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Short Communication

Soil Improvement by Dynamic Consolidation

by

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Introduction

There are several ways of improving soils in situ, and a comprehensive report on it has been prepared by ASCE (1978). Dynamic consolidation, developed in 1969 by the late French Engineer, Louis Menard, is one of the most successful methods for deep compaction. The depth of improvement by this method can be achieved to a considerable depth (10 to 30 m). The range of materials that has been successfully treated is surprisingly broad. Effective compaction has been achieved above ground water level in materials ranging from rock-fill to plastic silt, peat and building and domestic refuse. Below ground water level, dynamic consolidation is effective in improving nonplastic granular soils. More recently, dynamic consolidation has been used to reduce the liquefaction potential of loose sand and silts.

Dynamic Consolidation Technique

The technique of dynamic consolidation employs heavy tamping by dropping steel tampers (also known as pounders) 100 to 400 KN in weight from a height ranging from 10 to 40 m on the ground surface which needs to be compacted. Typically crawler crane or tripod are used to operate the pounder which is dropped 5 to 10 times at each location and at a spacing of 5 to 15 m depending on type soil and depth of treatment.

The theory or dynamic consolidation is explained by Menard and Broise (1975), Menard (1976), D'Appolonia (1978) and Gambin (1979). The mechanism of dynamic consolidation probably involves following four processes: (*a*) compression of air filled voids and pore water due to presence of micro bubbles, (*b*) gradual liquefaction under repeated impacts, (*c*) the change of permeability of soil mass due to the presence of fissures and/or the state of near liquefaction and the possible role played by adsorbed water, and (*d*) thixotropic recovery.

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The choice of equipment and working procedure depends on the soil type, and required depth of improvement. From the field study on granular fills, Leonards et al. (1980) proposed that the depth of improvement is approximately equal to half of the sequare root of the energy developed per blow. Based on the field study at eight sites consisting of natural fine sand to rubble and garbage fills, Lukas (1980) observed that the depth proposed by Leonards et al. (1980) gives a conservative value whereas the earlier relationship proposed by Menard and Broise (1976) gives higher values.

Case History

A case history selected for citation and detailed analysis where a dynamic consolidation technique have been used recently to reduce the liquefaction potential of the soil under earthquake and the future settlements of the ground. The site comprises approximately 55 acres of recently reclaimed land on a river bank and lies within the recent flood plain deposits. The thickness of these deposits are greater than 190 m and are basically uniform fine sands but are characterised by small variations and alternations in their bed. High mica contents were found in some layers. The hydraulic fill material is basically similar to the underlying soils and consequently, the elevation at which filling began was difficult to identify from the boring logs. Although most of the material is of a silt size, it is usually plastic due to high content of partly decomposed mica flakes. The four soil types from 0 to 20 m depth are classified as:

(*a*) Grey brown, medium dense micaceous fine sand (hydraulic fill).

(*b*) Brown micaceous, sometimes clayey, sandy silt with very thin horizontal layers of sand and silty clay (upper silt).

(*c*) Grey medium dense micaceous silty fine sand with occasional layers of sandy silt, silty clay and clayey silt (lower silty sand).

(*d*) Grey medium dense to dense micaceous silty fine sand interbedded with grey loose to compact micaceous, sometimes clayey sandy silt (lower silt and sand).

The equipment used for prforming dynamic consolidation consisted of a tripod, steel pounder (25 ton for 25 m free fall and 12 to 17 ton for 30 m free fall), cranes, drilling and grounding rigs, etc.

The soil resistance was measured by SPT, cone penetrometer and Menard Pressuremeter. The ground water level was monitored by Standpipe piezometers. The tests performed together with careful sampling enabled to get a very precise understanding of the mechanical properties of the dynamically consolidated soils.

