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Behavior of geosynthetic included granular aggregates as mattress foundation on soft soils

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ABSTRACT: Prefailure behaviour of geosynthetics included granular mattress foundations on soft media is reported. The laboratory part of the studies includes test results and interpretations from two test set ups. These comprised a footing test tank and a footing test cell. Model footing tests were conducted on mattress on soft media to investigate the settlement and distortion behaviour due to, mattress layer thickness, confining pressure and inclusion of geosynthetics. In the case study part, design, constructional and behavioural aspects of geosynthetics included granular mattress foundations for four and five storied buildings are presented. Continuous footings were designed and constructed for masonry and framed structures on the mattresses up to two meters in thickness. The deflection and distortion behaviour of these are presented.

1 INTRODUCTION

This paper reports on pre failure behaviour of geosynthetics included granular mattresses for use as foundation on soft soils. Unlike in road constructions, the technology of using a granular media with a geotextile interface layer is not common in constructing building foundations on soft soils. Although a good number of works have been reported on the stability or bearing capacity of such foundations, pre failure behaviour like the aspects of, stress analyses, settlement or deformation, especially differential settlements and distortions are not properly addressed. In this paper an effort has been made to study the deformation and distortion behaviour of geosynthetics encapsulated granular mattresses over soft media. The work may be divided into two parts.

The laboratory part deals with laboratory tests and analytical work. These include model footing tests in a test tank, under plane strain conditions, using a strip footing on granular mattress on soft subgrade materials. Tests were conducted on encapsulated granular mattress with and without geosynthetics interface layer. Suction was applied to the granular media to simulate confining effect due to overburden. Total and differential settlements as functions of H/B ratio, confining pressure and effect of geosynthetics layer are presented.

In a quest to develop a more versatile test set up, a model footing test cell was especially fabricated for this study. This is a hydraulic oedometer type apparatus, capable of applying hydraulic confining pressure, on a granular mattress on soft media system, through a rubber bellow. A geosynthetics layer was introduced between the granular mattress and soft media. Preliminary test results of deformations and distortions of an axisymmetric circular footing, on a geosynthetics included granular mattress on soft media under confined condition, are presented.

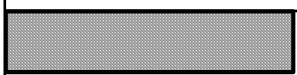
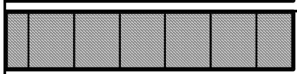
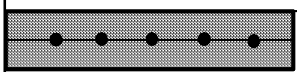
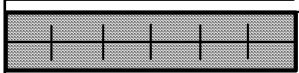
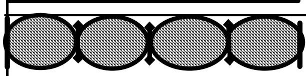
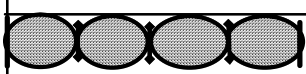
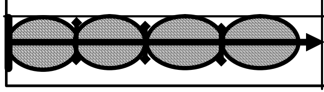
The case study part deals with application of this technology for Khulna Medical College (KMC) buildings, situated in south west Bangladesh. Four and five storied structures of two academic buildings and two buildings for student accommodation were constructed on strip footings on geosynthetics included granular mattresses on soft soils. These included foundations for load bearing walls as well as framed structures. The granular mattresses were up to two meters in thickness and were founded by remove and replace techniques. These were constructed by laying non woven needle punched geosynthetics on the soft clay, at base of excavations, on which graded mixtures of crushed brick aggregates and coarse sands were placed by vibrocompaction. A further layer of river sand was placed by vibrocompaction over the aggregate layer. The constructions of the buildings were completed in 1997. Deflections at gauge points were recorded time to time but not on a regular basis. All settlement and distortion values were with in those anticipated.

The presentation here follows the chronology of development at the Bangladesh University of Engineering and Technology. Results on laboratory studies in the model footing test tank is followed by the case study of KMC buildings, studies in test cell are reported at the end.

2 TYPES OF GRANULAR MATTRESSES

Several types of granular mattress foundations have been envisaged, on which spread footings may be constructed. Some of

Table 1 Types of granular mattress

Granular mattress	Description	
	Plain	Plain
	Geosynthetic geocell	Reinforced
	Geosynthetic reinforced	
	Geosynthetic multi anchored	
	Geosynthetic encapsulated	
	Geosynthetic 1-D prestressed	Prestressed
	Geosynthetic M-D	

these are already in use and others will probably see application in future. These include plain, reinforced and prestressed types. Geotextiles, geogrids and polymer coated steel wire nets may be used in construction of such mattresses. Schematic representation of some types is made in Table 1. The suitability of any type can only be ascertained through their behaviour in resisting bending and distortion. The thickness, material properties, depth of placement, consistency and heterogeneity of the underlying soil layer, spacing of footings, magnitude of loadings and the stiffness of superstructure will influence the behaviour of such foundations. In all the cases the granular mattresses will be underlain by a filter geotextile. This layer will provide multiple functions of reinforcement, separation and filtration.

