A comparison of soil improvement achieved using different vibro methods

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ABSTRACT

A liquefied natural gas (LNG) plant is currenlty being constructed on a hydraulic fill in El Musel Port (Gijon, Northern Spain). The hydraulic fill is mainly composed of marine sands dredged from nearby locations, and it was placed on site using the rainbow and pipeline discharge and the bottom dump methods. The dynamic loads imposed by some of the plant elements suggested the need to conduct soil improvement using vibro-methods. To identify the most suitable method among those available, several options (including vibro compaction, and vibro-substitution using the bottom and top feed methods) were considered in a trial field.. Monitoring and control methods included the use of geophysical methods as well as DPSH and SCPTU tests. This paper presents the results of the monitoring conducted at such trial field before and after the different treatments were employed, and it illustrates the degrees of improvement achived using each one.

1. INTRODUCTION

"Vibro" methods (with or without addition of stone) have been commonly employed in practice for densification of granular soils since the 1930´s (Slocombe et al., 2000). The main uses of the technique with granular soils have been to densify the soil, which leads to increasing stiffness and strength (hence reducing settlements and increasing stability; see e.g., Hughes et al. 1975; Hughes & Withers, 1974) and also to reduced liquefaction risk and reduced ground deformations during seismic events (see e.g., Adalier & Elgamal, 2004). The technique has been proven to be effective without addition of stone in soils with up to 15% fines (and less than approximately 2% fine silts to clays); and the addition of stone is usually required to increase the densification efficiency in soils with higher fines contents (Slocombe et al, 2000). In addition to soil type and type of stone added, the results obtained with the technique depend mainly on the total energy introduced into the soil by the vibrator (which itself depends on grid spacing, vibrator type and power, number of repetitions, etc.), and also on the quality of workmanship and on personnel's experience (Slocombe et al, 2000).

Because of the complexity of phenomenon and the number of factors involved, and despite some very interesting contributions and case histories (see e.g., Slocombe et al. (2000) and references therein), there is not much guidance in the literature on how to assess the degrees of densification that can be achieved in a specific project. For that reason, it is usually necessary to resort to the *observational method*, so that several improvement alternatives are tested to see how they perform at each site.

In this paper, we report the results of a recent experience of application of vibro-methods in a hydraulic fill made of marine sands (with a varying but generally small amount of silt) that were dredged from nearby locations. Three vibro-methods for soil improvement are compared: *(i)* stone columns executed by the water-flushing technique ("wet method") with stone added from the surface ("top-feed"); *(ii)* stone columns ("wet method") with bottom-feed delivery of stone; and *(iii)* vibro-compaction (with addition of the same sand to increase efficiency and to maintain site level). Three field tests were developed (one for each treatment type indicated above) and a series of in-situ tests were employed to compare the conditions before and after treatment. (In-situ tests included dynamic penetration using DPSH penetration tests; seismic cone penetration tests or SCPTU; and seismic wave velocity analyses.)

2. DESCRIPTION OF THE PROJECT

In this paper, we present results of a field tests conducted at a reclaimed port facility constructed by the hydraulic fill method (mainly using "rainbow" and "pipeline" discharge methods, as well as "bottom dumping" from barges; for a description see Lee et al. (1999) and Lee (2001)). The purpose of the project is to construct a Liquefied Natural Gas (LNG) regasification plant for ENAGAS in El Musel Port (Gijon, Spain). (ENAGAS is the Technical Manager of the Gas System and Common Carrier for the high pressure gas network in Spain; for further details, see http://www.enagas.es). Photo 1 shows an aerial photograph with the specific location of the project.

