14 Aug 2008, 2:15pm - 4:00pm

Enhancement of Bearing Capacity by Dynamic Compaction: A Case History

Liaqat Ali

National University of Sciences and Technology (NUST), Risalpur, Pakistan

Sarfraz Ali

National University of Sciences and Technology (NUST), Risalpur, Pakistan

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

ENHANCEMENT OF BEARING CAPACITY BY DYNAMIC COMPACTION A CASE HISTORY

Dr Liaqat Ali
National University of Sciences
and Technology (NUST)
Risalpur, Pakistan

Sarfraz Ali
National University of Sciences
and Technology (NUST)
Risalpur, Pakistan

ABSTRACT

Deep Dynamic Compaction technique was used to improve soil bearing capacity in one of the project in Pakistan. It was first project in the country where Deep Dynamic Compaction technique was used for soil improvement. The soil at construction site composed of alluvial deposits. The sub-surface profile with in the depth of influence of proposed structure comprised of different layers of varying thickness within the construction site. The top 1-2 meter strata was an imported fill compacted in layers and composed of sandy silty clayey soil with percentage of fines as high as 75 percent The water table was located at 12 m depth.

The construction alternatives included deep foundation and improvement of bearing capacity using dynamic compaction technique; the later was adopted in view of the economy of the project. The depth and degree of improvement was evaluated by comparing pre to post compaction Standard Penetration Tests (SPT) and measuring depth of the crater after each drop. The paper discusses briefly the compaction design, methodology for evaluation of effectiveness and resultant improvement in depth and lateral direction. The results of the compaction program of research project have also been compared with those of various case histories.

INTRODUCTION

The growing pace of development in the country has consumed most of the available prime lands. The scarcity of suitable construction sites has now necessitated construction of residential and industrial buildings at problem sites which need soil improvement. A local firm planned to construct two workshops in an industrial area located 65 km west of Islamabad. The reinforced cement concrete framed structure buildings had a covered area of 25000 m² and individual column loads varied from 1200 kN to 2300 kN.

Geotechnical site investigation of the proposed construction site revealed an allowable bearing capacity of 100 kPa against 150 kPa required to support the foundation. Also, in the backdrop of devastating earthquake of October, 8, 2005, the owner and local authorities were concerned regarding the safety of their structure. Therefore it was decided to improve the soil to avoid undesirable settlements and ensure stability of the structure.

In view of the large covered area of proposed workshops, cost–benefit analysis of various techniques of soil improvement such as deep foundation, vibratory compaction, soil replacement and dynamic compaction was carried out. Dynamic compaction technique; being the cheapest technique was selected to improve the bearing capacity of the foundation soil from existing 100 kPa upto 160 kPa.

RESEARCH OBJECTIVES

The research objectives included evaluation of improvement for various energy levels i.e. after 5 and 10 blows as following:

- depth of improvement directly under impact points at every 1 m depth interval upto of 8.5 m depth
- depth of improvement at lateral distances upto 1.75 D (D = 2.4 m, the diameter of tamper) and 3.00 D away from centre of impact points at every 1 m depth interval upto 8.5 m depth
- depth of improvement at the middle of two adjacent impact points at every 1 m depth interval upto 8.5 m depth
- compare crater depth measurements of this project with those of case histories
- compare depth of improvement of this project with the improvements achieved in various dynamic compaction case histories
- evaluate increase in bearing capacity for column foundations at depths of 2 m and 4 m

GENERAL SITE DESCRIPTION

Geologically the area is part of alluvial deposits formed by intermittent stream flows and Indus River catchments area run-offs. These deposits are composed of unconsolidated gravel, coarse to fine sand, silt and clay. The groundwater table exists at a depth of 12 m and rises to 7 m depth in rainy season. The site preparation involved demolishing of small existing buildings, removal of vegetation, leveling of undulations, and filling of perennial water channel passing through the construction site.

The two proposed buildings at the construction site were located side by side and only 50 m away from no. of existing small buildings spread over an area of 100 m x 200 m. To avoid any damage to these existing buildings, an isolation trench was excavated at the extreme left edge of the construction site. The isolation trench was 2 m wide and 4 m in depth. General layout of the construction site is shown in Fig. 1.

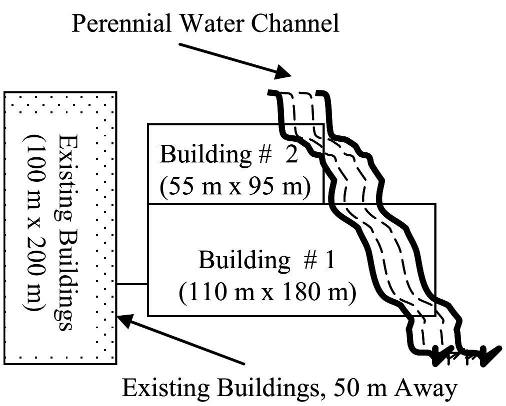


Fig. 1. Layout of the construction site

GEOTECHNICAL SOIL PROFILES

The upper 1 - 2 m layer was an imported fill of sandy silty clayey (CL-ML) soil. The fill was placed by the previous owner for construction of residential buildings and was compacted in layers to 100 percent compaction; almost one year prior to dynamic compaction. The new owner decided to construct workshops by improving the bearing capacity of soil.

For the purpose of research, geotechnical soil profiles upto 9 m depth were prepared at each building site. The soil profiles were prepared by carrying out grain size distribution tests (both sieve and hydrometer analysis) on samples collected during SPT at every 1 m depth interval. At building no. 1; the profile till 4 m depth, was also studied from an isolation trench (an isolation trench; 4 m deep and 2 m wide was excavated at the edge of compaction site to minimize ground vibrations and prevent damage to an existing building located at a distance of 50 m).The geotechnical soil profiles of building no. 1 and building no. 2 are shown in Fig. 2 and Fig. 3 respectively. The strata at proposed building sites are composed of 5 different types of soil layers.

