ISSN 2229-5518

Mathematical Approach to Simulate Soil Behavior Under Shallow Compaction

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Abstract— Surface or shallow compaction is one of the earliest, cheapest and commonly used techniques to improve the physical and mechanical properties of loose soil specially for imported structural fill. It is simply rearranging of soil particles to reduce air ratios using surface static or vibrating mechanical effort. Usually, shallow compaction procedure includes subjecting the loose soil to certain number of compacting equipment passes to archive the accepted compaction level; this number of passes is a function of many parameters such as type of soil, initial soil parameters, compacting equipment characteristics and thickness of soil lift. International codes, specifications and handbooks include just guidelines about the required number of passes; accordingly, it is usually determined based on personal experience and field trials. This research has two goals, the first is to estimate the properties improvement of certain natural surface loose soil under certain surface compaction procedure by calculating the enhancement in soil properties after each pass and updating the soil properties for next pass calculations. The second goal is to use the previous approach to develop set of equations to design surface compaction procedure for imported structural fill, this includes calculating minimum compaction equipment characteristics, maximum lift thickness and minimum number of passes to enhance certain imported fill from certain initial condition to certain final condition. The proposed approach for the first goal was verified using case studies and showed good matches, and the developed designing equations for surface compaction procedure were verified using case studies and showed good matches.

Index Terms— Surface compaction, Number of passes, Imported structural fill, Soil improvement, mathematical approach.

1 Introduction

Structural fill is one of the common activities in any construction project, the main difference between structural and non-structural fill is the quality control. Structural fill is systematically tested to grantee minimum accepted mechanical properties, in order to simplify quality control tests; dry unit weight of fill is usually used to present the mechanical proprieties since they are strongly correlated. Structural fill may be constructed using original site soil or using imported soil with certain specifications based on the purpose of the fill and the required proprieties. Usually structural fill is used as soil replacement, road embankments, manmade slopes, fill beyond retaining structures, fill on foundations or pipelines and many other applications. According to structural fill application, a certain dry unit weight corresponding to certain minimum accepted mechanical properties should be archived.

Shallow compaction is one of the most famous, cheapest and widely used densification techniques to improve both physical and mechanical properties of structural fill. It depends on dividing the fill into sub-layers (lifts) with limited thickness and subjecting each lift to certain number of passes using compacting equipment. Compaction quality of each lift presented by its dry unit weight should be tested and approved before constructing the next lift. Generally, the compacted layer is considered accepted if its field dry unit weight is ranged between 90%-100% of the dry unit weight determined in the lab depending on project specifications.

Both standard and modified Proctor tests are the most used lab tests to determine both of maximum dry unit weight and optimum water content of soil. There are wide verities of shallow or surface compaction equipment as shown in Fig. 1, they usually classified as follows:

-Based on compacting actions:
- Static weight compaction such as smooth wheel drums
- Vibration compaction, usually small & handy devices
- Duel action, a combination of static weight & vibration

-Based on equipment size:
- Small and handy compacting plates and Rammers
- Walk behind vibratory rollers
- Towed or Self Propelled Ride on rollers

-Based on roller type:
- Smooth wheel rollers
- Sheep foot rollers
- Tamping rollers
- Pneumatic rollers
- Grid rollers

Choosing the suitable equipment depends on many variables such as job size, accessibility, type of fill, cost and many other variables. Successful compaction plan must include the following items:

-Specification of filling material
-Type of compacting equipment
-Lift thickness and number of passes
-Type and number of quality control tests for each lift
-Acceptance criteria

Shallow compaction had been studied by many researchers and from different aspects and points of view. Each one of Gupta and Larson (1982), Bailey (1986), Assouline (1986) and Fritton (2001), has developed an empirical formula to correlate bulk density of compacted fill with the applied normal stresses. Abebe (1998) present an empirical relation between the lift settlement and number of passes. On other hand, the magnitude of contact area between rollers and soil was studied by Komandi (1976), Grecenko (1995), O'Sullivan (1999).

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Fig. 1. Types of shallow compaction equipment

Footprint shape was described as super-ellipse by Hallonborg (1996), Febo (2000) and Keller (2005). While stress distribution below roller was investigated by Helenelund (1974), Karafiath and Nowatsky (1978), Johnson and Burt (1990), Koolen (1992) and Keller (2004). Besides the previous empirical formulas and mathematical models, the interaction between tire and terrain was modeled using FEM by Kaiming Xia (2010) and Smith and Peng (2013). Also, the dynamic response of the vibrator-soil system was studied by Pietzsch & Poppy (1992), Wersäll (2016), Bejan & Acebo (2016).
Recently, artificial intelligence and soft computing techniques were used by Ebid (2004), Naderi (2012) and Gonzalez (2013) to predict surface compaction test results.

Codes guidelines and personal experience are usually the reference of most compaction plans, instead, the aim of this research is to provide procedure to design compaction plans based on geotechnical calculations, also, this research will be concerned in granular soil only since it is commonly used for structural fill works.