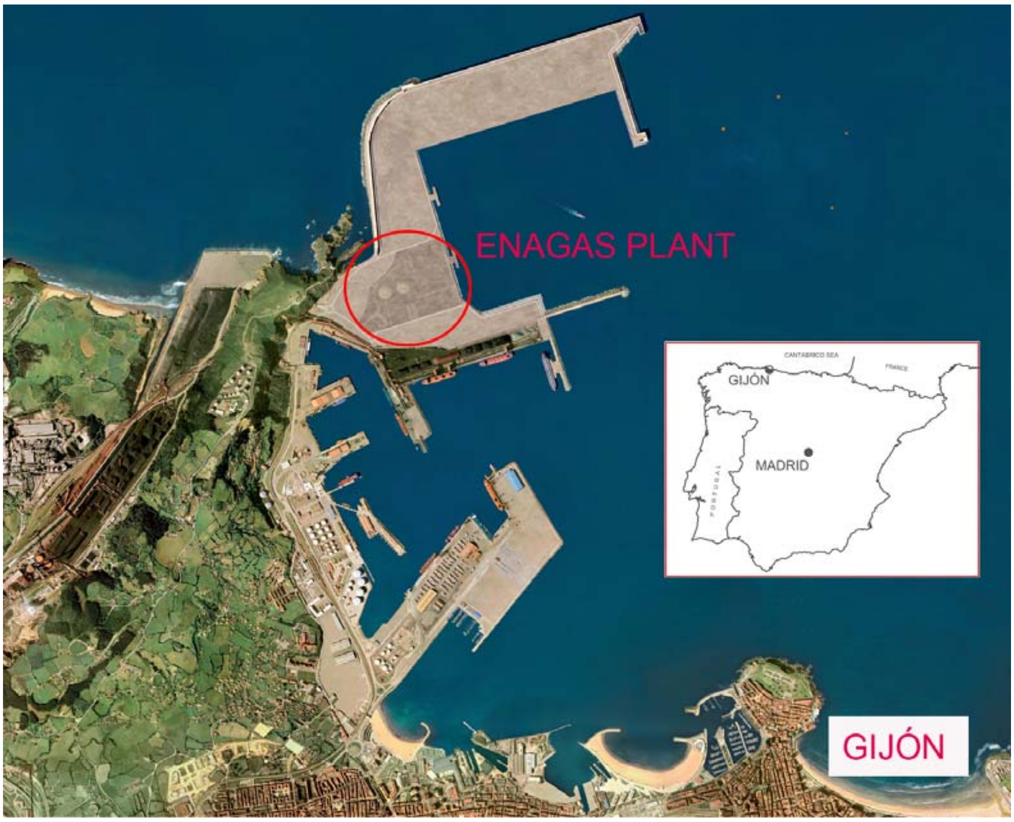

Photo 1 : Location of the project

The material used for the hydraulic fill is a marine sand obtained by dredging from nearby locations. The sands have a variable silt content (although in most cases it is smaller than 30%), and particles are mainly composed of shell fragments. The composition and properties of the fill sand are discussed in more detail in a companion paper (see Roman *et al.* (2012) "Preloading of a hydraulic fill for foundation of LNG tanks", Proceedings of ISSMGE - TC 211 International Symposium on Ground Improvement IS-GI Brussels 31 May & 1 June 2012.) Table 1 shows a typical column of soil at the site, whereas Photograph 2 illustrates the aspect of the hydraulic fill as observed at a temporary cut in the same site. (Note that some compositional variability can be observed due to the type of materials employed, as well as the variability of construction methods; for further discussion of characteristics of hydraulic fills, see Witman (1970), Sladen & Hewitt (1989).)

Table 1 : Typical soil column at the hydraulic fill site

Material	Depth <m>	SPT <N30>	**N_{20} DPSH**	CPTU Qc <MPa>	Water content ω <%>	Density γ_d <t/m^3>
Hydraulic Fill (Level I)	0 – 3,5	10	7	7	8	1.44
Hydraulic Fill (Level II)	3,5 – 10	5	3	5	23	1.68
Hydraulic Fill (Level III)	10 – 20	12	10	8	23	1.68
Cuaternary (Level IV)	20 – 25	20	20	10	23	1.70
Bedrock	> 25	R	R	R	-	-

