Quantifying the Zone of Influence of the Impact Roller

M. B. Jaksa, B. T. Scott, N. L. Mentha, A. T. Symons, S. M. Pointon, P. T. Wrightson and E. Syamsuddin
School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia
mark.jaksa@adelaide.edu.au

ABSTRACT

Rolling dynamic compaction (RDC) involves traversing the ground by means of a non-circular module consisting of 3, 4 or 5 sides. Over the last few decades, a number of studies have been carried out in an effort to quantify the effectiveness of RDC. In this study, the zone of influence of the 4-sided 'impact roller' was measured in a systematic fashion in the field by means of a series of earth pressure cells (EPCs) embedded in the ground, in situ density measurements and dynamic cone penetration tests. Measurements obtained from the field trial, which was conducted at an open-cut mine in South Australia, suggest that the depth of influence for which there is significant and quantifiable improvement with the roller is approximately 2.1 m below the ground surface and this corresponded to soil stress readings of between 150 and 200 kPa. Positive pressure readings due to RDC were also measured by the EPCs buried up to 3.85 m below the ground surface, indicating that the actual zone of influence (for which there is improvement) extends beyond this depth.

1. INTRODUCTION

Ground improvement is a fundamental and essential part of civil construction and comprises approximately 30 different methods of ground treatment, including modification, chemical alteration, reinforcement with steel or geosynthetic, strengthening by drainage, densification by vibration or consolidation and the use of electro-osmosis (Phear & Harris 2008). Of these, compaction is by far the most prevalent and involves increasing the density of the ground by means of mechanically applied energy such as static compaction, which employs drum, padfoot, sheepsfoot and tyre rollers or dynamic compaction, which makes uses of vibratory rollers and plates, rammers, heavy tamping, vibroflotation and rolling dynamic compaction (Hausmann 1990). The advantage of dynamic compaction is that it enables the ground to be improved to a much greater depth (>10 m as compared to 0.3 m for static compaction), with the depth of improvement depending on the energy applied (Mayne et al. 1984). When compared to other ground improvement techniques dynamic compaction is one of the most cost effective (Lukas 1995), but its use is limited by the large ground vibrations it induces, so that it is not suitable on small sites or adjacent to buildings and other infrastructure.

This paper is concerned with a specific type of dynamic compaction, known as rolling dynamic compaction (RDC), which involves traversing the ground with a non-circular 'roller'. RDC is a relatively new technology and is becoming more popular because it is able to compact the ground more effectively, i.e. to greater depths than its static and vibrating roller counterparts, and more efficiently because of its greater speed – 12 km/h compared with 4 km/h using traditional rollers (Pinard 1999). RDC was originally developed by Aubrey Berrangé in South Africa in the late 1940s, but its value was not fully appreciated until the mid-1980s. Since then RDC has been successfully implemented worldwide with different module designs having 3, 4, and 5 sides. RDC involves towing these heavy (6–12 tonnes) non-circular modules, which rotate about a corner and fall to impact the ground. Due to the combination of kinetic and potential energies, and the relatively large mass of the module, RDC has demonstrated compactive effort to more than one metre below the ground surface (and more than 3 m in some soils) (Avalle & Carter 2005) – far deeper than conventional static or vibratory rolling (Clegg & Berrangé 1971, Clifford 1976, 1978), which is generally limited to depths of less than 0.5 m. In addition, RDC is unique in that it is able to compact large areas of open ground at depth, both effectively and efficiently. As a result, it has been used successfully in large reclamation projects such as the Palm Islands in Dubai, in the compaction of sites with un-engineered fill, such as industrial land or brownfield sites; in the agricultural sector to reduce water loss (Avalle 2004b), in the mining sector to improve haul roads and tailings dams, in general civil construction works (Avalle 2004a) and for an 80 km highway rehabilitation project (Jumo & Geldenhuys 2004).

This paper seeks to quantify the zone of influence, that is the depth and lateral extent, of the 4-sided 'impact roller' (Photo 1), by means of a field trial involving in situ and laboratory testing and extends previous work by Avalle et al. (2009).

Photo 1 : Rolling dynamic compaction: Broons 4-sided 'impact roller'.

2. FIELD STUDY

The field trial was conducted in June 2011 at the Project Magnet Tailings Storage Facility at the Iron Duke Mine, which, as shown in Figure 1, is located 49 km west of the South Australian city of Whyalla. RDC was achieved by means of Broons' 8 tonne, 4-sided impact roller (BH-1300), traversing over three adjacent lanes in order to compact three loose lifts of approximately 1,200 mm thickness of coarse, magnetite iron tailings. Surveying, soil sampling and a suite of in situ tests were performed at intervals of 8 passes of the impact roller to measure ground improvement. The in situ testing included dynamic cone penetration testing in the form of the Perth penetrometer, sand replacement field density tests and the spectral analysis of surface waves (SASW) geophysical technique. In order to classify the soil and quantify its compaction characteristics, laboratory testing was undertaken which involved standard and modified Procter compaction tests, particle size distribution and Atterberg limits tests. In addition, earth pressure cells (EPCs) were installed at different depths to measure dynamic pressures induced by RDC.