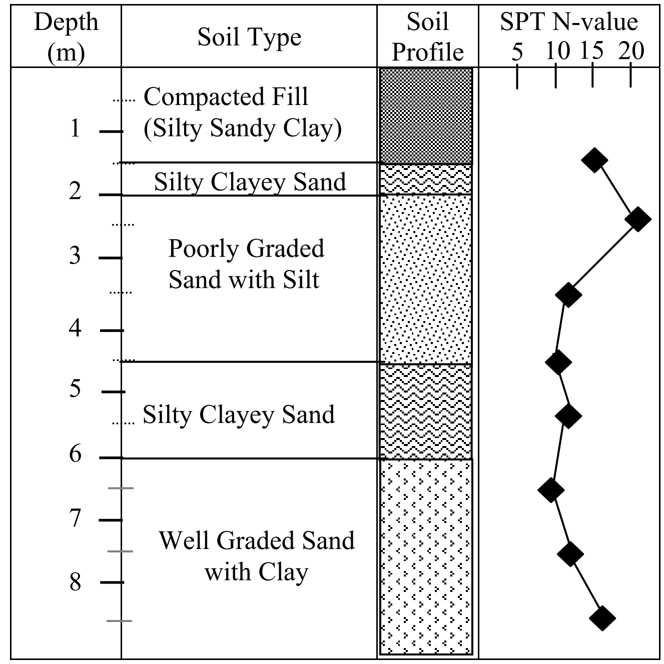


Fig. 2. Sub-surface soil profile at the site of building no. 1

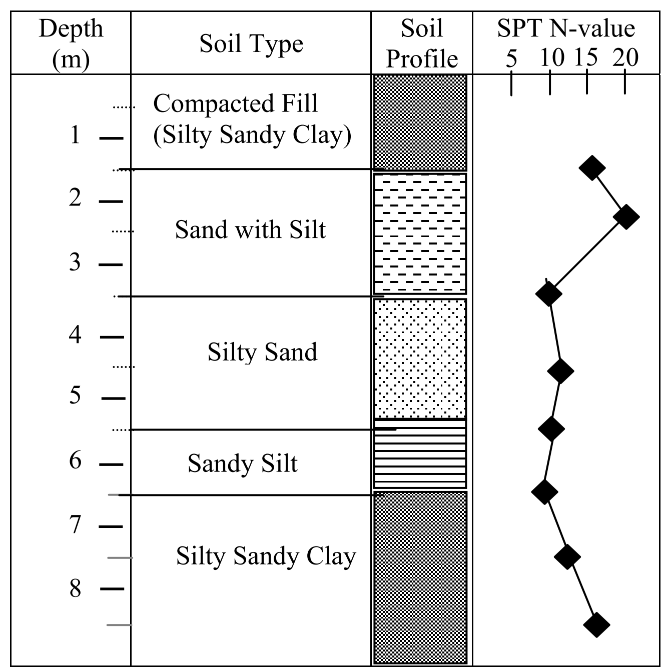


Fig. 3. Sub-surface soil profile at the site of building no. 2

IMPROVEMENT EVALUATION METHODOLOGY

Improvement was evaluated by comparing pre to post compaction SPT N-values. During the course of compaction program, monitoring of the desired depth of improvement was carried out by measuring crater depth after each blow.

Experimental Design for Evaluation of Improvement from SPT

The layout of test craters and location of boreholes was designed with a view to keep the distance between pre and post compaction boreholes as minimum as practically feasible. In this research, pre to post compactions SPT were performed within a distance of 2 m. Total of 9 test craters; crater no. 1 through crater no. 9, were used in this research. Layout of test craters is shown in Fig. 4. Total of 48 boreholes were drilled and 384 SPT performed to evaluate improvement at different points. Detail of experimental design is given as:

- improvement after 5 blows was evaluated at crater no 3, 4, and 7
- improvement after 10 blows was evaluated at crater no 2, 6, and 8
- lateral improvement after 5 blows was evaluated around crater no. 1, 5 and 7
- lateral improvement after 10 blows was evaluated around crater no 2, 6, and 8
- improvement at middle of adjacent craters was evaluated between crater no 1 & 2, crater no 5 & 6 and crater no 8 & 9 after full scale compaction i.e. after primary, secondary and ironing pass
- no compaction was carried out within 9 m of the test craters
- locations of all boreholes has been referenced to the centre of impact point and are given in terms of tamper diameter "D" (D = 2.4 m)

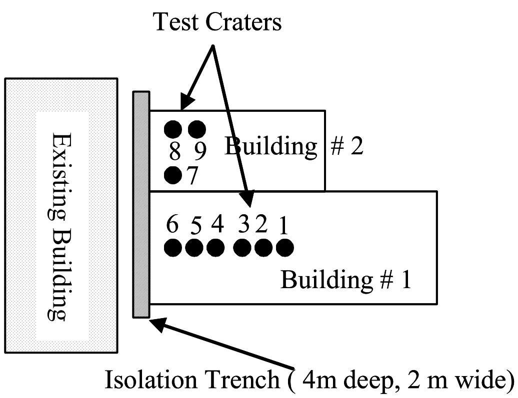


Fig. 4. Layout of test craters

Layout of Boreholes for Evaluation of Improvement under Impact Points

To evaluate improvement under impact points, pre-compaction SPT were performed in boreholes at a distance of 0.25 D (0.25 x 2.4 = 0.6 m) from centre of impact points while post-compaction SPT were performed in boreholes at 0 D (at the centre of impact points) and at 0.5 D (0.5 x 2.4 = 1.2 m, edge of the impact points) as shown in Fig. 5. Location of boreholes for evaluation of improvement at the middle of adjacent craters is shown in Fig. 6.

