13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Ground improvement of an old quarry (landfill) using dynamic compaction methods

J. Zeerak
EIC Activities Pty Ltd (A member of the CIMIC Group), Melbourne, Australia

A. Garrard
CMW Geosciences Pty Ltd, Melbourne, Australia

A. Abou Antoun
Cleanaway Waste Management, Melbourne Australia

ABSTRACT: A new lined leachate pond was proposed to be constructed at Cleanaway Waste Management's Melbourne Regional Landfill over the location of an old basalt quarry, which had been filled with waste. The proposed pond lining system comprised composite natural clay and geomembrane which was found to be sensitive to differential settlement of the pond subgrade. It was considered that dynamic compaction (DC) would be a suitable form of ground improvement to densify the fill, and collapse the near surface voids. To achieve the project technical specification requirement for settlement, three phases of dynamic compaction with varying energy levels were implemented across the site. Verification tests conducted following ground improvement works included SPTs, PMTs and trial embankments which indicated that a minimum Young's Modulus E value of 12MPa had been achieved. This paper discusses the nature of the waste fill, details of the dynamic compaction and results of the pre and post ground improvement verification tests.

1 INTRODUCTION

1.1 *Project overview*

A proposed new lined leachate pond was to be constructed just to the west of Melbourne at the Melbourne Regional Landfill (formerly the Boral Western Landfill) over the location of an old basalt quarry which had been backfilled with waste. The proposed pond lining system comprised composite natural clay and geomembrane. The area under consideration for the new leachate pond is approximately one hectare in plan area and is located near the northern boundary of the landfill site. The site layout is shown in Figure 1.

1.2 *Nature of the waste fill material*

An investigation of the quarry fill was conducted in December 2013 with findings presented in a geotechnical investigation report prepared for the project by SMEC. The fill was investigated using 3 boreholes drilled using sonic methods and 6 deep test pits excavated using a 25T tracked excavator. The points at which changes in fill thickness occurred were considered to be abrupt given the often vertical nature of basalt quarry walls. Figure 1 shows a contour plan of estimated depth to quarry floor which was interpreted to vary from 2m to 12m.

Standard penetration tests (SPT) conducted in boreholes suggested that the fill was loose and soft in places and contained many obstructions to the progress of the SPT spoon sampler. Significant voids, estimated to be between 0.2 and 0.5m^3 were also noted in the fill. The fill was generally found to comprise of loose gravel, soft clay, basalt boulders, concrete, steel reinforcement, some timber and a tractor tyre. Rusty 200 litre drums were also observed in earlier excavations by Boral.

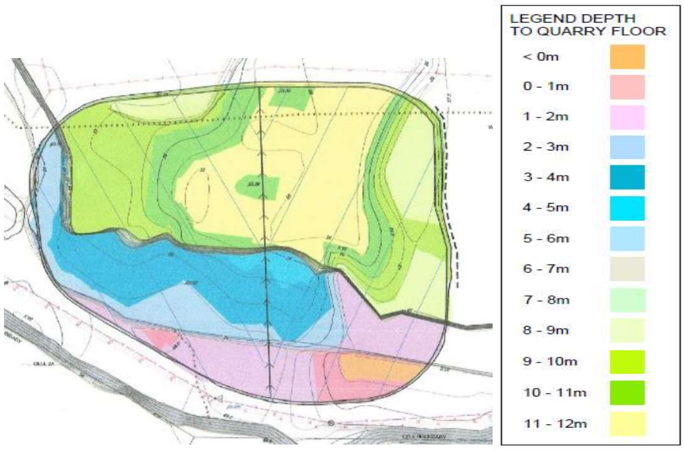

Figure 1. Site layout with depth (m) to quarry floor contour plan

1.3 *Leachate pond settlement analysis*

A settlement analysis was conducted to assess the potential effects of voids within the quarry fill and any abrupt changes in fill thickness. The design cases considered critical to the integrity of the pond lining system were:

- Differential Settlement due to an abrupt change in the thickness of quarry fill beneath the lining system.
- Differential Settlement due to the collapse of a void within the fill at some time during the pond service life.

