill. This was examined by performing a preload test in a specially instrumented area. The paper discusses the change in liquefaction potential as revealed by the comparison of CPTU tests performed before and after preloading.

2 PROPERTIES OF NATURAL SOIL AND FILL

The fill material was obtained by dredging the natural soil and placing it in designated areas by rainbowing. The rainbowing technique is the name given by dredging contractors to the practice of spraying large quantities of dredged material from a floating vessel on to reclaimed land. The state of the dredged material being placed is quite liquid and the excess water is drained as the soil sediments consolidate. Obviously the fabric of the hydraulic fill will be very different from that of the original natural material given the very different deposition processes:

- The natural deltaic material was deposited slowly roughly 3000 years ago (Manzano 1986) as part of the classic processes of delta formation and regression. Consequently, sediment layers are thin with varying grain sizes.
- The fill was deposited as part of a massive backfill operation in a very short time (a few months). It produces unstructured thick layers and very soft soils.

2.1 *Identification properties*

During the site investigation, a soil identification program of the hydraulic fill (the part which remind stable of Phase I and Phase II) and the natural ground was performed. Data was obtained concerning grain size distribution, fines content, plasticity index, natural and dry density, specific weight of solids and void ratio. The main properties of the fill are given in Figure 3. They were very similar to those of the natural ground. Dry densities lie in the range 1.4-1.7 Mg/m^3 and water contents are close to the liquid limit. Soils classify as low plasticity clays and silts or, alternatively, as clayey or silty sands. The upper levels of the fill, above the ground water level, are desiccated to some extent.

2.2 *CPTu and Marchetti dilatometer data*

Consider in Figure 4 a comparison of the point resistance and excess pore pressure in one of the CPTu's performed. The natural soil shows a closely spaced sequence of alternating layers. The fill is characterized by a thick homogeneous mass which reacts as a contractive material. The soil index parameter I_c and the friction ratio provide a criteria to rate the sensitivity of the soil (Robertson & Wride 1998) against liquefaction. As an example, data from CPTu 6a12 was used to plot Figure 4. Fill material appears to be fundamentally sensitive, unlike the natural soil.

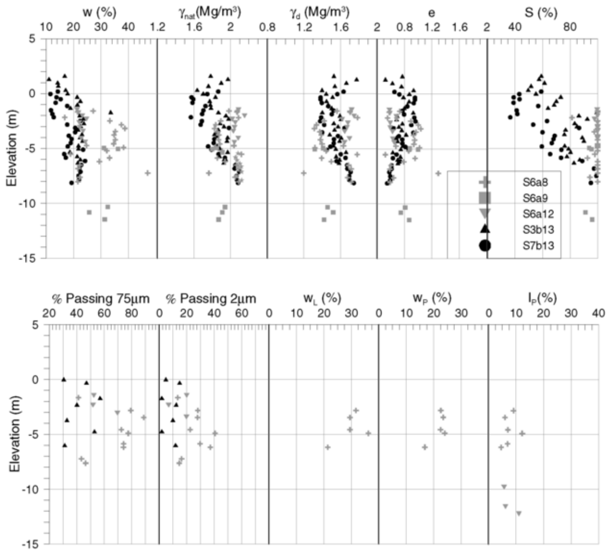

Figure 3. Fill properties in Phase I ("a" boreholes, grey symbols) and Phase II ("b" boreholes, black symbols).

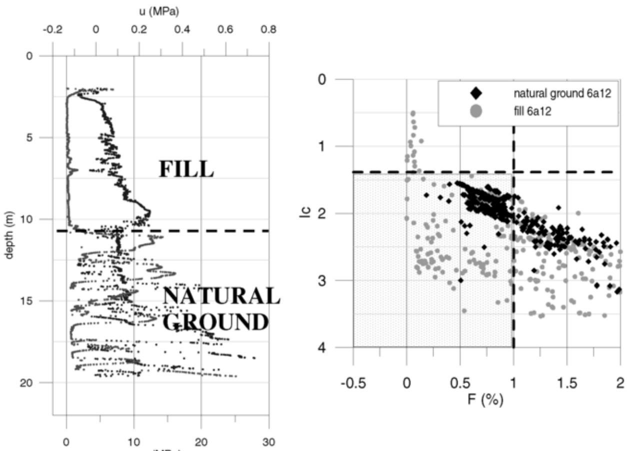

Figure 4. Results of the CPTu 6a12 test. The shaded area indicates sensitive material.