Figure 1 shows the mean energy and settlement for 10 m consolidated zone. It can be observed from the figure that the efficiency decreases rapidly

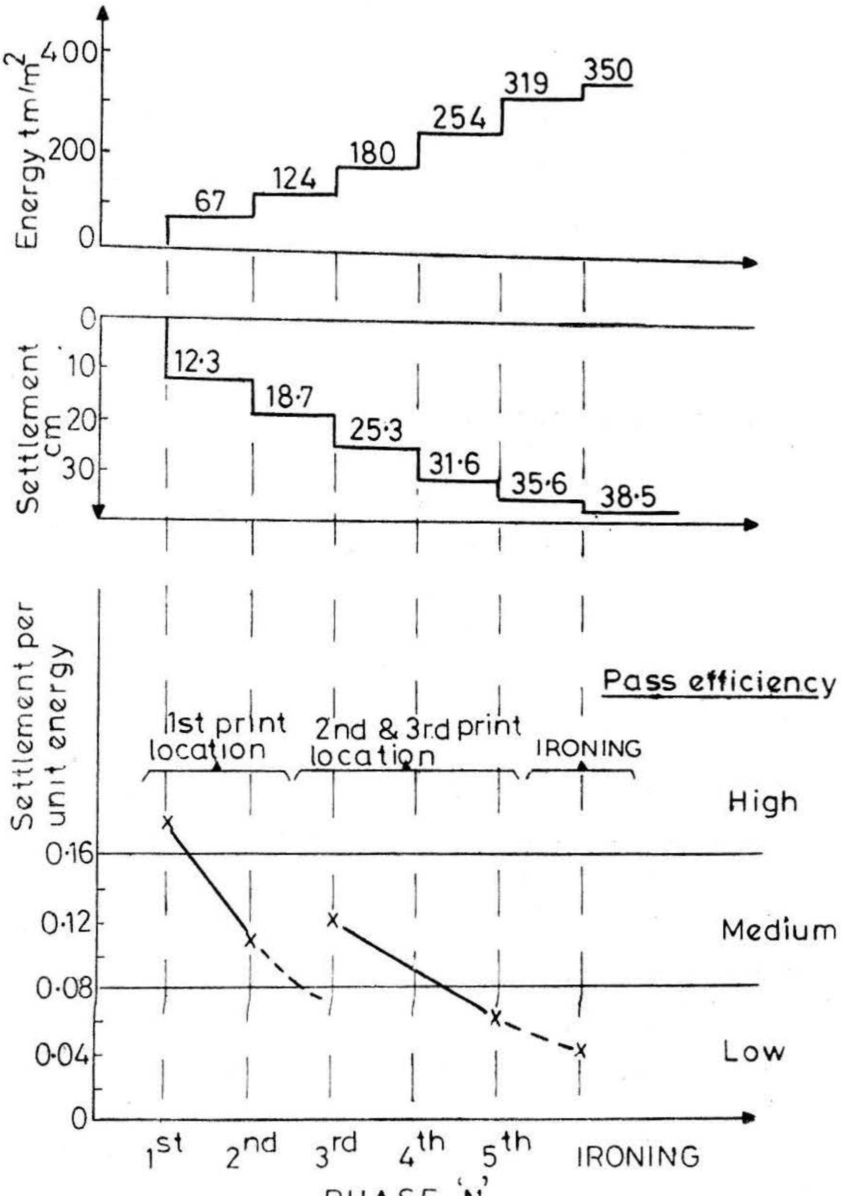

FIGURE 1 Applied Energy vs Enforced Settlement

from one pass to another. The change of pounder position always increases the efficiency. After the fourth pass, the efficiency becomes low due to the presence of highly densified soil layers near the surface which prevent the downward propagation of shock waves.

The typical soil properties in one of the zones of the treated area before and after compaction is presented in Fig. 2. The overall improvement can be summarized as follows:

From 0 to 1.5 m depth:	0 to 150% improvement
From 1.5 to 5.0 m depth:	150 to 250% improvement
From 5.0 to 8.5 m depth:	100 to 150% improvement
From 8.5 to 10 m depth:	60 to 100% improvement
From 10 to 14 m depth:	50 to 60% improvement
From 14 to 20 m depth:	10 to 50% improvement.