Most landfill sites are filled with domestic waste which is expected to undergo significant biodegradation over time and compress under self-weight. However, based on the geotechnical information, organic material did not comprise a significant proportion of the waste within this site. In addition, due to age of the landfill most of the biodegradation of the organic material would have been completed before the compaction. However, in discussions with landfill operators, Cleanaway Waste Management, CWM (Formerly Boral) and the Environmental Auditor for the project, a case of collapse of rusty 200 litre drums within the fill was considered to be feasible. Furthermore, it was considered prudent in the design to consider a void collapse the size of four 200 litre drums either standing upright or side by side within the fill. Settlement analysis showed that the proposed lining system would be compromised due to the collapse of voids this size within the fill within 4m depth directly below the base of the new pond lining system.

2 PERFORMANCE REQUIREMENTS CRITERIA

Settlement assessments indicated that a form of ground improvement was required to densify the fill, and collapse voids within the top 4m starting from the surface. It was also deemed prudent to densify the fill below 4m depth to the greatest practical extent. Dynamic compaction or dynamic replacement were assessed as the two likely options for ground improvement that were likely to achieve the required results.

The fill modulus requirements were assessed as the minimum which would satisfy the requirements of the leachate pond subgrade. However, during the procurement of the ground improvement works, it was agreed between the landfill operator, designers and the environmental auditors that higher performance targets should be incorporated into the Technical Specification issued to the ground improvement contractor to reduce the risk of the calculated targets not being met. The following dynamic compaction performance requirement “stretch” targets were included within the project Technical Specification issued to specialist geotechnical contractors.

Table 1. Project technical specification performance criteria

Verification Test	No of Tests	Performance Criteria min	Performance Criteria average
Standard Penetration Tests (SPT)	40 continuous SPTs	SPT N Value ≥ 12	SPT N Value ≥20
Pressuremeter Tests (PMT)	12 continuous PMTs	Youngs Modulus ≥ 12MPa	Youngs Modulus ≥ 20 MPa
Trial Embankment	3	Youngs Modulus ≥ 12 MPa	-

Given that performance of the pond lining system was sensitive to stiffness and collapse of voids within top 4m of the fill below subgrade, SPT & PMT tests were specified to target depth of 5m to enable assessment of the modulus of the improved ground within this zone. Continuous SPTs were specified at 0.5m interval i.e. 9 tests/ borehole while PMTs were specified at 1m intervals i.e. 4 tests/ borehole.

3 DYNAMIC COMPACTION METHODOLOGY

Design and execution of the Dynamic Compaction (DC) works, was undertaken by Menard Oceania (formerly Menard Bachy). The following sequence of works were implemented as part of the ground improvement works:

1. Establish Calibration Area No 1.
    a. Pre DC baseline SPTs & PMTs
    b. Phase 1 DC Pounding
    c. Post Phase 1 SPTs
    d. Phase 2 DC pounding
    e. Post Phase 2 SPTs & PMTs
2. Pounding of Phase 1 and Phase 2 prints across the site.
    a. Post Phase 2 verification SPT & PMT Tests
3. During the works it was found necessary to implement a third phase of the DC pounding (instead of the final ironing phase) for the required level of ground improvement. The sequence of work which followed included;
    a. Establish Calibration Area 2
    b. Pounding Phase 3 prints
    c. Post Phase 3 SPTs & PMT Tests
4. Phase 3 DC pounding prints across the entire site
    a. Post phase 3 verification tests – SPTs, PMTs and trial embankments

Dynamic compaction and dynamic replacement have been successfully used to improve many types of weak ground deposits (FHWA,1995) including landfill sites filled with domestic waste (e.g. Hsi, 2007). However, there seems to be little published data on the use and effectiveness of dynamic compaction for waste fill such as that described in section 1.2. Given the highly unknown nature of the fill material, it was necessary to conduct tests and trial pounding within smaller areas of the site to calibrate and optimise the level of compaction efforts required to achieve the desired stiffness as per project technical specifications. This is described in the next section.

4 CALIBRATION AREA 1

In order to test and refine the proposed compaction methods, pounding of a smaller area designated as 'Calibration Area 1' was undertaken prior to commencing the DC works across the site. The variables to be tested were the pounder drop height and number of drops per print by assessing the depth and volume of craters using Heave and Penetration Test (HPT) and conducting SPT and PMT tests both before and after the ground Improvement works. A calibration area was selected near the northern boundary of the site where the greatest thickness of the fill was encountered during the geotechnical investigations. Two phases of DC pounding were proposed for the Calibration Area 1 as shown in Figure 2.

