Rationalization of LRFD Method for Safe Bearing Capacity of Shallow Footings to Incorporate the Type of Shear Failure

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Abstract. The geotechnical design philosophy is in the transformation stage to implement Load and Resistance Factor Design (LRFD). IS 6403 uses working stress method to calculate safe bearing capacity for shallow foundations, while Euro Code 7 and AASHTO use the LRFD method and provide guidelines for proportioning shallow foundations using partial safety factors. Hence, in order to adopt the LRFD design method, it has to be rationalized to have the convincing bearing capacity with respect to IS Code results to incorporate the shear failure criteria. In present work, safe bearing capacity for shallow footing is calculated as per IS Code, Euro Code 7 and AASHTO by taking the variations in shear failure criteria i.e. with and without consideration of shear failure criteria (only for Euro Code design), soil parameters (cohesion, C and angle of internal friction, ϕ), size and depth of footing. Problems are then identified by checking the consistency of results obtained by Euro Code 7 and AASHTO with respect to IS Code results. Further, as a part of rationalization, the recommendation is given that in Euro Code 7 design, the partial safety factors must be applied to bearing capacity factors, instead of applying to soil properties (C, ϕ). Also, net safe load (kN) obtained from AASHTO is on lower side as compare to IS results because it considers higher average FOS than IS Code.

Keywords: LRFD; shallow footings; codes; rationalization; shear failure criteria.

1. Introduction

Structural Design Philosophy and implementation to Codes of Practice has transformed from conventional Working Stress Method to Limit State Method - Load and Resistance Factor Design (ACI) or Partial Safety Factor approach (IS Code). Geotechnical Design Philosophy is in the transformation stage to implement Load and Resistance Factor Design (LRFD). IS 6403 provides guideline to calculate ultimate bearing capacity for shallow foundations. It gives bearing capacity factors and other factors viz. inclination factors, depth factors, shape factors etc. and accounts for the effect of water table. To calculate allowable bearing pressure, a Factor of Safety 2.50 is recommended separately by IS 1080. Eurocode 7 uses LRFD method and provides guideline for proportioning shallow foundations using partial safety factors for Action, Material Parameters and Resistance. The Action includes Dead Loads as well as Imposed Loads. Material Parameters includes shear parameters ‘c’ and ‘φ’ in drained and/or undrained state. The Resistance Factors are assigned based on the design methods used. For shallow foundations, three design approaches are considered, for which partial safety factors are given. In Euro Code 7, shear failure criteria is not considered for design as in case of IS Code. As per the AASHTO LRFD, resistance side of the equation is multiplied by the statistically based resistance factor, φ, whose value is usually less than one. As applied to the geotechnical design of substructures, φ accounts for factors such as weaker foundation soils than expected, poor construction of the foundations, and foundation materials such as concrete, steel or wood that may not completely satisfy the requirements in the specifications. Also the partial factors for different load cases and load combination has been provided to get the design action. When properly developed and applied, the LRFD approach provides a consistent level of safety for the design of all structure components.

Euro Code 7 uses three partial safety factors i.e. for load action, material parameter and resistance, while AASHTO uses two partial safety factors i.e. for load action and resistance. Unlike IS Code and AASHTO, Euro Code 7 does not consider any kind of shear failure criteria for SBC calculation. Thus, the design philosophies adopted by Euro Code 7 and AASHTO differs from that of IS Code, Safe Bearing Capacity for shallow footing calculated as per these codes widely differs from each other. Hence, in order to adopt Euro Code 7 LRFD design method for calculation of SBC of shallow footing, it has to be rationalized in order to have the consistent results with respect to IS Code results to incorporate the shear failure criteria given by IS.

2. Method

The safe bearing capacity of shallow foundation as per IS Code, EC 7 and AASHTO are calculated for various range of soil parameter (C and ϕ) for a strip and square footing with variation in size and depth of foundation on a soil with bulk density 18 kN/m^3 and FOS of 2.5 for IS design as follows

Table 1. Parametric study

Parameter	Variations
Cohesionless soil with ϕ	24º to 44º
Cohesive soil with C (kN/m^2) (at interval of 15)	Upto 200 kN/m^2
Size of strip footing, m^2	1 x 5 m^2 2 x 10 m^2 3 x 15 m^2

	4 x 20 m^2
Size of square footing, m^2	1 x 1 m^2 2 x 2 m^2 3 x 3 m^2 4 x 4 m^2
Depth of footing D_f, m	0 to 3 m

Since Euro Code 7 is silent about shear failure criteria, for the pure cohesionless and cohesive soil, two cases in Euro code design are considered as follow:
EC7 (I): Considering type of shear failure based on factored values of angle of friction.
EC7 (II): Without considering type of shear failure based on angle of friction and using general parameters for all values.
The results are obtained for all the problems in terms of Net Safe Load (kN). Also, the graphs of net safe load ratio i.e. EC7 (I)/IS and AASHTO/IS vs soil properties (C, ϕ) are plotted for varying D_f/B. Let this be considered as Case I: Partial safety factors applied to soil properties (C, ϕ) as prescribed by Euro Code provision.

