The Influence Zone of the Impact Roller

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Abstract:
Various studies have been carried out in an effort to quantify the effectiveness of rolling dynamic compaction. However, it has been discovered that there is no existing form of verification for its zone of influence. For this reason, the impact roller is not widely recognised by geotechnical engineers as a trusted form of compaction. In this study, the zone of influence of the impact roller was quantified by measuring the stress distribution in the subgrade. This was undertaken through the use of Earth Pressure Cells (EPCs). The EPCs provided credible results which agreed with literature. Concurrently, a numerical model was developed using finite element analysis software, Midas GTS, which replicated in situ conditions and provided measurements for the zone of influence. From the numerical model, it could also be concluded that granular soils have a greater influence depth than cohesive soils. By comparing the field results with the numerical model, it was found that the dynamic effect of the roller can exert a load of approximately 415 kN with each strike. Finally, using Cone Penetration Tests (CPTs) in conjunction with the numerical model it was observed that the influence zone of the impact roller extends to a depth of 3-3.5m. At this depth the impact roller exerts a stress of approximately 75 kPa, according to Midas GTS, on soil which consists of a clay fill overlaying typical sand materials. The model developed in this research has identified the need for further investigation into the depth of influence of the impact roller. Furthermore it has the potential to assist in making rolling dynamic compaction an effective and reliable choice for geotechnical engineers.

Keywords: Impact roller, rolling dynamic compaction, influence zone, Earth Pressure Cells (EPCs), Midas GTS

1. INTRODUCTION

The impact roller, seen in Figure 1, is a relatively new earth compaction module. It is used with the same intention as any other type of earth compactor, which is to improve the subgrade until it is suitable for construction or agricultural use.

Figure 1 – The four-sided Impact Roller

The advantages of the impact roller were discovered as early as 1930 and throughout the last 40 years the design has continued to evolve. These improvements have developed through rigorous testing and field studies. However, its overall effectiveness is still uncertain and very difficult to quantify. It is therefore not widely recognised by geotechnical engineers as a trusted form of compaction.

Various studies by authors such as Clifford (1978) and Kelly (2000) have been carried out to quantify its effectiveness. However, there is currently no existing form of verification for the zone of influence on all soil types. None of the researched measurement techniques used for determining the zone of influence can provide reliable results under all circumstances due to the variability of subgrade materials. Hence, this research concentrated on measuring the depth of the influence zone of rolling dynamic compaction (RDC).

In order to determine the influence zone of the impact roller, two aligned bodies of work were undertaken. The first was field based and involved the calibration and installation of Earth Pressure Cells (EPCs). These were employed to measure the in-situ pressures at varying depths in a soil profile subject to RDC. The second body of work was based on developing a numerical model to simulate the effect of the impact roller. The pressure measurements taken during field work were used to help validate this model, which was then used to estimate the depth of influence of the impact roller.

The following paper outlines the background of the impact roller and the approach undertaken for this research. Furthermore, results and conclusions of the investigation will be discussed.

2. BACKGROUND

In 1949, Aubrey Berrangé invented the first full sized 7 t impact roller and patented it in 1959 (Berry, 2001). Broons Hire (SA) Pty Ltd further established the four-sided single module impact roller with a torsion bar springing system in 1984, seen in Figure 2.

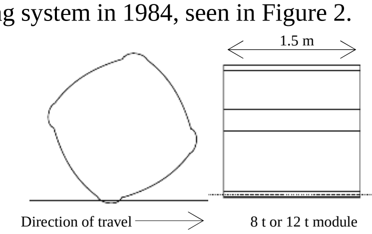

Figure 2 – The four-sided module (Avalle, 2004)

The average speed of the roller is 10 km/h and it can cover approximately 3500 m^2/hour (Broons, 2010). It is available in an 8 t or 12 t module. The hydraulics on the module lift the mass after each blow, allowing it to easily rotate into the next strike. The module supplies both potential and kinetic energy and therefore cannot be considered as a static load. As a result, its influence zone is difficult to quantify.

3. FIELD MEASUREMENTS

The field based section of work was conducted with the intention of measuring the ground pressure induced by the impact roller. A suitable testing site for the impact roller was made available in Gillman, SA during May 2010. It comprises a large, uncompacted, flat expanse of vacant land, ideal for the impact roller.