2 Objectives

This research has two goals, the first is to estimate the properties improvement of certain natural surface loose soil under certain surface compaction procedure by calculating the enhancement in soil properties after each pass and updating the soil properties for next pass calculations. The second goal is to use the previous approach to develop set of equations to design surface compaction procedure for imported structural fill, this includes calculating minimum compaction equipment characteristics, maximum lift thickness and minimum number of passes to enhance certain imported fill from certain initial condition to certain final condition.

3 Proposed approach

3.1 Numerical simulation procedure

In order to modeling the behavior of soil under surface compaction loads using mathematical approaches, the soil proprieties have to be correlated to each other mathematically and since dry unit weight is the governing property in compaction, hence, all soil properties are presented as functions in dry unit weight. Soil proprieties are collected from Naval Facilities Engineering Command - Design Manual 7.01&7.02 as shown in Tables 1 and 2 and correlated to dry unit weight as follows:

For pure granular soil:

$$E_S \quad (t/m^2) \approx 30\,\gamma^9 \tag{1}$$

$$\tan(\varphi) \approx (3.8\,\gamma - 1)/7 \tag{2}$$

For pure fine-grained soil:

$$E_S \quad (t/m^2) \approx 15\,\gamma^9 \tag{3}$$

$$C_U \quad (t/m^2) \approx (\gamma^{2.5} e^{(3.8\gamma-1)/2})/4 \tag{4}$$

Hence, the following is proposed for mixed soil with (F) fines percent:

$$E_S \quad (t/m^2) \approx 30\,(1-0.5F)\,\gamma^9 \tag{5}$$

$$\tan(\varphi) \approx (3.8\,\gamma - 1)/7 \tag{6}$$

$$C_U \quad (t/m^2) \approx F(\gamma^{2.5} e^{(3.8\gamma-1)/2})/16 \tag{7}$$

Correlating the ultimate bearing capacity with dry density starts with the classic Terzaghi's ultimate bearing capacity equation for surface loading:

$$\sigma_{ult} = C.Nc + \gamma.B.N_\gamma \tag{8}$$

Where Nc, Nγ are functions of angle of internal friction (φ). The best fitting functions between Nc, Nγ, (φ) and (γ) considering the values in Table 2 are:

$$N\gamma \approx (e^{(3.8\gamma-1)})/6 \tag{9}$$

$$N_C \approx 4(e^{(3.8\gamma-1)/2}) \tag{10}$$

3.2 Contact Stress

Compaction process depends on causing permanent deformations mass soil, in order to achieve that; the effective compacting contact stress should be high enough to cause plastic deformations. Hence, the contact stress must exceed the soil bearing capacity to generate plastic shear failure surfaces. The ultimate bearing capacity of soil could be approximated as follows:

$$\sigma_{ult} \approx (F.\gamma^{2.5}.e^{(3.8\gamma-1)})/4 + (\gamma.B.e^{(3.8\gamma-1)})/6$$
$$\approx \left[(F.\gamma^{2.5}/4) + (\gamma.B/6)\right] e^{(3.8\gamma-1)} \tag{11}$$

Contact stress between roller/tire and fill depends on the type of compacting equipment as follows:

1. For pneumatic rollers, contact stress is almost equal to tire pressure which ranged between 40 to 100 ton/m²
2. For static smooth wheel rollers, contact stress can be calculated by dividing the axe load by the contact area. Generally, the driving axe is about 50% to 66% of equipment total weight which is ranged between 8 to 25 tons on other hand, contact area could be calculated after Grecenko (1995) as follows:

   $$A = c\,.\,d\,.\,b \tag{12}$$

   Where:
   A : Contact area (m²),
   d : Drum diameter which is ranged between 1.0 to 1.5 m
   b : drum length (m) which is ranged between 1.2 to 2.8 m
   c : Constant as follows:
   c = 0.175 for rigid wheel on rigid soil
   c = 0.270 for rigid wheel on soft soil

   Generally, contact stress is ranged between 15 to 35 ton/m²
3. For grid roller, the equivalent contact stress can be calculated by dividing the equivalent smooth roller contact stress by solidity ratio which is about 50%, hence, the equivalent contact stress is ranged between 30 to 70 ton/m²
4. For sheepfoot roller, the equivalent contact stress can be calculated by dividing the equivalent smooth roller contact stress by coverage ratio which is about 8%-12%, hence, the equivalent contact stress is ranged between 125 to 500 ton/m²
5. For vibrator rollers, manufactures datasheets usually specify the characteristics of the vibrators using three parameters:

TABLE 1
Typical Properties for Granular Soils

Soil Class	SPT (N_{30})	e	γ_{dry} (t/m^3)	Φ (Degree)	Dr (%)	E_S (MPa)	CPT, qc (MPa)
Loose	0-10	1.2-0.9	1.2-1.4	27-32	15-35	15-50	0-5
Med.	10-30	0.9-0.7	1.4-1.6	32-36	35-65	50-200	5-15
Dense	30-50	0.7-0.5	1.6-1.8	36-40	65-85	200-600	15-25

