NARLabs
National Applied Research Laboratories

Development of Seismic Force Requirements for Buildings in Taiwan

Yuan-Tao Weng（翁元滔）
Associate Research Fellow, NCREE

ATP 2015
APEC Training Program for
Seismic Design of Structures and Hazard Mitigation

Oct. 13, 2015

www.narlabs.org.tw

NARLabs

Outlines

- Development of Taiwan Building Codes
  - Seismic Force Requirements in Taiwan before the 1999 Chi-Chi Earthquake
- Current Seismic Design Code (issued in 2005)
  - Seismic Force Requirements for Structures
    - Static analysis procedures
    - Dynamic analysis procedures

NARLabs
Commitment · Passion · Innovation

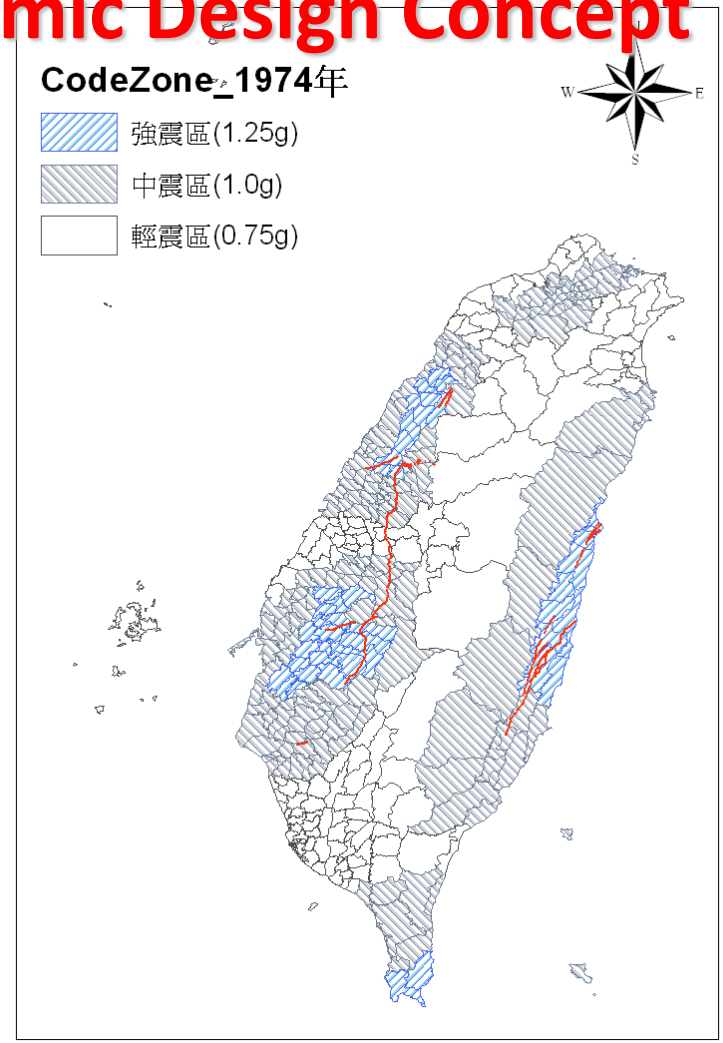
History

Development of Taiwan Building Codes

(issued in 1974, 1982, 1997)

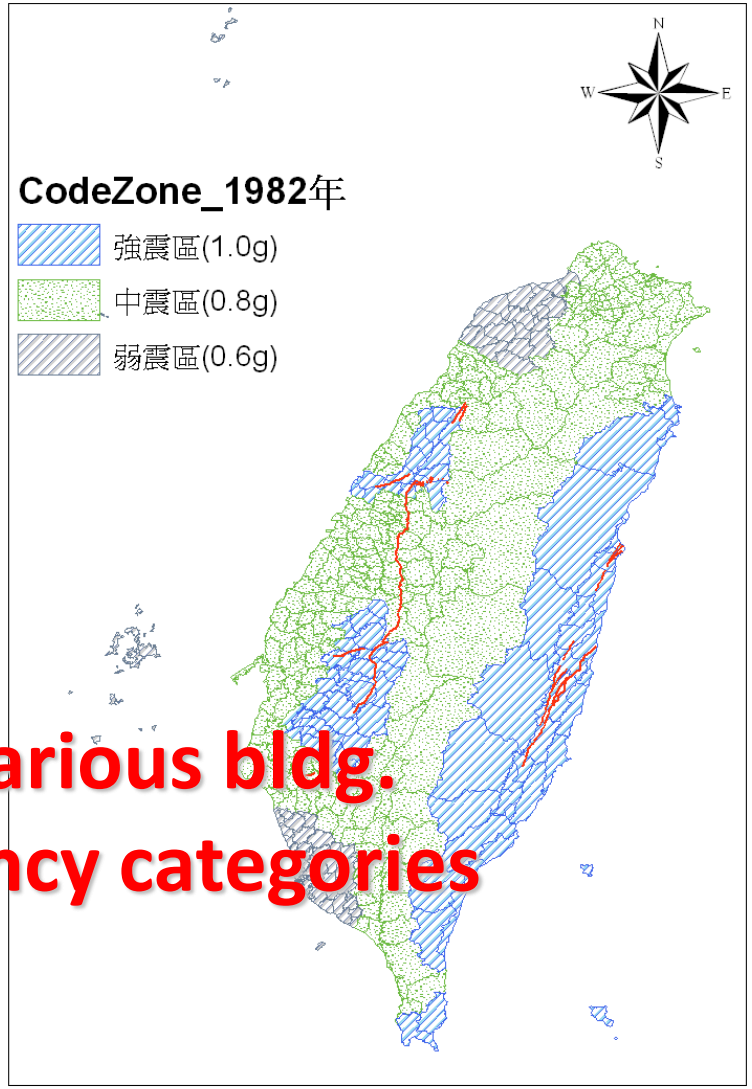
- Before 1974
  - Base shear: V=0.1W
- 1974 (the format of UBC)
  - Base shear: V=ZKCW
    - Z = 1.25, 1.0, 0.75
    - K = 0.67, 0.8, 1.0, 1.33
    - $C = 0.1/\sqrt[3]{T} \leq 0.1$
    - W = D+0.25L
  - Remarks
    - Seismic hazard
    - Structural ductility
    - Structural period

No Seismic Design Concept



- 1982
  - Base shear: V=ZKCIW
    - Z = 1.0, 0.8, 0.6
    - K = 0.67, 0.8, 1.0, 1.33
    - C = 1/8$\sqrt{T}$ $\leq$ 0.15
    - I = 1.0, 1.25, 1.5
    - W = D
  - Remarks
    - Importance factor: Occupancy categories

For various bldg. occupancy categories

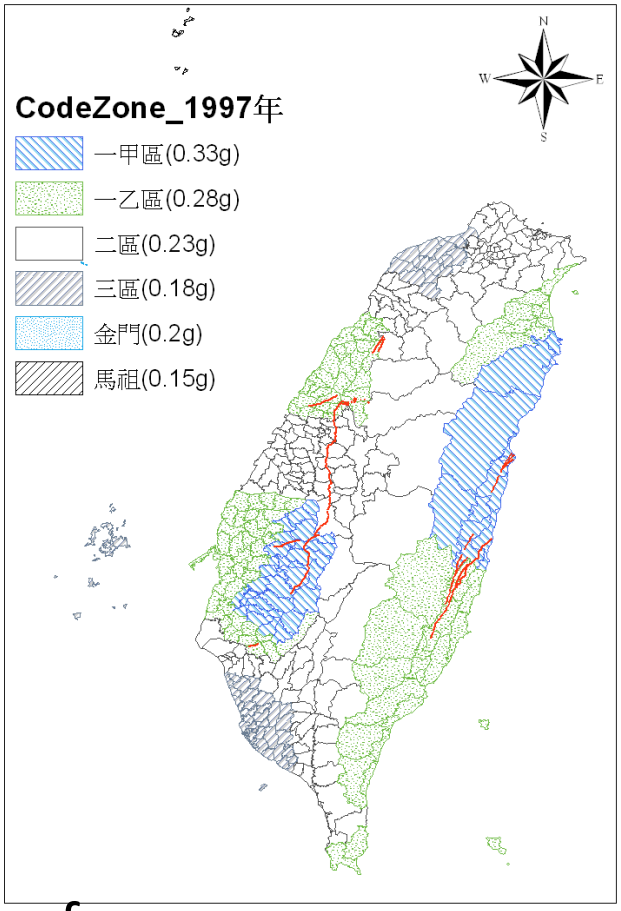


- Basin Effect
  - Mexico EQ (1985)
  - Hwa-lian EQ (Taiwan, 1986)

