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EQUALIZATION OF SINGLE AND MULTIPLE FUNCTION OF SAND COMPACTION PILE IN SOFT COHESIVE GROUND

Sharifullah Ahmed
Ph. D. Scholar (Geotechnical), Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka–1000, Bangladesh
sharif.geo.2006@gmail.com

ABSTRACT
In Bangladesh soft cohesive soil is often encountered in the construction of building structure. To design foundation on soft ground, Sand Compaction Pile (SCP) may be a cost-effective sustainable alternative of deep foundation to provide adequate bearing capacity. The bearing capacity of ground improved by SCP may be calculated considering single and multiple function of SCP. In general practice the lowest bearing capacity between single and multiple function has to be selected as ultimate bearing capacity for design. This paper gives a chart to obtain SPT ratio and diameter ratio for equalization of single and multiple function. If the ultimate bearing capacities of improved ground calculated considering single and multiple functions using those ratios and then two types of bearing capacity shall be equal.

Keywords: *Ground Improvement, Diameter ratio, Sand Compaction Pile (SCP), Single and multiple function, Soft Ground, SPT ratio*

I. INTRODUCTION

Ground strengthening by sand compaction pile is considered as one of the versatile and cost-effective ground improvement methods. An advanced practice in foundation construction is to install sand compaction pile for the purpose of densifying of soft soil. Significant increases in bearing capacity can be achieved by this method to withstand high level of foundation load.

II. PRINCIPLE OF SAND COMPACTION PILE IN COHESIVE SOIL

Densification of ground provides more bearing capacity immediately after installation of sand compaction pile (SCP).

Through the formation of these compacted sand piles, the bearing capacity of the ground can be increased due to ‘replacement effect’ and ‘stress concentration effect’. ‘Stress concentration’ means that external load is concentrated mainly on the sand compaction piles, as shown in Fig. 1.0 [1].

The principle of the SCP method for cohesive grounds is based on the theory for composite grounds [2]. Composite grounds consist of soft cohesive grounds and compacted sand piles formed therein; the composite ground formed has high shear strength and drainage capability owing to the presence of the sand compaction piles.

A. Replacement Area Ratio

The replacement area ratio, a_s is defined as the ratio of the sectional area of the sand pile to the hypothetical cylindrical area. For square patterns the replacement area ratio, a_s are formulated as Equation (1.0).

Replacement area ratio for square pattern,

$$a_s = \frac{A_s}{A} = \frac{\pi d^2/4}{D^2} \qquad (1.0)$$

where,

A: cross sectional area of clay ground and sand pile (m^2)

A_s*:* cross sectional area of sand pile (m^2)

d: diameter of sand pile (m)

D: interval of sand piles (m).

A clay ground improved by the SCP method can be considered to be a composite ground consisting of compacted sand piles and surrounding soft clay. External load is concentrated mainly on the sand piles as shown in Figure 2.0, because the compressive stiffness of sand piles is much higher than that of the surrounding clay ground, while due to less stiffness less load is applied to the soft clay between the sand piles [2].

B. Stress Concentration Ratio

The stress concentration ratio, n, is defined as the ratio of the vertical stresses acting on sand piles, σ_s, to that on the surrounding soft clay, σ_c. A simple analytical approach to provide a formulation of those stresses as shown in Equation (2.0) to Equation (5.0), which are derived from the stress equilibrium between sand compaction piles (SCP) and surrounding soft clay.

The vertical load, $\sigma A = \sigma_c A_c + \sigma_s A_s$ (2.0)

through introducing the stress concentration ratio,

$$n = \frac{\sigma_s}{\sigma_c} \quad (3.0)$$

the vertical stress on soft clay ground,

$$\sigma_c = \frac{\sigma}{\{1+(n-1)\ as\}} \quad (4.0)$$

and the vertical stress on sandy ground (SCP),

$$\sigma_s = \frac{n\sigma}{\{1+(n-1)as\}} \quad (5.0)$$

where:

A_c: cross sectional area of clay ground (m^2)

n: stress concentration ratio

σ : average vertical stress (kN/m^2)

The magnitude of stress concentration is subjected to the stiffness of sand column and the surrounding soft soil.

