Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

COMPARATIVE INVESTIGATION OF TWO DESIGN METHODS FOR SLAB-ON-GRADE FOUNDATIONS SUBJECTED TO CONCENTRATED LOADS

MOHAMAD NAZIEH JLILATI, VICKI LEE BROWN, and XIAOCHAO TANG

Dept of Civil Engineering, Widener University, Chester, USA

The concrete slab-on-grade is a type of shallow foundation commonly used in warehouse and other industrial facilities. The slab is constructed in formwork set into the ground with concrete poured directly onto compacted subgrade. Slab-on-grade foundations designed by the traditional linear elastic method may have overly conservative slab thicknesses. As the slab-on-grade foundation can account for up to 15% of construction costs for the projects in which they are employed, reduction in the slab thickness can result in significant cost savings. An alternate design method (Shentu *et al.* 1997) has been proposed but has not been widely accepted due to lack of confidence in its correlation with test results. The objectives of this study were to experimentally define a reasonable factor of safety for the Shentu method and compare with the traditional design method. Test slabs of varying thicknesses, 5 ft by 5 ft in area, were built on top of compacted local soils and aggregates inside a testing box and tested to failure under static loads to simulate storage rack post loads; companion slabs were constructed on top of compacted soils and aggregates and field-tested. Concrete mixes with and without fibers were used in the study. Factors of safety were determined. Test results indicate that the Shentu method is too liberal in its computations while the traditional design method is overly conservative.

Keywords: Experimental, Modulus of subgrade reaction, Factor of safety, Economic factor.

1 INTRODUCTION

A concrete slab-on-grade (SOG) is a common type of shallow foundation that is typically used in industrial buildings. The most popular type of SOG is unreinforced concrete poured directly onto compacted base. The design of concrete SOGs are typically governed by point loads from large storage racking systems. The point loads are transmitted to the foundation through various sized baseplates. The magnitude of the loads can fluctuate depending on the size of the storage rack and what is being stored, but typical loads can be upwards of 20 kips (90kN). The failure of a concrete SOG typically stems from onset cracking caused by moment. SOGs can also fail because of punching from the rack base plate. However, moment failure is more common than the punching failure mode. These two failure modes govern the design criteria. While it is not uncommon for micro cracks to form, because of shrinkage, concrete SOGs are designed to remain uncracked. Design charts from Ringo and Anderson (1996) are currently commonly used to design SOGs, which often results in a slab thickness ranging from 6 in to 10 in (15 cm to 25 cm);

however, Shentu *et al.* 1997 has revealed that the typical industrial slab thickness of 6 in to 10 in may be overly conservative. Shentu used finite element analysis to develop an analytical method for computing the ultimate load-carrying capacity of concrete SOGs. The Shentu design method, which is less conservative than the traditional design method, has not been widely accepted due to lack of confidence in the correlation between the Shentu equations and test results.

The main reason for the conservatism in the traditional design method, resulting in design of thicker slabs, is because traditional design does not take advantage of the elastoplastic properties of concrete. The linear elastic theory works well when loads are small, but as loads increase the accuracy decreases. The Shentu method takes advantage of increased load carrying capacity by accounting for the elastoplastic properties of concrete. The traditional method uses onset cracking as the failure criteria; the Shentu method relies on concrete's ability to carry additional load after onset cracking. If the Shentu method is correct, and concrete can in fact handle additional load after onset cracking, the required slab thickness could be reduced.

As in all shallow foundations, the subgrade is a very important parameter when considering the design of concrete SOGs. In typical reinforced concrete construction, the required tensile strength for flexure is obtained using steel reinforcement. However, most SOGs do not use any additional steel reinforcing. The flexural strength of a concrete SOG relies on ground contact and interaction. The modulus of subgrade reaction (k) is one of the most important parameters when designing SOGs. The modulus of subgrade reaction (k), represents the relationship between the applied load and the deformation of the subgrade. Both the traditional and Shentu methods rely on this subgrade parameter.

The objectives of this study were to experimentally define a reasonable factor of safety for the Shentu Method and another factor of safety for the traditional method based on linear elasticity. Test slabs of varying thicknesses (3-inch or 4-inch thick), 5 ft by 5 ft (1.5 m by 1.5 m) in area, were built on top of compacted local soils and aggregates inside a testing box at Bartholomew Civil Engineering Laboratory at Widener University and tested to failure under static loads to simulate storage rack post loads; companion slabs were constructed on top of compacted soils and aggregates and field-tested. Concrete mixes with and without fibers were used in the study.