- 1989 (minor modification)
  - Base shear: V=ZKCIW
    - Taipei Basin
      $C = 0.248/T_0 \leq 0.15$
      with T_0=1.65 sec.
  - Remarks:
    - Basin effect for Taipei Basin

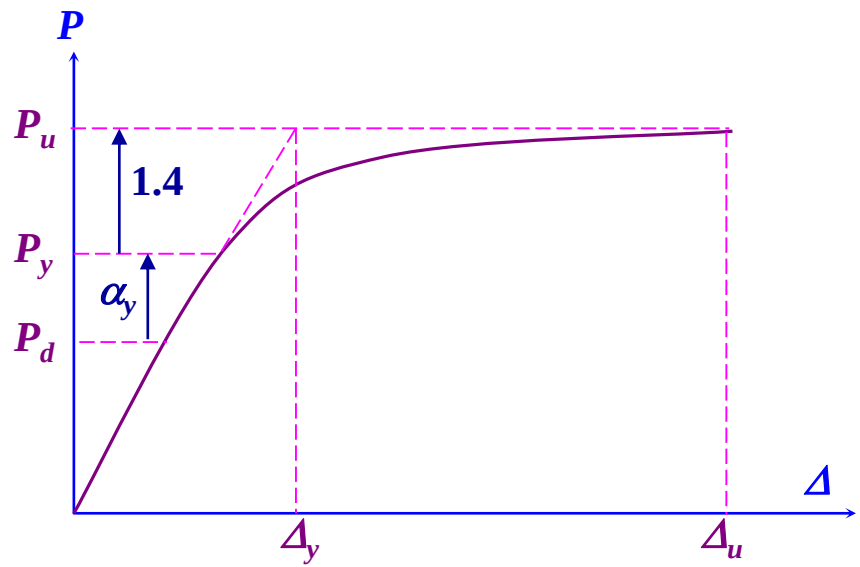
A building collapsed in Taipei Basin with ED >100 km (Hwa-lian EQ, 1986)

- 1997
  - Base shear: $$V = \frac{ZI}{1.4\alpha_y}\left(\frac{C}{F_u}\right)_m W$$
    - Dynamic analysis procedures using the response spectrum method
    - The number of seismic zones increased from 3 to 4
    - Z = 0.33, 0.28, 0.23, 0.18
    - C: 3 soil types + Taipei Basin



Associated with a hazard level of 10% chance of exceedance in 50 years (10/50 event).

- 1997
  - Base shear: $$V = \frac{ZI}{1.4\alpha_y}\left(\frac{C}{F_u}\right)_m W$$
    - I = 1.0, 1.25, 1.5
    - W = D
    - α_y = 1.2 for WSD
      = 1.5 for USD
    - $F_u(R_a) \approx$ 2.1, 2.5, 2.9

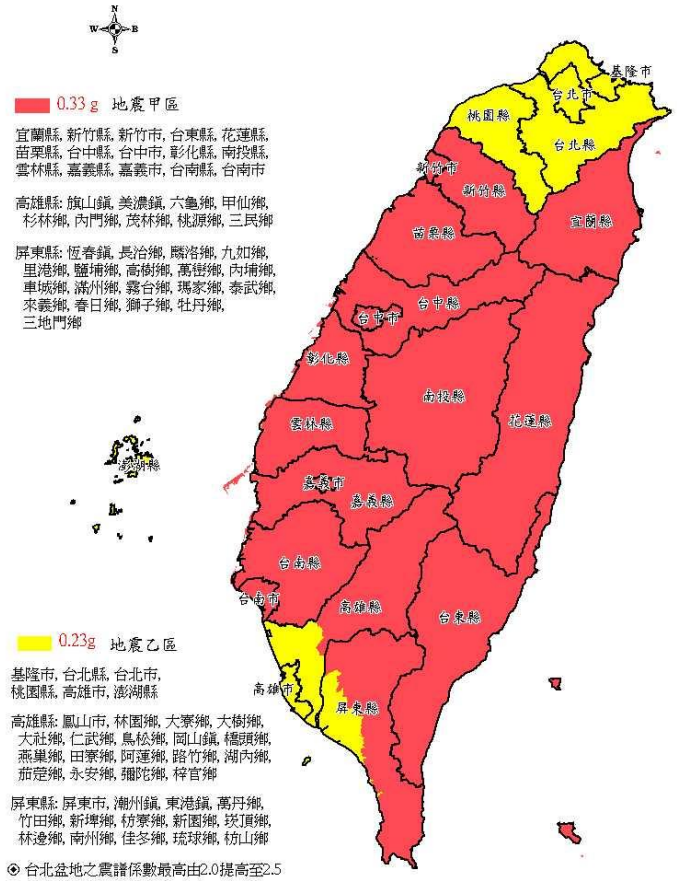


  - Remarks
    - Zoning factor Z: design PGA (10%/50 years)
    - Site classification (S1, S2, S3 and Taipei Basin)
    - Reduction factor F_u: Newmark-Hall recommendations
    - Dynamic analysis procedures (response spectrum method)

- 1999 (after Chi-Chi EQ)
  - Base shear:

$$V = \frac{ZI}{1.4\alpha_y}\left(\frac{C}{F_u}\right)_m W$$

    - Z = 0.33, 0.23
    - C_{max}= 2.5 for Taipei Basin
  - Remarks:
    - Emergency response:
      released three months after the event temporarily
    - Reduced the number of Taiwan seismic zones from 4 to 2.



臺灣地區震區劃分建議圖

NARLabs

Current Seismic Design Code

(issued in 2005)

Static Analysis Procedures for structures

– Design Base Shear

for general sites, near-fault sites and Taipei Basin

Concept of Performance-based Design

NARLabs
Commitment · Passion · Innovation

- Performance Objective: triple design goals
  - Design earthquake (10%/50 yrs) ⇔ **Life Safety (LS)** allowable ductility capacity R_a at design earthquake V
    R_a=1+(R-1)/1.5 or 1+(R-1)/2
  - MCE (2%/50 years) ⇔ **Collapse Prevention (CP)** nominal ductility capacity R at MCE V_M
    R_a=R
  - Small earthquake ⇔ **Intermediate Occupancy (IO)** response ductility under design earthquake ≤ 4.0 V^*

The value of base shear V_D to design structures should be defined by

$$V_D = \max\{ V, V_M, V^* \}$$

Base Shear at Design EQ Level

NARLabs

Commitment · Passion · Innovation

— for general sites

- Based on uniform hazard analysis→Mapped 5%-damped design spectral response acceleration parameters
  - Based on uniform hazard analysis (10%/50 yrs.)
  - For each municipal unit of village, town or city level
  - 5% damped spectral response acceleration at short periods and 1.0 second
  - Classification