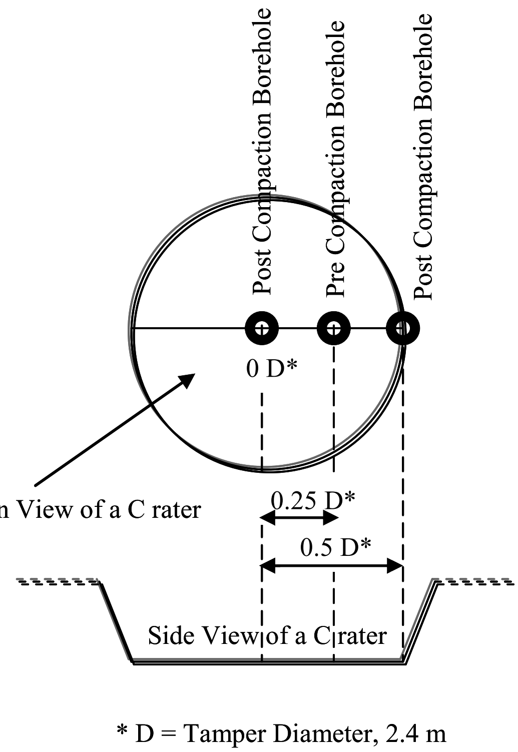


Fig. 5. Location of boreholes for evaluation of improvement under impact point

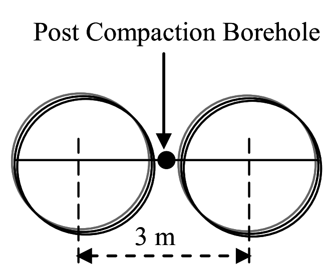
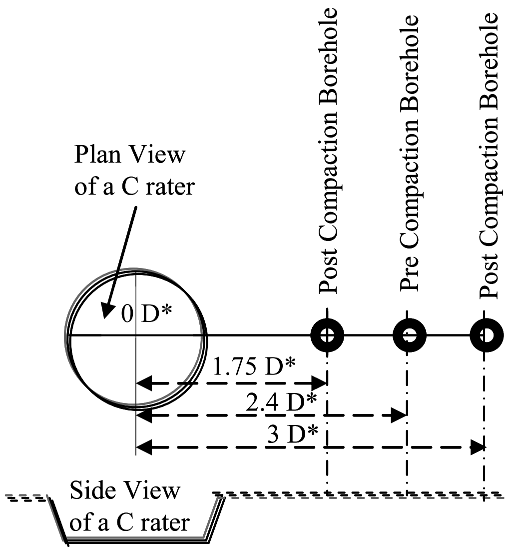


Fig. 6. Location of boreholes for evaluation of improvement at the middle of adjacent craters

Layout of Boreholes for Evaluation of Improvement in Lateral Direction

To evaluate improvement in lateral direction, pre-compaction SPT were performed in boreholes at a distance of 2.40 D (2.40 x 2.4 = 5.76 m) from the centre of impact points while post-compaction SPT were performed in boreholes at a distance of 1.75 D (1.75 x 2.4 = 4.2 m) and 3.00 D (3 x 2.4 = 7.2 m) from the centre of impact points. The layout of boreholes for evaluation of improvement in lateral direction is shown in Fig.7.



* D = Tamper Diameter, 2.4 m

Fig. 7. Location of boreholes for evaluation of improvement in lateral direction

COMPACTION PROGRAM

The compaction program was designed basing on empirical correlations to achieve a depth of improvement upto 5 m depth. It comprised two high energy passes and a low energy ironing pass. Each high energy pass comprised 10 blows per impact point from a height of 16 m and the low energy pass comprised 2 blows from a height of 5 m. Grid spacing of primary and secondary pass was 6 m from centre to centre in a square grid pattern. Secondary blows were placed in the centre of primary blows. The ironing pass was performed on overlapping grid with an overlap of one-third of tamper diameter. The circular tamper, 1.5 m high, 2.4 m in diameter and weighing 20 ton, was made of concrete with steel casing. The sequence of compaction is shown in Fig. 9.

IMPROVEMENT CRITERIA BY SPT N-VALUE

Post compaction SPT N-value of 15 (un-corrected) was selected as the minimum acceptable improvement after dynamic compaction since it corresponds to soil bearing capacity of 160 kPa, Bowles, [1997]. All SPT N-values in this paper are uncorrected N-values and the hammer efficiency was considered as 55 percent. For the purpose of discussion, increase, over and above pre-compaction SPT N-value was divided into four ranges as shown in Table 3.

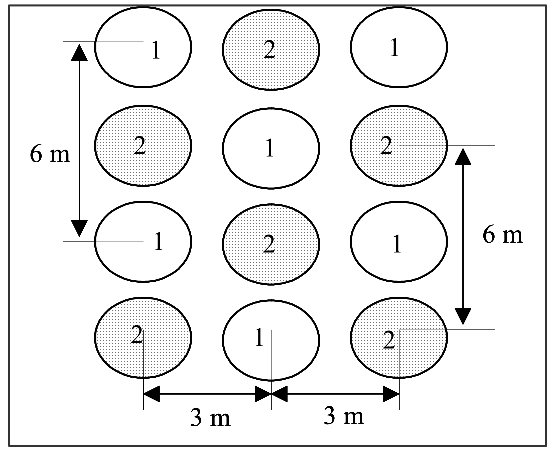


Fig. 9. Grid pattern; white circles depict primary while dotted circles depict secondary pass

Table 3. Improvement evaluation criteria

Increase in SPT N-Value	Degree of Improvement
≥ 15	Significant
7 - 14	Moderate
3 - 6	Marginal
≤ 3	No improvement

EVALUATION OF IMPROVEMENT DIRECTLY UNDER IMPACT POINTS BY SPT

Post compaction SPT were performed two weeks after compaction. Since SPT N-values at centre and 0.5 D (edge of the crater) were identical therefore post compaction SPT N-values at centre of each crater are considered in this paper.

Improvement after 5 Blows

Improvement after 5 blows was evaluated at crater no. 3, 4, and 7, shown in Fig. 9. Since pre compaction SPT N-value at 0.25 D of crater no. 3, 4, and 7 had little variations therefore to simplify the figure, pre compaction SPT N-value of only crater no. 3 is shown in Fig. 10.

Crater no. 3. Maximum improvement was observed at 2 m depth. Improvement in upper 3.5 m of treated area was moderate with an approximate increase in N-value of 1.5 times the pre-compaction value, a marginal increase was observed in strata between 3.5 m to 4.5 m, whereas no improvement took place below 6 m depth.

Crater no. 4. The improvement was moderate in the upper 2 m with 1.6 times increase in N-value. In strata between depths of 3 m to 6 m, marginal improvement was observed with 1.35 times increase in N-value. Improvement below 6 m was insignificant.

Crater no. 7. Moderate improvement was observed in the upper 2.5 m strata. Marginal improvement occurred in strata between 2.5 m to 5 m depth. Improvement below 5 m was insignificant.