A preliminary investigation was undertaken with the intention of gaining a clear understanding of the subgrade characteristics at the site and to identify appropriate testing areas for the impact roller and EPCs. A thorough appreciation of the subgrade characteristics was important so that the influence of the impact roller could be analysed and measured accurately. Borehole drilling, Cone Penetration Tests (CPTs) and a geometrical survey of the area were all conducted during this preliminary investigation.

To measure the depth of influence, testing was undertaken using Geokon 3500 circular series semiconductor type EPCs, seen in Figure 3, to measure the total normal stresses exerted by the impact roller. CPTs were also conducted in order to infer a zone of influence with an increasing number of impact roller passes.

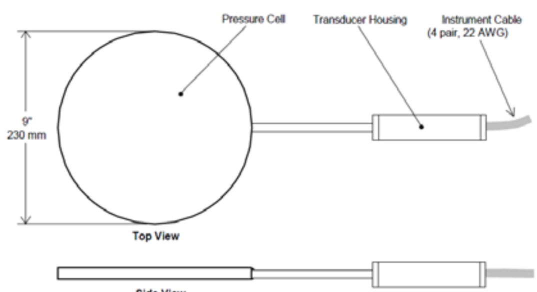

Figure 3 – Geokon 3500 circular series (Geokon, 2007)

EPCs were installed on two different sites to measure both the static and the dynamic influence of RDC. This type of measurement has only previously been conducted to investigate the influence of vibratory rollers in a study by Rinehart & Mooney (2009). The first testing area, Area 3, had a trench excavated to 0.8 m. A 300 mm layer of gravelly sand with a Penrice by-product (Penrice sand) was compacted at the bottom of the trench to provide a firm, level base for the EPC. Furthermore, this layer raised the trench depth to approximately 0.5 m to avoid water damaging the EPC equipment. This can be seen in Figure 4. Penrice sand was backfilled into the trench, providing a typical sand profile for analysis.

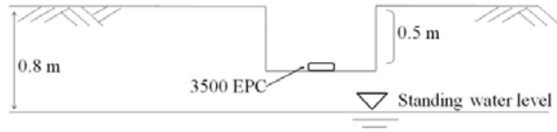

Figure 4 – Cross-sectional view of trench and EPC placement (Area 3)

Three EPCs were also installed on a second testing area, Area 1, to measure the influence of the impact roller at a variety of depths. As shown in Figure 5, EPCs were installed in a stepped arrangement, separated by 1.45 m horizontally, coinciding with a quarter rotation of the impact roller. The vertical spacing between EPCs was 0.5 m in order to avoid stress shadowing.

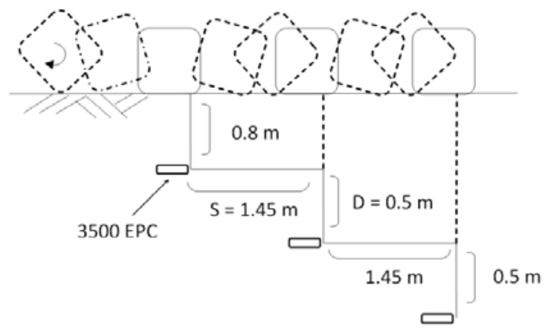

Figure 5– Cross-sectional view of stepped configuration for EPCs (Area 1)

The installation process undertaken at Area 1 was similar to that of Area 3. However, an additional 630 mm layer of clay fill was compacted on top of the Penrice sand to provide a firm surface for impact rolling. Testing lanes were again set up for the operator to ensure a consistent rolling pattern.

A static analysis was undertaken on both Areas 1 and 3 which involved placing the impact roller module over each EPC. This was undertaken for two reasons; firstly, to ensure that all EPCs were functioning correctly and secondly, to compare the results with the static numerical model.

Table 1 shows that when the impact roller was placed over each EPC an increase in stress was recorded. The results also show an increase in stress from the deepest cell (1.8 m) through to the shallowest cell (0.8 m). This is a logical result as the load the impact roller induces into the ground dissipates with increased depth. On Area 3, where only 1 EPC was placed at 0.5 m, a stress of 50.4 kPa was measured. This is consistent with the trend observed at Area 1 as it is 0.3 m above the shallow EPC and 11 kPa greater.

Dynamic analyses were also undertaken above the EPCs on Areas 1 and 3, involving 20 passes of the impact roller. Each pass of the impact roller was recorded by the EPCs at a frequency of 2 kHz for a period of 15 s.