TABLE 2
Typical Properties for (50%) Fine-Grained Soils

Soil Class	SPT (N_{30})	e	γ_{dry} (t/m^3)	C_U (t/m^2)	LL-Wc / LL-PL	E_S (MPa)	CPT, qc (MPa)
Soft	2 - 4	1.6-1.2	1.0-1.2	1.2-2.5	0.50-0.63	0-12	0.0-1.5
Med.	4 – 8	1.2-0.9	1.2-1.4	2.5-5.0	0.63-0.75	12-50	1.5-3.5
Stiff	8 -15	0.9-0.7	1.4-1.6	5.0-10.0	0.75-1.0	50-150	3.5-7.0
V. Stiff	15-30	0.7-0.5	1.6-1.8	10.0-20.0	Wc=SL	150-300	7.0-15.0
Hard	30-50	0.5-0.33	1.8-2.0	20.0-40.0	Wc<SL	300-600	15.0-25.0

- Vibration frequency, it is ranged between (15 to 50 Hz) which is close to 1.0 to 1.5 the natural frequency of the granular soil lift
- Vibration maximum amplitude, which presents the peek dynamic displacement, it is generally between 0.8 to 2.0 mm
- Centrifugal force, which present the peek exciting force and equals to (ω^2.mr.e) where ω is the angular velocity, (mr) is the rotating mass and (e) is the eccentricity.

Dynamic contact stress can be calculated by multiplying equivalent static contact stress by dynamic factor which depends on the ratio between vibrating mass and total mass of roller, vibration amplitude and vibration frequency. For Static loading, dynamic factor equals unity. Fig. 2 shows the relation between compacting frequency to natural frequency ratio and dynamic factor for different damping ratios, generally, soil damping ratio decreases with densification, it is generally ranged between 15% to 35% after Das (2013). As shown in Fig. 2, the dynamic factor is ranged between 1.5 and 3.35, practically; it is ranged between 1.4 and 3.0 as reported by Maher & Gucunski (1999). In absence of accurate data, dynamic factor could be assumed between 2.00 and 2.50.

Tables (3),(4) summarized the contact stress and dynamic factor for some selected compactors with different weights and from different manufactures, based on that data, the effective contact stress of certain compactor could be correlated to its weight as follows:

Equipment weight (ton) = σ / 1.7 For pneumatic
= σ . S / (1.2 I) For steel rollers
……… (13)

Where (σ) is the calculated effective contact stress (ton/m²), (S) is coverage ratio, which is about (0.5) for grid roller and (0.25) for sheepfoot roller, and (I) is the dynamic factor (I = 1.0 for static rollers and I = 2.0 to 3.0 for vibrators).

3.3 Lift Thickness

Compaction process depends on causing plastic deformations mass soil using effective compacting stress. Since compaction stress is dissipated in soil with depth, hence, the effective depth could be defined as the thickness of soil layer that is subjected to vertical stress exceeded its ultimate bearing capacity due to compaction. That effective depth increases with increasing compacting stress and decreases with increasing soil strength.

Calculating the effective depth is complicated because soil properties including its ultimate bearing capacity are enhanced after each pass. In order to calculate the effective depth, compaction stress should be presented as function of depth, then that function to be solved to get the depth where the compaction stress equals the ultimate bearing stress corresponding to the current dry density and fines percent.

Regarding compaction stress dissipation with depth, Boussinesq's equation for vertical stress distribution beneath strip footing shows that the ratio between stress at certain depth and the stress at surface equals (σz/σo). Fig.3 indicates that the stress at depth equals four times the load width is less that 10% the stress at the surface and so, it could be neglected.

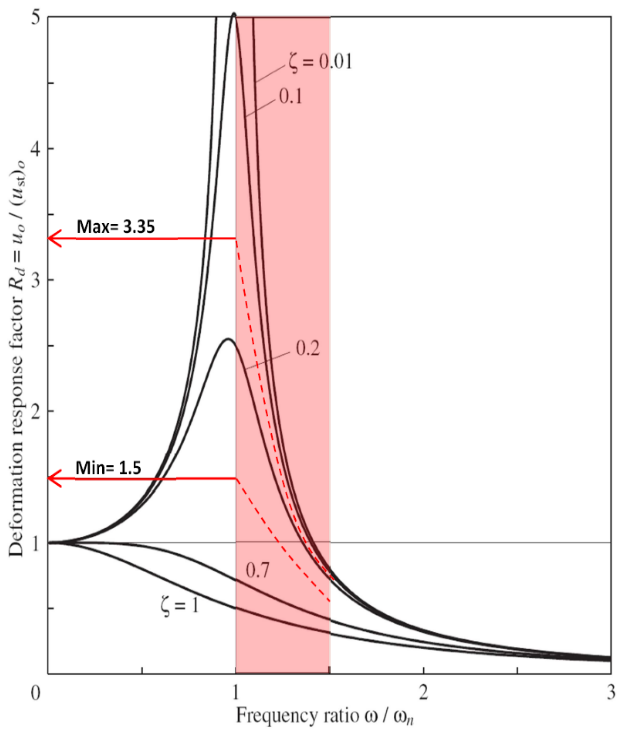

Fig. 2. Relation between compacting frequency to natural frequency ratio and dynamic factor for different damping ratios, After Das (2013)

