Seismic Analysis, Design, and Detailing Requirements of RC Mat Foundations Based on ASCE7 and ACI 318

An Online Continuing Education Course for Engineers

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G-2025: Seismic Analysis, Design, and Detailing Requirements of RC Mat Foundations Based on ASCE7 and ACI 318

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1. Introduction

In the past 20 years, there has been a major advancement in the seismic design of reinforced concrete mat foundations. The mathematical modeling of these continuous structural elements has led to seemingly more precise designs as analytical capabilities have progressed, mainly through the use of finite element analysis. However, basic concerns about these thick foundation systems' seismic performance still exist.

For a structural engineer to move forward with a seismic design in an informed manner, this course aims to address the known and unknown aspects of this subject. Designs that take this unpredictability into account are encouraged, as many of the characteristics related to a mat foundation design can be highly changeable.

This course is organized to lead the reader through the following sequence of topics:

- What is a Mat Foundation?
- Historical Perspectives
- Soil Properties
- Soil-Structure Interaction
- Load Combinations
- Proportioning
- Analysis
- Design
- Mats Supported on Deep Foundation Elements
- Detailing
- Constructability Issues

1.1 What is a Mat Foundation?

Many structures employ a form of foundation technology called a reinforced concrete mat foundation. It is a particular kind of shallow foundation; it transfers loads to the soil by means of the earth's carrying capability at or close to the building base. A mat foundation can cover all or just a portion of the building's footprint, as opposed to separate spread footings. In comparison to a regular slab on grade, a reinforced concrete mat is significantly thicker and experiences more loads from the building.

When soil and load conditions may result in significant differential settling between individual spread footings but are not so bad as to necessitate a deep foundation system, a mat foundation is frequently utilized. It is common practice to use a mat foundation for buildings with significant overturning moments, which can arise from superstructure irregularities or high seismicity regions. This helps to resist significant uplift forces that may develop and/or distribute bearing pressure over a large footprint. Where individual spread footings would be big and close together is another common use for a mat foundation. Similarly, digging and forming separate spread footings may not be as cost-effective as erecting a single mat foundation in situations when several grade beam links between footings are needed. In order to keep a basement dry and use the weight of the mat to resist hydrostatic uplift forces, a "bathtub" system is frequently created in basements below the water table using a mat foundation. A mat serves as both the pile cap and support when it is situated atop deep foundation elements.

The behavior of a mat foundation can be correlated to a two-way slab system turned upside down. The distributed soil pressure applied to the bottom of the mat is analogous to a distributed slab load, and the columns and walls above the mat become the supports for the mat foundation. Therefore, it is common to apply analysis and design methods from two-way slabs to a mat foundation.

The design forces, load combinations, and some analysis requirements for a mat foundation are in ASCE7, which has been adopted into the IBC. In adopting ASCE7 provisions, IBC includes some modifications and additions that will be discussed later. As noted in the sidebar on the previous page, IBC 2012 is the current version of this code but may not yet be adopted by all jurisdictions; therefore, the governing code should be confirmed for each particular project jurisdiction as appropriate. The design and detailing requirements for a reinforced concrete mat foundation are presented in ACI 318, which the IBC has adopted as an incorporated standard.

For concrete design, structural engineers predominately consider ultimate strength design methods where the ultimate/ factored loading is compared to the member’s nominal strength.

This method has been incorporated into ACI 318 since the 1960s. However, geotechnical engineers predominately consider allowable stress design, comparing service loads to allowable stresses and soil-bearing pressures. This fundamental difference must be understood and addressed when designing a mat foundation. There is an ongoing development in building code committees to codify ultimate strength design for geotechnical engineers, but its use is not yet commonplace. This issue of coordination between the structural engineer and geotechnical engineer will be addressed in greater detail throughout this course.

2. Historic Perspectives

2.1 General

The design of mat foundations has long been recognized as a problem in Soil-Structure Interaction that designers have strived to simplify by designing mats that can be classified as rigid bodies. More recent requirements for earthquake-resistant design have made that approach less appealing and have increased the need for detailed considerations of soil-structure interaction effects for mats. The increasing use of finite element analyses in the mid-1980s and subsequent increases in available computing power have made such detailed considerations more realistic and reliable. Hence, it is convenient to confine this historical perspective on mat foundation design to the body of knowledge developed prior to the mid-1980s and to have the remainder of this document address knowledge developed since then as a result of detailed finite element analyses. At approximately the same time as computational capabilities evolved significantly, structural engineers adopted ultimate strength design. Thus, the division of knowledge that existed prior to the mid-1980s and that developed since is also consistent with the timeline of two ACI 336 committee reports (ACI Committee 336 1966, 1988) on foundation design. The procedures of the 1966 report were repeatedly reaffirmed until the publication of the second report in 1988. The 1988 report has continued to be reapproved by ACI, pending completion of work on an updated document.

