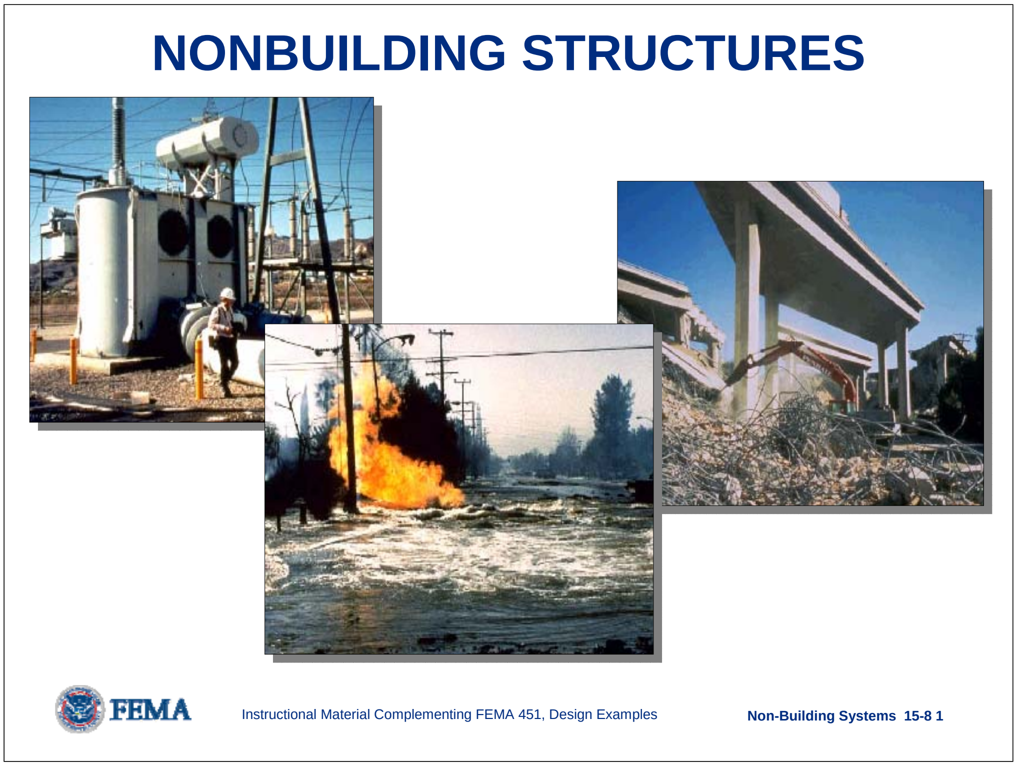


NONBUILDING STRUCTURES

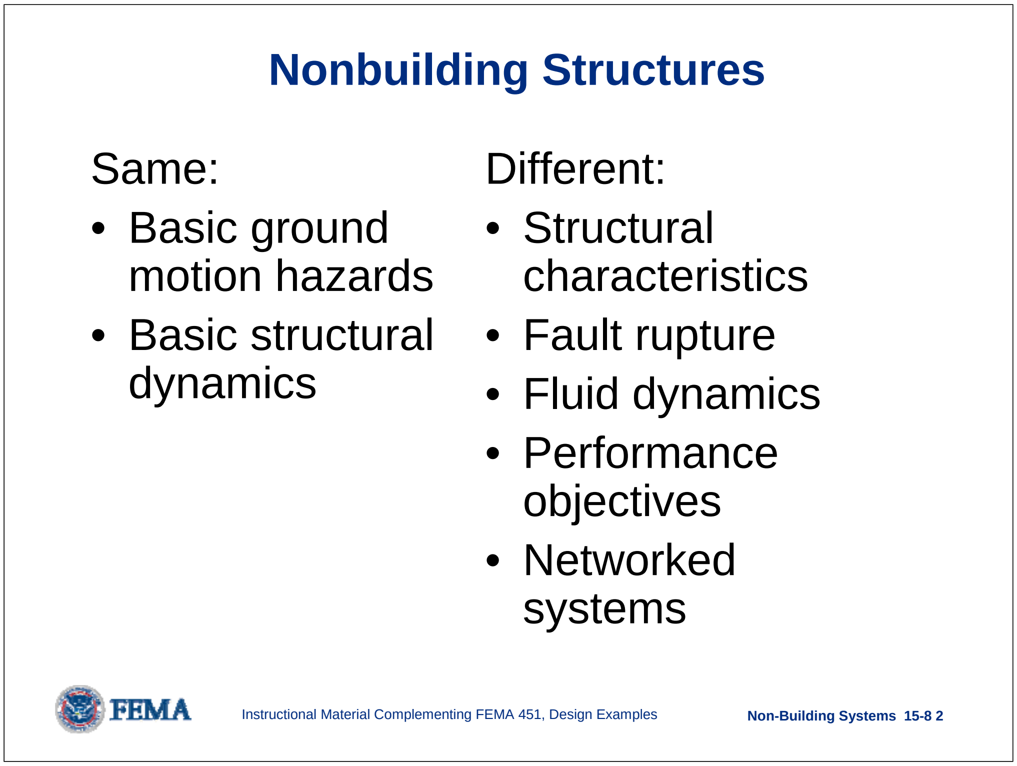
FEMA

Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 1

This unit is only a brief introduction to the subject of earthquake resistant design of nonbuilding structures. It has been developed by Jim Harris from two primary sources: the content of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* and two slide collections of the Earthquake Engineering Research Institute: the “Annotated Slide Collection” and the “EERI Northridge Earthquake of January 1994 Collection.”

The images here are all taken from the 1994 Northridge event: failed transformers in an electric power distribution substation (Sylmar), fire and flood from breaks in buried gas and water mains (Balboa Blvd, Granada Hills), and demolition of damaged highway interchange structures (Gavin Canyon undercrossing, Interstate 5).



Nonbuilding Structures

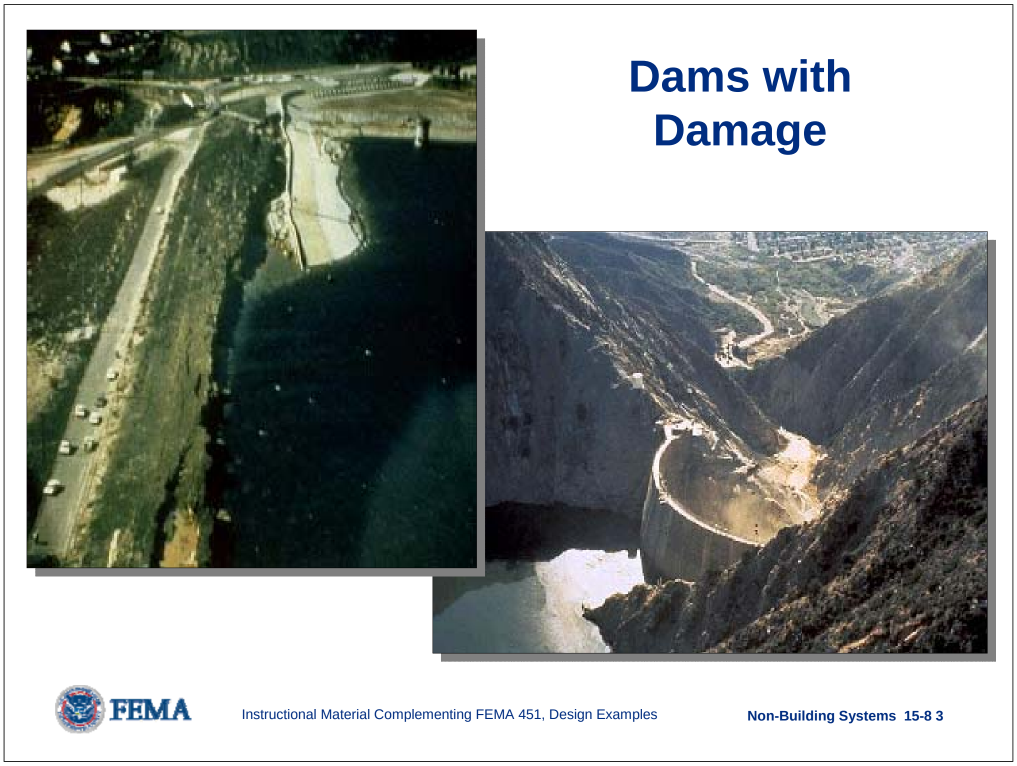
Same:

- Basic ground motion hazards
- Basic structural dynamics

Different:

- Structural characteristics
- Fault rupture
- Fluid dynamics
- Performance objectives
- Networked systems

There are many issues with nonbuilding structures that are not considered in earthquake engineering for buildings



Dams with Damage

Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 3

Left: San Fernando EQ (1971); partial failure of upstream face of lower Van Norman dam, a 40m high earthfill dam about 20 km from epicenter; pga estimated to be 0.3 to 0.5 g; 80,000 people downstream evacuated for several days until water level could be lowered.