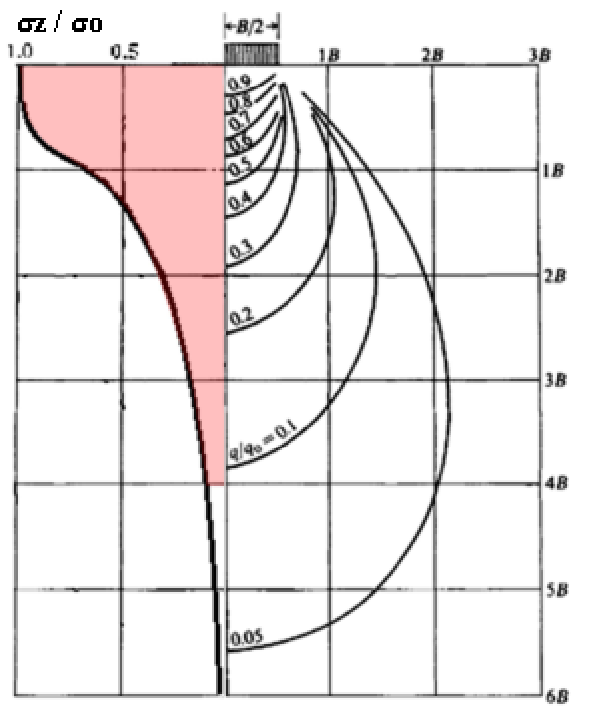

Fig. 3 Boussinesq's equation for vertical stress distribution beneath strip footing, After Das (2013)

TABLE 3
CONTACT STRESS AND DYNAMIC FACTOR VALUES FOR SELECTED ROLLER COMPACTORS WITH DIFFERENT WEIGHTS FROM DIFFERENT MANUFACTURES

Manufacture	Model	Drum diameter (mm)	Drum width (mm)	Operating weight (ton)	Linear Load (kg/cm)	Centrifugal force (KN)	Contact stress (t/m^2)	I_{max}	I_{min}
AMMANN	ASC 70 TIER	1300	1680	7.2	23.7	145/130	10.42	3.0	2.8
	ASC 110 TIER	1500	2130	11.5	34.5	277/206	13.14	3.4	2.8
	ASC 130 TIER 3	1500	2130	12.5	39.1	300/230	14.90	3.4	2.8
	ASC 150 TIER 4F	1500	2130	15.0	48.8	325/237	18.59	3.2	2.6
	ASC 170 TIER 4F	1500	2130	16.3	51.0	335/260	19.43	3.1	2.6
	ASC 200 TIER 3	1600	2130	19.8	58.6	375/300	20.93	2.9	2.5
	ASC 220 TIER 3	1600	2130	21.6	66.9	375/300	23.89	2.7	2.4
HAMM	Series 3000-3410	1500	2140	10.7	27.0	246/144	10.29	3.3	2.3
	Series 3000-3412	1500	2140	12.2	31.3	256/215	11.92	3.1	2.8
	Series 3000-3516	1500	2140	15.8	43.5	256/215	16.57	2.6	2.4
	Series 3000-3518	1600	2220	17.8	48.6	331/243	17.36	2.9	2.4
	Series 3000-3520	1600	2220	19.8	56.3	331/243	20.11	2.7	2.2
	Series 3000-3625	1600	2220	24.8	72.6	331/243	25.93	2.3	2.0
BOMAG	BW 124	900	1200	3.3	13.3	86/43	8.44	3.6	2.3
	BW 145	1060	1450	4.8	17.5	80/56	9.43	2.7	2.2
	BW 177	1225	1690	6.5	23.5	115/75	10.96	2.8	2.2
	BW 211	1500	2130	10.8	27.5	245/165	10.48	3.3	2.5
CAT	CS34	1000	1270	4.5	16.0	67	9.14	2.5	2.5
	CS44	1220	1676	6.9	20.5	134/67	9.60	2.9	2.0
	CS54	1535	2135	10.4	27.0	234/133	10.05	3.3	2.3
	CS64	1535	2135	12.0	33.5	234/133	12.47	3.0	2.1
	CS68	1535	2135	14.3	43	300/140	16.01	3.1	2.0
	CS74	1535	2135	16.0	50	330/166	18.61	3.1	2.0
	CS78	1535	2135	18.7	63	330/166	23.45	2.8	1.9

TABLE 4
CONTACT STRESS VALUES FOR SELECTED TIER COMPACTORS WITH DIFFERENT WEIGHTS FROM DIFFERENT MANUFACTURES

Manufacture	Model	Tier diameter (mm)	Tier width (mm)	Number of tiers	Compacting width (mm)	Operating weight (ton)	Tire load (kg)	Contact width (mm)	Contact stress (t/m^2)
AMMANN	AP 240 TIER 3	1000	280	8	2000	24.0	3000	275	39.0
HAMM	HD 14 TT	800	270	7	1275	3.5	500	220	8.4
	GRW 180i-10	1000	280	8	2000	8.8	1100	275	14.3
	GRW 180i-12H	1000	280	8	2000	11.5	1450	275	18.8
	GRW 280i-20	1000	280	8	2000	19.2	2400	275	31.2
	GRW 280i-24	1000	280	8	2000	23.3	2900	275	37.7
	GRW 280i-28	1000	280	8	2000	26.8	3350	275	43.5
BOMAG	BW 11 RH-5	760	190	9	1750	10.9	1200	209	30.2
	BW 27 RH-4I	1000	280	8	2000	26.8	3350	275	43.5
CAT	CW16	760	190	9	1730	5.2	520	209	13.1
	CW34-10	800	330	8	2090	10.0	1250	220	17.2
	CW34-27	800	330	8	2090	27.0	3375	220	46.5

