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Analysis of Dynamic Compaction of Loose Soils Under Impact Loads

J. L. Pan

University of Durham, U.K.

A. R. Selby

University of Durham, U.K.

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J.L. Pan
University of Durham
Durham, DH1 3LE, UK.

A.R.Selby
University of Durham,
Durham, DH1 3LE, UK

ABSTRACT

Dynamic compaction has become a popular method world-wide for deep improvement of loose soils in recent years. The method involves the repeated application of high-energy impacts on the soil surface using tampers weighing 10-20 Mg, dropping from heights of 10-20 m, compacting the soil strata to a considerable depth. Previous analytical methods have been used to investigate the effectiveness of dynamic compaction of loose soils, most of which were based on a rigid tamper striking a vertical soil column represented by springs, masses and dampers. This study analysed the dynamic compaction of loose soils under impact loads numerically, using ABAQUS© to generate response to rigid-body impacts of an axisymmetric elasto-plastic finite element (FE) representation of the soils. The analysis also included the stiff plug formed under the treatment area. Various comparisons were made in terms of the plug depth, the compression wave propagation, peak vertical particle accelerations with depth and the mass penetration. The peak vertical particle velocities at ground surface within some 50 metres were computed for estimation of environmental disturbance in the vicinity.

INTRODUCTION.

Dynamic compaction (DC) is a well-known soil improvement technique used to densify loose deposits of cohesionless soils into a state of low void ratio through compaction of the soil fabric and expulsion of void fluids, by means of high-energy impact. It has also been used successfully on cohesive soils of high void ratio, and on wastes and fills. The heavy tamping is achieved by dropping a heavy mass (M) of 10 to 20 Mg from a height (H) generally varying between 10 and 20 m onto predetermined grid points on the treatment area. A 'hammering' which occurs local to the impact forms a stiff soil plug immediately below the drop mass as shown in Figure 1. However, the main beneficial effect, to more considerable depths, is achieved from the outgoing high-energy ground waves. Compression waves, or P-waves, are generated by the impact, which spread downwards and outwards on a hemi-spherical wave front. The energy density is a maximum on the vertical axis of symmetry and reduces with increasing angle from the vertical axis. Also, as the wave penetrates to a greater depth around a larger hemispherical front, the energy density attenuates geometrically. Since the soil improvement is a function of particle vibration, the spread and attenuation of the P-waves define the zone of the compacted soil. Therefore, in this analysis peak vertical particle acceleration was chosen to define the depth of treatment which is considered to be most closely related to soil improvement.

For DC, the distribution and magnitude of P-waves are relevant in choosing the spacing of the impact grid points on the treatment area. The depth to which vibrations penetrate while in excess of the peak vertical particle acceleration of 2g was chosen to indicate the region of soil improvement, where g is the acceleration of gravity, Forssblad [1981], Bement & Selby [1997]. The depth of effective treatment is the main concern of the designer for efficient DC. The mass penetration at impact is another key feature of the DC process. With other parameters constant, a deeper penetration implies that the impact energy is applied over a longer time duration. Consequently, the peak vertical particle acceleration of outgoing waves is reduced, and depth of treatment is smaller.

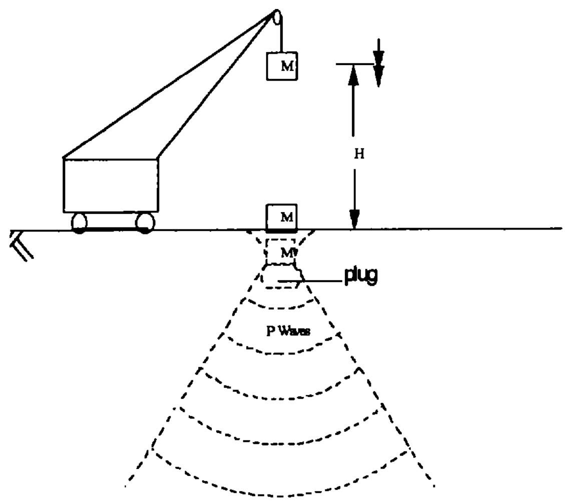

Figure 1 Dynamic compaction

Ground waves due to pile-driving have been modelled successfully using ABAQUS© by Ramshaw *et al.* [1998]. In addition, some researchers have studied DC by experimental means, e.g. West & Slocombe [1973], Menard & Broise [1975], Leonard *et al.* [1981], Mayne *et al.* [1984], Slocombe [1993], Orje [1996] and Kroge & Lindgren [1997]. Others have studied DC by analytical techniques, e.g. Scott & Pearce [1975], Mayne & Jones [1983], Roesset *et al.* [1994], Deeks & Randolph [1995], and Thilakasiri *et al.* [1996]. Chow *et al.* [1992] proposed a one-dimensional wave-equation model that can predict the mass penetration and the depth of soil improvement beneath the impact, and calibrated effectively against site records.

