DESIGN OF DYNAMIC COMPACTION ON LANDFILLS

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SUMMARY

Dynamic compaction is a ground improvement technique currently used to reduce void space, increase density and reduce long term settlement in soils. It has been used with varying success as a treatment for landfill deposits. Thirteen case studies have been evaluated to assess the success of dynamic compaction on unengineered landfills.

The results suggest that current dynamic compaction design practices tend to overestimate the treatment depth achieved. A damping of input energy due to a cohesive component in the landfill as well as the presence of groundwater in the treatment zone are presented as possible explanations. Based on back analysis of available data, modified design constants are suggested for unengineered landfill deposits.

Relationships between four characteristics associated with dynamic compaction in landfill (i.e. landfill age, depth, input energy, induced settlement) are also explored and alternative design equations are proposed based on these relationships.

INTRODUCTION

The increasing scarcity of good building land coupled with the need to redevelop inner city areas and reclaiming industrial waste lands has increasingly led to the development of landfill sites. Of particular engineering concern in the redevelopment is the engineering properties of the landfill. A landfill is generally weak, highly compressible and exhibits low bearing capacity and large long term settlements. A range of ground improvement techniques are available to improve the engineering properties of landfill. Such techniques include: vibro compaction, stone columns, dynamic compaction, dewatering, preloading or surcharge and drainage.

This paper examines the effectiveness of dynamic compaction (DC) in treating unengineered landfills by examining a detailed case study from a site in the UK and makes comparisions with 12 published examples. The validity of the design equations presently used are reviewed in light of the available data and modifications to the present design practices are suggested. Furthermore, the relationships of four characteristics associated with DC on landfills are explored and correlations between these characteristics lead to alternative design equations presented in this paper. It is not the intention of this paper, to present a detailed discussion on the DC technique, or the problems associated with DC on landfills.

PRINCIPLES OF DYNAMIC COMPACTION

Dynamic compaction is a ground improvement technique based on the improvement of weak soils by controlled high energy tamping. The technique was pioneered in the early 1970's by Louis Menard [16, 17]. This saw the increased application of this technique for ground improvement. Following on, other workers considered the behaviour of different soil types to DC ie. clay fills [2, 24]; loose deposits [14]; and granular fills [7].

Several papers summarise the 'state-of-the-art' of dynamic compaction, namely Mitchell [18], Mitchell & Katti [19], Greenwood & Kirsch [12], and more recently Slocombe [22]. There are also numerous published accounts of DC for the construction of airports, roads, and building foundations.

The technique requires repeated surface tamping using a heavy steel or concrete weight. Typically, the tamper weighs between 6 to 20 tonnes dropping in free fall from a height of up to 20 metres. A common approach is to divide the soil to be treated into three layers; deep, middle and shallow. The first tamping pass is aimed at treating the deepest layer by adopting a relatively wide grid pattern and a suitable number of drops from the full height of the crane. The middle layer is next treated by tamping on an intermediate grid with a reduced number of drops and drop height. The final (surface) layer is treated by a continuous tamp of a small number of drops from low height over the entire surface[22]. This is often termed a rolling pass and smooth wheeled vibrating rollers can be used instead of the tamper.

In the design of DC a number of factors should be considered. The main factors are outlined below:-

1. Type of material to be treated:- is of fundamental importance in the design of the DC programme. Granular and cohesive soils behave differently when subjected to high energy impacts. In granular soils DC reduces the void ratio, increases relative density, and improves load bearing and settlement characteristics. When load is applied to a clay soil, it exhibits consolidation settlement as a result of the expulsion of pore water from between the clay particles causing a reduction in volume, and an increase in strength over a long period of time[27]. The presence of soft layers or groundwater within the treatment depth has a damping influence on the dynamic forces. Therefore it is very important to have a detailed knowledge of the soil constituents. Landfill is a combination of coarse and fine grained materials which can include soil, domestic refuse, timber, bricks etc. The importance of a thorough ground investigation prior to the design of a DC programme cannot be stressed too strongly.