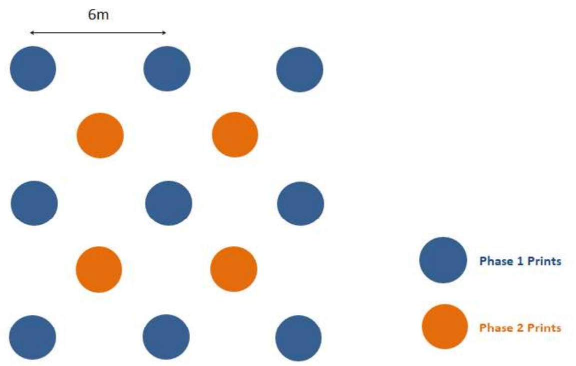

Figure 2. Calibration Area 1 DC Prints

To establish baseline SPT N values, continuous SPTs were performed to a depth of 5m in two boreholes prior to pounding of the area. SPT N values obtained varied between 2 and 31 with an average of 29. It is noted SPT N values reported within this paper are uncorrected N values. In addition, four Pressuremeter Tests (PMT) were performed within 1 borehole prior to commencement of the pounding. Youngs Modulus 'E' values obtained of the Pre PMT tests ranged between 3 and 13 MPa with an average of 8MPa.

Once baseline SPT and PMT tests were conducted in Calibration Area 1, 9 no Phase 1 prints (blue) were implemented at a grid spacing of 6m with varying drop heights of 7m to 20m with 7 to 14 drops per print. Pounding was undertaken using a Liebherr Crane 855 with an 18.6t, 2.5m diameter Menard pounder.

SPT tests conducted post Phase 1 pounding returned SPT N values in the range of 7 and 59 with average N value 20.

As per proposed methodology, 4 no Phase 2 prints (orange) located in between the Phase 1 prints were then implemented. SPT N values obtained post Phase 2 pounding, varied between 5 and 55 with average N value of 17. A number of SPT N values were below the project technical specification requirement. Four PMT tests were also conducted post Phase 2 pounding with Young's Modulus values obtained from the PMT tests ranging between 19MPa and 42MPa with an average of E value 30MPa.

Results of the verification tests conducted post Phase 2 pounding indicated an insufficient level of ground improvement. A number of SPT N values obtained were below the minimum specified N value of 12. Accordingly, it was decided that the pounding energy would be increased by 30% for Phases 1 & Phase 2 prints by increasing the no of drops per print. Phase 1 and Phase 2 prints were then implimented across the site with the refined pounding energy obtained from Calibration Area 1.

Figure 3. View of site wide craters (L), measuring crater diameter (R)

5 SITE WIDE PRE DC BASELINE PMT TESTS

PMT tests were performed at 12 locations across the site prior to compaction works to enable a direct comparison between the Young's Modulus of ground before and after the compaction works. The tests were spread across the site such that greater concentration of tests occurred towards the north and centre of the site where the fill thickness was expected to be greatest i.e. >10m and fewer tests located across the rest of the site. PMT tests were undertaken by Menard Oceania in accordance with ASTM Standard D 4719-00: Standard Test for Prebored Pressuremeter Testing in Soils. Baseline E values obtained from Pre PMT test results varied between 2MPa and 47MPa with an average E value of 13MPa.

6 PHASE 1 & 2 DC WORKS

With the refined pounding energy obtained as a result of calibration works within Area 1, two phases of dynamic compaction were implemented across the site.

A total of 425 Phase 1 prints were pounded with a varying drop height of 15-20m with average of 9 drops per print. Craters created as a result of Phase 1 pounding varied between 1.3m to 3.7m deep with average crater diameter of 2.8m.

Phase 2 included 444 prints which were pounded from similar drop heights with 6 drops per print. Craters created post phase 2 pounding were between 1.2m to 2.9m deep with an average crater diameter of 3.0m. Craters depths post Phase 2 craters were shallower than Phase 1 as expected. However, craters with slightly larger diameters at the top were observed post Phase 2 pounding which was attributed to the backfill material within Phase 1 prints which had not yet been fully compacted.