Based on that, ($\sigma z/\sigma o$) value could be approximated down to four times the load width as follows:

$$\sigma_Z/\sigma_O \approx 1.35\, e^{-0.7(Z/B)} \leq 1.0 \qquad (14)$$

Hence,

$$\sigma_Z \approx 1.35\, \sigma_O\, e^{-0.7(Z/B)} \leq \sigma_O \qquad (15)$$

Where (B), (Z), (σo) and (σz) are strip width, considered depth, stress at ground surface and stress at depth (Z) respectively. By solving Eqs. (1), (15), effective depth (Heff) could be calculated as follows:

$$H_{eff} \approx 1.4B\left[1 - 3.8\gamma - LN\left(\frac{\gamma.B + 1.5\,F.\gamma^{2.5}}{8\sigma_o}\right)\right] \qquad (16)$$

The total settlement of the effective zone could be calculated using Boussinesq's chart as follows:

$$\Delta h = A\,.\,B\,.\,\sigma o\,/\,Es \qquad (17)$$

Where (A) is the shaded area under Boussinesq's chart as shown in Fig. 3. For ($0.0 < Z/B < 4.0$), the area (A) could be approximated as follows:

$$A \approx 0.555\, Ln\, (Heff\,/B) + 0.93 \qquad (18)$$

3.4 Procedure

The proposed approach depends on calculating the lift settlement after each pass considering the fact that only effective depth is affected by compaction effort, and accordingly fill proprieties will be updated to be used to calculate the settlement of the next pass. Pass after pass, the effective depth decreases due to ultimate bearing capacity enhancing until it equal to zero when the ultimate bearing capacity exceeds the effective contact stress, at this time, the dry density reaches its maximum value and any mare passes will not have any effect on the soil.

The following steps conclude the procedure to simulate the surface compaction process:

1. Effective contact stress could be estimated based on compacting equipment characteristics such as:
   - Axis / roller static weight
   - Axis / roller length
   - Roller diameter
   - Tire pressure
   - Dynamic factor

   If previous data are not available, effective contact stress could be roughly estimated from compactor weight using Eq. (13).

2. Contact area and contact width (contact area per unit length) could be calculated as follows:
   - For pneumatic tire,
     Contact area = Load per tire / Tire pressure
     Contact width (B) = Contact area / Tire width
   - For rigid rollers, using modified Grecenko formula as follows:
     Contact width (B) = ($0.45 - 0.15\,\gamma$) x Roller diameter
     Contact area = Contact width x Roller length

   If previous data are not available, contact width could be roughly estimated between 0.2 to 0.4 m.

3. Using given or assumed initial dry density and fines percent, the initial modulus of elasticity (Es) could be calculated using Eq. (5).

4. Effective depth to be calculated using Eq. (16).

5. Permanent settlement due to compactor pass to be calculated using Eq. (17) considering the effective depth calculated using Eq. (16).

6. Compacted layer thickness is the current layer thickness minus the calculated settlement from Eq. (17).

7. Compacted dry density could be calculated as follows:

   $$\gamma_{n+1} = \gamma_n\, (H_n / H_{n+1}) \qquad (19)$$

   Where (γ n), (Hn) are the dry density and layer thickness before pass number (n) and (γ n+1), (Hn+1) are the dry density and layer thickness after pass number (n).

8. Steps from (2) to (6) are repeated considering the updated dry density from the previous cycle as initial density in the next one. The cycles stopped when the calculated effective depth from Eq. (16) equals to zero, then the enhancement in soil proprieties stops.

4 Verification of Proposed Approach

4.1 Rhode Island test Site

Alperstein (1992), reported a site in Rhode Island was to accommodate the construction of a submarine assembly building. The building was a single story steel frame industrial building with plan dimensions of 150x200m and height of 30m. The soil profile was generally consists of 17m thick layer of Loose to dense fine sand with some silt (SP to SM) rested 7.0m thick on non-plastic silt (ML) layer supported on the bed rock. Loose areas of upper sand layer are randomly distributed all over the site, hence, a decision was taken to improve the building location by removing the upper 2.0m of and compact the excavation bed using with eight passes of a heavy Ingersoll-Rand SP-60 DD drum drive self-propelled vibratory compactor with a 2.5m drum width and 1.5m drum diameter, delivering an applied centrifugal force of 37.5 ton and having a static drum weight of 10.8 ton. Geotechnical field tests includes standard penetration tests (SPT), cone penetration tests and plate load tests were carried out before and after the compaction to estimate the improvement in soil mechanical proprieties. Results of field tests are summarized in Fig. 4. The target of the compaction process is to densify the upper 2.0m sand layer beneath the foundation. Survey measurements showed a total settlement of 9.0 cm after compaction.