However, fully developed computational modelling of the ground waves and the DC effects due to impact appears not to have been produced numerically. Modern computational packages are now available to model ground waves using elements to estimate outgoing compression, shear and surface waves, and to include elasto-plastic soil behaviour. Site measurement records are becoming available. Granular soil compaction in response to vibration is also better understood. The combination of these facilities offers the potential for progress in the understanding of the ground waves and DC effects due to impact.

The objective of the study was to investigate the ground waves generated during the DC of loose soils numerically, using ABAQUS©, and then to identify zones where peak vertical particle acceleration exceeds 2g. The analysis was implemented by applying three or more blows of rigid-body impacts onto the ground surface. The effects of consecutive impacts were simulated by defining a stiff plug and zones of stiff soil below the drop mass after each blow. Various comparisons were made in terms of the ground waves, peak vertical particle acceleration with depth and mass penetration. The peak vertical particle velocities (ppv) at ground surface within some 50 metres were computed for estimation of environmental disturbance in the vicinity.

NUMERICAL MODELLING

The axisymmetric FE model for the analysis is shown in Figure 2. The dimensions of the model were chosen to be 50 m by 50 m after some mesh experiments. The FE mesh chosen takes into account the wavelength λ, the wave propagation velocity c and the time-step interval Δt adopted in the analysis. Initially, infinite elements were included in the analysis around the outer boundary, Zienkiewicz *et al.* [1983], but were later discarded as unnecessary, since the critical part of the analysis was the first passage of the outgoing spherical wave front of the P-waves.

The soil parameters used for the analysis are summarised in Table 1, which were chosen by taking into account the typical soil properties before treatment and the effects of dynamic compaction on the soil stiffness and density. The 'soft layer' refers to the top layer of either 1 m or 2 m thick for the first blow of the impact, the 'stiff plug' the dense soil plug, immediately below the impact, of either 1 m or 2 m thick and of the same diameter as the hammer after the first impact, the 'stiffer region' below the impact the effective treatment zone and beyond the 'stiff plug' induced by the first and/or second blow of the impact, the 'underlying soil' beyond the effective treatment zone of the impact.

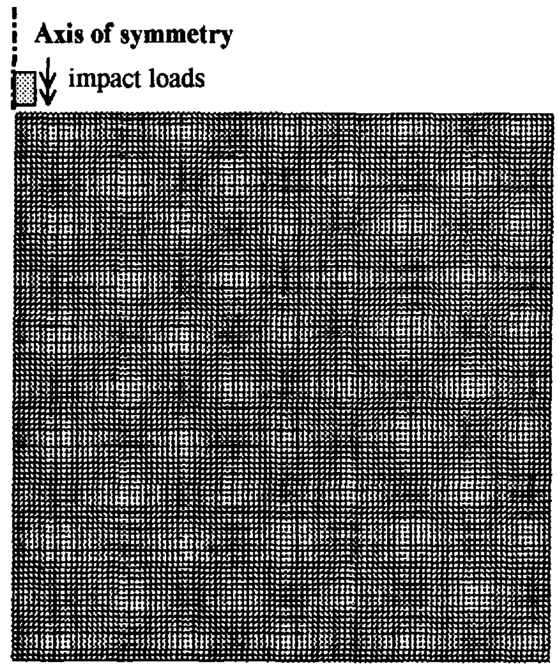

Figure 2 Finite Element Mesh

The soil and impact models were the same as those used in Pan & Selby [2000] and are described briefly below. The analysis employed a Mohr-Coulomb plasticity model for the soil. A total stress technique was employed without taking into account pore water pressure change, as the duration of each impact is only a few milliseconds. First-order 4-node bilinear axisymmetric quadrilateral finite elements were used for the soil, as shown in Figure 3. They have a lumped mass formulation and can better model the effect of impact and ground waves than the consistent mass formulation used in the second-order elements, ABAQUS© [1998].