This corresponds to an overall improvement of about 130% from ground surface to 10 m depth and about 40% between 10 to 20 m depths.

Some shear planes have been observed in the upper silt layer after dynamic consolidation, which indicates that some of the plastic layers did shear rather than liquefy. The downward movement of the silt during early passes, where the impact energy was greater, facilitated the compaction of the lower sand, and improved the drainage of the clayey silt.

After 4 to 8 phases of consolidation, using various energy levels, the soils settled 38 cm in the 10 m compaction zone and 53 cm in the 20 m compaction zone. The in-situ relative density increased to 60%, reducing the liquefaction potential of the soil.

Detailed investigations were carried out at two soft spots to study the thixotropic recovery which was taking place. It consisted of in-situ testing of soil at increasing time intervals of 10 days to 90 days in very closely spaced bore holes in order to avoid local soil variation. At both locations, after 90 days, the recovery was almost 4 times greater than the value, just after compaction.

Analysis of Foundation Conditions after Improvement by Dynamic Consolidation:

In order to illustrate the usefulness of the dynamic consolidation for improving the subsoil conditions, three basic soil design parameters are discussed below:

(*a*) *Q—value:* Standard Penetration Test (SPT) results have been used to estimate the ϕ values. The empirical relationship proposed by Peck et al (1974) has been used for estimating ϕ—values and the results are given in Table 1 for various depths for two cases, viz. before and after compaction. Similarly ϕ can be calculated from CPT using the relationships given by Dayal and Jain (1981).

