Geosynthetic reinforced & unreinforced rail track foundation comparison of analytical methods and numerical modelling

Mayuresh Bakare
M-Tech, Geotechnical Engineering, Department of Applied Mechanics, SVNIT, India
Ratnakar Mahajan
DGM Technical, Maccaferri Environmental Solutions Pvt. Ltd., India
C. H. Solanki
Professor, Department of Applied Mechanics, SVNIT, India

ABSTRACT: Design of Railway track foundations (RTF) given by Research Designs & Standards Organization, India (RDSO) is studied for its reference methods, material specifications and the design criteria. Considering the new demands of heavier and fast freight transport there is a need to optimize and economize the design and maintenance of the RTF. An analytical design method for design of geogrid reinforced RTF is discussed and modified aiming for its application in the same. The design considers loading mechanism of the wheel, rail and sleeper in pseudo static nature, elastic properties of track elements, geogrid ballast interaction, stress diffusion in the ballast and sub ballast and empirical distress formulae for critical rutting under cyclic loading. Modifications in the design are done by changing the critical rut ratio, subgrade strength criteria and the applied dynamic augment. A detailed parametric study is done which encompasses the various design cross sections thus obtained with different granular layer thicknesses and properties (Resilient modulus) possible in Indian Scenario using a plane strain finite element (FE) model in Plaxis 2D. Deviator stress transferred on the subgrade top due to train loads is used for the design. The three designs thus obtained are compared. It was found that different layers of RTF can be optimized by using geogrid. Also maintenance period of RTF can be increased for same thickness of the granular layers. Modified analytical method of geogrid reinforced RTF corroborates with results of numerical model

Keywords: RDSO; geogrid, reinforced; resilient modulus, FEM, Plaxis 2D

1 INTRODUCTION

Design of Railway track foundations by RDSO GE-0014 follows empirical (E) approach (UIC code 719 R, British Railways method, AAR method) which is based on the experience (observations over long period of time) and / or certain index properties such as CBR, limiting shear failure, limiting deflections etc. Such index and empirical properties may not include effects of the multidimensional geometry, dynamic loading, stresses and strains in a multilayered railway track foundation. So use of such empirical approach should be considered of limited capabilities.

Mechanistic empirical (ME) approach follows limited use of the concepts of the mechanics like elasticity, plasticity and/or viscoelasticity. It involves two stages. In first stage RTF is analyzed for stresses and strains developed, using a mechanistic model such as layered elastic theory (Boussinesq, Westergaard, Burmister etc.) and/or finite element method that includes elastic, nonlinear elastic or elastoplastic (Mohr Coulomb) soil models. The stresses and strains calculated in stage one are used in second stage in empirical formulas (used by AAR, BR etc.) for calculation of different distresses, mostly uniaxial quantities like deviator stress on subgrade top, surface deflection (sleeper), vertical compressive strains along the depth of the embankment layers. These are used to assess the stability and performance of the designed cross section.

1.1 *Need for the study*

Though there are numerous studies done till date emphasizing the advantages of the geogrid-geotextile reinforced RTF design, it has not been adopted yet in India. One of the reasons could be lack of generalization of the results or lack validation of the results for different Indian site (e.g. alluvial soils in Indo-Gangetic plains) conditions, so it is but natural to study, modify and adopt a design of RTF which is analytical in nature and is flexible to the degree which encompasses the overall scope of the geogrid reinforced RTF.

1.2 *Objectives*

I. To study RDSO design for unreinforced RTF and Rimoldi's design of reinforced RTF
II. To prepare designs of geogrid reinforced RTF using Rimoldi method.
III. To model the design cross sections in FEM using PLAXIS 2D (plane strain idealization) to validate the designs obtained from objective 2 for different material and load parameters

2 EMPIRICAL MODEL BY RDSO

Typical RTF (Figure 1) consists of granular layer over the subgrade soil or the formation level of the embankment (in the case of filling) comprising two layers namely Ballast and Sub ballast. Ballast consists of high quality course grained material with high hydraulic conductivity for rapid drainage of the runoff water and an elastic modulus to sustain the cyclic loading of the wheels. It suffers from lateral spreading and breakage of the material due to which it loses its shape, stiffness and the hydraulic conductivity resulting in concentrated loading patterns and mud pumping which further reduces the hydraulic conductivity of the ballast. Sub ballast is also a granular layer but consist of graded layers of sands to work as an inverse filter against mud pumping and a cushion between ballast and subgrade to avoid attrition. However the main function of the sub ballast is to distribute the deviator stress such that the pressure transferred to the subgrade will not cause it to fail under rutting (serviceability) or total shear failure (strength). Considering the mechanism and functions of the layers discussed above RDSO has developed a detailed empirical design for heavy axle loads (>250 kN) based on some of the well-known Empirical Methods which are practiced all over the world.