2.1. Test Pad Construction

In order to measure the zone of influence and effectiveness of the impact roller a test pad was constructed in three separate lifts of 1,200, 1,530 and 1,460 mm in thickness, as illustrated in Figure 2(a), which also shows the locations of the embedded earth pressure cells (EPCs). These are discussed later. Figure 2(b) shows a plan view of the test pad, which enabled the impact roller module to compact the soil in three adjacent lanes. In each case, as shown in Figure 2(b), the direction of travel of the module was to the top of the page.

The first lift of the test pad was constructed by mine dump trucks end-tipping loose material adjacent to the pad, whereby a large front-end loader subsequently spread the material over the pad. This process caused the soil to be partly compacted by the weight of the loader. This was repeated until a lift height of approximately 1,200 mm was achieved. For the remaining two lifts, the soil was placed by dump truck and then leveled using a 30 tonne excavator (Photo 2), which meant that the placed material was slightly less compact than the first lift, since the excavator did not pass over the surface as much, since it used a combination of spreading the soil with its bucket and tracking over the top layer to level the surface.

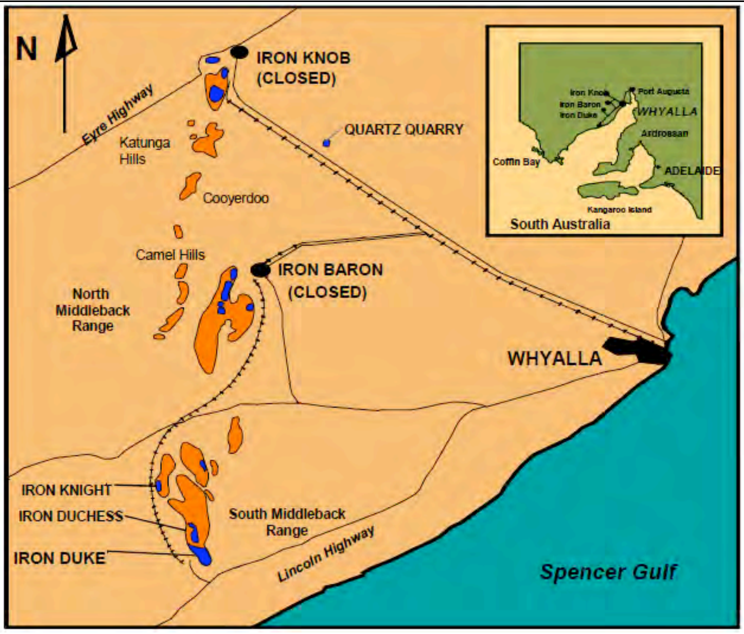
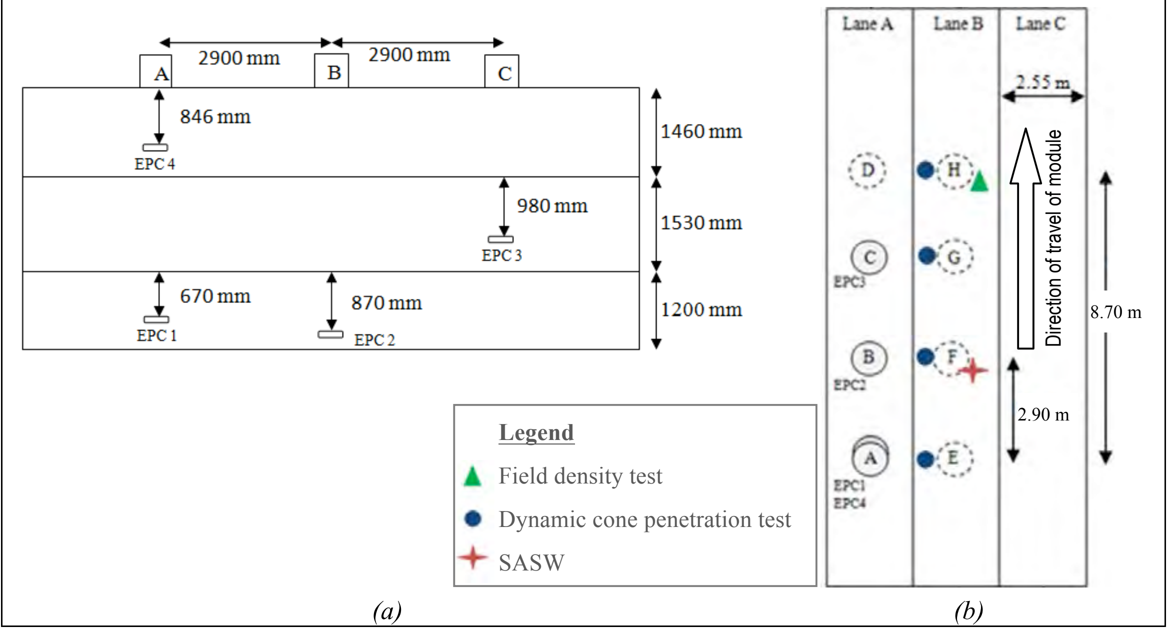


Figure 1 : Location of field study site – Iron Duke Mine, South Australia (OneSteel, 2004).



(a) (b)

Figure 2 : Details of test pad: (a) cross-sectional view, (b) plan view.