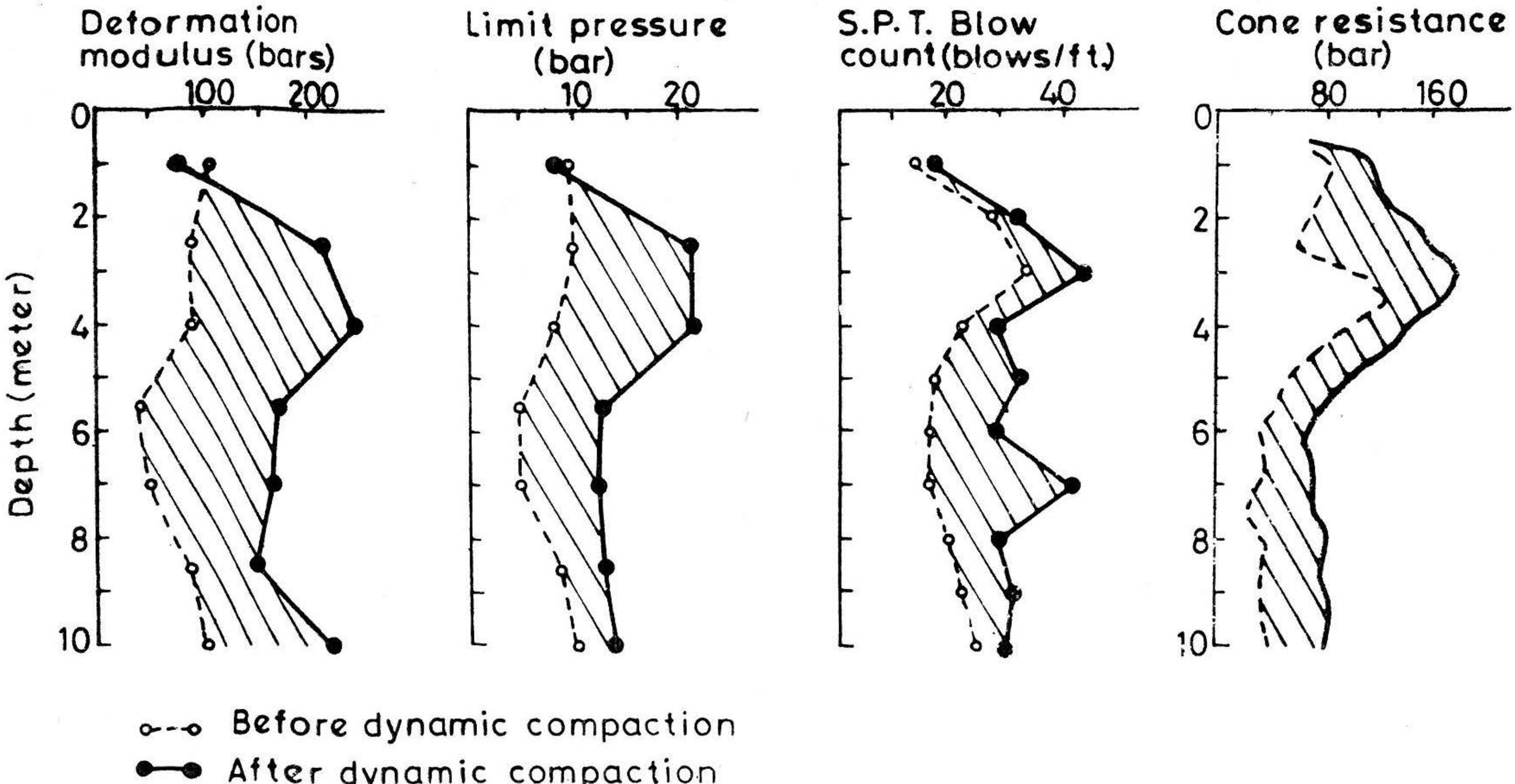

FIGURE 2 Improvement of Soil Properties

TABLE 1

Angle of Internal Friction (0)

Depth (m)	Before compaction		After compaction	
	N (blows/ft)	ϕ (degree)	N (blows/ft)	ϕ (degree)
1	14	31.5	18	32.5
2	29	36	33	37
3	34	37	44	40
4	22	34	30	36
5	17	32	33	37
6–10	18	32.5	30	36

(*b*) *Bearing Capacity:* Prior to dynamic consolidation the subsoil is more or less homogeneous and, therefore the bearing capacity (B.C.) has been calculated using Terzaghi's bearing capacity formula. After dynamic consolidation the simplified soil profile may be assumed of two layer system, the top one is much stiffer compared to the bottom one. In such condition the B.C. can be computed from the following relationship given by Winterkorn and Fang (1975).

The ultimate bearing capacity q_u'' for shallow foundation on homogeneous soil of infinite depth is given by Terzaghi as:

$$q_u'' = C N_c S_c + \gamma D N_q S_q + \tfrac{1}{2} \gamma B N_r S_r$$

where c = Cohesion

B = Width of footing

D = Depth of footing

γ = Unit weight of soil

N_c, N_q and N_r = B.C. factors

S_c, S_q and S_r = Shape factors.

The ultimate bearing capacity (q_u) of layered soil system is given by:

$$q_u = (q_u'' + \frac{c_1}{K} \cot \phi_1) \exp 2 \left(1 + \frac{B}{L} \right) K \tan \phi_1 \left(\frac{H}{B} \right) - \frac{c_1}{K} \cot \phi_1$$

where, for upper stiff layer strength parameters are c_1, ϕ_1 and for lower weak layer the parameters are c_2, ϕ_2, and

$K = (1 - \sin^2 \phi_1)/(1 + \sin^2 \phi_1)$

q''_u = bearing capacity of lower weak layer.

Assuming the depth of footing D = 1 m, the bearing capacity is calculated for different sizes of footings viz. B = 2, 4, 6, 10, 20 and 30 m. The values of ultimate bearing capacity before and after dynamic consolidation are tabulated in the Table 2. As can be noted from the table, a gain of more than double the bearing capacity is achieved after dynamic consolidation.