Initial field tests showed that the average of (SPT) value of the loose sand is about (10), hence, as per Table 1, the corresponding dry unit weight is about 1.40 t/m^3 and initial lift thickness is 2.0m.

Table 5 shows the results of applying the proposed approach, it could be noted that after eight passes the average dry density is increased from 1.40 to 1.48 t/m3 (about 6%), accordingly (SPT) value is increased from 10 to 20 and (qc) value is increased from 500 to 1000 t/m2 as per Table 1. The calculated improved soil properties match the measured ones as shown in Fig. 4. Also the calculated total settlement is 11.0 cm which is close to the measured value 9.0 cm.

Although, the values of the measured elastic modulus from plate load tests are not matching the calculated ones which predict the lab tests modulus of elasticity, but the ratio between initial and final values are the same (1.62).

The acceptance criteria was defined as (qc = 1000 t/m²) which is archived as per both measured and calculated results.

TABLE 5
SUMMARY OF PROPOSED APPROACH RESULTS OF RHODE ISLAND SITE

Pass no.	Initial γ_{dry} (t/m³)	Initial Lift thick (m)	Contact width (m)	Contact Stress (t/m²)	Elastic Modulus (t/m²)	Eff. Depth (m)	Lift sett. (m)	Final Lift thick (m)	Final γ_{dry} (t/m³)
1	1.40	2.00	0.36	41.40	443	0.29	0.027	1.97	1.42
2	1.42	1.97	0.36	41.90	501	0.24	0.021	1.95	1.43
3	1.43	1.95	0.35	42.32	552	0.20	0.017	1.93	1.45
4	1.45	1.93	0.35	42.66	597	0.17	0.014	1.92	1.46
5	1.46	1.92	0.35	42.94	636	0.15	0.011	1.91	1.47
6	1.47	1.91	0.35	43.17	669	0.13	0.009	1.90	1.47
7	1.47	1.90	0.34	43.36	698	0.12	0.007	1.89	1.48
8	1.48	1.89	0.34	43.52	721	0.10	0.005	1.89	1.48

	Before (Average)	After (Average)	After/Before Ratio
qc (t/ft²)	55±	110±	2
N	10±	22±	2
qc/N	5.5 (4-6)	5±	1
E (t/ft²)	224	369	1.65
E/qc	4	3.3±	0.8
E/N	22	17	0.8

Fig. 4 Summary of field tests results, after Alperstein (1992)

CURVE	LOAD/WHEEL ton	(kips)	TIRE PRESSURE kg/sq cm	(lb/sq in)	DEPTH OF LOOSE LAYERS cm	(inches)
1	10.15	22.3	10.0	142	30.5	12
2	5.00	11.0	6.3	90	30.5	12
3	1.35	3.0	2.5	36	23.0	9

Fig. 5 Characteristics of the used pneumatic roller, Study Report No. (GE- R-76, Sep.-2005)

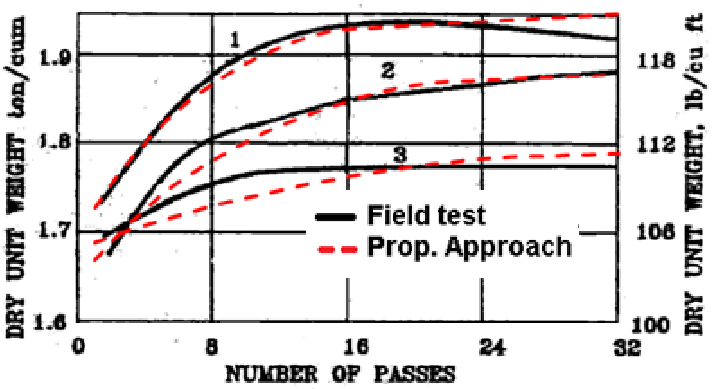

Fig. 6 Comparison between field test and proposed approach results

4.2 STUDY REPORT, MINISTRY OF RAILWAYS, INDIA

A series of field shallow compaction test for different sandy soil using different sizes of pneumatic roller was listed in Report No. (GE- R-76, Sep.-2005) for the ministry of railways, India. Three field tests were selected to verify the proposed approach.

Fig. 5 shows the characteristics of the used pneumatic roller and depth of loose layer for each test. Proposed approach was applied using available data and assuming tire width 400mm for equipment 1,2 and 300mm for equipment 3, considering fines percent between 5% to 10%.

The results were plotted on the original chart for comparison as shown in Fig. 6.

The predicted soil behavior showed good matches with field test results. Both results shows that degree of compaction increased with increasing the compactor weight and soil improvement almost stopped after 16 passes regardless the compactor weight.

5 Designing Surface Compaction Plan Using Proposed Approach

5.1 Developing Design Equations

In order to setup a compaction plan for imported structural fill, it is required to determine the following specifications:

- Imported fill properties, mainly fines percent, maximum dry density and its corresponding optimum water content are essential to make sure that this fill will meet the required specifications after compaction.
- Compacting equipment characteristics, equipment weight, compacting action (static of vibratory) and drum type (smooth, pneumatic, grid or sheepfoot) are the most important and wildly used parameters to specify the compactors.
- Compaction procedure includes construction sequence, maximum lift thickness and minimum number of passes for each lift.
- Quality control plan includes type and number field tests for each lift to assure its acceptance.