2.2. Material Characteristics

The material used to construct the test pad consisted of coarse iron magnetite tailings. In order to classify the tailings and to determine its compaction characteristics, a series of index tests (i.e. particle size distribution and Atterberg limits tests) were performed, as well as standard and modified Proctor compaction tests. Figure 3 shows the average grading curve obtained from 9 particle size distribution tests, which were performed in accordance with AS 1289.3.6.1 (Standards Australia 2009). The 9 tests exhibited a very tight distribution about the average. The Atterberg limits tests and the particle size distributions suggest that the soil is a well-graded sand (SW) with some clay fines of low plasticity.

Standard and modified Proctor compaction tests were performed in accordance with AS 1289.5.1.1 and AS 1289.5.2.1 (Standards Australia 2003a, b), respectively. The results are summarised in Figure 4. The large dry unit weights are a consequence of the sand consisting of crushed magnetite.

Photo 2 : Test pad construction showing excavator used.

2.3. In Situ Testing

The locations of the in situ tests were shown previously in Figure 2(b) and consisted of field density tests, dynamic cone penetrometer tests, and geophysical testing in the form of the spectral analysis of surface waves (SASW). Due to space constraints, the SASW results are not presented here, but will be the topic of a future paper.

2.3.1. Field Density Testing

In order to obtain direct measurements of in situ density, sand replacement tests were performed in accordance with AS 1289.5.3.1 (Standards Australia, 2004). Three tests were performed at depths of approximately 300 mm below the surface of each lift, approximately at Location H [Figure 2(b)]; prior to rolling, and after 8 and 16 passes. These are time consuming tests, which limited the number that could be carried out within the available time.

The field dry density results are shown in Figure 5. Neglecting the measurements for Lift 2, which are inconclusive, and may be the result of surface disturbance, the measurements indicate that the majority of the increase in soil density occurred in the first 8 passes, with a diminishing rate of increase thereafter. These results are consistent with settlement measurements obtained by surface levelling.

Figure 6 combines all field density test data for the site and shows a plot of the average modified dry density ratio against the depth below ground surface for 8 passes of the impact roller and can be used to determine the depth at which a target dry density ratio (e.g. 95% with respect to modified compaction) is

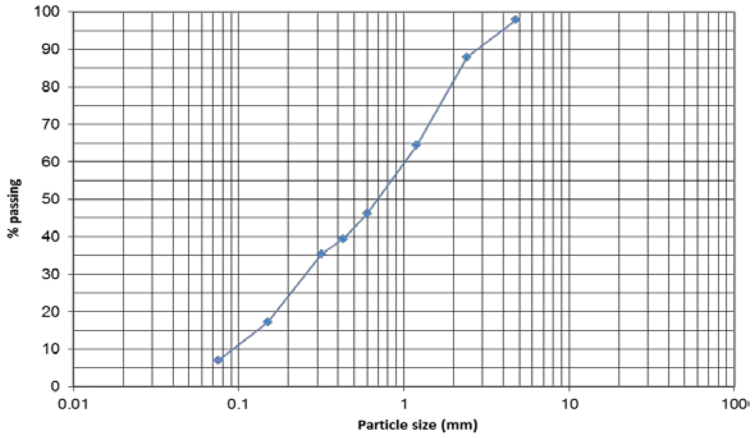


Figure 3 : Average particle size distribution from 9 tests.

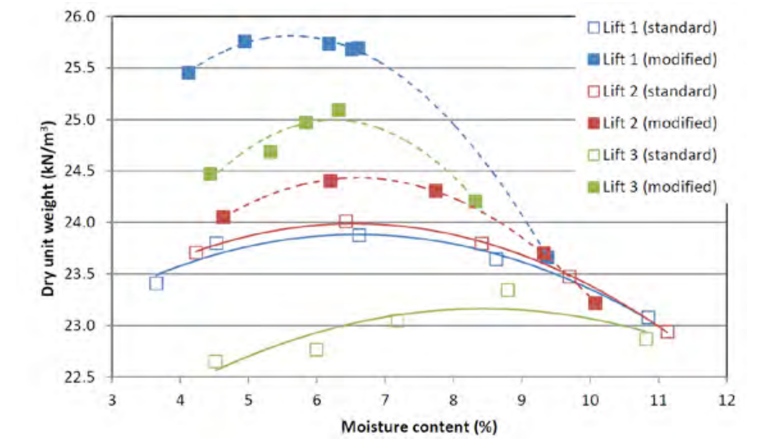


Figure 4 : Results of standard and modified Proctor compaction tests for each lift.