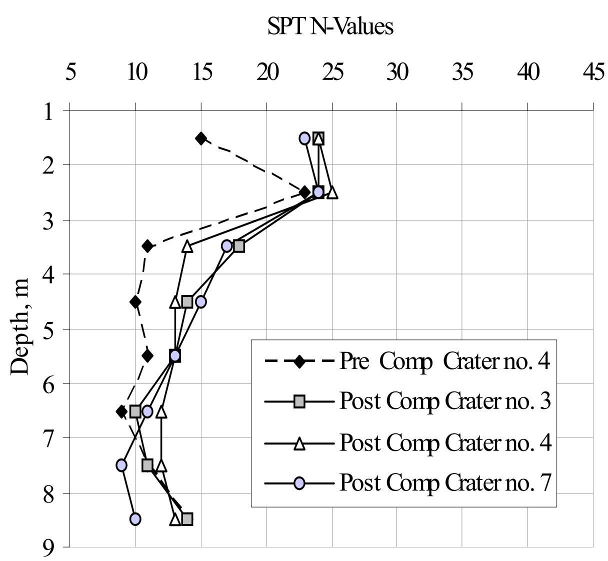


Fig. 10. Improvement under impact points after 5 blows

Improvement after 10 Blows

Improvement after 10 blows was evaluated at crater no. 2, 6, and 8, as shown in Fig. 11. Since pre compaction SPT N-value at 0.25 D at crater no. 2, 6, and 8 had little variations therefore to simplify the figure, pre compaction SPT N-value of only crater no. 2 is shown in Fig. 11.

Crater no. 2. Significant improvement was noted in top 3.5 m strata, moderate improvement in strata between depths of 3.5 m to 5 m, and improvement was marginal in strata depth of 5 m to 7 m. Improvement below 7 m depth remained insignificant.

Crater no. 6. The improvement was significant in upper 4 m strata, moderate in strata depth of 4 m to 5 m and marginal from 5 m to 6 m. Improvement below 6 m depth was insignificant.

Crater no 8. Significant improvement was noted in top 4 m strata, moderate improvement in strata between depths of 4 m to 5.5 m. Improvement was marginal in strata depth of 5.5 m to 7.5 m. Improvement below 7.5 m depth was insignificant.

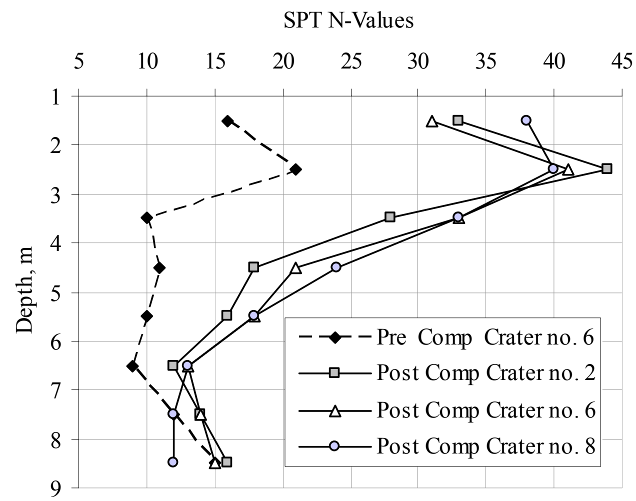


Fig. 11. Improvement under impact points after 10 blows

EVALUATION OF IMPROVEMENT IN LATERAL DIRECTION BY SPT

Pre compaction SPT were performed at lateral distance of 2.4 D from centre of impact point. Post compaction SPT were performed two weeks after the compaction at lateral distance of 1.75 D and 3.00 D from centre of impact point.

Lateral Improvement after 5 Blows

Lateral improvement after 5 blows was evaluated at crater no. 3, 4, and 7. Pre to post compaction comparison of SPT N-values at crater no. 3, 4 and 7 are shown in Fig. 12, 13 and 14 respectively.

Crater no. 3. At lateral distance of 1.75 D (1.75 x 2.40 = 4.20 m) away from the centre of impact point, improvement was moderate in the upper 2 m and marginal in 2 m to 3.5 m depth. At a distance of 3.00 D (3.00 x 2.40 = 7.2 m) away from the centre of impact point, marginal improvement was observed in the upper 2 m of strata.

Crater no. 4. Marginal improvement was observed in upper 4 m of the strata till lateral distance of 1.75 D away

