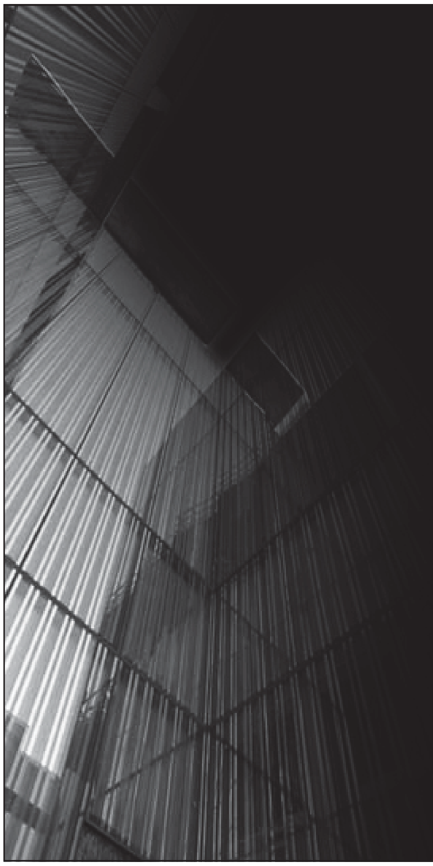

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Frequently Misunderstood Foundation Design Provisions

Ian McFarlane, S.E.
Magnusson Klemencic Associates

Summary

- Load combinations for foundation design
- Liquefaction risks and how to address
- Basics of SSI, how it relates to typical design parameters
- Mat foundation design
- Deep foundation detailing

Load Combinations

- Typically we will use both ASD and LRFD/USD load combinations for foundation design
- ASD, used for:
  - **Sizing the soil-foundation interface (bearing pressure)**
  - **Communication with geotechnical engineer (service level loads)**
- LRFD / USD, used for:
  - **Design of flexural reinforcement**
  - **Design of shear reinforcement, punching shear**

Load Combinations

- Frequent Misunderstanding
  - **Incorrect application of load combinations**
  - **Lack of understanding of two options for ASD load combinations**
  - **Misunderstanding of factors associated with seismic effects**

Load Combinations

- Strength Design / LRFD [1605.2]
  - **1.2D+1.6L**
  - **0.9D+1.0W**
  - **0.9D+1.0E**
- Allowable Stress Design – Basic [1605.3.1]
  - **D+L**
  - **0.6D+0.6W**
  - **0.6D+0.7E**
- Allowable Stress Design – Alternative Basic [1605.3.2]
  - **D+L**
  - **D+0.6W**
  - **0.9D+E/1.4**

Load Combinations

- LRFD and Basic ASD (ASCE 7)
  - **In general they are consistent regarding overturning factor of safety**
  - **0.6D factor on ASD was added in ASCE 7-98 to address inconsistency in the treatment of counteracting loads in ASD vs strength design, and to emphasize the importance of checking stability**

Load Combinations

- Alternative Basic ASD (UBC-97 and before)
  - **Considered 'legacy' load combinations, some west coast engineers did not want to take the overturning safety factor increase**
  - **Some day we expect these to be removed from the code…**

Load Combinations

- Alternative Basic ASD from UBC-97 (and before)
  - When dead load is counteracting wind load, only 2/3 the dead load likely to be in place may be used to resist overturning. Effectively a 1.5 factor of safety.
  - Therefore, similar design for wind when compared to Basic ASD, but not for seismic

Load Combinations

- Which should you use?
  - Alternative Basic ASD will result in lower factor of safety for seismic overturning, not consistent with LRFD
  - Basic ASD will be consistent with LRFD and avoid a potential analysis stability issue

Load Combinations

- Reduction in seismic overturning per ASCE 7-10 12.13.4
  - 10% reduction for modal analysis
  - 25% reduction for ELF
  - Recognizes that these methods overestimate foundation overturning
  - Reduction for Basic ASD and LRFD load combinations
  - Cannot be used with Alternative Basic ASD

Load Combinations

- Vertical Seismic Load Effects
  - Per ASCE 7-10 12.14.3.1.2 Exception A, where determining demands on soil-structure interface of foundations E_v shall be taken as zero when subtracted from E_h.
  - Therefore $0.6D-0.14S_{DS} \rightarrow 0.6D$
  - $0.6D+0.14S_{DS}$ should be considered but is not likely to control

Load Combinations

- Seismic load effect considerations
  - Seismic demand modified by response factor "R" which depends on lateral system
  - Unusual geometries or systems such as cantilever column or discontinuous lateral system trigger additional overstrength factors

Load Combinations

- Seismic load effect considerations
  - Directionality factors (eg 100% / 30%) should be applied to foundation consistent with superstructure design
  - Redundancy factor (ρ) should be applied to foundation consistent with superstructure design

Load Combinations

- Seismic demand levels
  - **Is design of foundation for same "R" as superstructure appropriate?**
  - **ACI 318 commentary – inelastic response should be above the foundation level**
  - **Certain building types may consider higher foundation demand levels (Performance based design)**

Load Combinations

- Seismic demand levels
  - **Methods to consider higher foundation demand levels include:**
    - Evaluate demands predicted by nonlinear time history analysis
    - Introduce code-defined overstrength factors to ensure yielding of lateral system prior to inelastic foundation behavior
    - Design the foundation for reduced R value compared to main lateral force resisting system
    - Detailing the foundation to avoid brittle failure

Load Combinations

- Ultimate Strength Design for Foundations – New Code Provisions
  - **Provide a framework for strength design for nominal foundation geotechnical capacity**
  - **Incorporated into 2015 NEHRP Provisions and ASCE 7-16**

What is liquefaction?