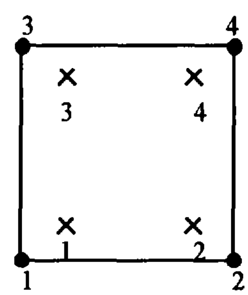

Figure 3 First-order 4-node bilinear axisymmetric quadrilateral finite element

The impact loads (Figure 2) were simulated by a rigid body (i.e. hammer) of 10 Mg and 4 m diameter dropping from 10 m and striking the ground surface. The input in ABAQUS© was implemented by applying an initial vertical velocity of 14 m/s for the rigid body. The simulation of the impacts were as follows: the first blow was applied on the top of the 'soft layer' of either 1 m or 2 m thick, below is the 'underlying soil'; the second blow was applied on the 'stiff plug', immediately below the impact, of either 1 m or 2 m thick and of the same diameter as the hammer and induced by the first blow, below are the 'stiffer region' in the effective treatment zone due to the first blow and the 'underlying soil'; the third blow was applied on the very 'stiff plug', immediately below the impact, of either 1 m or 2 m thick and of the same diameter as the hammer and induced by the second blow, below are the 'stiffer region' in the effective treatment zone due to the second blow and the 'underlying soil'.

Table 1. Soil Parameters.

Soil parameters	Soil zone	No. of blow		
		1	2	3
Density, kg/m³	Soft layer,	1500	-	-
	stiff plug,	-	1800	1800
	stiffer region	-	1800	1800
	underlying soil	1800	1800	1800
Modulus, kPa	Soft layer,	1000	-	-
	stiff plug,	-	550000	800000
	stiffer region	-	10000	20000
	underlying soil	5000	5000	5000
Friction angle	Soft layer,	20	-	-
	stiff plug,	-	45	45
	stiffer region	-	35	35
	underlying soil	25	35	35
Dilation angle	Soft layer,	0	-	-
	stiff plug,	-	15	15
	stiffer region	-	5	5
	underlying soil	5	5	5
Cohesion, kPa	Soft layer,	5	-	-
	stiff plug,	-	100	100
	stiffer region	-	10	10
	underlying soil	5	10	10
Poisson's ratio	All soil	0.35	0.35	0.35

RESULTS AND DISCUSSIONS

The soil parameters used for the analysis were chosen by taking into account the typical soil properties before treatment and the effects of dynamic compaction on the soil strength and density. Further improvement of the adopted soil parameters should be made when site data become available.

Figure 4 shows the variations of peak vertical particle acceleration with depth along the symmetrical axis under consecutive blows for 1 m and 2 m soft layers and stiff soil plugs respectively. The maximum peak vertical particle acceleration for the first blow is much smaller than that for the second and third blows; the soil is much softer before treatment by compaction, so the impact is longer and with a smaller peak force.