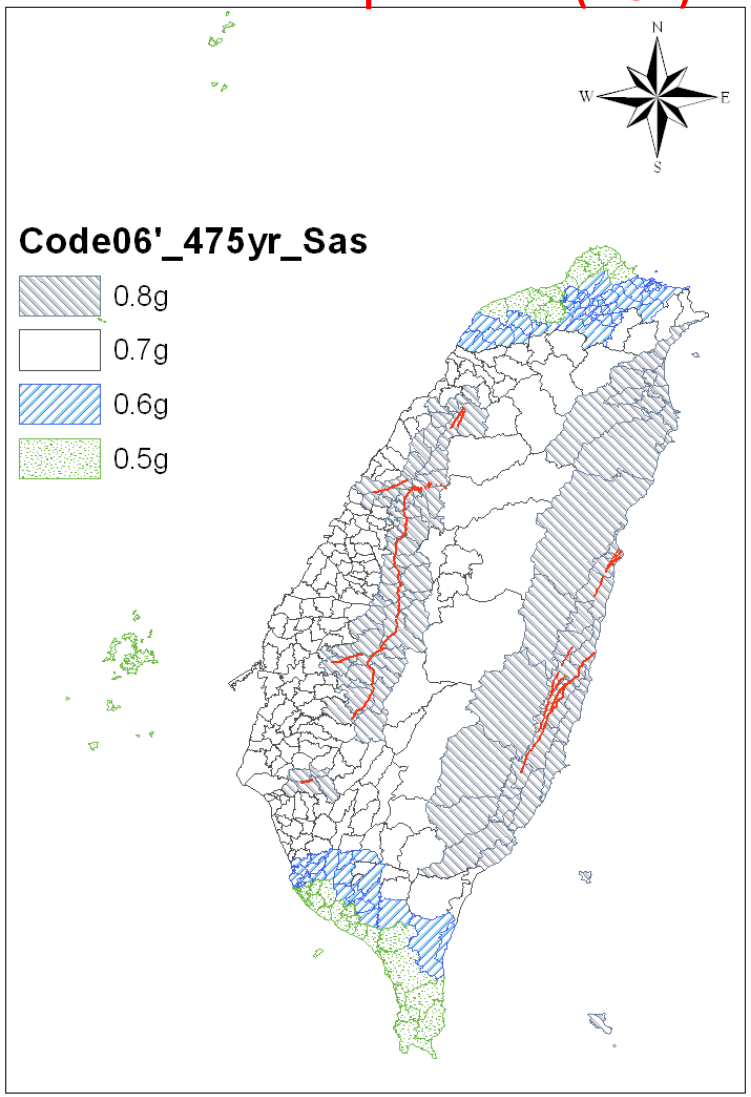
S_S^D	0.8g	0.7g	0.6g	0.5g
S_1^D	0.45g	0.40g	0.35g	0.30g

the mapped design 5%-damped spectral accelerations

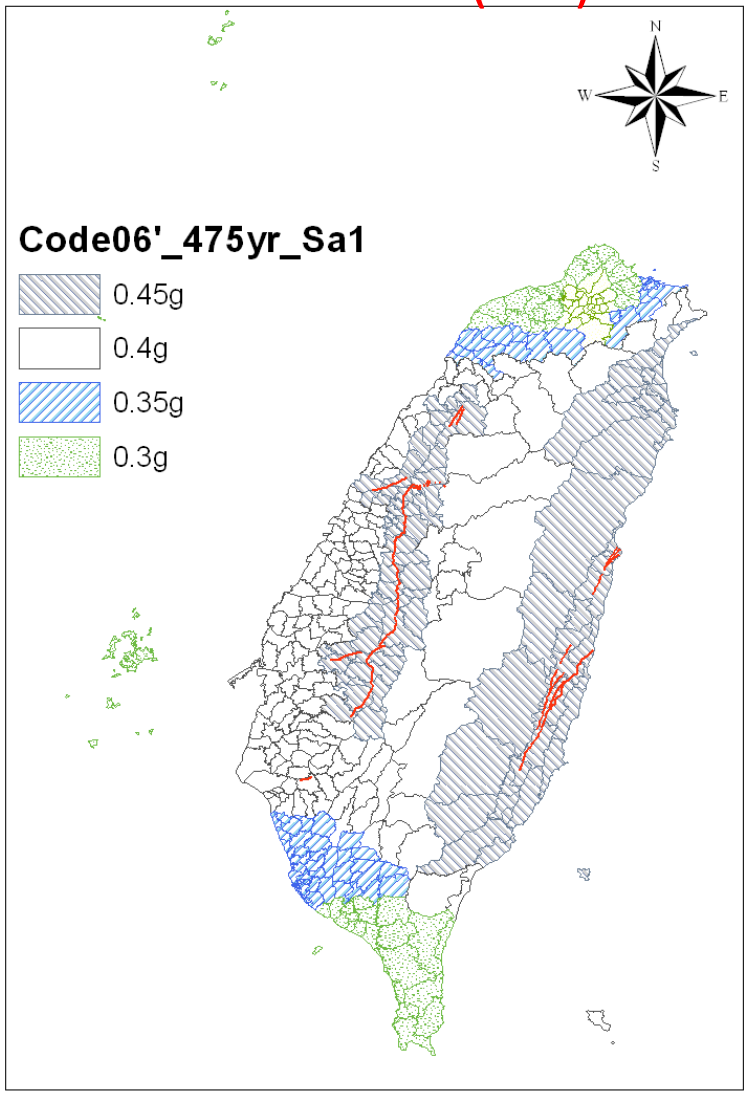
NARLabs

Commitment · Passion · Innovation

at short periods (S_s^D)



at 1.0 second (S_1^D)



- **Site-adjusted spectral response acceleration parameters S_{DS} and S_{D1}**

  - Include local site effects by site coefficients F_a and F_v

$$S_{DS} = F_a S_S^D \quad ; \quad S_{D1} = F_v S_1^D$$

  - Site coefficients
    - Functions of site class and mapped spectral acceleration parameters (Nonlinear amplification effect)

Site Class	Values of F_a				
	$S_S \leq 0.5$	$S_S = 0.6$	$S_S = 0.7$	$S_S = 0.8$	$S_S \geq 0.9$
S1 (Hard Site)	1.0	1.0	1.0	1.0	1.0
S2 (Normal site)	1.1	1.1	1.0	1.0	1.0
S3 (Soft Site)	1.2	1.2	1.1	1.0	1.0

Site Class	Values of F_v				
	$S_1 \leq 0.3$	$S_1 = 0.35$	$S_1 = 0.4$	$S_1 = 0.45$	$S_1 \geq 0.5$
S1 (Hard Site)	1.0	1.0	1.0	1.0	1.0
S2 (Normal site)	1.5	1.4	1.3	1.2	1.1
S3 (Soft Site)	1.8	1.7	1.6	1.5	1.4

– Site classification

- Based on the soil structures in the upper 30 meters below the ground surface
- Site classification

Site Class	V_{S30}-method (m/s)
S1 (Hard site)	V_{S30}>270
S2 (Normal site)	180≤ V_{S30}≤270
S3 (Soft site)	V_{S30}<180

For all soil layers in the top 30 m

$$V_{S30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \left(d_i / V_{si}\right)}$$

for a cohesive soil layer:

$$V_{si} = \begin{cases} 120 q_{ui}^{0.36} & ; \quad N_i < 2 \\ 100 N_i^{1/3} & ; \quad 2 \le N_i \le 25 \end{cases}$$

for a cohesionless soil layer:

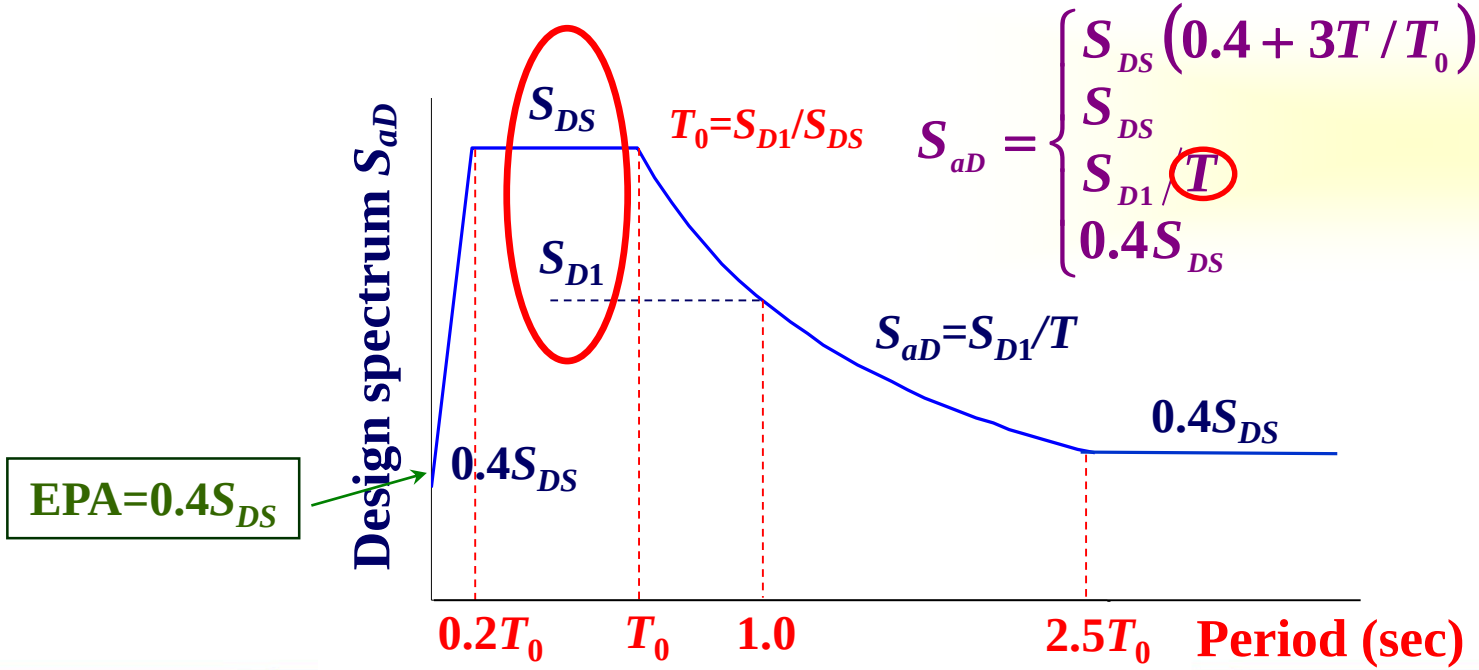
$$V_{si} = 80 N_i^{1/3} \quad ; \quad 1 \le N_i \le 50$$

N_i **: standard penetration resistance**

q_{ui} **: unconfined compression strength** (in kgf/cm^2).

- Design spectral acceleration S_{aD}
  - Based on the site adjusted spectral acceleration parameters S_{DS} and S_{D1}
  - Design response spectrum curve

$$S_{aD} = \begin{cases} S_{DS}\left(0.4 + 3T/T_0\right) & ; \quad T \le 0.2T_0 \\ S_{DS} & ; \quad 0.2T_0 < T \le T_0 \\ S_{D1}/T & ; \quad T_0 < T \le 2.5T_0 \\ 0.4S_{DS} & ; \quad T > 2.5T_0 \end{cases}$$



- Approximate fundamental period
  - Moment resisting frame systems not enclosed or adjoined by more rigid components that will prevent the frames from deflecting under seismic forces
    - Steel frames: $T=0.085\times h_n^{3/4}$
    - RC frames: $T=0.070\times h_n^{3/4}$
  - Eccentrically braced steel frames: $T=0.070\times h_n^{3/4}$
  - Others: $T=0.050 h_n^{3/4}$
- Coefficient for upper limit on calculated period
  - Determined by other rational methods
  - Calculated period $\leq$ Cu $\times$ Approximate fundamental T (i.e. Cu=1.4)

• Structure System Seismic Reduction Factor F_u

– Ductility effect

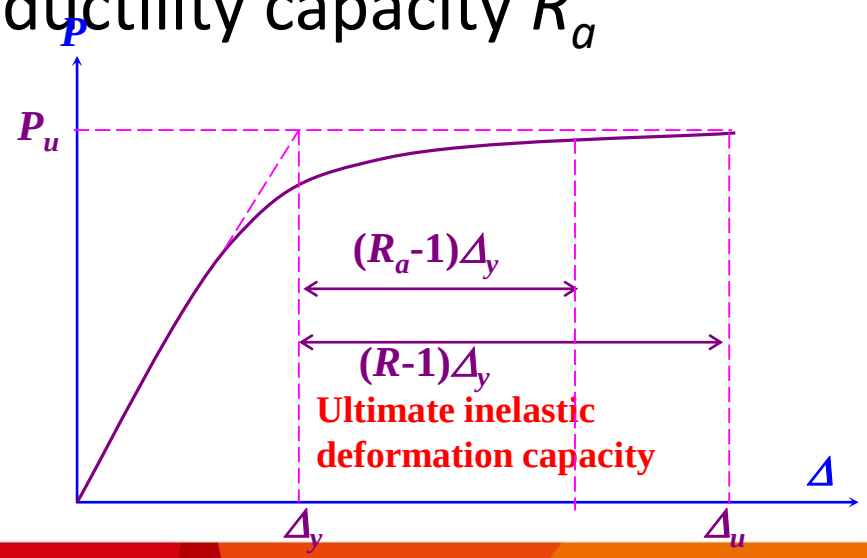
- Represents the transformative relationship between elastic spectral demand and inelastic spectral demand.

– Structure system ductility capacity R

- $R=\Delta_u/\Delta_y$
- Defined for some specified structure systems

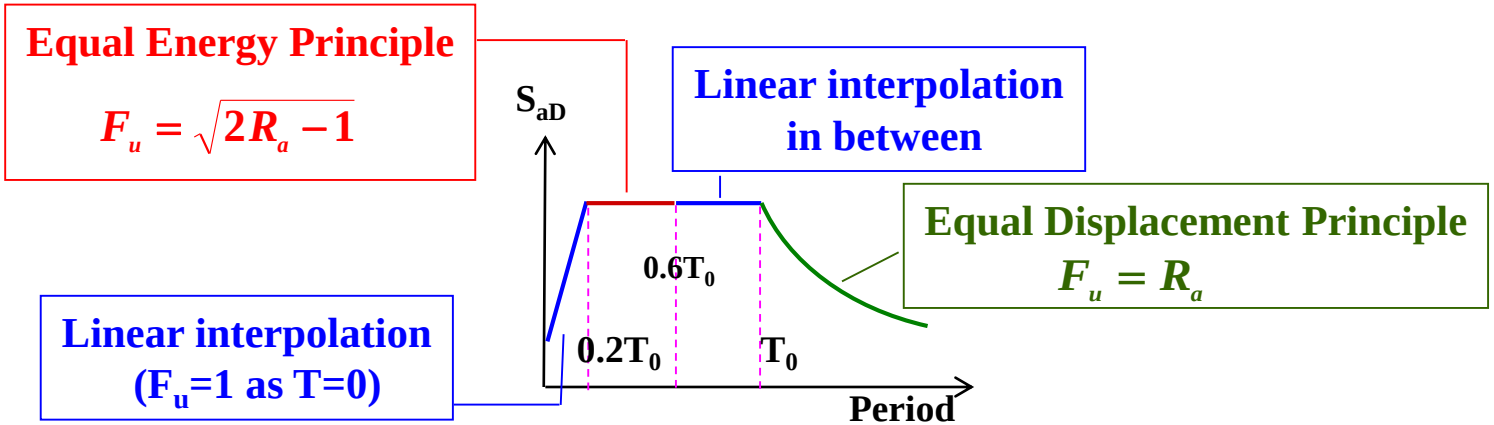
– Allowable structure system ductility capacity R_a