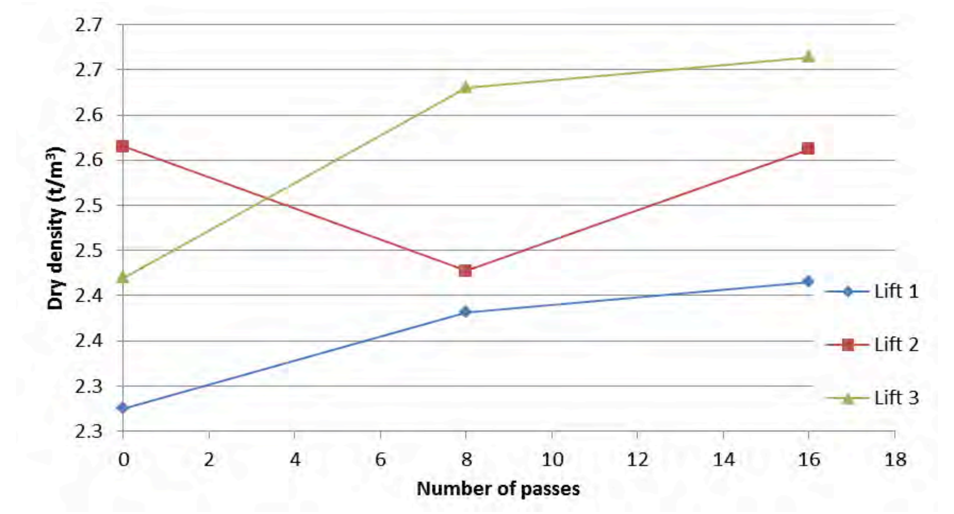


Figure 5 : In situ dry density plotted against number of passes.

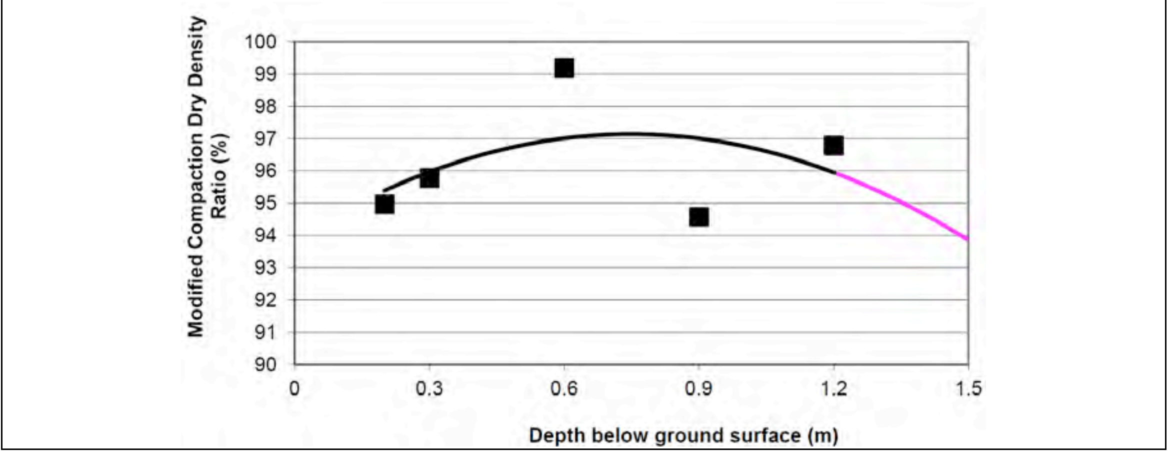


Figure 6 : Modified dry density ratio versus test depth (8 passes of the impact roller).

expected to be achieved. Extrapolating the trend line obtained from the data shown in this figure, it can be estimated that the effective depth for 8 passes is approximately 1.3 m (i.e. 8 passes of the impact roller will achieve a dry density ratio of 95%, provided that the layer thickness does not exceed 1.3 metres).

2.3.2. Dynamic Cone Penetrometer Testing

In order to assess density improvement with depth, the Perth penetrometer test (PPT) was performed with blows recorded every 50 mm, in accordance with the standard procedure AS 1289.6.3.3 (Standards Australia 1997). Figure 7 summarises the average results across all tests undertaken (i.e. all lifts), so as to determine a general trend with increasing passes and also to determine the depth of influence of the impact roller. Each test was terminated at a depth of 850 mm due to the physical limit of the equipment. Between depths of 0.3 to 0.85 m, there is a noticeable increase in the number of blows with greater number of passes of the impact roller. Above a depth of 0.3 metres, results are inconclusive, again likely due to surface disturbance caused by the roller. Figure 7 suggests that the impact roller is effective in improving the in situ density of the tailings from 0.3 metres to beyond the penetrometer depth of 0.85 m.

