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# A Soil-Structure Interaction Study using Sustainable Structural Fill below Foundations

P.H. Dalal [1], M. Patil [2], T.N. Dave[3], K.K.R Iyer [3, *]

[1] Department of Civil Engineering, Research Scholar, Institute of Infrastructure Technology Research and Management, Ahmedabad-380026, India
[2] Department of Civil Engineering, Research Scholar, Institute of Infrastructure Technology Research and Management, Ahmedabad-380026, India
[3] Department of Civil Engineering, Assistant Professor, Institute of Infrastructure Technology Research and Management, Ahmedabad-380026, India

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**Abstract**

Structural fill is utilized to improve the bearing capacity and reduce settlement below foundations supported on weak soils or when foundations are supported on filled up soil. The present study evaluates the potential application of municipal solid waste finer fraction (MSW-FF) as a sustainable structural fill material. The finer fraction constitutes significant proportion of old landfill waste in cities, and do not easily find applications as compared to the other fraction of old waste. The present work determines the engineering properties of MSW-FF. A detailed assessment has also been carried out to evaluate the bearing capacity, settlement and modulus of subgrade reaction for the shallow foundation of different sizes and shapes resting on (a) soil with low subgrade modulus and (b) soil improved with a layer of MSW-FF as structural fill. A soil-structure interaction analysis has also been carried out by utilizing STAAD Pro. software, to understand the effect of soil and foundation stiffness on the foundation design parameters, viz., base pressure, settlement, bending moment and shear stress in shallow foundations for both cases (natural soil and with MSW-FF as structural fill). The comparison of different foundation systems resting on soil improved with MSW-FF structural fill layer and soil with low subgrade modulus has been presented to demonstrate the efficacy of MSW-FF as a suitable structural fill material. From the soil-structure interaction analysis, it is observed that the effect of soil subgrade modulus on foundation base pressure and settlement is prominent, while having a negligible effect of bending moment and shear stress in the foundation. Further, the relative stiffness of foundation and soil has a significant effect on the foundation design parameters. The study results are quite encouraging with respect to the potential of utilizing MSW-FF as a sustainable structural fill and put forward a new and promising alternate material for application in different infrastructure projects.

*Keywords*: Sustainable structural fill, Municipal solid waste finer fraction, Soil-structure interaction, Soil improvement, Foundation

## 1. Introduction

The solid waste disposal at open landfill sites is still a big challenge for developing countries, as it occupies valuable land and results in air, land and water pollution. On the other hand, due to an increase in population and urbanization, there is a need of land for various purposes, viz., residential, industries, farming, commercial, etc. To overcome this problem many cities, like Mumbai, Ahmedabad, Indore, etc. have started landfill mining. Researchers have reported that from the mined waste material, about 50-70% is the finer fraction of municipal solid waste [1, 2]. This finer fraction has very limited applications such as daily cover at a landfill site or as compost [3, 4]. The municipal solid waste finer fraction (MSW-FF) consists of mostly non-biodegradable waste and exhibits similar properties like sand [2, 4].

Generally, natural soils such as loose sand and soft clay have poor strength and a high potential for settlement [5-7]. Hence, soil improvement is required to increase the bearing capacity and decrease the settlement of weak soil before the construction of any Civil Engineering structure, viz., stabilization with cement, lime or fly ash [6, 8-11], providing reinforcement [12-17]. Further, researchers have also studied different waste material as structural fill to increase the bearing capacity of natural weak soil, viz., red mud, steel furnace slag, coffee grounds-fly ash geopolymer, coal wash-slag blend, etc. [18-23].

The present study evaluates the potential of MSW-FF as sustainable structural fill material. The study has been done to evaluate the basic properties and shear strength parameters of MSW-FF. The analytical study has also been carried out for different sizes and types of foundation resting on weak soil having a low modulus of subgrade reaction and improved by providing MSW-FF structural fill layer of 1m and 2m thickness below foundation. Further, a soil-structure interaction analysis has also been carried out by utilizing STAAD Pro. software, to understand the effect of soil and foundation stiffness on the foundation design parameters, viz., base pressure, settlement, bending moment and shear stress in shallow foundations for both cases (natural soil and with MSW-FF as structural fill).