2 METHODS AND PROCEDURES

2.1 Analytical Procedures

Equations for the traditional and Shentu methods were adjusted to represent ultimate load capacity; using slab thickness, modulus of subgrade reaction, and 28-day concrete compressive strength as universal parameters. Eq. (1) is the traditional design method equation:

$$P_u = \frac{d^2}{A \log\left(\frac{Bd^3}{C}\right)} \tag{1}$$

Where:
P_u = Ultimate load capacity (lbs)
d = Thickness of Slab (in)
$A = 0.03/\sqrt{f'_c}$
$B = 915{,}000\ \sqrt{f'_c}$
f'_c = 28-Day Concrete Compressive Strength (psi)
$C = kd^4$
k = Modulus of subgrade reaction (pci)

Eq. (2) is the Shentu Method equation:

$$P_u = 1.72\left[\left(\frac{kR_1}{E_c}\right)10^4 + 3.60\right] \tag{2}$$

Where:
R_1 = ½ the width or diameter of the column base plate (in), whichever is smaller
E_c = Modulus of Elasticity of Concrete (psi) = $57{,}000(f'_c)^{0.5}$
f'_t = Tensile Strength in Flexure of Concrete (psi) = $6.5(f'_c)^{0.5}$

Eq. (3) gives the design load capacity for both the traditional and Shentu methods.

$$P_a = \frac{P_u}{F.S.} \tag{3}$$

Where:
P_a = Design or Allowable Load Capacity (lbs)
F.S. = Factor of Safety

The recommended factor of safety for the traditional design method based on linear elasticity is between 1.5 and 2. The Shentu method recommends a factor of safety of 3.

2.2 Experimental Procedures

2.2.1 *Concrete mix designs*

Three concrete mix designs were used for this study: plain concrete, shrinkage fiber-reinforced concrete (MasterFiber Mac 100), and structural fiber-reinforced concrete (SikaFiber Force 650). The plain concrete mix design was used both with and without geogrid reinforcement (Polypropylene triaxial geogrid with 40 mm × 40 mm × 40 mm triangular apertures). The fiber types and geogrid reinforcement were chosen with economic impact in mind. The fiber reinforcement types were relatively cost effective and required little additional labor.

A total of 13 concrete slabs were tested: six plain concrete, three structural fiber concrete, two plain concrete with geogrid reinforcement, and two shrinkage fiber concrete slabs. The slabs were tested either as (1) pre-cast and tested in the lab test box, (2) cast in place and tested in the lab test box, or (3) cast in place and tested in the field. A base mix design, with a target compressive strength of 4500 psi, was provided by Conewago Enterprises, a design-build general contractor with considerable experience in SOG. The plain concrete mix design is shown in Table 1.

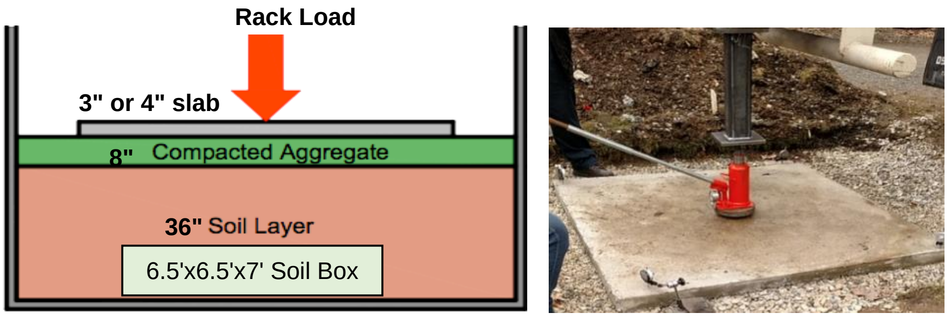
Table 1. Plain concrete mix design.