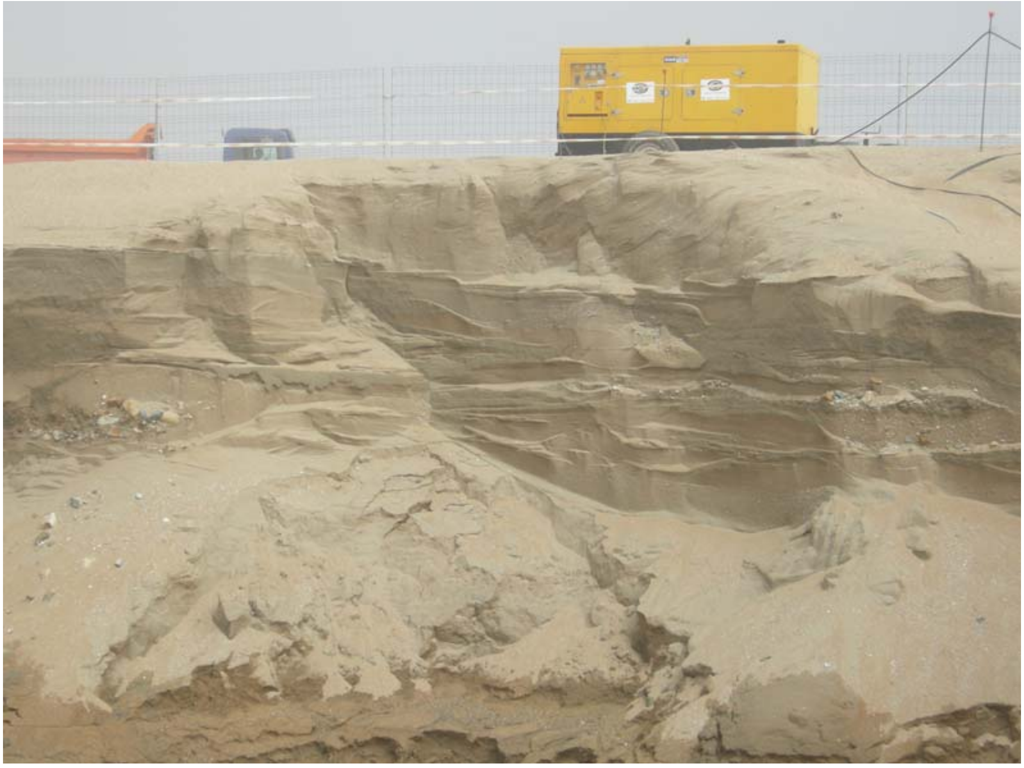

Photo 2 : View of typical soil column

To provide an adequate foundation for the tanks, preloading was selected as the main ground improvement technique (see Roman et al. (2012) for details); however, there were some locations in which more strict requirements for the foundation material were specified, such as areas where critical structures (e.g., a very high torch) or dynamic equipment (such as compressors, etc.) were going to be founded. The vibro-compaction and vibro-replacement methods for ground improvement were considered for such locations. To make a selection among the available options, a trial field was designed at the compressor's area to compare the degrees of improvement achieved by three different "vibro" methods: *(i)* stone columns constructed with the "wet" method and top feed; *(ii)* stone columns constructed with the "wet" method and bottom feed; and *(iii)* vibro-compaction (with addition of the same sand with which the fill is constructed). The details of the trial field design, as well as the methods employed and results obtained, are presented below.

3. GROUND IMPROVEMENT BY VIBRO METHODS

To compare the relative performances of the different vibro-methods employed, three trial fields (or test sites) were developed, and seven (7) treatments of each type were conducted at each site (the central "column" was constructed first). Treatments were situated within a triangular grid with a theoretical area replacement ratio of approx. 12% (a 80cm "target" diameter for treatments, and 2,15m distances between centres). Control tests conducted at the sites included continuous dynamic penetration values (using DPSH N20 values); (seismic) cone penetration values (qc of SCPTU); and measurement of seismic wave velocities (cross-hole). The three trial fields were developed adjacent to each other to minimize the likelihood of changes in the underlying materials, and also to reduce the need for boreholes in the development of a "continuous" profile using the cross-hole method. Figure 1 shows a plan view of the theoretical locations of treatments at each of the three test sites, and also of the geotechnical tests conducted at each site (preliminary; before treatment; or after treatment). In the discussion below, Test Site 1 corresponds to stone columns executed with the "wet" bottom-feed method; Test Site 2 corresponds to stone columns executed with the "dry" top-feed method; and Test Site 3 corresponds to vibro-compaction (with sand addition).