Young's modulus of soil (E), commonly referred to as soil elastic modulus, is a measure of soil stiffness. A secant slope of stress-strain curve is secant modulus E_s. This is the most representative to non-linear behavior of soil as a plastic material. Hence, the stress concentration ratio may be obtained from the ratio of secant modulus (Equation 6.0):

$$n = \frac{E_s\,(\text{SCP})}{E_s\,(\text{clay ground})} \quad (6.0)$$

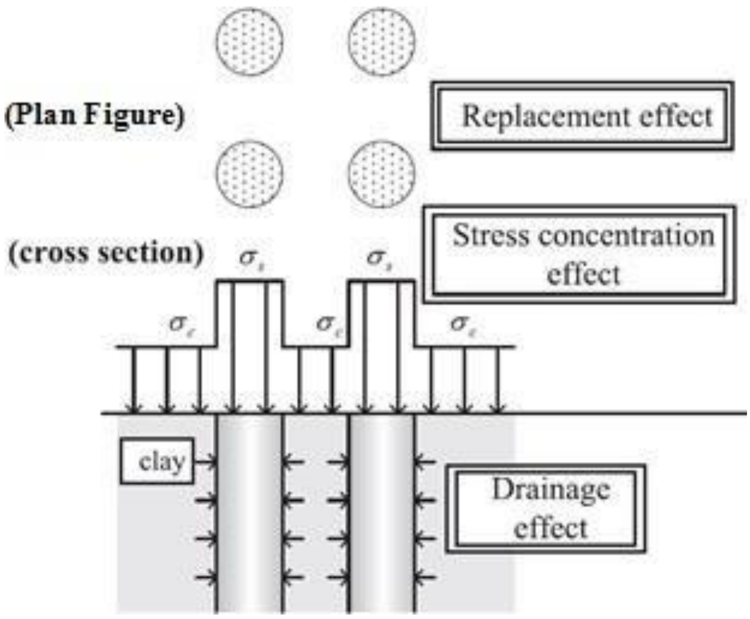

Fig. 1 Concept improvement of bearing capacity of the cohesive or clayey ground through installation of compacted sand piles.

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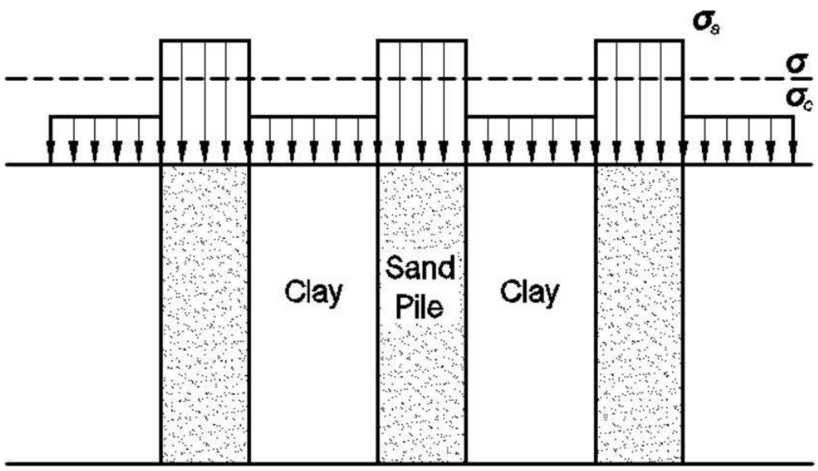

Fig. 2 Illustration of stress concentration.

The modulus of elasticity (E_s) of soil may be obtained from plasticity and Standard Penetration Test (SPT) values. For plastic silts or clayey silt, E_s=0.3N_1+1.8 (MPa) [3] and for non-plastic sand E_s=0.5N_2+7.5 (MPa) [4], where, N_1 is the corrected SPT value of clay ground and N_2 is the corrected SPT value inside SCP.

C. Bearing Capacity of Single Sand Compaction Pile

Bering capacity of Clayey Ground Improved by Sand Compaction Piles has been described in this section according to Masaki Kitazume [2]. The drainage effect does not been considered in current study.

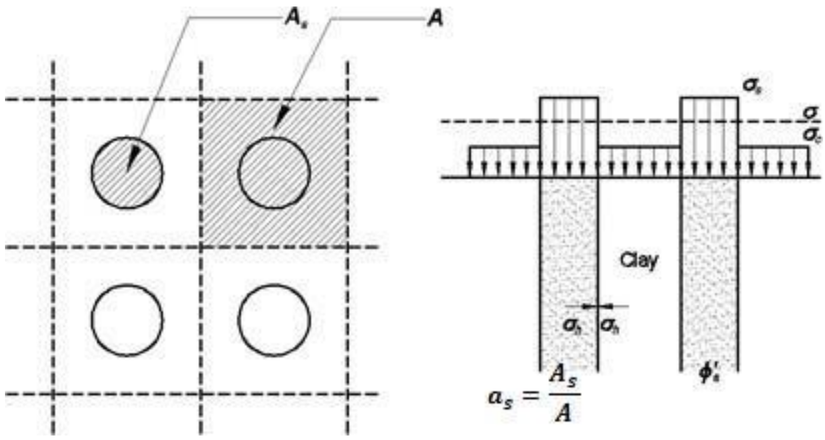

Fig. 3 Illustration of bearing capacity of a single sand pile.

