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Significance of bearing capacity of clayey subgrade in flexible pavement design

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Clays as subgrades pose serious problems to flexible pavements built over them as they retain moisture for a longer period and possess low strength. Excessive settlements along the wheel tracks on pavement surface and bearing capacity failures in the subgrade soil are often observed in the flexible pavements constructed over such subgrades. So, the present status of flexible pavements in clayey subgrades necessitates investigation into the design procedure. The present paper is intended to assess the adequacy of flexible pavement design thickness based on CBR method against possible risk of shear failure in subgrade soil. A design methodology for flexible pavements based on safe bearing capacity (SBC) of subgrade soil has been presented for evaluating the safety of pavements against shear failure risk. The pavement thickness designs have been carried out in clays of different compressibility from CBR and proposed SBC methods. Two case studies have also been presented wherein shear failure of subgrade has been noticed. Detailed discussion has been made and conclusions have been drawn for efficient design of flexible pavements.

Keywords: Clays; Bearing capacity; Shear failure; Flexible pavements; Subgrade soil; Soil intrusion

1. Introduction

Construction of flexible pavements over clayey subgrades has been a challenging task due to higher cost of construction and poor performance. Clayey soils have poor drainage and low strength in wet condition. The softened clay subgrades during rainy season lead to subsoil intrusion and penetration of subbase/base course material into subgrade under wheel loads. As a result, the designed pavements exhibit undulating surfaces and cracking along wheel tracks arising from excessive/differential settlements. At times, bearing capacity failures are also noticeable in such subgrade soils. So, review of existing flexible pavement building technology reveals that the design methodologies are not properly accounting for safety of subgrade soil. It is impressed by Saxena (1991) that most of the flexible pavement failures can be avoided by adequately designing the subgrade. Natarajan and Shanmukha Rao (1979) and Steinberg (1985) have reported that shear failures in clay subgrade soils occur in the edge regions of pavements due to ingress of moisture into subgrade. It is further reported by Patel and Qureshi (1979) that the chances for shear failure are more during rainy season in single lane pavements due to offtracking of vehicles during overtaking resulting from improperly designed shoulders.

Permanent pavement deformation results from densification and repetitive shear deformations of pavement component layers with considerable contribution from subgrade, particularly in clays (Saxena 1991, Koga *et al.* 2000). As excessive deformation resulting from densification can be handled by enforcement of compaction specifications, the second mechanism has been one of the basic distress modes upon which most of the pavement structural designs are based. CBR method, elastic layer theories, quasi-static and visco-elastic approaches are such design procedures based on empirical correlation of excessive deformations and predicted accumulated deformations in pavement systems (Hueklom and Klomp 1964, Yoder and Witczak 1975, Haas and Hudson 1978).

CBR method of flexible pavements, developed by California Division of Highways during 1928–1929 is a widely used method of design worldover. The test used in evaluation of CBR values has many limitations because of

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its empirical nature. Though CBR test considers the effect of overlying layers in the form of surcharge loading, the condition of subgrade soil in the edge region of pavement is not properly reflected. The other methods such as Group Index, Mc Leod, AASHTO (1993) have been developed mostly based on semi-theoretical procedures and observations of constructed pavements and do not really cover the aspect of avoiding shear failure risk of subgrade soil at the design stage.

The flexible pavement thickness design by CBR method is based on load–penetration behaviour of subgrade soil. The method appears to account for settlement failure of subgrade to some extent, but does not deal with the aspect of shear failure of subgrade soils. As clayey soils have increased chances of shear failure than settlement failure, the pavement design should also ensure safety against possible risk of shear failure in subgrade soil. So, in the present paper a methodology for flexible pavement design based on safe bearing capacity (SBC) of subgrade soil has been presented. The pavement thickness designs based on CBR method over clayey subgrades of different compressibility have been compared with the proposed SBC design methodology to assess the risk of bearing capacity failure in subgrade.