Material	**Volume Per Cubic Yard (ft^3)**	**Weight Per Cubic Yard (lb)**
Water	5.45	340
Cement	3.46	680
Coarse Aggregate #67	10.7	1782
Sand	7.03	1150
Air	0.41	1.50%
Total	**27.0**	**3952**

A similar mix design was used for the fiber/geogrid reinforced slabs by adding (4 lbs/yd^3) of the various fibers. Concrete strength was verified by testing 4-inch by 8-inch cylinders in accordance with ASTM C39M (ASTM 2008).

2.2.2 *Subgrade Preparation*

Prior to testing slabs, the subgrade must be prepared. A 36" soil layer was installed in the 6.5-foot by 6.5-foot test box in 6" lifts, with water added to ensure the soil was at its optimum level of (16.8%) to achieve the maximum unit weight of (112 lbs/ft^3). A plate compactor was used to compact the soil to create the subgrade modulus value desired (150~190 pci), tested in accordance with ASTM D1196M-12 (ASTM 2016). Eight inches of #67 coarse aggregate was then added and compacted as shown in Figure 1a.



(a) (b)

Figure 1. Testing facilities: (a) soil box layers; (b) in field test arrangements.

The outside procedure for testing was slightly different, as seen in Figure 1b. Top soil was removed, with coarse aggregate filled in the excavation to a height of 12-inch above the compacted subgrade and then compacted using a plate compactor. For both soil box and field tested slabs, standard Proctor Tests from ASTM 698 (ASTM 2014) and Static Plate Load Tests from ASTM D1196M-12 (ASTM 2016) were performed.

2.2.3 Testing the Slabs

A bottle jack was used throughout the slab testing. Before the jack could be used, a calibration curve was developed to convert the pressure on the bottle jack gauge into load in pounds. The calibration curve generates an equation, which may be used to determine the load in pounds that has been applied. The calibration curve shown in Figure 2 was developed using a universal testing machine to apply load.

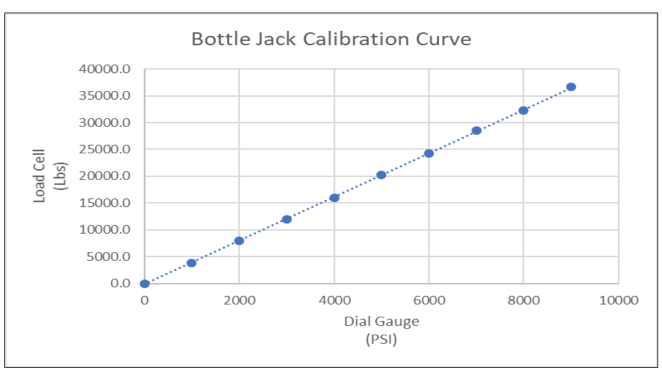


Figure 2. The bottle jack calibration curve.

The bottle jack was positioned above the centroid of the concrete slab, with the contact area a 3-inch by 3-inch steel plate. The slab dimensions were controlled by the soil box dimensions; therefore the slab thickness and the steel plate dimensions were calculated to remove the boundary condition influence on the slab strength, based on the radius of the relative stiffness. The adopted criteria to specify failure of the experimental models was a 15% force drop, where the ultimate load is specified as the highest load reached before failure, as shown in Figure 3.

3 RESULTS AND DISCUSSION

The slab loading test results are summarized in Table 2. The safety factor was examined for the traditional method as well as for the Shentu method. The limiting factor in calculating a valid safety factor is that said factored load must be less than the proportional limit of the slab. Figure 3 shows the load vs. deflection curve for a plain, cast-in-place slab. The elastic zone remains approximately linear until the slab reaches the proportional limit of 25 kips. To design safe and economical slabs, theoretical computations should remain below the proportional limit. It was assumed that design loads should stay below one-half of the ultimate load. This will ensure that design load-carrying capacities will be below one-half of the proportional limit.

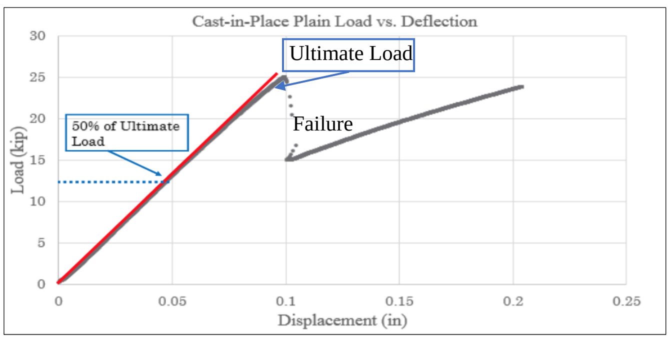


Figure 3. Cast-in-place plain load vs. deflection graph.