The total bearing load on a single sand compaction pile and surrounding clayey soil, P has been mentioned as Equation (7.0) to Equation (11.0), in which the stress equilibrium of sand compaction piles and surrounding soft ground and the stress concentration effect are incorporated (Figure 3) [2].

The principle of the calculation is that the sand compaction piles and surrounding soft clay ground are subjected to equal vertical settlement, leading to a stress concentration on the sand compaction piles.

In this principle, the stress conditions of sand compaction pile and surrounding soil are assumed as an ultimate active state and an ultimate passive state respectively [2].

The average vertical load,

$$P = A\sigma = \sigma_c(A_c + A_s n) \qquad (7.0)$$

Now, the vertical stress,

$$\sigma = \frac{P}{A} \qquad (8.0)$$

the horizontal stress,

$$\sigma_h \geq \frac{1-\sin\phi_s}{1+\sin\phi_s}\sigma_s \qquad (9.1)$$

$$\sigma_h \leq \sigma_c + \sigma_u \qquad (9.2)$$

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the stress concentration ratio,

$$\frac{\sigma_s}{\sigma_c} = n = \frac{1+\sin\phi_s}{1-\sin\phi_s}\left(1 + \frac{\sigma_u}{\sigma_c}\right) \qquad (10.0)$$

where:

σ_u : upper yield stress of clay ground (kN/m^2)

ϕ_s : internal friction angle of sand compaction pile may be obtained from Correlation between $(N_1)_{60}$ and Friction Angle [5].

From Equations (10.0):

$$n\frac{1-\sin\phi_s}{1+\sin\phi_s} = 1 + \frac{\sigma_u}{\sigma_c}$$

or, $\frac{n(1-\sin\phi_s)}{1+\sin\phi_s} - 1 = \frac{\sigma_u}{\sigma_c}$

or, $\frac{\sigma_u}{\sigma_c} = \frac{n(1-\sin\phi_s)-(1+\sin\phi_s)}{1+\sin\phi_s}$

or, $\sigma_c = \frac{1+\sin\phi_s}{n(1-\sin\phi_s)-(1+\sin\phi_s)}\sigma_u \qquad (11.0)$

The upper yield stress of soft clay ground, σ_u can be estimated as $2c_u = q_u$ where c_u and q_u are undrained shear strength and unconfined compressive strength of surrounding soft clay ground respectively (assume failure of the clay by an ultimate passive condition.

The value of σ_u may be assumed as $0.7q_u$ by considering that no infinite creep deformation took place in the clay ground [2].

Using this value, the ultimate vertical load capacity of improved ground, P can be obtained as,

$$P = 1.4c_u\frac{1+\sin\phi_s}{(n-1)-(n+1)\sin\phi_s}(A_s n + A_c) \qquad (12.0)$$

Now, the ultimate compressive strength of combined ground,

$$q_u = P/A \qquad (13.0)$$

The undrained shear strength of combined ground may be calculated from the ultimate compressive strength of combined ground.

The ultimate bearing capacity of combined ground considering single function of sand compaction pile, q_1 has been obtained from multiplication of undrained shear strength, $c_{u\ (improved)}$ and bearing capacity factor for cohesion, N_c using Terzaghi's theory and these values are used in parametric study.

D. Bearing Capacity of Multiple Sand Compaction Piles

In case of multiple action of SCP, the bearing capacity of improved ground is often evaluated by Terzaghi's bearing capacity theory [2].

The bearing capacity of SCP improved ground is calculated by the weighted average of bearing capacity of clay ground, q_{uc} and bearing capacity of SCP, q_{us} using the replacement area ratio (Figure 4.0).

Ultimate bearing capacity of clay ground,

$$q_{uc} = \frac{1}{F_s}cN_c \qquad (14.0)$$

Ultimate bearing capacity of sandy ground [2],

$$q_{us} = \frac{1}{2}B\gamma_s\beta N_\gamma + qN_q \qquad (15.0)$$

where:

B : width of foundation (m)

β : shape Factor

c : undrained shear strength of clay ground (kN/m^2) = $7N_1$

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q : surcharge pressure

N_c N_q and N_γ: bearing capacity factor for cohesion, overburden pressure and self-weight

γ : unit weight of surrounding ground (kN/m^3).