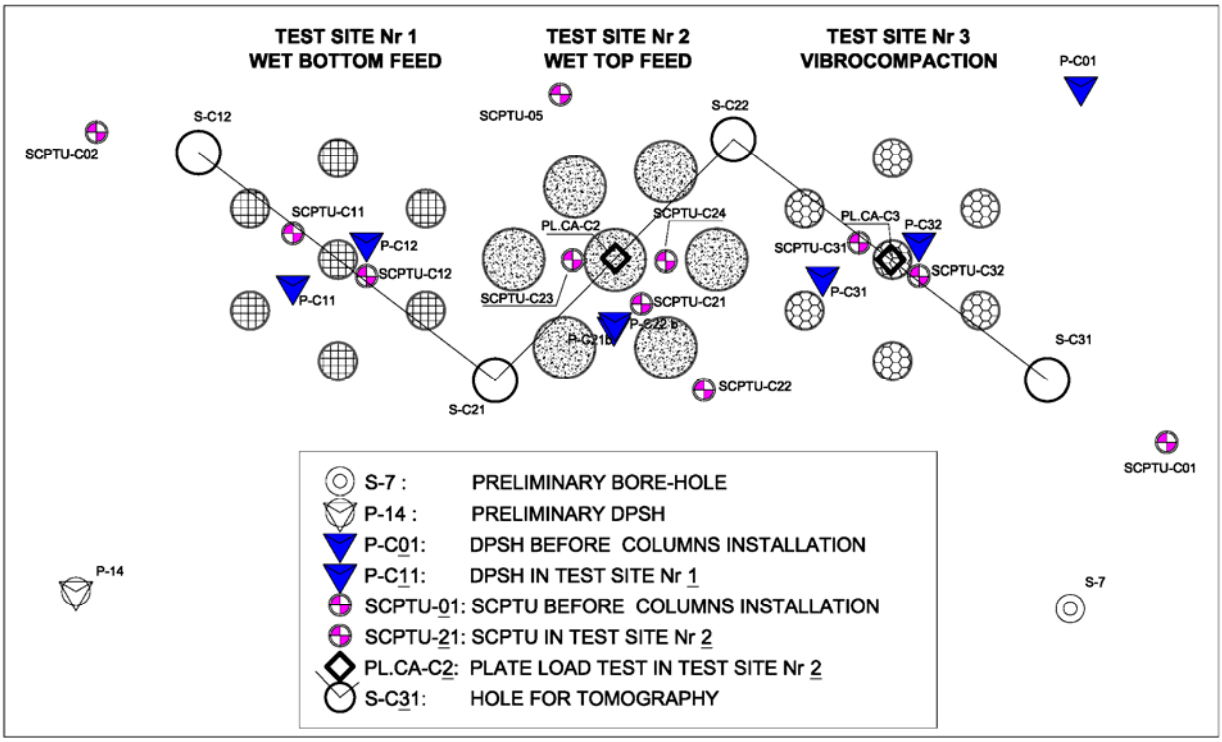

Figure 1 : Location of treatments and of control tests at test sites

4. COMPARISON OF FIELD TEST RESULTS

By comparing the situations before and after improvement, it is possible to assess the degree of improvement achieved by each of the methods considered at Tests sites 1 to 3.
For instance, Figure 2 presents a comparison between DPSH N_{20} dynamic penetration values measured before and after treatment for each of the test sites. (There were two DPSH available before treatment ---one at the lower-left corner and one at the upper-right corner---; since their results are very similar, they have been considered as representative of “before treatment” conditions in all test sites.) It can be observed that the vibro-treatments produce a significant increase in the compacity (as measured by penetration resistance) of the fill, and they are also shown to produce a more “homogeneous” material in the vertical direction. (Note that the increase with depth is less significant in the case after treatment). DPSH N_{20} values in the order of 15-20 are obtained in all cases (there seems to be no large difference between methods) and, in some cases, even higher values have been observed for tests conducted at a very short distance to the treatment. (Such values would correspond to SPT N-values in the order of 25-40, which suggests that a “medium” to “dense” sand condition is being achieved.)
Similarly, Figure 3 presents the comparison of SCPTU tip resistances measured before and after the tests. In general, it can be observed that the three tests available before the ground improvement (one on the upper-left part; one on the top; and one n the lower-right part) show very similar results, hence suggesting the homogeneity of fill initial conditions. (Note also that cone tip resistance values agree with other values reported in the literature for other hydraulic fill projects; see e.g., Lee (2001)) As in the DPSH case, it seems clear that the ground improvement techniques have the consequence of producing a vertical homogenization of ground conditions, and also that tests that are closer to the “as-built” column location tend to give higher values of tip penetration resistance. (Increases of qc tip resistance values ranging from 100% to 500% ---and probably more in some cases—have been obtained in most cases; such values compare well with values presented in the literature for other case histories (see *e.g.*, Slocombe *et al.* (2000))