2.1 *Empirical reference methods*

UIC (Union Internationale des Chemins de fer) code 719R, 1994 gives the thickness of track bed consisting of ballast and blanket (sub-ballast) with an empirical formula which considers quality (modulus of elasticity, E) of the sleeper and granular layers, speed of the train, Gross metric tonnage (or number of axle load repetitions) etc. In British Railway Method the design curves for the subgrade giving the depth of granular layer (ballast & blanket) have been developed for different axle loads and threshold strength of soil, and are given in ORE Report No. D-71 RP 12, which was based on laboratory studies undertaken on London Clay samples (Heath et al., 1972). Association of American Railroads (AAR) method gives design charts for granular layer thickness corresponding to deviator stress experienced by different types of clay subgrades and number of axle loads adopted by American Railways System (Li and Selig, 1998).

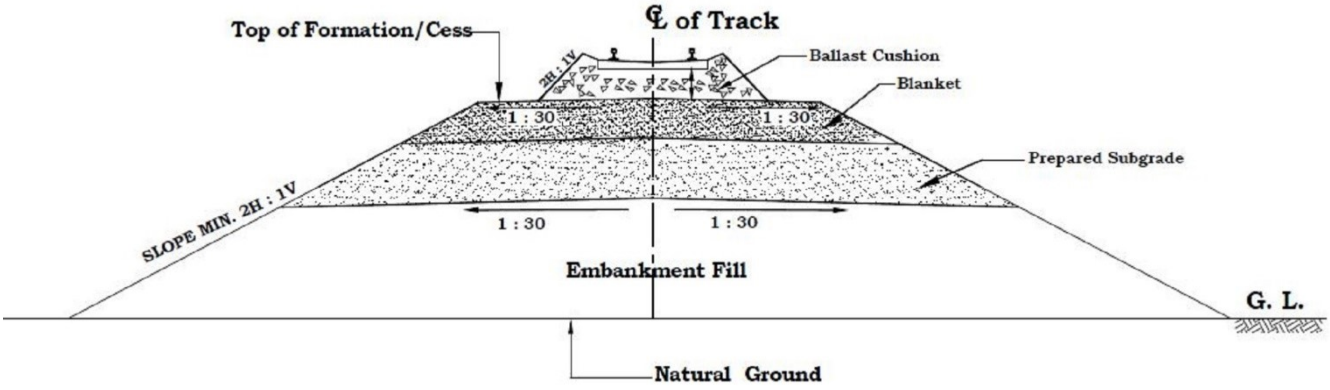


Figure 1. Typical RTF considered (RDSO GE-0014).

RDSO has considered all these methods while developing the designs for unreinforced RTF. The general outline of the design cross section of RTF consist of track equipment and granular layer supported by prepared subgrade and natural subgrade. This arrangement is similar to that of given in UIC code 719R. While the criteria for distress considered corresponds to that of discussed by Li and Selig in AAR method. The strength criteria of the subgrade is considered as deformation modulus E_{V2} (DIN 18134). Axle loads considered are 250, 300 and 325 kN. Details of the design thicknesses of different layers are given in (Fig. 4)

3 ANALYTICAL MODEL BY RIMOLDI

Rimoldi (2012) has given an analytical formula to calculate the thickness of the RTF for reinforced design. It considers the stress distribution by Bossinesq's theory and distress mechanism given by Leng and Gabr (2002, 2005 and 2006). The derivation of the formula follows the framework given by Giroud and Han (2004).