- Reduction in strength and stiffness of soil from shaking
- See video from Japan earthquake (2011)

Liquefaction

- Frequent Misunderstanding
  - **Unknown or overly conservative acceptance criteria for differential settlement and lateral spread**
  - **Liquefaction requires deep foundations**

Liquefaction – Geotechnical Report Requirements

- Addition to IBC 2012
- Seismic Design Categories C, D, E, F, simply evaluate site for liquefaction [1803.5.11]

Liquefaction – Geotechnical Report Requirements

- Seismic Design Categories D, E, F, [1803.5.12]:
  - **Potential for liquefaction and soil strength loss evaluated for site peak ground acceleration**
  - **An assessment of potential consequences of liquefaction and soil strength loss, including:**
    - Estimation of total and differential settlement
    - Lateral soil movement
    - Lateral soil loads in foundations
    - Reduction in foundation soil bearing capacity and lateral soil reaction

Liquefaction – Geotechnical Report Requirements

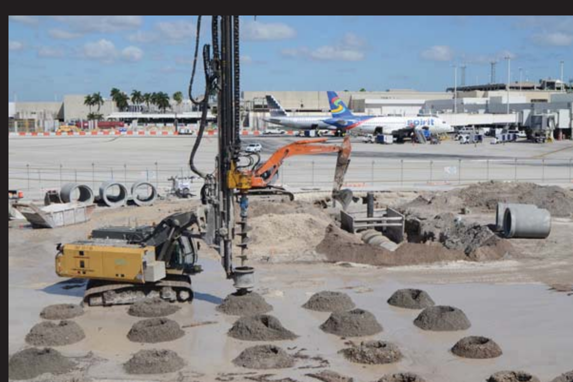
- Seismic Design Categories D, E, F, [1803.5.12]:
  - **…including:**
    - Soil downdrag and reduction in axial and lateral soil reaction for pile foundations
    - Increases in soil lateral pressures on retaining walls
    - Flotation of buried structures

Liquefaction – Geotechnical Report Requirements

- Seismic Design Categories D, E, F, [1803.5.12]:
  - **Discussion of mitigation measures**
    - Selection of appropriate foundation type and depths
    - Selection of appropriate structural systems to accommodate anticipated displacements and forces
    - Ground stabilization
    - Any combination of these measures and how they shall be considered in the design of the structure

Liquefaction

- Mitigate effects with ground improvements – total or partial mitigation

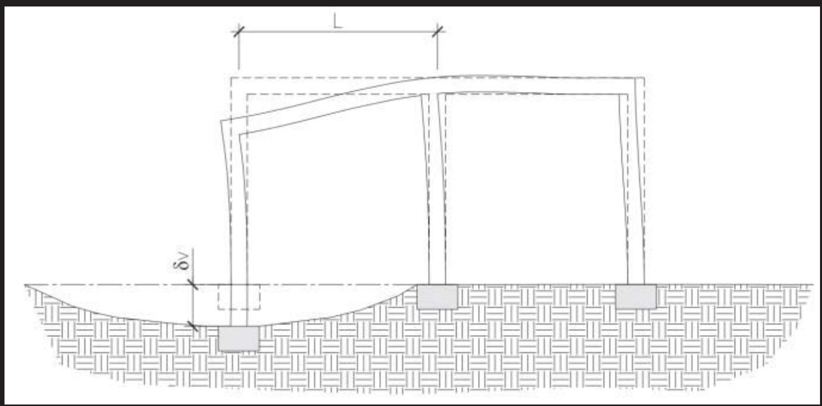


Liquefaction

- Options to design structure for effects
  - **Directly design for induced moments, shears**
  - **Limit differential settlement to what is permissible for type of structure, risk category, etc.**
- New code changes to address liquefaction:
  - **Methods are codified in NEHRP 2015 provisions (FEMA P-1050), now available**
  - **Incorporated into ASCE 7-16**

Liquefaction – Shallow Foundations

- Differential Settlement
  - **Determine chord rotation δ_v/L**



Liquefaction – Shallow Foundations

- Differential Settlement Limits

Table 12.13-3 Differential Settlement Permissible Limit for Shallow Foundations Depending on Structure Type, δ_v/L^a

Structure Type	Risk Category - I	Risk Category - II	Risk Category - III	Risk Category - IV
Single-story concrete or masonry wall systems.	0.0075	0.0075	0.005	0.002
Other single-story structures.	0.015	0.015	0.010	0.002
Multi-story structures with concrete or masonry wall systems.	0.005	0.005	0.003	0.002
Other multi-story structures.	0.010	0.010	0.006	0.002

Note: $^a\delta_v$ is the differential settlement between two points, as indicated in the geotechnical report
Note: L is the horizontal distance between the indicated two points

- Multi-story concrete wall, Risk Category II: 30' bay, 1.8" permissible differential settlement

Liquefaction – Shallow Foundations

- Lateral spread limits

Table 12.13-2 Lateral Spreading Horizontal Ground Displacement Permissible Limit for Shallow Foundations

Risk Category			
I	II	III	IV
18 in.	18 in.	12 in.	4 in.