6.1 *Post Phase 2 verification testing*

After completion of Phase 2 pounding across the site, SPT tests were conducted in a 25x25m grid in 16 locations. SPT N values obtained post Phase 2 DC works across the site varied between N=5 and 55 with average SPT N value of 17. In addition, PMT tests were conducted within 12 boreholes. Results of post Phase 2 SPT and PMT tests are presented in Figure 4 below.

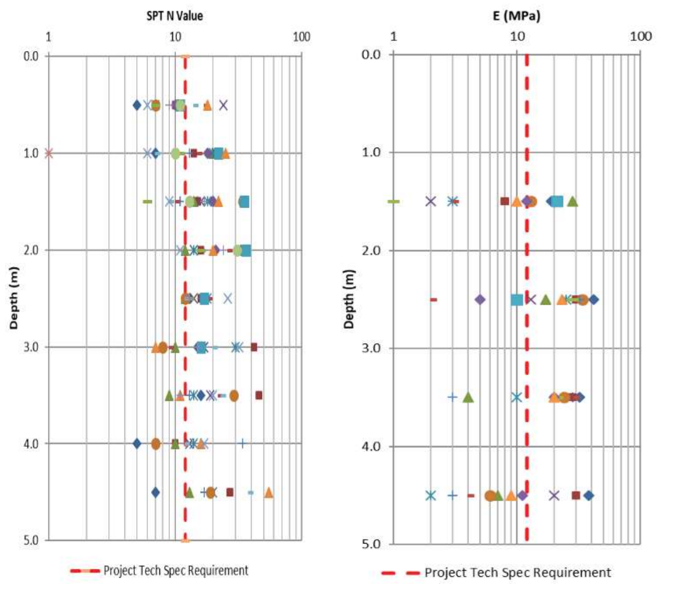

Figure 4. Post Phase 2 SPTs (L), PMTs (R). (Colors and symbols indicate SPTs conducted at various locations)

As can be seen from the SPT & PMT plots above, some of the verification SPT & PMT did not meet the project specification. As SPT & PMT tests were predominantly conducted in the areas outside the DC prints, these results showed that the level of ground improvement achieved outside the DC print area was not sufficient.

7 CALIBRATION AREA 2

As discussed above, results of the verification testing conducted post Phase 2 pounding indicated that sufficient and consistent level of ground improvement had not been achieved across the site and that further improvement works were necessary. Accordingly, 'Calibration Area 2' was established in order to assess the level of further compaction efforts required to achieve the requirements of the project technical specifications.

Accordingly, 12 no additional DC prints were implemented in the areas in between the Phase 1 and Phase 2 prints reducing DC prints grid spacing to 3m centres which resulted in overlapping of the craters in most locations. Phase 3 pounding was undertaken with reduced pounding energy of 4-8 drops per print with drop heights between 10-20m using the same pounder. Phase 3 craters were between 0.8m and 3.1m deep with an average crater diameter of 2.8m. Layout of the DC prints within the Calibration Area 2 is shown in Figure 5.

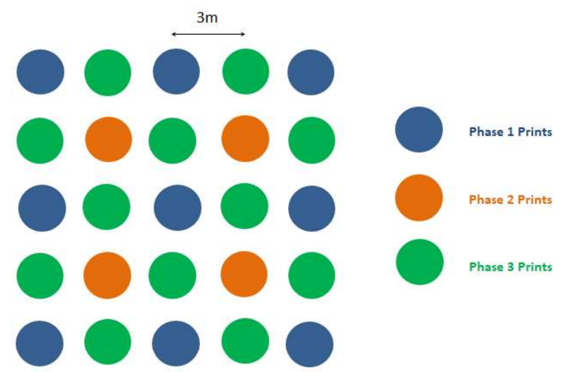

Figure 5. Calibration Area 2 – Layout of DC Prints

SPT N values obtained from two SPT boreholes post Phase 3 pounding were in the range 9 to 37 with average SPT N value of 21. The lower SPT N value of 9 was in the top 1.5m depth which was expected to be improved by final proof rolling. Similar improvement results were obtained from PMT tests which returned E values ranging between 13MPa to 48MPa, with an average E value of 28MPa.

Figure 6. Pounding in progress (L), Crater and pounder (R)

8 PHASE 3 POUNDING

With the result of the verification tests within Calibration Area 2 confirming that a third phase of pounding was likely to sufficiently improve the ground, a third phase of DC was implemented across the rest of the site.
A summary of total prints for phases 1, 2 and 3 together with crater depths and diameter are presented in table below.