Right; Northridge EQ; Pacoima dam, a concrete arch in a rock canyon; used for flood control, thus low water level; measured 2g pga at abutments; extensive rock slides; opened a 2 inch gap at southern thrust block and created several cracks

Issues: liquefaction of hydraulic fills; site conditions; hydrodynamic loads; sloshing

Dam and Water Treatment Plant

FEMA

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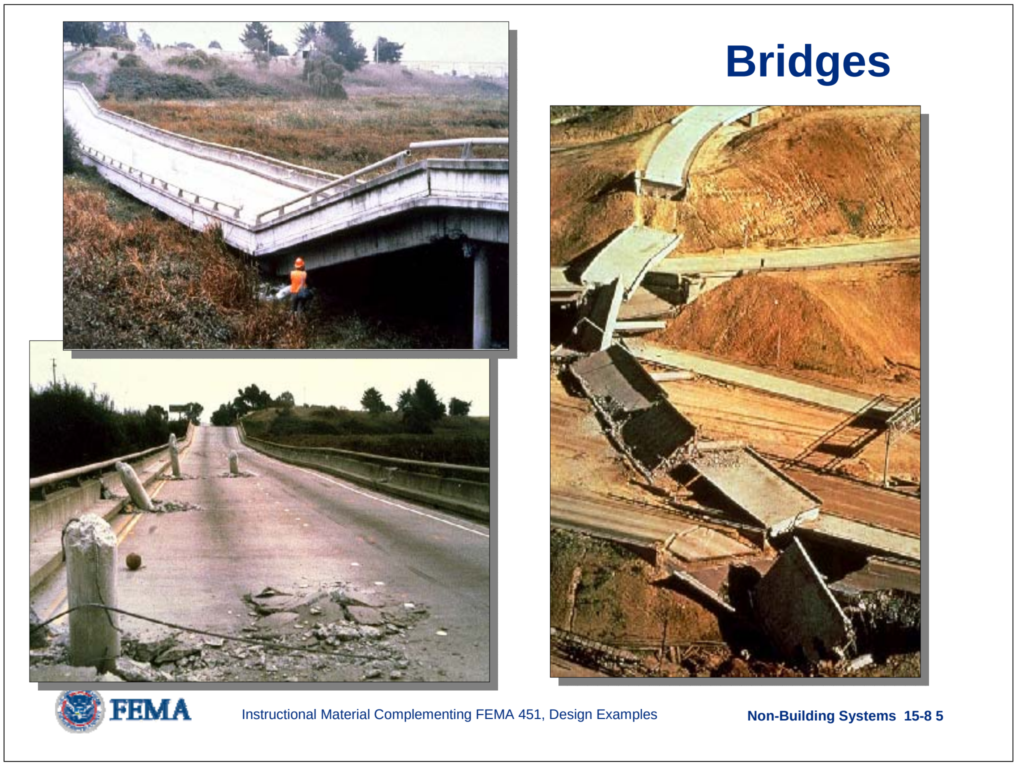
Non-Building Systems 15-8 4

Northridge EQ: Jensen water filtration plant, site of old San Fernando (Van Norman dam) embankment, and new Los Angeles dam above. PGA at Jensen approached 1g at Jenson and were 0.42 g at the abutment of Los Angeles dam. Newer parts of the plant performed quite well, as did the dam

Issues: newer compacted fills/designed dams are vast improvements over hydraulic fills; sloshing, etc.



Bridges

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Non-Building Systems 15-8 5

Left (both): Loma Prieta EQ: Struve Slough bridge (1964, concrete T beam on vertically extended concrete piles, 4 piles per bent)

Right: San Fernando EQ (1971); interchange on San Diego Freeway; failures due to strong ground motions and due to ground failures

Joints at Long Spans

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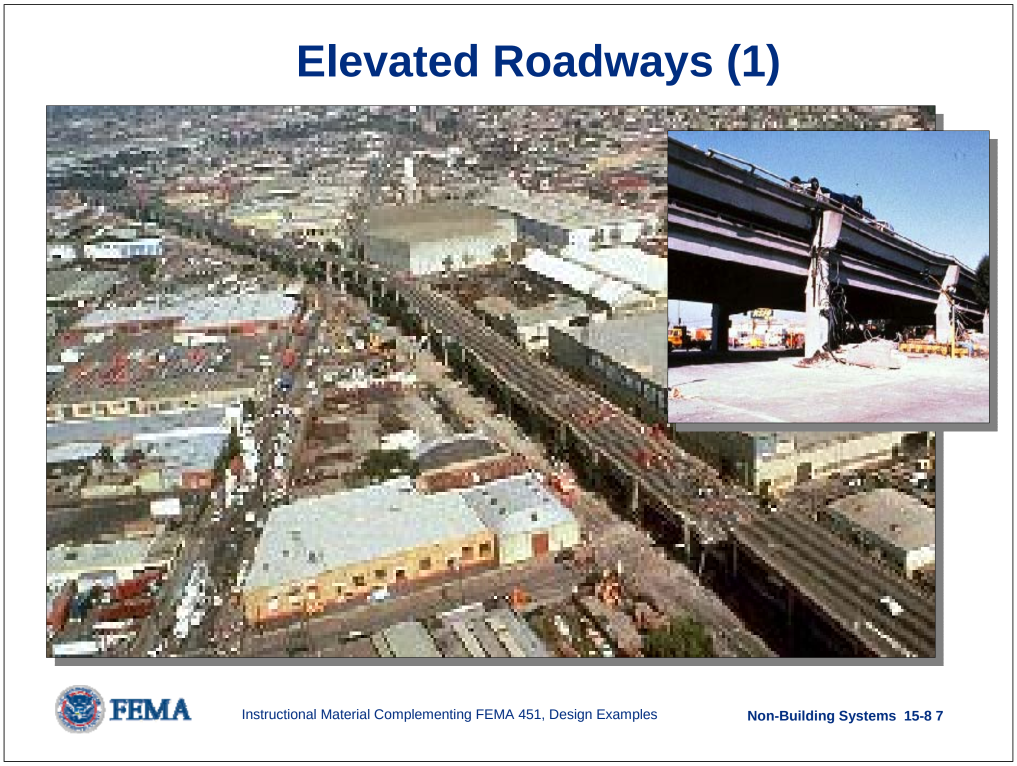
Non-Building Systems 15-8 6

Left: Loma Prieta EQ: San Francisco – Oakland Bay bridge, east end of long cantilever truss bridge, small span dropped off seat at expansion joint

Right: Kobe EQ: Nishinomiya Port arch bridge with similar failure; on Kobe-Osaka freeway; evidence of large soil movement at pier

Issues: large displacements of large structures on soft soils



Elevated Roadways (1)

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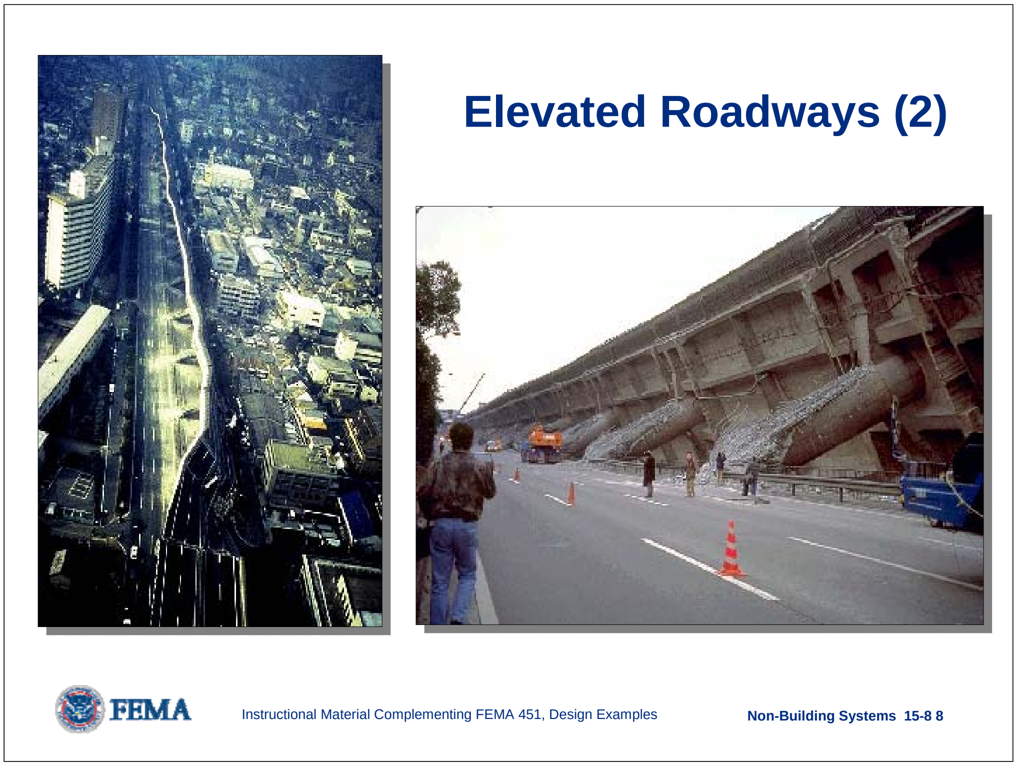
Non-Building Systems 15-8 7