2. SBC method of design of flexible pavements

In the proposed SBC method of design, the design pavement thickness is determined by equating the vertical stress at subgrade due to dispersed wheel load and overburden to the permissible bearing capacity of subgrade soil. The assumptions involved in SBC based design methodology are:

(1) The SBC of subgrade soil is reduced by 20 percent to account for action of repetitive wheel loads, which may produce some impact due to uneven pavement surface and speed breakers.
(2) Pavement thickness design based on consideration of 80 percent SBC of subgrade soil is critical over the case of increasing static wheel loads by 15 percent.
(3) The loading due to moving vehicles in saturated clayey subgrades is taken equivalent to strip load since in saturated condition the excess pore water pressures do not get dissipated quickly. This will be more appropriate in case of heavy traffic pavements.
(4) The load bearing mechanism of pavement component layers is due to passive resistance offered by material of the layers under applied wheel loads and so 2:1 load dispersion is valid for dispersion of wheel load through the flexible pavement layers.
(5) The shape of contact area of tyre with pavement is considered as rectangular with two semi circular areas at the ends.
(6) The pavement width equivalent to dispersed width of wheel at subgrade level acts as a surface strip footing over weak subgrade soils, particularly saturated clays.
(7) Vesic's bearing capacity theory is valid for clayey subgrades.

Based on the above considerations, the design pavement thickness (h) can be calculated as

$$\frac{P_e}{(B+h)(L+h)} + \gamma_{av} \cdot h = 0.8 q_s$$

Where,

P_e is equivalent single wheel load, based on equal contact pressure.
B is effective tyre width taken in load dispersion = $b + s$.
b, L are width and length of tyre contact.
γ_{av} is average unit weight of pavement layers.
s is centre to centre distance of tyres.
q_s is SBC of soil.

3. Evaluation of CBR method of design from proposed SBC method of design

To check the adequacy of pavement thickness design from CBR method for safety against risk of bearing capacity failure in subgrade, clays of low, intermediate and high compressibility have been procured and their engineering properties have been evaluated from laboratory investigations as per standard codes of practice (ASTM 1997). The engineering properties of the soils are presented in table 1. The undrained shear parameters have been determined from Triaxial tests by testing specimens prepared under modified and standard proctor compaction conditions in saturated state for CL, CI and CH group soils (IS 1498 1970), respectively.

3.1 SBC method of design

The design pavement thickness values based on the consideration of risk of shear/bearing capacity failure have been evaluated for the clayey subgrade soils under the study using the procedure formulated based on SBC of subgrade soil. The SBC values have been evaluated using Vesic's theory under local shear failure conditions using a factor of safety of 2.5. The effect of overburden (surcharge) on bearing capacity of subgrade has not been taken into account as pavements are generally constructed at ground surface and serve as surface footings ($D_f = 0$). Shape, depth and inclination factors have been taken as unity in evaluation of SBC of subgrade soils. The average unit weight of pavement layer material has been taken as 22 kN/m^3. The contact area of the tyres has been taken to be of the shape formed by a rectangle with two semi-circular areas at the ends as shown in figure 1.

Considering a standard axle load of 10.2 tons with dual wheel configuration, the contact area has been evaluated and the width and length of contact area have been obtained as 17.7 and 29.5 cm for a tyre contact pressure as

Table 1. Engineering properties of clayey soils used in the study.

Engineering property	CL group soil			CI group soil			CH group soil		
	1	2	3	1	2	3	1	2	3
Specific gravity	2.68	2.66	2.69	2.67	2.71	2.69	2.69	2.70	2.63
Grain size analysis									
(a) Gravel (%)	1.5	0.8	3.2	2.0	3.2	1.2	2.0	1.4	3.2
(b) Sand (%)	38.2	46.2	37.2	32.5	43.8	27.6	18.6	24.0	29.2
(c) Fines (%)	60.3	52.8	59.6	65.5	53.0	71.2	79.4	74.6	67.6
Atterberg limits									
(a) Liquid limit (%)	33.6	30.9	29.1	40.2	38.0	43.1	82.5	74.3	66.7
(b) Plastic limit (%)	22.4	23.2	21.5	22.1	21.2	23.6	30.2	28.8	26.4
(c) Shrinkage limit (%)	18.5	19.4	19.6	19.1	19.8	18.5	9.8	10.3	12.1
Compaction characteristics									
(a) Optimum moisture content (%)	14.8	15.2	14.6	15.2	14.6	16.1	19.3	21.0	18.4
(b) Maximum dry density (g/cc)	1.77	1.83	1.86	1.71	2.01	1.88	1.58	1.61	1.65
Shear parameters									
(a) Cohesion (kN/m^2)	35.2	45.6	30.2	30.2	32.0	38.5	34.0	36.0	45.2
(b) Angle of internal friction	23°	20°	18°	12°	15°	10°	5°	3°	8°
Soaked CBR value (%)	6.2	7.5	5.8	3.5	5.1	3.2	1.2	1.4	2.1

5.62 kg/cm^2. The centre to centre distance of the tyres has been taken as 30 cm.