- $R_a=1+(R-1)/1.5$
- DBE, 10/50 event



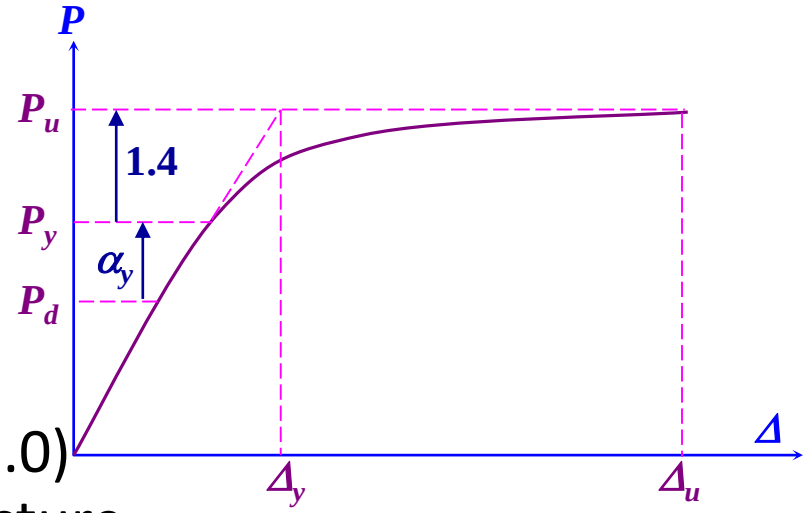
– Newmark-Hall recommendations

$$F_u = \begin{cases} R_a & ; \quad T \geq T_0 \\ \sqrt{2R_a - 1} + \left(R_a - \sqrt{2R_a - 1}\right) \times \dfrac{T - 0.6T_0}{0.4T_0} & ; \quad 0.6T_0 \leq T \leq T_0 \\ \sqrt{2R_a - 1} & ; \quad 0.2T_0 \leq T \leq 0.6T_0 \\ \sqrt{2R_a - 1} + \left(\sqrt{2R_a - 1} - 1\right) \times \dfrac{T - 0.2T_0}{0.2T_0} & ; \quad T \leq 0.2T_0 \end{cases}$$



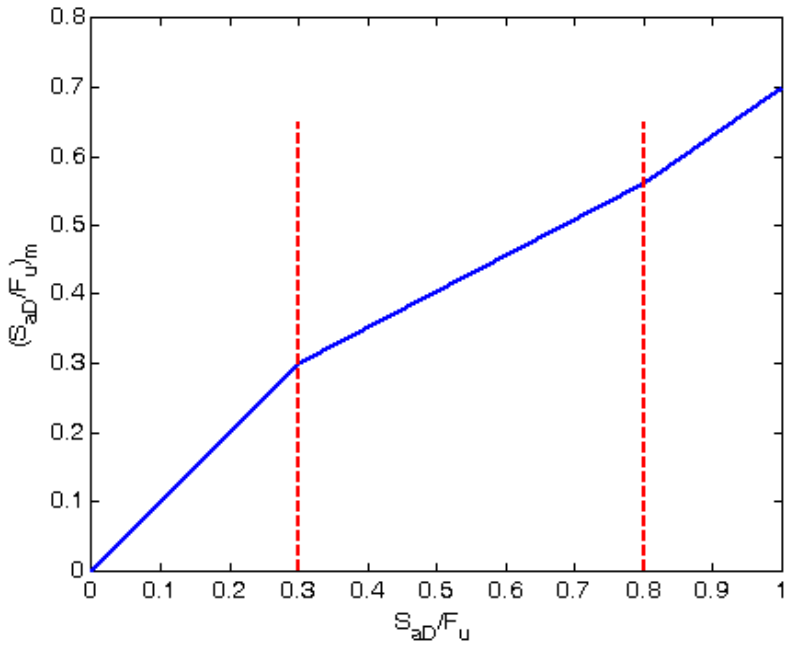
• Seismic Design Base Shear

$$V = \frac{IW}{1.4\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m$$



- *I*: Important factor (I=1.5, 1.25 1.0)
- *W*: Total gravity load of the structure
- S_{aD}: Design spectral response acceleration
- F_u: Structure system seismic reduction factor
- α_y: First yield seismic force amplification factor
  - Dependent on the structural types and design method
- 1.4: Over strength factor for buildings
  - Dependent on the redundancy of structure system (e.g. 1.2 for bridges)

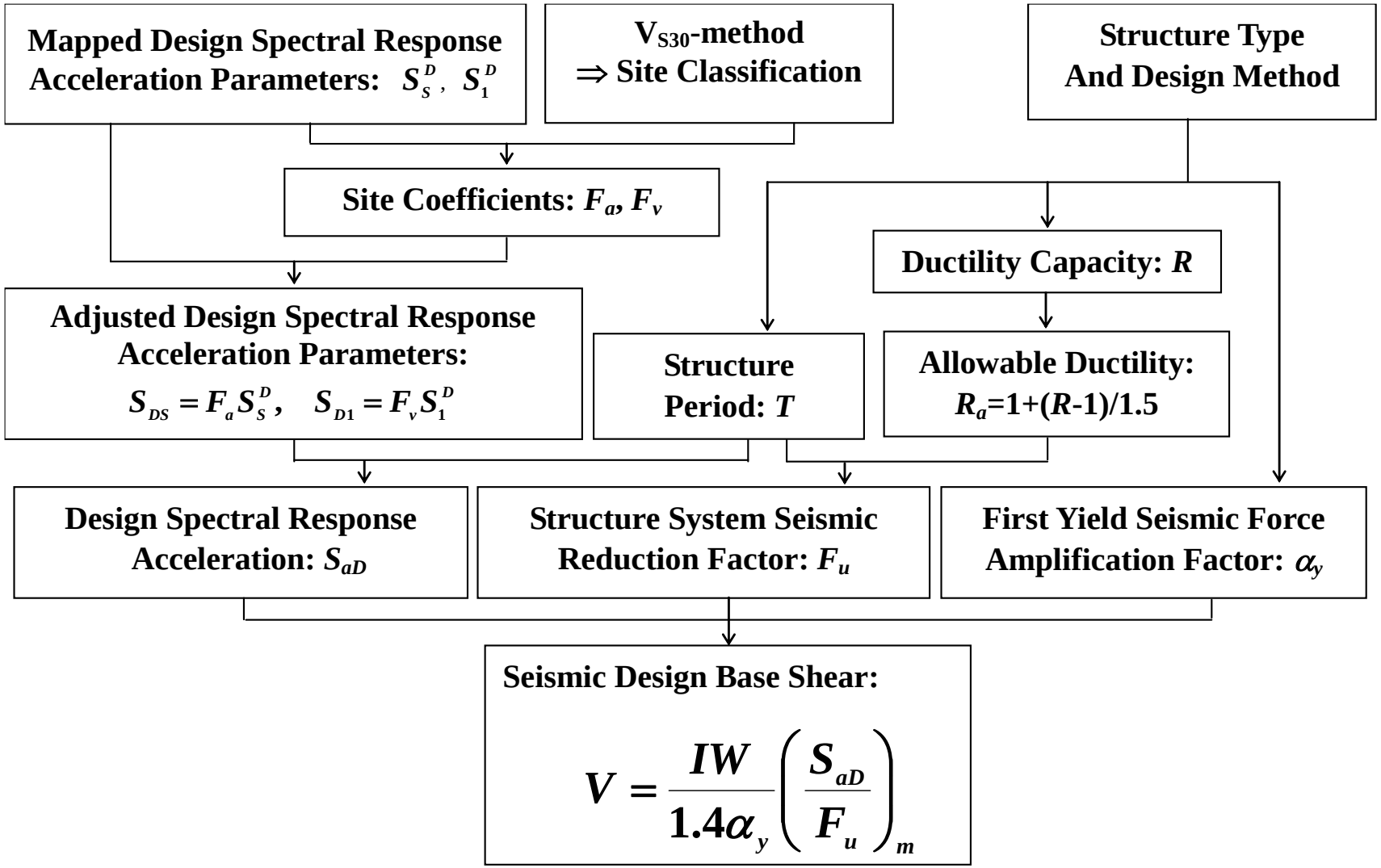
- Modified ratio of $(S_{aD}/F_u)_m$
  - Reduce seismic demand for short period structures
    - Higher damping ratio (5%-10%) caused by soil-structure interaction