- Foundation ties (grade beams or structural slab on grade) are still required

Liquefaction – Deep Foundations

- Goals
  - **Design for associated ground deformations that occur during lateral spreading**
  - **Some yielding is anticipated**
  - **Limit the amount of nonlinear behavior in order to maintain stability and gravity support**

Liquefaction – Deep Foundations

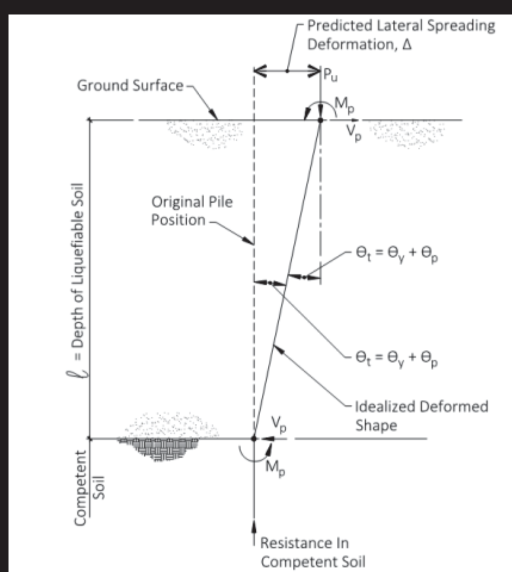


Figure Reference FEMA P-1051

Liquefaction – Deep Foundations

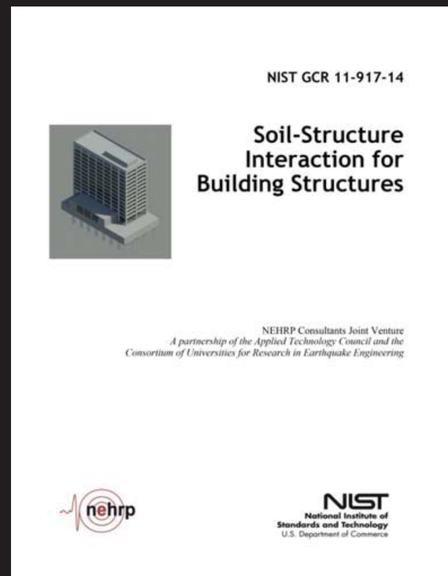
- **Axial and Flexural Strength**
  - P-M interaction
  - Calculate curvature demands
- **Detail for Ductility**
  - Volumetric confinement per ACI, 7D below interface
- **Shear Strength**
  - Provide shear strength to develop the plastic hinges. $V_u = 2\ M_{PR} / L$
- **Downdrag**
  - May or may not occur simultaneously with lateral spread

Break #1

- 5 minute break, Submit your questions

Soil Structure Interaction

- Lag between state of knowledge and state of practice, implementation is limited but growing
- Expect development as the practical implementation continues


NIST GCR 11-917-14

Soil-Structure Interaction for Building Structures

NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering

nehrp

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Soil-Structure Interaction

- State of practice summary (NIST document, Chapter 6), key observations: (not specific to SSI)

  1. Dialogue between structural and geotechnical engineers varies widely in extent and sophistication. Many geotechnical engineers are not sure how their recommendations are ultimately being used and thus do not know whether their recommendations are being appropriately implemented.

Soil-Structure Interaction

- State of practice summary (NIST document, Chapter 6), key observations: (not specific to SSI)
  2. **Development and implementation of static and dynamic springs to model soil properties are not being consistently or properly addressed by geotechnical and structural engineers.**
  3. **Understanding of SSI is limited among structural engineers, primarily limited to vertical foundation springs.**
  4. **For typical foundation situations, there is no consensus among structural engineers on best modeling approaches to use.**

Soil-Structure Interaction

- Collaboration
  - **Communication and collaboration varies substantially between projects**
  - **Many times SE and GE never meet in person and have few, if any, email or telephone conversations**
  - **GE is often hired well in advance of structural design, meaning GE work may be complete before the design team begins work**
  - **Typical fee structure and schedule does not encourage discussion**

Soil-Structure Interaction

- Information requests by Structural Engineer
  - **Fairly common set of recommendations is needed**
  - **Sample checklist of items needed is a valuable aid***
- Information provided to Geotechnical Engineer
  - **Can provide better recommendations when more detailed information about the structural design is provided**
  - **Plan of column locations and anticipated loads is extremely helpful**
  - **Building fundamental period**
  - **Tolerances for differential settlement**
  - **Site specific response spectra (if needed)**
  - **Sample of checklist would be valuable aid as well***

* Sample Checklists are part of NIST Document

Soil-Structure Interaction

- Understanding SSI
  - **Most engineers know SSI effects are pronounced on soft soils, and that free field ground motions and those experienced by buildings can be different**
  - **SSI effects are actually more significant on stiff, squat, short-period buildings**
- Benefits of SSI
  - **Better understanding of force and displacements in the structure**
  - **Lower forces due to period lengthening, embedment, and base slab averaging effects**

