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Development of methodology for design of grade slab using numerical approach

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Abstract: Presently, the design of grade slab for heavy industrial floors is generally carried out by empirical approaches, as provided in different national or international literature. With advances in numerical methods and computational resources, efforts have been made to apply numerical approaches in analysis of grade slab or pavements; however, such applications have been primarily restricted to the research area. For practical industrial implementation, numerical analysis methodology for design of grade slab is scarce in literature. In this article, a methodology for analysis of grade slab for practical design is developed with parametric analysis using commercial finite element software SAP2000®. The results are compared with empirical approaches for validation. The method proposed would be useful for practicing engineers for the design of grade slabs using numerical analysis.

Keywords: Grade slab; Empirical approach; Numerical approach; Design methodology.

1. Introduction

A slab fully supported by soil below is known as a grade slab. This type of slab is preferred for the ground floor of industrial buildings where heavy loading or machinery is supported. The advantage of providing a grade slab is that the load is transferred directly to the founding media (through the foundation, in certain cases), bypassing the structural system. The construction of grade slab also provides flexibility in the sequence, and this can be suited to the particular project schedule. The junctions between the grade slab and the reinforced concrete (RC) structure are provided with paper joints such that there would be no load transfer from the grade slab to the structure, allowing some expansion that might occur due to thermal gradients, etc. Traditionally, the thickness of the grade slab was designed using the empirical approaches, and then nominal reinforcement was provided to take care of the tensile stresses arising out of shrinkage, thermal gradients, etc. There are a few design guidelines available in the literature for design of grade slab.

American Concrete Institute guidelines on design of slab on ground, reinforced for structural action [1] suggests three approaches, namely, the Corps of Engineers (COE) method (included in [2]), the PCA method (same as [3]), and a third approach called Wire Reinforcement Institute (WRI) method. United States Army and Air Force developed their guidelines for design of grade slab for heavy loads based on experiments conducted at their facilities [2]. As some nominal reinforcement is always provided in grade slabs supporting heavy loads, though they might not be designed as reinforced concrete slab, some reduction in thickness can be made possible by taking advantage of the provided reinforcing bars. This aspect was addressed in the TM / AFM [2] and a nomogram was provided for this purpose. Packard [3] developed a set of guidelines for the design of grade slab based on the experiments conducted at the Portland Cement Association (PCA) and this is another useful reference for this purpose. The third (WRI) method is chart based, involving approximations and unit conversions and hence is not considered in this study. Thus, out of the three methods suggested by ACI 360R-10 [1], the first two are covered in this study.

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In India, extensive studies were conducted at the Central Building Research Institute (CBRI) and from the results of these studies Chetty et al. [4] presented the design guidelines for grade slab. For the uniformly distributed load (UDL), Chetty et al. [4] provided equations as well as tables for ready reference. A report [5] presented the design guidelines for grade slab, and this appears to have originated from the same studies at CBRI (as [4]) and is by and large, same. However, there is no design code or standard for design of grade slab in India till date. Furthermore, the available guidelines [4,5] are more than 40 years old and revisions in the code of practice for concrete [6] since then have not been incorporated in those guidelines. Comparison of the design of grade slab using these different references could bring out new insights about the behaviour of grade slab and the various aspects of design.

There have been many applications of numerical modelling in grade slab or pavement research over the years, and a few of them are discussed. ACI 360R-10 [1] suggests that numerical methods offer a good potential for complex analysis, but, its use in practical design has been limited. Chuangchid and Krarti [7] employed numerical model to analyse three-dimensional steady-state heat transfer problem for slab on grade foundation. The total heat loss from the slab was found to be strongly influenced by size of slab and its thermal characteristics, whereas the depth of water table had little effect. Kim and Nelson [8] discussed experimental results with numerical analysis of plain cement concrete (PCC) overlays on PCC grade slab for climatic loading. They presented two-dimensional and three-dimensional models and examined the sensitivity of performance with respect to elastic modulus, slab length, thickness, and coefficient of thermal expansion, on the interfacial shear and normal stresses. The developed model was incorporated in software for application. Fredlund et al. [9] attempted to analyse the grade slab for residential buildings on expansive soils, where the deformations are mostly due to the matric suction. They used finite element method to examine the various aspects of the complex stress-cum-seepage analysis. Aure and Ioannides [10] presented numerical analysis of the fracture process of concrete pavements, for which they employed special cohesive finite elements. They considered only internal loading condition and indicated future scope of extending this methodology for other loads and finally into design procedure of pavements, as an improvement over the empirical-mechanistic design approach. Skar et al. [11] presented cohesive crack-hinge model for simulation of fracture in one-way grade slab along with a two-parameter model of founding media. Compared to the traditional cohesive zone model, the proposed model was found to be attractive for further development and implementation. Analysis of heat of hydration in grade slab constructed with limestone blended cement was presented by Tahersima and Tikalsky [12] using finite element approach, and was validated with experimental results. They presented the design data which can be later used by the designers for heat of hydration calculations for such slabs. Tiberti et al. [13] examined the cracking susceptibility of grade slab due to shrinkage of concrete with glass microfibre using numerical modelling technique, for various slab dimensions and sub-grade conditions. Sucharda et al. [14] examined the punching shear capacity of ground supported slab with numerical modelling with non-linear analysis and application of fracture-plastic model. The void beneath ground supported slab and the load transfer efficiency of the joints affect the overall load carrying capacity and these factors were investigated by Liu et al. [15] with finite element analysis. The aspect of void below pavement was explored with numerical analysis by Puri and Toyeb [16] as well. Curling of ground supported slabs caused by differential shrinkage could lead to deterioration such as cracking of slab. Short term and long-term curling estimates were reported by Jaafri et al. [17] using discrete element formulation and with the proposed approach, good performance was obtained for both the kinetics and magnitude of curling. The issue of differential settlement was also examined for slab track using a three-dimensional model based on damage mechanics theory [18].