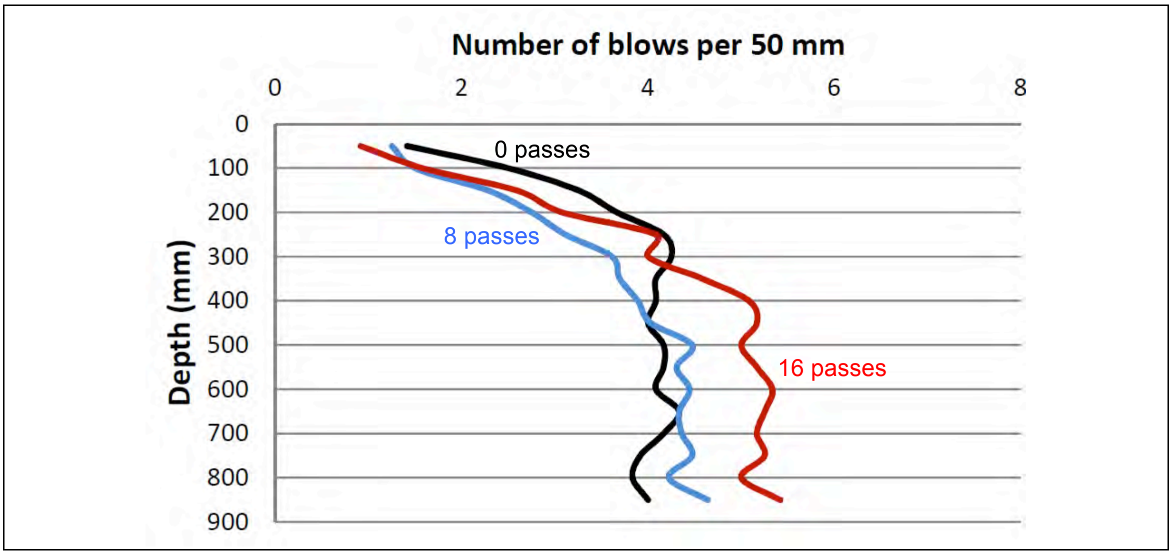


Figure 7 : Results of dynamic cone penetrometer tests.

3. EARTH PRESSURE CELLS

Each time the impact roller strikes the ground, it creates a pressure wave which travels through the soil from the surface. A key aspect of this research project was to gain knowledge about how that pressure wave propagates through the soil and to use that understanding to develop a model of the zone of influence of the impact roller. A total of 4 × Geokon 3500 earth pressure cells (EPCs) were buried at different depths and used to measure pressure within the ground, as shown previously in Figure 2(a). The EPCs were offset horizontally by a half turn of the roller (2.90 m) to prevent stress shadowing. Measurements from the EPCs were acquired at a sampling frequency of 2 kHz (i.e. one sample every 0.0005 seconds). That frequency proved appropriate to balance the conflicting requirements, on the one hand to detect the sudden increase in pressure caused by the roller striking the ground and, on the other, without generating overly excessive data.

The EPCs were installed at each depth by using the excavator to create a trench. As suggested by Rinehart and Mooney (2009), coarse bedding sand was used when positioning the EPCs in the trench, as shown in Photo 3. The sand was used to form a solid base beneath the cell so that it was less likely to move and yielded more accurate measurements. Given that the test pad material itself consisted of coarse sand, this detail may have been unnecessary. The soil was then replaced in the trench by the excavator and its was then compacted slightly by means of its bucket. This process replicated the virgin construction of each lift.

Photo 3 : Preparing the EPCs in situ on bedding sand.

The EPC testing program consisted of 16 passes per lane, 3 lanes per lift and a total of 3 lifts, as shown previously in Figure 2. Each of the passes was considered separately, thereby producing a total of 144 data sets characterising an individual pass of the impact roller. An indication of the depth of influence can be obtained by determining how pressure induced by a strike of the roller varies with depth. To develop that relationship, data from all three lifts were used. Again, as shown in Figure 2, two EPCs were installed in Lift 1, 3 in Lift 2 and 4 in Lift 3, together providing pressure readings at 9 different depths below the surface, as the test pad is progressively constructed, each lift in succession.

An example of the data obtained from the EPCs is shown in Figure 8. Here a direct impact is measured by the impact roller striking the ground immediately above the embedded EPC, where a single main pressure peak of over 200 kPa is recorded. Two smaller peaks are also measured either side of the main peak, at intervals of approximately half a second, which corresponds to the module striking the ground each quarter revolution before and after the location of the EPC. In this particular pass, the two adjacent peaks were readily visible; however all other peaks were barely detectable since the pressure dissipates rapidly through the soil as the impacts occur farther away. In contrast, Figure 9 shows an example of measurements obtained when the roller did not impact the ground directly above an EPC.

An example of superimposed data from each EPC is given in Figure 10. As shown previously in Figure 2(a), EPC1 was located immediately below EPC4, at respective depths of 3,337 and 846 mm below the ground surface; EPC2 was located 3,850 mm below the ground; and EPC3 2,512 mm below the ground surface, once all 3 lifts had been placed. These depths account for non-uniformity of the ground surface and were established by on site levelling. Figure 10 clearly shows the decay in maximum imposed dynamic pressure as the depth increases, as well as the increase in static pressure with depth recorded by each EPC, which represents the overburden stress.

Figure 11 shows the measured peak pressures averaged over all of the EPCs plotted against depth below ground. Only peak pressures corresponding to module impacts striking the ground directly over an EPC were used to develop this and the remaining figures. The plot shows that the highest pressure reading obtained in the field trial was 604 kPa at 0.67 m depth. The pressure then quickly dissipated, decreasing by over 50% to around 260 kPa at 1 m depth. By 2 m depth the pressure had again halved to 120 kPa, just over double the overburden pressure at that depth. The deepest EPC, located 3.85 m below ground, measured a pressure of 38 kPa. That value represents less than 10% of the highest value recorded, but was still nearly equivalent to the static pressure of the roller at the surface, suggesting that, even at that depth, the roller was having some influence.