A multilayer cross section in lateral direction (Fig. 1) is considered. The axle load is considered to be shared by 3 adjacent sleepers (along the length of the track) in 1:2:1 ratio so the wheel load (half the axle load) transferred by a rail on a single sleeper being only one fourth of the actual axle load of the wagon. The stress transferred by sleeper on the ballast (p) is then converted into a circular load to be used in the Bossinesq's equation to find out the stresses at subsequent layer interfaces. Before then, the layers with different modulus of elasticity and poison's ratio (E, μ) are converted in to an equivalent homogeneous elastic half space using the theory given in the book pavement analysis (Ullidtz, 1987). The concept being, stress transferred by layers with different thicknesses and elastic properties but same stiffness is equal. Empirical models considering lateral spreading of the ballast with the number of load cycles (Leng and Gabr, 2005) and mobilized bearing capacity (mN_cC_u) with respect to the maximum allowable depth of rutting at the top of clayey subgrade (Vecchiotti and di Prisco, 2006). The final formula to calculate the design thickness (h) of the different layers under consideration is given here.

$$h = \frac{0.85a(1 + k_2 \log N)}{\tan \alpha}\left[\left(\sqrt{p / mN_cC_u}\right) - 1\right] \tag{1}$$

where, a is the radius of the circular area on which the wheel load is distributed on a layer under consideration, p is the corresponding deviator stress on that layer, N is the number of axle passes for design period, α is the initial angle of stress diffusion, k_2 is a coefficient (Leng and Gabr, 2006) which defines the degradation of α with N number of load cycles.

The method is modified for the Indian scenario with inclusion of the dynamic multiplier (equal to 2 for wheel dia. 1.090m and speed of 55.55 m/sec or 200 kmph) to convert the wheel load from static to pseudo static (Li and Selig, 1998 II), considering threshold stress as subgrade strength and changing the modification factor for limiting rut depth of 50 mm. the properties for subgrade are considered as per given in Table 1. Excel sheets were prepared based on equation mentioned above to calculate thicknesses of the different layers of the RTF reinforced with the geogrid for different axle loads.

4 NUMERICAL MODEL

A plane strain idealization of RTF given by RDSO is considered, which implies that the longitudinal strains in RTF are negligible or zero compared to the lateral strains. RTF is discretized using 15 noded triangular elements available in Plaxis 2D V8.2 which is a commercial platform for FE operations. Only half of the RTF is considered due to its symmetry. Standard fixities are selected for boundary conditions.

Mohr coulomb (MC) material model is considered for all the soil layers (Table 1). The MC model considers ideal behaviour of the soil in two parts, elastic and perfectly plastic. Soil is considered to follow elastic behaviour till it reaches the yield stress after which it is considered to follow a perfectly plastic behaviour. The material parameters to be considered are E, μ (stiffness parameters), ø, c (strength parameters) and ψ (angle of dilatancy). This model was chosen as it is best suited to predict deformations in RTF for pseudo static approach because strains corresponding to maximum rut depth are very small so the material is considered to follow perfectly elastic stress path and it gives an indication of failure if any which is not there in the linear elastic model. So for simplicity, computational economy and to get an indication of any incipient failure MC model was chosen. Material properties considered are directly taken from the literature. For granular layers of ballast and sub ballast extensive research (laboratory and field as well) done by Indraratna et al., (2010 and 2013) is followed. For prepared subgrade and embankment fill layers RDSO GE-0014 guidelines were followed and IRC 113 (2013) was used to get parameters for soft subgrade of Indo-Gangetic alluviums. The ground water table is considered at the top of the subgrade layer. Track elements (sleeper and rails) are modelled as linear elastic material with standard E values (Selig et al. 1979).

Table 1. Material properties considered

Material	Ballast	Sub-ballast	Prepared subgrade	Embankment fill	Subgrade
Drainage Condition	D	D	D	D	UD
γ_d (kN/m3)	15.3	21.8	18	16	13
γ_{sat} (kN/m3)	16	23	20	18.5	15.5
k(m/day)	1	0.1	10^{-2}	10^{-3}	10^{-5}
E_{ref} (MPa)	200	120	45	30	20
μ	0.33	0.33	0.35	0.35	0.40
C_{ref} (kN/m2)	1	5	15	20	25
ϕ (°)	55	40	10	5	0
ψ (°)	20	10	0	0	0
e_0	0.74	0.52	0.7	0.8	2.0

Sensitivity analysis is performed to ascertain the optimum mesh density required (fine mesh) for consistency and accuracy in the results (deviator stress at the subgrade top). Vertical stresses developed in the RTF (Fig. 3) are compared with published field measurements of the Facility for Accelerated Service Testing (FAST) research track in Pueblo, Colorado (Selig et al., 1979) and the 3D FEM analysis done in Abaqus 6.11 (Sowmiya et al., 2011) for validation of the FE model to be used.