Soil-Structure Interaction

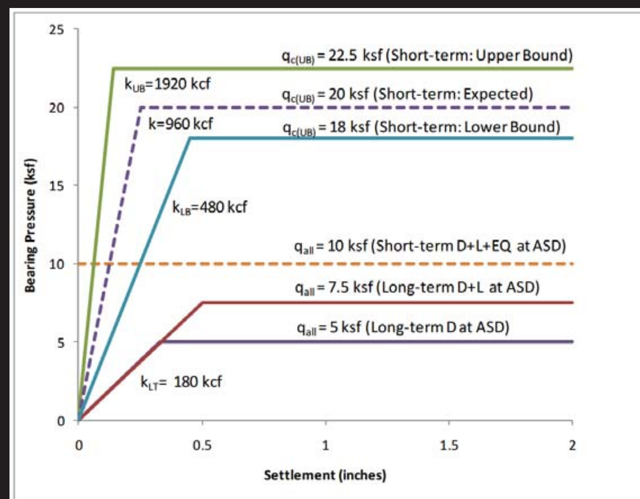
- Soil spring issues
  - **Vertical springs commonly used, horizontal springs less frequently used**
  - **When not provided by geotechnical engineer, engineers may turn to FEMA 356 or ASCE 41 or use rule of thumb checks associated with anticipated settlement**

Soil-Structure Interaction

- Soil spring issues
  - **Soil spring given for long term gravity loading is often incorrectly used for dynamic loading conditions! Can underestimate soil stiffness, overestimate displacement/rotation**
  - **Lack of understanding between geotechnical engineer and structural engineer regarding the difference between short term and long term loading effects on soil**
  - **There is uncertainty in single spring values, consider using upper bound values**

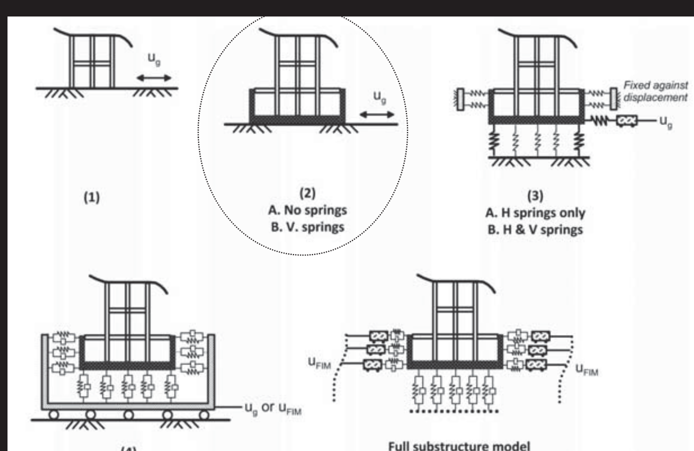
Soil-Structure Interaction

- Example of excellent format for soil spring characterization



Soil-Structure Interaction

- Modeling Guidance for Typical Foundation Situations
  - **See NIST GCR 11-917-14**



Mat Foundation Design

- Frequent Misunderstanding
  - **Incorrect application of soil springs / subgrade modulus**
  - **Incorrect analysis procedures**
  - **Unconservative shear design**
  - **Lack of understanding of constructability issues**

Mat Foundation Design

- Subgrade Stiffness Parameters / SSI
- Analysis Basics
- Design for shear and flexure
- Detailing / Constructability

Subgrade Stiffness Parameters

- Common Misunderstanding:
  - **Geotechnical engineer provides bearing pressure in report**
  - **Structural engineer designs mat for given bearing pressure with an assumed subgrade modulus**
- This approach does not provide compatibility between structural and geotechnical analysis/design

Subgrade Stiffness Parameters

- Conventional parameter: Modulus of Subgrade Reaction
  - **Force per volume parameter – kcf, pci, etc**
  - **Historically based on plate load test**

- 144 kcf = 12 ksf bearing pressure causes 1” vertical deformation

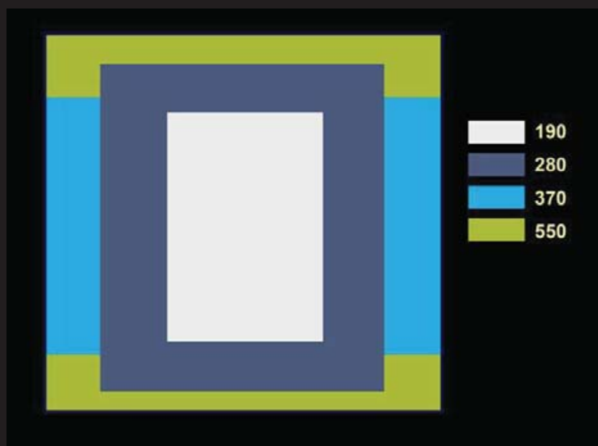
Subgrade Stiffness Parameters

- Issues with Modulus of Subgrade Reaction
  - Does not address interaction between soil and mat foundation, ie 'dishing' effects or redistribution of bearing pressure

  - Traditionally only addresses static conditions
  - Vast simplification of true subgrade response

Subgrade Stiffness Parameters

- Best practice method: Foundation Deflection and Subgrade Response Compatibility ("FDSRC")
- More simply put: Iterate subgrade stiffness with geotechnical input
- Target is an acceptable and compatible bearing pressure distribution and settlement