Table 1 – Static EPC recordings (Area 1)

Static weight applied above (EPC)	*Shallow Cell increase (kPa)*	*Middle Cell increase (kPa)*	*Deep Cell increase (kPa)*
Shallow	39	0	0
Middle	6	19	0
Deep	0	0	15

Figure 6 shows the data obtained from the shallow and deep EPCs on Area 1. There were inconsistencies with the magnitudes recorded from the middle EPC and hence for this research, was excluded from further analysis.

The shallow EPC had, on average, the highest stress readings, as it was closest to the surface. Both EPCs had an increasing linear trend line between the number of passes and recorded EPC stress. This was attributed to the impact roller decreasing the void ratio in the soil and therefore increasing its density. With an increased density the imparted energy into the ground propagates more freely and hence generates greater stress values at depth. The shallow EPC had a greater sensitivity to where the module struck the surface. This can be seen in Figure 6, which shows erratic results for the shallow EPC.

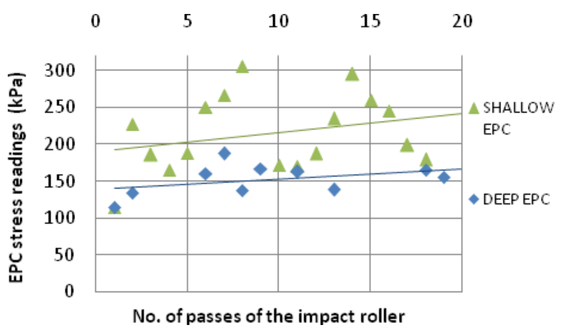

Figure 6 – Summary of induced stress

The dynamic results for Area 3 did not show the same trend as discussed for Area 1 as the stress decreased with the number of passes rather than increased. This was not expected. Due to the EPC being placed at a depth of 0.5 m erratic recordings were produced, contributing to the decreasing trend observed. The EPC recorded a stress of 190 kPa during the first pass.

As mentioned, EPC analyses have not been previously conducted for RDC and hence cannot be verified against existing literature. Any conclusions about the depth of influence for RDC cannot be verified further than 1.8 m. However, the stress readings recorded at 0.8 m and 1.8 m were approximately 190 kPa and 140 kPa respectively, inferring the influence depth would continue further than 1.8 m.

In addition to the two testing sites, another 5 lanes were compacted to compare the relative change in density at depth with an increasing number roller passes. CPTs were conducted to infer the influence depth of this compaction scheme. The CPTs were taken over a highly variable fill material consisting of different sand and clay materials. The varying cone tip resistance, measured by the CPTs, was plotted for 0, 10 and 20 passes, seen in Figure79. This shows an increase in cone tip resistance for both 10 and 20 passes. It also shows that the increase in cone tip resistance with number of passes is decreasing with depth, which agrees with current literature. Figure 7 also suggests that the influence zone extends to a depth of 3 – 3.5 m. However, due to the heterogeneity of fill, these results can only be taken as an approximation.

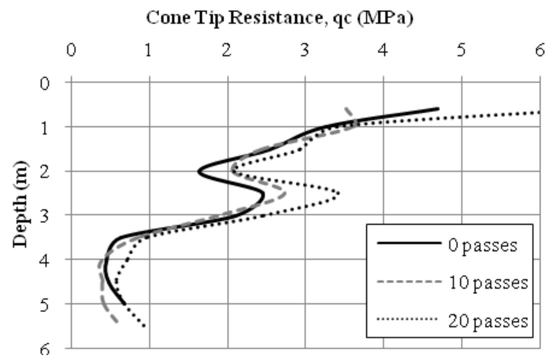

Figure 7 – CPT results for 0, 10 and 20 passes

4. NUMERICAL MODEL

To complement the field investigation, a numerical model was established to simulate the effect of the impact roller. Geotechnical finite element analysis software, Midas GTS, was used to establish this model to predict the stress distribution induced by the impact roller. The variation in stress throughout the soil profile provided an indication of the roller's influence zone.

The general process for using Midas GTS involved simulating the load of the impact roller over theoretical soil profiles. These profiles were characterised by entering selected soil parameters. Using this information, the model was then able to make estimations of how the subgrade responded to the loading conditions. The model output was used to produce the distribution of soil stress induced by the simulated load. The influence zone of the impact roller could then be approximated using this distribution.