2.1 Theoretical Formulation

2.1.1 Formulation as per IS 6403:1981

For General Shear Failure Criteria

$$q_{na} = \frac{1}{FOS} * C\, N_c\, d_c\, s_c\, i_c + q\,(N_q - 1)\, d_q\, s_q\, i_q + 0.5\, B\, \gamma\, N_\gamma\, d_\gamma\, s_\gamma\, i_\gamma\, W'$$

For Local Shear Failure Criteria

$$q_{na} = \frac{1}{FOS} * \frac{2}{3} C\, N'_c\, d_c\, s_c\, i_c + q\,(N'_q - 1)\, d_q\, s_q\, i_q + 0.5\, B\, \gamma\, N'_\gamma\, d_\gamma\, s_\gamma\, i_\gamma\, W'$$

Where,
q_{na} = Net allowable bearing pressure, kN/m^2
N_c, N_q, N_γ = Bearing capacity factors based on ϕ for general shear failure
N'_c, N'_q, N'_γ = Bearing capacity factors based on ϕ for local shear failure,
where, $\phi = \tan^{-1}(0.67\ \tan\phi)$
B = Width of footing
D = Depth of footing
γ = Unit weight of footing
W' = Effect of water table
d_c, d_q, d_γ = Depth factors
s_c, s_q, s_γ = Shape factors
i_c, i_q, i_γ = Inclination factors = 1 for vertical loads

Table 2. Shape Factors

Sr. No.	Shape of base	[illegible]	[illegible]	[illegible]
1	Continuous strip	1	1	1

2	Rectangle	1 + 0.2 B/L	1 + 0.2 B/L	1 - 0.4 B/L
3	Square	1.3	1.2	0.8
4	Circle	1.3	1.2	0.6

Table 3. Depth Factors

Sr. No.	Depth factor	
1	d_c	$1 + 0.2 (D/B) \sqrt{N_\phi}$
2	$d_q = d_\gamma$	1 for $\phi < 10$
3	$d_q = d_\gamma$	$1 + 0.1 (D/B) \sqrt{N_\phi}$ for $\phi > 10$

Table 4. Effect of Water Table

W′	1 if D_w [illegible] (D + B)
	0.5 if D_w [illegible] D & for GWT at and above footing level

For Mixed Shear Failure

$$q_{na} = \frac{1}{FOS} * C N''_c d_c s_c i_c + q (N''_q - 1) d_q s_q i_q + 0.5 B \gamma N''_\gamma d_\gamma s_\gamma i_\gamma W'$$

Where,

$$N''_c = N'_c + \left(\frac{N_c - N'_c}{8}\right) * \text{difference}$$

$$N''_q = N'_q + \left(\frac{N_q - N'_q}{8}\right) * \text{difference}$$

$$N''_\gamma = N'_\gamma + \left(\frac{N_\gamma - N'_\gamma}{8}\right) * \text{difference}$$

Difference = ϕ_m - 28º, ϕ_m =29º to 35º

2.1.2 Formulation as per Eurocode 7

ULS verifications are carried out with the three possible Design Approaches:
DA1 – Combination 1: A1 + M1 + R1
DA1 – Combination 2: A2 + M2 + R1
DA2: A1 + M1 + R2
DA3: (A1/A2)* + M2 + R3
*A1 is for Structural actions and A2 is for Geotechnical actions.