Subgrade Stiffness Parameters

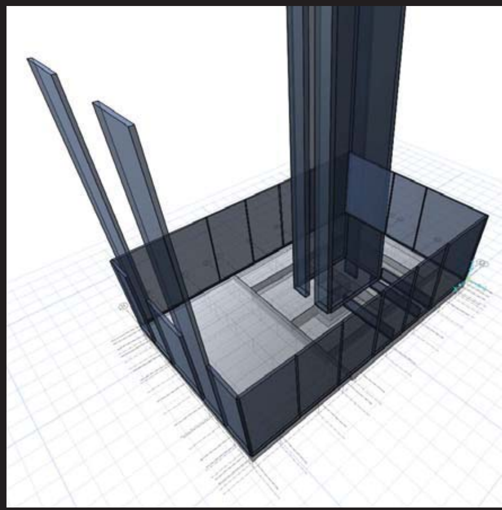
- FDSRC Procedure
  - **Typically start with uniform subgrade modulus provided by geotech, perform analysis and send resulting bearing pressure and deflected shape back to geotech**
  - **Geotech reviews for compatibility with the subgrade response model of their choice. This model may vary in complexity**
  - **Geotech will suggest alternative subgrade modulus values as necessary, they may vary across the site to correctly capture 'dishing' effects**
  - **Structural engineer calculates revised bearing pressure, deflected shape, and re-sends to geotechnical engineer for review**
  - **Repeat as necessary until compatibility is achieved**

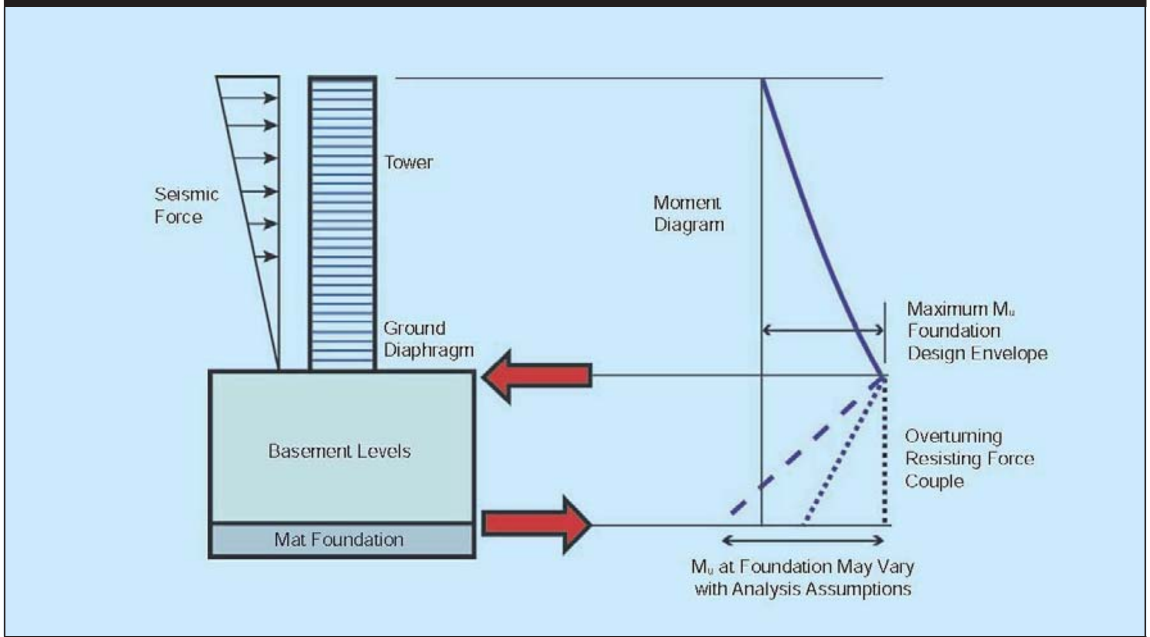
Subgrade Stiffness Parameters

- Summary of Foundation Deflection Subgrade Response
  - **Results in 'subgrade modulus' values that reflect both soil behavior and foundation flexibility (soil structure interaction)**
  - **For simplicity we may still call this subgrade modulus, but it captures more than just subgrade response**
- Clear communication with your geotechnical engineer is key for success of this method!

Analysis

- Shear Deformations / Thick Plate formulation for span to depth less than 10
- Foundation / Superstructure Stiffness to be included





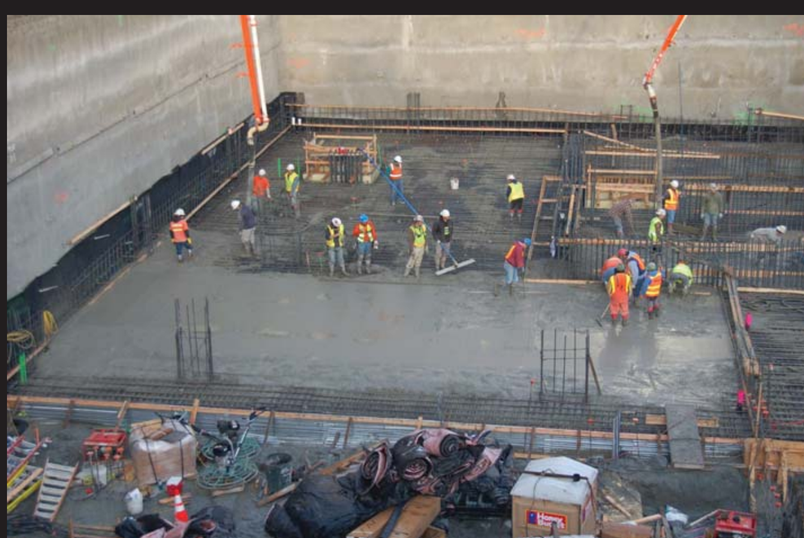
Backstay Effect on Moment Diagram

Sensitivity Analysis

- Sensitivity analysis
  - **Compare metrics such as:**
    - Bearing pressure
    - Moment and shear diagrams
    - Settlements
  - **Use results of sensitivity analysis to validate analysis model and envelope the final design**