The numerical modelling was divided into two major segments; static and dynamic analyses. The static investigation involved simulating only the static load of the impact roller. The dynamic analysis was an advanced investigation which involved applying a load that varied with time. Both static and dynamic analyses began with a sensitivity analysis to determine which aspects of Midas GTS had the greatest influence on the model. Following this, idealised soil profiles were considered and compared. Finally, both static and dynamic analyses were applied to the Gillman testing site. The purpose of this was to validate the model against the EPC measurements. Table 2 displays the soil parameters that were found to best represent a typical sand and a typical clay profile. These parameters were applied to all the static and dynamic analyses in Midas GTS.

Table 2 – Soil parameters used to represent typical granular and cohesive soils in Midas GTS for both static and dynamic analyses

Parameter (units)	Granular	Cohesive
Cohesion (kPa)	2	50
Friction Angle (°)	30	0
Dry Unit Weight (kN/m^3)	20	18
Saturated Unit Weight (kN/m^3)	22	19
Modulus of Elasticity (MPa)	15	25
Poisson's Ratio	0.3	0.45*

*For static analysis, Poisson's Ratio was 0.35

The static investigation was conducted to gain an understanding of the stresses induced by the weight of the impact roller. An 18 by 18 m model with an 8 by 12 m finer zone was found to provide the best balance between computation time and accuracy of results. The finer zone had a resolution of 0.125 m, whilst the remaining area had a 0.25 m mesh.

The soil parameter sensitivity analysis for the static model established that cohesion and internal friction angle had a significant influence on soil stress distribution within Midas GTS. Therefore, these two parameters were highlighted as the most important input data for the static influence zone estimation model. For this reason, when a soil profile was applied to the model, evaluation of these soil parameters was particularly critical.

Two basic, single-layered soil profiles that represented a typical sand and typical clay were modelled. These cases were used to develop an understanding of how the stress distribution, resulting from the static load of the impact roller, varied with soil type.

Another static analysis was conducted that simulated the weight of the roller over a simplified soil profile representing Area 1 at the Gillman site. This profile consisted of a 630 mm clay fill layer overlying gravelly sand with Penrice by-products.

A uniformly distributed load of 51.67 kN/m was applied to each profile that simulated the pressure induced by the impact roller. This load was estimated based on the approximate static weight and span of the roller. The model output was then used to produce a soil stress distribution in which the depth to particular stress contours could be measured. These depths are displayed in Table 3.

Table 3 – Stress contour depths for all static analyses

	Depth to Vertical Stress Contours (m)				
Material	**0.8q = 41.3 kPa**	**0.6q = 31.0 kPa**	**0.4q = 20.7 kPa**	**0.3q = 15.5 kPa**	**0.2q = 10.3 kPa**
Sand	1.09	1.79	2.94	3.92	5.47
Clay	0.77	1.33	2.22	3.05	4.6
Gillman Area 1	0.53	1.14	2.26	3.27	5.07

The main objective of the numerical model research was to simulate the dynamic effect of the impact roller. Dynamic analysis in Midas GTS requires that the magnitude of the dynamic load be specified with time. A study by Avalle et al. (2009) found that the impact roller exerted a force of 137 kN over 0.1 seconds. This magnitude was measured using embedded load cells that were installed flush to the surface. To represent the dynamic effect of the impact roller in Midas GTS, this 137 kN or 91.3 kN/m force was applied over 1.5 m for 0.1 seconds.

A 22 by 22 m square profile with an 8 by 12 m finer zone was used to produce the most accurate results. Again, the finer zone had a mesh size of 0.125 m, whilst the remaining area had a 0.25 m mesh. Due to the limitations of Midas GTS, cohesion and internal angle of friction were not considered in the dynamic analysis. Poisson's Ratio had the most significant effect on soil stress distribution in the dynamic analysis.

A model was established that simulated the effect of the 91.3 kN/m dynamic load for 0.1 seconds. This was applied to a typical sand, typical clay and the Gillman soil profiles. Based on the input load and soil parameters, a soil stress distribution was produced. The depths to particular stress contours in this distribution were measured. These depths are displayed in Table 4. Figure 8 displays the induced soil stress distribution and stress contours at Gillman compaction Area 1.