Usually, a test ramp of about 30m long, 10m width, 15cm starting thickness and 55cm end thickness to be constructed at the site with the used backfilling material to test compaction results for different lift thicknesses, water contents, number of passes and equipment characteristics.

The proposed approach could help in selecting the suitable equipment, maximum lift thickness and minimum number of passes per lift as follows:

1. Maximum lift thickness for the chosen equipment should not exceed contact width (B) to make sure that all the lift is subjected to equal compacting stress which equals the effective contact stress. Practically, maximum lift thickness is ranged between 15 to 30 cm

2. Minimum compactor weight for certain soil type, certain lift thickness and certain degree of compaction presented by target dry density could be calculated by equating the compactor effective contact stress from Eq. (13) with the ultimate soil strength from Eq. (11) considering loading width (B) equals to lift thickness, hence, minimum contact stress (σ min) could be calculated as follows:

$$\sigma \text{ min } (t/m^2) = \left[(F.\gamma^{2.5}/4)+(\gamma.B/6)\right] e^{(3.8\gamma-1)} \quad \text{............} \quad (20)$$

Min. compactor weight (ton)

$$= \sigma \text{ min } /1.7 \quad \text{For pneumatic}$$
$$= \sigma \text{ min } . S/(1.2\ I) \quad \text{For steel rollers} \quad \text{............} \quad (21)$$

Where:

(γ) is the target soil dry density (t/m³)

(S) is coverage ratio, which is about (0.5) for grid roller and (0.25) for sheepfoot roller

3. Minimum number of passes for each lift could be found by applying the proposed approach cycle after cycle until the dry density reaches the target value. Instead of that, the proposed approach were developed based on the fact that vertical stresses is almost constant and equal to contact stress down to depth equals loading width. Starting from equation (19),

$$\Delta hn = Hn - Hn+1$$
$$= Hn \,.\, \sigma / Es$$
$$1-(Hn+1 / Hn) = 1-(\gamma n / \gamma n+1) = (\sigma / Es)$$
$$(\gamma_n / \gamma_{n+1}) = 1 - \frac{\sigma}{30(1-0.5F)\gamma_n^9} \quad (22)$$

It is very difficult to convert this relation from series form to function form mathematically; hence, numerical approach is used to figure out an approximated function by calculating its value for different inputs and then the best fitting surface is calculated using multi-regression technique, the developed function is:

$$n = \frac{17.5(1-0.5F)}{\sigma}(\gamma_f^7 - \gamma_o^7) \quad (23)$$

Where (n) is the required number of passes to densify the fill from certain initial dry density (γo) to certain final dry density (γf), (σ) is the chosen contact stress and (F) is fines percent. All in (ton & m).

Usually (γo) is not the minimum density of the backfilling material, it is its density after spreading, wetting and preparing for compaction, during this process, the lift subjected to equipment traffic loads approximately equals to their tire pressure (about 20 t/m²), hence, (γo) value could be from Eq. (11) considering loading width (B) equals to lift thickness and (σ ult) equals to tire pressure (20 t/m²).

Also, (γf) is not the maximum density of the backfilling material, it is the minimum accepted dry density as per the specifications (90% to 98% the maximum dry density). In absence of lab test results, maximum dry density could be assumed as follows:

CLAY	1.85	t/m³
SAND, clean	1.85	t/m³
SAND, clayey	1.95	t/m³
SAND & GRAVEL	2.00	t/m³
SAND & GRAVEL, clayey	2.15	t/m³

5.2 Verifying Design Equations

In order to verify the developed design equations (Eq. 20,21,22,23), they were applied for different soil types and lift thicknesses to determine the minimum compactor weight and minimum number of passes considering different compactor types, the results were compared with the following design codes:

- Naval Facilities Engineering Command "NAVFAC" DM-7.02, "Foundations & Earth Structures", 1986
- Guidelines for Earthwork in Railway Projects, Ministry of Railways, INDIA (2003), After BS: 6031 – 1981
- Code of practice for the filling of surface trenches, Cologe, Germany
- Egyptian Code of Practice ECP 202/8 - 2001 Egyptian code for soil mech. & foundation - part 8 - Slope stability

Studied cases are listed below, Table (6) summarize the recommendations of the four design codes

Clean Sand (fines < 10%):
Assume fine = 10%
For 15 cm lift
$\gamma o = 1.70\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.75\ t/m^3$ for σ min $= 25\ t/m^2$
Opt-1: 15 ton pneumatic roller, no. of passes= 6
Opt-2: 20 ton static roller, no. of passes= 6
For 20 cm lift
$\gamma o = 1.66\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.75\ t/m^3$ for σ min $= 29\ t/m^2$
Opt-3: 8 ton vibratory roller, no. of passes= 8
For 25 cm lift
$\gamma o = 1.63\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.75\ t/m^3$ for σ min $= 33\ t/m^2$
Opt-4: 20 ton pneumatic roller, no. of passes= 10
Opt-5: 10 ton vibratory roller, no. of passes= 10
Opt-6: 40 ton pneumatic roller, no. of passes= 5