Table 5. L-M-R Combination for Shallow Foundation

Partial safety factor			
Design	Action	Material	Resistance

approach	Permanent load γ_G	Variable load γ_Q	Drained γ_ϕ, γ_C	Undrained γ_{Cu}	Bearing γ_{Rv}
DA1-C1	1.35	1.50	1.00	1.00	1.00
DA1-C2	1.00	1.30	1.25	1.40	1.00
DA2	1.35	1.50	1.00	1.00	1.40
DA3	1.00	1.30	1.25	1.40	1.00

For Drained Conditions:

The design bearing resistance is calculated as:

$$R/A' = C' N_c b_c s_c i_c + q' N_q b_q s_q i_q + 0.5 B' \gamma' N_\gamma b_\gamma s_\gamma i_\gamma$$

Where, $N_q = e^{\pi \tan \phi'} \tan^2(45 + \frac{\phi'}{2})$

$N_c = (N_q - 1) \cot \phi'$

$N_\gamma = 2(N_q - 1) \tan \phi'$

are dimensionless factors for bearing resistance and

b_c, b_q, b_γ = Inclination factors of the foundation base

s_c, s_q, s_γ = Shape factors of foundation

i_c, i_q, i_γ = Inclination factors of load

$A' = B' L'$ = Effective foundation area

Table 6. Shape Factor for Drained Condition

Shape factor	Value	Shape of footing
s_c	$(s_q N_q - 1)/(N_q - 1)$	Rectangular, square or circular
s_q	$1 + (B'/L') \sin \phi'$	Rectangular
	$1 + \sin \phi'$	Square or circular
s_γ	0.7	Square or circular
	$1 - 0.3 (B'/L')$	Rectangular

2.1.3 Formulation as per AASHTO

The AASHTO LRFD specifications prescribe the procedures used to compute loads and detail how to factor and combine the loads for comparing to the factored resistance.

For the present work, the partial safety factor for permanent and live load are considered as 1.25 and 1.75 respectively.

Bearing Resistance of soil :

The factored resistance, q_R, at the strength limit state shall be taken as:

$$q_R = \phi_b * q_n$$

Where,

ϕ_b = Resistance factor (taken as 0.45 as per AASHTO specifications for all soil)
q_n = Nominal bearing resistance (ksf) .

The nominal bearing resistance of a soil layer, in ksf, should be taken as:

$$q_n = C\,N_{cm} + q\,N_{qm}\,C_{wq} + 0.5\,B\,\gamma\,N_{\gamma m}\,C_{w\gamma}$$

in which,
$N_{cm} = N_c s_c i_c$
$N_{qm} = N_q d_q s_q i_q$
$N_{\gamma m} = N_\gamma s_\gamma i_\gamma$
Where,
N_c, N_q, N_γ = Bearing capacity factors
$N_c = (N_q - 1)\cot\phi$, (from Prandtl, 1921)
$N_q = e^{\pi \tan\phi} * \tan^2(45 + \frac{\phi}{2})$, (from Reissner, 1924)
$N_\gamma = 2(N_q + 1)\tan\phi$, (from Vesic, 1975)
C = Cohesion, (ksf)
Φ = Friction angle
B = Width of footing (ft)
D = Depth of footing (ft)
γ = Unit weight of footing (kcf)
C_{wq}, $C_{w\gamma}$ = Correction factor for GWT
d_q = Depth correction factor
s_c, s_q, s_γ = Shape correction factors
i_c, i_q, i_γ = Inclination factors = 1 for vertical loads

Table 7. Shape Correction Factor

Factor	Friction angle	Cohesion term (s_c)	Unit weight term (s_γ)	Surcharge term (s_q)
Shape factor s_c, s_q, s_γ	$\phi = 0$	$1 + (\frac{B}{5L})$	1	1
	$\phi > 0$	$1 + (\frac{B}{5L})(\frac{N_q}{N_c})$	$1 - 0.4\,(\frac{B}{L})$	$1 + (\frac{B}{L}\tan\phi)$

Table 8. Correction for Groundwater Depth

D_w (ground water depth)	C_{wq}	$C_{w\gamma}$
0	0.5	0.5
D_f	1	0.5
>1.5B + D_f	1	1

If local or punching shear failure is possible, the nominal bearing resistance shall be estimated using reduced shear strength parameters C* and Φ* in nominal bearing resistance equation. The reduced shear parameters may be taken as
C* = 0.67 C

$\Phi^* = \tan^{-1}(0.67\ \tan\phi)$

3. Results and Discussion

3.1 Results and Observation Obtained from Parametric Study.

Some representative results obtained from parametric study are shown below:

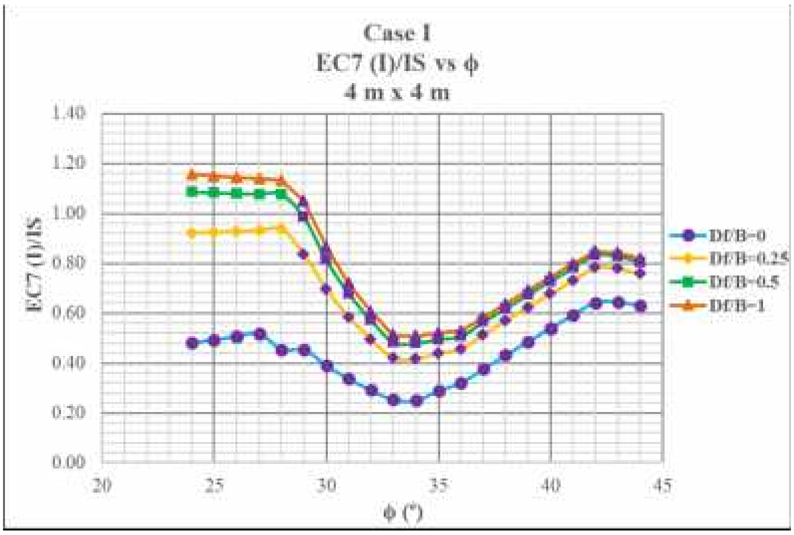

Fig. 1. Net safe load ratio vs ϕ for EC7 (I) Case I (4m x 4m)

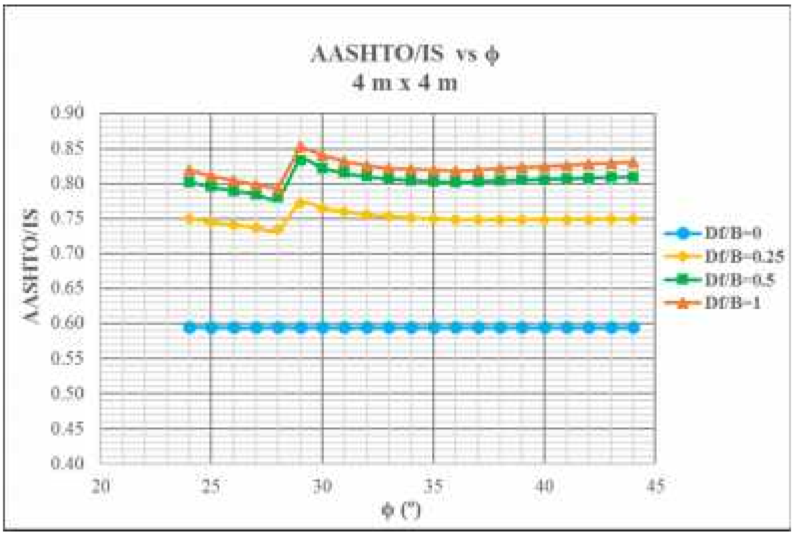

Fig. 2. Net safe load ratio vs ϕ for AASHTO (4m x 4m)

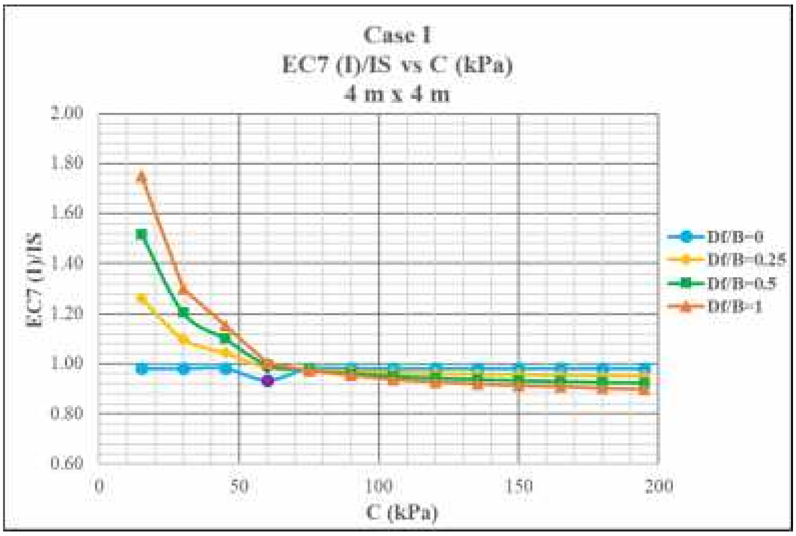

Fig. 3. Net safe load ratio vs C (kPa) for EC7 (I) Case I (4m x 4m)