3 STUDIES PERFORMED

The studies were initiated with laboratory investigations on model footings in a test tank described in art 4. This was followed by application of the technology in field, in construction of KMC building foundations described in art 5. In a quest to develop more advanced testing techniques, led to the development of model footing test cell apparatus described in art 6.

4 TESTS IN MODEL FOOTING TEST TANK

4.1 *Model footing test tank*

As a primary study to investigate the deformation and distortion behaviour of mattress foundation on soft subgrades, a test programme was carried out. Tests on model footing were conducted, under plain strain conditions, in a test tank having thick glass sides. Schematic diagram of the tank is presented in Figure 1. A rigid metal footing having width B=100 mm and length L=335 mm was used. Polyurethane foam was used to simulate a thick layer of compressible media. Gravel mattress of thickness H equal to 0.5B, 1B and 1.5B were tested. In an effort to simulate the effect of bedding pressure from overburden, suction was applied in the gravel mattress layer. This was achieved by encapsulating the gravel mattress layer by a thin polyethylene membrane. The magnitude of suction or confining pressure was variable in these tests. Four tests were conducted for each mattress thickness conditions. These are at suction values of 0 mm, 127 mm, 254 mm and 381 mm of Hg, corresponding to confining pressures of 0, 17, 34 and 51 kPa. Suction was applied from a vacuum source, which was maintained at high vacuum. Load was applied to the footing through a proving ring. Surface deformations were measured at the footing location and at distances, R = 1.5B, 4.5B and 7.5B from the centre line, on either side of the footing (Fig. 1). The primary objective of this research was to investigate the deformation and bending behaviour of granular mattresses rather than their load carrying capacities.

4.2 *Materials used*

River run gravels with a maximum diameter of 8 mm was used. A grade of polyurethane foam was used as the soft media. A geogrid, Tensar SR55 (named G_T in the paper), was used as the base reinforcement layer. Some properties of these materials are presented here.

Gravel: type-uniform sub rounded: D_{10}=2.9 mm; C_U=2.0; γ=15 kN/m^3 and Ø = 38°.

Polyurethane foam: γ = 0.22 kN/m^3; modulus = 39 kN/m^2.

Geogrid: type-G_T; unit wt. = 925 gsm; T= 55 kN/m; elongation = 20 %.

4.3 *Test Results*

Results from model footing tests in the test tank are presented here. Based on these, differential settlement analysis for a pair of model footings were conducted, which are also presented.