There is some contention in the published literature as to the suitability of DC as a ground improvement technique for landfill [12, 22]. General consensus is that DC is less successful in fine grained or variable soils. It is believed that a maximum of 25% to 30% fines (<0.02mm) in a soil is the maximum before DC becomes ineffective. In granular soils DC is very successful [15].

2. Depth of treatment: is a function of the size of equipment adopted ie. impact energy, soil type and the degree of improvement of the soil. The depth of treatment (Z) can be calculated from a number of different relationships depending upon the soil type. The total energy input per square metre (E) is the major requirement and is given in Eq. 1.

$$E = \frac{No.of\ Drops\, x\, D\, x\, W}{A} \tag{1}$$

Current design methods are related to the empirical rule [17]:-

$$Z = \sqrt{(WxH)} \tag{2}$$

Where:

H = Thickness of layer to be improved (m)

E = Impact energy (Tonnes/m^2)

W = Tamp weight (T)

D = Drop height (m)

A = Treatment area (m^2)

This relationship has been modified to take into account the treated soil type by using a varying constant multiplier, d. These are summarised in Table 1 below.

Table 1 Summary of Design Equations used for Dynamic Compaction

Soil Type	Treatment depth Relationship	Reference
Coarse Granular Soil	0.5√ (WxH)	13
Coarse Granular Soil	0.65 to 0.80√ (WxH)	14
Coarse Granular Soil	0.375 to 0.7√ (WxH)	19
Loose Fills	0.4√ (WxH)	6
Stiff Clay Fill	0.35√ (WxH)	4
Domestic Refuse	0.4√ (WxH)	4
Sand Fill	0.5√ (WxH)	4

It should be noted that Eq. 2 and its derivatives do not take into account other factors which influence the depth of treatment. Such as the fact that soils are rarely homogeneous, and are commonly layered and the presence of soft cohesive soils causes a damping influence on the dynamic forces. This is the situation within landfill sites. Initial strength and groundwater conditions also influence the result.

Equation 2 evaluates the soil properties such that the depth of treatment is inversely proportional to the dynamic resistance (q) of the soil skeleton to compression [1].

$$Z = \frac{WgD}{qB^2} \qquad \text{or} \qquad Z = \frac{WkD}{B^2} \tag{3}$$

where:
q = Dynamic resistance of soil skeleton
g = Acceleration of gravity (m/sec^2)
B = Plan dimension of tamp (m)
k = g/q

Since the soil parameter q is rarely known, it is usually necessary to adjust the initial design following preliminary trials. The value of K typically lies in the range 0.1 to 0.16 [25].

Both Eq. 2 and 3 are used commercially in the UK and USA to produce design charts for DC.

3. Amount of induced settlement: The net volume imprint ie. the total imprint minus the amount of heave, is a measure of the total void reduction beneath a tamping position. Unfortunately, the distribution of the void reduction below the ground surface is not known and is likely to be different for every soil type. The initial imprint is used as an initial guide to the amount of compaction obtained. The average depression of the site after levelling gives the cumulative volume change. Therefore imprint volume relative to the number of blows should be monitored. Total volume change depends on the initial state of the soil but 5% to 10% is usual. Substantial depressions must be formed if compaction is to be achieved, especially in fine grained or cohesive soils.

USE OF DYNAMIC COMPACTION ON LANDFILL

In the UK and USA DC is used on landfill sites prior to their redevelopment with varying success. Data available from thirteen case studies have been evaluated to assess the effectiveness of DC on a non engineered landfill. The published case studies present various amounts of detail regarding the design and success of the treatment used. A case study made available by the Department of Transport in the UK (DoT) provides the most detailed information on the use and success of DC on a landfill [9]. In particular, the study has been able to evaluate the depth of treatment achieved by comparison of pre and post treatment cone penetration tests. Detailed on site measurement of impact craters has also provided data to calculate average induced settlements and volume reduction.

