2012

Characterising compacted fills at Penrith Lakes development site using shear wave velocity and matric suction

Ana Heitor
University of Wollongong, aheitor@uow.edu.au

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Cholachat Rujikiatkamjorn
University of Wollongong, cholacha@uow.edu.au

R Golaszewski
Penrith Lakes and Development Corporation, Ltd, Robert.Golaszewski@pldc.com.au

Publication Details

Heitor, A., Indraratna, B., Rujikiatkamjorn, C. & Golaszewski, R. (2012). Characterising compacted fills at Penrith Lakes development site using shear wave velocity and matric suction. In G. A. Narsilio, A. Arulrajah & J. Kodikara (Eds.), 11th Australia - New Zealand Conference on Geomechanics: Ground Engineering in a Changing World (pp. 1262-1267).

Characterising compacted fills at Penrith Lakes development site using shear wave velocity and matric suction

A. Heitor[1], B. Indraratna[2] PhD, FTSE, FIEAust, C. Rujikiatkamjorn[3] PhD, R. Golaszewski[4].

[1] PhD candidate, Centre for Geomechanics and Railway Engineering, ARC Centre of Excellence for Geotechnical Science and Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2500, Australia, aprh838@uowmail.edu.au,
[2] Professor of Civil Engineering and Research director, Centre for Geomechanics and Railway Engineering, ARC Centre of Excellence for Geotechnical Science and Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2500, Australia, indra@uow.edu.au
[3] Senior Lecturer, Centre for Geomechanics and Railway Engineering, ARC Centre of Excellence for Geotechnical Science and Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2500, Australia, cholacha@uow.edu.au
[4]Infrastruture Project Manager, Penrith Lakes and Development Corporation, Ltd, 89 - 151 Old Castlereagh Road, NSW 2749 Australia, Robert.Golaszewski@pldc.com.au

ABSTRACT

Conventional quality control of compaction during construction is currently based on an in-situ determination of dry unit weight and moisture content via nuclear procedures, but because this is a localised procedure, poor compaction can often occur. Moreover, with older compacted embankments where few or no records of the control done during construction are available, there is no existing methodology that can help practising engineers assess their post-construction condition. This means that the scope of the nuclear method renders it as inadequate and alternative methods should be considered. The use of shear wave velocity (V_s) surveys (i.e. MASW) to assess the quality of larger, previously compacted surface areas and depths seems to be a promising method. Furthermore, shear wave velocity can be readily related to the soil modulus, which is a variable commonly used in construction design. Fills are placed on, at, or near the OMC (optimum moisture content) so the compacted soil is in an unsaturated condition at the time of construction and therefore a field determination of V_s should also include the evaluation of matric suction (u_a-u_w). In this study, a field application at Penrith Lake Development Corporation (NSW, Australia) was investigated. A silty sand material collected from the site, was compacted and subjected to different confining pressures. In each specimen the V_s and (u_a-u_w) were measured with Bender elements and the filter paper method, respectively. The laboratory results showed that V_s trends together with (u_a-u_w) or moisture content, could effectively predict the compaction characteristics of the soil.

Keywords: compacted fills, compaction control, shear wave velocity, matric suction

1 INTRODUCTION

The compaction quality during construction is usually evaluated based on minimum deviation interval from the key parameters previously established in the laboratory (i.e. the maximum dry unit weight and optimum moisture content, OMC). Although quality control using these criteria has been well established, adopting methods such as sand cone and nuclear gauge, areas of insufficient compaction that lead to poor fill performance (i.e. differential settlements, bearing capacity) can still occur. This is mainly because of its localised nature and the limited depth of investigation. Conversely, alternative cost effective geophysical methods can cover large surface areas and higher depths in a relatively short time.

Shear wave velocity surveys, such as the multi-channel analysis of surface waves (MASW), have been used extensively in many geotechnical applications to evaluate the dynamic properties of ground subjected to cyclic loads (i.e. vibrations caused by the traffic of heavy, fast moving vehicles, and earthquakes). The shear wave, which propagates through the soil skeleton, is an adequate variable to verify the quality of compaction during construction (Waddel et al, 2010). However, it's direct application for assessing the current state of compacted fills (post-construction stages) is not straightforward because compacted soil is under unsaturated condition and the in-situ matric suction plays an important role in controlling the shear strength. For this reason the shear wave velocity and matric suction should both be measured in the field.