The ultimate bearing capacity of improved ground [2],

$$q_2 = a_s . q_{us} + (1 - a_s)q_{uc} \qquad (16.0)$$

III. RESULT OF ANALYSIS AND PARAMETRIC STUDY

The graphical relation of ultimate bearing capacities q_1 and q_2 with SPT ratio N_2/N_1 has been presented in Figure 5.1 to Figure 8.4 for value of the diameter ratio D/d=2.0, 2.5, 3.0 and 3.5.

Generally, the minimum value of q_1 and q_2 has to be selected as ultimate bearing capacity of provided ground. In this way maximum bearing capacity shall not be utilized.

However, at a specific value of SPT ratio N_2/N_1 the same value of q_1 and q_2 has been observed.

Value of N_2/N_1 at $q1=q2$ has been termed as η which value indicate equalization of ultimate bearing capacity considering single and multiple functions for a specific diameter ratio D/d.

The equal bearing capacity points obtained from Figure 5.1 to 8.4 through close observation of the charts at 0.1 scale (not shown in this paper). These points are presented in Table 1. In those values of N_2/N_1 corresponding to D/d the improved ground shall represent dual function.

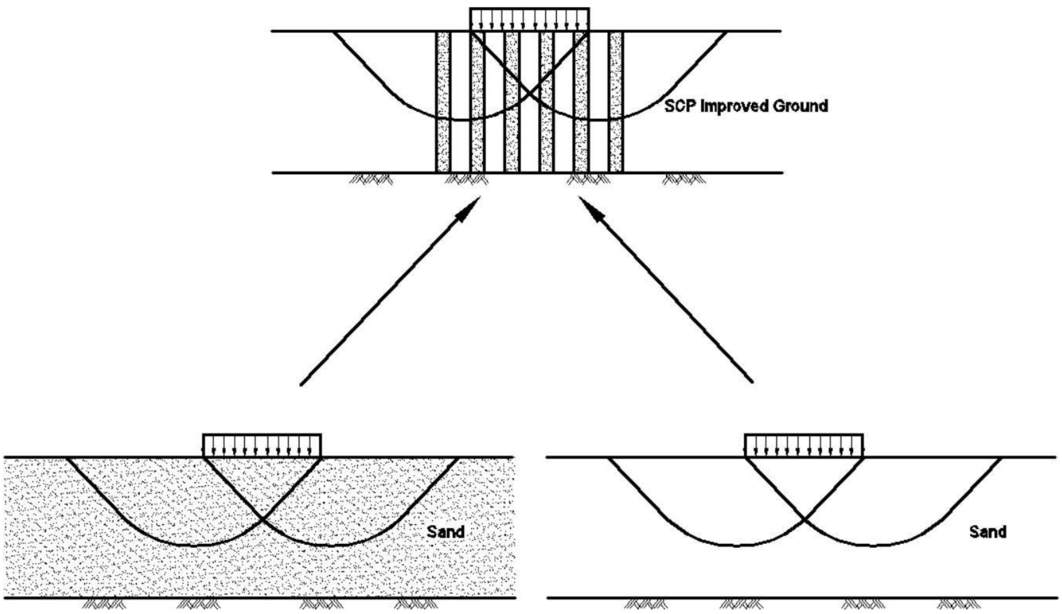

Fig. 4 Bearing capacity calculation by Terzaghi's theory.