*Corresponding author. Tel: +919833427915; E-mail address: kannaniyer@iitram.ac.in

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## 2. Experimental Investigation

For the study, MSW-FF is procured from the landfill site at Ahmedabad, India. The material is stored in air tight container at the university campus. For the study, samples were taken from three different containers and allowed to air dry for 2-3 days. The samples were labelled as samples S1, S2, and S3. Based on the experimnetal studies MSW-FF consists of 20% gravel and 79% sand, with only about 1% fines. The average organic content has been observed in this study as 9.71%. The average liquid limit is 32.8% with non-plastic characteristics. MSW-FF is classified as SW (Well graded sand with gravel). The maximum dry density and optimum moisture content based on Standard Proctor test has been obtained as 1.61 g/cc and 18.77%, respectively.

### 2.1. Direct shear test results

To determine the shear strength parameters, undrained direct shear tests were performed on MSW-FF specimens. The tests has been conducted for all the three samples (S1, S2 and S3) at six different normal stresses, i.e. 25, 50, 75, 100, 125 and 150 kPa. The samples were prepared by adding water equal to optimum moisture content and maintaining the corresponding Standard Proctor density of the sample. The horizontal and vertical displacement readings, as well as shear force, were recorded and calculations were done for obtaining the shear strength parameters such as cohesion and angle of internal friction, and peak shear stress at failure (peak shear strength) from the data. The results are shown in table 1 and figures 2, 3, 4.

Based on the results of the direct shear test, the shear strength parameters for MSW-FF have been noted to be similar to granular (sandy) soil with some cohesion. The low cohesion may be attributed to the presence of some organic fraction in the material. Hence, MSW-FF can be noted to be a potential material for fill applications. To evaluate in details this aspect, the analytical study has been carried out.

Table 1. Average shear strength parameters

| Shear strength Parameter | Average value for 3 samples |
|---|---|
| Cohesion (c) | 21.68 kPa |
| Angle of internal friction (ϕ) | 34.83° |

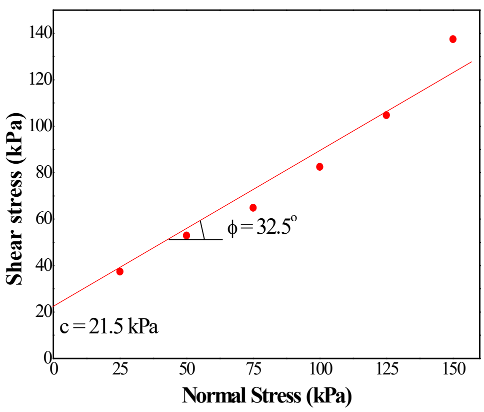



Fig. 1. Typical graph of Normal stress vs Shear stress for MSW-FF (sample S1)

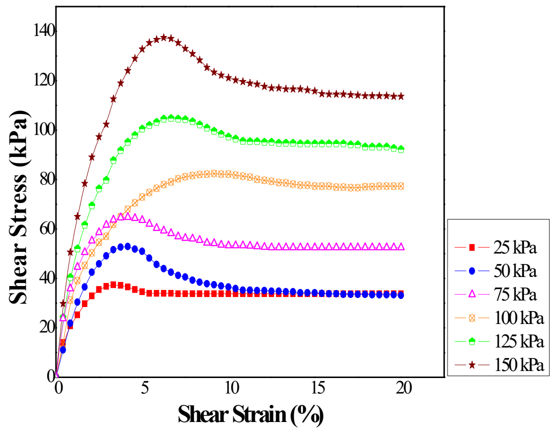



Fig. 2. Typical graph of Shear strain vs Shear stress (Sample S1)

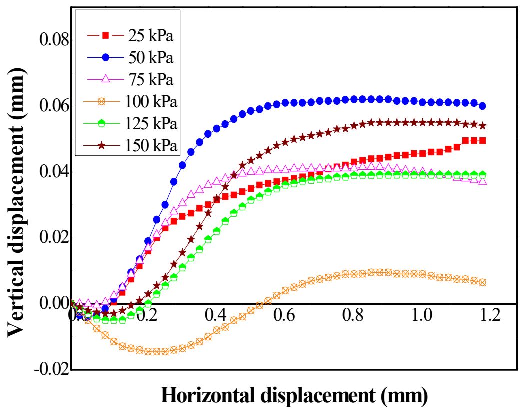



Fig. 3. Typical graph of Horizontal displacement vs Vertical displacement for MSW-FF (Sample S1)

## 3. Analytical Study

To evaluate the potential of MSW-FF as structural fill material, an analytical study has been conducted. The calculations have been carried out with the help of the Microsoft Excel program. For the analytical study, MSW-FF and two different types of soils ($SO_1$ and $SO_2$) have been considered. The different cases considered in the study are described in table 2. The shear strength parameters for MSW-FF have been obtained from the direct shear test (refer table 1). The properties of soils $SO_1$ and $SO_2$ have been considered for soft clay and medium stiff silty clay [24]. To determine the safe allowable pressure for the foundation of different shapes, aspect ratio (length/width ratio) and size, a detailed study has been carried out. The safe bearing capacity and allowable pressure based on settlement criteria have been evaluated for each case and the safe allowable pressure has been determined as the minimum of the two values [25-27]. The details of different foundations considered in this analytical study are tabulated in table 3.