Recent research into the influence of matric suction on the shear wave velocity showed that for the same soil structure, varying the matric suction (i.e. equivalent to field drying and wetting cycles) causes significant differences in the values of the shear wave velocity (Cho and Santamarina 2001; Ng and Menzies 2007). Conversely, fewer contributions were attempted in terms of establishing more general relationship between as-compacted shear wave velocity and matric suction for soils compacted under different conditions (moisture content and energy). A new methodology that relates the compaction characteristics and field wave velocity, together with the matric suction, is therefore proposed. The suitability of this methodology was evaluated in laboratory controlled set-ups and compared with field measurements.

2 EXPERIMENTAL WORK

2.1 Soil type

The soil used in this study was silty sand classified as SP-SM (Unified Soil Classification System, USCS). The soil is a by-product of cobble quarrying activities and has been widely used to fill low line areas at the Penrith Lakes site in Penrith. Its main properties are listed in Table 1 and the particle size distribution curves of samples collected at two different locations are shown in Figure 1. The soil consists of particles ranging in size from silt to cobbles. The size of the cobble fraction is far less representative so the larger size particles were removed. The material was air dried and then carefully separated using a mortar and pestle so that the particles could meet a nominal size of 2mm.

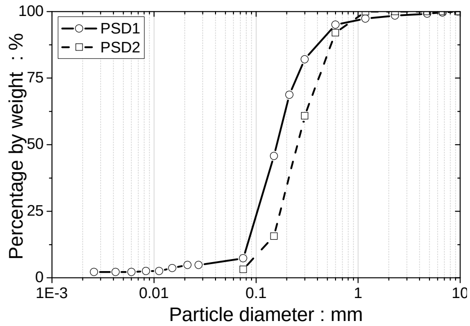

Figure 1. Particle size distribution of the silty sand soil.

Table 1: Main properties of silty sand soil

Soil Properties	
Liquid limit (%)	25.5
Plasticity index	10
C_u (Coefficient of Uniformity)	5.0
C_c (Coefficient of Curvature)	0.99
Specific gravity G_s	2.7

2.2 Laboratory testing program

The laboratory testing program included the execution of compaction tests using the Proctor compaction test (AS1289.5.1.1-2003) under standard level of compaction energy (i.e. 25 blows per layer). The required amount of water was added to the sample and the mixture was thoroughly mixed with a masonry trowel and then left under constant temperature and humidity conditions to ensure a uniform distribution of moisture. To measure the shear wave velocity, additional specimens were compacted using a 50mm diameter mould following the procedure described in Sridharan and Sivapullaiah (2005). The compaction energy was adjusted to ensure that the dry unit weights were the same as those obtained from the Standard Proctor compaction test. The compaction curve obtained is represented in Figure 2.

2.2.1 Shear wave velocity and matric suction

The shear wave velocity (V_s) propagation in the compacted specimens was evaluated using Bender elements. A pair of Bender elements adapted in a Bishop-Wesley standard triaxial cell set up apparatus was able to generate and detect shear waves through the unsaturated (compacted) soil specimens. The signal was controlled with software designed by GDS Instruments (UK) and a sinusoidal pulse with a sampling rate of 300 kHz was selected. The system had 2 channels of data acquisition with16 bits of resolution each. The background noise was minimised by stacking a series of 20 signals. A testing frequency of 3.03 kHz was used so that the testing variables would approximate the intervals proposed in the literature (i.e. Leong et al, 2005 and Arulnathan et al, 1998) without compromising the strength of the received signal. The shear wave velocity was computed based on the length of the wave path (L_{tt}) that corresponds to the tip to tip distance between the transmitter and receiver (Viggiani and Atkinson, 1995) and the travel time (Δt), as follows:

$$V_s = \frac{L_{tt}}{\Delta t} \tag{1}$$

The tip to tip distance was determined using a digital calliper. The travel time was taken as the time taken to travel to the first maximum bump in the received signal, as proposed by Lee and Santamarina (2005).