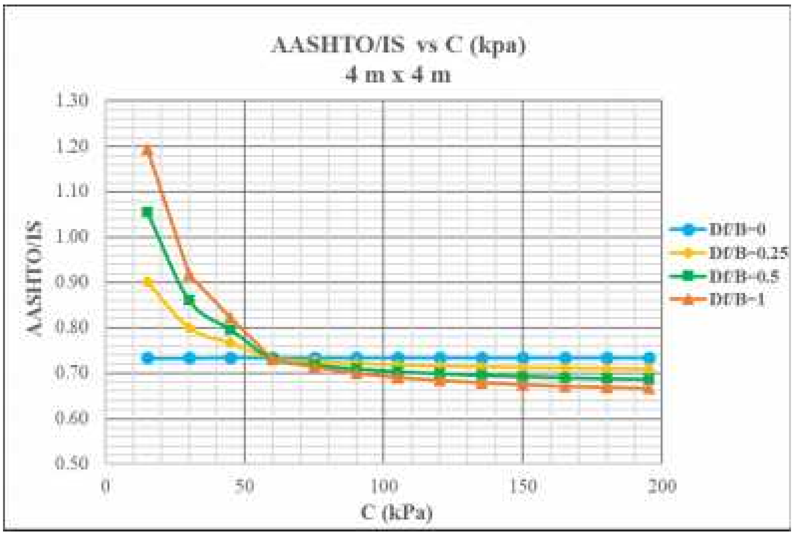

Fig. 4. Net safe load ratio vs C (kPa) for AASHTO (4m x 4m)

Note: In representation of graph for Euro Code, the below mentioned markers indicates design approach governed by DA1-C2, while other markers indicate DA2.

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Observation for ϕ soil:

- For square footing, net safe load obtained by EC7 (I) ranges from 0.25 to 1.19 times IS results with drop in value as 0.25 to 0.5 times IS values for ϕ = 29 to 35.
- Net safe load obtained by EC7 (II) are 2 to 3 times higher than IS results for both square and strip footing.
- For square footing, AASHTO gives consistent values as 0.6 times IS results for surface footing while it ranges from 0.75 to 0.83 times IS results for other depth of foundation.
- Similar trends were observed for strip footing.

Observation for C soil:

- For square footing, EC7 (I) gives consistent values of net safe load as 0.98 times IS results for surface footing while it ranges from 0.84 to 1.75 times IS results for other depth of foundation.
- For both square and strip footing, EC7 (I) shows drop in value of net safe load for C = 60 kPa as governing design approach changes from DA-2 to DA1-C2.
- Net safe load obtained by EC7 (II) are 2 to 2.5 times higher than IS results for both square and strip footing.

- For square footing, AASHTO gives consistent values as 0.73 times IS results for surface footing while it ranges from 0.63 to 1.20 times IS results for other depth of foundation.

3.2 Recommendation and Results Obtained from Revised Parametric Study:

On the basis of the above observation and as a part of rationalization, another case for Euro Code 7 is considered where partial safety factors are applied to bearing capacity factors (NC, Nq, Nγ) instead of material properties (C, ϕ) in order to incorporate the shear failure criteria in Euro Code design and to bring the results in considerable range with respect to IS Code design. Considering the above recommended case, the parametric study is repeated for all variations mentioned in table 1 to get the revised net safe load (kN). Let this be considered as Case II: Partial safety factors applied to bearing capacity factors (N_C, N_q, N_γ), recommended as a part of rationalization to incorporate shear failure criteria in Euro Code design. Some of the results obtained from this revised parametric study is shown below in order to compare with the results obtained from case I shown above.

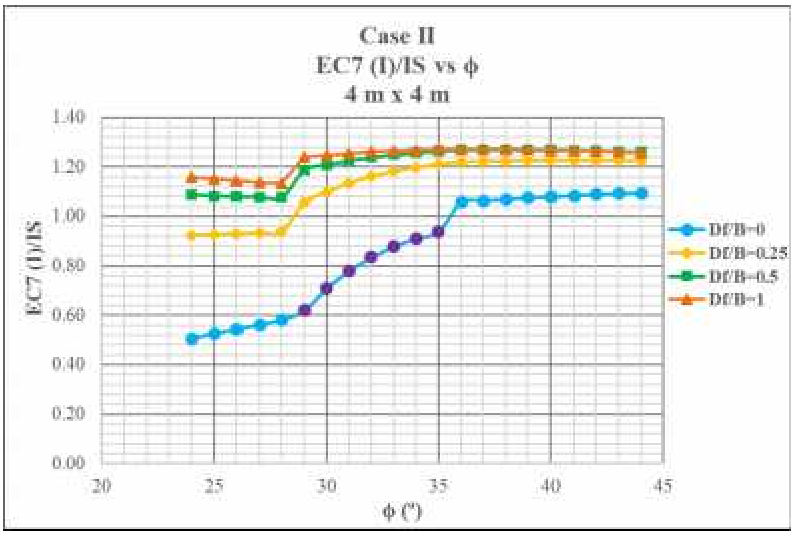

Fig. 5. Revised Net safe load ratio vs ϕ for EC7 (I) Case II (4m x 4m)