The pressure measurements from the 3 test lanes were combined to produce a cross section showing the zone of influence in the plane perpendicular to the direction of travel. Figure 12 shows a summary contour plot of peak pressure imparted by the impact roller with depth after 16 passes of the impact roller. It can be observed that the highest pressure readings recorded (> 200 kPa) are located in the upper 2 m;

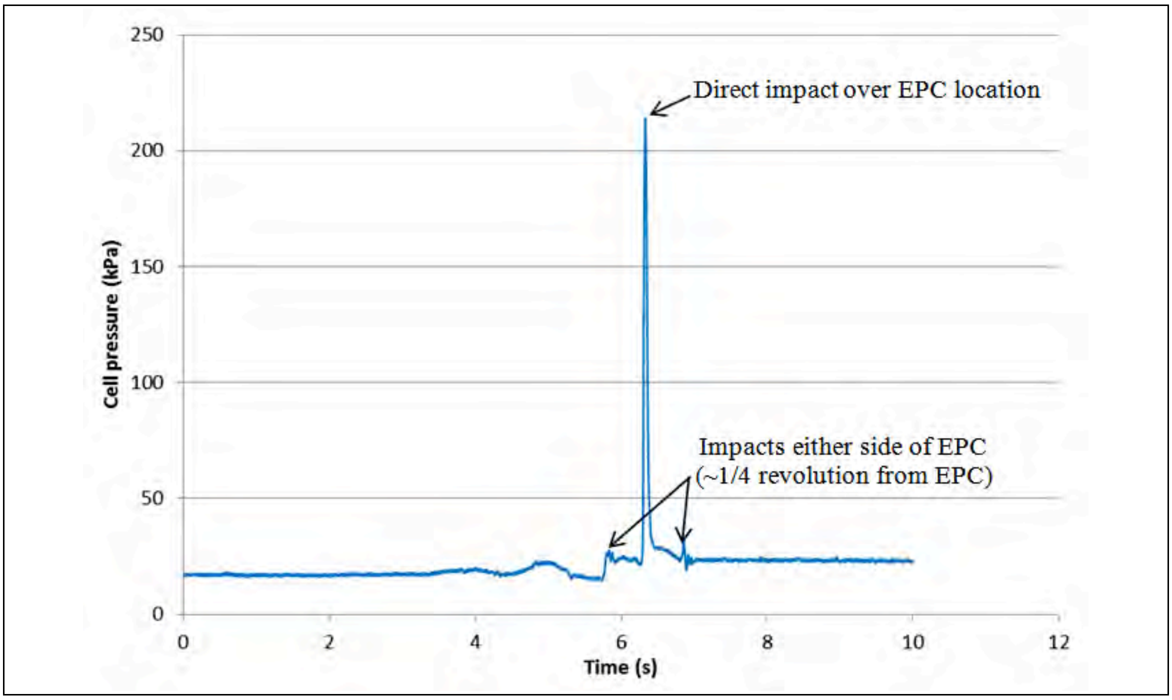


Figure 8 : Example results obtained from direct impact over an EPC (EPC3, Lift 2, Lane A, Pass 2).

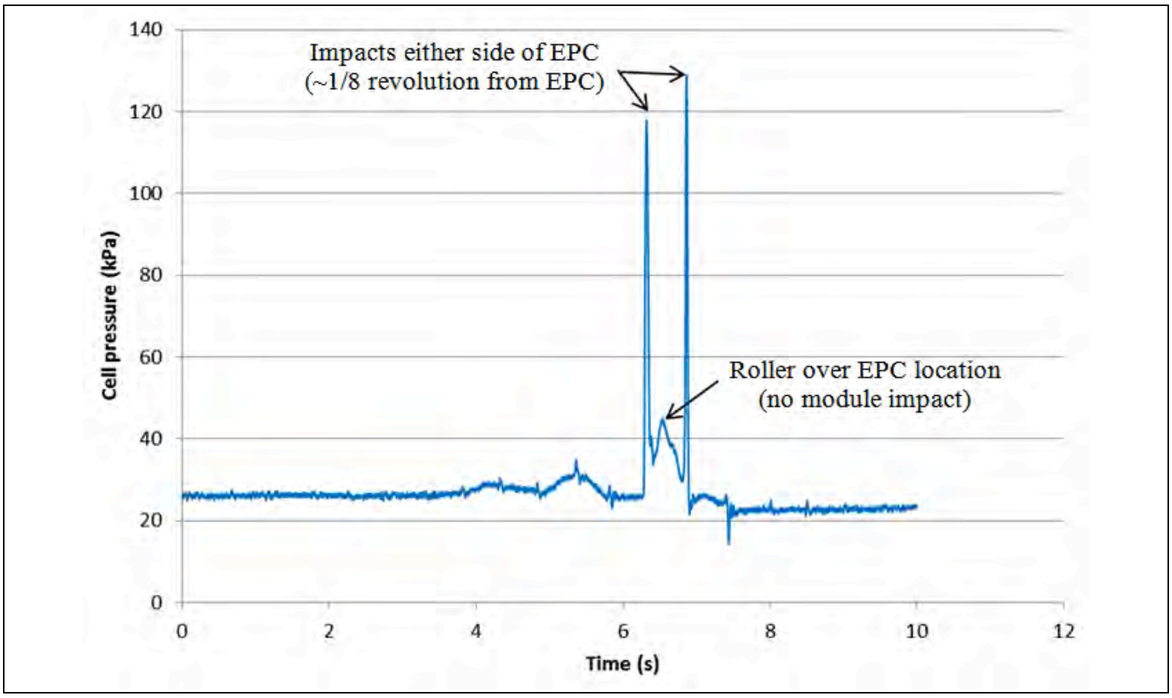


Figure 9 : Example data from an impact not directly over an EPC (EPC3, Lift 2, Lane A, Pass 7).