The compacted specimens were also subjected to isotropic confining pressures of up to 250 KPa, which represented an increase in pressure corresponding to greater depths under field conditions. The tests were conducted in stages where the V_s values were measured. A one hour period was allowed between each stage to ensure that the stress equilibrium of each sample had occurred before measuring V_s. For each confinement stage, L_{tt} was monitored using a LVDT attached to the exterior of the triaxial cell. Thus, the axial compression or volumetric strain could also be measured.

Matric suction was evaluated using the filter paper (55mm Whatman No.42) technique, and was conducted in accordance with ASTM D5298, 2003. The contact method (matric suction) was used for most of the tested specimens, but the non-contact method (total suction) was sometimes used for the specimens compacted on the dry side of OMC. The influence of osmotic suction was considered negligible because the content of salts in the tested soil was negligible. Thus, the values of total suction were equal to the matric suction. The equilibration time adopted was typically 7 to 10 days, while suction was computed using the bi-linear calibration curves given in ASTM D5298.

2.3 Results and Discussion

An example of the results for the shear wave time domain series for a specimen compacted at OMC is given in Figure 3. The most common time domain methods for interpreting the BE results are also illustrated.

Figure 4 shows the shear wave velocity with moisture content under unconfined conditions. In general, V_s remained approximately the same or in a similar order of values to those on the dry side ($V_s \approx 225 m/s$ for $8\% < w < 11\%$). Just before attaining the OMC, the V_s started to decrease sharply towards a minimum value of *70m/s* at higher moisture contents (Figure 4). This tendency can be attributed to the increase in dry unit weight inter-related to the decrease in suction together with the corresponding change in the soil structure (Delage et al., 1996).

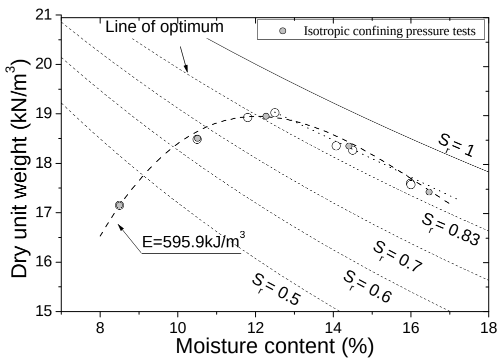

Figure 2. Compaction curve for the standard energy level.

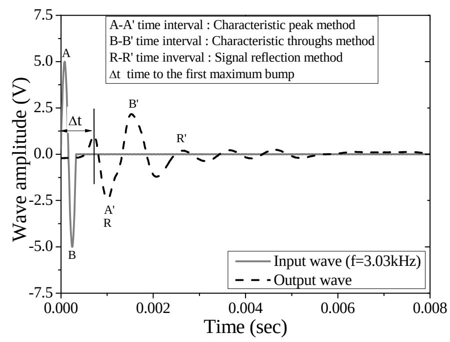

Figure 3. Time domain shear wave velocity traces for a specimen compacted at OMC.

The suction values obtained for the compacted specimens are also given in Figure 4. Overall, the suction decreased as the moisture content increased. Moreover, the specimens compacted at different initial moisture contents converged to a common line that was found using a logarithmic regression analysis (the equation and correlation factor are shown in Figure 4). This suggests that the influence of the moisture content on suction was considerably more important than the associated dry unit weight, and the field suction may be estimated once the moisture content is known. Sawangsuriya et al. (2008) reported similar results for compacted specimens. Note that because the specimens compacted at different moisture contents yielded different initial void ratios and soil structure; the points represented in Figure 4 merely illustrate the suction obtained in an as-compacted condition. In fact, each point could yield a completely different SWCC curve, as reported by Marinho and Stuermer (2000).

Figure 5 illustrates the relationship between V_s and applied isotropic confining pressures (up to 250 kPa). Overall the shear wave velocity increased with the isotropic confining pressure, with a slightly higher rate of increase in the specimens compacted at OMC, owing to its lower compressibility. Although higher compressibility values were observed for those specimens compacted on the wet side of OMC ($w>12.5\%$), the ensuing reduction in the length of the wave path (L_{tt}) was not enough to produce significant changes in the velocity of the shear wave.