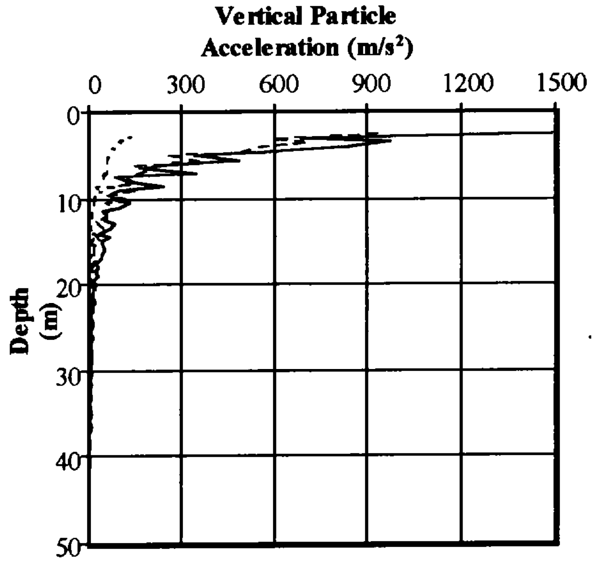

Figure 4(a) 1 m soft layer and stiff soil plug

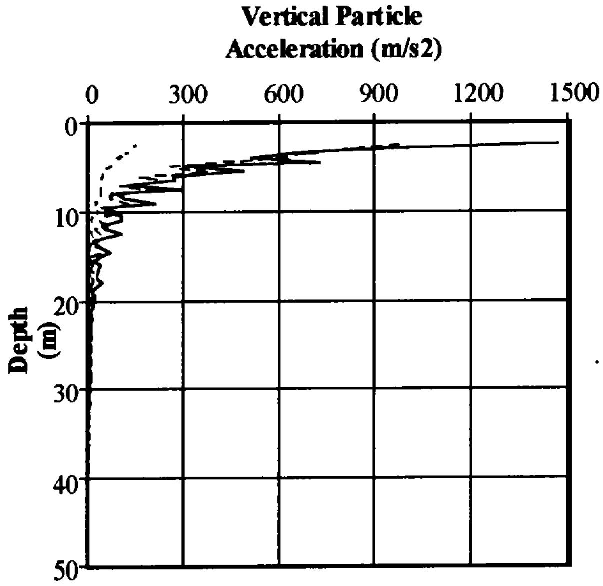

Figure 4(b). 2 m soft layer and stiff soil plug

.... 1st blow

------- 2nd blow

——— 3rd blow

Figure 4 Variations of peak vertical particle acceleration with depth.

Peak accelerations are similar for blows two and three. Further blows give only limited further improvement.

The shapes of the treatment zones under consecutive blows for 1 m and 2 m soft layers and stiff plugs are illustrated in Figures 5 and were found to be very similar. The trends of the contours of the treatment zones are also consistent, with a wider treatment zone for the second blow than for the third blow and a deeper treatment zone in the consecutive blows.

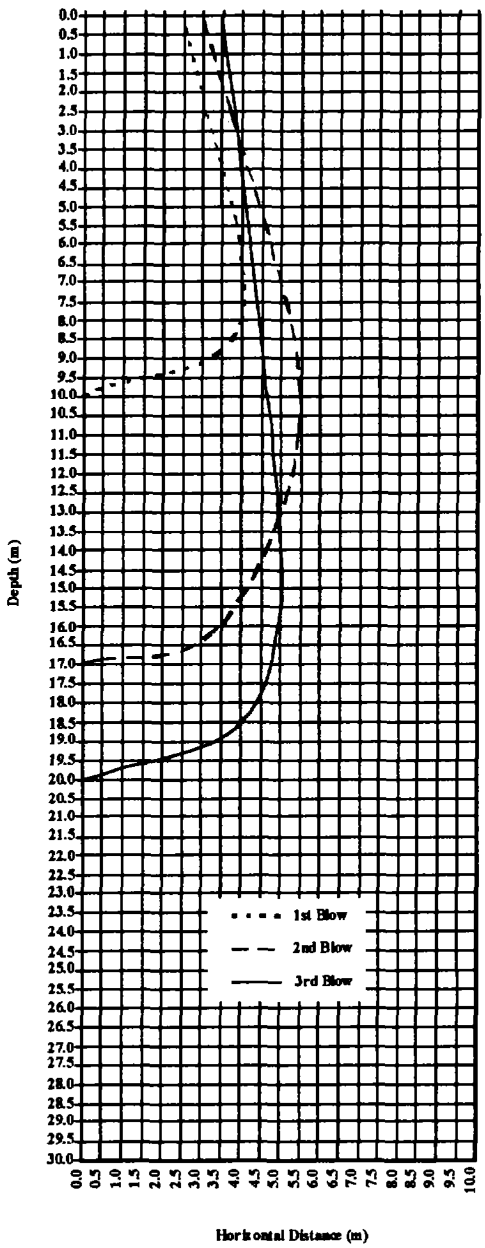

Figure 5(a). Shapes of treatment zones for 1m soft layer and stiff soil plug.