### 3.1. Determine the safe bearing capacity

The safe bearing capacity (SBC) is determined by the IS code method considering the general shear failure as per IS 6403:1981 [25] considering depth, shape, inclination factor, and water table effect. The factor of safety (F.O.S.) is considered as 3 for the study.

Table 2. Notations used for different cases in the study

| Notation | Case |
|---|---|
| $SO_1$ | Soft clay |
| $SO_2$ | Medium stiff silty clay |
| $L_1SO_1$ | Layer of MSW-FF up to 1 m from bottom of foundation followed by $SO_1$ |
| $L_2SO_1$ | Layer of MSW-FF up to 2 m from bottom of foundation followed by $SO_1$ |
| $L_1SO_2$ | Layer of MSW-FF up to 1 m from bottom of foundation followed by $SO_2$ |
| $L_2SO_2$ | Layer of MSW-FF up to 2 m from bottom of foundation followed by $SO_2$ |

3.2. Determine the allowable pressure based on settlement criteria

Allowable pressure is determined by obtaining the pressure required to cause total settlement equal to the limiting settlement value (Table 4) as defined by IS 1904 (1986) [26]. The total settlement of foundation within the zone of influence (refer table 5) is determined as per IS 8009(Part I) – 1976 [27].

The depth of the zone of influence as considered in this study for different shapes/types of the foundation is presented in Table 5. The values are obtained based on recommendations by Bowles [24] for strip, square and raft foundation, where B is the width of the foundation. To compute the stress distribution from the bottom of the foundation upto the depth of zone of influence, Boussineq's equation is used (refer Eqn.1). The calculation is done by dividing the total depth of zone of influence into 16 equal parts.

$$Q = q_o I \qquad (1)$$

Where,

Q = Stress at center of foundation at any depth, z (kN/m$^2$)
$q_o$ = foundation pressure (kN/m$^2$)
I = 4$I_o$ = influence factor depends on m and n [24]
m = B/z, B is width of foundation and z is depth below bottom of foundation
n = L/z, L is length of foundation

Table 3. Details of foundation considered in the study

| Sr. No. | Type of foundation | Size of foundation (m x m) | Depth of foundation below ground level (m) |
|---|---|---|---|
| 1 | Strip | 5 x 1 | 2 |
| 2 | | 10 x 1 | 2 |
| 3 | | 10 x 2 | 2 |
| 4 | Square | 1 x 1 | 2 |
| 5 | | 1.5 x 1.5 | 2 |
| 6 | | 2 x 2 | 2 |
| 7 | | 2.5 x 2.5 | 2 |
| 8 | | 3 x 3 | 2 |
| 9 | Raft | 5 x 5 | 2 |
| 10 | | 10 x 10 | 2 |
| 11 | | 15 x 15 | 2 |
| 12 | | 20 x 20 | 2 |

Table 4. Limiting values of settlement [26]

| Type of foundation | Settlement (mm) | |
|---|---|---|
| | Sand and Hard Clay | Plastic clay |
| Isolated (Strip and square) | 50 | 75 |
| Raft | 75 | 100 |

Table 5. Depth of zone of influence

| Type of foundation | Depth of zone of influence below bottom of foundation |
|---|---|
| Strip | 4B |
| Square | 2B |
| Raft | 2B |

Table 6. Input parameters for analysis

| Parameter | MSW-FF | $SO_1$ | $SO_2$ |
|---|---|---|---|
| Cohesion (c) | 21.68 kPa | 40 kPa | 70 kPa |
| Angle of internal friction ($\phi$) | 34.83° | - | - |
| Poisson's ratio ($\mu$)# | 0.30 | 0.45 | 0.40 |
| Modulus of Elasticity (E)# | 65000 kN/m$^2$ | 25000 kN/m$^2$ | 40000 kN/m$^2$ |
| Compression index ($C_c$) | - | 0.405 | 0.200 |
| Initial void ratio ($e_o$)* | - | 0.70 | 0.52 |

*Initial void ratio is determined by assuming compression index, using the equation given in literature [28]. $C_c = 1.15(e_o - 0.35)$
#Values are assumed based on recommendation by Bowles [24]

The analysis is done by considering the cases as presented in table 2 and the input parameters for materials considered for the analysis are tabulated in table 6.