Clayey Sand (fines 10% - 30%):
Assume fine = 20%
For 10 cm lift
$\gamma o = 1.64\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.85\ t/m^3$ for σ min $= 51\ t/m^2$
Opt-1: 30 ton pneumatic roller, no. of passes= 13
Opt-2: 15 ton vibratory roller, no. of passes= 13
Opt-3: 40 ton static roller, no. of passes= 13
For 15 cm lift
$\gamma o = 1.61\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.85\ t/m^3$ for σ min $= 58\ t/m^2$
Opt-4: 35 ton pneumatic roller, no. of passes= 13
Opt-5: 15 ton vibratory roller, no. of passes= 13
Opt-6: 65 ton pneumatic roller, no. of passes= 6
For 25 cm lift
$\gamma o = 1.56\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.85\ t/m^3$ for σ min $= 71\ t/m^2$
Opt-7: 20 ton vibratory roller, no. of passes= 11
Opt-8: 65 ton pneumatic roller, no. of passes= 7

Fine grain soil (fines > 50%)
Assume fine = 66%
For 15 cm lift
$\gamma o = 1.40\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.75\ t/m^3$ for σ min $= 95\ t/m^2$
Opt-1: 55 ton pneumatic roller, no. of passes= 5
Opt-2: 25 ton vibratory roller, no. of passes= 5
Opt-3: 20 ton sheepfoot roller, no. of passes= 5
For 25 cm lift
$\gamma o = 1.39\ t/m^3$ for $\sigma o = 20\ t/m^2$
$\gamma f = 1.75\ t/m^3$ for σ min $= 105\ t/m^2$
Opt-1: 65 ton pneumatic roller, no. of passes= 4
Opt-2: 30 ton vibratory roller, no. of passes= 4
Opt-3: 25 ton sheepfoot roller, no. of passes= 4

Comparing studied cases with codes recommendations shows good matching considering the varieties of target compaction degree between codes depending of the backlighting purpose. Also, the assumed fines percent has significant effect on the results specially for high fines percentages.

TABLE 6
SUMMARY OF DIFFERENT GUIDELINES

	Max. Lift (cm)	No. of passes	Compactor type and weight (ton)
NAVFAC DM-7.02, "Foundations & Earth Structures", 1986			
Clean Sand (Fines<10%)	25	3-5	Pneumatic tire 40-60 ton Vibratory Roller 15 ton
Clayey Sand (fines 10% - 30%)	15-25	4-6	Pneumatic tire 60 ton
Fine grain soil (fines > 50%)	15-20	4-6 18	Sheepfoot roller 20 ton Vibratory Roller 10 ton
Guidelines for Earthwork in Railway Projects, Ministry of Railways, INDIA, (2003) After BS: 6031 – 1981			
Clayey Sand (fines 10% - 30%)	8-28	3-16	Pneumatic roller 16 ton Vibratory Roller 12 ton
Fine grain soil (fines > 50%)	10-45	4-8	Sheepfoot roller 20 ton Vibratory Roller 20 ton
Code of practice for the filling of surface trenches, Cologe, Germany			
Clean Sand (Fines<10%)	20	4-6	Vibratory Roller 8 ton
Clayey Sand (fines 10% - 30%)	20	5-6	Vibratory Roller 8 ton
ECP 202/8 - 2001 Egyptian code for soil mech. & foundation - part 8 - Slope stability			
Clean Sand (Fines<10%)	15 15 20-30	10 10 4-12	Pneumatic roller 12 ton Static roller 12 ton Vibratory Roller 8-10 ton
Clayey Sand (fines 10% - 30%)	12-15 12-15 15-28	6-12 12 4	Pneumatic roller 20-100 ton Static roller 12 -20 ton Vibratory Roller 3-10 ton
Fine grain soil (fines > 50%)	12-45 12-15 15-28	4-6 4-10 4	Pneumatic roller 20-100 ton Static roller 12 -20 ton Vibratory Roller 3-10 ton

6 Conclusions

The results of this research could be concluded as follows:

1. The proposed approach for predicting natural loose soil behavior under surface compaction starts by correlating soil properties with the dry density and accordingly, soil properties is updated after each compactor pass based on the calculated lift settlement and the cycle goes on until the soil gains bearing capacity equals to the effective contact stress and then no additional permanent settlement will occur because the plastic zone (effective depth) becomes zero and hence the compaction process is completed.

2. That proposed approach was verified using field test results from different case studies where natural surface loose soil were compacted using different compactor types and it successfully predicted the soil behavior under shallow compaction.

3. The verified proposed approach was used to develop a procedure to determine the minimum compactor characteristics, maximum lift thickness and minimum required passes to increase the dry density of imported backfill with certain fines percentage from certain initial value to certain target value.

4. The developed procedure was verified for soils with different fines percentage, lift thickness, compactor types against four codes recommendations and showed good matching.

5. This research considered that compacted soil has the optimum water content and compactors moved with the optimum speed. Further studies may consider the effect of actual water content and actual compactor speed on the behavior of soil under shallow compaction.

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