Seismic (SDMT) and regular (DMT) Marchetti dilatometer tests provided additional data on the hydraulic fills and the underlying natural soils. The derived undrained strength parameters seems to follow accurately the relationship c_u=0.25σ'v in the fill as well as in the natural ground. Shear wave velocities, V_s, also increased with vertical effective stress in an approximately linear manner. It was also found that the soil identification parameter (I_d) from DMT was consistent with the analogous parameter I_c from CPTu tests.

3 LIQUEFACTION POTENTIAL

3.1 *Liquefaction criteria*

Several liquefaction criteria are available. Some of them rely only on identification properties such as plasticity indices and clay content (Modified Chinese criteria – Seed et al. 2003, and Andrews & Martin 2000). Available laboratory data for fill and natural soil allowed the application of these criteria; see Figure 5. Regarding Figure 5a, some locations within the fill and natural soil fall in "zone A" which indicates a "potentially liquefiable soil". Zone B is a possible liquefiable zone if further testing confirms it. The application of Andrews & Martin (2000) criterion (Figure 5b) is not very conclusive. It indicates that further studies are required.

The criterion derived from CPTu data, reported by Robertson & Wride (1998), is based on the comparison of I_c and F parameters. Figure 6 shows the variation with depth of the calculated F and I_c values for cone test 6a8. Only a few points in the fill and the natural soil (circled in the Figure) satisfy this liquefaction criterion.

An alternative criterion, proposed by Senneset & Janbu (1985), requires the calculation of the parameter B_q which is defined as the ratio between the excess pore pressure and the corrected tip resistance. When $B_q > 1$ the pore pressure increases faster than the point resistance and liquefaction conditions are met (Shuttle & Cunning, 2007). Figure 7 shows the variation of B_q with depth for cone test 6a8, within the fill material. The criterion shows now larger areas of potentially liquefiable fill.

Criteria for soil liquefaction based on the data from DMT and SDMT tests have been reported by Monaco et al. (2005) and Andrus et al. (2004) respectively. In the first case the criterion combines the horizontal stress index (K_D) and the Cyclic Stress Ratio ($CSR=0.65(a_{max}/g)\cdot(\sigma_{v0}/\ \sigma'_{v0})\cdot r_d$). This criterion does not predict fill liquefaction for the CSR derived form expected design earthquake in Barcelona (a_{max} = 0.07g). SDMT allows the application of an alternative criterion based on the consideration of the shear wave velocity V_{s1} (V_{s1} is the corrected shear wave velocity for overburden stress intensity) and the CSR (Figure 8). In this case the fill appears to be a liquefiable soil.

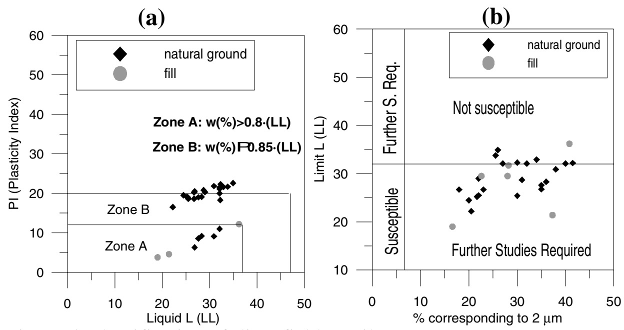

Figure 5. Identification of 'liquefiable' soil types.
(a) Recommendations by Seed et al. (2003) (b) Criterion of Andrews & Martin (2000).