Figures 4, 5 and 6 depict the schematic views of the different cases considered in the study. Figure 4 shows the three different locations of ground water table considered for the computation of safe bearing capacity of MSW-FF intended to be used as structural fill layer. Figures 5 and 6 show the properties of soil and structural fill, for 1m and 2m thickness of structural fill below foundation, respectively. Further, Modulus of subgrade reaction is determined for all the cases by using Eqn. 2, which have been used in STAAD Pro. analysis for defining the soil spring support below foundation.

$$\text{Modulus of subgrade reaction} = \frac{Foundation\ pressure\ (\frac{kN}{m^2})}{Total\ Settlement\ (m)} \qquad (2)$$

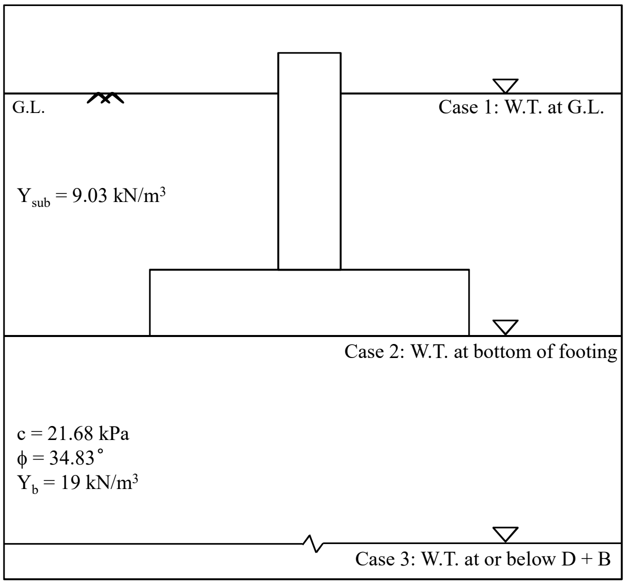



Fig. 4. Water table effect on SBC of MSW-FF

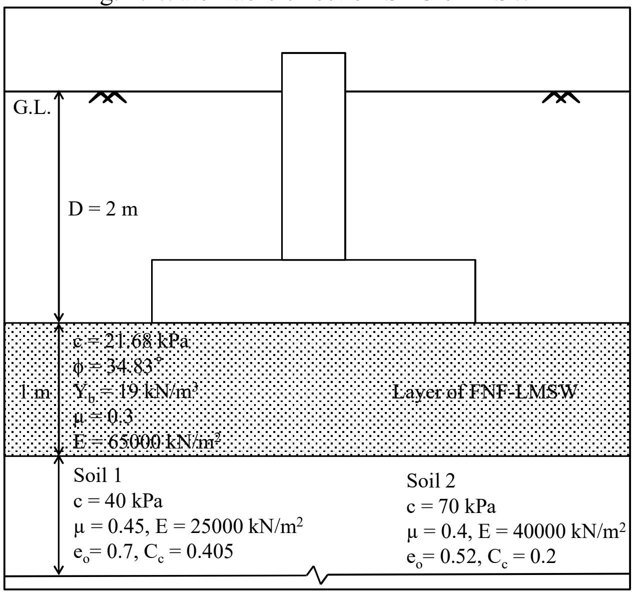



Fig. 5. Layer of MSW-FF up to 1 m from bottom of foundation followed by natural soil

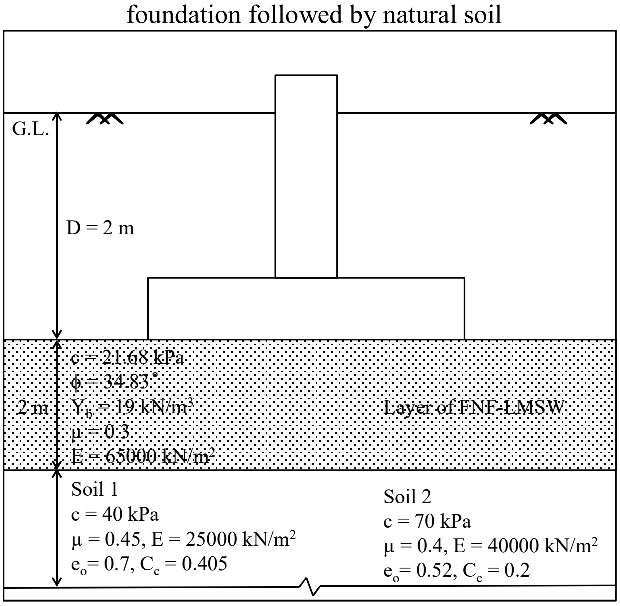



Fig. 6. Layer of MSW-FF up to 2 m from bottom of foundation followed by natural soil

## 4. Numerical soil structure interaction study

The soil structure interaction analysis is carried out by using STAAD Pro. software. The study is done for strip, square and raft foundation and the soil support are defined using the computed values of modulus of subgrade reaction (refer Eqn. 2) for different cases based on the analytical study. The numerical study is carried out to understand the effect of soil and foundation stiffness on the foundation design parameters, viz., base pressure, settlement, bending moment and shear stress in shallow foundation. The different cases considered for numerical analysis is summarized in table 7.