Table 2. Project Technical specification performance criteria

Phase		Phase 1	Phase 2	Phase 3
No of Prints		425	444	849
No of drops	Min	7	5	4
	Max	14	9	8
	Avg	9	6	4
Crater Depth (m)	Min	1.3	1.2	0.8
	Max	3.7	2.9	3.1
	Avg	2.2	1.8	1.5
Crater Diameter (m)	Min	2.2	2.0	2.1
	Max	3.9	3.9	3.8
	Avg	2.8	3.0	2.8

At the end of Phase 3 pounding, an estimated total of 18,000m^3 of crushed rock was imported to backfill the craters across the site.

9 FINAL VERIFICATION TESTING

9.1 *Post Phase 3 – SPTs & PMTs*

252 SPT tests were performed within 40 SPT boreholes to target depth of 5m across the site after the completion of Phase 3 pounding. Where refusal was encountered other than on the inferred quarry floor, an SPT N value of 50 was considered for the purpose of assessment of the test results. Shallow refusals in 13 locations were inferred to be on obstructions (not on quarry floor) and were re-attempted at a distance of 1m from the original location. In addition, 48 no PMT tests were performed within 14 PMT boreholes across the site.

Figure 7. Pressuremeter testing in progress (L), Settlement Plate Setup prior to trial embankment construction (R)

From a total of 252 SPT tests performed within 40 SPT boreholes, 59 SPTs returned N value <12 and 13 boreholes returned average SPT N value <20. 1 out of 48 PMT tests conducted within 14 boreholes did not meet the minimum E of 12MPa and the PLT results did not indicate an E value of >20MPa. The above were deemed to have not passed the project technical specification requirements. However, as described in Section 2, the Technical Specification for DC works was set with performance criteria at a higher level than was required in accordance with settlement analysis results (stretch targets). This was to provide an additional level of comfort that sufficient ground improvement would be achieved. The minimum performance criteria agreed with the environmental auditor is presented in the table below;

Table 3. Performance requirement required for the design as agreed with the environmental auditors

Verification Test	No of Tests	Performance Criteria min	Performance Criteria average
Standard Penetration Tests	40 continuous SPTs	SPT N Value ≥ 5	SPT N Value ≥12
Pressuremeter Tests	12 continuous PMTs	Youngs Modulus ≥ 10MPa	Youngs Modulus ≥ 12 MPa
Trial Embankment Plate Load Tests	3	Youngs Modulus ≥ 12 MPa	-

When measured against these requirements, all post Phase 3 DC verification tests met the minimum performance criteria with an exception of one SPT borehole which returned an average SPT N value of 10 i.e. <12.

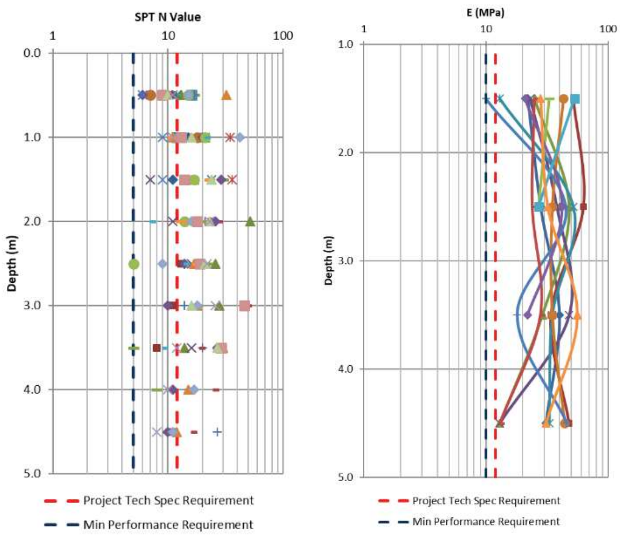

Figure 8. Post Phase 3 SPT (L) and Post Phase 3 PMT (R) compared against project tech spec and min performance requirements. (PMTs (R). (Colors and symbols indicate SPTs conducted at various locations)