In the last few decades, with the advances of the computation power and knowledge of numerical methods of analysis, the state-of-the-art structural analysis is invariably performed with finite element models. It is high time that the finite element approach is applied for analysis and design of grade slab as well. The methodologies for generation of the finite element model, application of loads, analysis and design are well established for structural systems in industrial applications. For research purposes, numerical modelling of grade slab has found many applications, as discussed above. However, in case of grade slab, such methodologies for application in practical engineering problems are scarce in literature. Methodology and guidelines for analysis and design of grade slab using finite element models would be extremely useful to upgrade the state-of-the-art for grade slab design. With this objective, numerical experimentations have been performed in SAP2000® [19] to arrive at analysis and design guidelines for grade slab using numerical analysis. Comparison of the design thickness of grade slab between empirical and numerical approaches is also presented in the article.

2. Data and methodology

2.1 Design data

The data essential for design of grade slab are the modulus of sub-grade reaction (k), the grade of concrete, and the intensity of the UDL. The modulus of sub-grade reaction is estimated from field tests (plate load test) or correlation with some soil property (liquid limit, compression index) determined from laboratory tests, as convenient. For filled-up soil, the minimum available k-value for Indian conditions is 3 kg/cm^3 [4]. This value of modulus of sub-grade reaction has been adopted for the case study in this article. The grade of concrete determines the tensile strength of concrete, which in turn determines the allowable tensile stress in concrete for grade slab design. The modulus of elasticity can also be estimated from the grade of concrete. The calculations have been performed for three grades of concrete for comparison, namely, M30, M45, and M60 [6], wherein the numbers indicate the characteristic compressive strength of the concrete in MPa. The intensity of UDL is another input for design of the grade slab, and for this present demonstration, an intensity of UDL has been considered as 7 T/m^2 (or 0.7 kg/cm^2).

Generally, sub-base is provided below the grade slab in the form of brick soling, plain cement concrete (PCC), rubble packing, gravel packing, or other materials, or a combination of more than one of those. Sub-base help to drain off the water below the grade slab and ensures a firm support to the grade slab all around. Essentially, providing sub-base results in improvement of the modulus of sub-grade reaction, and depending on the provided sub-base, for Indian materials and practice, improvement factors ranging from 1.33 to 3.61 have been suggested [4,5]. However, according to literature [3], for distributed heavy loads covering large areas, the k-value for the sub-grade and not the k-value at top of sub-base should be considered. Hence, in this study, two cases are considered for comparison: first where improvement of k-value due to sub-base is not considered and modulus of sub-grade reaction is 3.00 kg/cm^3; second where an improvement factor of 1.36 is considered and modulus of sub-grade reaction is 4.08 kg/cm^3.The respective margins in the k-value would help to offset the decrease in modulus of sub-grade reaction on account of variations of moisture content, insufficient compaction, loose pockets, long-term settlement differentials, etc.

Another input data required for determination of thickness of grade slab is the allowable tensile stress in concrete. According to Indian standard for concrete design [6], the modulus of elasticity of concrete (E in MPa) can be taken as Eq. 1 and the modulus of rupture of concrete (σ_R in MPa) can be taken as Eq. 2 below:

$$E = 5000 \times \sqrt{f_{ck}} \tag{1}$$

$$\sigma_R = 0.7 \times \sqrt{f_{ck}} \tag{2}$$

Where, f_{ck} is the characteristic compressive strength of concrete in MPa (given by the grade of concrete).

For this study, three grades of concrete have been considered, namely, M30, M45, and M60, for which the corresponding characteristic strength values are 30 MPa, 45 MPa, and 60 MPa respectively. Thus, the modulus of elasticity for M30, M45, and M60 is calculated as 273860 kg/cm^2, 335410 kg/cm^2, and 387300 kg/cm^2 respectively. And, the modulus of rupture works out to be 38.34 kg/cm^2, 46.96 kg/cm^2, and 54.22 kg/cm^2 for M30, M45 and M60 respectively. To obtain the allowable tensile stress in concrete, the modulus of rupture is divided by a factor of safety (FOS) to account for the uncertainties in the concrete strength, imposed loads, impact and fatigue effects, temperature effects (if not separately considered), etc. The various guidelines regarding the FOS in literature include that of 2.0 [2,4,5] and 1.4 to 2.0 [3]. Generally, for industrial floors designed for heavy loads, a FOS of 2.0 is adopted and the same has been considered in this study as well. Thereby the allowable tensile stress in extreme fibre of concrete works out to be 19.17 kg/cm^2, 23.48 kg/cm^2, and 27.11 kg/cm^2 respectively for M30, M45 and M60 grades of concrete. These values have been considered in the subsequent sections for the design of the thickness of grade slab.

2.2 Methodology

To start with the grade slab is designed according to the empirical formulations available in literature, for the different grades of concrete and modulus of sub-grade reaction of the sub-soil and the results are compared. The empirical formulations inherently provide design of grade slab for a particular critical loading dimension and position, as determined by the respective authors / standards. Subsequently, numerical analysis using commercial finite element package SAP2000® [19] is undertaken for designing the grade slab with the same set of variables. For numerical approach of design, the various considerations would be the loading pattern and dimension, as well as the design limit state. These are methodically examined to arrive at a consolidated design guideline for grade slab using numerical approach. The design results obtained from numerical analysis are compared with the corresponding empirical formulations. More details of the approaches would be discussed in subsequent sections, along with the results.