Break #2

- 5 minute break, Submit your Questions



Mat Foundation Design

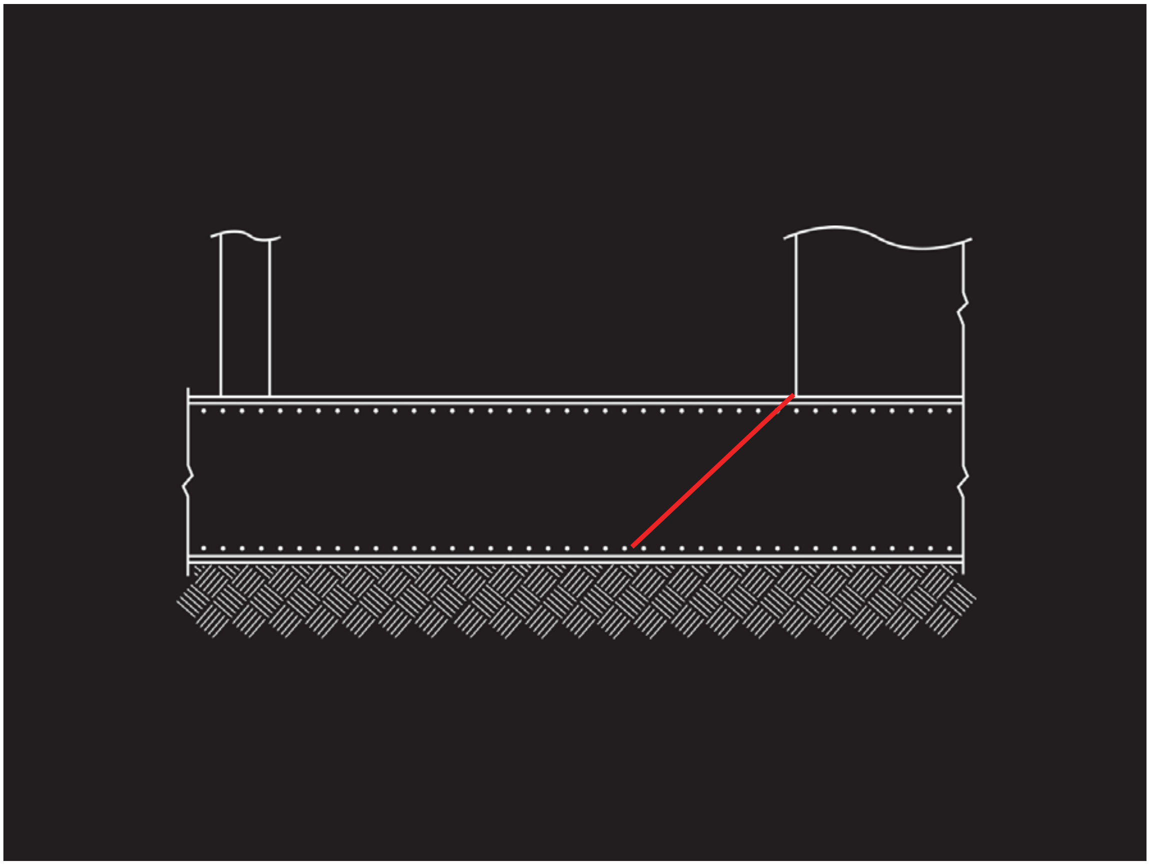
- Capacity considerations

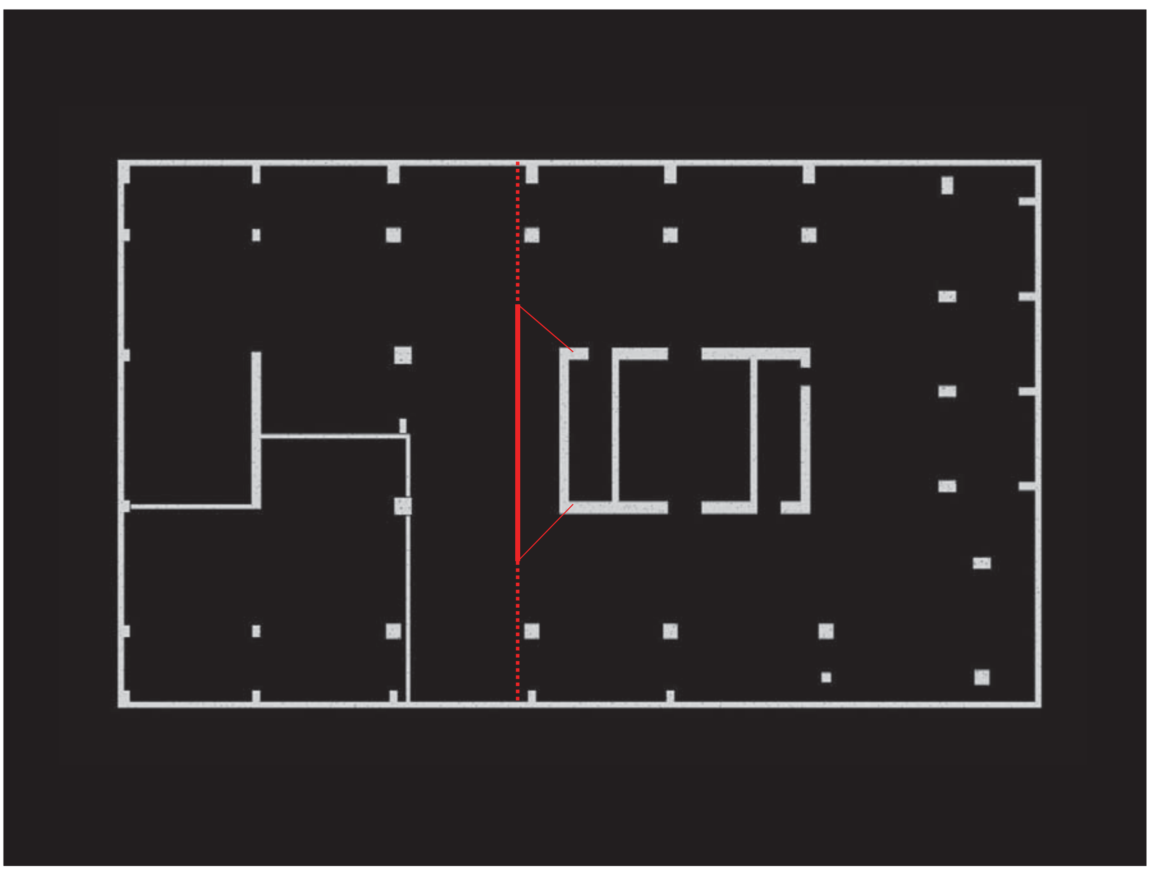
$$\Phi = 0.6 \ ?$$

- Per ACI 318-11 9.3.4, for SDC D, E, F, special moment frame or structural wall that resists earthquake effects, ϕ shall be modified if nominal shear strength is less than shear corresponding to development of nominal flexural strength.

Capacity Considerations

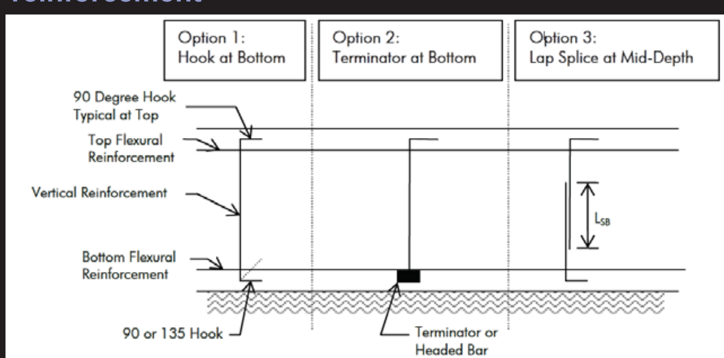