After the final proof roll which comprised six passes with a pad foot roller, followed by 4-6 passes with a 23t dump truck, two Dynamic Cone Penetrometer (DCP) tests were conducted in the proximity of the 'failed' SPT borehole location. DCP test results were converted to SPT N and averages reassessed which returned $N_{average}$=13. This meant that all verification test results met the minimum performance requirement. A summary of the verification SPT, PMT and PLT test results for pre DC (baseline), post Phase 1, Phase 2 and Phase 3 DC pounding is presented below;

Table 4. Summary of verification tests results

Phase	Pre DC/ Baseline		Post Phase 1 DC	Post Phase 2 DC*	Post Phase 3 DC	
	Calib. Area 1	Site wide			Calib. Area 2	Site Wide
SPT Max	31	-	59	55	37	52
SPT Min	2	-	7	5	9	5
SPT Avg	29	-	20	17	21	17
PMT Max	13	47	-	42	48	63
PMT Min	3	2	-	1	13	10
PMT Avg	8	13	-	16	28	35
PLT Min	-	-	-	-	-	12

SPT's are uncorrected N values. PMT and PLT results are in MPa.
* Post Phase 2 DC verification tests include min, max and averages for tests undertaken within the calibration areas 1& 2 and sitewide.

9.2 *Post Phase 3 DC trial embankment tests(PLT)*

Three locations with the greatest thickness of fill were identified for trial embankments which were built over plates whose settlement was monitored during and following fill placement. Embankment heights were proposed to replicate the leachate pond embankments heights of 3m. Survey readings were obtained during fill placement and up to three days after the embankment construction when settlement readings had stabilised. Monitored settlement readings varied between 7mm and 17mm for the 3m high embankment as shown in Figure 9.

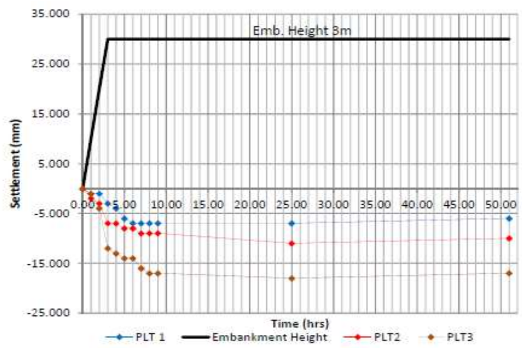

Figure 9. Monitored settlement results against fill height (black line indicates fill height; dotted lines indicate embankment settlement at 3 locations)

Using a relationship between settlement and elasticity, a minimum Youngs Modulus of 12MPa was assessed which met the project technical specification requirements.

10 SUMMARY AND CONCLUSIONS

Dynamic compaction was selected as suitable form of ground improvement to densify the fill and collapse voids below the base of a proposed lining system for a new leachate pond at CWM's Melbourne Regional Landfill site.

Three phases of dynamic compaction were implemented on site. Verification tests, including 252 SPT tests, 48 PMT tests and 3 trial embankment PLT tests indicated that a sufficient level of ground improvement had been achieved across the site.

Lessons learnt from the project and verification testing campaigns were that the use of SPT as the only form of verification test can be unreliable due to the highly variable nature of the fill and the susceptibility of the SPT to hitting obstructions. The PLT testing was found to be a more reliable verification method due to the fact that the test loads a greater volume of fill. In this type of ground improvement verification exercise, it is essential to utilise a number of test methods and to cross-correlate the results. Furthermore, results of the verification tests after each of the three phases of the DC pounding, indicated that significant improvement in stiffness of the fill was not achieved until the crater grid spacing was reduced to 3m centres. At this spacing, the craters overlap slightly in most locations as measured on site. This indicated that fill stiffness improvement was confined mostly to the footprint of the craters as measured by the verification tests within the top 4-5m depth zone. This ground improvement project also demonstrated the importance of setting stretch targets for the stiffness improvement required to ensure the success of the permanent works constructed upon the improved ground.

11 ACKNOWLEDGEMENTS

The authors wish to thank Dr Jeff Hsi – Technical Principal EIC Activities and Philippe Vincent of Menard Oceania for their peer review and feedback on the paper.

REFERENCES

Hsi, J. 2007. Landfill treatment for Westlink M7. Engineering Advances in Earthworks; Proceedings of AGS Symposium, Sydney, 10 October 2007. Sydney, Australia.

Lukas, R. 1995. Dynamic Compaction. Geotechnical Engineering Circular No. 1. Federal Highway Administration, US Department of Transportation, Washington DC, USA.