Different references provided the formulations in different units and they have been converted to the units listed in Table 1. For this study, unless otherwise noted, the adopted units would be as listed in Table 1.

Table 1 – List of variables, symbols, and units

Variable	Symbol	Unit
Modulus of sub-grade reaction	k	kg/cm^3
Depth of grade slab	h	cm
Allowable stress in concrete	σ_t	kg/cm^2
Modulus of elasticity / rupture of concrete	E / σ_R	kg/cm^2
Characteristic strength of concrete	f_{ck}	kg/cm^2
UDL	P_u	kg/cm^2

3. Results and discussions

3.1 Design of grade slab using empirical approach

3.1.1 Design formulations

<u>Chetty et al. [4] and Unwalia [5]</u>

In the article by Chetty et al. [4] and the report by Unwalia [5], same two formulations for determination of the thickness of the grade slab were presented, and they are reproduced below:

$$h = \left(0.1201\frac{P_u}{\sigma_t}\right)^2 \times \frac{E}{k} \tag{3}$$

$$h = \frac{1}{k} \times \left(\frac{P_u}{0.26}\right)^2 \tag{4}$$

<u>TM / AFM [2] (Also included in [1])</u>

The formulations in the original document had been provided in foot-pound system (FPS) units and the same has been converted for uniformity of units for all the formulations presented in this article.

$$h = \frac{E}{k} \times \left(\frac{P_u}{1.7908 \times \sigma_t}\right)^2 \tag{5}$$

<u>Packard [3] (Also included in [1])</u>

Similar to Eq. 5, the expression from Packard [3] had been provided in FPS units and this has also been converted for uniformity of units in this article.

$$h = \frac{1}{k} \times \left(\frac{310.32 \times P_u}{\sigma_t}\right)^2 \tag{6}$$

3.1.2 Results of design of grade slab using empirical approach

The results of the empirical design are presented in tabular form for the different grades of concrete and UDL of 7 T/m^2 (or 0.70 kg/cm^2) with modulus of sub-grade reaction as 3.00 kg/cm^3 and 4.08 kg/cm^3 in Table 2. The values of the depth of grade slab calculated according to the equations (no. 3 to no. 6) are tabulated in 'cm' in Table 2 corresponding to the modulus of sub-grade reaction and grade of concrete. In all cases, except for Eq. 4, which does not consider the concrete strength in calculation of thickness of grade slab, the increase in grade of concrete results in decrease of required thickness, which is according to expectations. Similarly, with increase in modulus of sub-grade reaction, the required thickness of grade slab decreases, and this is also as expected.

Table 2 – Thickness (cm) of grade slab from empirical approaches designed for uniformly distributed load of 0.70 kg/cm^2

Grade of concrete	Modulus of sub-grade reaction (kg/cm^3)							
	3.00				4.08			
	Eq. 3	Eq. 4	Eq. 5	Eq. 6	Eq. 3	Eq. 4	Eq. 5	Eq. 6
M30	1.76	2.42	37.98	42.83	1.29	1.78	27.92	31.49
M45	1.43		31.00	28.55	1.05		22.80	20.99
M60	1.24		26.85	21.41	0.91		19.75	15.75

3.1.3 Comparison of empirical approaches

The formulations by Packard [3] yields the highest thickness for M30 grade~~s~~ of concrete, followed by the TM / AFM [2] and the minimum thickness being given by the formulations by Chetty et al. [4] and Unwalia [5]. Whereas Eq. 3 and Eq. 5 considers the modulus of elasticity of concrete and the allowable tensile stress of concrete in addition to the UDL and the modulus of sub-grade reaction for design of the thickness of grade slab, Eq. 6 does not consider the modulus of elasticity, and Eq. 4 ignores the allowable tensile stress of concrete as well. Thus, Eq. 4 results in the same thickness of grade slab for any grade of concrete, and this is a limitation of the formulation. The tensile stress developed in grade slab would be dependent on the deformation of the slab under load, and there the modulus of elasticity would definitely play a role. TM / AFM [2] considers this effect and thus results in different slab depth as compared to Packard [3] where the modulus of elasticity of concrete is not considered. In case of Chetty et al. [4] and Unwalia [5] formulations, the authors considered the grade slab to be uniformly supported at bottom by the sub-grade and thus arrived at the thickness which was independent of the grade of concrete (Eq. 4). This is a strict ideal condition and may have possibly resulted in the very low thickness of the grade slab.

The large difference in the design depth according to Eq. 3 (or 4) and Eq. 5 (or 6) could be due to the variations in the experimental conditions, on which the respective empirical equations were developed. Use of well-prepared and good sub-grade in the experiments conducted for development of Eq. 3 or Eq. 4 could have resulted in the minimal thickness requirement for the uniformly distributed loading condition.

3.2 Design of grade slab with numerical approach

3.2.1 Numerical modelling

The design of grade slab is performed in the numerical approach with the same design data (uniform intensity of loading, material properties, etc.) discussed in Section 2.1. Finite Element (FE) software package SAP 2000® [19] is used for modelling and analysis of grade slab. Grade slab is modelled as a thin shell element resting on a backfill soil. For numerical design approach results are presented for M30, M45 and M60 grade of concrete and these results are compared with the corresponding results of empirical design approach. As the external loading is acting only in vertical gravity direction (z-direction), only vertical translation springs, capable of resisting only compression load, are modelled below the grade slab for simulation of the boundary condition. Movement of slab is restricted in horizontal directions by applying restraint against translation to peripheral nodes. The numerical design of the grade slab is performed in two stages, as discussed in following sub-sections.