3.2 *The effect of preloading*

Preloading and vertical drainage are procedures that can reduce liquefaction risk. A preloading test was performed and CPTu tests before preload and after the full consolidation of the fill and natural ground were carried out. Data on similar locations are compared in Figure 9 in terms of the B_q index. The improvement of the fill is readily observed. B_q values are substantially reduced by preloading. The effect is less marked at depth (natural soil) because of the reduction in the intensity of the stress increase induced by the preload.

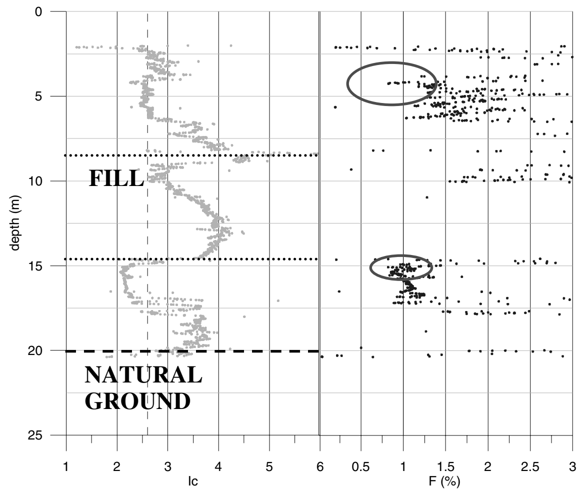

Figure 6. Application of (I_c & F) liquefaction criteria for CPTU 6a8. Circled points indicate potential liquefaction

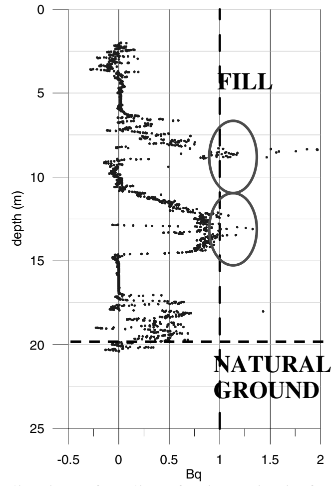

Figure 7. Application of B_q liquefaction criteria for CPTU 6a8 test. Circled points indicate potential liquefaction.

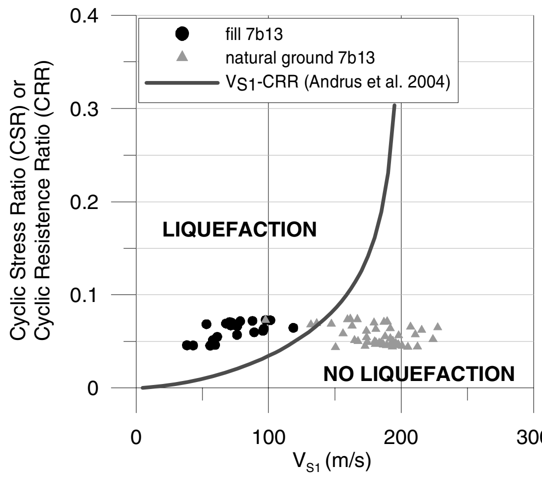

Figure 8. Assessment of the potential for liquefaction based on SDMT results. Test 7b13.

4 DISCUSSION

Since the basic identification of the natural soil and fill is essentially the same, the Seed et al. (2003) and the Andrews &

Martin (2000) criteria (Figure 5) are not expected to discriminate between the two layers. The caisson failure however pointed towards the fill liquefaction as the main reason for the caisson sliding on its base. The (I_c, F) criterion, based on CPTu data provides only a slight indication of liquefaction risk on the fill and the natural soil (Figure 6). Moreover, no higher risk is associated with the fill, a result which probably does not reflect reality. The simple B_q criterion, based also on CPTu data, indicates a more definite risk of liquefaction within the fill. The Seismic Marchetti Dilatometer (SDMT) provides data to characterize the risk of liquefaction under seismic loading. Its application to the man made fill indicated a substantial liquefaction risk. However, the criterion based on the K_D parameter, for the same earthquake acceleration, resulted in a "no risk" assessment.