$$\left(\frac{S_{aD}}{F_u}\right)_m = \begin{cases} \dfrac{S_{aD}}{F_u} & ; \quad \dfrac{S_{aD}}{F_u} \le 0.3 \\ 0.52\dfrac{S_{aD}}{F_u} + 0.144 & ; \quad 0.3 < \dfrac{S_{aD}}{F_u} \le 0.8 \\ 0.70\dfrac{S_{aD}}{F_u} & ; \quad \dfrac{S_{aD}}{F_u} > 0.8 \end{cases}$$

soil-structure interaction causes a damping ratio higher than 5% for short period structures

• Flow chart to determine base shear demand at design level (for general sites)



Base Shear at Design EQ Level — for near-fault sites

NARLabs

Commitment · Passion · Innovation

- Near-fault factors N_A and N_V
  - For specific active faults in Taiwan
  - Characteristic earthquake model & Seismic hazard analysis for Taiwan area
  - Functions of *r* (shortest distance between the building site and the interesting nearby faults)
- Site-adjusted spectral acceleration parameters

$$S_{DS} = F_a N_A S_S^D \quad ; \quad S_{D1} = F_v N_V S_1^D$$

- Base shear at design level

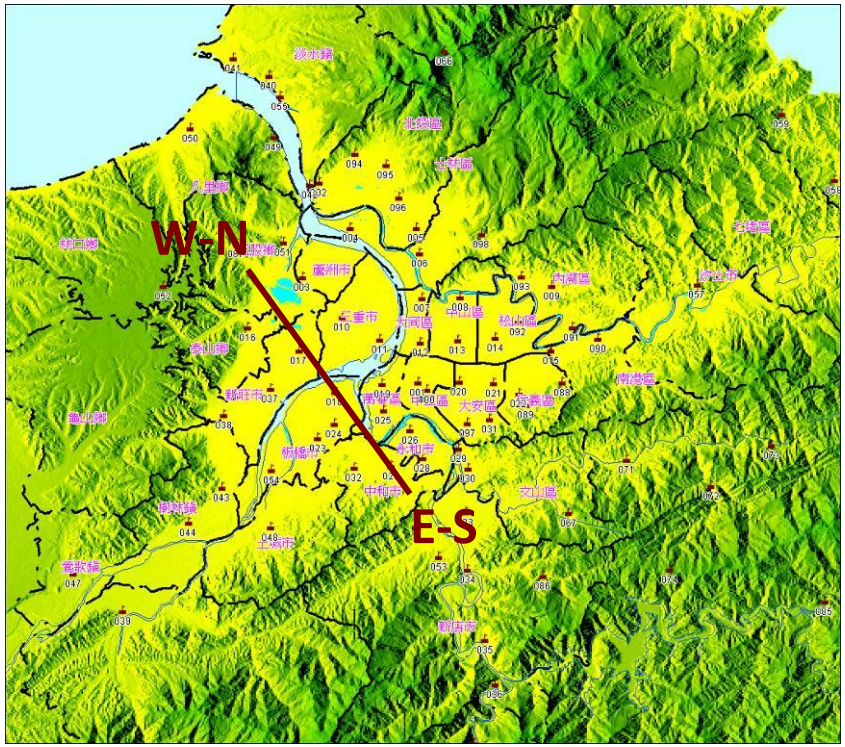
$$S_{DS} \ \& \ S_{D1} \rightarrow S_{aD} \rightarrow \text{design base shear} \quad V = \frac{IW}{1.4\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m$$

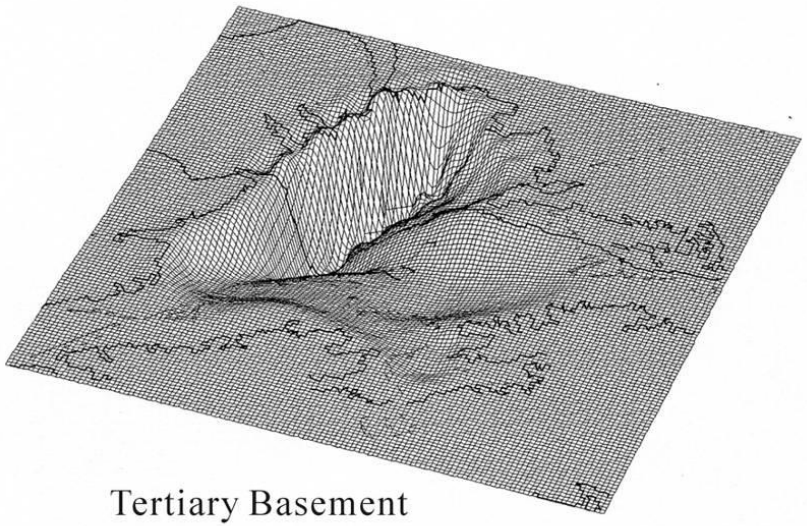
Base Shear at Design EQ Level — for Taipei Basin

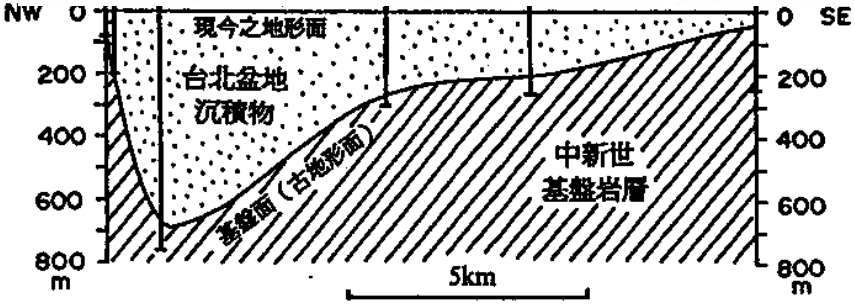
NARLabs

Commitment · Passion · Innovation

- Deep sinking sedimentary basin (WN)
  - Asymmetric U-shape
- Low-lying alluvium (ES)