3.2.2 Identification of critical loading pattern/s

Approach

In case the grade slab is uniformly loaded and uniformly supported below, then there is no bending stress developed in concrete. But this ideal condition seldom exists in reality. In empirical approaches, the critical loading pattern is identified by differentiation. In the numerical approach, this is proposed to be performed by trials, and seven various possible patterns have been identified for examining the stress and deflection in concrete (Fig. 1). For this purpose, a representative square panel size of 6m has been considered and UDL is applied in seven different arrangements. For this analysis concrete grade of M30 and slab thickness of 200mm is considered.

In Fig. 1, the square panel has been divided into nine equal smaller square areas, the hatched smaller areas denoting the loaded portion of the entire panel. The maximum principal tensile stresses produced within the slab for each loading pattern, along with the maximum deflection are recorded. The contour plots of the maximum stress and deflection are also examined.

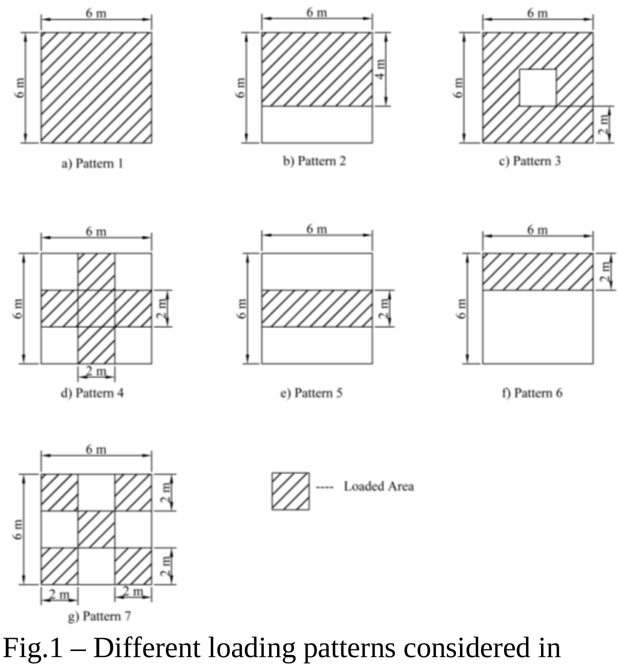
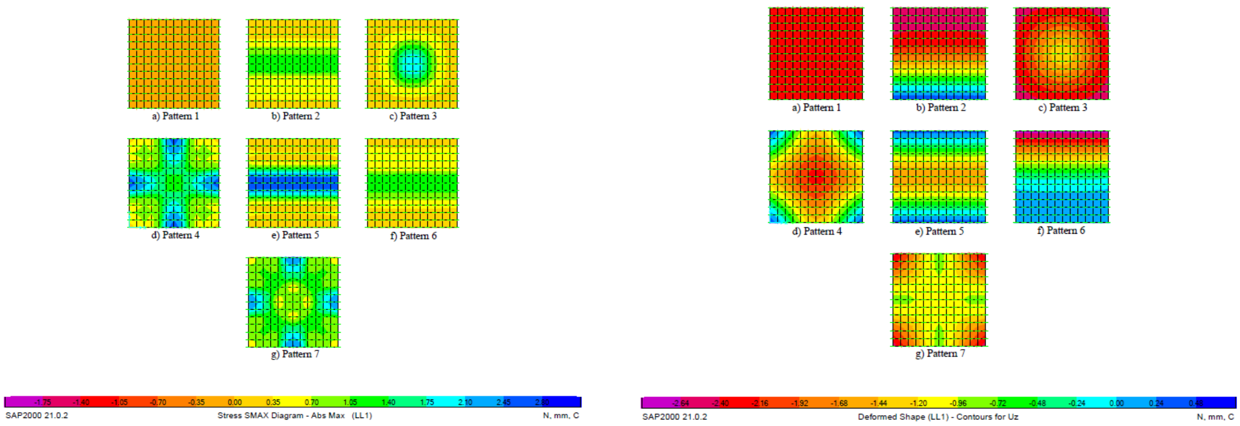


Fig.1 – Different loading patterns considered in numerical analysis of grade slab panel

Results of identification of critical loading pattern

For the purpose of identification of the critical loading pattern, first the stress and deflection contours are examined for all the patterns and these are presented in Fig. 2 for modulus of sub-grade reaction value of 3 kg/cm^3. Exactly similar patterns were observed for modulus of sub-grade reaction value of 4.08 kg/cm^3 as well and they are not included for brevity. The stress and deflection patterns are consistent with the corresponding loading patterns. As expected, the maximum stresses generated in concrete reduced with the increase in modulus of sub-grade reaction, thereby allowing lower thickness of grade slab with other conditions remaining same.

The loading pattern 1 (total area loaded) produced minimum stress and high deflection in concrete. The comparison of the maximum values of stress and deflection are presented in Fig. 3(a) and Fig. 3(b) respectively. It is observed that the stress is high in loading patterns 4, 5, and 7 (within 10% of the maximum) for both values of modulus of sub-grade reaction, whereas the deflection is high for loading patterns 3, 6 and 7 (within 10% of the maximum) – again this is observed for both values of modulus of sub-grade reaction accordingly.