Loma Prieta EQ: Nimitz elevated freeway (I-880, Cyprus viaduct); 50 spans (about 4000 lf) of upper level of two level elevated freeway collapse (out of 124 such spans); 42 fatalities

Issues: very large mass; changes in design considerations over time



Elevated Roadways (2)

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Non-Building Systems 15-8 8

Kobe EQ: Hanshin elevated freeway

Issues: massive structures, lack of redundancy

Lack of Redundancy

Instructional

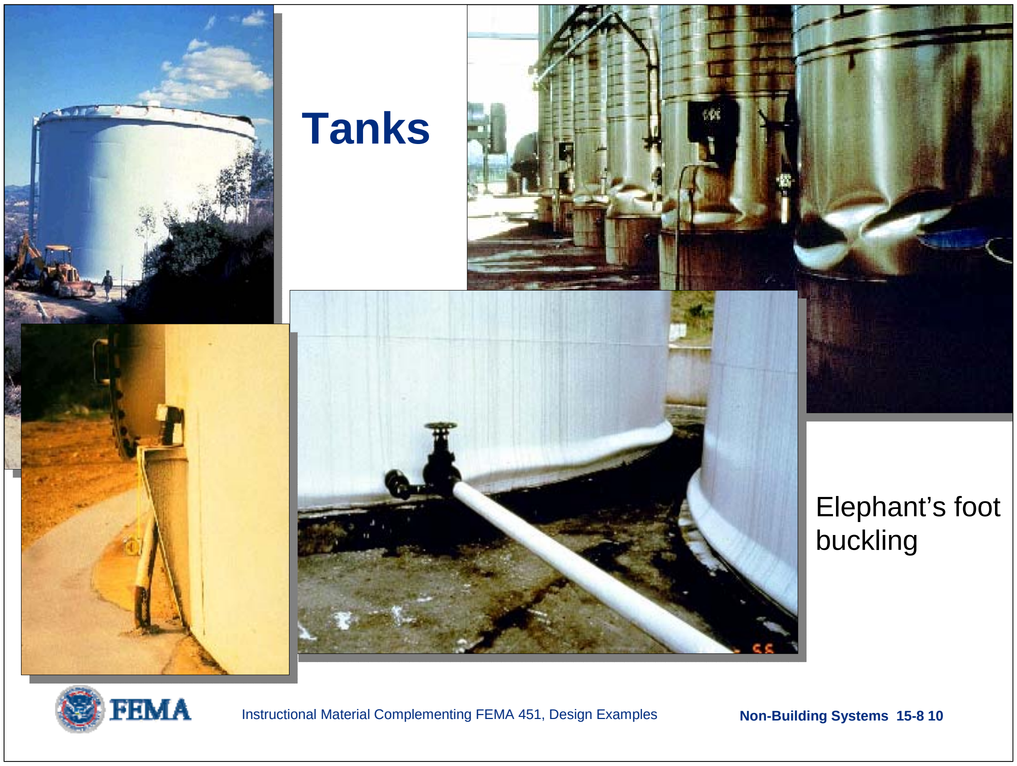
Non-Building Systems 15-8 9

Loma Prieta EQ: Nimitz freeway, Oakland

Left: Upper columns on left side had two hinges; on right side had one hinge, thus upper portal was statically determinate, in order to avoid retraint forces from creep of the post-tensioned girder (1954 design)

Center: Upper column on right side had hinge at its base, thus only moment resisting joint was at the top. Failure here was shear capacity at the lower hinge.

Right: Upper column that completely failed at upper joint



Tanks

Elephant’s foot buckling

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Non-Building Systems 15-8 10

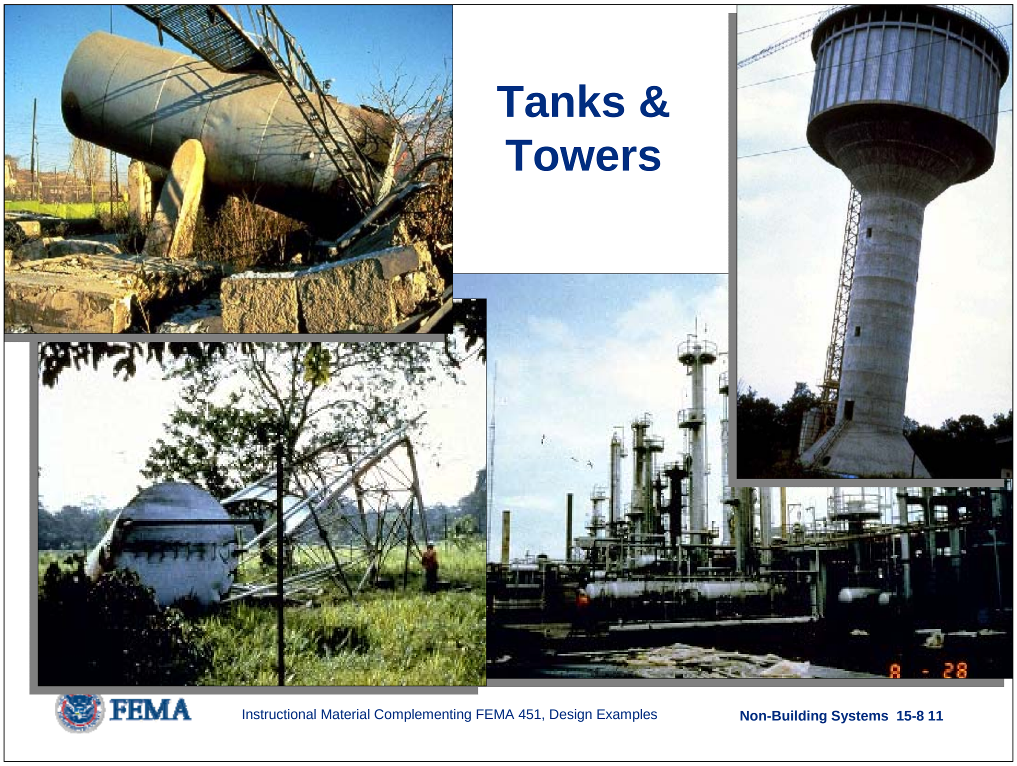
Upper left: Northridge EQ; treated water supply tank. Lost contents due to rupture in piping. Also suffered roof damage and elephants foot buckling.

Upper right: Coalinga EQ; thin wall stainless steel tanks; elephant foots buckling at base of tank

Center: Costa Rica EQ, 1991; benzene storage tanks which buckled but did not fail or lose their contents

Lower left: Northridge EQ; firewater tank with base anchor bolts

Issues: fluid-structure interaction; very compression in shell due to vertical cantilever action of tank; mass



Tanks & Towers

FEMA

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Non-Building Systems 15-8 11

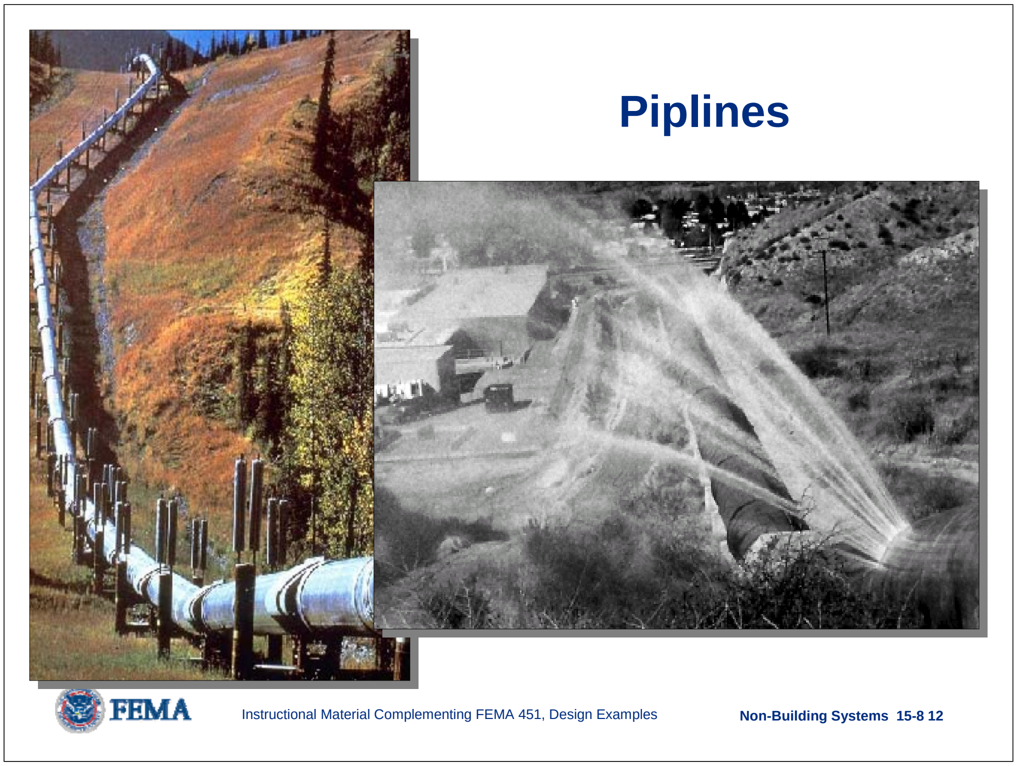
Upper left: Spitak, Armenia EQ; horizontal tank on vertical “saddle” walls; wall at one end overturned, dropping the entire tank and tearing out the piping