TRRL reports that the wheel loads of high speed vehicles showed an increase of up to 15 percent (Leonard *et al.* 1974). The SBC values are generally reduced by 20 percent for design of the foundations of structures subjected to repetitive or dynamic loads (Prakash 1981). So in the present work, design thickness values of flexible pavements have been determined considering increased wheel load as per TRRL using actual SBC of subgrade soil and actual wheel load using reduced SBC values. The obtained values of design thickness have been given in table 2.

Based on the results presented in table 2, it may be noticed that pavement design thickness based on 0.8 times SBC is governing the designs as it is critical over increased wheel load criteria. Hence, the design pavement thickness values based on reduced SBC values of subgrade soils have been used to evaluate risk of shear failure in subgrade of pavements designed from CBR method.

3.2 CBR method of design

The design pavement thickness values for flexible pavements based on CBR values of subgrades have been determined by using modified US army Corps of Engineers Formula (1961) given below.

$$h = (0.447 \log_{10} C + 0.305)\{P/(3.6045\,\mathrm{CBR}) + \mathrm{A}/(6.45\,\pi)\}^{0.5}$$

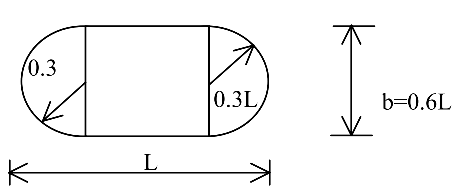

Figure 1. Shape of tyre contact area.

Where,

h is the design pavement thickness in cm.
C is the anticipated number of vehicle passes in terms of standard axles.
P is the equivalent single wheel load in kg.
A is contact area in cm^2.

For estimation of design pavement thickness values, 30 million standard axles were considered as vehicular traffic over a design period of 15 years and a standard axle load of 10,200 kg with dual wheel configuration and a tyre contact pressure of 5.62 kg/cm^2 have been taken. The design pavement thickness values obtained from CBR and SBC methods of design are presented in table 3.

4. Discussion

The strength characteristics of CH group subgrade soils are determined in standard proctor compaction condition since they are not heavily compacted to minimise swelling whereas strength characteristics of CL and CI group soils are determined in modified proctor compaction condition. It may be seen from table 3 that the pavement design

Table 2. Design pavement thickness from SBC and increased wheel load criteria.

Subgrade soil	Reduced SBC concept (cm)	Increased wheel load concept (cm)
CL group soil 1	34	27
CL group soil 2	26	21
CL group soil 3	61	52
CI group soil 1	90	73
CI group soil 2	68	60
CI group soil 3	70	61
CH group soil 1	Not possible	Not possible
CH group soil 2	Not possible	Not possible
CH group soil 3	95	76

Table 3. Comparison of pavement designs based on CBR and SBC approaches.

	CL group soil			CI group soil			CH group soil		
Pavement thickness (cm)	1	2	3	1	2	3	1	2	3
CBR approach	50	44	52	73	46	80	123	114	92
SBC approach	34	26	61	90	68	70	Not possible	Not possible	95

thickness based on SBC method of design is more than CBR method for CH group soil 3, whereas for CH group soils 1 and 2, it is not possible to have design thickness that is safe against risk of shear failure of subgrade. However, CBR method of design still gave pavement design thickness, which indicates that the design has the risk in terms of shear failure of subgrade. In CH group soils 1 and 2, at smaller thicknesses, vertical stress due to wheel loads is high and at higher thicknesses, the overburden pressure is more and so it is not possible to arrive at design pavement thickness safe against risk of shear failure in subgrade from SBC based design methodology. In such cases, either the strength of subgrade soil needs to be increased through chemical stabilisation and design can be carried out, or reinforced flexible pavement construction may be adopted. Apart from this, measures must be taken to suppress swell, if any, of the high compressible clays.