(a) Stress contour (b) Deflection contour

Fig. 2 – Contours for different loading patterns (modulus of sub-grade reaction of 3.00 kg/cm3)

Recommendations for identification of critical loading pattern

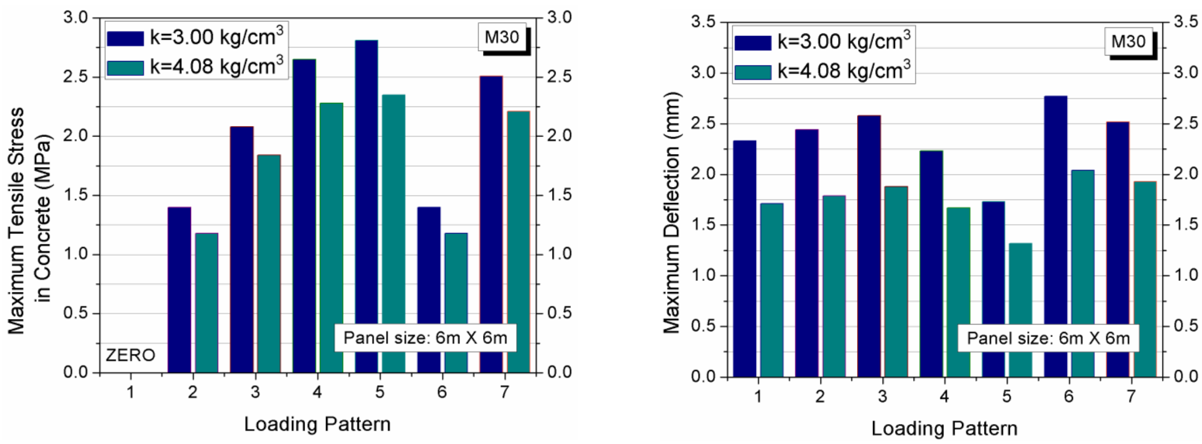
It is possible that the loading patterns with less than 10% difference from the maximum, observed for this panel dimension, could become the maximum for a panel of different dimensions. Hence, for the grade slab with stress as the design criterion, the loading patterns 4, 5, and 7 should be further explored, whereas for the grade slab with deflection as the design criterion, the loading patterns 3, 6, and 7 should be examined in more detail.

3.2.3 Identification of critical loading dimensions

Approach

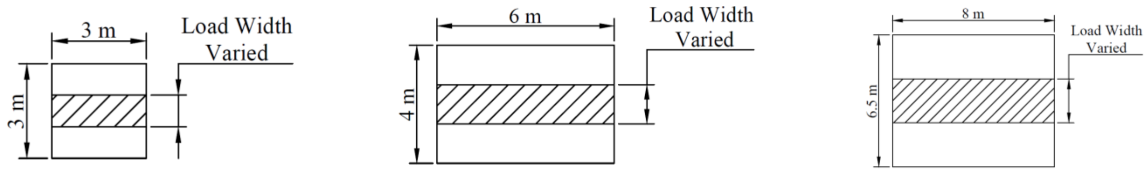
In the earlier exercise, the dimensions of loaded area were considered as one-third of the panel width. Once the loading pattern is fixed, the critical dimensions of the loaded area for design ~~need~~ of grade slab needs to be identified. Further, for different panel dimensions, this critical dimension value might vary. Hence, the study is presently expanded to include three different panels of sizes 3m × 3m, 4m × 6m, and 6.5m × 8m (Fig. 4) and considering stress as the design criterion, one loading pattern: Pattern 5 (as selected in Section 3.2.2) is applied on each slab. For identification of the critical loading dimension, the width of loaded area is varied for all three slab panels and stresses produced within the slab are noted for every case.

Load width for which absolute maximum stress occurs in the slab would be the critical load dimensions for that slab panel. This exercise is performed for a variety of slab thicknesses (200 mm, 250 mm, 300 mm, 350 mm, 400 mm, 450 mm and 500 mm) and absolute stress values are compared with permissible tensile stress till the absolute stress in the grade slab comes below the allowable tensile stress for concrete. Design thickness of slab would be identified as the minimum slab thickness for which absolute stress value becomes less than the permissible stress value.



Stress Deflection

Fig. 3 – Maximum responses for different loading patterns and modulus of sub-grade reaction



(a) Panel size 3 m × 3 m (b) Panel size 4 m × 6 m (c) Panel size 6.5 m × 8 m

Fig. 4 – Variation of the loading width in loading pattern 5 for identification of the critical loading width for various panel sizes