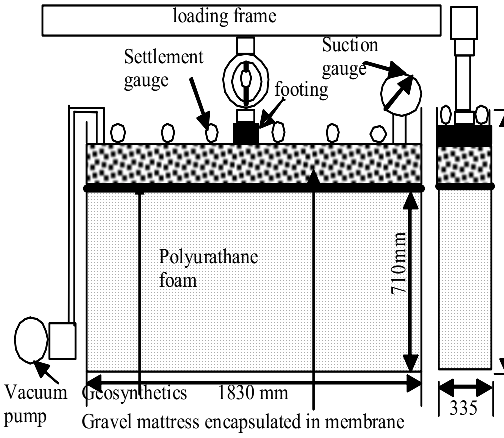


Figure 1. Model footing test tank

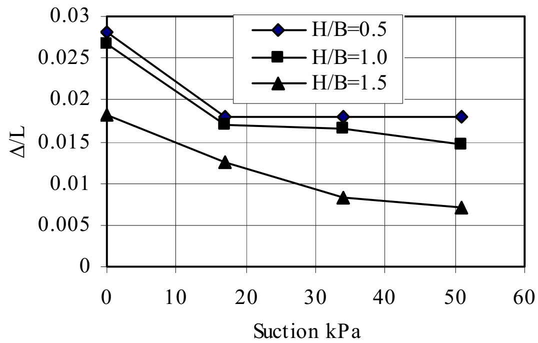


Figure 2. Curvature of deflection vs confining pressure and H/B ratio

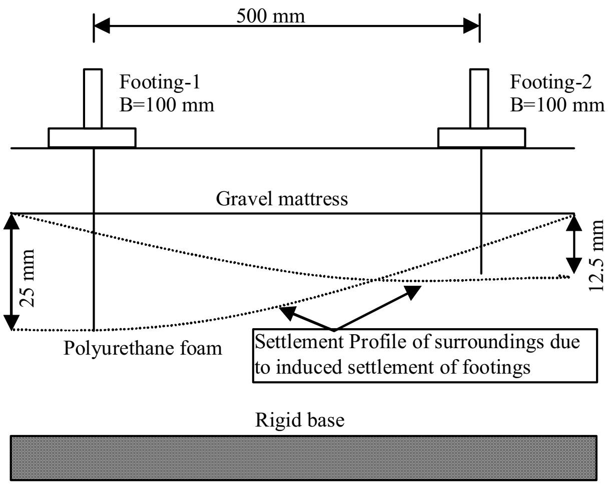


Figure 3. Diagram of model footing design example

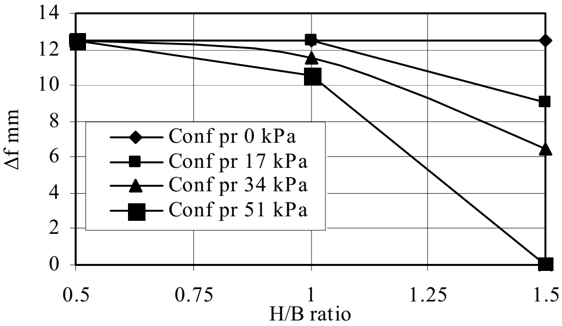


Figure 4. Differential settlement of model footings (Fig. 3) as a Function of confining pressure and H/B ratio

From the tests described in art 4.1, values of Δ/L, a parameter defined here as distortion ratio, are plotted as a function of confining pressure for different H/B ratios and are presented in Figure 2. This is a measure of the curvature of the deflected shape of the granular mattress. Where Δ is the maximum deflection (at mid point) and L is is is the span length of the deflected granular mattress, H is the thickness of the granular mattress and B is the width of the footing. These show that the distortion ratio reduces drastically, from that under no confining condition, even for low increase in confining pressure. For small thickness of gravel layer (H/B=0.5) the distortion ratio remains unaffected due to confining pressure increase between 17 kPa and 51 kPa. Increase in layer thickness between H/B=0.5 and H/B=1 has small affect on the distortion ratio but between values of H/B=1 and 1.5 the effect is profound, which is true for all confining pressures. Moreover, it is seen that a thin layer under confined condition may behave like a thick layer under unconfined condition. A mattress layer having H/B=0.5 confined at a low pressure of 17 kPa is almost showing the same value of distortion ratio (Δ/L=0.018) as a layer with H/B=1.5 under unconfined condition. This shows the beneficial effects of the concept of prestressing gravel mattresses, which may also be achieved by burying these deeper.

In an effort to analyze the settlement and distortion behaviour of a pair of footing on gravel mattress foundation on compressible media, the following example was considered. Each of the model footing was 100 mm in width with centre to centre distance of 500 mm as shown in Figure 3. This model is a 9:1 representation of a prototype structure having continuous footings, 900 mm wide, with centre to centre spacing of 4.5 meters. This is a common grid structure in residential constructions in Bangladesh. These model footings were loaded unequally to such degrees that Footing-1 will produce a deflection of 25 mm in every case when loaded individually. For example for a layer thickness ratio H/B=1 and confining pressure of 34 kPa Footing-1 will be subjected to a pressure of 22.5 kN/m^2, whereas for H/B=1.5 and under zero confining condition the footing will be subjected to a pressure of 14.0 kN/m^2. Details are presented by Kabir et. al. 1992. Similarly Footing-2 is subjected to pressures of such magnitudes that it would produce a deflection of 12.5 mm, in all the individual cases. This means that if the influence of deformation of Footing-1 and Footing-2 does not affect each other, then their differential settlement will be 12.5 mm. Deformation analysis using superposition principle was used to analyze the differential settlement of these two footings for different values of layer thickness ratio (H/B) and confining pressure (p).

The results of the differential settlement, Δ_f, as a function of H/B ratio for different confining pressures are presented in Figure 4. These show the following. The differential settlement remains at its maximum value (12.5 mm) for H/B between 0.5 and 1.5 under no confining condition. That is, under these conditions, the deformation bowl of one footing does not spread far enough laterally, to affect the other. This is also the case for H/B=0.5 for all confining pressures between 0 and 51 kPa. However, between H/B=1 and 1.5 under confining conditions, deformation bowls spread laterally so far that they affect each other, resulting in reduction of differential settlement values. The reduction of differential settlement with increase in confining pressure is more profound for higher value of thickness ratio (H/B=1.5) than for lower value ((H/B=1). At H/B=1.5 and p=51 kPa the deformation bowls of the two footings interacts to such degree that the differential settlement approaches equal to zero.