.Table 7. Input parameters for STAAD analysis

| Type of Foundation and Size | Case | Foundation thickness | Applied load | Modulus of subgrade reaction |
|---|---|---|---|---|
| | | m | kN | kN/m$^3$ |
| Square 2m × 2m | $SO_1$ | 0.5 | 73.8 | 246.3 |
| | $SO_1$ | 1 | 73.8 | 246.3 |
| | $L_2SO_1$ | 0.5 | 124.6 | 415.27 |
| | $L_2SO_1$ | 1 | 124.6 | 415.27 |
| | $SO_2$ | 0.5 | 144 | 477.12 |
| | $SO_2$ | 1 | 144 | 477.12 |
| | $L_2SO_2$ | 0.5 | 240 | 795.78 |
| | $L_2SO_2$ | 1 | 240 | 795.78 |
| Strip 10m × 2m | $SO_1$ | 0.5 | 299.4 | 199.55 |
| | $SO_1$ | 1 | 299.4 | 199.55 |
| | $L_2SO_1$ | 0.5 | 435 | 289.71 |
| | $L_2SO_1$ | 1 | 435 | 289.71 |
| | $SO_2$ | 0.5 | 550 | 367.88 |
| | $SO_2$ | 1 | 550 | 367.88 |
| | $L_2SO_2$ | 0.5 | 790 | 526.13 |
| | $L_2SO_2$ | 1 | 790 | 526.13 |
| Raft 10m× 10m | $SO_1$ | 0.5 | 1010 | 100.63 |
| | $SO_1$ | 1 | 1010 | 100.63 |
| | $L_2SO_1$ | 0.5 | 1230 | 123.18 |
| | $L_2SO_1$ | 1 | 1230 | 123.18 |
| | $SO_2$ | 0.5 | 1750 | 174.16 |
| | $SO_2$ | 1 | 1750 | 174.16 |
| | $L_2SO_2$ | 0.5 | 2060 | 207.01 |
| | $L_2SO_2$ | 1 | 2060 | 207.01 |

## 5. Results and discussion

### 5.1. Analytical study

Figures 7, 8 and 9 show the comparison of safe bearing capacity based on shear failure criteria (SBC) and allowable pressure based on settlement criteria (APSC) for square, strip and raft foundations, respectively, for different cases. From the figures, it can be observed that the settlement criteria govern the limiting pressure for foundation design for each type of soil condition considered. The percentage increase in the values of SBC and APSC for different types of foundation, when MSW-FF is utilized as structural fill, has been presented in tables 8 and 9, respectively.

It is observed that maximum benefit of providing MSW-FF structural fill is achieved for square foundation and minimum benefit is achieved for raft foundation. This can be attributed to higher depth of zone of influence for raft foundation due to higher width of foundation, resulting in less benefit in terms of increase in bearing capacity and reduction in settlement. Further, providing 2 m thick layer of MSW-FF as structural fill gives significant improvement compared to 1 m thick layer. This may be explained by the fact that MSW-FF is more stiff material compared to natural soil, and its higher thickness reduces the settlement and