$$V_c = 2\sqrt{f'_c} \ ?$$





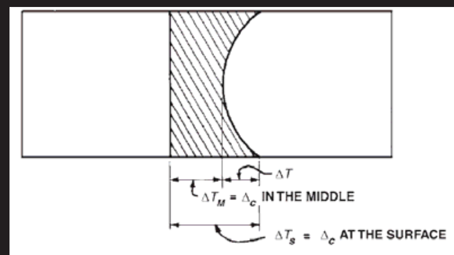
Mat Foundation Shear Reinforcement Detailing

- Shear reinforcement
  - Extend as close as possible to tension and compression surfaces
  - Hook around longitudinal reinforcement
  - See ACI 318-11 12.13.2
  - Can be difficult to place with multiple layers of longitudinal reinforcement



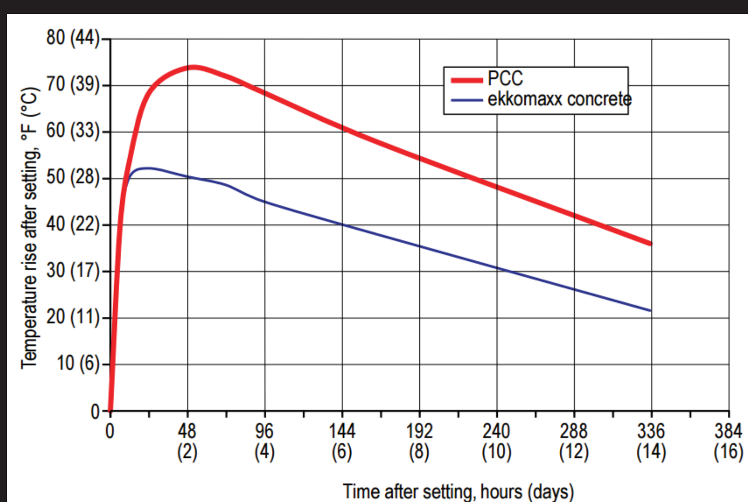
Mat Foundation Constructability

- Massive Concrete
  - Thermal Cracking
  - Delayed ettringite formation
  - Reduced f'c