Coming to CI group clayey soils, it may be noticed from table 3 that only one soil out of the three soils under study has ensured safety against the risk of shear failure of subgrades when they were designed from CBR method of design. The pavement thickness design over clays of low compressibility is mostly governed by CBR method, but still there is also chance for shear failure as one soil under study indicated higher design pavement thickness based on SBC approach. Hence there is a need to check the CBR method of pavement design thickness for safety against possible risk of shear failure of subgrade, particularly in case of medium to high plastic clays. It is preferable to adopt higher design thickness values obtained from SBC and CBR approaches, to construct flexible pavements that are safe against the aspects of shear failure and excessive settlement in subgrade. However, in case of lime treated soils the risk against shear failure of subgrade may not be there and hence design based on CBR value of subgrade may be valid and used.

5. Case studies

The study has been extended to investigate the pavement failures that occurred in flexible pavements built over two clay subgrades. Shear failure of subgrade soil has been noticed in the roads of the Food Corporation of India, Kazipet (Case Study Area 1) leading to the godowns. The pavements have shown uneven surface with a number of undulations and large depressions along wheel tracks followed by side upheaval of pavement surface (figure 2). Also, the flexible pavements constructed over expansive soil at Hanamkonda (Case Study Area 2) have been found to have large number of surface undulations with signs of shear failure in the subgrade. The edge regions of the pavements have shown large depressions followed by upheaval of surrounding ground (figure 3). The problem has been observed to have recurring occurrence though the local authorities are taking up steps to level the surface. Some portion of the pavements have shown slight upheaval of ground due to swelling where there was only limited traffic.

Investigations have been carried out to determine the causes for failure of the pavements. Field pits were made to physically verify the existing pavement sections and the materials used in subbase and base layers. Undisturbed and disturbed samples have been collected from the bituminous surface, subbase course and subgrade for laboratory analysis. Aggregates used in the water bound macadam base courses have also been collected for assessing their quality. The engineering properties of subgrade soils, subbase material and aggregate used in base courses at the case study areas obtained from the laboratory investigations are presented in tables 4–7. The details of existing pavement component layers have been noted from the exposed sides of field pits. The details of existing double lane pavement at study area 1 and single lane pavements at study area 2 are given in table 8.

The engineering properties of subgrade soils presented in table 4 reveal that subgrade at study areas 1 and 2 are clays of intermediate and high compressibility,

Figure 2. Shear failure of flexible pavements noticed along wheel tracks at case study area 1.

Figure 3. Shear failure of subgrade in edge region of flexible pavement at case study area 2.

respectively. Further, it has been observed that subgrade at study area 2 has marginal swelling ability as it is found to have free swell index of 60 percent in laboratory testing. Referring to table 5, it can be seen that the soils used in subbase courses of pavements are meeting the requirements of strength (CBR $>$ 20%) and plasticity ($<$6%) as per Ministry of Surface Transport, Government of India specifications (MOST 1998). The *in-situ* dry density values of subgrade soils and subbase material presented in tables 4 and 5 indicate that the degree of compaction is above 95 percent and hence compaction of the material is satisfactory. Tables 6 and 7 infer that the quality of aggregate used in base courses of pavements is good. It has been observed that material used for subbase has been used as screening–binding material in aggregate base layers of the pavements. The estimated quantities of screening–binding material in base courses of pavements at case study areas 1 and 2 were 0.19 and 0.21 m^3, respectively per 10 m^2 area for a compacted base layer of 75 mm thick. The core samples of 15 × 15 × 5 cm^3 size were collected from the existing bituminous surface layers and bitumen extraction tests were conducted. The bitumen percentages in the mixes were observed to be 4.7 and 4.2, respectively, at study areas 1 and 2 and the grade of bitumen used was found to be 80/100, which mean that the quantity and quality of bitumen used are satisfactory. As quality of pavement construction as well as materials of construction was found to be satisfactory, the pavement thickness adopted at study areas have been evaluated for safety against risk of shear failure in subgrade. For this, the design pavement thickness requirement over the clayey subgrades have been determined from the CBR and proposed SBC approaches and are presented in table 9.

Table 4. Properties of subgrade soils at study areas.