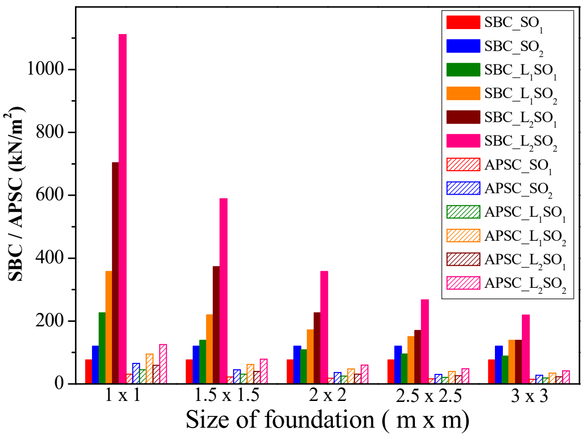



Fig. 7 Comparison of SBC / APSC for square foundation for different cases

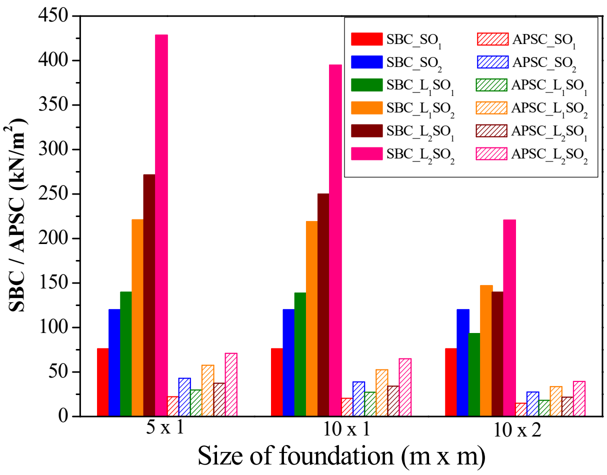



Fig. 8 Comparison of SBC / APSC for strip foundation for different cases

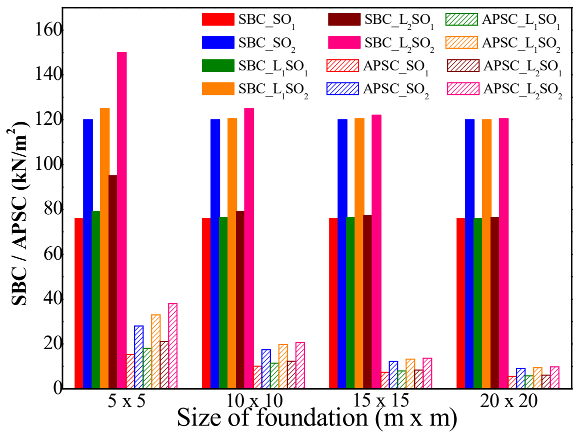



Fig. 9 Comparison of SBC / APSC for raft foundation for different cases

Table 8 Increase in safe bearing capacity (SBC) when MSW-FF structural fill is provided

| Sr.No. | Type of foundation | Increase in SBC (%) | | | |
|---|---|---|---|---|---|
| | | $L_1SO_1$ | $L_1SO_2$ | $L_2SO_1$ | $L_2SO_2$ |
| 1 | Strip | 83.68 | 84.1 | 257.1 | 257.1 |
| 2 | Square | 197.4 | 198 | 825 | 825.8 |
| 3 | Raft | 4.16 | 4.16 | 25 | 25 |

Table 9 Increase in allowable pressure based on settlement criteria (APSC) when MSW-FF structural fill is provided

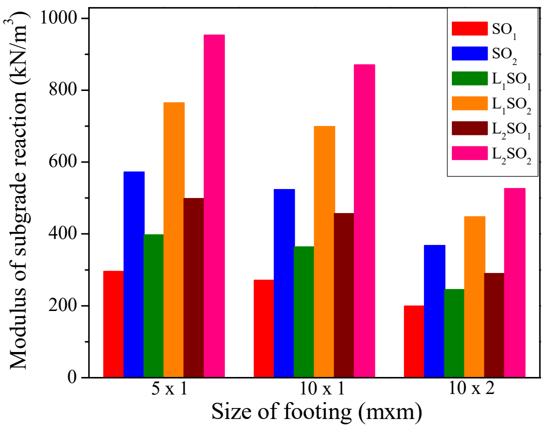
| Sr.No. | Type of foundation | Increase in APSC (%) | | | |
|---|---|---|---|---|---|
| | | $L_1SO_1$ | $L_1SO_2$ | $L_2SO_1$ | $L_2SO_2$ |
| 1 | Strip | 34.5 | 33.7 | 68.8 | 65.1 |
| 2 | Square | 45.7 | 46.2 | 91.6 | 92.3 |
| 3 | Raft | 17.97 | 17.86 | 37.6 | 35.7 |

increases the safe allowable pressure of soil below the foundation (by reducing the stress on the natural soil layer and allowing better distribution of stress below foundation). It can be concluded based on the study that providing the layer of MSW-FF is more beneficial for the smaller size of the foundation as compared to larger size of the foundation.