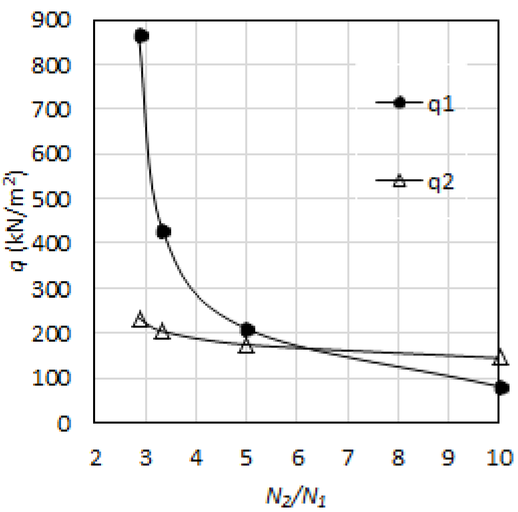

Fig. 5.1 N_2/N_1 Vs q_1 and q_2 for D/d =2.0 and N_1=10

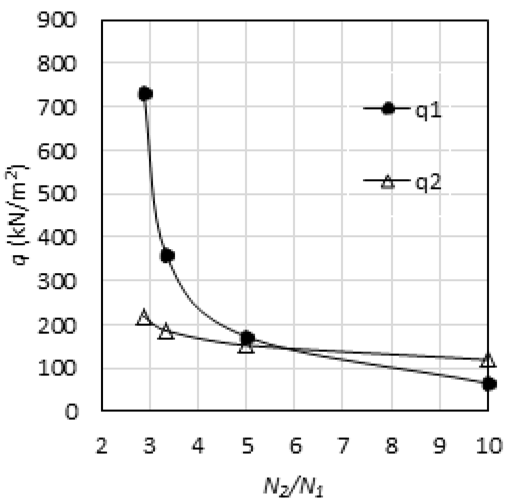

Fig. 5.2 N_2/N_1 Vs q_1 and q_2 for D/d =2.5 and N_1=10

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Table I: Values of *H* for Equal Bearing Capacity, *Q1=Q2*

Diameter ratio, *D/d*	2	2.5	3	3.5	Corrected SPT of SCP
η	6.2	5.7	5.52	5.45	N_2=10
	7.03	6.52	6.28	6.12	N_2=15
	8.14	7.35	6.95	6.71	N_2=20
	9.2	8.33	7.98	7.8	N_2=25

The graphical relation of ultimate bearing capacities q_1 and q_2 with the diameter ratio *D/d* has been presented in Figure 9.0 according to Table 1. Figure 9.0 may be used as the design chart for maximum bearing capacity of Sand Compaction Pile in cohesive soil.

From the subsoil investigation corrected value of soft ground N_1 is known. For known value of N_1 and target value of N_2, the diameter ratio *D/d* may be obtained to get equal value of q_1 and q_2.