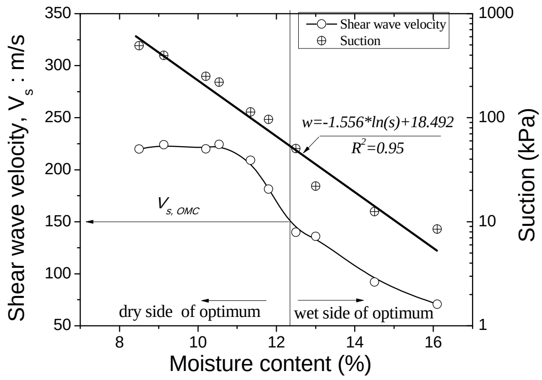

Figure 4. Unconfined V_s and matric suction relationship with moisture content.

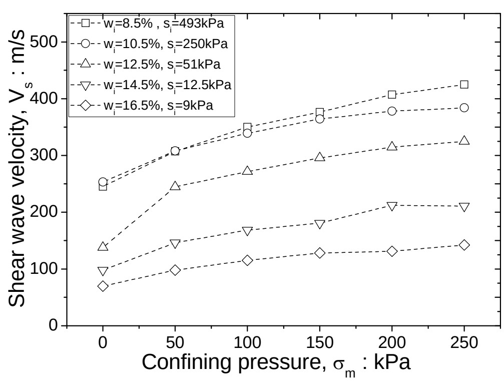

Figure 5. V_s with confining pressure for the selected compacted specimens.

3 FIELD TESTS

3.1 Site condition

The Penrith Lakes scheme, just north of Penrith, NSW covers over 2000 hectares. The site has operated as a quarry over many decades and involved the removal of overburden, sand, and gravel to depths of 20m. The beginning of the Penrith lakes scheme in the early 80's involved removing sand and gravel and subsequent rehabilitation by backfilling the quarried areas.

In general, the filling work was achieved according to the specifications on the Deed of Agreement (DOA), with placement and compaction using scrapers and compaction control based on certain relative MDD specifications. However, before the DOA a significant portion of the landform was already constructed without any historical records of the placement methodology. Due to insufficient compaction records, these particular fill areas can be deemed as uncontrolled fill. As a consequence, the scope for future land use is restricted to parkland without suitable verification methods to confirm the level of compaction. Thus, the assessment of the current conditions in terms of strength, that is, sufficient bearing capacity is of paramount importance. Preliminary field testing was carried out in a smaller area represented in Figure 6. This area was selected as a benchmark to verify the methodology because it was previously subjected to soil improvement by dynamic compaction (Figure 7), and subsequently assessed as satisfactory in terms of bearing capacity to support the design requirements.

3.2 Field testing program

To evaluate *in situ* the shear wave velocity profiles of the ground, seismic surface wave testing using multi-channel seismographs (MASW) and an array of linear surface detectors was adopted. In the MASW method, the sub-surface V_s distribution can be recovered from the analysis of the dispersion and numerical inversion of the seismic data, produced by a surface impact source and recorded on standard, digital multi-channel seismographs.

Figure 8 shows a schematic illustration of the of the data analysis procedure for a multi-layered profile. The test frequency range in the MASW was established by considering the target depth of investigation. In this particular case depths up 25m were surveyed and the frequency range reached the 50Hz. Figure 9 shows the phase velocity spectrum of the seismic data and the fitted curve that enabled the V_s to be evaluated with depth.

Figure 10 shows the velocity of the inverted shear wave profile for the location selected (Figure 7). The in situ moisture content evaluated in tube density tests (Coffey, 2007) are also shown. In the field, the V_s increased with depth and varied from a minimum of 150m/s for depths of 5m to 8m to a maximum of 420m/s for depths greater than 17m. In some ways, the increase of depth contributed to the increase of V_s on its own, as shown in Figure 5. The effect of confinement should be minimised so that the values can be compared with those obtained in the laboratory. For this reason, the shear wave velocities were normalised by following Kim and Park (1999) expression, as follows,

$$V_{s,n} = V_s \left(\frac{P_a}{\sigma_m^{'}} \right)^{0.25} \tag{2}$$

where $V_{s,n}$ is the normalised shear wave velocity (also represented in Figure 10), P_a is the reference stress (typically atmospheric pressure), σ'_m is mean effective stress computed based on the vertical effective stress (σ'_v) and k_0 is the earth pressure coefficient at rest.