Geogrid reinforced section is designed based on the vertical strains observed in the unreinforced sections. The geogrid is provided at the interfaces of the layers as well as between the layers with a minimum spacing of 0.5 m. The axial stiffness of the geogrid is considered as 500 kN/m and the interface factor R is considered as 1 to get full bond strength between the geogrid and soil adjacent to it.

4.1 *Parametric study*

Parameters for materials are considered based on the work done by Shahu et al., (1999), Chawla and Shahu (2016), RDSO GE 0014 and study by Indraratna et al., (2006) The different thicknesses of the sub ballast layers are considered such that it will encompass the design outcomes of the analytical design (Rimoldi, 2012) and the designs given in RDSO GE 0014, here it should be noted that the ballast depth is kept constant as 350 mm which is the minimum allowable depth considered by RDSO. Total four different Sub-ballast thicknesses (H1 to H4) and four different pairs (M1 to M4) of the resilient moduli for ballast and sub-ballast layers are considered to calculate the modular ratios of the whole granular layers (Shahu et al., 1999) which represents their stiffness. Thicknesses of the filler layers i.e. prepared subgrade and embankment fill are kept constant at 0.5 m and 1.0 m respectively. The wheel loads considered are similar to

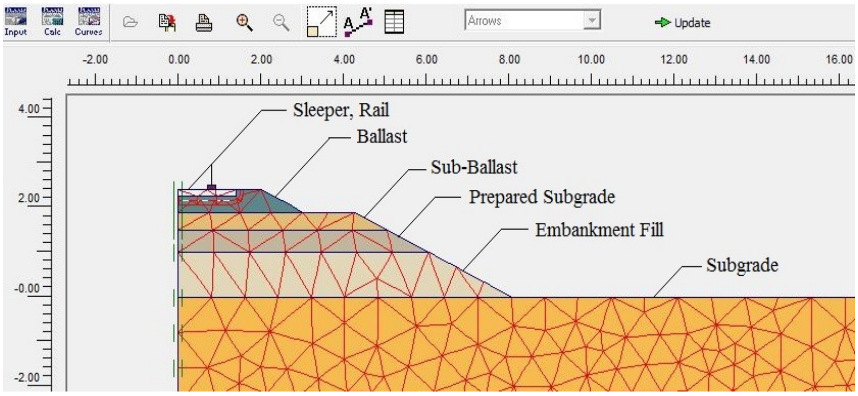


Figure 2. Discretized RTF cross section

the analytical design. Total 16 different combinations of the RTF (4 heights × 4 modular ratios) (Table 2) are tested for 3 different axle loads (250, 300 and 325 kN) for reinforced as well as unreinforced conditions (total 96 tests).

