Chapter 33: Response and Design Spectra

Introduction

In the context of earthquake engineering, understanding how structures respond to dynamic loads such as seismic ground motions is essential. One of the most powerful tools for this purpose is the **response spectrum**, which provides a concise and effective means to represent the peak response (e.g., displacement, velocity, or acceleration) of a structure as a function of its dynamic properties, particularly the natural period and damping ratio.

Complementing this, the **design spectrum** is a modified version of the response spectrum, tailored to be used in seismic design codes for ensuring structural safety and compliance. These spectra are indispensable in both linear and nonlinear dynamic analysis of structures subjected to earthquake ground motion.

This chapter aims to explore the theoretical background, development, and practical application of response and design spectra in the seismic design and analysis of structures.

33.1 Basic Concepts of Response Spectrum

33.1.1 Single-Degree-of-Freedom (SDOF) System Response

- A response spectrum is built from the dynamic response of an SDOF system subjected to a ground motion.
- Governing equation:

$$m\ddot{u}(t)+c\dot{u}(t)+ku(t)=-m\ddot{u}_g(t)$$

  where:

  - $u(t)$: Relative displacement
  - $\ddot{u}_g(t)$: Ground acceleration
  - m, c, k: Mass, damping, and stiffness

33.1.2 Peak Response Parameters

- **Displacement response spectrum** S_d

- **Velocity response spectrum** S_v
- **Acceleration response spectrum** S_a

Each parameter is plotted against the natural period T or frequency ω of the system.

33.2 Construction of Response Spectra

33.2.1 Time-History Analysis for SDOF Systems

- Step-by-step numerical integration (e.g., Newmark-beta method) is used to obtain peak responses.
- Spectra are constructed by varying the natural period and damping ratio.

33.2.2 Normalization

- The spectrum may be **normalized** by peak ground acceleration (PGA), peak ground velocity (PGV), or peak ground displacement (PGD).

33.3 Damping and its Influence on the Spectra

33.3.1 Damping Ratio (ζ)

- Common damping levels: 2%, 5%, 10%
- The higher the damping, the lower the spectral ordinates.

33.3.2 Family of Response Spectra

- Multiple spectra are developed for different damping ratios.
- Useful in assessing the influence of damping on structural response.

33.4 Elastic vs. Inelastic Response Spectra

33.4.1 Elastic Response Spectrum

- Assumes linear behavior of structures.
- Used for initial structural design and analysis.

33.4.2 Inelastic (Reduction) Spectra

- Accounts for plastic deformation.

- Uses a **response modification factor (R)** or **ductility factor (μ)** to reduce elastic demands.

33.5 Pseudo-Spectral Quantities

- **Pseudo-acceleration**: $S_a = \omega^2 S_d$
- **Pseudo-velocity**: $S_v = \omega S_d$

These are not exact values but are used in spectral analysis for simplification, especially in code-based procedures.

33.6 Design Spectra

33.6.1 Need for Design Spectrum

- Real earthquake data varies with location, magnitude, and soil.
- Standardized **design spectra** provide a generalized approach for engineering use.

33.6.2 Features of Design Spectra

- Piecewise linear or curved plots
- Defined for different soil types: rock, stiff soil, soft soil
- Based on zoning and seismic hazard data

33.6.3 Parameters in Code-Based Design Spectra

- **Zone factor (Z)** – defines seismic intensity for a location
- **Importance factor (I)** – depends on structure's use
- **Response reduction factor (R)** – accounts for ductility, redundancy, overstrength

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33.7 IS 1893 Design Spectrum

33.7.1 Spectrum Shape

- Typically a plot of **spectral acceleration (Sa/g)** vs. **time period (T)**
- Divided into three regions:
    a. Acceleration-sensitive region (short-period)

b. Velocity-sensitive region (medium-period)
c. Displacement-sensitive region (long-period)

33.7.2 Design Acceleration Spectrum (IS 1893: Part 1 – 2016)

$$S_a/g = \begin{cases} 1+15T, & 0 < T \leq 0.1 \\ 2.5, & 0.1 < T \leq 0.55 \\ 1.36/T, & 0.55 < T \leq 4.0 \end{cases}$$

Multiplied by $Z/2 \times I/R$ to get final spectral ordinates.

33.8 Site Effects and Soil Amplification

33.8.1 Influence of Local Geology

- Soil profile can amplify or de-amplify ground motion.
- Site-specific design spectra are used in critical infrastructure projects.