2.2 Early Designs

Mat foundations were originally envisaged as floating foundations with distinct advantages where the soil was poor or unacceptable differential settlements were likely to occur. Early work showed that mats on sand (loose, compacted, medium, or dense) posed few problems. The factor of safety assumed for such mats was twice that for an individual spread footing, and therefore, no strength difficulties were to be expected if the loading imposed on the mat by the superstructure was effectively uniform. The allowable soil pressure was governed by settlement and differential settlements between the walls and columns supported by a mat. Typically, these allowable soil-bearing pressures were less than those for isolated footings subject to the same loading.

By contrast, mats on clays had factors of safety against bearing failures that were the same as those for footings and were dependent on the length-to-width ratio of the mat or footing. Otherwise, the bearing strength was practically independent of the area loaded by the mat or footing. Many of the initial uses of mats were for large grain elevators, and their performance demonstrated those findings. A mat foundation was envisaged as a large combined footing and designed as an inverted slab system spanning between columns and walls, carrying the building weight as a load assumed to be uniformly distributed over the soil. The principles of reinforced concrete design were used to design the mat with three types of mats recognized: flat plates, beams with a slab underneath (like waffle slab construction), and beams with a slab on top. For plates, the design for moments and shears was based on the coefficients for flat slab design specified in the building code, with the slab thickness based on stiffness considerations and punching shears around columns and walls. By theory, a perfectly rigid structure located on an elastic subgrade has a minimum pressure near the center and maximum pressure at the edge. Designs were prepared assuming the ratio of the maximum to minimum pressure was about two, and the two design conditions of both uniform and varying soil pressures were used to proportion the mat. Consequently, resulting designs called for providing more reinforcement than that required by a more rigorous analysis. In addition, it was common to provide the same amount of reinforcement top and bottom of the mat. Where the primary design consideration was differential settlements resulting from uneven column or wall loads and a compressible layer or variations in the properties of the soil below the mat were present, beams were often used to stiffen the mat.

The typical rule of thumb used for a mat on the sand was, for uniform loading, that the superstructure could tolerate a differential settlement of about 0.75 inches between adjacent columns, with a maximum settlement of 2 inches overall. For a mat on clay, the differential settlement was chiefly due to dishing and was roughly half the maximum settlement. Dishing refers to the deflected shape of the mat foundation. However, the mat thickness was typically not greater than about 0.01 times the radius of curvature, with some local increases acceptable around columns and walls.

2.3 Basic Foundation Design Procedures

The existing procedures of ACI 318 for the design of mats are based primarily on the results of tests reported by Talbot (1913), Richart (1948), and ACI-ASCE Committee 326 (1962, 1974). The procedures effectively assume that foundations are designed using allowable stress for the soil and strength design for the concrete foundation. Three limiting conditions were assumed for the soil supporting the foundation: bearing failure of the soil under the foundation, serviceability failure because of excessive differential settlements causing nonstructural or structural damage to the superstructure, and excessive total settlements. Two limiting conditions must be considered for the concrete foundation below the columns and walls of the superstructure: local flexural failure of the foundation (including reinforcement anchorage failure) and shear failure of the foundation. The geotechnical engineer typically specifies an allowable soil bearing pressure, qa, and service load stress that takes into consideration the three limiting conditions for the soil. The structural engineer then typically designed the foundation for an ultimate soil pressure, q_u, that resulted from the factored loads applied to the foundation. Soil pressures were traditionally calculated by assuming the linear elastic action of the soil in compression and no tension capacity offered by the soil. For a centrally loaded foundation, as shown in **Figure 2-1**, the stress under the footing is given by:

$$q = P/A \pm My/I$$

where, as illustrated in **Figure 2-1(a)** and **Figure 2-1(b)**:
P = axial force
A = area of contact surface between the soil and the foundation
I = moment of inertia of contact area *A*
M = moment about the centroidal axis of area *A*
y = distance from the centroidal axis to position
Where *q* is calculated

If separation (uplift) between the soil and the foundation is to be avoided, the eccentricity *e* = *M*/*P* must lie within the kern of the contact surface. The kern area, which is the shaded area in **Figure 2-1(c)**, is the area for which applied loads within that region will produce only compression over the area of the footing.