To investigate the effect of reinforcing, test with H=0.5B was repeated for condition with out confining pressure. A layer of geogrid G_T introduced at the bottom of the gravel mattress. Footing pressure versus deformation diagrams are presented in Figure 5 for cases with and without geosynthetic base layer. These show substantial improvement in limiting deformation due to reinforcing action of geogrid reinforcement

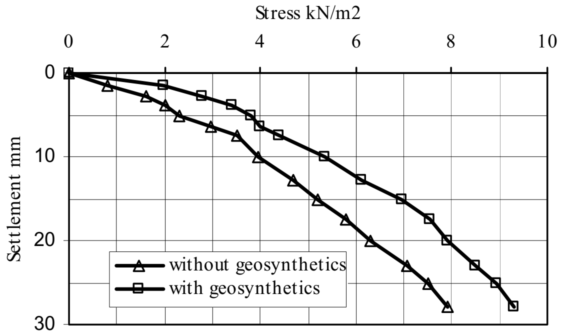


Figure 5. Stress vs settlement diagrams for granular mattresses with and without geosynthetics

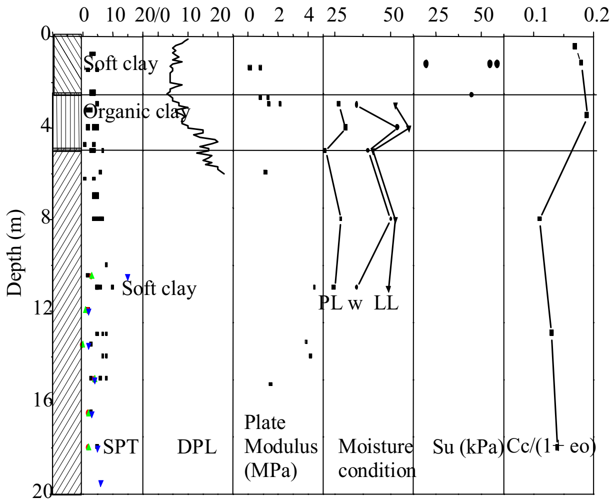


Figure 6. Typical borelog of subsoil at Khulna medical college

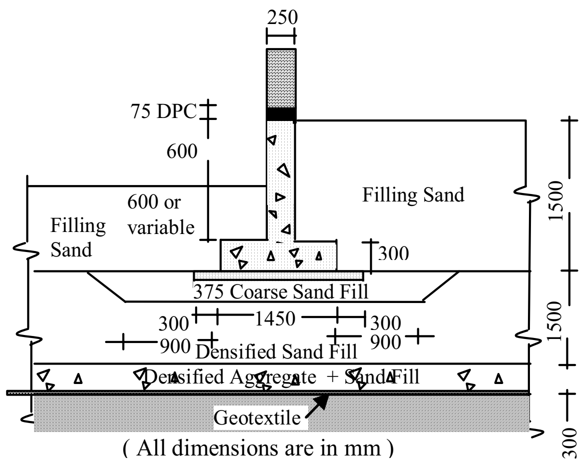


Figure 7. Details of wall footing on granular mattress

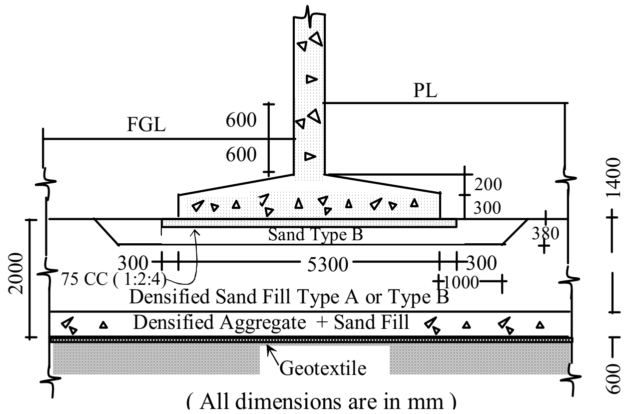


Figure 8. Details of column footing on granular mattress

5 FOUNDATION FOR KMC BUILDINGS

In 1994 the author, in collaboration with Public Works Department (PWD) of Bangladesh, decided to investigate on the feasibility of use of granular mattress foundations for 3 to 5 storied-buildings of the Khulna Medical College (KMC). The philosophical and analytical bases of the project emanated from a case study (Wu and Scheessele, 1982) and research in this area presented here in art. 4.3 (Kabir et. al. 1992). Initially four buildings were taken up. These are the Academic Building (AB), Nurses Training Centre (NTC), Girls Hostel (GH) and Boys Hostel (BH). The AB complex has a framed structure with wings 3 to 5 storied in height. The other three buildings are load bearing wall types with height between 4 and 5 stories. The granular mattresses, up to 2 m in thickness, were constructed by remove and replacement technique. The construction of the buildings was completed in 1997. Settlements at gauge points were recorded time to time, but not on a regular basis