Table 4 - Stress contour depths for all dynamic analyses

	Depth to Vertical Stress Contours (m)				
Material	**0.8q = 41.3 kPa**	**0.6q = 31.0 kPa**	**0.4q = 20.7 kPa**	**0.3q = 15.5 kPa**	**0.2q = 10.3 kPa**
Sand	2.16	3.04	4.59	6.05	9.07
Clay	1.87	2.63	4.1	5.35	7.33
Gillman Area 1	1.88	2.70	4.25	5.75	8.70

Figure 9 shows a summary of the static and dynamic results on both a typical sand and a typical clay. The model suggests dynamic loads have a greater influence zone than static loads and a greater influence zone can be achieved in granular soils than in cohesive soils. These conclusions support the consensus amongst literature.

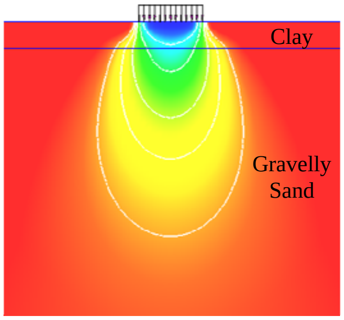

Figure 8 – The simulated soil stresses at Area 1

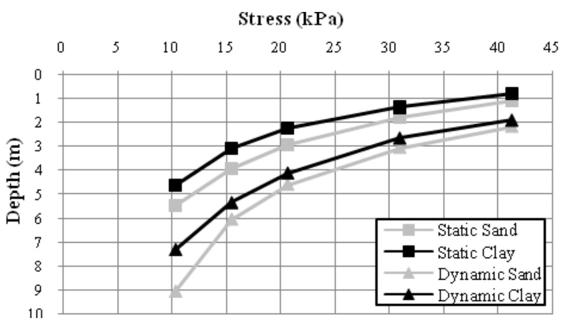

Figure 9 - Summary of the depth to stress contours for both static and dynamic analyses on granular and cohesive soils

5. COMPARISON BETWEEN FIELD MEASUREMENTS AND THE NUMERICAL MODEL

In order to validate the results a direct comparison of the field measurements and the numerical model was made. This was undertaken by comparing the stresses obtained with depth in both bodies of work for static and dynamic analyses. The EPC recordings were then used in the numerical model to calibrate the induced load. This established a relationship between soil stress and depth.

Figure 10 shows the comparison of the static results from the numerical model and the field measurements. It can be seen that the stresses for depths of 0.5 and 0.8 m have small variations of 1.9 and 2.6 kPa respectively. This suggests that for the shallow readings, the EPCs were measuring stress accurately. The two deeper EPCs however, measured lower stresses than in the numerical model with a difference of approximately 10 kPa. Realistically, this isn't a large difference in stress, however it shows that there are some inaccuracies recorded by the EPCs at these depths. The reason for these inaccuracies could be based on the precision of the module and EPC alignment during testing or the uniformity of the soil used in the numerical model compared to the field profile.

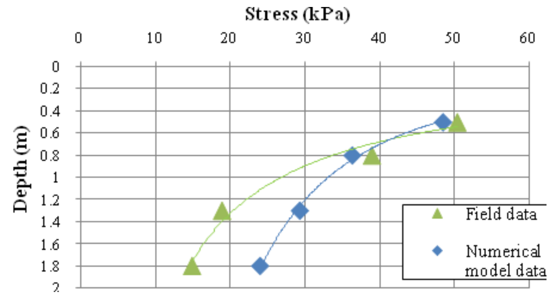

Figure 10 – Summary of static analysis

Due to the limited capabilities of Midas GTS with multiple strikes, only the first passes were compared for the dynamic analysis. Figure 11 presents the comparison of these results. It is important to note that the load used for the numerical model in the dynamic case was taken as an estimate from Avalle et al. (2009) as 137 kN and consequently caused large differences in stress measurements. These large differences could also be due to Midas GTS using elastic theory principles, hence not taking plastic deformation into account. Soil naturally undergoes a plastic deformation after compaction, which cannot be modelled by Midas GTS, hence possibly causing inaccurate results. The EPC values appear to be more realistic, however further testing would need to be undertaken into the dynamic analysis in both field work and numerical modelling to be able to estimate a zone of influence.