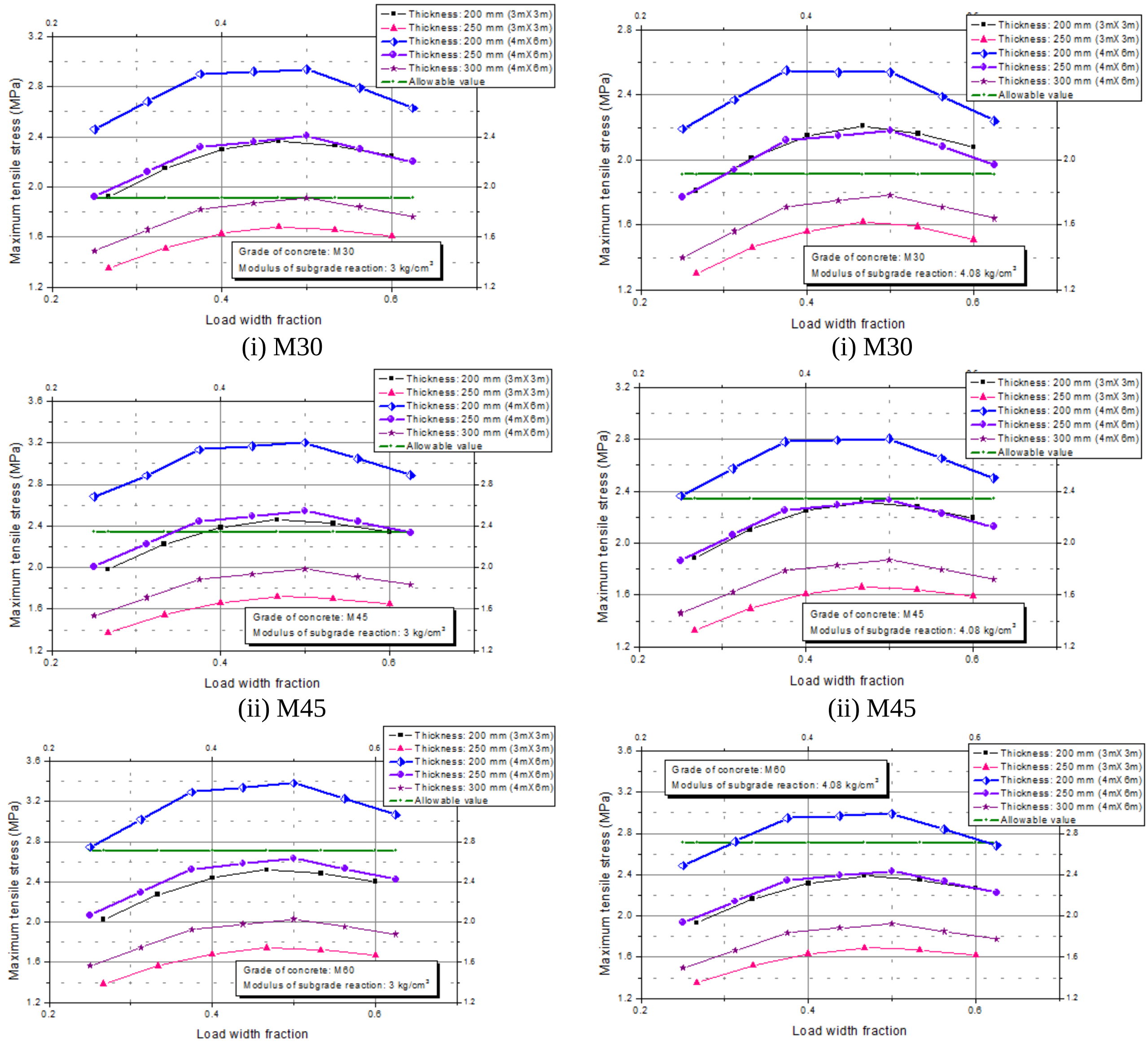
Results of identification of critical loading dimensions

As an example for identification of critical loading dimension, the loading pattern 5, corresponding to the maximum stress, is selected. Therefore, the maximum stress values for the chosen three panel dimensions for various slab thicknesses are recorded with varying loading dimensions. The starting slab thickness was taken as 200 mm and increased by 50 mm till the maximum tensile stress in concrete was below the allowable stress for that grade of concrete, for all width ratios. This final thickness would be the design thickness for that panel size, modulus of sub-grade reaction and grade of concrete. The results of this exercise are presented in pictorial form.

The critical loading width fractions, for which the maximum stress in concrete was less than the allowable tensile stress, were noted to be different for the various panel dimensions / aspect ratios and the design thicknesses. Table 4 lists the variation of critical loading width fraction that ranged from 0.38 to 0.50, for different aspect ratios of the slab panels, but it is noted that in majority of the cases, the aspect ratio was around 0.80 only. The comparison corresponding to the varying design thicknesses indicate that with increasing design thickness of the grade slab panel, the range of critical width fraction narrows down. But this could be again due to a smaller number of cases for which the design thickness was of higher values. The critical width fraction appears to almost unaffected by the grade of concrete as can be noted in Table 4, whereas for the lower modulus of sub-grade reaction, the critical width is on the higher side (0.46 – 0.50) when compared to the higher modulus of sub-grade reaction (0.38 – 0.50). Hence it may be concluded that for stiffer soils, the critical load width range to be explored would be wider, as against the less stiff sub-grades. While considering the lower panel dimension, the larger panel (6.5 m) appears to have lower values, but wider range when compared to the smaller panels (3 m). However, this could also be due to the limited data for smaller panels.

Recommendations for identification of critical loading dimensions

From the foregoing discussion, it is concluded that identification of a generalized critical width fraction applicable irrespective of the variables involved such as, panel dimensions, aspect ratios, concrete grade, modulus of sub-grade reaction, ~~or~~ design depth of slab was inconclusive from the results of this study. This would be due to the complex interaction of the concrete properties (modulus of elasticity and allowable tensile stress as defined by grade of concrete), the modulus of sub-grade reaction, and aspect ratio of the grade slab panel coupled with the support provided by the sub-grade – for arriving at the design thickness of the grade slab. Therefore, it is recommended that such detailed exercise, as demonstrated here for one loading pattern, should be undertaken for finalizing the design of grade slab using numerical approach. It can be mentioned here that the critical loading dimension could be different for other load patterns and therefore, such exercise is required for the various loading patterns selected as possible critical ones in the previous step, according to the design criterion (stress / deflection).



(i) M30 (i) M30

(ii) M45 (ii) M45

(iii) M60; (iii) M60

(a) Modulus of sub-grade reaction = 3 kg/cm^3 (b) Modulus of sub-grade reaction = 4.08 kg/cm^3

Fig. 5 – Variation of critical loading width for load pattern 5 for grade slab (panel dimensions: 3m × 3m; 4m × 6m)

3.2.4 Summary of design by numerical approach

Summary of the design results from numerical approach is presented for loading pattern 5 corresponding to the different panel sizes and grades of concrete in Table 5 and Table 6 for modulus of sub-grade reaction of 3.00 kg/cm^3 and 4.08 kg/cm^3 respectively.