The subsoil in the area is composed of Recent soft soils, with interlayer of decomposed and partially decomposed vegetative organic matters, originating from subsidence of mangrove forest. A generalised soil profile of the project site is presented in Figure 6. This figure shows the SPT, DPL, screw plate modulus, moisture condition, undrained shear strength and compressibility parameters. The DPL (Dynamic Probing Light) tests revealed the extents of the soft top layer, more precisely than that by SPT.

Granular mattress foundations were envisaged, designed and constructed for KMC buildings for a number of reasons. These are, (a) cost and time savings, (b) ease of construction by available local technical skill with the prospect of easy adaptability and (c) sound load carrying capacity, settlement and distortion. The mattress system resembles inverted road macadam with the coarsest layer buried as deep as possible. This made the system, used in this study, special. The effect of confining pressure on stress strain modulus of brick aggregates were established using suction triaxial tests (Kabir et. al. 1992). To achieve the highest confining effect the coarse aggregate layer is placed as the deepest layer of the mattress. The beneficial effect of confining on settlement and distortion has been discussed earlier. A typical cross section of the granular mattress for load bearing wall footing (type A) used in GH, BH and NTC buildings is presented in Figure 7. That for a continuous column footing for framed structure (type B), used in AB building, is presented in Figure 8.

5.1 *Materials used*

The properties of materials used, are presented in the following.

Aggregates: The aggregate layer consisted of a 2:1 mix of crushed brick aggregates and coarse sand. Aggregates, 25 mm down graded conforming to the ASTM grading was used. The coarse sand consisted of river sand from the north east of the country, having fineness modulus (FM) ≥ 2.5.

Sands: The sand fill layer consisted local river sand having fineness modulus (FM) greater than 1.0. Fines passing number 200 sieve was limited to 5% for FM < 1.5 and 10% for FM $\geq$ 1.5. The sands and aggregates were densified, in layers, by using twin steel drum vibratory rollers. Field densities were monitored by TRL dynamic penetrometer tests.

Geotextile: A geotextile layer was placed at the bottom of the excavation on the soft clay layer. A nonwoven needle punched geotextile was used. The weight, grab tensile strength and permeability were greater than or equal to 250 gsm, 1000 Newton and 1×10^{-3} m/s respectively.

5.2 *Functions of granular mattress and geosynthetics*

The functions of the granular mattress for the KMC building foundations are described the following. (a) Increase in bearing capacity. There will be an increase under undrained condition, which will increase further due to increase in shear strength of the clay layer as drainage sets in. The highly permeable mattress will allow fast dissipation of pore pressure, especially from the region immediately underneath the geotextile layer where the pore pressure will be the maximum. (b) Distribution of stress over a large area. (c) Minimize total and differential settlement. An elaborate discussion on these will be presented elsewhere.

The geotextile layer acts as separator, filter, containment layer and reinforcement. As separator, the geotextile prevented mixing of clean aggregate layer with the clay underneath. This function was crucial during the vibro compaction stage but also quite dominant during the full loading of the footings. On loading, as the consolidation of the underlying clay sets in, water will flow mainly through the highly permeable geotextile into the mattress layer. At this stage and also during vibro compaction stage the geotextile will work as a filter allowing the pore water to pass freely without allowing soil particles to contaminate the overlaying aggregates. As contaminant layer the frictional geotextile ($\delta > 3/4\phi$) will not allow the aggregates to slip away from the loaded zone during vibro compaction as well as full loading. Without geotextile, would result in a loose boundary layer of aggregates and on loading, larger settlement will occur due to poor stress distribution and slippage of aggregates away from loaded area. Tension membrane reinforcing effect by mobilizing tension in the geotextile will result in small shear strains around the geotextile allowing large bearing stresses at low deformations.