Lower left: Costa Rica EQ; elevated tank on trussed tower; apparent buckling of legs

Upper right: Manjil, Iran, 1990; empty water storage tank, just constructed; similar full tank completely destroyed

Lower right: Costa Rica EQ 1991; refinery process columns undamaged; designed for hurricane winds

Issues: large mass, little redundancy



Piplines

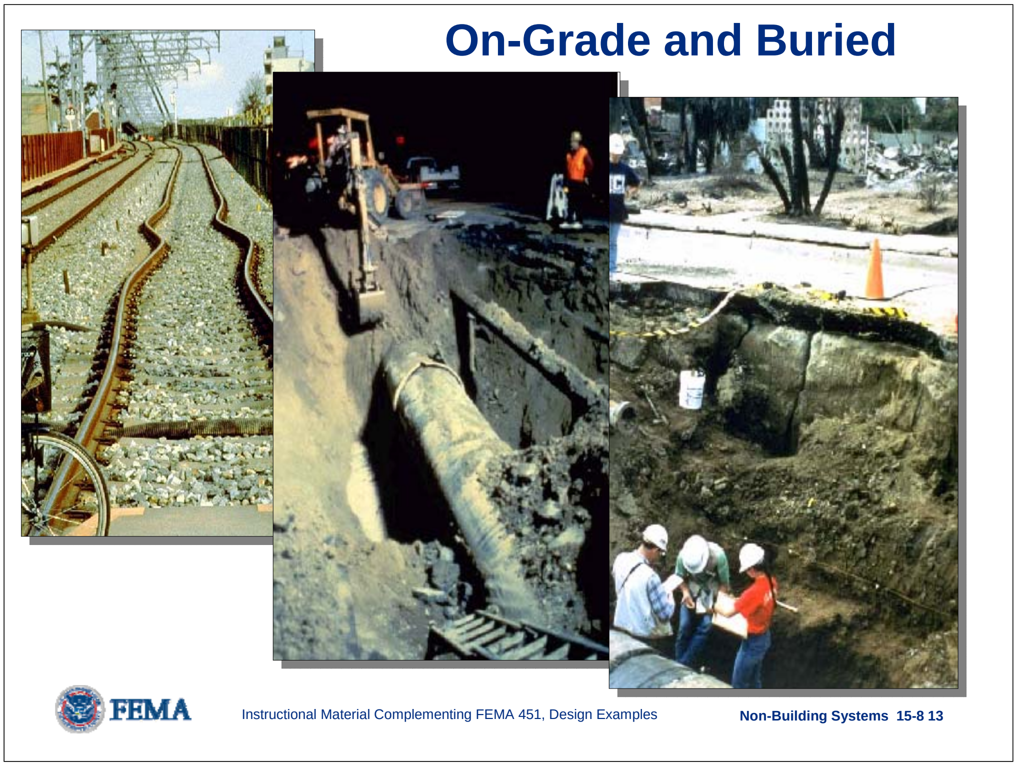
Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 12

Left: No earthquake damage; Trans-Canada gas transmission pipeline; design must account for potential fault displacement, among many other issues

Right: Northridge EQ; Soledad inverted syphon, 120” diameter, 3/8” wall welded steel water supply system carrying water from the Owens Valley system to Southern CA.

Issues: need to resist/accommodate displacements of ground



On-Grade and Buried

Instructional Material Complementing FEMA 451, Design Examples

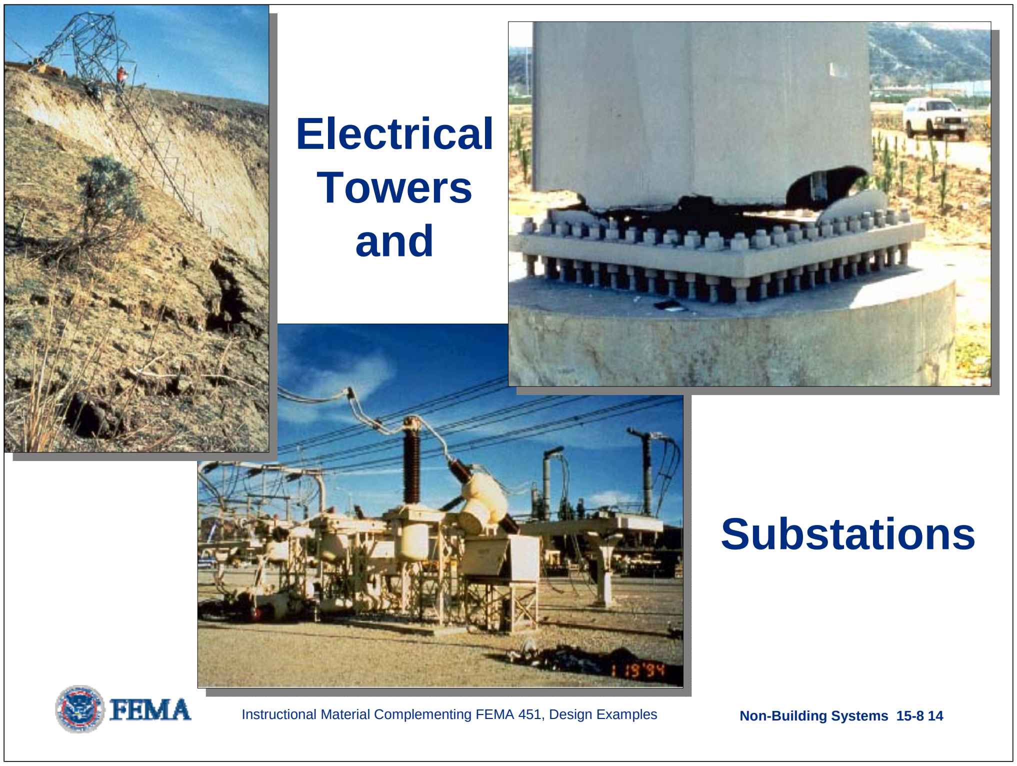
Non-Building Systems 15-8 13

Right: Kobe EQ: buckling of rails

Center: Northridge EQ; compression failure in 48” water line

Right: Northridge EQ; tension cracks in soil where buried pipe pulled apart; not far from compression photo

Issues: Linear structures must cross zones of likely ground failure; network concepts of system performance are important



Electrical Towers and Substations

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Instructional Material Complementing FEMA 451, Design Examples

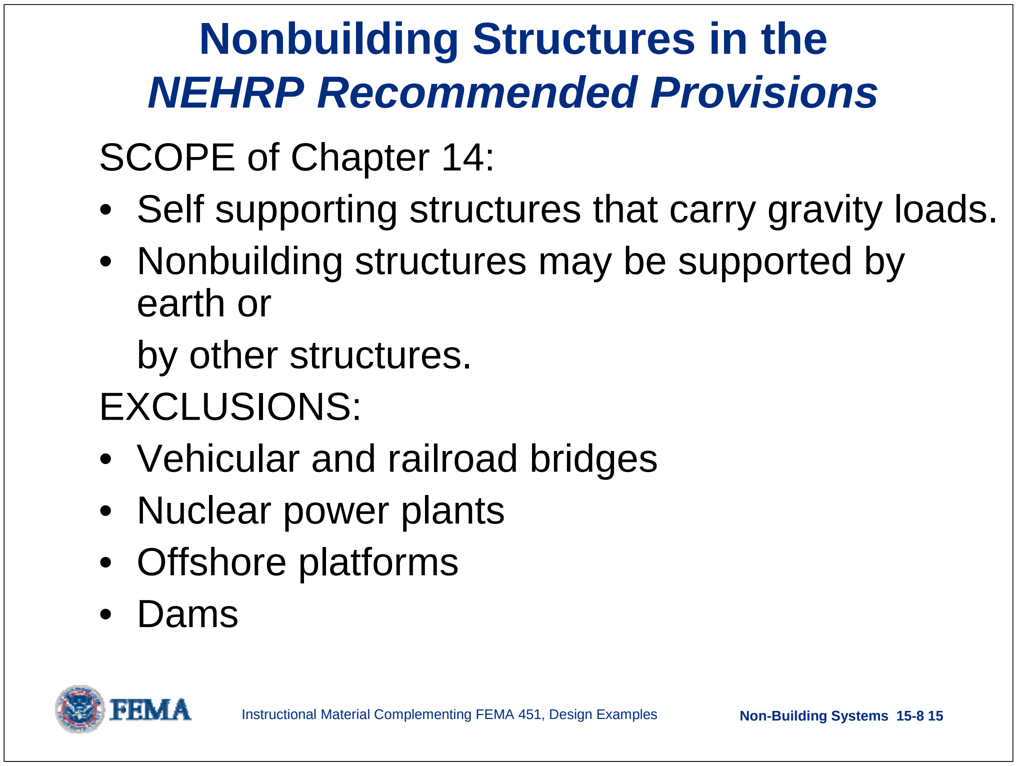
Non-Building Systems 15-8 14

Left: Northridge EQ; first observed failure of lattice-type steel transmission line tower; located on a ridge crest and failed due to differential foundation movement; all six conductors snapped, bringing down four adjacent towers