33.8.2 Code Provisions for Soil Types

- IS code provides different spectra shapes for:
  - Type I: Rock or hard soil
  - Type II: Medium soil
  - Type III: Soft soil

33.9 Vertical Spectra and Multi-Directional Effects

33.9.1 Vertical Response Spectra

- Often 2/3rd or 1/2 of horizontal spectra
- Required for analysis of elements sensitive to vertical motions (e.g., bridges, cantilevers)

33.9.2 Combination of Directional Effects

- SRSS (Square Root of Sum of Squares)
- CQC (Complete Quadratic Combination)

33.10 Application of Design Spectra in Structural Design

33.10.1 Seismic Load Calculation

$$V_b = \frac{Z I S_a}{2 R g} \cdot W$$

Where:

- V_b: Base shear
- W: Seismic weight
- S_a/g: Spectral acceleration

33.10.2 Response Spectrum Method (Linear Dynamic Analysis)

- Used in high-rise and irregular structures.
- Modal responses combined using SRSS or CQC.

33.11 Comparison with Time History Analysis

Aspect	Response Spectrum	Time History Analysis
Complexity	Low	High
Computation Time	Fast	Slow
Accuracy	Approximate	More accurate
Use Case	Regular, simple structures	Critical structures

33.12 Limitations and Assumptions

- Assumes response is governed by linear SDOF systems.
- Ignores phase information in ground motion.
- Cannot be used for detailed non-linear time history evaluation.

33.13 Development of Site-Specific Response Spectra

33.13.1 Necessity for Site-Specific Spectra

- Used for critical or important structures such as nuclear power plants, dams, hospitals, etc.

- Accounts for:
    - Local soil conditions
    - Basin effects
    - Historical seismicity

33.13.2 Steps in Site-Specific Spectrum Development

1. **Ground motion selection**: Choose compatible real or synthetic ground motions based on seismic hazard.
2. **Ground response analysis**: Perform equivalent-linear or nonlinear site response analysis.
3. **Spectral analysis**: Calculate response spectra from ground motion time histories.
4. **Statistical aggregation**: Use average or envelope spectra.

33.14 Uniform Hazard Spectrum (UHS)

- Represents the **spectral ordinates corresponding to a uniform probability of exceedance** at different periods.
- Derived from **Probabilistic Seismic Hazard Analysis (PSHA)**.
- Used in performance-based seismic design.

33.15 Comparison Between Code-Based and Site-Specific Spectra

Feature	Code-Based Spectrum	Site-Specific Spectrum
Source	National seismic code	Ground motion records + site data
Soil Amplification	Generalized by soil types	Detailed via geotechnical data
Seismic Hazard Representation	Deterministic or semi-probabilistic	Fully probabilistic
Accuracy	Moderate	High
Application	General structures	Critical/infrastructure projects

33.16 Use of Design Spectrum in Performance-Based Design

33.16.1 Performance Objectives

- **Operational** (minor damage)
- **Life safety** (moderate damage)
- **Collapse prevention** (major damage)

Design spectra are modified based on performance levels and hazard exceedance probabilities.

33.16.2 Demand-Capacity Ratios

- Spectrum used to estimate demand
- Compared against structural capacity curves (pushover analysis)

33.17 Spectral Matching Techniques

- Modify ground motion time history so that its spectrum closely **matches the target design spectrum**.
- Used in nonlinear time history analysis.
- **Techniques**:
  - Frequency domain spectral matching (e.g., wavelet-based)
  - Time domain adjustment

33.18 Design Spectra in International Codes

33.18.1 ASCE 7 / UBC / Eurocode

- Use site class, seismic zone, and importance category
- Typically provide elastic spectra and allow scaling for inelastic behavior
- Define two spectra:
  - **MCER** (Maximum Considered Earthquake Response)
  - **Design Response Spectrum**

33.18.2 Comparison with IS 1893

- Indian code spectrum is generally conservative in low-period range.
- Less site-specific than Eurocode or IBC/ASCE.

33.19 Future Developments in Response and Design Spectra

- Integration with **Machine Learning** for automated site response modeling
- Use of **Artificial Ground Motions** based on stochastic models
- Development of **Real-time Design Spectra** from early warning systems
- Coupling with **GIS and remote sensing** for regional seismic response estimation

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