As can be observed from the tables, with increase in the panel size, design thickness requirement of grade slab increased and was maximum for the largest panel dimension explored in this study, i.e. 6.5m × 8m. Increase in grade of concrete aids to reduce the design depth of grade slab. However, the enhancement in the modulus of sub-grade reaction does not, for the cases examined, affect the design depth of grade slab appreciably.

Table 3 – Variation in maximum stress in grade slab (panel size: 6.5 m × 8.00 m) for different load width ratios for modulus of sub-grade reaction of 3.00 kg/cm^3

Grade Slab Thickness (mm) ➔	200	250	300	350	400	450
Load Width Fraction ▼	Maximum tensile stress in M30 concrete (MPa)					
0.15	2.26	1.89	1.62	1.41	1.22	1.06
0.19	2.47	2.12	1.86	1.63	1.43	1.25
0.23	2.68	2.34	2.08	1.84	1.61	1.41
0.27	2.73	2.45	2.22	1.98	1.76	1.55
0.31	2.78	2.56	2.34	2.11	1.87	1.65
0.35	2.72	2.56	2.40	2.19	1.97	1.74
0.38	2.66	2.58	2.44	2.24	2.02	1.79
0.42	2.53	2.53	2.44	2.27	2.06	1.84
0.46	2.38	2.47	2.42	2.28	2.06	1.87
0.50	2.23	2.37	2.36	2.24	2.06	1.85
0.54	2.05	2.26	2.29	2.20	2.03	1.84
Load Width Fraction ▼	Maximum tensile stress in M45 concrete (MPa)					
0.15	2.45	2.05	1.75	1.51	1.29	1.11
0.19	2.70	2.31	2.02	1.75	1.52	1.31
0.23	2.94	2.57	2.26	1.98	1.72	1.48
0.27	3.03	2.71	2.43	2.15	1.88	1.63
0.31	3.11	2.84	2.57	2.28	2.00	1.74
0.35	3.07	2.88	2.65	2.38	2.11	1.85
0.38	3.03	2.91	2.70	2.44	2.17	1.90
0.42	2.91	2.88	2.72	2.49	2.22	1.96
0.46	2.77	2.82	2.72	2.51	2.25	1.99
0.50	2.61	2.72	2.65	2.47	2.23	1.97
0.54	2.44	2.61	2.59	2.43	2.20	1.96
Load Width Fraction ▼	Maximum tensile stress in M60 concrete (MPa)					
0.15	2.59	2.17	1.84	1.57	1.34	1.15
0.19	2.87	2.46	2.13	1.84	1.58	1.35
0.23	3.15	2.74	2.39	2.07	1.78	1.53
0.27	3.26	2.91	2.58	2.26	1.96	1.69
0.31	3.36	3.05	2.73	2.40	2.09	1.80
0.35	3.34	3.12	2.83	2.52	2.21	1.91
0.38	3.31	3.15	2.89	2.58	2.27	1.97
0.42	3.21	3.13	2.92	2.64	2.33	2.03
0.46	3.08	3.09	2.93	2.66	2.36	2.07
0.50	2.92	3.00	2.87	2.63	2.34	2.05
0.54	2.74	2.89	2.81	2.59	2.32	2.04

Table 4 – Range of critical loading width ratio observed for different values of chosen variables

(A) Aspect ratio of slab, grade of concrete, and modulus of sub-grade reaction

Aspect ratio of slab	Critical loading width ratio	Grade of concrete	Critical loading width ratio	Modulus of sub-grade reaction (kg/cm^3)	Critical loading width ratio
1.00	0.47	30	0.42 – 0.50	3.00	0.46 – 0.50
0.67	0.50	45	0.42 – 0.50	4.08	0.38 – 0.50
0.81	0.38 – 0.46	60	0.38 – 0.50	---	---

(B) Minimum panel dimension, and final design thickness of panel

Minimum panel dimension (m)	Critical loading width ratio	Design thickness of panel (mm)	Critical loading width ratio
3	0.47	200	0.47
4	0.50	250	0.38 – 0.50
6.5	0.38 – 0.46	300	0.42 – 0.50
---	---	350	0.46
---	---	400	0.46
---	---	450	0.42 – 0.46

Table 5 – Thickness of grade slab from numerical approaches: Modulus of sub-grade reaction of 3.00 kg/cm^3

Panel Size	M30			M45			M60		
	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading Fraction (%)	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading Fraction (%)	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading fraction (%)
3 m × 3 m	250	1.4	46.7	250	1.4	46.7	200	1.4	46.7
4 m × 6 m	300	2.0	50.0	300	2.0	50.0	250	2.0	50.0
6.5 m × 8 m	450	3.0	46.2	400	3.0	46.2	350	3.0	46.2

3.3 Comparison of empirical and numerical approaches

The comparison of the results of design thickness of grade slab by empirical approach and numerical approach are presented in Fig. 6 for modulus of sub-grade reaction of 3 kg/cm^3 and Fig. 7 for modulus of sub-grade reaction of 4.08 kg/cm^3 respectively. For this purpose, the empirical design by Chetty et al. [4] / Unwalia [5] was not considered as the design thickness by that reference is very low.

Though the empirical design is proposed for any panel dimension, from the results of this study, it is observed that for both values of modulus of sub-grade reaction, the empirical design by TM / AFM [2] would be applicable for panel dimension up to 4m × 6m whereas empirical design by Packard [3] would be applicable only for M30 concrete, for the aforementioned panel dimension. For larger panel dimensions, the numerical approach would result in higher design thickness. This could be because of the fixed critical loading considered in the empirical approach, whereas by numerical experimentation, the critical loading width has been identified individually for each slab panel, grade of concrete and modulus of sub-grade reaction in this study.