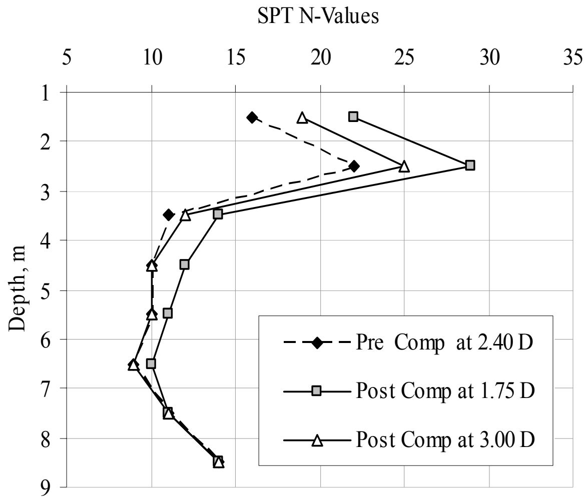


Fig. 12. Lateral improvement at crater no. 3 after 5 blows

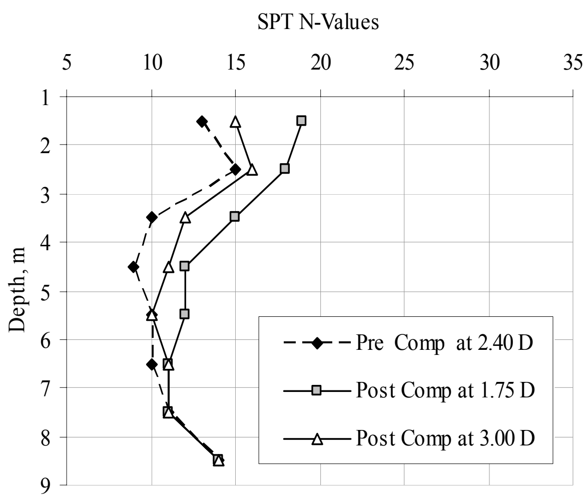


Fig. 13. Lateral improvement at crater no. 4 after 5 blows

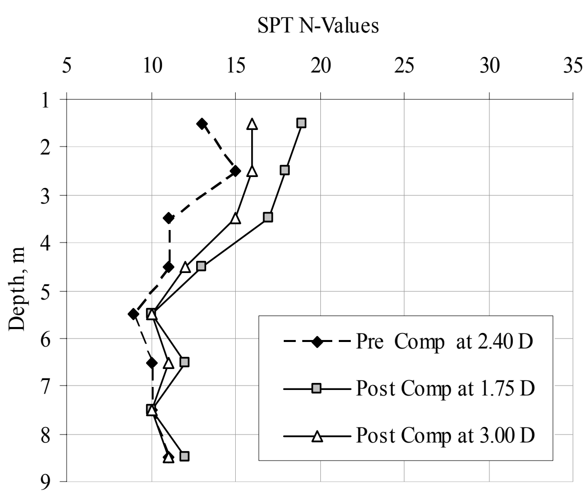


Fig. 14. Lateral improvement at crater no. 7 after 5 blows

from centre of impact point. Improvement was insignificant at lateral distance of 3.00 D away from centre of impact point.

Crater no. 7. Improvement was moderate in upper 2.5 m strata and marginal from 2.5 m to 3.5 m strata at lateral distance of 1.75 D from centre of impact point. Lateral improvement was marginal in the upper 1.5 m strata from 1.75 D to 3 D from centre of impact point. Improvement below 1.5 m depth at lateral distance of 1.75 D to 3.00 D was insignificant.

Lateral Improvement after 10 Blows

Lateral improvement after 10 blows was evaluated at crater no. 2, 6, and 8. Pre to post compaction comparison of SPT N-values at crater no. 2, 6, and 8 after 10 blows is shown in Fig. 15, 16 and 17 respectively.

Crater no. 2. Marginal improvement was noted in upper 4 m strata till lateral distance of 1.75 D from centre of impact point. Lateral improvement from 1.75 D to 3.00 D from centre of impact point was marginal in the upper 3 m strata and insignificant below 3 m depth.

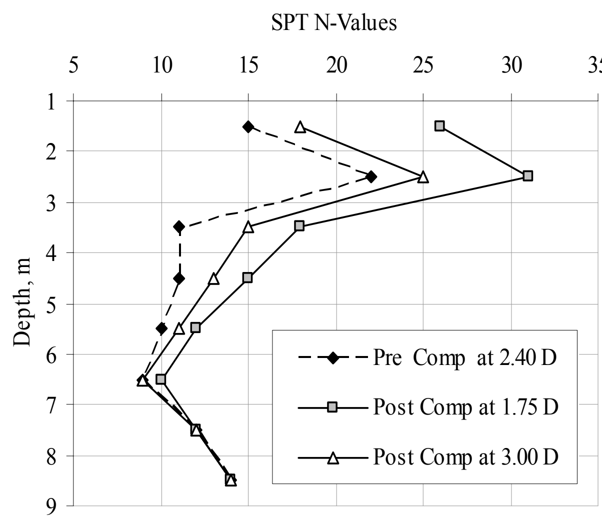


Fig. 15. Lateral improvement at crater no.2 after 10 blows

Crater no. 6. Lateral improvement at distance of 1.75 D from centre of impact point was moderate in upper 3 m strata and marginal from 3 m to 4 m depth. Improvement at lateral distance from 1.75 D to 3.00 D from centre of impact point was marginal in the upper 4 m strata and insignificant below 4 m depth.

Crater no. 8. Improvement was moderate in upper 3 m strata and marginal from 3 m to 5 m strata from centre of impact point to lateral distance of 1.75 D. Improvement was marginal in the upper 1.5 m strata from lateral distance of 1.75 D to 3.00 D from centre of impact point and improvement below 1.5 m depth was insignificant.

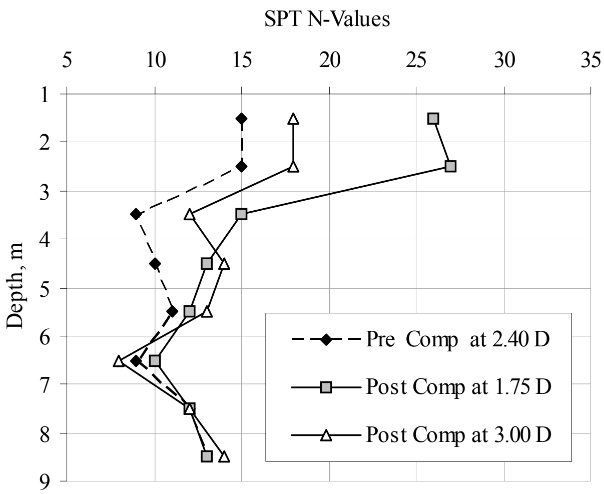


Fig. 16. Lateral improvement at crater no.6 after 10 blows

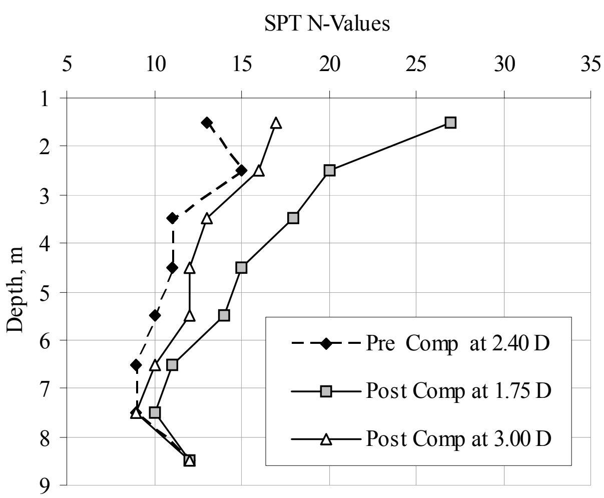


Fig. 17. Lateral improvement at crater no. 8 after 10 blows

IMPROVEMENT AT THE MIDDLE OF TWO ADJACENT IMPACT POINTS

The depth of improvement at the middle of adjacent craters was evaluated after full scale compaction i.e. after primary, secondary, and ironing passes. The improvement was evaluated at the middle of crater no. 1 & 2, crater no. 5 & 6, and crater no. 8 & 9 as shown in Fig. 18, 19, and 20 respectively.