$$\sigma'_m = \frac{(1+2k_0)\sigma'_v}{3} \tag{3}$$

The normalised shear wave velocities ranged between 160m/s to 400m/s. Up until depths of 10m (ground water level), the ground was unsaturated and both the shear wave velocity and matric suction (or moisture content, Figure 4) were monitored. For depths of 5m to 8m, $V_{s,n}$ had a minimum value of 160m/s and moisture content of 12%. Based on the unconfined laboratory results, the soil is likely to be at OMC condition (Figure 4). For depths between 8-10m, $V_{s,n}$ increased to a higher value of 338m/s and moisture content increased to 13%, which indicated that the dry unit weight in field exceeded the 100% Proctor condition. Below 10m the soil entered a saturated domain which was clearly highlighted by an increase of 30% in the in situ moisture. In this range, high values of wave velocity were directly related to the density of the soil because the influence of matric suction was nil.

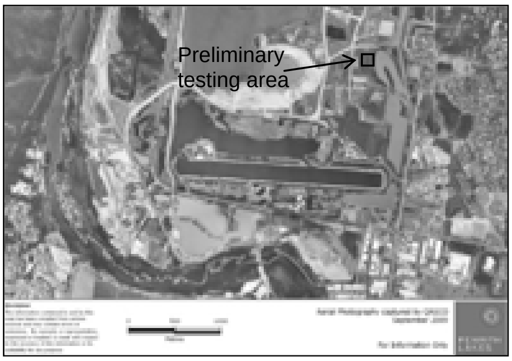

Figure 6. Aerial photograph of the site location and benchmark testing area (courtesy of PLDC).

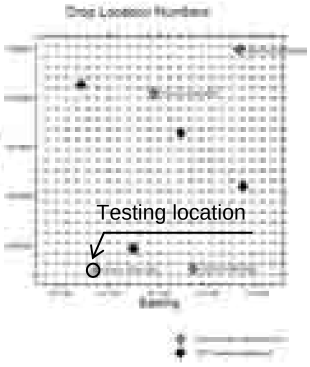

Figure 7. Diagram of Dynamic compaction treatment (Coffey, 2007).

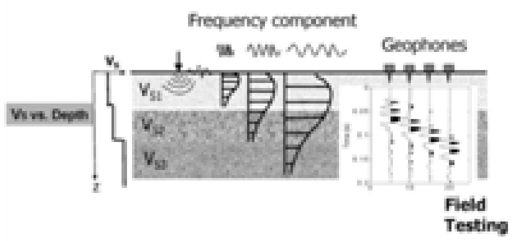

Figure 8. Simplified diagram of the MASW analysis (Waddell et al. 2010)

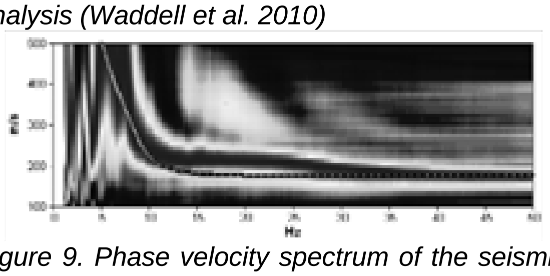

Figure 9. Phase velocity spectrum of the seismic recorded data (courtesy of University of Western Sydney, UWS)

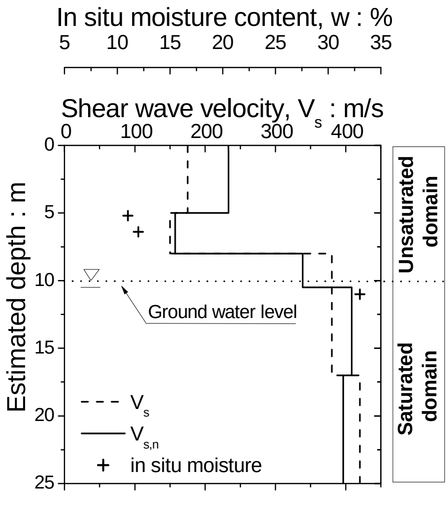

Figure 10. Site characteristic preliminary inverted V_s profile and in situ moisture content values with depth (V_s data is courtesy of UWS).