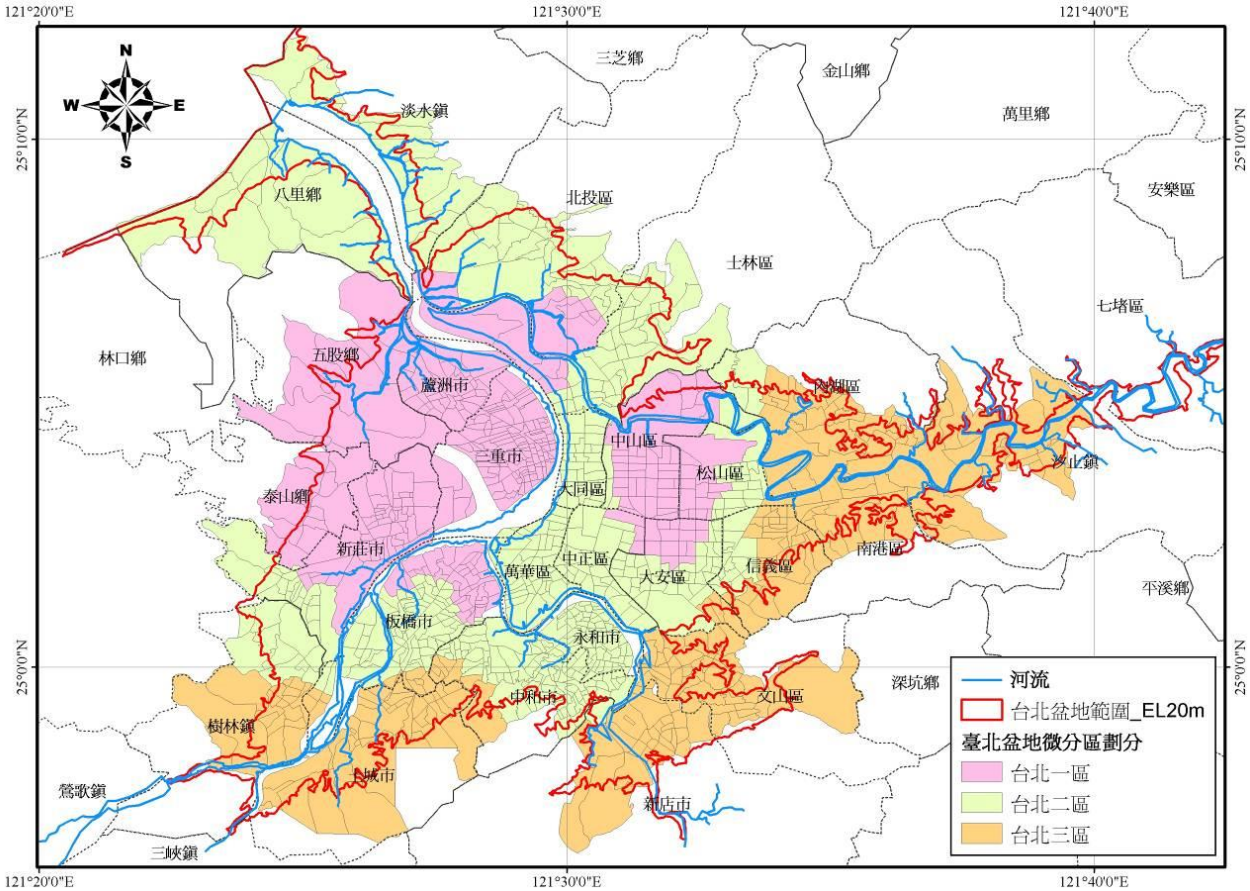






- Basin effect
  - The corner periods are almost larger than 1.0 second
    - It implies that the parameters S_{DS} and S_{D1} to develop the design response spectrum for general sites can not be still applied for Taipei Basin
  - Site-specific amplification conditions should be considered
- Microzonation in Taipei Basin
  - Three seismic microzones in Taipei Basin
    - In accordance to the administration unit
  - Representative corner period T_0
    - Taipei Z1 (T_0=1.6 sec.)
    - Taipei Z2 (T_0=1.3 sec.)
    - Taipei Z3 (T_0=1.05 sec.)

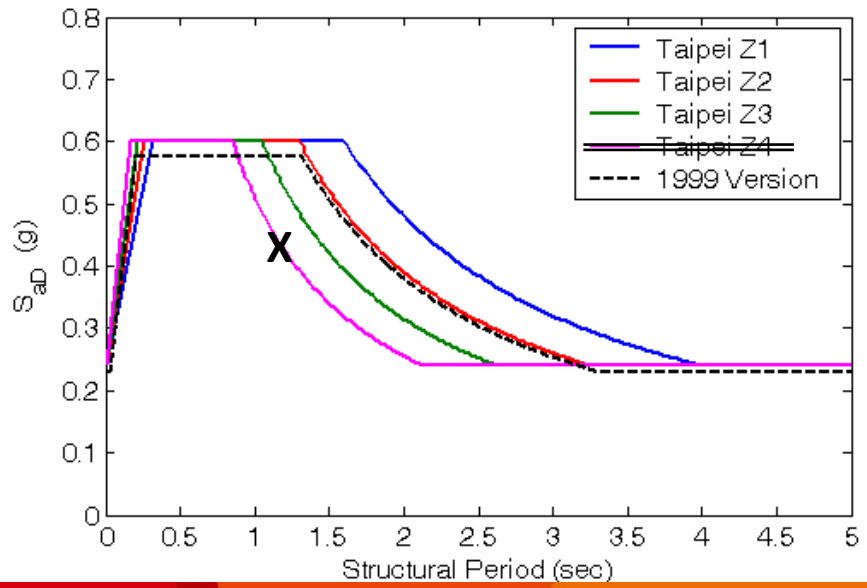
- Three microzones (revised in 2011)
  - Boundary of Taipei Basin (EL 20m)



The distribution of the three micro-zones is in accordance to the Taipei basin shape and reflects the thickness of the sedimentary soil layers in Taipei Basin

• Design Spectral Response Acceleration

- Uniform Hazard Analysis (return period: 475 years)
  - Design spectral acceleration at short periods S_{DS}= 0.6g
  - EPA=0.4S_{DS}= 0.24g
- Design Spectral Response Acceleration
  - Based on two parameters S_{DS} and T_0



$$S_{aD} = \begin{cases} S_{DS}\left(0.4 + 3T/T_0\right) & ; \quad T \le 0.2T_0 \\ S_{DS} & ; \quad 0.2T_0 \le T \le T_0 \\ S_{DS}T_0/T & ; \quad T_0 \le T \le 2.5T_0 \\ 0.4S_{DS} & ; \quad 2.5T_0 \le T \end{cases}$$

- Allowable Ductility Capacity R_a
  - Fatigue consideration
    - Basin effect
      → Elongation of duration
      → The numbers of cyclic loading will be increased
    - Only half of the ultimate inelastic deformation capacity is permitted for design

$$R_a = 1 + (R-1)/2.0$$

- Design Base Shear for Taipei Basin

design base shear

$$V = \frac{IW}{1.4\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m$$

By the same procedures as specified for general sites

Base Shear Demand at MCE Level

NARLabs
Commitment · Passion · Innovation

- Avoid collapse during an extremely large EQ
- Mapped spectral response acceleration parameters (MCE, 2%/50)

S_S^M	1.0g	0.9g	0.8g	0.7g
S_1^M	0.55g	0.50g	0.45g	0.40g

- Spectral response acceleration S_{aM}
  - General sites: $S_{MS} = F_a S_S^M$ & $S_{M1} = F_v S_1^M$
  - Near-fault sites: $S_{MS} = F_a N_A S_S^M$ & $S_{M1} = F_v N_V S_1^M$
  - Taipei Basin: $S_{MS} = 0.8g$ & T_0
- Allowable ductility capacity $R_a \Rightarrow$ Permitted to reach full capacity R
- Base shear demand at MCE Level

$$V_M = \frac{IW}{1.4\alpha_y}\left(\frac{S_{aM}}{F_{uM}}\right)_m$$

with $$\left(\frac{S_{aM}}{F_{uM}}\right)_m = \begin{cases} \dfrac{S_{aM}}{F_{uM}} & ; \quad \dfrac{S_{aM}}{F_{uM}} \le 0.3 \\ 0.52\dfrac{S_{aM}}{F_{uM}} + 0.144 & ; \quad 0.3 < \dfrac{S_{aM}}{F_{uM}} \le 0.8 \\ 0.70\dfrac{S_{aM}}{F_{uM}} & ; \quad \dfrac{S_{aM}}{F_{uM}} > 0.8 \end{cases}$$