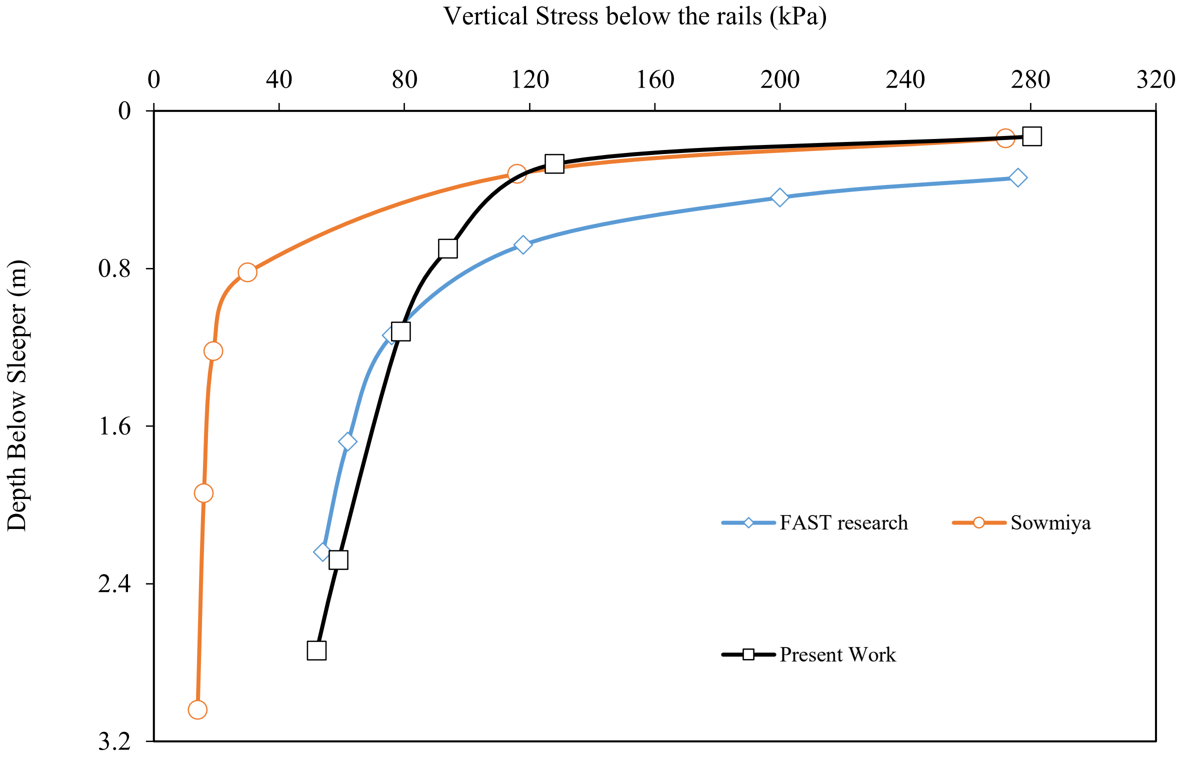


Figure 3. Validation of the current FEM model

4.2 *Details of the numerical analysis*

Deviator stress (σ_d) due to train load at the top of the subgrade layer is calculated by taking difference between total stress after the loading phase and that of the construction phase. (Hydrostatic stress being total stress due to construction of the embankment layers at the top of the subgrade)

Table 2. Different combinations of the modular ratios and thicknesses for the granular layers

	H1 (0.4m)	H2 (0.6m)	H3 (0.8m)	H4 (1.0m)
M1 (110,80)	94.00	91.00	89.13	87.77
M2 (200,120)	157.33	149.50	144.35	140.70
M3 (300,120)	204.00	186.30	174.78	166.66
M4 (300,225)	260.00	252.63	247.82	244.44

4.2.1 *Design Criteria (Empirical)*

Limiting values for Cumulative plastic strain (ε_p) and excessive plastic deformation of the subgrade layer are the two criteria given by Li and Selig (1998 I) which is adopted by AAR method and RDSO GE-0014 as well. The ε_p criteria considers the progressive shear failure phenomenon which is estimated by using equation (2).

$$\varepsilon_p = a\left[\frac{\sigma_d}{\sigma_s}\right]^m N^b \tag{2}$$

Where N is the no of load cycles or axle passes for given design period and the regression coefficients a, m, b are considered for Fat clay as subgrade layer (Li and Selig, 1996). Soil static strength i.e. σ_s =

(N_cC_u/FS) where $N_c = 5.7$ is Terzaghi's bearing capacity factor for strip footing, C_u (undrained cohesion) is taken as 25 kPa which is the least acceptable value of subgrade strength without the requirement of modification techniques (RDSO GE 0014) and FS is the factor of safety equal to 1.5 (strip footing).

The design criteria considered is $\varepsilon_p = 2\%$ for a traffic of 150 GMT (gross mega tonne) or $1.5*10^9$ kN which corresponds to approximately N = 513700 (considering average of the three axle loads). Cumulative plastic deformation criteria for design is not considered in this study due to lack of information regarding the nominal depth of the subgrade considered in RDSO GE-0014. However as the percent strain is a length invariant quantity, it is considered to compare the two designs.

Sample results for 325 kN axle load are tabulated here (Table 3). The average values of σ_d corresponding to all four modular ratios are taken for each depth. These are used to calculate the ε_p% for both the reinforced and unreinforced sections. The minimum thickness (in bold letters) for which ε_p% is less than or equal to 2 is considered as the design depth.

Table 3 Design results for 325 kN axle load

Model	Avg. Deviator Stress σ_d (kPa)		σ_S (kPa)	εp% for $1.5*10^9$ kN	
	UR	R		UR	R
H1	55.14	49.84	95	3.32	2.60
H2	50.06	44.68	95	2.63	**2.00**
H3	44.32	41.00	95	**1.96**	1.63
H4	41.56	39.13	95	1.68	1.46