Right: Northridge EQ; Pardee substation; one leg of two legged transmission tower for 220 kV line; 60” square at base, ¾” thick plate, sized for stiffness; weld that did not develop strength of plate. Ten such towers were leaning

Lower: Northridge EQ; Pardee substation; porcelain insulator components damaged at 230 kV live tank circuit breakers

Issues: generally low mass; some components inherently brittle; network concepts



Nonbuilding Structures in the *NEHRP Recommended Provisions*

SCOPE of Chapter 14:

- Self supporting structures that carry gravity loads.
- Nonbuilding structures may be supported by earth or
  by other structures.

EXCLUSIONS:

- Vehicular and railroad bridges
- Nuclear power plants
- Offshore platforms
- Dams

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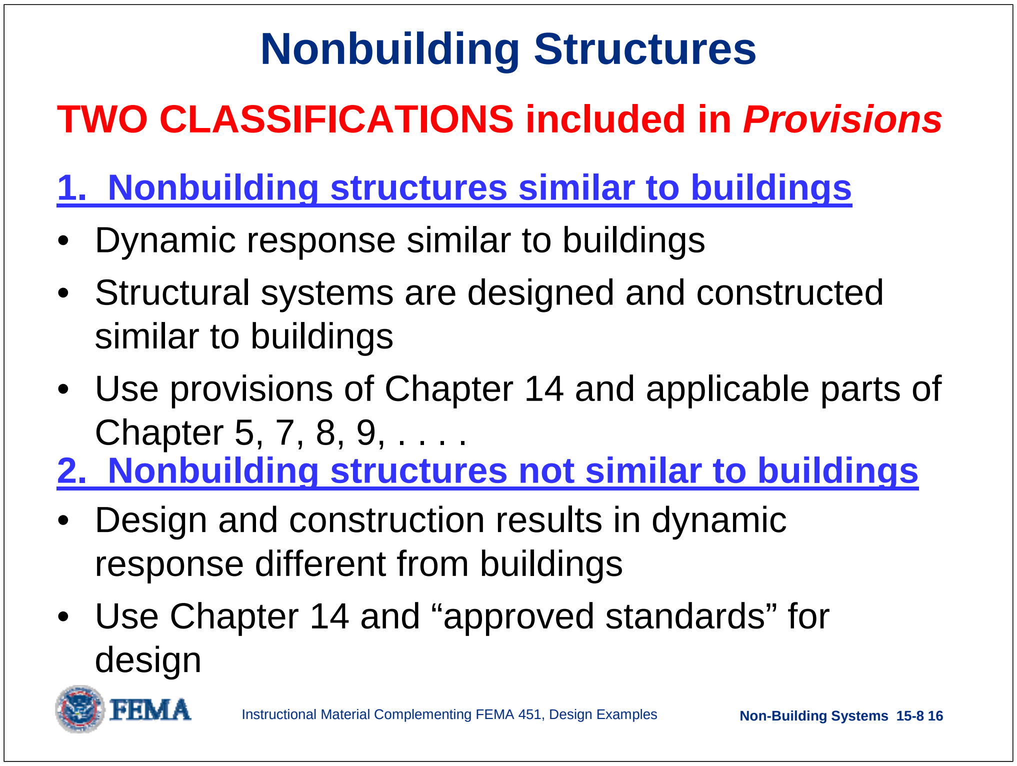
Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 15

The structural design of the excluded items is covered by other well established standards. For example, structural design of highway bridges is covered by the AASHTO *Bridge Design Specification.* Although it was not at the time the Nimitz elevated freeway was designed.



Nonbuilding Structures

TWO CLASSIFICATIONS included in *Provisions*

1. Nonbuilding structures similar to buildings

- Dynamic response similar to buildings
- Structural systems are designed and constructed similar to buildings
- Use provisions of Chapter 14 and applicable parts of Chapter 5, 7, 8, 9, ...

2. Nonbuilding structures not similar to buildings

- Design and construction results in dynamic response different from buildings
- Use Chapter 14 and “approved standards” for design

FEMA Instructional Material Complementing FEMA 451, Design Examples **Non-Building Systems 15-8 16**

Some nonbuilding structures are quite similar to buildings in their configuration, construction and dynamic behavior. These structures can be designed using the appropriate sections in the body of the NEHRP *Provisions* with exceptions provided in Chapter 14. Nonbuilding structures not similar to buildings require the use of alternative design provisions which are published in industry standards by such organizations as ASCE, ASME, API (American Petroleum Institute), AWWI (American Water Works Institute), and many others. Among the differences between buildings and nonbuilding structures similar to buildings are that partitions and cladding usually add significant damping to buildings. One example of nonbuilding response quite different from buildings is the sloshing of fluids in a tank.

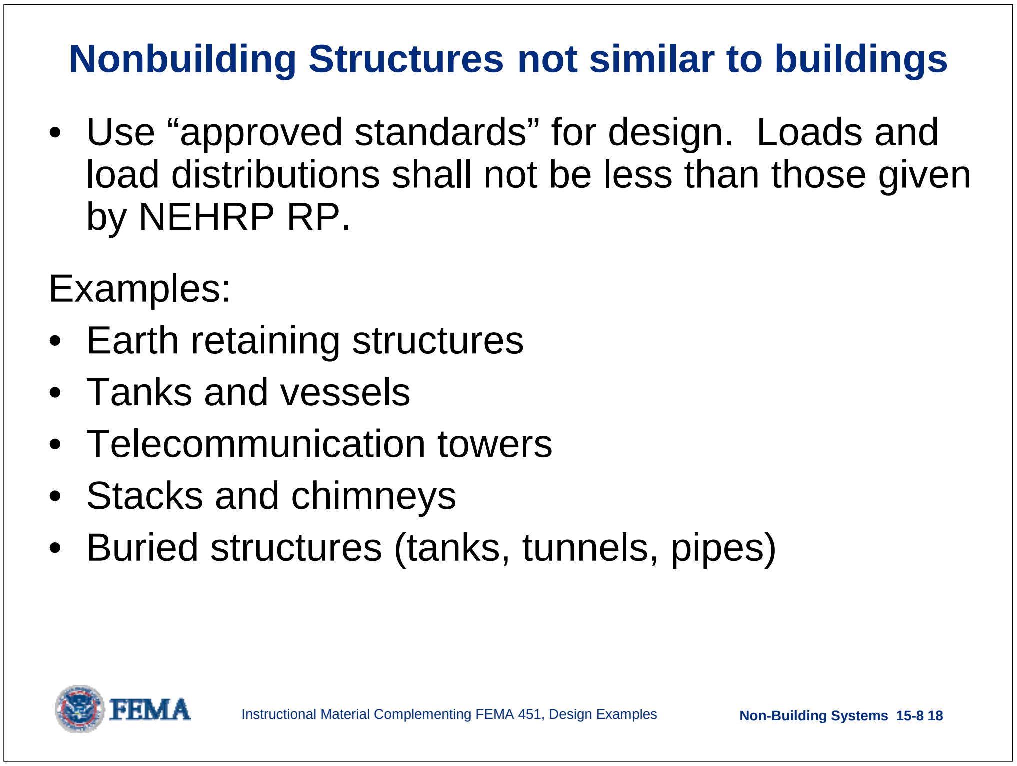
Nonbuilding Structures defined similar to buildings (2000)

Examples:

- Pipe racks
- Steel storage racks
- Electric power generation facilities
- Structural towers for tanks & vessels

(Many of these have changed in the 2003 edition)

Examples of nonbuilding structures that are considered similar to buildings. The design of steel storage racks should follow the requirements in the RMI design standard, *Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks*. Clearly, damping is not necessarily similar to buildings.