The implicit safety factor is calculated by dividing the theoretical traditional or Shentu load by the experimental ultimate load. From this calculation, the traditional method's implicit safety factor ranges from 2.61 to 6.67, so there is no need to further reduce the allowable load. For the Shentu Method, implicit safety factors ranged from 0.36 to 0.91, so the in-use factor of safety is not enough to ensure a safe design. Therefore, adjustment factors should be made for both methods. The proportional limit of the slabs ranged between 4.5 kips and 17.5 kips. Prior to a reduction factor being applied, only the traditional method is under the proportional limit for all slabs tested.

As shown in Table 2, the traditional method multiplied by an adjustment factor of 0.9 still allows for design loads under the proportional limit. The Shentu method with an adjusted factor of safety of 6 brought the design load under the proportional limit. As it might be confusing to have a factor of safety less than one, the authors recommend referring to the 0.9 adjustment to the traditional method as an economic factor which has the effect of increasing the traditional method's design load. However, to reduce the Shentu method allowable design load a factor of safety of 6 was proposed. The proposed adjustment factors of 0.9 for the traditional method and 6 for the Shentu method ensure a safe but not overly conservative design.

Table 2. Modified factor of safety results.

Slab Type & Thickness	K (pci)	Linear-Elastic Method Load (kpis)	Linear-Elastic Method Load / 0.9 (kpis)	Shentu Method Load (kips)	Shentu Method Load / 6 (kips)	Allowable load (kips) = Ultimate/2
Pre-cast shrinkage fiber 3"	178	3.40	3.78	24.89	4.15	4.50
Pre-cast shrinkage fiber 4"	178	5.20	5.78	44.30	7.38	7.50
Pre-cast plain 3"	178	3.40	3.78	24.89	4.15	5.50
Pre-cast plain 4"	178	5.20	5.78	44.30	7.38	7.50
Pre-cast geogrid 3"	178	3.40	3.78	24.89	4.15	10.50
Pre-cast geogrid 4"	178	5.20	5.78	44.30	7.38	12.00
Pre-cast plain 3"	164	3.90	4.33	28.60	4.77	10.50
pre-cast structural fiber						12.45
Cast in place plain 3"						13.00
Cast in place structural fiber 3"						12.95
Cast in place plain 3" (Outside)	174	3.90	4.33	28.90	4.82	8.43
Cast in place plain 3" (Outside)						7.90
Cast in place structural fiber 3" (Outside)						8.05

4 CONCLUSION

The objectives of this study were to experimentally define a reasonable factor of safety for the Shentu method and more economical adjustment to the linear elastic method. From the test results, it was found that the Shentu method's recommended factor of safety of 3 is very unconservative; rather, a safety factor of 6 should be used with the Shentu Method. On the other hand, the linear elastic method load should be factored by (1.11) as an economic factor that results in a safe and economically viable design. This is because the traditional method proved highly conservative with respect to safety, whereas the Shentu method was very liberal.

Acknowledgments

The authors wish to thank Aaron Schneck, Bradley Smith, Thomas Jones IV, Timothy Sabatino, and William Orangers for conducting experimental work. Financial support from Conewago Enterprises is gratefully acknowledged.

References

ASTM, ASTM C39M: *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM International, West Conshohocken, PA, 2008.

ASTM, ASTM D1196 / D1196M-12: *Standard Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements*, ASTM International, West Conshohocken, PA, 2016.

ASTM, ASTM D698: *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3(600 kN-m/m^3))*, ASTM International, West Conshohocken, PA, 2014.

Ringo, B. C., and Anderson R. B., *Designing Floor Slabs on Grade: Step-by-Step Procedures, Sample Solutions, and Commentary,* Aberdeen Group, Addison, IL, 1996.

Shentu, L., Jiang, D., and Hsu, C., Load-Carrying Capacity for Concrete Slabs on Grade, *Journal of Structural Engineering,* 123(1), 95-103, 1997.