<u>Improvement at Middle of Crater no. 1 & 2</u>

Improvement at middle of crater no. 1 & 2 was slightly less than the improvement under impact point of crater no. 1. However, the improvement was significant in upper 3.5 m strata. Improvement below 3.5 m depth at the middle of these two craters was almost same as that of improvement under impact point of crater no.1.

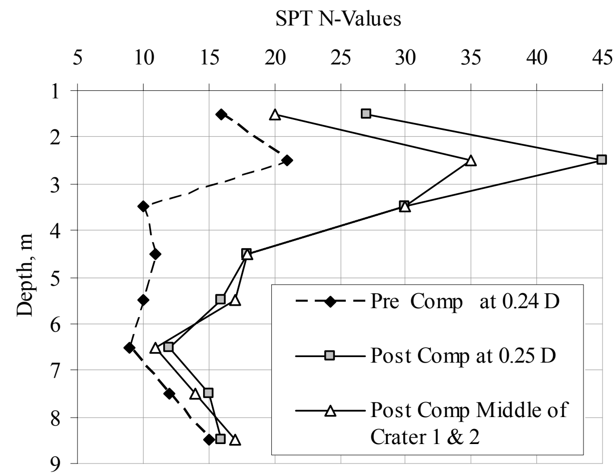


Fig. 18. Improvement at middle of crater no. 1 & 2

<u>Improvement at Middle of Crater no. 5 & 6</u>

At the middle of crater no. 5 & 6, improvement was slightly less than the improvement under impact point of crater no. 5 however the improvement was significant in upper 3 m strata. Improvement below 3 m depth at the middle of these two craters was same as that of improvement under impact point of crater no.5 with slight variation at depths of 4 m and 8 m.

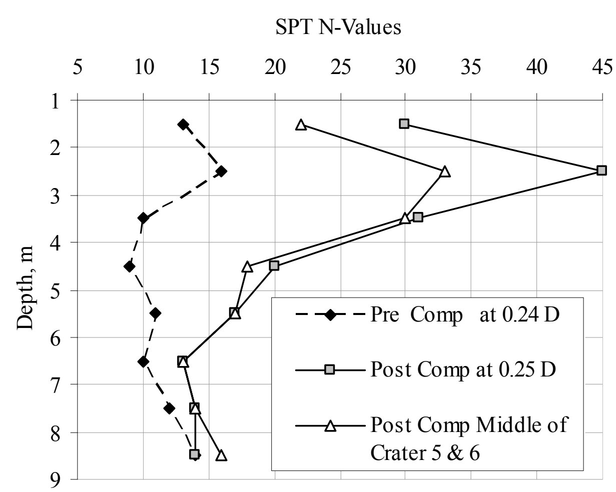


Fig. 19. Improvement at middle of crater no. 5 & 6

<u>Improvement at Middle of Crater no. 8 & 9</u>

At the middle of crater no. 8 & 9, improvement in the upper 2 m strata was slightly less than the improvement under impact point of crater no. 8. Improvement below 2 m depth at the middle of these craters was same as that of improvement under impact point of crater no. 8 as shown in Fig. 20.

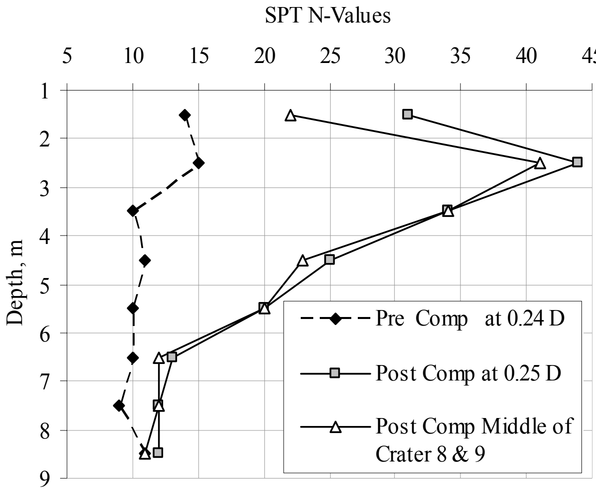


Fig. 20. Improvement under impact at crater no. 8 & 9

QUALITY CONTROL AND MONITORING BY CRATER DEPTH MEASUREMENTS

During dynamic compaction, crater depth measurements provide a visible and immediate indication of the improvement achieved, Rollins and Kim. [ND], and therefore was selected as one of the quality control criteria. During field trial of designed dynamic compaction program, crater depths were correlated to SPT N-values to form quality control criteria. In this project, a settlement of 5 cm between any two successive blows was found to have achieved the desired improvement upto 5 m depth and was therefore selected as the acceptable criteria to seize tamping at any given impact point.

Although 5 cm settlement between any two successive blows was selected as criteria for desired depth of improvement, to ensure maximum compaction the contractor decided to keep the no. of blows per impact point upto 10 blows where settlement of 5 cm was encountered within 10 blows. The criteria, however was followed where 5 cm settlement was achieved after 10 blows. Crater depths of test craters after 5 blows and 10 blows are shown in Fig. 21 and 22. Observations on crater depths are:

- almost same trend in crater depths has been observed at all craters after 5 and 10 blows
- crater depths increased with increase in no. of blows
- crater depths are more for initial 5 blows (from 0 to around 96 cm) than for next 5 blows (from 96 cm to around 155 cm)
- slightly more crater depths for 5 blows at crater no. 7 to crater no. 9 because the strata at these craters were relatively loose before compaction