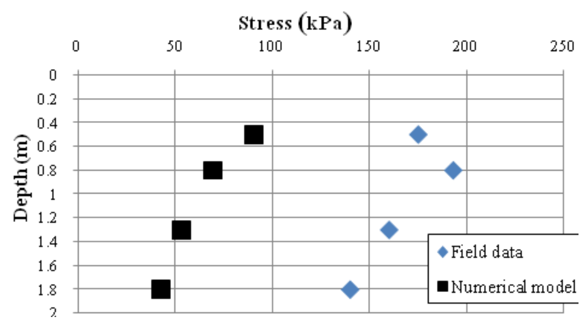

Figure 11 – Summary of dynamic analysis

Finally, a dynamic model was established on Midas GTS that analysed the same profile encountered at compaction Area 1; a 630 mm clay fill layer overlying Penrice sand. The EPC stresses recorded at Area 1 were approximately 190 kPa at 0.8 m depth and 140 kPa at 1.8 m depth. The surface load in the dynamic model was varied until similar soil stress conditions were achieved. It was found that a load of 275.5 kN/m, over the 1.5 m span of the roller, resulted in the closest representation of the field stress conditions. The 275.5 kN/m uniformly distributed load corresponds to a total load of approximately 415 kN, or 42 tonnes.

The loading of 275.5 kN/m was used in a dynamic Midas GTS model to establish an estimation of the entire stress distribution. Figure 12 displays the comparison between the EPC results and the soil stresses induced by the 275.5 kN/m applied dynamic load.

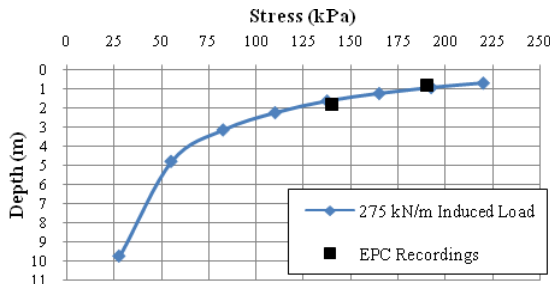

Figure 12 – Soil stress with depth for 275.5 kN/m load

The definition of influence depth is subject to the conditions and desired outcomes of the compaction process. For this reason, the impact roller cannot be labelled with a definitive influence depth for all cases. However, using a distributed load of 275.5 kN/m to represent the module in Midas GTS, the expected induced stress distribution can be predicted. Figure 13 displays the soil stress with depth for a granular soil and a cohesive soil when the 275.5 kN/m impact roller load was applied.

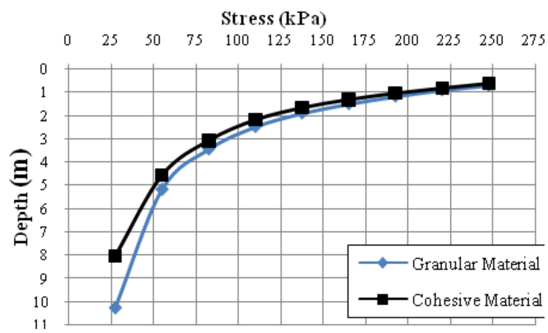

Figure 13 – Soil stress with depth for 275.5 kN/m load

6. CONCLUSIONS

The results obtained from field work were encouraging as the EPCs returned values that were consistent with current literature. It was found that the depth of the impact roller is expected to exceed 1.8 m as EPCs recorded changes in stress of up to 160 kPa at this depth after 20 passes of the impact roller. Also, it was established that RDC exerts greater energy into the ground than the module's static weight as EPCs recorded an increase in stress of 125 kPa and 151 kPa at 0.8 m and 1.8 m, respectively. These results show that EPCs are an effective way of measuring the soil stresses with minimal ground disturbance.

From the CPTs an influence zone to a depth of approximately 3 – 3.5 m can be achieved. Such measurements are highly dependent on the nature of the fill material and will vary accordingly.

The numerical model developed using Midas GTS provided several clear conclusions while investigating the influence zone of the impact roller. The input soil parameters that had the strongest influence on soil stress distribution were cohesion, friction angle and Poisson's Ratio. In both static and dynamic analyses, a greater influence depth was achieved in typical sand than in typical clay profiles. Furthermore, the dynamic effect of the roller induced greater stresses at depth than the static weight of the roller.

Further research would need to be undertaken to gain a better understanding of the zone of influence as a whole. This research could be expanded to investigate influence depth with different subgrade materials, hence giving geotechnical engineers a better understanding of the versatility and benefits of impact rolling.

7. ACKNOWLEDGEMENTS

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