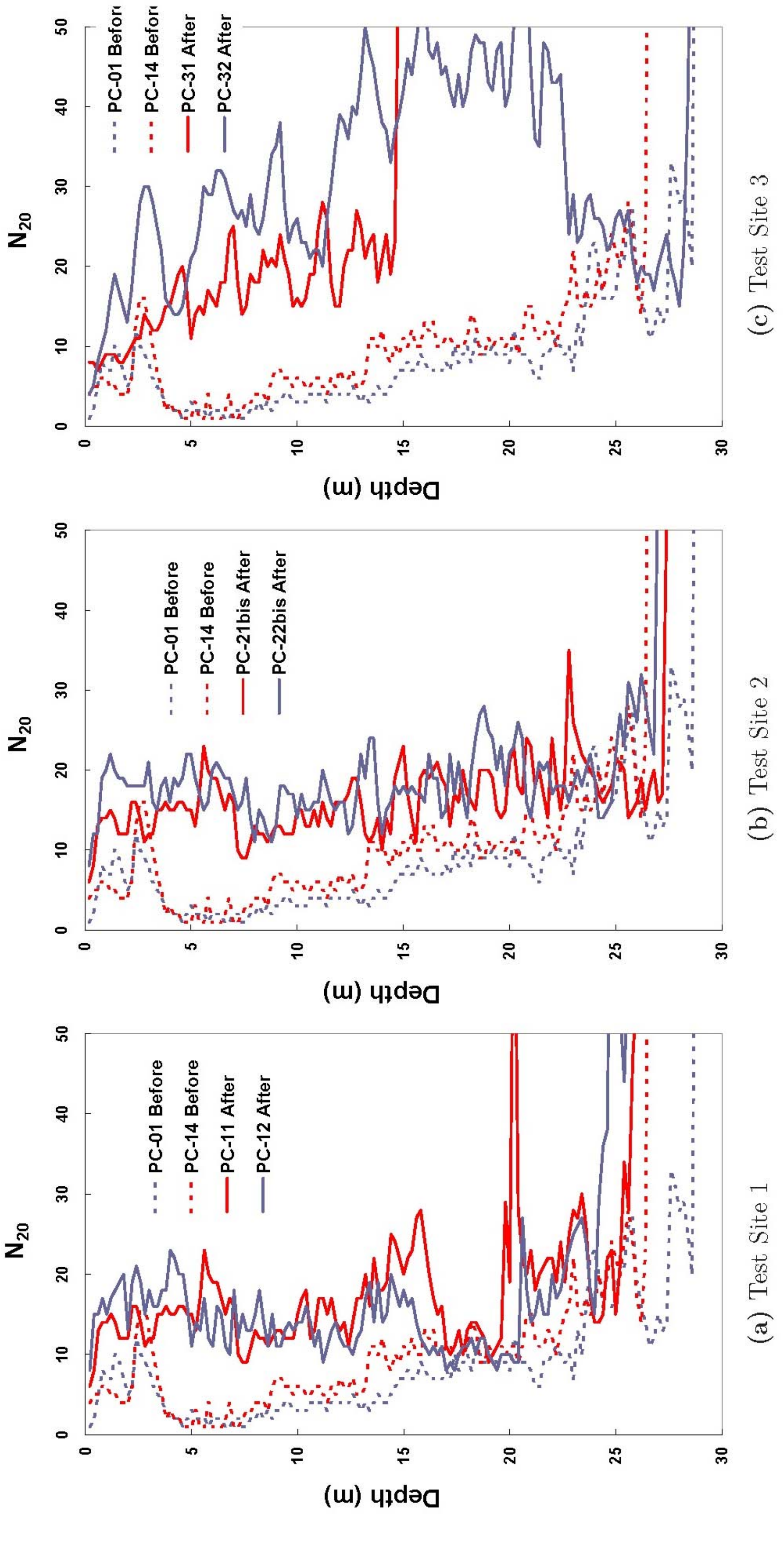

Figure 2 : Comparison of DPSH values

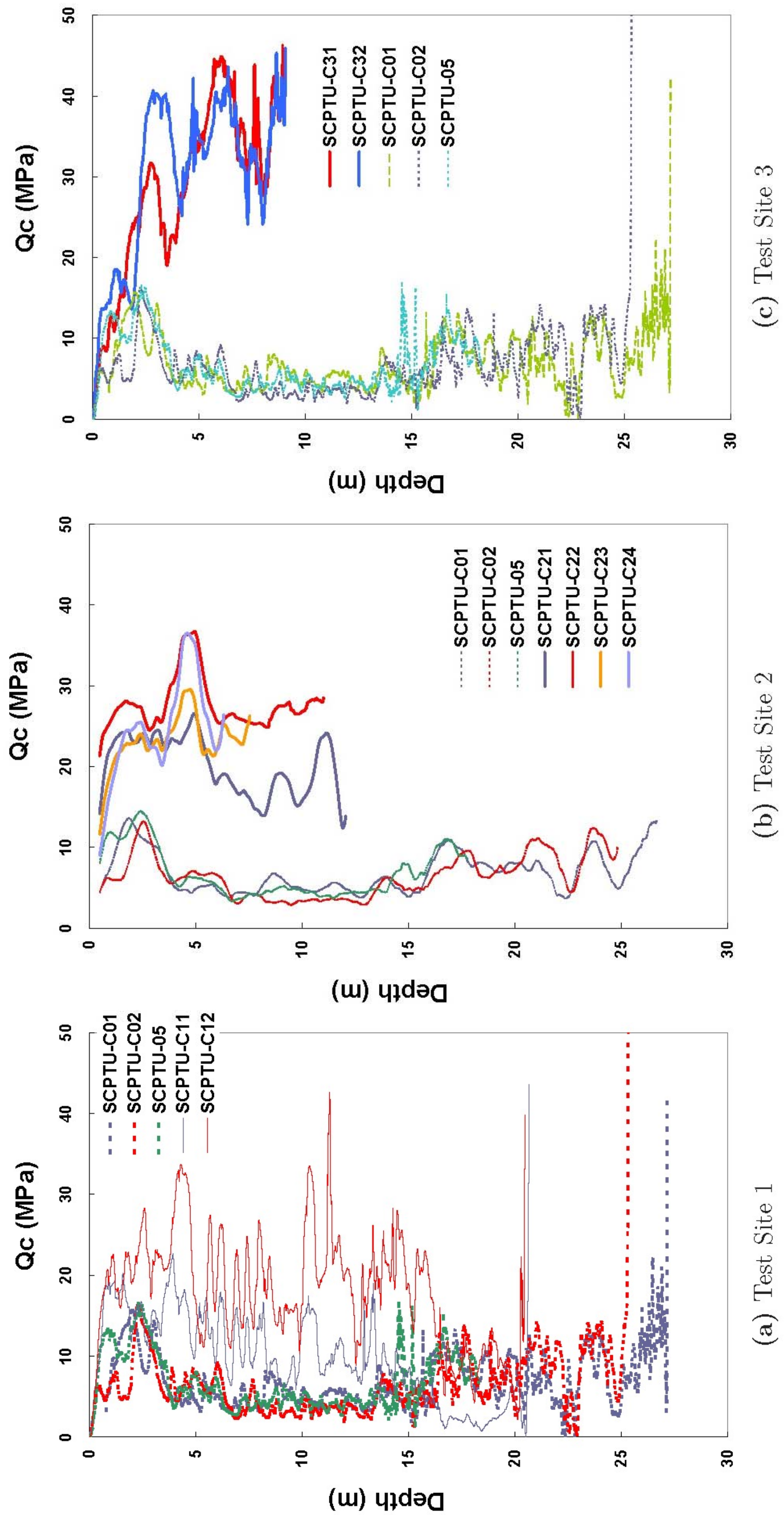

Figure 3 : Comparison of SCPTU tip resistance

Figure 4 presents the results of seismic velocities of S-waves measures with the SCPTU. It can be observed that available data again suggest that there is a significant increase (in the order of 25% to 100% higher, with most common increases in the order of 50-100%) of measured wave velocities after treatment, and also that velocities measured across the actual "columns" are higher.