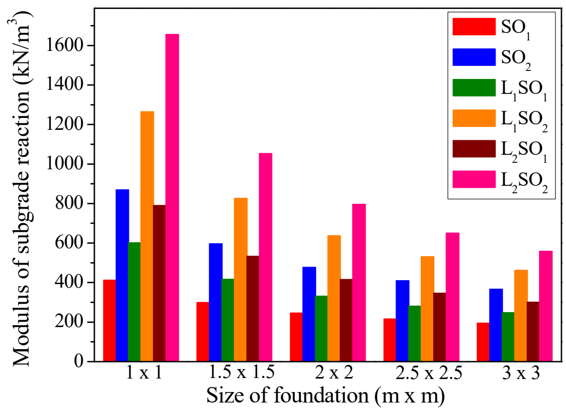
It can be concluded from Tables 8 and 9, that provision of MSW-FF as structural fill over soft soil ($SO_1$) and medium stiff silty clay ($SO_2$) has limited benefits on reducing the settlement, but improvement in the safe bearing capacity varies from 4.16 to 825.8% times that for cases without structural fill. It is recommended that to reduce the settlement of soft soil, geosynthetics reinforcement or ground improvement technique can be additionally considered along with provision of structural fill. Further, it may be noted that MSW-FF has about 9.71% organic matter, as noted in this study. The amount of organic matter may vary based on source of MSW-FF, its age and composition. As the material is estimated to be in the landfill for atleast 15-20 years, it is anticipated that the residual organic matter is slow degrading material. However, the effect of residual organic matter on long term performance of foundations on MSW-FF needs further study. Also stabilization of MSW-FF can be explored as an option to arrest the effect of volume change caused by possible decomposition of residual organic matter with time.

Table 10 Percentage increase in modulus of subgrade reaction when MSW-FF structural fill is provided

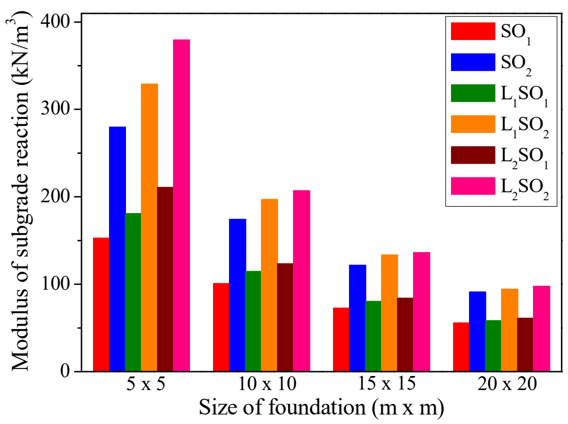
| Sr. No. | Type of foundation | $L_1SO_1$ | $L_1SO_2$ | $L_2SO_1$ | $L_2SO_2$ |
|---|---|---|---|---|---|
| 1 | Strip | 34.33 | 33.62 | 68.51 | 66.52 |
| 2 | Square | 45.85 | 45.54 | 91.48 | 90.63 |
| 3 | Raft | 18.35 | 17.54 | 38.07 | 35.64 |




(a) Strip foundation




(b) Square foundation




(c) Raft foundation

Fig. 10 Modulus of subgrade reaction for different types of foundation

In order to understand the effect of providing MSW-FF as structural fill on the modulus of subgrade reaction, the same has been plotted for different cases in figure 10. It can be observed from the figure that modulus of subgrade reaction reduces with increase in width of foundation for all the cases. Further, the value of modulus of subgrade reaction is higher for square foundation and lowest for raft foundation. The improvement in the values of modulus of subgrade reaction due to provision of MSW-FF layer as structural fill is evident, and has been presented in table 10. It can be observed from the table that maximum improvement of 91.48% is obtained for the square foundation. Benefit of providing MSW-FF structural fill layer in soft clay ($SO_1$) is slightly higher as compared to medium stiff silty clay ($SO_2$).

## 5.2. Soil structure interaction study

From the soil structure interaction study using the STAAD Pro., it has been observed that the modulus of subgrade reaction has a significant effect on foundation base pressure and settlement as compared to shear stress and bending moment in the foundation. Further, there is no