5.3 *Settlement and distortion*

Continuous inverted Tee beam type footings were used for load bearing walls and continuous tapered footings were used for column foundations of framed structures. A beam on elastic foundation program based on finite element analysis was used to analyze both the types of footings. Settlement and distortion under working load dictated the proportioning and design of the footings. As described earlier footing types A and B were considered on the mattresses on soft clay layers. The deflected shapes for the mattress foundations for wall (type A) and column (type B) footings are presented in Figures 9 and 10 respectively. Four cases of foundations were considered to provide a comparative representation of cases with and without mattress foundation as well as those under undrained and drained conditions. The results in Figure 9 are for an inverted Tee beam wall footing, 1.45 m wide, 33.2m long having 250 mm wide web and 300 mm thick flange. The results show that provision of mattress foundations will reduce the settlement to less than 1/3. This is also the order of values for differential settlement for this case. Figure 10 shows results of a typical strip footing for carrying column loads. The footing is 5.3 m wide, 410 mm deep and 27.3 m long. It can be seen that provision of mattress foundations will reduce the total and differential settlement by more than half compared with those without mattress. Settlements and deformations were monitored time to time. The order of values for maximum settlement for both the cases agreed well with calculated values.

6 TESTS IN MODEL FOOTING TEST CELL

The model footing tank lacked facilities for applying bedding pressures beyond the limits of laboratory suction (< 60 kPa). Test cells, two meters in diameter, are being constructed with facilities for application of higher bedding pressure. A smaller version was constructed as a preliminary to the large cells.

6.1 *Model footing test cell*

As preliminary to development of large diameter cells a smaller version was constructed. Details of the 150 mm diameter cell with the relevant instrumentation are shown in Figure 11. The model footing test cell was built as a modified version of hydraulic oedometer apparatus. The base plate of a 150 mm diameter hydraulic oedometer was removed to house an extended flanged cell 240 mm in length. A base plate was fitted at the bottom with small holes to pass wires for application of footing load and to house dial gauges. The cell housed the rubber bellow of the hydraulic oedometer at top with room for (50 mm thick) gravel mattress, followed downwards by geotextile sheet and the soft media. The geotextile sheet could be attached between the flanges or may be used as a layer encapsulating the gravel mattress. A 50 mm diameter metal footing was used, which was screwed to the central pipe of the hydraulic oedometer. The footing had provision for loading from the bottom by a lubricated thin wire attachment, passing through the gravel mattress and soft media system, with a loading pan at the bottom. The deflected shape of the footing system was measured by using five dial gauges. The central dial was housed at the top of the central pipe of the cell. The other four were housed at the bottom of the cell, with two on either side of the footing. These were housed at a distance of 30 mm and 60 mm from the center of the footing. Gauge points were established at the central horizontal plane of the gravel mattress by placing small diameter (10 mm) metal pallets which were connected to the dial gauges at the bottom of the cell by thin wires (4mm in diameter). Side friction of the gravel mattress and the soft media was minimized by using grease. Water pressure with a large volume constant pressure system was used to apply and control the bedding pressures. Footing load was applied in increments and dial gauge readings were taken at the end of every load increment. The footing size was 50 mm and bedding pressure of 65 kPa was used. Two tests were conducted, one on the soft media (rubber foam) only and the other with a gravel mattress on the soft media. In both the cases, the deflection readings were recorded at the center, 30 mm and 60 mm positions for footing pressures of 25, 50 and 100 kPa. The tests in this apparatus are at the preliminary stage. As mentioned earlier large (two meter) diameter cells are being constructed to run tests on 300 mm diameter footings.

6.2 *Materials used*

8 mm down graded broken angular brick aggregates were used as the gravel mattress media. A non woven needle punched geosynthetics was used as base reinforcement layer. Soft rubber foam was used as the soft media. Some relevant properties of these materials are presented in the following

Aggregate: type-uniform angular: D_{10}=2.7 mm; C_U=2.2; γ=13 kN/m^3 and $\O$ = 40^o.

Soft rubber foam: γ = 2.1 kN/m^3; modulus = 500 kN/m^2.

Geosynthetic: type BJ300; unit wt. = 320 gsm; T= 20.8 kN/m; elongation = 68 %; EOS= <75 µm; k_g= 4.5 mm/s.

6.3 *Test Results*

Results of the two tests are presented in two different forms. In set 1, the footing pressure versus deformation curves are presented as functions of location from the center line of footing. Figure 12a presents the footing pressure versus deflection at different points for the case without mattress. Figure 12b presents those for the case of footing loading on geosynthetic included granular mattress. In Figure 12c comparative results of the cases without and with mattress are presented. These showing the footing pressure versus deflection curve to have double curvature in case of footing on soft media only (Fig. 12a) this behaviour was not observed in case of mattress on soft media (Fig. 12b). This phenomenon is more vivid in the comparative results (Fig. 12c). The deflections in case of mattress foundation were less than 8% of those on soft media only under all loading conditions.