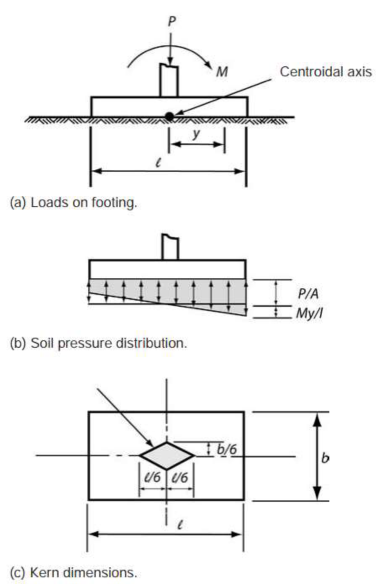


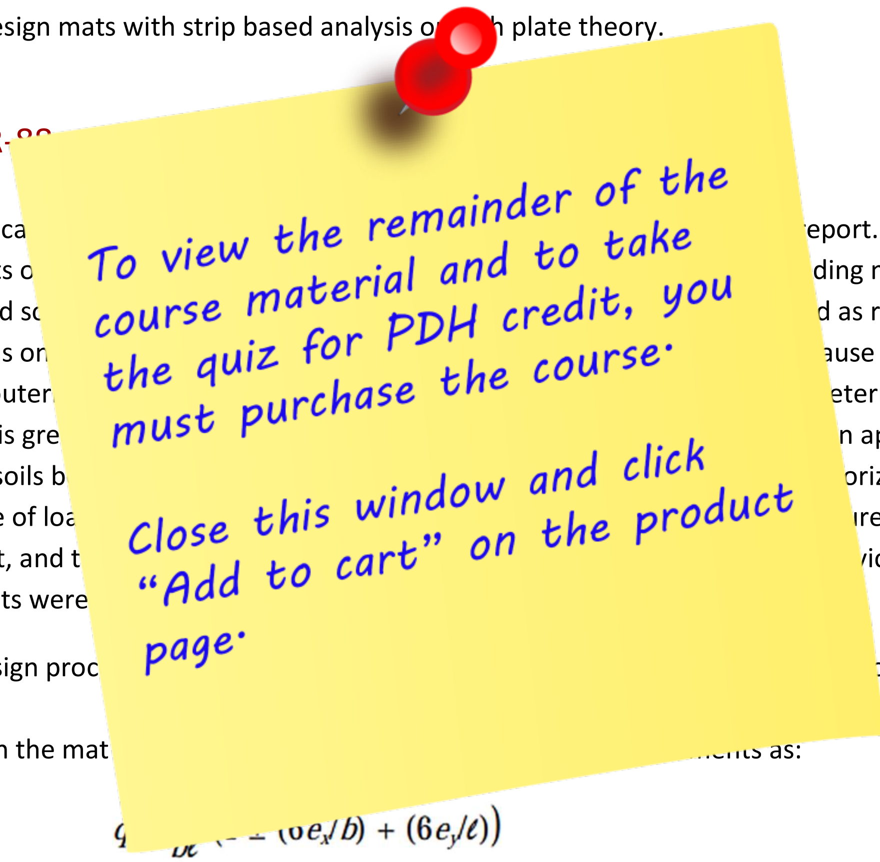
Figure 2-1 *– Soil pressure under centrally loaded foundation*

Critical sections and design requirements for moments in footings are specified in §15.3 and §15.4 of ACI 318. Those requirements have remained essentially unchanged between the 1941 and the 2011 standards. In the 2011 standards, critical sections and design requirements for shear in footings are specified in §15.5. The shear strength is to be evaluated using the same provisions as those for elevated slabs. This design philosophy has remained essentially unchanged since 1941. However, nominal shear strengths and bond requirements have changed substantially over the same period. The current punching shear strength concepts date essentially from the 1963 edition of ACI-318 and development length concepts from the 1971 edition.

2.4 ACI 336.2R-66

This report (American Concrete Institute 1966) addresses the design of foundations carrying more than a single column or load. The report suggests that the contact pressures at the base of the foundation be taken as either a straight-line distribution for a rigid foundation or a distribution governed by elastic subgrade reaction, for a flexible foundation. The report provides recommendations to determine the foundation rigidity, considering the spacing of columns or walls, the relative rigidity of the foundation compared to the soil, and the rigidity of the superstructure. Given this determination, analysis guidelines are provided to design mats with strip based analysis o... h plate theory.

2.5 ACI 336.2R-...



This report (America... eport. It provided detailed comments o... ding moments, displacements, and so... d as rigid bodies or as flexible plates on... ause the state-of-the-art in computer... etermine soil properties. There is gre... n approximate properties to the soils b... orizontally and vertically, and rate of loa... re loads and their development, and t... vice versa. For those reasons, mats were...

The suggested design proc... ollows:

1. Proportion the mat ... ents as:

$$q \ldots (6e_x/b) + (6e_y/\ell))$$

where the eccentricities e_x and e_y of the resultant column loads ΣP include the effects of any column moments and any overturning moments because of wind and other effects. The value of q is required to be less than the allowable limiting soil stress recommended by the geotechnical engineer. The value q is then scaled to a pseudo "ultimate" value as:

$$q_u = (\text{sum of factored design loads/sum of unfactored loads}) \cdot q$$