TABLE 2

Computed Bearing Capacities

B, m	2	4	6	10	20	30
			Bearing Capacity, $q_u(t/m^2)$			
Before compaction	162	217	272	292	286	493
After compaction	362	493	623	677	751	768

(*c*) *Settlement:* For uniformly distributed loads acting on a circular or a rectangular areas near the surface of a relatively deep stratum, the vertical settlement can be estimated from the following relationship (Winterkorn and Fang, 1975):

$$S = C\,P\,B\,(1 - \mu^2/E)$$

In this expression S is the settlement of a point at the surface, P is the magnitude of uniformly distributed load, B is the characteristic dimensions of loaded area, E is Young's modulus, μ is Poisson's ratio for the elastic medium and C is shape factor.

Settlement at the centre of uniformly loaded circular footing resting on ι stiff elastic layer underlain by an infinite depth of less stiff elastic material :an be estimated using the following relationship:

$$S_I = a\,S_\infty$$

where S_I is settlement at centre of a uniformly loaded circular area at the surface of layer with elastic modulus E_1, Poisson's ratio μ_1 and thickness H, underlain by infinite depth of material with elastic modulus E_2 and Poisson's ratio μ_2. S_∞ is the settlement for second layer, and a is correction factor related to two settlements which is a function of $\frac{H}{B}$ and $\frac{E_1}{E_2}$. Assumping $P = 10\ T/m^2$, $C = 0.79$ and $\mu_1 = \mu_2 = 0.4$, the settlements are calculated for different sizes of footings, i.e., $B = 2, 4, 6, 10, 20$ and 30 m and the values are given in Table 3 for before and after the dynamic consolidation. The percentage reduction of the settlement is the function of the depth of improvement of soil. For the smaller size of footing, the reduction of the settlement is more than fifty percent whereas for the larger size of footing, it is much less.

TABLE 3

Computed Settlements

B (m)	2	4	6	10	20	30
			Settlement, S (cm)			
Before compaction	2.2	4.4	6.6	11	22	33
After compaction	0.86	0.93	3.3	5.6	14.4	26.6

Summary and Conclusions

(1) The Dynamic Consolidation is a method of improving the mechanical characteristics of compressible soils down to depth of 30 m by repeated application of very high intensity impacts at the surface following a well defined programme with regard to time and grid appropriate to the site. The method is applicable to any type of soil, either onshore or offshore. It is proved to be more economical compared to alternative methods when the surface area to be treated is large.

The results of treatment by this method are dramatic and immediate. Surface settlement is 2% to 5% or more of the thickness of the material per pass. Strength in terms of bearing capacity is improved by a factor of 2 to 4. Compressibility in terms of total and differential settlement can be reduced by a factor of 3 to 10. The liquefaction potential of subsoil can be eliminated by the application of this technique.

(2) The rapid densification of the soil by this technique is a result of several physical phenomena such as compression of air filled voids, pore water, liquefaction, release of adsorbed water, and thixotropic recovery.

(3) A case history has been presented for the site consisting of alluvial deposits of flood plain. In-situ tests were carried out before and after the dynamic consolidation. The results of the dynamic consolidation test programme indicated an acceptable improvement of bearing capacity and settlement. The procedure is given for

calculating the angle of internal friction —ϕ, bearing capacity and settlement of layered soils formed from dynamic consolidation.

In author's knowledge, the technique of Dynamic Consolidation has not been used in India so far in the reclamation of land. But it has a great scope for improving the weak soil economically, considering the great need to reclaim many of its lands for habitational, industrial and other purposes. The required equipment of Dynamic Consolidation is either to be imported or fabricated in India, and once it is available, the technique presents no problem in its applicability.

It is difficult to make blanket statements about costs but, in general, the preliminary calculation shows that the cost could vary between Rs. 30/m^2 to Rs. 50/m^2.

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