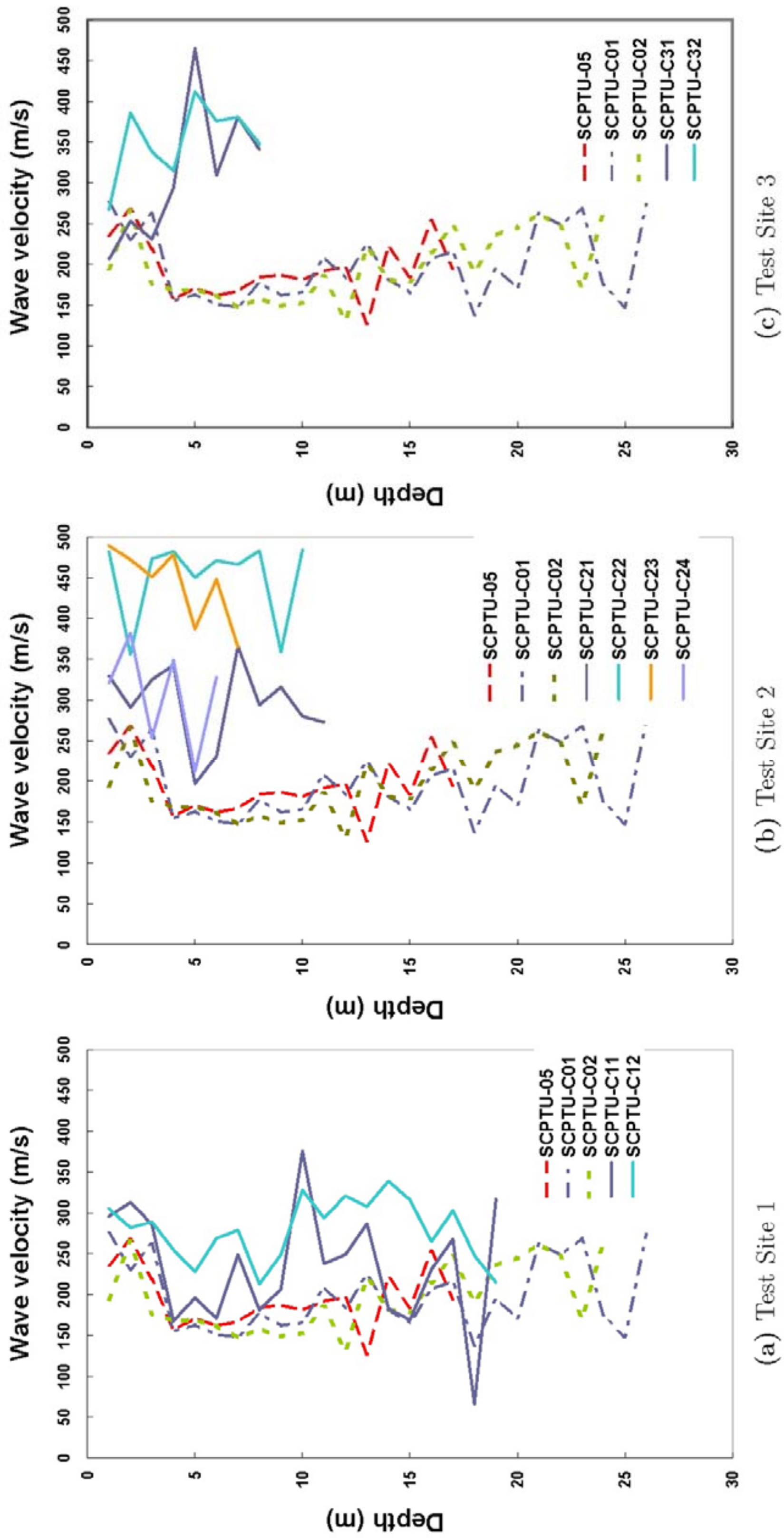

Figure 4 : Comparison of wave velocities (vs) measured with SCPTU

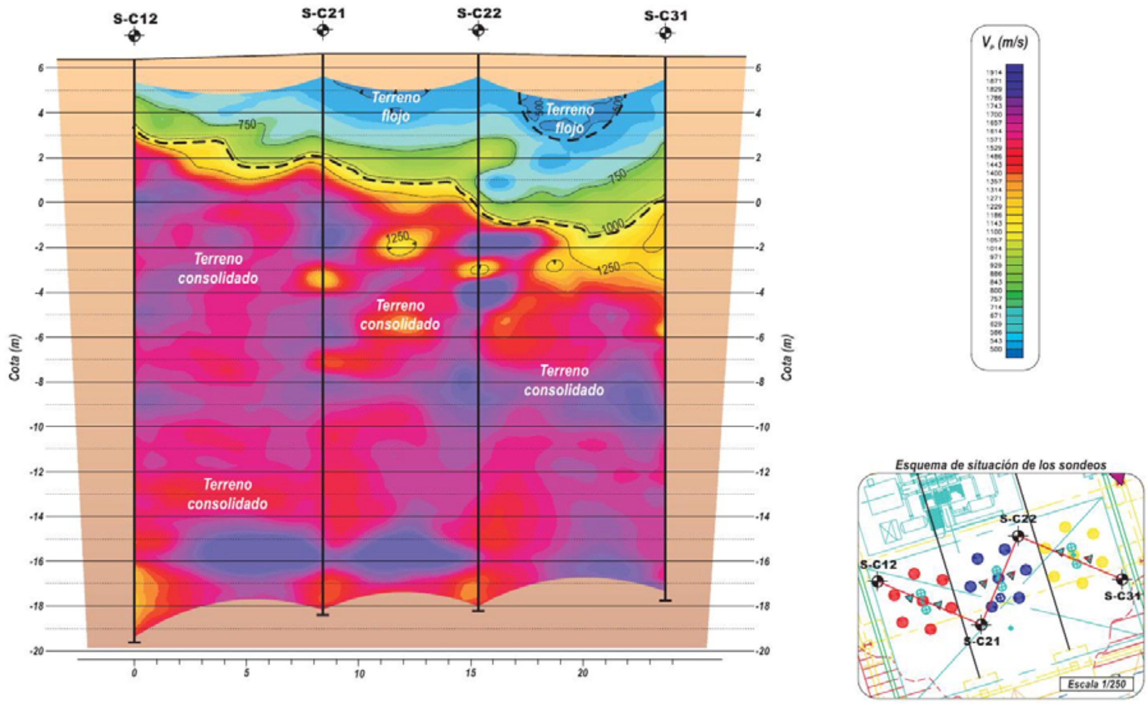

Figure 5 : Profiles of seismic velocities (vp) across test sites (GEOCISA-ICT, 2010)

Figure 5 shows the result of a seismic tomography (using the cross-hole method) that has been developed employing the boreholes indicated in Figure 1. It can be noted that, in all cases, a “loosened” zone remains at locations close to the surface. (In this case, and to fulfil the required design specifications, the surface had to be excavated and replaced by a granular and compacted material.) . It is also observed that areas treated with stone columns tend to produce higher seismic velocities than those observed in the area treated with vibro-densification (with sand addition). Similarly, and although differences are not very high, results suggest that the bottom-feed method employed at Test Site 1 provides higher (and more uniform) seismic velocities. (Note the “gaps” observed at the location of the bottom feed treatment at Test Site 2.) This is probably due to the higher diameter control achieved with the bottom-feed method (in agreement with previous observations of Slocombe et al. (2000), our experience suggests that a more controlled and uniform shape is obtained), although more research is probably needed on this topic to verify this observation.

5. CONCLUSIONS

This paper presents the results of recent field tests executed in El Musel Port to select the “best” vibro-method for soil improvement (among those available) in the context of a LNG regasification plant project. The need for vibro methods was because some parts of the plant (compressors, torch) needed special requirements for their foundation material, so that the preloading technique that was employed in the rest of the plant (see Roman *et al.* (2012)) was considered not sufficient. To compare the relative performances of the different vibro-methods employed, three trial fields (or test sites) were developed, and seven (7) treatments of each type were conducted at each site. Treatments were situated within a triangular grid with a theoretical area replacement ratio of approx. 12%. The vibro-methods considered for soil improvement were: *(i)* stone columns constructed with the “wet” method and top feed; *(ii)* stone columns constructed with the “wet” method and bottom feed; and *(iii)* vibro-compaction (with addition of the same sand with which the fill is constructed).