Table 6 – Thickness of grade slab from numerical approaches: Modulus of sub-grade reaction of 4.08 kg/cm^3

Panel Size	M30			M45			M60		
	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading Fraction (%)	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading Fraction (%)	Design Depth (mm)	Critical Loading dimension (m)	Critical Loading fraction (%)
3 m × 3 m	250	1.4	46.7	200	1.4	46.7	200	1.4	46.7
4 m × 6 m	300	2.0	50.0	300	2.0	50.0	250	2.0	50.0
6.5 m × 8 m	450	2.75	42.3	400	3.0	46.2	350	3.0	46.2

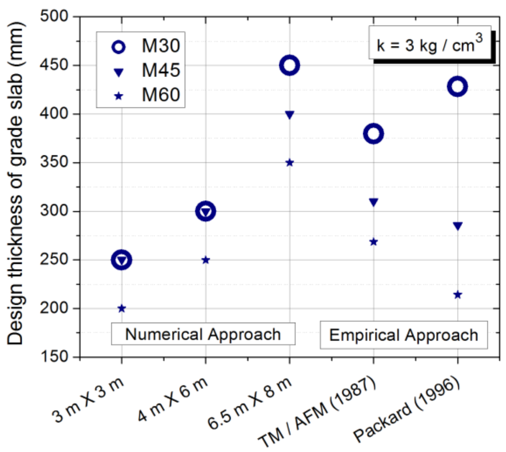


Fig. 6 – Comparison of design thickness of grade slab by empirical and numerical approaches for modulus of sub-grade reaction = 3 kg/cm^3

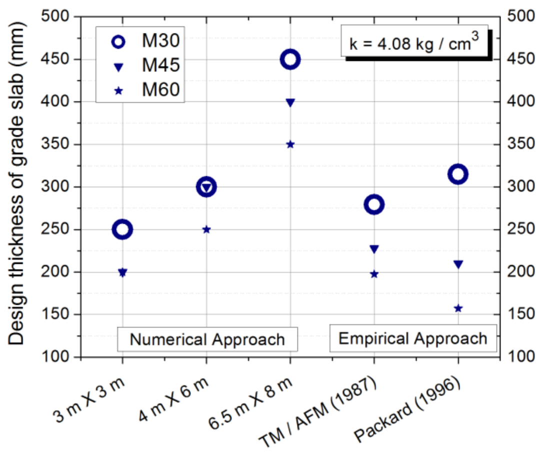


Fig. 7 – Comparison of design thickness of grade slab by empirical and numerical approaches for modulus of sub-grade reaction = 4.08 kg/cm^3

3.4 Proposed methodology for design of grade slab using numerical approach

The limited study highlights that the design thickness of the grade slab subjected to heavy loading would have non-linear relationship with the various factors, including the grade of concrete (allowable tensile stress and modulus of elasticity), modulus of sub-grade reaction, panel dimensions, and loading pattern, among others. It has been demonstrated that the critical loading pattern could be different for the design criterion critical for the grade slab, namely, strength (stress) or serviceability (deflection) and could further be influenced by the panel size, loading dimensions, etc. The thickness design from stress criterion has been explained with loading pattern 5, along with identification of critical loading dimension, as a case study. For complete strength design, it is suggested to carry out similar exercise for the loading patterns 4 and 7 as well. For the serviceability design, loading patterns 3, 6 and 7 would be suitable for detailed study. Among all the cases considered, the final design thickness can be chosen as the lowest thickness of grade slab for which the maximum tensile stress (or maximum deflection) would be less than the respective allowable value for all loading patterns.

4. Summary and conclusions

In this article, the design methodology of grade slab design has been proposed using a numerical approach, which has been compared with empirical approaches from the literature. From the results of the limited study, the following can be concluded:

1. Grade slab design by empirical formulation from Chetty et al. [4] and Unwalia [5] resulted in very low design thickness value, when compared to other empirical methods [2,3]. This could be due to the uniform support from sub-grade assumed for grade slab by Chetty et al. [4] and Unwalia [5].
2. The empirical approaches described in TM/AFM [2] and Packard [3] would be limited in application for panel dimensions higher than 6m × 4m for modulus of sub-grade reaction of 3 kg/cm3, and to M30 grade concrete for panel dimension of 4m × 6m for modulus of sub-grade reaction of 4.08 kg/cm^3. This limitation possibly arises from the fixed critical loading width assumed in case of the empirical approaches. As concluded from the numerical experiments, the critical loading pattern and corresponding critical loading width would vary according to the design parameters, namely, panel dimension, concrete grade, grade slab thickness, and modulus of sub-grade reaction.
3. The critical loading pattern to be considered in design of grade slab could be different for the design criterion adopted: strength (maximum concrete tensile stress) or serviceability (deflection).
4. The critical loading width ratio could depend on the loading pattern and would further vary according to the design parameters, namely, panel dimension, concrete grade, grade slab thickness, and modulus of sub-grade reaction.
5. A design methodology has been proposed for determining the thickness of grade slab using numerical simulation approach, which would help in extending the numerical modelling philosophy for the important structural element of industrial buildings: grade slab.

Future studies can be directed towards more detailed numerical experimentation with wider range of panel dimensions, loading intensity, etc. to arrive at more generalized guidelines for design of grade slab adopting numerical approach. Extension of the proposed design methodology for other static loading conditions (wall load, point load, etc.), for dynamic loads (seismic), and for impact loads could be other contributions to literature, which can be attempted. Another challenge would be to account for the loss of contact under load or the effect of improper compaction of sub-grade / presence of voids in sub-grade in the design methodology, which could arrest attention of future researchers.

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