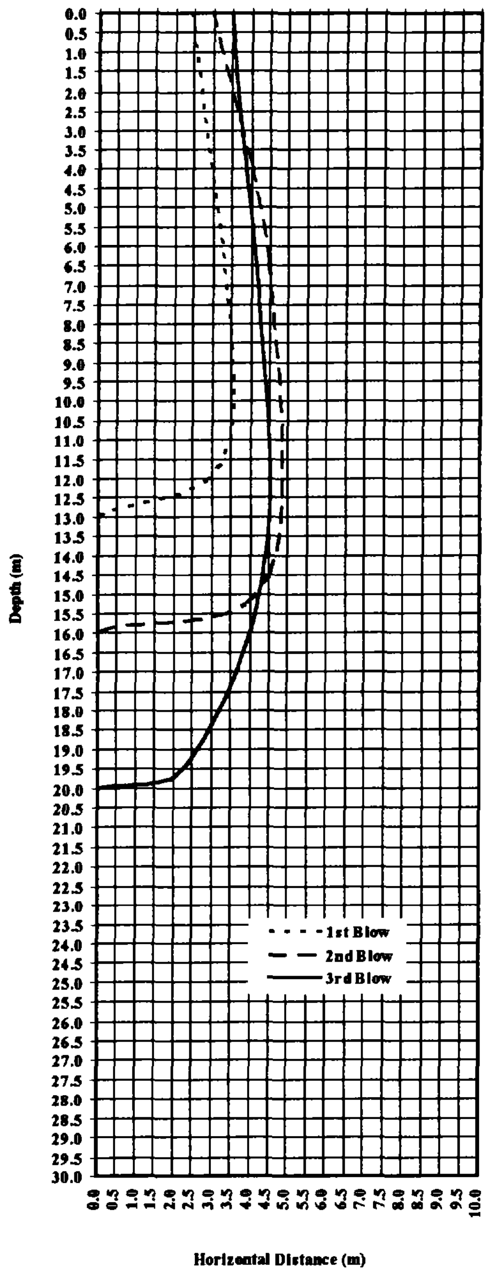

Figure 5(b) Shapes of treatment zones for 2m soft layer and stiff soil plugs

This zone of improvement is of considerable significance in offering guidance on the choice of spacing of the DC grid. However, the zone width is surprisingly uniform with depth. For the chosen condition, it appears that a nearly uniform cylindrical zone of soil is treated, of some 5 m radius. If a triangular grid is chosen with say 8 m spacing, a highly effective overall treatment would be achieved.

Table 2 Summary of test results, 1m plug.

	Blow 1	Blow 2	Blow 3
Depth to 2g, D (m)	10.0	17.0	20.5
$D/(M.H)^{1/2}$, (M=10Mg, H=10m)	1.00	1.70	2.05
Mass penetration mm	294	54	46
Cumulative penetration mm	294	348	394
Influenced zone, m, where ppv>10mm/s	29.5	34.0	34.5

Table 3 Summary of test results, 2m plug.

	Blow 1	Blow 2	Blow 3
Depth to 2g, D (m)	13.0	16.0	19.5
$D/(M.H)^{1/2}$, (M=10Mg, H=10m)	1.30	1.6	1.95
Mass penetration mm	396	32	28
Cumulative penetration mm	396	428	456
Influenced zone, m, where ppv>10mm/s	27.0	34.0	34.5

The depth of effective treatment (2g), mass penetrations and influenced zones (in terms of the ppv > 10 mm/s), Pan & Selby, [2000] under different blows are summarised in Tables 2and 3. Analysis of the results showed that the peak vertical particle acceleration of 2g under the first blow would propagate down to 10 m assuming a 1 m compressible layer. The depth of effective treatment D for assumed 1m soft layer agreed well with the empirical estimation $D = 0.5\sqrt{MH} \sim 1.0\sqrt{MH}$ (D = 5 m ~ 10m). However, the empirical equation probably underestimated the depth of effective treatment if a 2m plug is developed.

Figure 6 illustrates the penetration - time plots for 1m and 2m soft layer under the first blow. The shapes of the plots are similar, but the mass penetration for 1m soft layer (294 mm) was approximately 25% lower than that for 2m soft layer (396 mm) although the input energy was the same. This indicates that the depth of the soft layer has significant effects on the induced mass penetration. As the overall soil stiffens after the first blow, the same energy is applied over a shorter period, so a higher impact is given. The additional depth of effective treatment (16 to 20m) under the second and third blows is because of the shorter contact time and less energy absorption in the upper layers. However, a reducing benefit is obtained as the blow number increases.