S. No.	Engineering property	Case study area Soil 1	Case study area Soil 2
1	Specific gravity	2.66	2.69
2	Grain size analysis		
	(a) Gravel (%)	3.0	4.0
	(b) Sand (%)	35.5	37.5
	(c) Fines (%)	61.5	58.5
3	Atterberg limits		
	(a) Liquid limit (%)	45.2	66.5
	(b) Plastic limit (%)	22.3	27.6
	(c) Shrinkage limit (%)	17.8	13.9
4	IS classification symbol	CI	CH
5	Compaction characteristics (from standard proctor test)		
	(a) Optimum moisture content (%)	12.3	17.9
	(b) Maximum dry density (g/cc)	1.78	1.61
6	Soaked CBR value (%)	3.3	2.6
7	Shear parameters		
	(a) Cohesion (kN/m^2)	26.2	26
	(b) Angle of internal friction	16°	12°
8	*In-situ* dry density (g/cc)	1.72	1.54
9	*In-situ* moisture content (%)	28.2	40.1

Table 5. Properties of subbase material at study areas.

S. No.	Engineering property	Study area 1	Study area 2
1	Specific gravity	2.66	2.68
2	Grain size analysis		
	(a) Gravel (%)	29.5	32.5
	(b) Sand (%)	42.3	45.2
	(c) Fines (%)	28.2	22.3
3	Plasticity characteristics		
	(a) Liquid limit (%)	23.7	24.4
	(b) Plastic limit (%)	19.2	20.1
	(c) Plasticity index (%)	4.5	4.3
4	Compaction characteristics (from modified proctor test)		
	(a) Optimum moisture content (%)	7.8	7.2
	(b) Maximum dry density (g/cc)	1.98	2.03
5	Soaked CBR value (%)	23.1	26.1
6	*In-situ* dry density (g/cc)	1.91	1.95

Table 6. Gradation characteristics of aggregate used in base courses of pavements at study areas.

Sieve size (mm)	Percent passing by weight	
	Case study area 1	Case study area 2
90	100	100
63	98	100
53	65	58
45	13	12
22.4	2	0

Table 7. Engineering properties of aggregate used in base courses of pavements at study areas.

S. No.	Property	Case study area 1	Case study area 2
1	Specific gravity	2.83	2.81
2	Water absorption value (%)	0.10	0.12
3	Aggregate impact value (%)	18.2	18.8
4	Aggregate crushing value (%)	24.4	23.8
5	Los Angels abrasion value (%)	14.6	15.0

both case study areas is inadequate to protect the subgrade soils from risk of shear failure.

6. Conclusions

Unlike other pavement structural materials, soil subgrade is a highly variable material and is subjected to changes in hostile environments. So, it is essential to have reasonable safety against risk of shear failure, besides controlling settlement in pavement design methodologies for construction of durable and efficient pavements. As the designs of pavements over clayey subgrades based on CBR method are indicating chances of shear failure in subgrade, the design pavement thickness needs to be checked for safety against risk of shear failure of subgrade and a decision taken accordingly on safe design of pavement thickness. Pavements are to be constructed by adopting higher values of design thickness obtained from SBC and CBR methods to keep them safe against shear failures and excessive settlements in subgrades. The case studies presented revealed the occurrence of shear failure prior to design life of the pavements. As the required design pavement thickness values for safety against shear and settlement failures are high and also, there are chances for mixing of subgrade and subbase materials, it will be advantageous to adopt geofabric reinforced flexible pavements.

Table 8. Details of existing pavements at study areas.

Case study area	Pavement thickness (cm)	Bituminous surface (cm)	WBM base layer (cm)	Moorum subbase layer (cm)
1	66	5	25	36
2	60	5	25	30

In CBR approach, the design thickness has been calculated by taking 150 commercial vehicles a day at study area 1 and 50 commercial vehicles a day with an annual traffic growth rate of 5 percent. Considering vehicle damage and traffic distribution factors as per Indian Standard code of practice (IRC 2000), the design traffic has been estimated to be 10 and 2 million standard axles at study areas 1 and 2, respectively, for a design period of 15 years. In designs, a standard axle load of 10,200 kg with dual wheel configuration has been considered.

Based on the design thickness values presented in table 9, it can be seen that the pavement design thickness values based on CBR method are less than that required from SBC method. So, the existing pavement thickness at

Table 9. Requirement of design pavement thickness over subgrade soil at study areas.

Case study area	Design pavement thickness (cm)	
	CBR approach	SBC approach
1	67.2	78.0
2	62.8	80.0

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