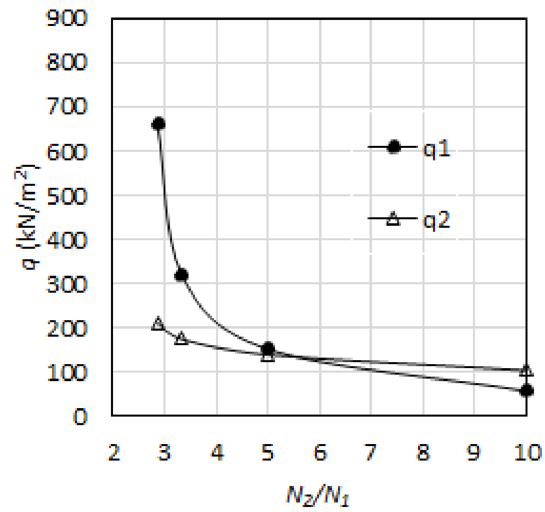

Fig.5.3 N_2/N_1 Vs q_1 and q_2 for *D/d* =3.0 and N_2=10

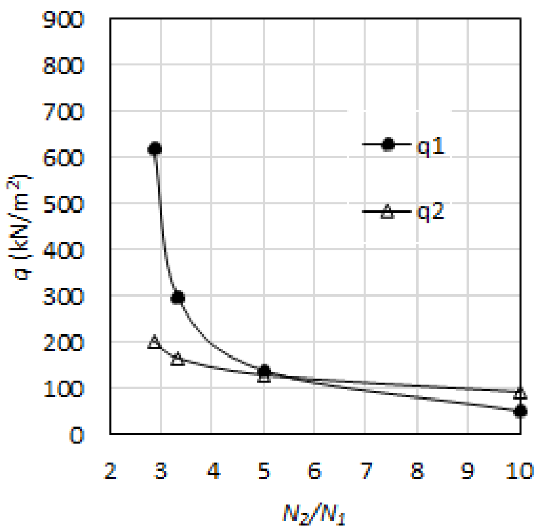

Fig.5.4 N_2/N_1 Vs q_1 and q_2 for *D/d* =3.5 and N_2=10

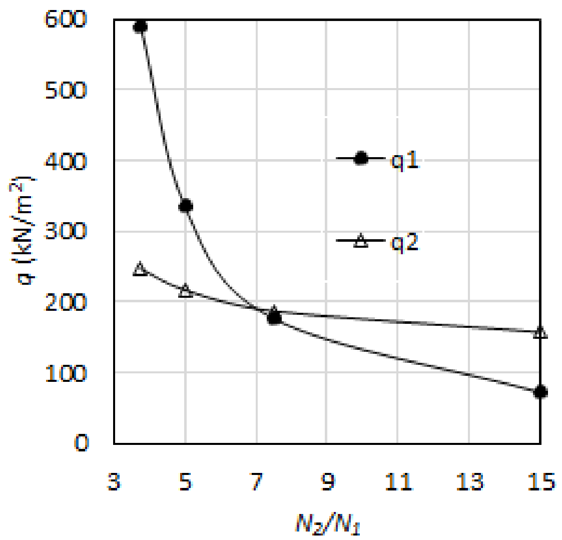

Fig. 6.1 N_2/N_1 Vs q_1 and q_2 for *D/d* =2.0 and N_2=15

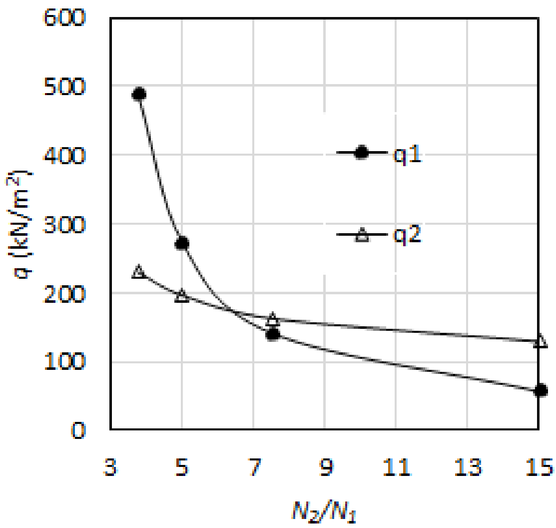

Fig. 6.2 N_2/N_1 Vs q_1 and q_2 for *D/d* =2.5 and N_2=15

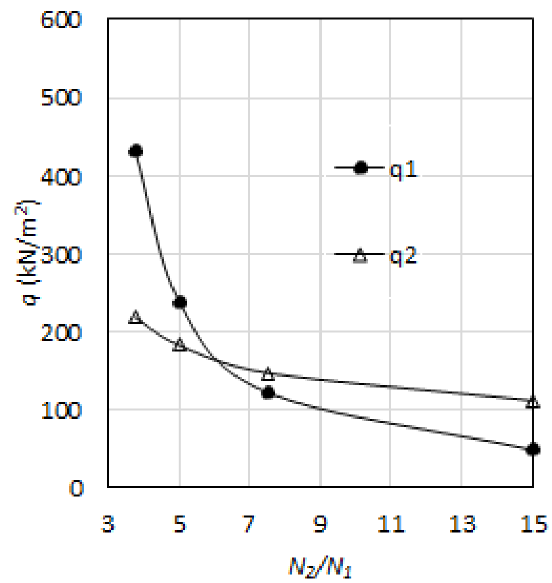

Fig. 6.3 N_2/N_1 Vs q_1 and q_2 for D/d =3.0 and N_2=15

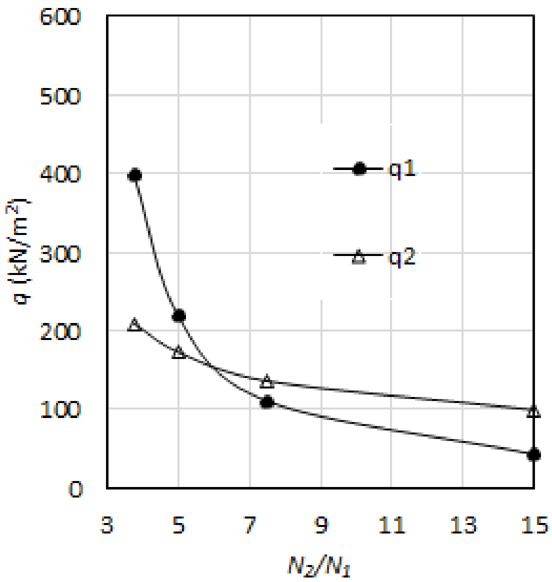