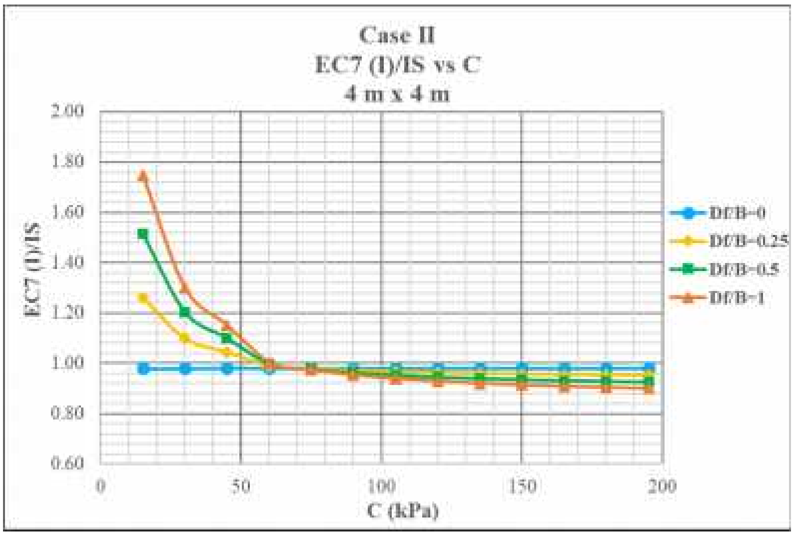

Fig. 6. Revised Net safe load ratio vs C (kPa) for EC7 (I) Case II (4m x 4m)

4. Observations Obtained From Revised Parametric Study:

For ϕ soil:

- For square footing, case I gives net safe load by EC7 (I) ranging from 0.25 to 1.19 times IS results, while case II gives this range as 0.98 to 1.25, thereby showing reasonable results of Euro Code with respect to IS Code.
- The drop observed in net safe load ratio EC7 (I)/IS obtained for ϕ = 29 to 35 for case I is removed by considering case II.
- For surface footing, net safe load ratio EC7 (I)/IS for case II varies from 0.51 to 0.62 for local shear failure, thereby showing the need of change in depth correction factor.
- The net safe load obtained from EC7 (II) are quite on higher side with respect to IS results for both case I and case II and hence, it is not advisable to consider EC7 (II) for design of shallow footing.
- AASHTO gives consistent values as 0.6 times IS results for surface footing while it ranges from 0.75 to 0.83 times IS results for other depth of foundation. The differences in results are due to the fact that the average factor of safety adopted by AASHTO is 3.15, whereas that of IS Code is 2.5.
- Similar trends were observed for strip footing as well with slight variation in net safe load ratio.

For C soil:

- There is no difference in results obtained by case I and case II for both square and strip footing.
- For both square and strip footing, EC7 (I) shows drop in value of net safe load for C = 60 kPa for case I as governing design approach changes from DA-2 to DA1-C2, while for case II, no such drop in value is observed as the governing design approach for case II is DA2.
- Net safe load obtained by EC7 (II) are 2 to 2.5 times higher than IS results for both square and strip footing designed by both case I and case II, which is not considerable.
- For square footing, AASHTO gives consistent values as 0.73 times IS results for surface footing while it ranges from 0.63 to 1.20 times IS results for other depth of foundation. For strip footing, AASHTO gives consistent values as 0.79 times IS results for surface footing while it ranges from 0.68 to 1.39 times IS results for other depth of foundation. The differences in results are due to the fact that the average factor of safety adopted by AASHTO is 3.15, whereas that of IS Code is 2.5.

Thus, from above all observations, it can be recommended that for Euro Code design, material partial safety factors must be applied to bearing capacity factors (NC, Nq, Nγ) instead of applying to material properties in order to incorporate the shear failure criteria for Euro design.

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