4 CONCLUSION

From a number of Bender element tests it was noted that the shear wave velocity varied with the moisture content and confining pressure. Furthermore, experimental data also confirmed that in the assessment of the current conditions of compaction fills (i.e. estimating the dry unit weight, shear strength), the use of shear wave velocity alone was not enough because V_s remained approximately constant across the dry side of the compaction plane. Thus, an additional variable was required. The experimental data showed that the suction-moisture content in compacted specimens was relatively independent of the initial moisture content; indeed these two variables were related using a logarithmic linear expression. Moreover, the field evaluation of suction may be limited to the measuring capacity (i.e. 100kPa) of available instruments. For this reason, a field determination of the moisture content may be preferable.

The field tests included an evaluation of the *in situ* shear wave velocity using the MASW method and moisture content using density tube tests. The field values were compared with the V_s -w relationship established for specimens compacted in the laboratory. The ranges of dry unit weights suggested by V_s-w field values were all above the V_s -w curve obtained for the unconfined test. This indicated that the tested ground satisfies more than 95% of the relative compaction criteria initially anticipated, given that the area was previously treated by dynamic compaction.

The use of this methodology compared to the conventional geotechnical surveys, offers a valuable alternative that has tremendous implications in terms of cost and time savings.

The aspects related with the change of moisture in ground in the post-compaction stage were not considered because only the top layer of soil is likely to be exposed to climatic changes. Moisture and suction would likely remain around the same vales as in its as-compacted state.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial assistance provided by the Australia Research Council (Australia), Penrith Lakes Development Corporation, Ltd and Coffey Geotechnics. The assistance provided by Mr. Alan Grant and Mr. Ian Laird in the execution of tests herein reported is gratefully acknowledged.

REFERENCES

ASTM 2000. “Annual book of standards 2000, section four, Construction, volume 04.08, soil and rock (I): D5298-94”, Easton, MD, U.S.A

Australian Standard: AS1289.5.1.1-2003 Soil compaction and density tests – Determination of the dry density/moisture content relation for a soil using standard compactive effort.

Arulnathan, R., Boulanger, R. W., and Riemer, M. F., (1998). “Analysis of Bender Element Tests”, Geotechnical Testing Journal, 21, 2: 120–131.

Cho, G. C. and Santamarina, J. C., (2001). “Unsaturated Particulate Materials—particle level studies”, J. Geotech. Geoenviron. Eng., ASCE, 127, 1: 84–96.

Coffey Geotechnics (2007). “Geotechnical Investigation and Monitoring report : Dynamic compaction prototype trial compaction area 9-Penrith Lakes Development Corporation”, Coffey Geotechnics, 125pp.

Delage, P., Audiguier, M., Cui, Y. J., and Howat, M. D., (1996). “Microstructure of a Compacted Silt”, Can. Geotech. J., 33: 150–158.

Lee, J. S. and Santamarina, J. C. (2005). “Bender elements: Performance and signal interpretation”. J. Geotech. Geoenviron. Eng. 131(9): 1063-1070.

Leong, E. C.,Yeo, S. H., Rahardjo, H. (2005). “Measuring Shear Wave Velocity Using Bender Elements”, Geotechnical Testing Journal, 28, 5:1-11.

Marinho, A. M. and Stuermer, M. M. (2000). “The influence of compaction energy on the SWCC of a residual soil”. Proc. of the sessions of Geo-Denver: 125-141. Denver.

Ng, C., Menzies, B. (2007). “Advanced Unsaturated Soil Mechanics and Engineering”, Taylor and Francis, 587pp.

Sawangsuriya, A., Edil, T.B., Bosscher, P. (2008). “Modulus-suction-moisture relationship for compacted soils”, Can. Geotech .J., 45: 973-983

Sridharan, A., Sivapullaiah, P.V., (2005). “Mini Compaction Test Apparatus for Fine Grained Soils”, Geotechnical Testing Journal, 28, 3: 1-6

Viggiani, G. & Atkinson, J. H. (1995). “Interpretation of bender element tests”. Géotechnique, 45, 1:149–154

Waddell, P. J., Moyle, R. A., Whiteley, R. J. (2010). “Geotechnical Verification of Impact Compaction”. Procedings of the 5th International Conference on Prevention, Assessment Rehabilitation & Development of Brownfields Sites: 14-16, Portugal.