DISCUSSION

Existing Design Equations

The data set currently available on the effective depth of treatment provides an opportunity to assess the suitability of the design equations currently used and comment on their applicability to landfills. The relationship between the amount of energy used and the effective depth of treatment is of paramount importance in design of DC. Figure 1 presents this relationship with superimposed design lines whose gradient is equivalent to the constant d. Using the effective depth of treatment it is possible to back analyse the data to calculate more appropriate constant values for use in the design equations. A summary of these results is presented below in Table 2.

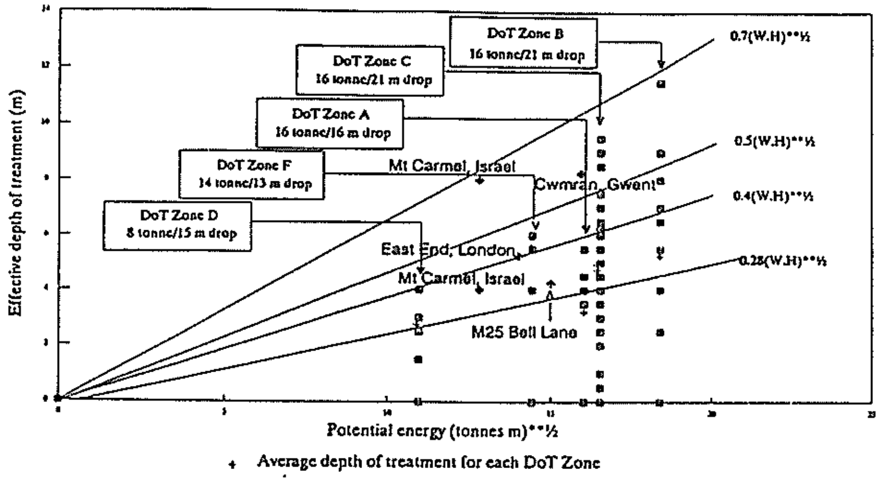

Figure 1 Effective Depth of Treatment against Potential Energy

Table 2 Summary of back calculated constants, d and k, for each treatment site

Case Study Reference	Design Constant d			Design Constant k		
9 UK	Minimum	Maximum	Average	Minimum	Maximum	Average
Zone A	0.22	0.34	0.26	0.06	0.09	0.07
Zone B	0.00	0.63	0.33	0.00	0.12	0.08
Zone C (east)	0.00	0.66	0.24	0.00	0.16	0.07
Zone C (west)	0.09	0.62	0.33	0.20	0.14	0.09
Zone D	0.00	0.37	0.38	0.00	0.16	0.07
Zone F	0.00	0.42	0.32	0.00	0.13	0.12
Average of Data	0.00	0.50	0.28	0.00	0.13	0.08
8 UK	0.41			-		
20 UK	0.28			0.23		
3,4 UK	0.39			0.45		
10[1] Israel	0.31			-		
10[1] Israel	0.62			-		

Footnote: 1. This site reported DC trials and the difference in depth of treatment is due to a difference in energy input.

There is a considerable range of design constant (d) values varying from a minimum of zero for areas of no improvement to a maximum of 0.66. Similar back analyses have been carried out to calculate the constant, k, used in Eq. 4. The values obtained are summarised on Table 2 and range from a minimum of zero to a maximum of 0.45. All the data show a considerable scatter in terms of effective depth of treatment and the back calculated design constants. However, the general trend indicates that the design constants currently used in commercial practice are too high. The difference in values obtained must be related, in some way, to the behaviour of the fill and its composition. The data available does not allow for the further differentiation of constant d values based on fill composition. Based on the data reviewed in this discussion values of $d = 0.3$ and $k = 0.08$ are considered to be more appropriate for landfill materials in design Eq. 2 and 5.