Nonbuilding Structures not similar to buildings

- Use “approved standards” for design. Loads and load distributions shall not be less than those given by NEHRP RP.

Examples:

- Earth retaining structures
- Tanks and vessels
- Telecommunication towers
- Stacks and chimneys
- Buried structures (tanks, tunnels, pipes)

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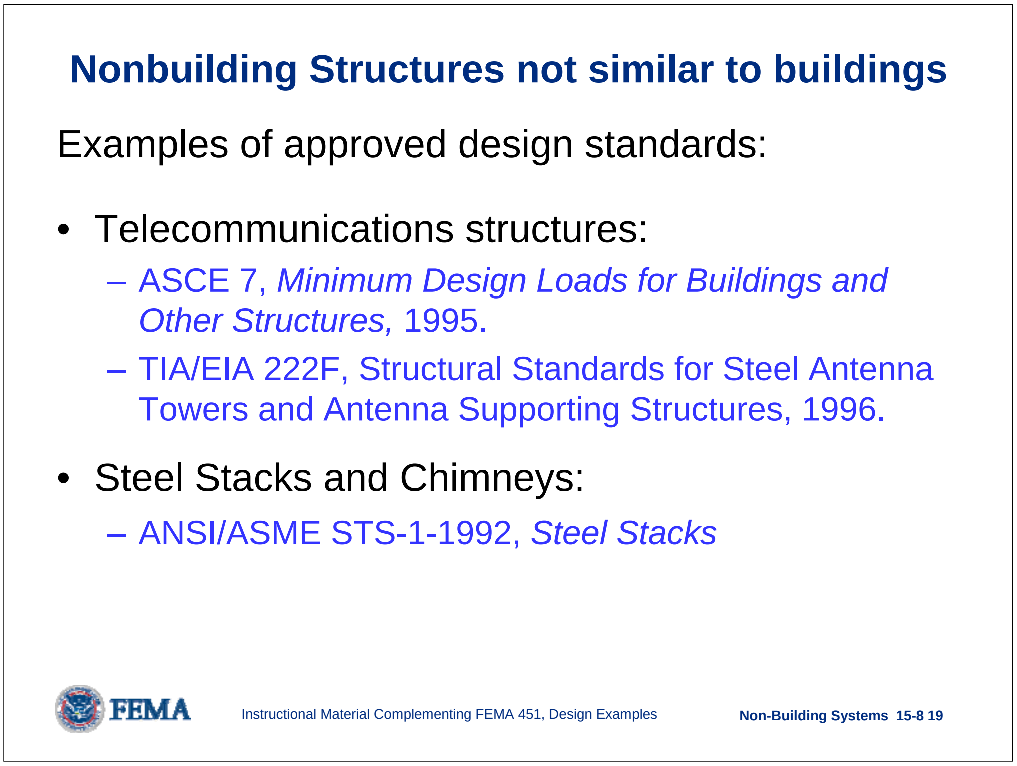
Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 18

Examples of nonbuilding structures not similar to buildings. Most such structures will be designed according to other standards. The Appendix to Chapter 14 lists many such standards. The *Provisions* provide a few additional requirements for the seismic design of these structures–mostly in the Appendix. The primary issue is that the ground motion and design spectrum are based upon the *Provisions.*

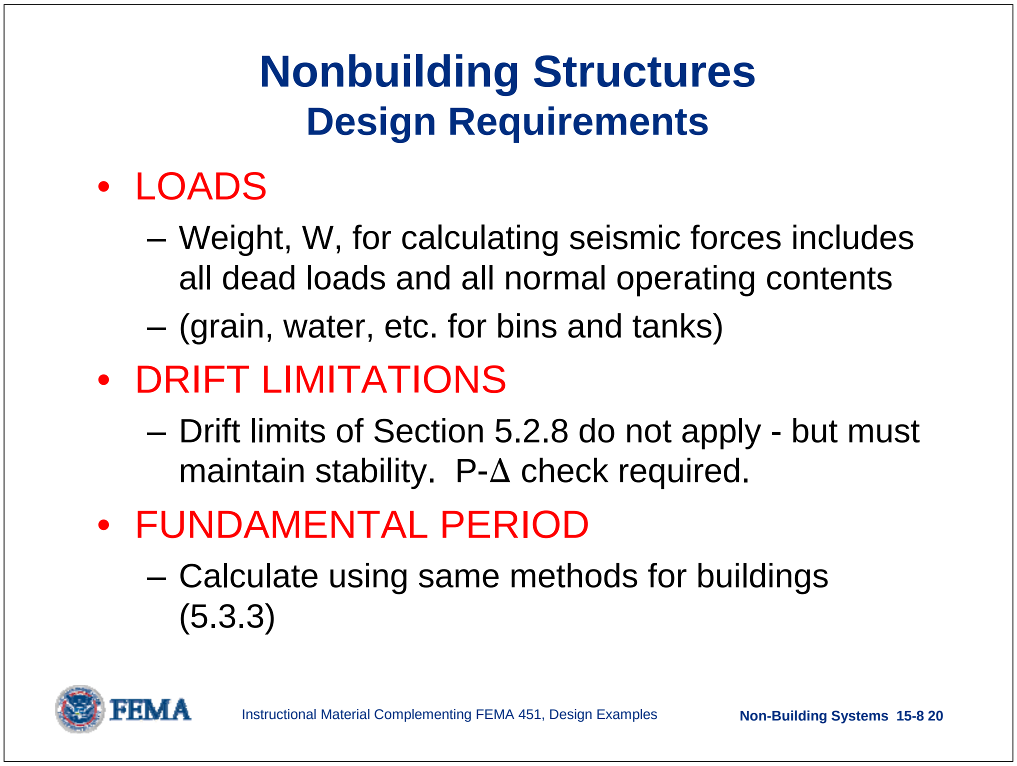


Nonbuilding Structures not similar to buildings

Examples of approved design standards:

- Telecommunications structures:
  - ASCE 7, *Minimum Design Loads for Buildings and Other Structures,* 1995.
  - TIA/EIA 222F, Structural Standards for Steel Antenna Towers and Antenna Supporting Structures, 1996.
- Steel Stacks and Chimneys:
  - ANSI/ASME STS-1-1992, *Steel Stacks*

A very brief listing of example design standards. TIA stands for Telecommunications Industry Association. *ASCE 7 Seismic* is the same as *NEHRP*; the use of *ASCE 7* for towers is primarily for wind.



Nonbuilding Structures
Design Requirements

- LOADS
  - Weight, W, for calculating seismic forces includes all dead loads and all normal operating contents
  - (grain, water, etc. for bins and tanks)
- DRIFT LIMITATIONS
  - Drift limits of Section 5.2.8 do not apply - but must maintain stability. P-Δ check required.
- FUNDAMENTAL PERIOD
  - Calculate using same methods for buildings (5.3.3)

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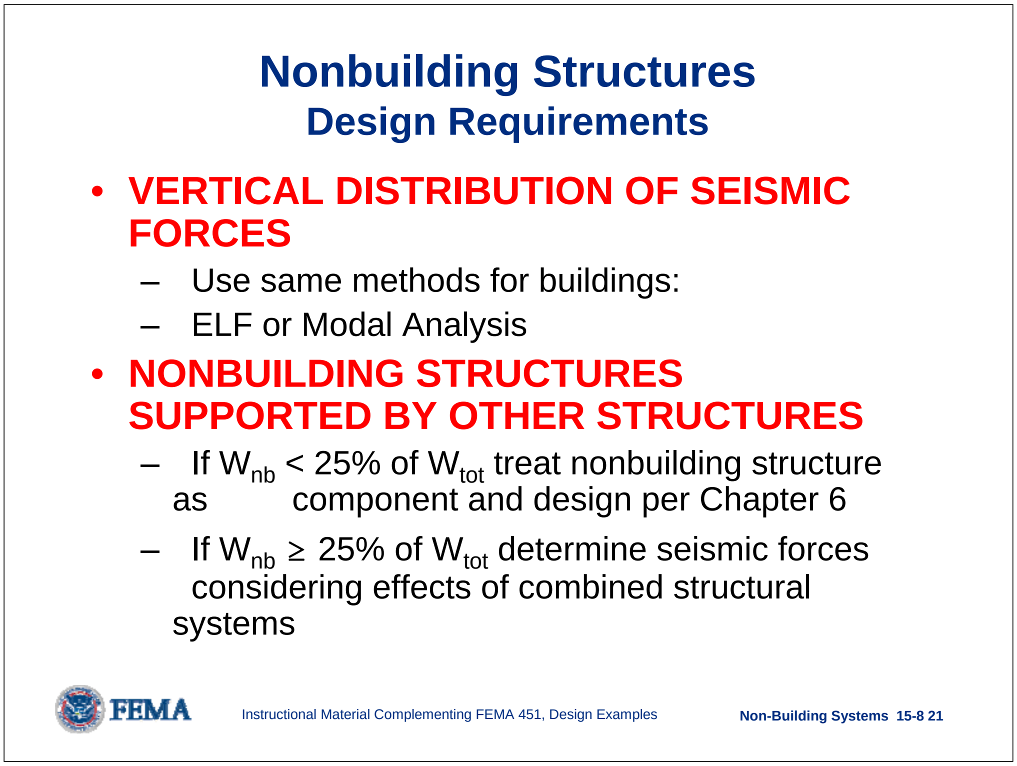
Seismic design requirements and general design rules for nonbuilding structures (Sections 14.1 and 14.2).