The deflection patterns across the width of the mattress, as a function of footing pressure, are presented in Figures 13a, 13b and 13c. These show that, in case of footing on soft media only (Fig. 13a); the deflection is localized at the center compared with that for mattress foundation (Fig. 13b). The comparative diagrams in Figure 13c show that the magnitude and curvature, of deflection reduced to less than eight percent due to use of a geosynthetic included granular mattress

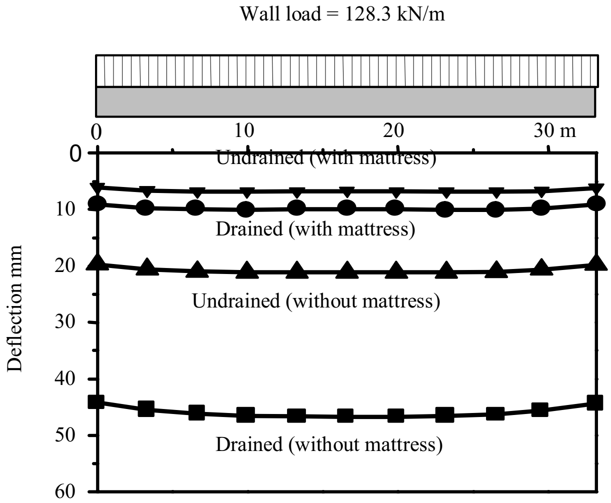


Figure 9. Deflection of wall footing

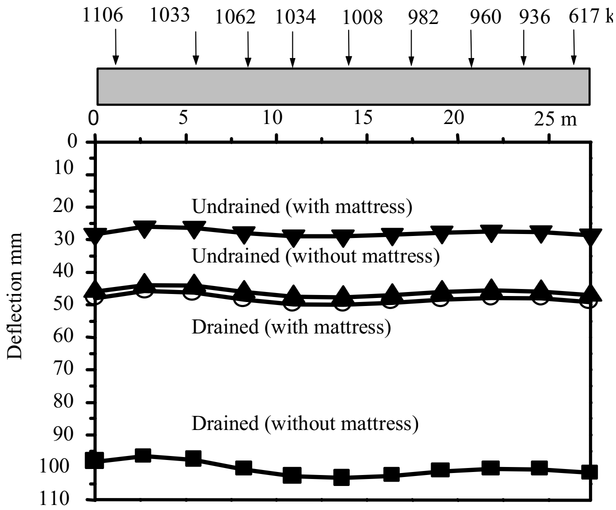


Figure 10. Deflection of column footing

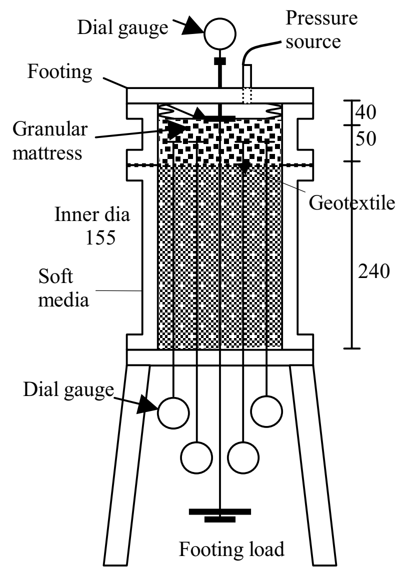


Figure 11. Model footing test cell

7 CONCLUDING REMARKS

Tests in model footing test tank revealed that settlements and distortions will be minimized due to introduction of granular mattress foundations on soft media. This reduction is a function of thickness of the mattress and bedding pressure on this. Use of a geogrid base reinforcement will further reduce these values. Preliminary test results from the footing test cell revealed the effect of confining pressure and geosynthetics in minimizing settlements and distortions of granular mattress layer on soft media

The Khulna medical college buildings provide good case studies on buried granular mattress foundations on soft soils. The effect of confining by overburden on the granular mattress with geosynthetics interface worked satisfactorily to keep the settlements and distortions values with in tolerable limits.