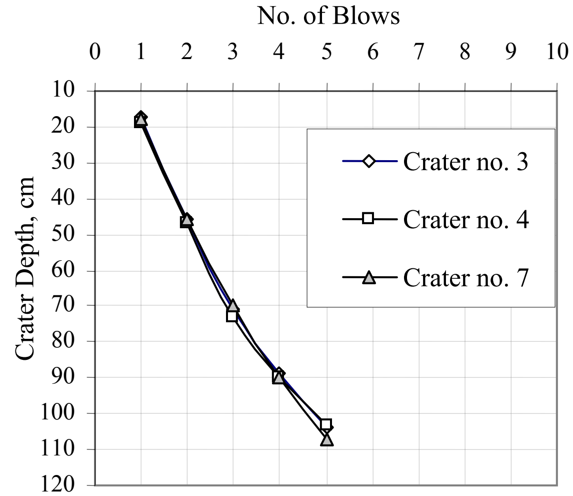


Fig. 21. Crater depth measurements for 5 blows

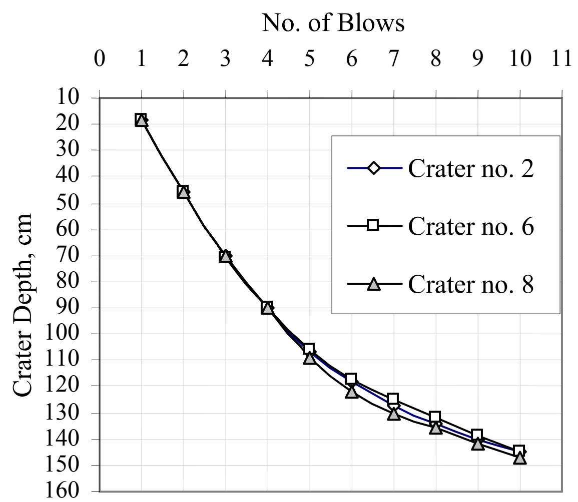


Fig. 22. Crater depth measurements for 10 blows

COMPARISON OF CRATER DEPTH MEASUREMENTS WITH CASE HISTORIES

In order to make comparison between various projects which all used different drop heights and weights, Mayne, et al. [1984] normalized crater depth data by square root of the energy per drop. Fig. 23 shows the normalized crater depth data from case histories and the research project. The bold lines indicate the typical range of crater depth data for non-collapsible soils, Mayne et al. [1984]. The normalized crater depth data of the research project falls within the range proposed by Mayne et al. [1984], which suggest that the compaction behavior of soil at research project is similar to non-collapsible soils.

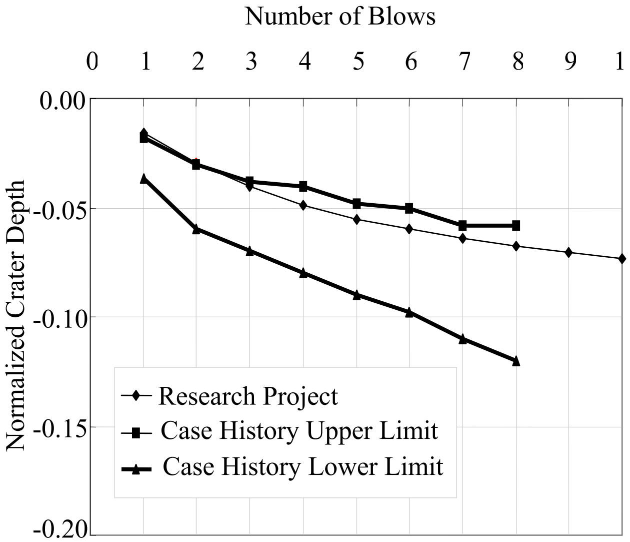


Fig. 23. Comparison of normalized crater depth measurements with data of case histories, Mayne et al. [1984]

DEPTH OF IMPROVEMENT FROM EMPIRICAL CORRELATIONS CASE HISTORIES

Improvement of the research project, both in depth and lateral direction has been compared with empirical correlations and case histories reported in the literature. The comparison is discussed below:

Meyerhof. [1959]

Meyerhof. [1959], proposed that effect of dynamic compaction is quite similar to compaction of cohesionless soil beneath the tips of driven piles and caissons. The level of soil densification decreases progressively with increasing distance from point of impact, pile, or caisson to lateral distance of about 3.5 times the respective diameter, beyond which there is little densification, equation (1). Accordingly, lateral improvement is given as:

Lateral Improvement = 3.5 D (1)
= 3.5 x 2.4 m = 8.4 m

Menard and Broise. [1975], Correlation

Menard and Broise. [1975], proposed that max depth of improvement achieved by dynamic compaction is square root of the impact energy, equation (2). Depth of improvement of research project from this correlation is given as:

$$D_{max} = \sqrt{WH} \quad (2)$$

$$D_{max} = \sqrt{20 \times 16}$$

$$D_{max} = 17.88 \text{ m}$$

Lukas. [1986], Correlation

Lukas. [1986], proposed that max depth of improvement is given by equation (3). Lukas. [1986], also proposed that maximum improvement occurs within one third to half of the depth of improvement achieved, i.e., if D_{max} = 8 m, the max improvement will occur within depth of 2.66 m to 4 m. Depth of improvement of research project suggested by this correlation is given as:

$$D_{max} = n\sqrt{WH} \quad (3)$$

$$D_{max} = 0.65\sqrt{20 \times 16}$$

(n = 0.65 for silty sandy soils, Lukas - 1986)

$$D_{max} = 11.62 \text{ m}$$

Oshima and Takada. [1998]

Depth of improved zone by dynamic compaction is usually between 10 m to 12 m while Lateral improvement (radius of improved zone) by dynamic compaction is usually between 5 m to 7 m.

Case Histories

Depth of improvement of various case histories, as proposed by Rollins and Kim, [1994], is shown in Fig. 24. According to this figure, the research project's energy level of 17.88 ton-m ($\sqrt{20x16}$ = 17.88) should have improved the soil upto a depth of 7.5 m.

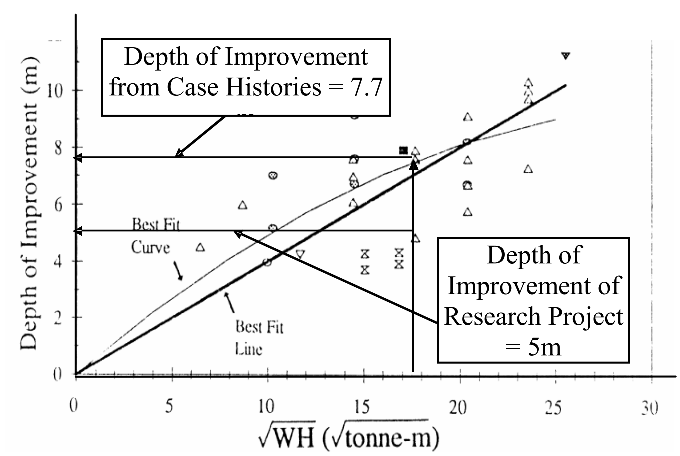


Fig. 24. Prediction of depth of improvement on the basis of normalized energy of various case histories, Rollins and Kim, [1994]

ENHANCEMENT OF BEARING CAPACITY (q_a) AFTER DYNAMIC COMPACTION

Allowable bearing capacity has been calculated for footings with embedment depth of 2 m and 4 m separately. SPT

N-values used for calculation of allowable bearing capacity are the average SPT N-value within the influence depth of 0.5 B above and 2 B below the base of footing where "B" is the width of footing.