Landfill and DC Treatment Characteristic Relationships

Four characteristics unique to each site are considered which provide the basis for comparison of the data:-

1. landfill depth
2. landfill age
3. amount of input energy used during DC
4. the amount of settlement induced by DC

Although a data set of thirteen (Refs. 3,4,5,8,9,10,11,15,20,23,26,28,29) is not large enough to provide unequivocal empirical correlations, approximate relationships between each of the above characteristics can be shown .

The nature of the design of DC is such that the amount of input energy used is related to the depth of the landfill to be treated. Figure 2 shows a wide spread of data with deeper landfills requiring a higher input energy for treatment. The best fit line through all data could be used as an initial DC design curve, such that input energy can be identified. Once this is obtained it then only requires the identification of satisfactory combination of weight, drop height, number of blows and grid spacing to maximise the amount of induced settlement.

There are six data points which fall outside the general cluster. These are: Case Studies in Refs. 8,15,20, Zones A, B, D in Ref. 9. The amount of cohesive material in the Zones A and B may account for the damping effect. It is considered possible that the case studies in Ref. 8 and 15 may also have a high fines content. The dampening effects in the Ref. 20 results are probably due to groundwater within the treatment zone.

If the data is considered in terms of the fill content two linear best fit lines can be drawn, one for granular type refuse and the other for landfill with a probable fines content of greater than 25% (Figure 2). Regression analysis on these two data sets has enabled the following relationships to be defined.

For Granular Refuse:
Input energy I (Tm/m^2) = 9 x Landfill depth (m) (4)

For material with a cohesive content > 25%:
Input energy I (Tm/m^2) = 18 x Landfill depth (m) (5)

or alternatively
$$Z = \frac{W \, x \, D \, x \, No.of\ blows}{A} x \frac{1}{\tau} \tag{6}$$

Where $\tau = 9.44$ for granular refuse $\tau = 18$ for fill with cohesive content >25%

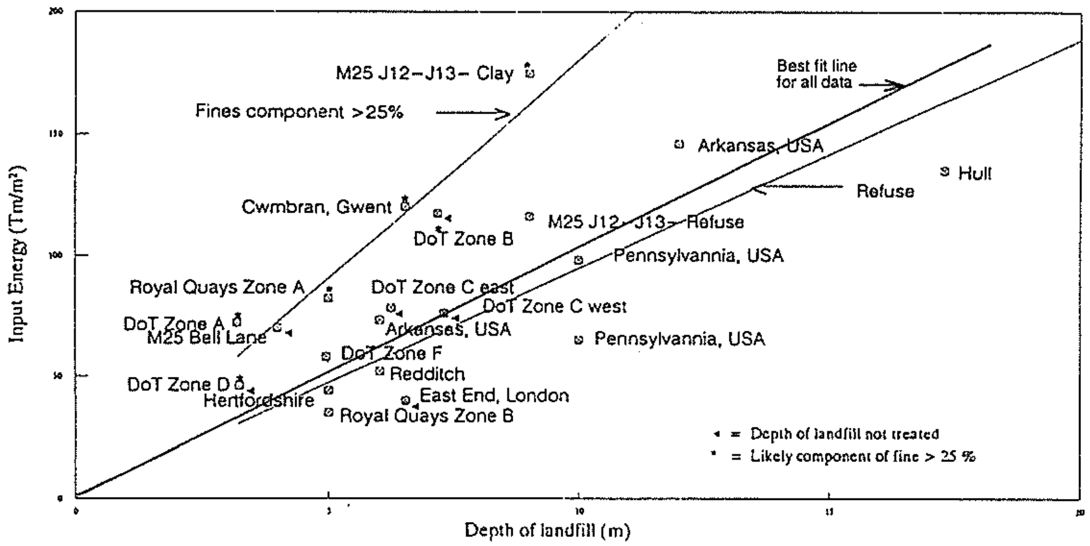

Figure 2 Graph of Input Energy against Depth of Landfill from published case studies.