Fig. 6.4 N_2/N_1 Vs q_1 and q_2 for D/d =3.5 and N_2=15

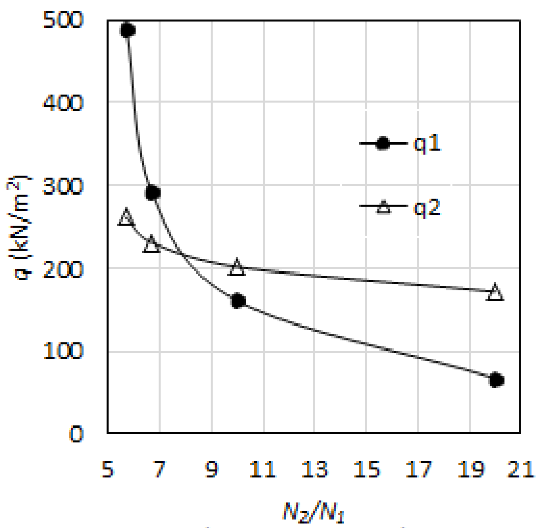

Fig. 7.1 N_2/N_1 Vs q_1 and q_2 for D/d =2.0 and N_2=20

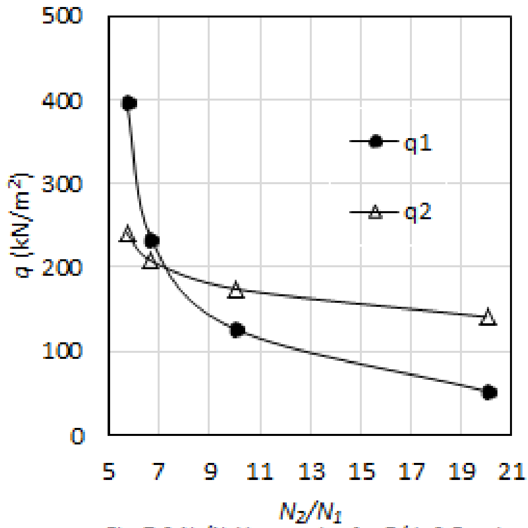

Fig. 7.2 N_2/N_1 Vs q_1 and q_2 for D/d =2.5 and N_2=20

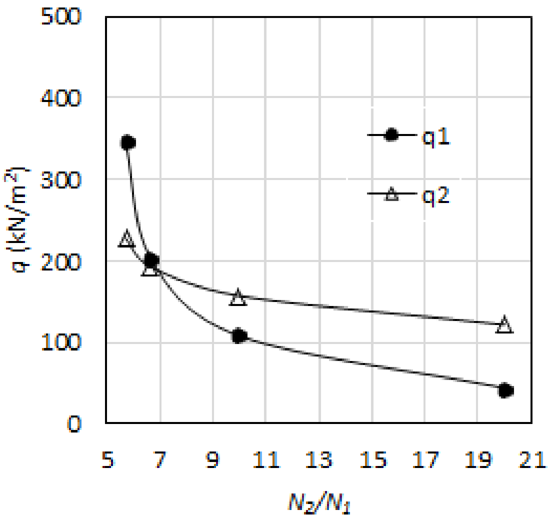

Fig. 7.3 N_2/N_1 Vs q_1 and q_2 for D/d =3.0 and N_2=20

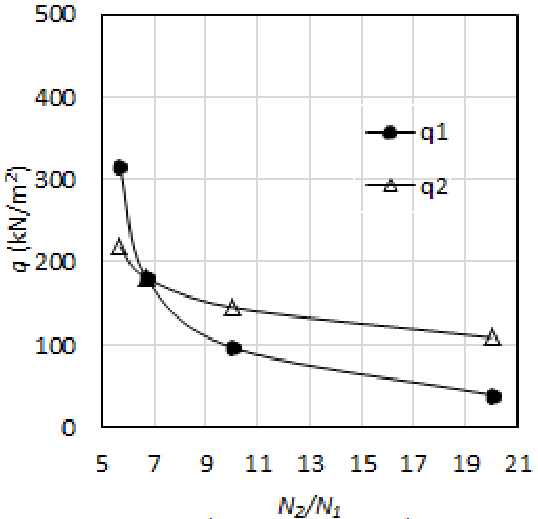

Fig. 7.4 N_2/N_1 Vs q_1 and q_2 for D/d =3.5 and N_2=20

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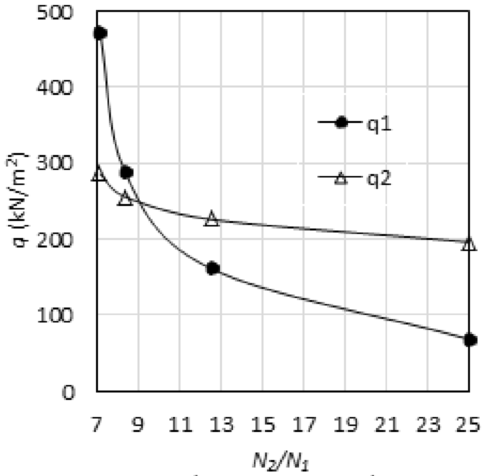