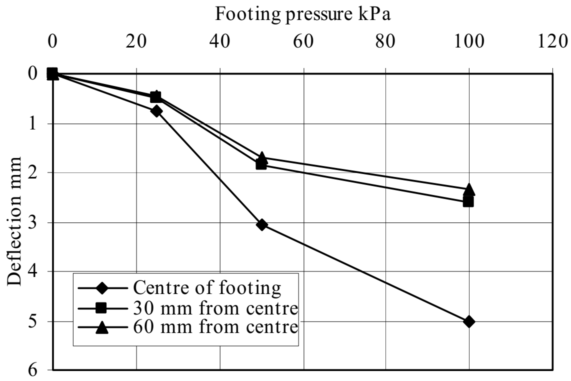


Figure 12a. Deflection of soft media as a function of footing pressure (bedding pressure; 65 kPa)

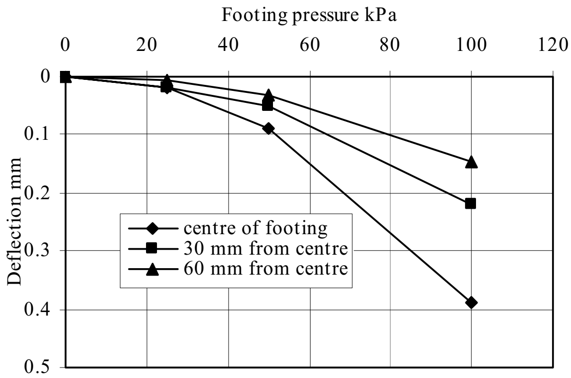


Figure 12b. Deflection of gravel mattress as a function of footing pressure (bedding pressure; 65 kPa)

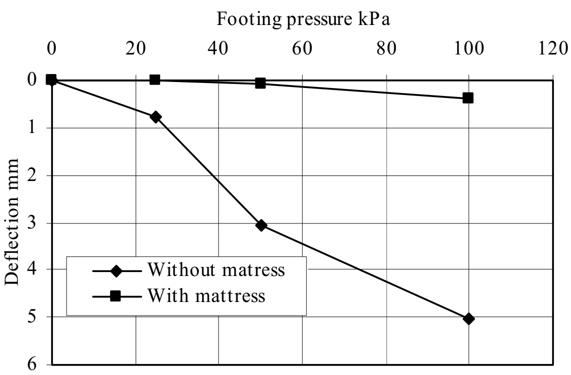


Figure 12c. Deflection at footing centre as a function of footing pressure (bedding pressure, 65 kPa)

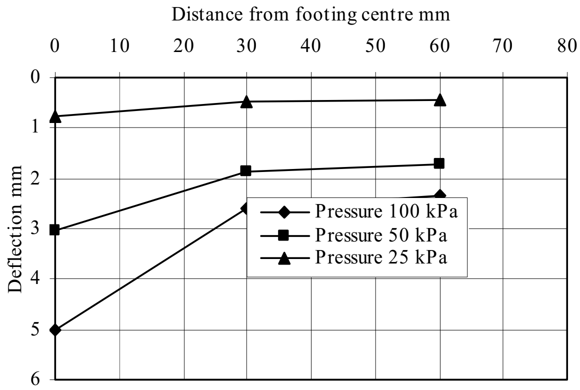


Figure 13a. Deflected shape of soft media at various footing pressure (bedding pressure; 65 kPa)

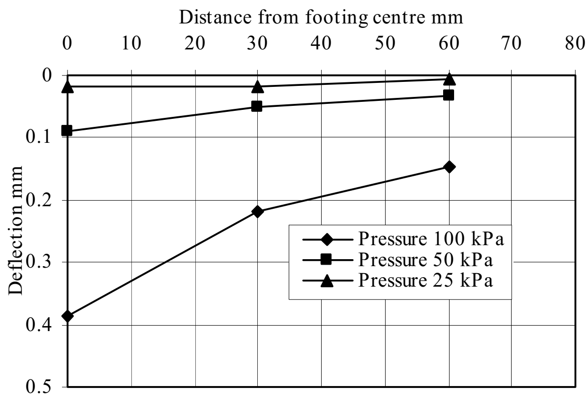


Figure 13b. Deflected shape of granular mattress as a function of footing pressure (bedding pressure; 65 kPa)

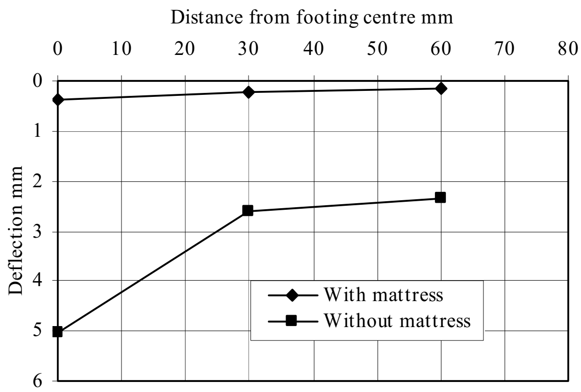


Figure 13c. Deflected shapes of foundations (footing pressure 100 kPa: bedding pressure 65 kPa)

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