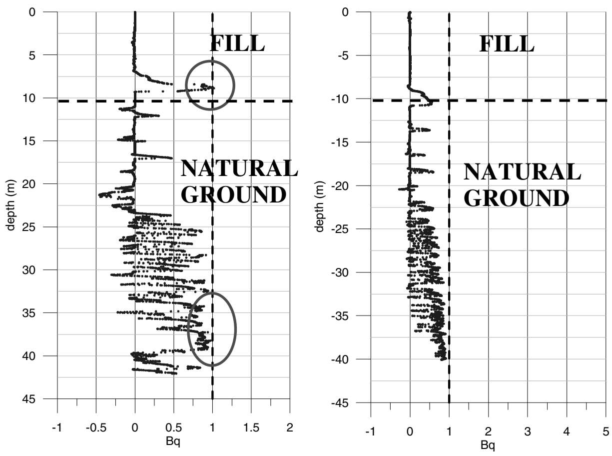

Figure 9. B_q values for cone test CPTu-5dp before preloading (left) and after preloading (right).

Preloading induces a substantial reduction of the B_q value within the fill, a satisfactory result which is readily reflected in the pore pressure response of the densified fill.

It is felt, however, that some of the available liquefaction criteria did not identify properly the high liquefaction risk of the hydraulic fill. This risk was also apparent when low intensity repeated tamping was applied to the surface of the fill (Figure 10), small mud volcanoes developed immediately. Several reasons may explain the high susceptibility of the fill: the silty nature of the fill (Yamamuro & Lade 1998), the young age of the sedimented soil, the rainbowing technique which probably leads to open soil structures (and perhaps to some gas trapped) and the thick homogeneous layers of relatively low uniform permeability, created by this construction procedure.

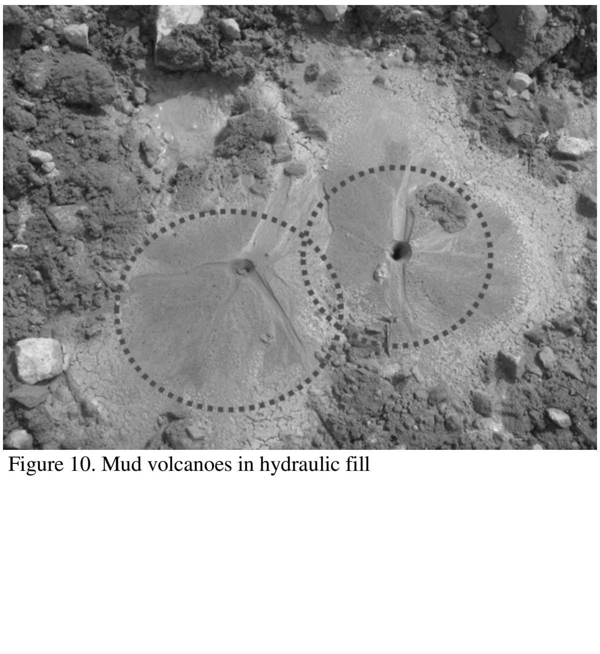

Figure 10. Mud volcanoes in hydraulic fill

5 SUMMARY AND CONCLUSIONS

Failure of a caisson quay, triggered by the static liquefaction of the hydraulic fills, motivated a field investigation aimed at establishing field criteria to identify liquefaction potential. Hydraulic fills in this case were built by means of rainbowing technique. Standard and seismic CPTU´s and Marchetti dilatometer tests were performed on the hydraulic fill. Several liquefaction indices were estimated and compared for both the hydraulic fill and the underlying normally consolidated natural soil. The effect of preloading was also examined by comparing liquefaction indices, before and after preloading. The experience gained in this case history highlights the risk of static liquefaction of hydraulic fills and provides an evaluation of current liquefaction indices as well as an estimation of the beneficial effects of preloading with respect to liquefaction risk.

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