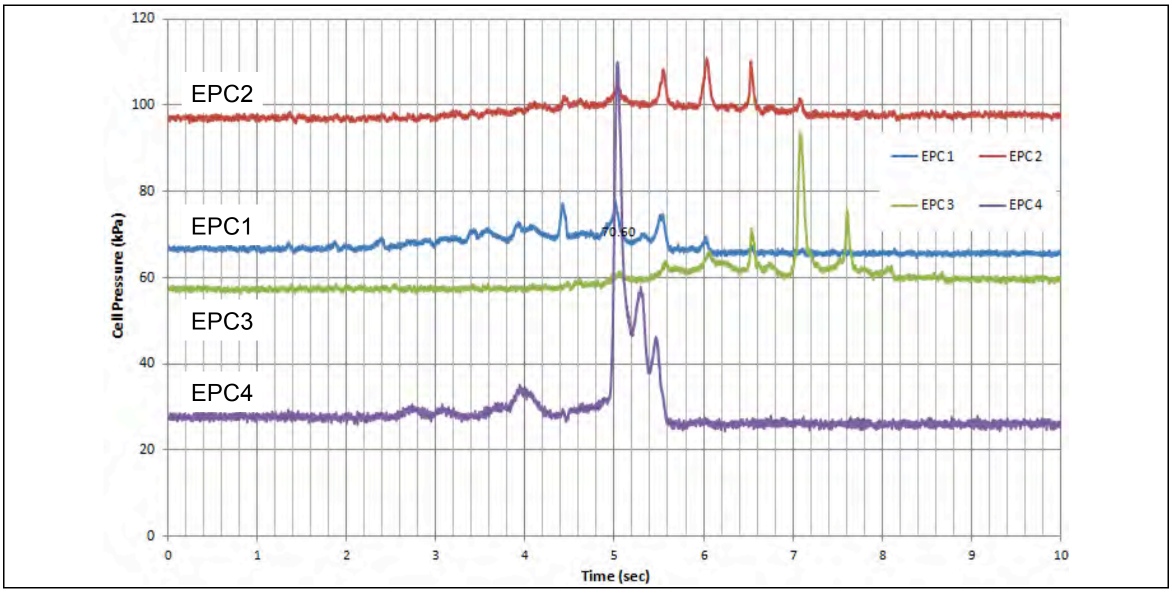


Figure 10 : Example of superimposed results from all 4 EPCs.

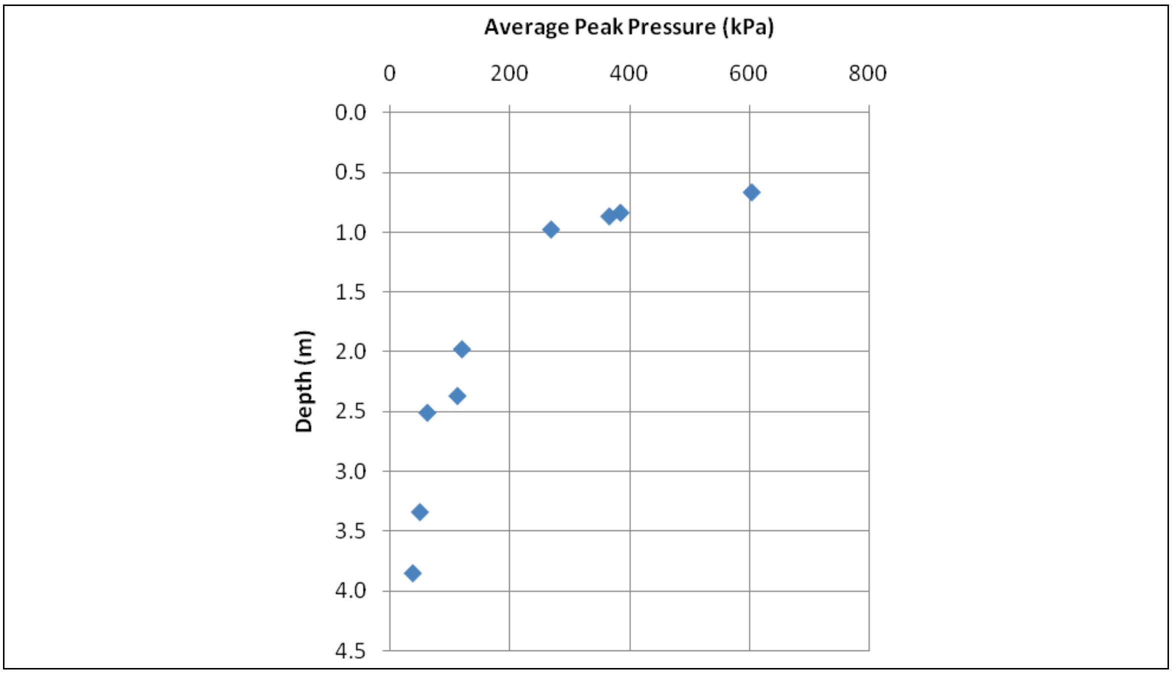


Figure 11 : Average peak pressure versus depth below ground.

supporting other test data that suggests most of the quantifiable ground improvement occurs within this zone. Even the deepest pressure cells (buried at 3.85 metres below the ground surface) registered positive pressure readings due to the impact roller; suggesting that the zone of influence extended beyond this depth. It should be noted that the somewhat linear nature of the contours is related to the spacing and relative sparsity of the EPC locations. In reality, the contours would be curvilinear in shape. Figure 13 shows a summary contour plot of pressure imparted by the impact roller with depth after 16 passes in theplane parallel to the direction of travel. It can be observed that the highest pressure readings recorded (> 200 kPa) are located within the upper 1.5 m.