For the design of tanks, bins, vessels, etc., it is necessary to include the total weight of all the operating contents when calculating seismic design forces. This is a slight departure from building structures where only a portion (if any) of the live load is considered in the seismic mass.

Drift limitations for nonbuilding structures are waived because damage control of architectural finishes (cladding, windows) is not an issue.

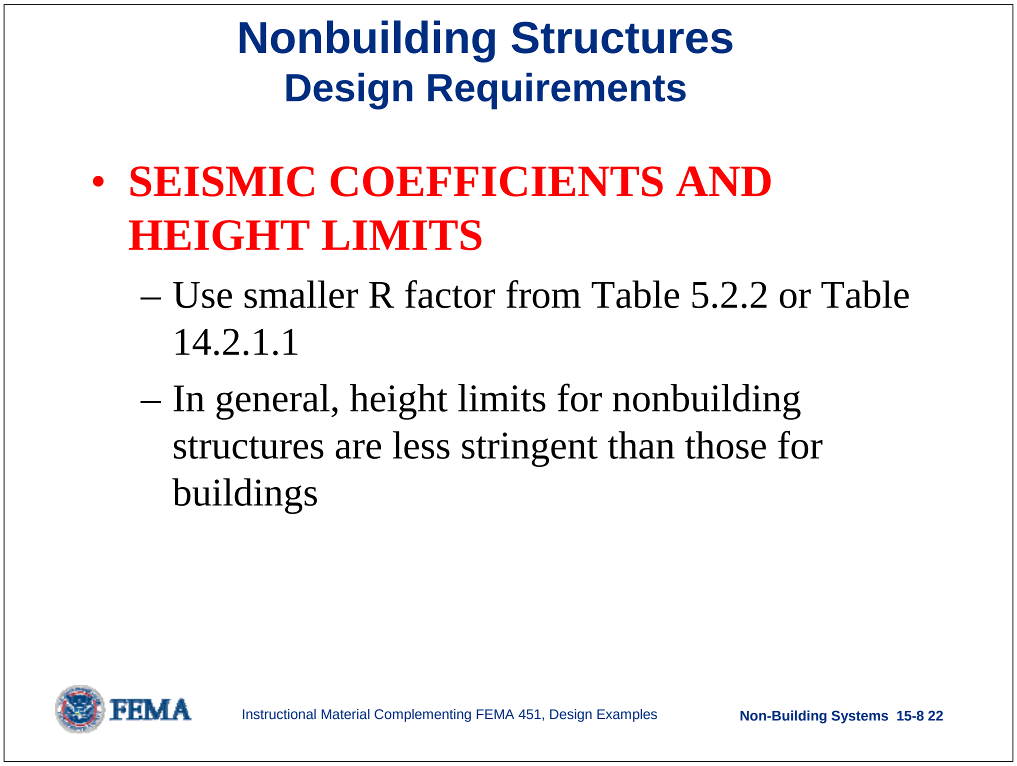
Special analysis techniques to calculate period are required for nonbuilding structures not similar to buildings.



Nonbuilding Structures
Design Requirements

- VERTICAL DISTRIBUTION OF SEISMIC FORCES
  - Use same methods for buildings:
  - ELF or Modal Analysis
- NONBUILDING STRUCTURES SUPPORTED BY OTHER STRUCTURES
  - If W_{nb} < 25% of W_{tot} treat nonbuilding structure as component and design per Chapter 6
  - If $W_{nb} \geq$ 25% of W_{tot} determine seismic forces considering effects of combined structural systems

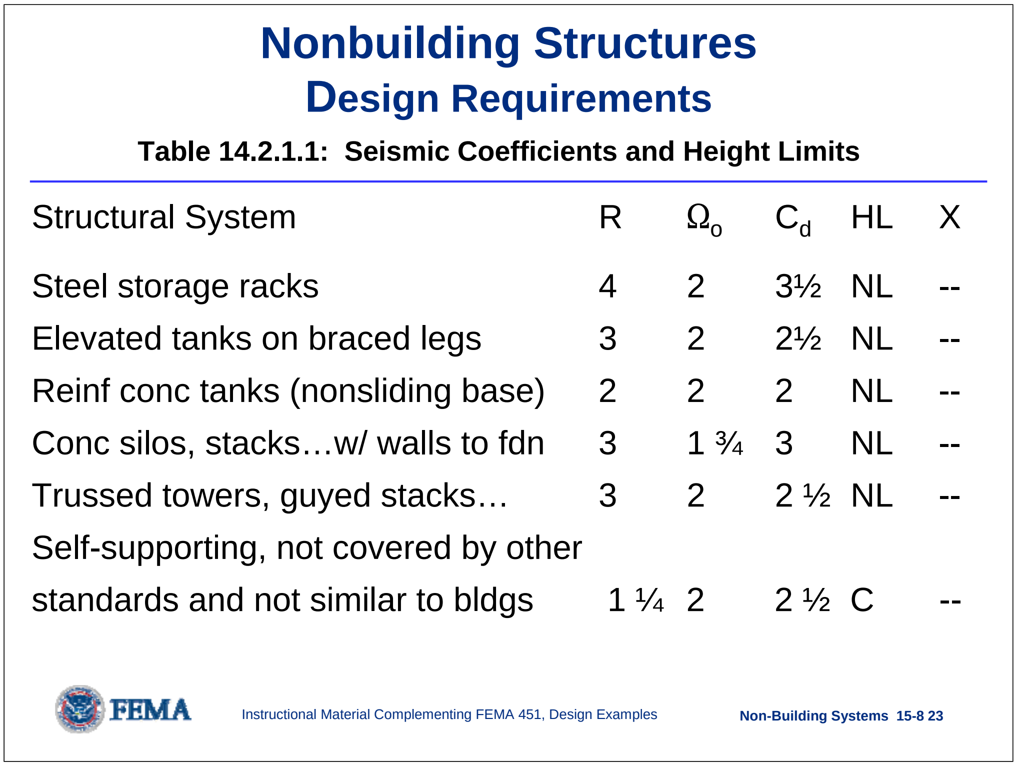
Nonbuilding structures with irregular distribution of mass are good candidates for modal response spectrum analysis. When a nonbuilding structure is supported by another structure, the design procedures are dependent on the relative weight of the non-building structure (W_{nb}) and the supporting structure. If the non-building structure is relatively light the design can follow the rules given in Chapter 6 for components and attachments. If the non-building structure is relatively heavy, the weight and structural system of both structures must be accounted for in the design.



Nonbuilding Structures
Design Requirements

- **SEISMIC COEFFICIENTS AND HEIGHT LIMITS**
  - Use smaller R factor from Table 5.2.2 or Table 14.2.1.1
  - In general, height limits for nonbuilding structures are less stringent than those for buildings

Table 14.2.1.1 lists seismic coefficients and height limitations (by SDC) for a wide variety of nonbuilding structures. Some structural systems are also covered in Table 5.2.2. In general, the limitations on height for a given structural system are not as strict as those for buildings.