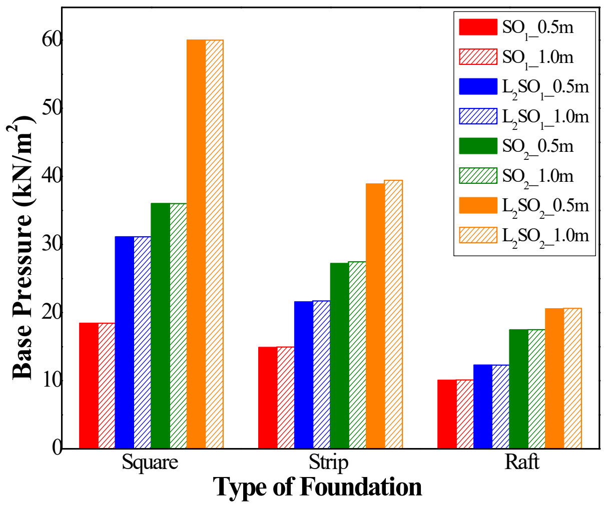



Fig. 11. Base pressure analysis by STAAD Pro. software

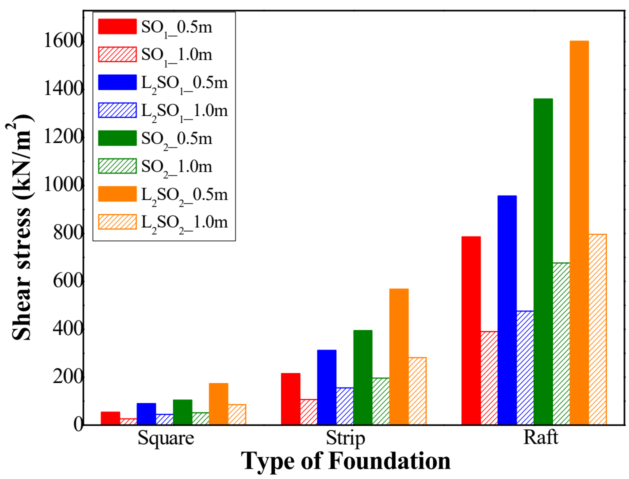



Fig. 12 Shear stress analysis by STAAD Pro. software

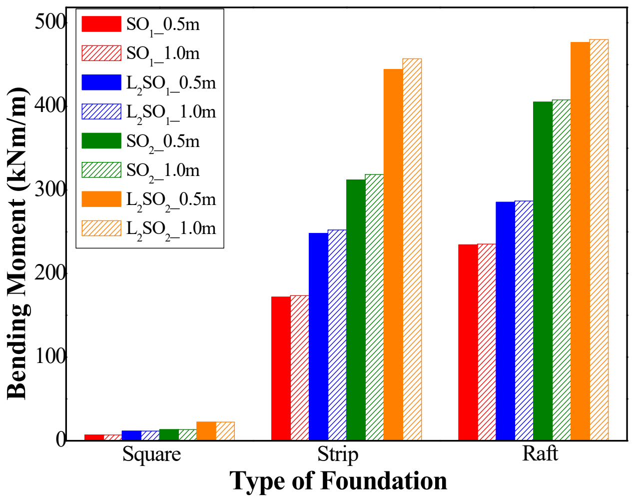



Fig. 13 Bending moment analysis by STAAD Pro. software

significant effect of foundation thickness on base pressure and bending moment of the foundation, while higher shear stress is observed for 0.5 m thick foundation as compared to 1 m thick foundation.

It can be observed from figure 11 that the maximum base pressure is achieved in square foundation and minimum in raft foundation. Further, from figure 12 and 13 it is observed that the maximum shear stress and bending moment are observed in the raft foundation and significant less shear force and bending moments are observed in the square foundation. In the figures 0.5m and 1.0m indicate foundation thickness.

## 6. Conclusion

From this study, conducted with an aim to utilize municipal solid waste of finer fraction (MSW-FF) as a fill material; the following conclusions have been obtained:

- When, MSW-FF is provided as structural fill layer on soft clay or medium stiff silty clay soils (as considered in this study), it can be concluded from the analytical study that the safe bearing capacity improves by about 4.16 to 825.8% times. Further, the effect of providing MSW-FF layer structural fill layer (1m or 2m) has less prominent effect on improving the allowable pressure based on settlement criteria (APSC). The improvement in APSC varies from 17.97 to 92.3 %.
- From the study, it is concluded that provision of MSW-FF structural fill layer below foundation, results in higher improvement in load carrying capacity for square foundation, and minimum improvement is observed in case of raft foundation. Further, the improvement in modulus of subgrade reaction is lower for raft foundation (17.54 – 38.07 %) and maximum for square foundation (45.85 – 91.48%).
- From the soil structure interaction study, it can be concluded that the effect of modulus of subgrade reaction on foundation base pressure and settlement is prominent, while having a negligible effect of bending moment and shear stress in the foundation.
- Based on the experimental, analytical and numerical studies, it can be concluded that the MSW-FF can be utilized as structural fill and appears as promising alternate material for application in different infrastructure projects. However the organic content of the MSW-FF is in general, somewhat higher than general acceptable limits for different Civil Engineering applications, and hence studies may be required to check the performance of MSW-FF in long term.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## Disclosures

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