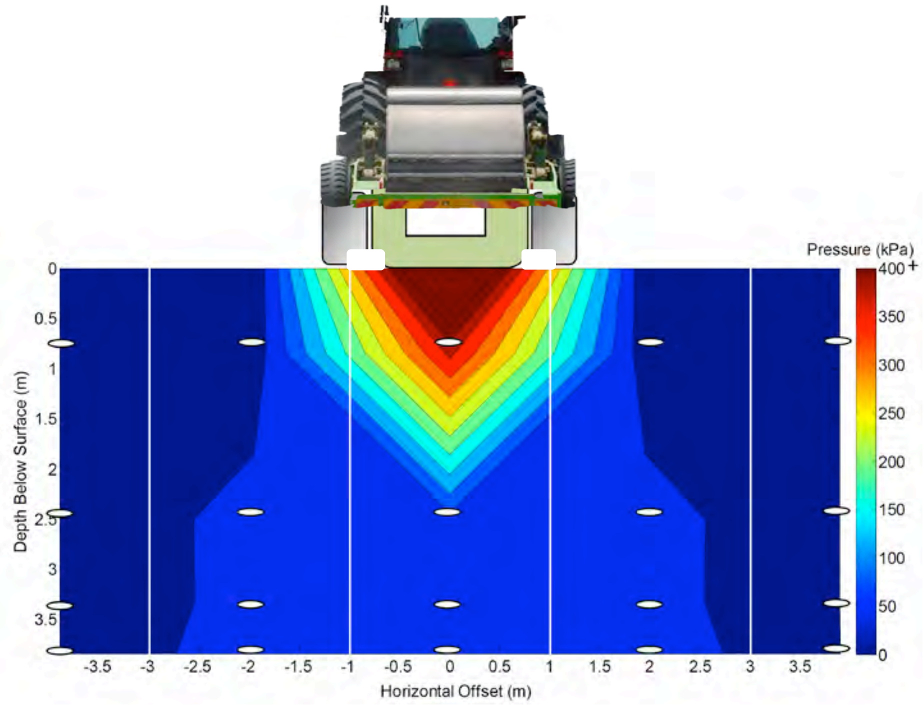


Figure 12 : Pressure contours with depth after 16 passes in plane perpendicular to direction of travel.

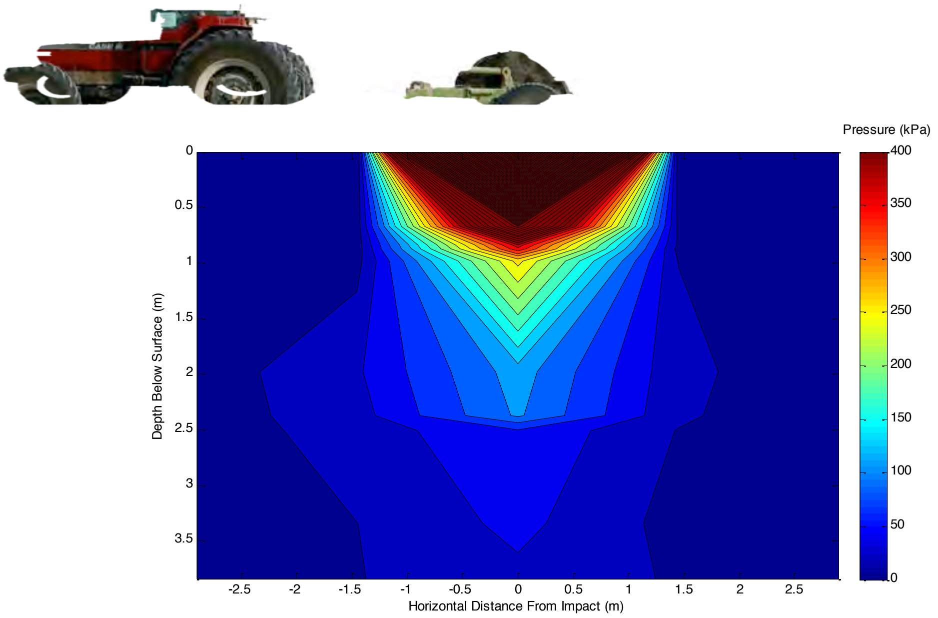


Figure 13 : Pressure contours with depth after 16 passes in plane parallel to direction of travel.

4. CONCLUSIONS

This paper has presented the results of a field study, conducted at Iron Duke Mine, near Whyalla, South Australia, which aimed to measure the zone of influence of the 4-sided impact roller. Instrumentation and testing confirmed that quantifiable ground improvement occurs within the upper 2 m below the ground, although influence was measured at a depth of 3.85 m by means of earth pressure cells. Contour plots were developed which quantified the influence zone at various stress levels. Future work will focus on measuring the ratio of density improvement with depth and lateral extent.

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