Nonbuilding Structures

Design Requirements

Table 14.2.1.1: Seismic Coefficients and Height Limits

Structural System	R	Ω_o	C_d	HL	X
Steel storage racks	4	2	3½	NL	--
Elevated tanks on braced legs	3	2	2½	NL	--
Reinf conc tanks (nonsliding base)	2	2	2	NL	--
Conc silos, stacks…w/ walls to fdn	3	1 ¾	3	NL	--
Trussed towers, guyed stacks…	3	2	2 ½	NL	--
Self-supporting, not covered by other standards and not similar to bldgs	1 ¼	2	2 ½	C	--

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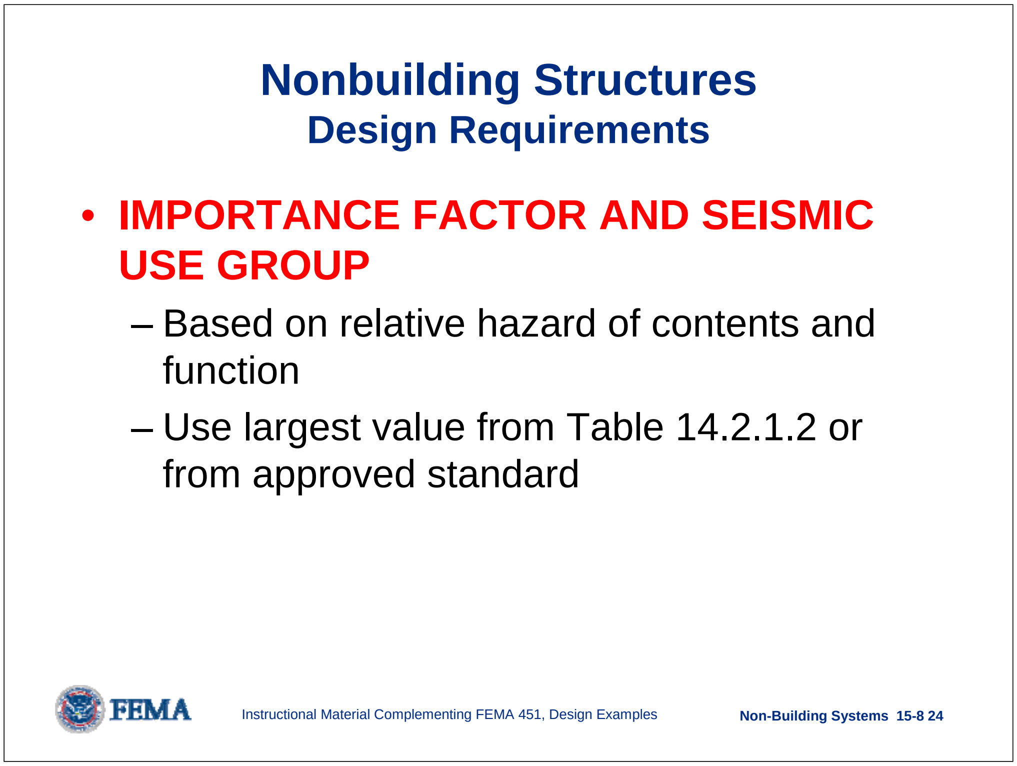
Non-Building Systems 15-8 23

A sample of nonbuilding structural systems. Note that for SDC D an intermediate concrete moment frame has a 50 ft. height limitation for nonbuilding structures (Table 14.2.1.1) but for buildings, this structural system is not allowed at all.

Much of this information is changing in the 2003 edition.



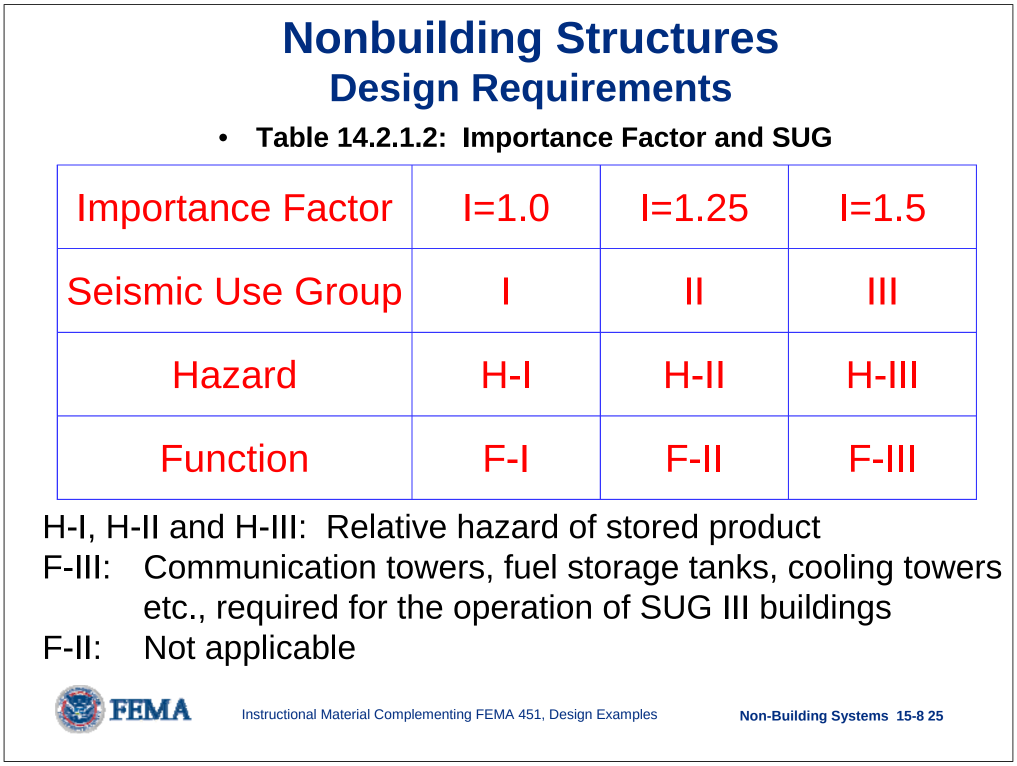
Nonbuilding Structures
Design Requirements

- **IMPORTANCE FACTOR AND SEISMIC USE GROUP**
  - – Based on relative hazard of contents and function
  - – Use largest value from Table 14.2.1.2 or from approved standard

Instructional Material Complementing FEMA 451, Design Examples

Non-Building Systems 15-8 24

The basis for determining importance factors for nonbuilding structures is the same as that for buildings Structures deemed especially hazardous or critical to post earthquake recovery are given a larger importance factor.



Nonbuilding Structures

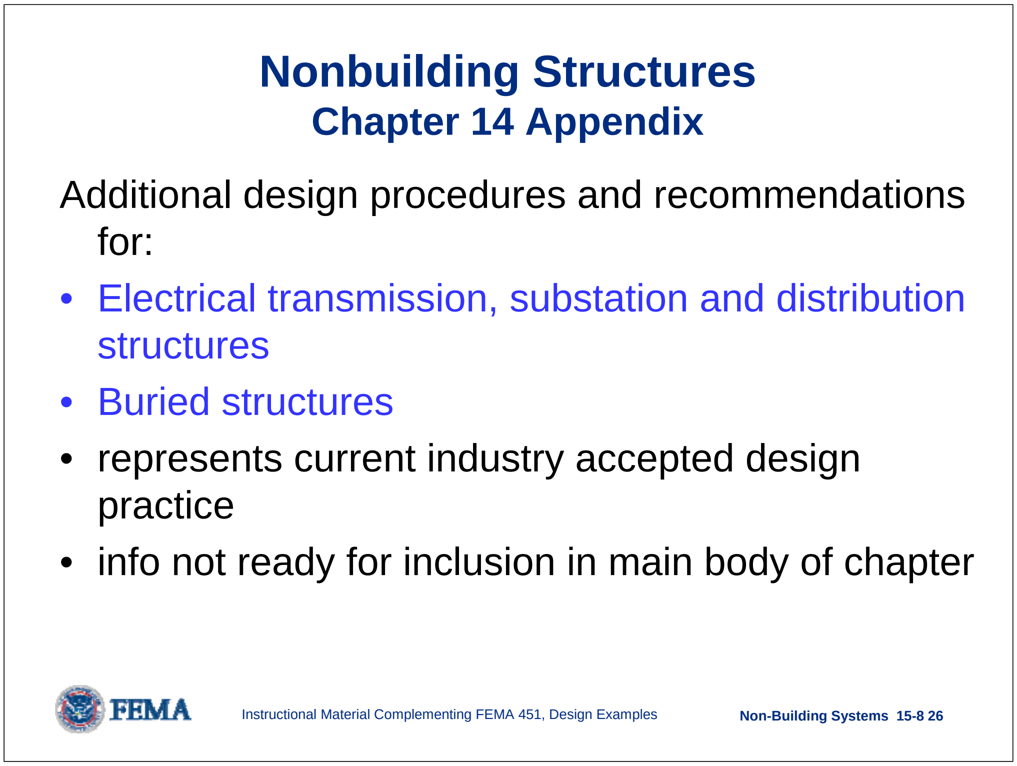
Design Requirements

- **Table 14.2.1.2: Importance Factor and SUG**

Importance Factor	I=1.0	I=1.25	I=1.5
Seismic Use Group	I	II	III
Hazard	H-I	H-II	H-III
Function	F-I	F-II	F-III

H-I, H-II and H-III: Relative hazard of stored product
F-III: Communication towers, fuel storage tanks, cooling towers etc., required for the operation of SUG III buildings
F-II: Not applicable

‘Hazard’ in this table is applicable only to tanks and other vessels which may contain materials posing biological, environmental, fire or other risks if these structures should fail. Nonbuilding structures are classified in this table in regards to ‘Function” as either F-I or F-III. F-II is not used.



Nonbuilding Structures

Chapter 14 Appendix

Additional design procedures and recommendations for:

- Electrical transmission, substation and distribution structures
- Buried structures
- represents current industry accepted design practice
- info not ready for inclusion in main body of chapter

The design requirements found in the Appendix to Chapter 14 require additional review and support of consensus documents before they can be included in the main body of the chapter.