The difference between Eq. 4 and 5 reflects the damping effect of energy in fine grained soils. Equation 2 should be applied to landfill with a cohesive component less than about 25% and Eq. 5 to landfill with a cohesive component in excess of about 25%.

It is expected that the amount of volume reduction induced is proportional to the input energy used. This relationship is shown on Figure 3 and in general there appears to be a linear relationship. However, there is a wide spread in the data and a possible reason for this may be that the amount of volume reduction achieved by DC is also a function of fill density. The older fills are denser whilst younger fills will be less dense. Comparison of the ages of the landfill at the time that DC are shown on Figures 3. The older landfills (10 to 40 years) show only 10% or less volume reductions, whilst the younger landfills exhibit much higher volume reductions. Unfortunately, it is not known whether any compaction was carried out as part of the infill process at each site. However, consideration of volume reduction in terms of the fines content gives two possible relationships as shown on Figure 3. Linear regression of the two data sets (less than and greater than 25% fines) enabled the definition of the following expressions:-

For granular refuse:
Input energy I (Tm/m^2) = 5 x Volume reduction (%) (7)

For material with a cohesive content >25%
Input energy I (Tm/m^2) = 10 x Volume reduction (%) (8)

or alternatively
$$\delta = \frac{W \, x \, D \, x \, No.of\ blows}{A} x \frac{Z}{\beta} \tag{9}$$

Where $\beta = 545$ for granular refuse $\beta = 989$ for fill with a fines content >25%

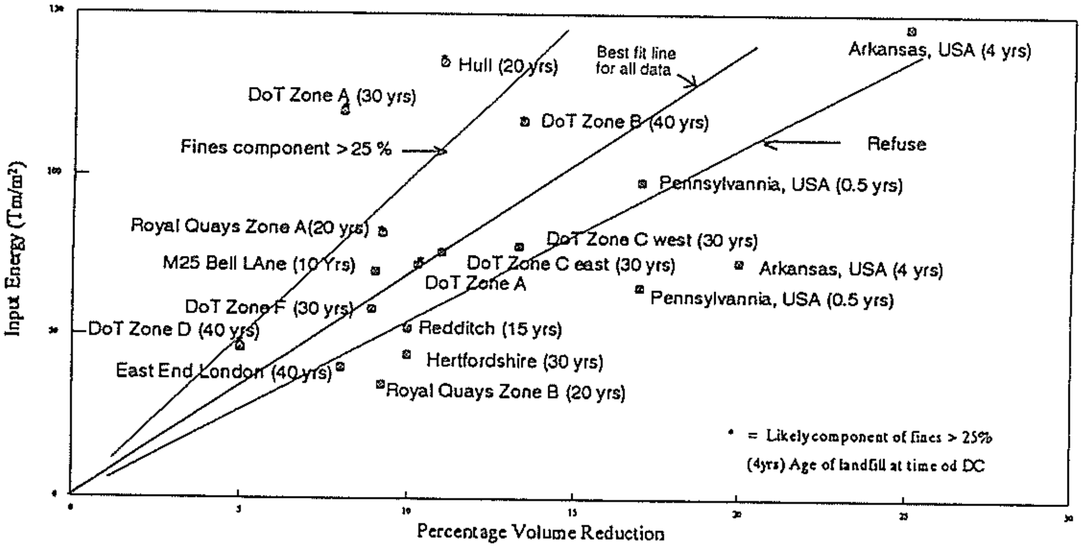

Figure 3 Graph of Input Energy against Percentage Volume Reduction from published case studies.

All of the expressions given above can be considered as alternative design formulae for DC on landfill. These expressions allow the energy required to be assessed for any given landfill depth or requisite amount of settlement. For that particular energy it only remains for the appropriate combination of weight, drop height, number of blows and grid spacing to be established. However, the main difference between Eq. 4 and Eq. 3 [1] is the way in which the input energy is expressed. Equation 6 considers the number of blows used to calculate the input the energy, whilst Eq. 3 does not.