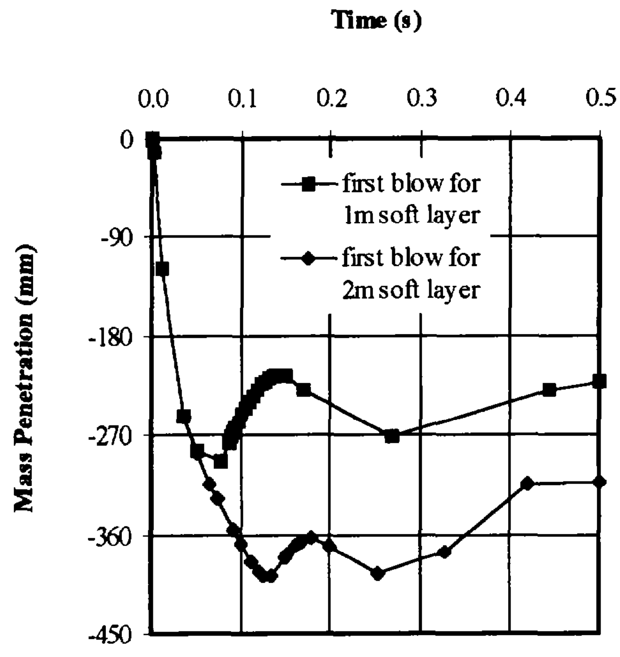

Figure 6. Penetration – time curves.

The zone influenced by extraneous surface vibrations from the impact is of concern to contractor. Such vibrations could cause disturbance to the nearby residents and even cosmetic or structural damage of their houses. The severity of surface disturbances due to the impact is usually assessed by ppv. The ppv - horizontal distance plots for 1m and 2m soft layer under the first blow are shown in Figure 7. The shapes of the plots are similar. As summarised in Tables 2 and 3, the influenced zone where ppv exceeded 10 mm/s was predicted to be within a circular area with a radius of between 27 m and 35 m, which are in reasonable agreement with the literature, e.g. Slocombe [1993]. The influenced zone was found to be nearly constant under the second and third blows. Lower disturbance was caused by the first impact on the softer soil.

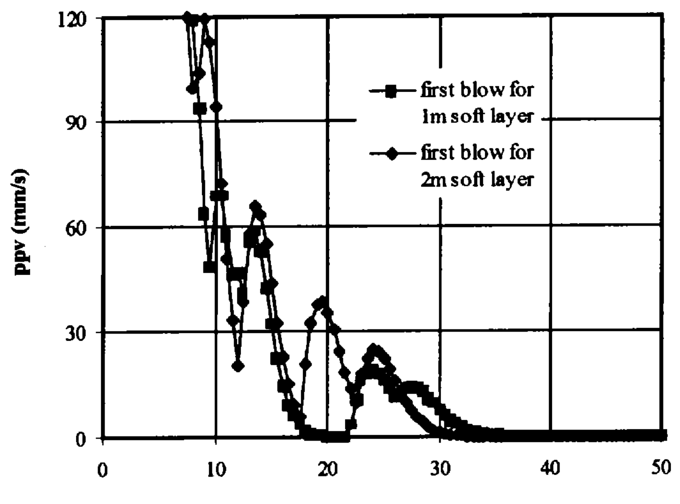

Figure 7 Vertical ppv - horizontal distance plots

CONCLUSIONS

The results showed that the model simulated the P-wave propagation in the soils effectively. The peak vertical particle accelerations for the first blow are much smaller than that for the second and third blows. The peak accelerations for the second and third blows are more similar, indicating that further treatment beyond the third blow has a reducing effect on the improvement of weak soil at depth.

The shapes of the treatment zones under consecutive blows for 1 m and 2 m soft layers and stiff soil plugs were found to be very similar. The trends of the contours of the treatment zones are also consistent, with a wider treatment zone for the second blow than for the third blow and a deeper treatment zone in the consecutive blows.

The depth of effective treatment for an assumed 1m soft layer agreed well with the empirical estimation. However, the empirical equation probably underestimated the depth of effective treatment for the 2m soft layer for the first blow as well as under the second and third blows.

The shapes of the penetration - time plots are similar for 1m and 2m soft layers under the first blow, however, the mass penetration for 1m soft layer (294 mm) was approximately 25% lower than that for 2m soft layer (396 mm). This indicated that the depth of the soft layer has significant effects on the induced mass penetration. The additional depth of effective treatment (16 to 20.5 m) under the second and third blows is attributed to the shorter contact time and less energy absorption in the upper layers. However, a reducing benefit is obtained as the blow number increases.

The shapes of the ppv - horizontal distance plots for 1m and 2m soft layer under the first blow plots are also similar. The influenced zone was within a circular area with a radius of between 27 m and 35 m, which are in reasonable agreement with the literature, e.g. Slocombe [1993]. The influenced zones were found to be consistent for the impact of 1 m and 2 m stiff soil plugs under the second and third blows.

Further research aims to study the effects of different soil models, e.g. a crushable foam plasticity model and a strain-hardening model, on the computation results, and to make detailed comparisons with published case history data.

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