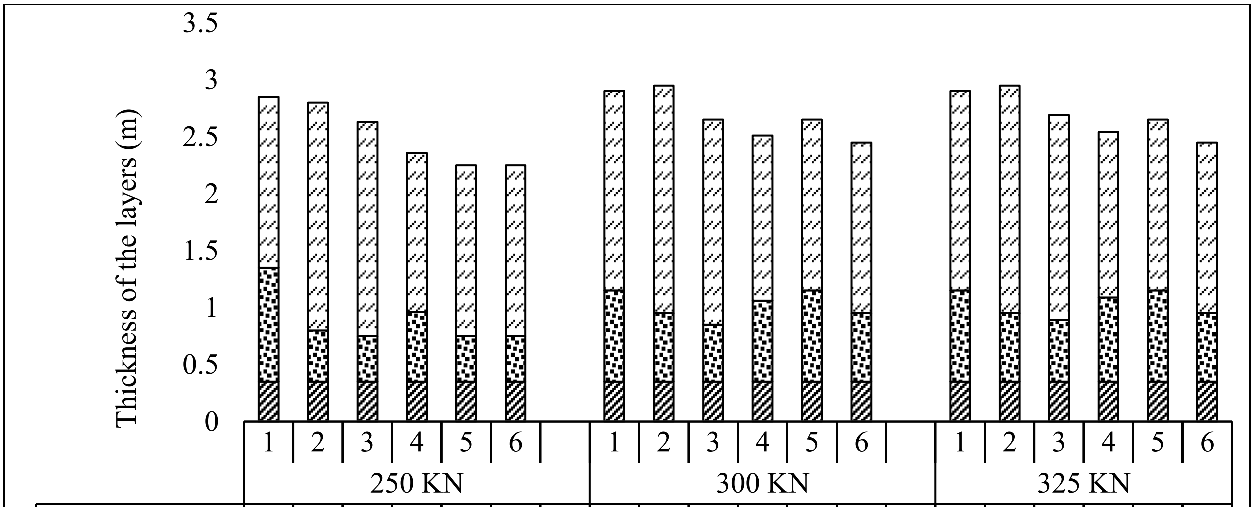
5 RESULTS AND CONCLUSION

As shown in Table 3 the thickness of the granular layers corresponding to the different parameters and load conditions are calculated and summarized in Figure 4, where 1, 2 stands for RTF designs of RDSO single liner, RDSO double liner (unreinforced, empirical); 3, 4 stands for Rimoldi m factor, Rimoldi modified with threshold strength criteria (geogrid reinforced analytical) and 5, 6 stands for unreinforced and reinforced designs from numerical analysis (ME approach). H_b, H_{sb} and $H_{psb+emb\ fill}$ are the thicknesses of ballast, sub ballast and the prepared subgrade plus embankment fill layers respectively.

The current study analyzed the stress transfer and resulting distresses in RTF with ME approach. In pseudo static loading dynamic aspect of the train load is considered in two parts i.e. dynamic augment to the static load to consider the stresses generated while speeding up and breaking down operations and the no. of load cycles N considered in the ε_p calculation. The ME approach included analytical (Ullidtz, Boussinesq) and numerical analysis (FEM). Major conclusions of the study are as given below.

- 'Geogrid reinforcement' to 'subballast layer thickness' tradeoff (for required stress diffusion) is equal to 0.2 m for a given design tonnage ($1.5*10^9$ kN) and maintenance period (in table 3 is can be seen that the UR RTF is safe for H3 subballast thickness. But when reinforced with geogrid the required thickness reduces to H2 i.e. from 0.8 m to 0.6 m)
- Design thicknesses of RDSO double liner (DL) sections are in good accordance with the results of the numerical analysis for higher loads. The double liner design reduces the thickness of the sub ballast by increasing height of prepared subgrade layer whereas it is not required if the section is reinforced with geogrid (compare bar 2 and 5 for higher loads). For 250 kN axle load the RDSO design is conservative.
- The geogrid reinforced design given by Rimoldi when considered with the modifications suggested is in good accordance with that of the numerical analysis.

This study underlines the fact that empirical approach is conservative compared to ME approach. It proves the importance of geogrid reinforcement in RTF and that the Rimoldi method (with modifications suggested) can be used to design the RTF reinforced with the geogrid.



	250 KN						300 KN						325 KN					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
▨ Hpsb+emb fill	1.5	2	1.9	1.4	1.5	1.5	1.8	2	1.8	1.5	1.5	1.5	1.8	2	1.8	1.5	1.5	1.5
▦ Hsb	1	0.5	0.4	0.6	0.4	0.4	0.8	0.6	0.5	0.7	0.8	0.6	0.8	0.6	0.5	0.7	0.8	0.6
▩ Hb	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Figure 4. Design Summery comparing the designs discussed in the paper.

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