Constructability

- #1 Solution: Mix Design



Deep Foundation Detailing

- Frequent Misunderstanding
  - **Overly conservative minimum reinforcement**
  - **Lack of understanding for Site Class E, F conditions**

Deep Foundation Detailing

- Cast-in-place provisions per 1810.3.9
- Provisions are organized by Seismic Design Category and Site Class
- Compliance with ACI 318 Equation 10-5 is not required [1810.3.2.1.2]
  - $\rho_s = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_{yt}}$
- SDC A, B – no requirements in IBC

Deep Foundation Detailing

	SDC C	SDC D, E, F Site Class A, B, C, D	SDC D, E, F Site Class E, F
Minimum Longitudinal Reinforcement Ratio	0.0025 (4) Bars Min	0.005 (4) Bars Min	0.005 (4) Bars Min
Minimum Reinforcement Length	Greatest of: -1/3 Length -10 feet -3 times least element dimension -Distance from top of pile to ‘cracking moment’	Greatest of: -1/2 Length -10 feet -3 times least element dimension -Distance from top of pile to ‘cracking moment’	Greatest of: -1/2 Length -10 feet -3 times least element dimension -Distance from top of pile to ‘cracking moment’

Cracking moment defined as $\varphi M_n = 3\sqrt{f'_c}S_m$

Deep Foundation Detailing

	SDC C	SDC D, E, F Site Class A, B, C, D	SDC D, E, F Site Class E, F
“Hinge Zone” Length	3 times least element dimension	3 times least element dimension	7 times least element dimension
Minimum Transverse Reinforcement in “Hinge Zone”	Closed ties or spirals with 3/8” minimum diameter Spacing shall not exceed 6 inches or 8 longitudinal bar diameters	Confinement per ACI 318-11 21.6.4.2, 21.6.4.3, 21.6.4.4 Minimum spiral ratio not less than half of 21.6.4.4(a)	Confinement per ACI 318-11 21.6.4.2, 21.6.4.3, 21.6.4.4 Minimum spiral ratio not less than 21.6.4.4(a)

Deep Foundation Detailing

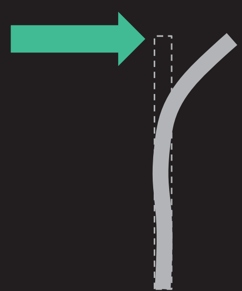
	SDC C	SDC D, E, F Site Class A, B, C, D	SDC D, E, F Site Class E, F
Minimum Transverse Reinforcement in Remainder of Reinforced Length	Closed ties or spirals with 3/8" minimum diameter	Closed ties or spirals, minimum #3 for least dimension up to 20 inches, #4 for larger elements	Closed ties or spirals, minimum #3 for least dimension up to 20 inches, #4 for larger elements
Transverse Reinforcement Spacing Outside of Hinge Zone	Maximum spacing of 16 longitudinal bar diameters	Maximum spacing not to exceed least of: 12 longitudinal bar diameters, ½ least dimension of element, or 12 inches	Maximum spacing not to exceed least of: 12 longitudinal bar diameters, ½ least dimension of element, or 12 inches

Deep Foundation Detailing

- SDC D, E, F and Site Class E or F [1810.2.4.1]
  - **Deep foundation element shall be designed and constructed to withstand maximum imposed curvatures from earthquake ground motions and structure response...**

Deep Foundation Detailing

- Inertial: Due to loads imparted by structure
- Kinematic: Due to free-field soil strains modified for soil-foundation-structure interaction



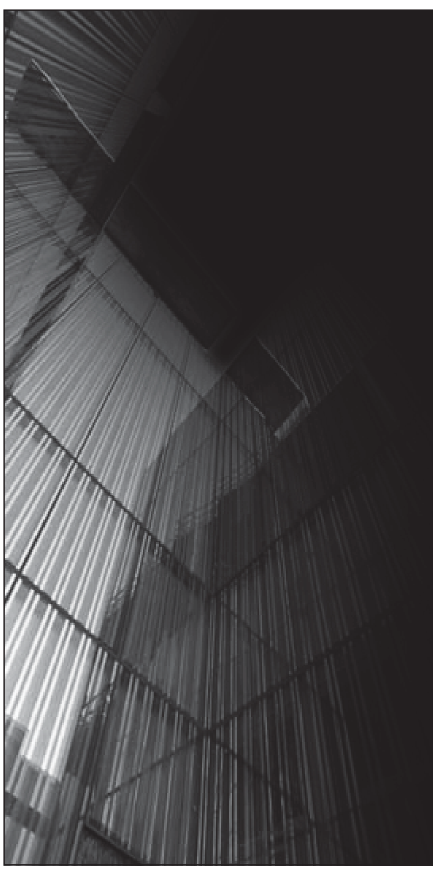
Free-field curvature

$\approx PGA/v_s^2$

Deep Foundation Detailing

- OR follow the deemed to comply detailing:
- Cast in place deep foundations
  - **Minimum longitudinal reinforcement ratio of 0.005 extending full length**
  - **Confinement per ACI 318-11 21.6.4.2, 21.6.4.3, 21.6.4.4 within 7-times least element dimension from top of pile cap, and within 7 "D" of interface**

Final Q&A



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