CONCLUSIONS

A landfill is recognised as being neither homogeneous nor inelastic and hence its behaviour as a result of DC is not well predicted by current practice. Twelve published examples and a further detailed case study have been analysed to assess the suitability and appropriateness of DC on landfill using the current standard practise. The results show that existing design equations overestimate the effective depth of treatment achieved by DC in landfills. Possible reasons for this are:

1. The landfill material is heterogeneous, and that soft cohesive layers or a high component of fine grained material has a damping influence on the energy transmission through the soil.

2. Perched or natural groundwater tables within the zone of treatment also tend to damp energy transmission.

3. The landfill may be denser than initially considered, (ie. it may have been compacted at the time of emplacement), hence the expected results for a specific amount of energy input are not achieved.

The implication of the underestimated treatment depth is that there remains within the landfill zones of material that has not been treated which may still have the capacity for large amounts of long term settlement. The design equations currently used in industry to calculate effective depth of treatment are clearly inappropriate for landfill. Analysis of the case studies suggest that the commonly used design equations for landfill materials be modified, as detailed below.

$$Z = 0.28\sqrt{(W x H)} \qquad (10)$$

$$Z = \frac{0.08MH}{B^2} \qquad (11)$$

Furthermore, four characteristics of a landfill have been shown to be important in the evaluation of DC. These are: depth of landfill, age of the deposit, input energy used in DC and the amount of enforced settlement achieved. The data available suggest that linear relationships can be defined between the depth of landfill and the energy used for treatment and the amount of enforced settlement achieved. These relationships are given in Eq. 6, and 9. In all cases assessed in this paper, it has been assumed that the landfill was not compacted significantly on deposition. Thus the correlations discussed apply only to non engineered landfill sites.

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REFERENCES

1. Billam, J 1979. Depth of treatment in dynamic compaction *Engineering Behaviour of Industrial and Urban Fill. Symposium Proceedings 23-25th April 1979.* Midland Geotechnical Society. pp. E138-E140.

2. Charles, J A 1978. Methods of treatment of clay fills. *Clay Fills. Proceedings of the Conference held at the Institution of Civil Engineers, 14-15 November 1978.* The Institution of Civil Engineers, London, General Report pp. 315-321.

3. Charles, J A 1979. Field observations of a trial of dynamic consolidation on an old refuse tip in the East End of London. *Engineering Behaviour of Industrial and Urban Landfill. Proceedings of the Symposium held at the University of Birmingham. 23-25th April 1979.* pp. E1-E7.

4. Charles, J A 1984. Settlement of fill. Attewell P B and Taylor R K (eds.). *Ground movements and their effects on structures.* Surrey University Press. pp. 26-42.

5. Charles, J A; Burford, D; Watts, K S. 1981. Field studies of the effectiveness of "Dynamic Consolidation". *Proceedings of the 10th International Conference of Soil Mechanics and Foundation Engineering, Stockholm.* Vol. 3 pp. 617-622.

6. Department of Transport 1987. *Specification for Highway works.* 6th Edition 1987. HMSO. Department of Transport 1991. Earthworks. Design and preparation of contract documents. Department of Transport Highways Safety and Traffic Departmental Advice Note HA 44/91.

7. Dobson, T; Slocombe, B 1982. Deep densification of granular fills. *The proceedings of the second Geotechnical Conference and exhibit on Design and Construction. Las Vegas Nevada.*

8. Downie, A R; Treharne, G 1979. Dynamic consolidation of refuse at Cwmbran. *Engineering behaviour of Industrial and Urban Landfill. Proceedings of the Symposium held at the University of Birmingham.* 23-25th April 1979. pp. E15-E24.

9. Fellows, D L 1993. *The design and specification of Dynamic Compaction on Landfill.* Unpublished MSc Thesis, University of Surrey, UK.