Tests conducted at the site to verify the degree of improvement achieved included dynamic penetration (DPSH) tests; seismic cone penetration (SCPTU); and seismic wave velocity measurements (using the cone and also the cross-hole method). Results indicated that (except for a limited depth in the vicinity of the surface, the extent of which was dependant on the type of method employed) a significant improvement is achieved by the use of vibro methods in this case, and that such achievement has been verified by all testing methods employed. In addition, they show that the soil densification achieved by the vibro methods has the additional advantage of being quite homogeneous in the vertical direction. (The densification effect decreases as the distance to the treatment increases.) In addition, the seismic tomography obtained by the seismic cross-hole method suggests that the improvement obtained by the bottom-feed method is more "uniform" than that obtained by the top-feed method. (This is probably a result of the more "uniform" columns that are obtained due to the better diameter control provided by the bottom-feed method.)

Based on the results available from the test sites, both types of stone columns were considered acceptable to provide the required "target" material, and the top feed approach was selected in this case on the basis of economic considerations. (The vibrator employed was the Pennine 400 vibroflot; see http://www.penninevibropilin.com for details.) Furthermore, to avoid the "loosened" zone at the surface, columns were constructed from the "original" ground surface; in that way, the "looser" material at the surface was later excavated and substituted by a compacted granular material. (The bottom of the excavation was also compacted.)

Finally, it should be emphasized that conclusions presented herein can only be taken as guidance in similar projects since, as explained above, there are multiple variables that influence the performance of ground improvement techniques by vibro methods.

6. ACKNOWLEDGEMENTS

FLUOR is the project manager of the overall works. The main civil engineering contractor at the site is a Joint-Venture between "Flota Proyectos Sigulares" (FPS) and Dragados S.A.. GEOCISA conducted the ground improvement works at the trial fields and at the plant; they also conducted and managed the site characterization program. Geophysical tests were conducted by International Geophysical Technology (IGT). Their support, as well as the support of ENAGAS engineering department, is gratefully acknowledged.

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