Allowable Bearing Capacity for Footings with Embedment Depth of 2 m

Allowable bearing capacity for footings with embedment depth of 2 m at the two building sites was calculated as under:

Crater no. 1, 2 and 3

SPT N-value $_{(0..5\,B - 2\,B)}$ = (48+30+18+16+12)/5
= 24.8 ≈ 25

q_a = *350 kPa* Bowles, [1997]

Crater no. 4, 5 and 6

SPT N-value $_{(0..5\,B - 2\,B)}$ = (45+31+20+17+13)/5
= 25.2 ≈ 25

q_a = *350 kPa* Bowles. [1997]

Crater no. 7, 8 and 9

SPT N-value $_{(0..5\,B - 2\,B)}$ = (44+34+25+20+13)/5
= 27.2 ≈ 27

q_a = *360 kPa* Bowles. [1997]

Allowable Bearing capacity for Footings with Embedment Depth of 4 m

Allowable bearing capacity for footings with embedment depth of 4 m was calculated using equation suggested by Parry, [1977], for cohesionless soils, equation (4). Factor of safety (FOS) of 3.0 was used in this case.

q_{ult} = 30 x N (SPT N-value) kPa (D≤B) (4)

Where,

N = SPT N-value at depth of 0.75B below the proposed footing. The N-value used for calculation of allowable bearing capacity for research project is the average of SPT N-values of respective craters at a depth of 0.75B.

Crater no. 1 to 3

N = (16+12+15) / 3 = 14.33 ≈ 14
q_{ult} = 30 N = 30 * 14 = 420 kPa Parry, [1977]
q_a = q_{ult} / FOS = 420 / 3

= *140 kPa*

Crater no. 4 to 6

N = (17+13+14) / 3 = 14.66 ≈ 15
q_{ult} = 30 N = 30 * 15 = 450 kPa Parry, [1977]
q_a = q_{ult} / FOS = 450 / 3

= 150 *kPa*

Crater no. 7 to 9

N = (20+13+12) / 3 = 15
q_{ult} = 30 N = 30 * 15 = 450 kPa Parry, [1977]
q_a = q_{ult} / FOS = 450 / 3

= *150 kPa*

Before compaction, allowable bearing capacity of the site was around 100 kPa. It improved by a factor of more than three times the pre compaction bearing capacity for surface-loaded footings. For footing at depths of 4 m, bearing capacity improved upto 150 kPa.

SUMMARY AND CONCLUSIONS

Though the firm claimed to have achieved required depth of improvement upto a depth of 5 m however its comparison with depth of improvement suggested by empirical correlations and the case histories reveal that the achieved depth of improvement is less than what should have been possible with the given energy levels.

In the light of research conducted for evaluation of improvement under impact points in lateral direction after 5 blows, 10 blows and full scale compaction, following conclusions are presented:

- directly under impact points, the bearing capacity of soil improved to 160 kPa upto a depth of 5 m
- max improvement under impact points occurred at depths from 2 m to 4 m
- sharp decrease in improvement is observed below 4 m depth
- improvement was negligible below 6.5 m depth
- with the increase in no. of drops from 5 blows to 10 blows, the degree of improvement also increased from maximum 35 blows to 45 blows
- increase in no. of blows from 5 to 10, had negligible effect on degree of improvement below 6.5 m depth
- in upper 2 m of strata, improvement at the middle of any two adjacent impact points was comparatively less than improvement under the impact point

- after 5 drops, the soil improved laterally upto 1.75 D (4.2 m) in the upper 3.5 m strata only
- after 10 drops, the soil improved laterally upto 1.75 D (4.2 m) in the upper 4.5 m strata only
- allowable bearing capacity in the improved zone increased from 100 kPa to 350 kPa for footings placed at a depth of 2 m and 140 kPa for footings placed at a depth of 4 m.

REFERENCES

Bowles, E. Joseph [1997]. "*Foundation Analysis and Design*". McGraw-Hill Book Company, Inc., New York.

Lee, F.H., and Gu, Q., [2004]. "Method for Estimating Dynamic Compaction Effects on Sand". J. of Geotch. and Envmt. Eng., ASCE. No. 130(2), pp. 139-152.

Lukas, R.G. [1986]. "*Dynamic Compaction for Highway Construction*". FHWA, US DOT, Report No. FHWA/RD-86/133.

Mayne, P.W., Jones J.W., and Dumas, J.C., [1986]. "Ground Response to Dynamic Compaction".J. of Geotech. Eng., ASCE, No. 110(6), pp. 757-774.

Menard, L., and Broise, Y. [1976]. *"Theoretical and Practical Aspects of Dynamic Consolidation"*. Ground Treatment by Deep Compaction, The Institute of Engineers, London. pp. 3-18.

Meyerhof, G. G., [1976]. "Bearing Capacity and Settlement of Pile Foundation". J. of Geotech. Eng. Div. Am. Soc. of Civ. Eng., No. 102(3), pp. 195-228.

Oshima, A., and Takada, N. [1998]. " Evaluation of Compacted Area of Heavy Tamping by Cone Point Resistance". *Proc. Int. Conf. Centrifuge 98.,* Kimura, Kusakabe, and Takemurs, eds., Balkema, Rotterdam, pp. 813-818.

Rollins Kyle, M., and Kim, Ji Hyoung [1994]. "US Experience with Dynamic Compaction of Collapsible Soils", in *In-Situ Deep Soil Improvement, Geotechnical Special Publication,* Am. Soc. of Civ. Eng., New York, pp. 27-43.