Fig. 8.1 N_2/N_1 Vs q_1 and q_2 for D/d =2.0 and N_2=25

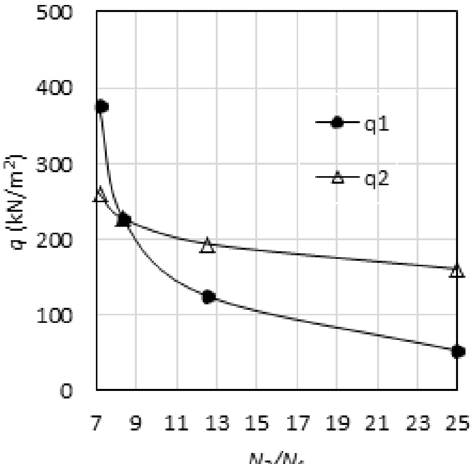

Fig. 8.2 N_2/N_1 Vs q_1 and q_2 for D/d =2.5 and N_2=25

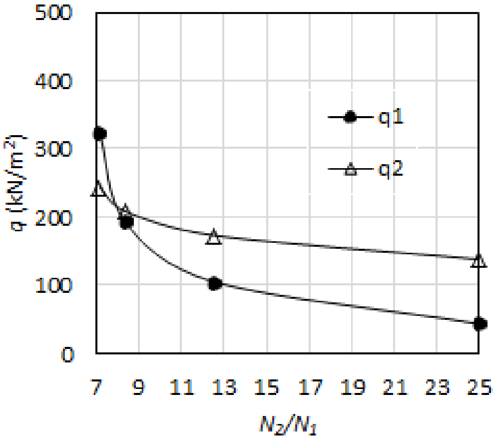

Fig. 8.3 N_2/N_1 Vs q_1 and q_2 for D/d =3.0 and N_2=25

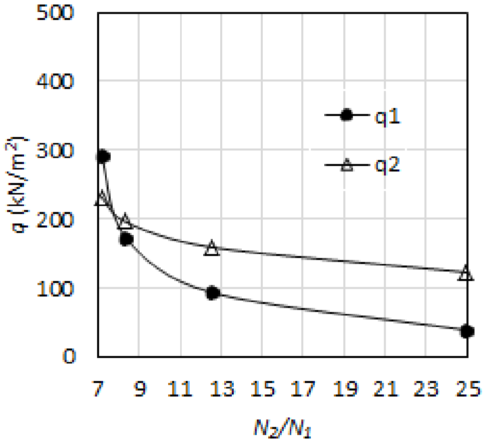

Fig. 8.4 N_2/N_1 Vs q_1 and q_2 for D/d =3.5 and N_2=25

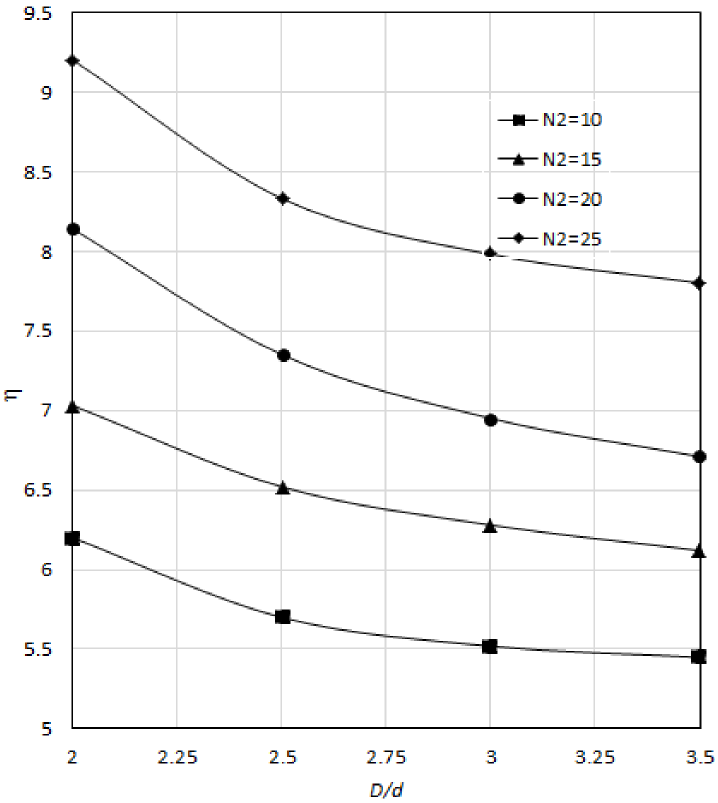

Fig. 9 D/d Vs η for Equalization of Ultimate Bearing Capacity, $q_1=q_2$

IV. CONCLUSION

Through current parametric study a relation between SPT ratio and the diameter ratio has been obtained to design the Sand Compaction Pile for dual function. The ultimate bearing capacities of improved ground may be calculated considering single and multiple functions using those ratios and two types of bearing capacity shall be equal. In this way, selecting the minimum value of ultimate bearing capacity and neglecting the maximum value may be avoided to make design of ground improvement more economic.

This is to be noted that, design and implementation of Sand Compaction Pile have to be done by qualified Geotechnical Engineer experience on related field.

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