10. Frydman, S; Baker, R. 1987. Construction of a bus parking station on a waste deposit site. *Building on Marginal and Derelict Land.* Thomas Telford Ltd. pp. 255-266.

11. Galante, V N; Eith, A W; Leonard, M S; Finn, P S 1991. An assessment of deep dynamic compaction as a means to increase refuse density for an operating municipal waste landfill. *The Planning and Engineering of Landfills. Proceedings of the Conference organised by the Midland Geotechnical Society, University of Birmingham 10-11 July 1991.* pp 183-191.

12. Greenwood, D A; Kirsch, K 1984. Specialist ground treatment by vibratory and dynamic methods. *Proceedings of Conference on Piling and Ground Treatment.* Thomas Telford, London. pp. 17-45.

13. Leonards, G A; Cutter, W A; Holtz, R D 1980. Dynamic Compaction on Granular Soils. *Journal of Geotechnical Engineering Division of American Society of Civil Engineering.* 106 pp. 35-44.

14. Lukas, R G 1980. The densification of Loose deposits by pounding. *Journal of Geotechnical Engineering Division of the American Society of Civil Engineers.* 106 GT4 April 1980. pp. 435-446.

15. Mapplebeck, N J; Fraser, N A 1993. Engineering landfill by Dynamic Compaction to support Highways and Buildings. *Proceedings of Conference on Engineered Fills 93.* Paper 39, p. 492-504.

16. Menard, L 1974. *La Consolidation dynamique des sols de foundation Conferences.* ITBTP.

17. Menard, L; Broise, Y 1976. Theoretical and practical aspects of dynamic compaction. *Ground treatment by deep consolidation. Institution of Civil Engineers, London.* pp. 3-18.

18. Mitchell, J M 1981. Soil improvement - state of the art report. *Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm.* Vol. 4 pp. 509-559.

19. Mitchell, J M; Katti, R J 1981. Soil improvement - state of the art report. *Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm.* Vol. 4 pp. 567-575.

20. Perelberg, S; Boyd, P J H; Monutague, K N; Greenwood, J R 1986. M25 Bell Lane Pit: Ground improvement by dynamic compaction. *Building on Marginal and Derelict Land.* Thomas Telford Ltd. pp. 267-280.

21. Schlosser, F; Juran, I 1979. General report - Design parameters for artificially improved soils. *Proceedings of VII European Conference on Soil Mechanics and Foundation Engineering. Brighton.*

22. Slocombe, B C 1993. Dynamic Compaction. Moseley M P (ed). *Ground Improvement.* Chapman & Hall. pp. 20-39.

23. Swain, S; Holt, D N 1986. Dynamic compaction of a refuse site for a road interchange. *Building on Marginal and Derelit Land.* Thomas Telford Ltd. pp. 339-357.

24. Thomson, G H; Herbert, A. 1979. Compaction of clay fills in situ by dynamic consolidation. *Clay Fills. Proceedings of the Conference held at the Institution of Civil Engineers, 14-15 November 1978.* The Institution of Civil Engineers, London. pp. 197-204.

25. Vibroflotation Ltd 1993. *Method Statement for Contract on Confidential Site.*

26. Welsh, J P 1984. Dynamic compaction of sanitary landfill to support superhighway. *Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering. Helsinki. 1983.* Balkema, Rotterdam. Vol. 14 No. 1 pp 31-36.

27. West, J M 1976. The role of ground improvement in Foundation Engineering. *Proceedings of Conference on Ground Improvement by Deep Compaction, Institution of Civil Engineers,* 1975, London. pp. 71-78.

28. Williams, P J 1983. Preparing Motorway Junctions. *Consulting Engineer.* October pp 18-19

29. Willams, P J 1984. Construction Over Water Filled and Back Filled gravel Pits. *The Journal of the Institution of Highways and Transportation.* pp. 26-30.