Minimum Requirement of Base Shear Demand

NARLabs

Commitment · Passion · Innovation

- Avoid yielding during frequently small earthquakes
- Determined from the design level
  - Ductility ratio of a long period structure can not exceed 4.0 under the design EQ
    - $R \leq 4$, $F_u = R_a \leq 2.5$ (Taipei Basin) or 3.0 (others)
  - No near-fault effect ($N_A = N_V = 1.0$)
- Minimum Requirement

design base shear

$$V = \frac{IW}{1.4\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m W \quad \times F_u/3.0 \quad \text{for general sites and near-fault sites}$$

$$V = \frac{IF_u}{3.5\alpha_y}\left(\frac{S_{aD}}{F_u}\right)_m W \quad \times F_u/2.5 \quad \text{for Taipei Basin}$$

;(for general sites and near - fault sites)

;(for Taipei Basin)

Design Base Shear Demand

NARLabs
Commitment · Passion · Innovation

- Design earthquake (10%/50 yrs) ⇔ LS
  allowable ductility capacity R_a at design earthquake $\Big\}\ V$
- MCE (2%/50 years) ⇔ CP
  Full ductility capacity R at MCE $\Big\}\ V_M$
- Small earthquake ⇔ IO
  response ductility under design earthquake ≤ 4.0 $\Big\}\ V^*$

The value of base shear V_D
to design structures should be defined by
$$V_D = \max\{ V, V_M, V^* \}$$

Other Requirements

NARLabs

Commitment · Passion · Innovation

- Distribution of Design Base Shear V_D
  - Vertical distribution
    - Lateral force applied at roof (F_t): $F_t = 0.07TV_D$ *(T >0.7 sec)*
    - Lateral force applied at each floor level (F_x):

$$F_x = \frac{(V_D - F_t)W_x h_x}{\sum_{i=1}^{n} W_i h_i}$$

W_x : Building weight located on floor level x
h_x : Height from the base to floor level x

  - Horizontal distribution
    - The seismic forces at each floor level shall be distributed according to the distribution of mass at that floor level

- Torsional Moment
  - Actual torsional moment
    - Resulted from the eccentricity between the centers of mass and rigidity
  - Accidental torsional moments
    - Caused by the offset of the center of mass
    - A distance equal to 5% of the dimension of the building perpendicular to the direction of the applied forces
  - Torsional irregularity
    - Torsional amplification factor A_x

$$A_x = \left(\frac{\delta_{\max}}{1.2\delta_{avg}} \right)^2 \leq 3.0$$

δ_{max} : **maximum displacement at level x**

δ_{avg} : **average of the displacement at the extreme points of the building at level x**

- Overturning Effect
  - Overturning moments at level *x*

$$M_x = \tau \sum_{i=x}^{n} F_i \left(h_i - h_x \right)$$

F_i : seismic force applied at level i $(x \leqq i \leqq n)$
h_i and h_x : height from the base to level i or x
τ : overturning moment reduction factor

$$\tau = \begin{cases} 1.0 & ; \quad n - x \leq 10 \\ 1.0 - 0.02(n - x - 10) & ; \quad 10 < n - x \leq 20 \\ 0.8 & ; \quad n - x > 20 \end{cases}$$

- Limitation to Inter-story Drift Ratio
  - Seismic demand

$$V_{Base} = \begin{cases} \dfrac{IF_u}{4.2}\left(\dfrac{S_{aD}}{F_u}\right)_m W & \text{;(for general sites and near - fault sites)} \\ \dfrac{IF_u}{3.5}\left(\dfrac{S_{aD}}{F_u}\right)_m W & \text{;(for Taipei Basin)} \end{cases}$$

$$\theta = \frac{\textit{Difference of deflections at the top and bottom of the story}}{\textit{Story height}}$$

  - Acceptance criteria:
    Maximum inter-story drift ratio $\theta_{max} \leq 0.5\%$

- Separation Distance between Adjacent Structures
  - Prevent pounding during an earthquake
  - Minimum separation distance
    - $0.6 \times 1.4\alpha_y R_a \times$ Displacement caused by V_D

Due to the low probability that two adjacent buildings will move in the opposite directions and reach the maximum displacement simultaneously

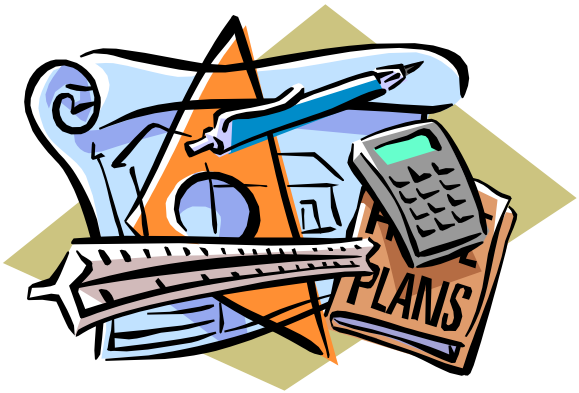
- Vertical Seismic Response
  - Especially for the cantilever and pre-stressed components and elements of structures
  - Vertical design spectral response acceleration $S_{aD,V}$
    - Determined from the horizontal design spectral response acceleration S_{aD}

$$S_{aD,V} = \begin{cases} S_{aD}/2 & \text{;(for general sites and Taipei Basin)} \\ 2S_{aD}/3 & \text{;(for near-fault sites)} \end{cases}$$

NARLabs

Dynamic Analysis Procedures for structures

– Response Spectrum Method
– Time History Analysis



General Requirement

NARLabs

Commitment · Passion · Innovation

- Irregular building
  - Must be designed by dynamic analysis
  - If base shear $V_{(dynamic)} \leq V_{D\ (static)}$
    The response determined by dynamic analysis shall be amplified by: $V_{D\ (static)} / V_{(dynamic)}$
- Regular building
  - Can be designed by static analysis
  - If base shear $V_{(dynamic)} \leq 0.9V_{D\ (static)}$
    The response determined by dynamic analysis shall be amplified by: $0.9V_{D\ (static)} / V_{(dynamic)}$

Response Spectrum Method

NARLabs

Commitment · Passion · Innovation

- General Requirements
  - Peak modal response
    - For sufficient modes to capture at least 90% of the participating mass of the building
    - In each of two orthogonal principal horizontal directions of the building
  - Combination of peak modal response
    - SRSS (square root sum of squares) rule
    - CQC (complete quadratic combination) rule

- Modal Spectral Response Acceleration
  - Damping coefficients B_S and B_1
    - Site-adjusted spectral response acceleration parameters S_{DS} and S_{D1} → S_{DS}/B_S and S_{D1}/B_1
    - Function of modal damping ratio of the *m*-th mode

According to Rayleigh damping theory, each effective modal damping ratio can be determined

Effective modal damping ratio ξ (%)	B_s	B_1
≤2	0.80	0.80
5	1.00	1.00
10	1.33	1.25
20	1.60	1.50
30	1.79	1.63
40	1.87	1.70
≥50	1.93	1.75

The damping coefficient should be based on linear interpolation for effective modal damping ratios other than those given

– Elastic demand for general sites and near-fault sites

- Elastic modal spectral response acceleration
  (T_m : modal period of the m-th mode)
  - S_{DS} and S_{D1} → S_{DS}/B_S and S_{D1}/B_1

$$S_{aD}^{m} = \begin{cases} S_{DS}\left[0.4 + \left(\dfrac{1}{B_S} - 0.4\right)\dfrac{T_m}{0.2T_{0m}}\right] & ; \quad T_m \le 0.2T_{0m} \\ S_{DS}/B_S & ; \quad 0.2T_{0m} < T_m \le T_{0m} \\ S_{D1}/(B_1 T_m) & ; \quad T_{0m} < T_m \le 2.5T_{0m} \\ 0.4S_{DS}/B_S & ; \quad T_m > 2.5T_{0m} \end{cases}$$

Conner period: $T_{0m} = \dfrac{S_{D1}B_S}{S_{DS}B_1}$

Time History Analysis

NARLabs
Commitment · Passion · Innovation

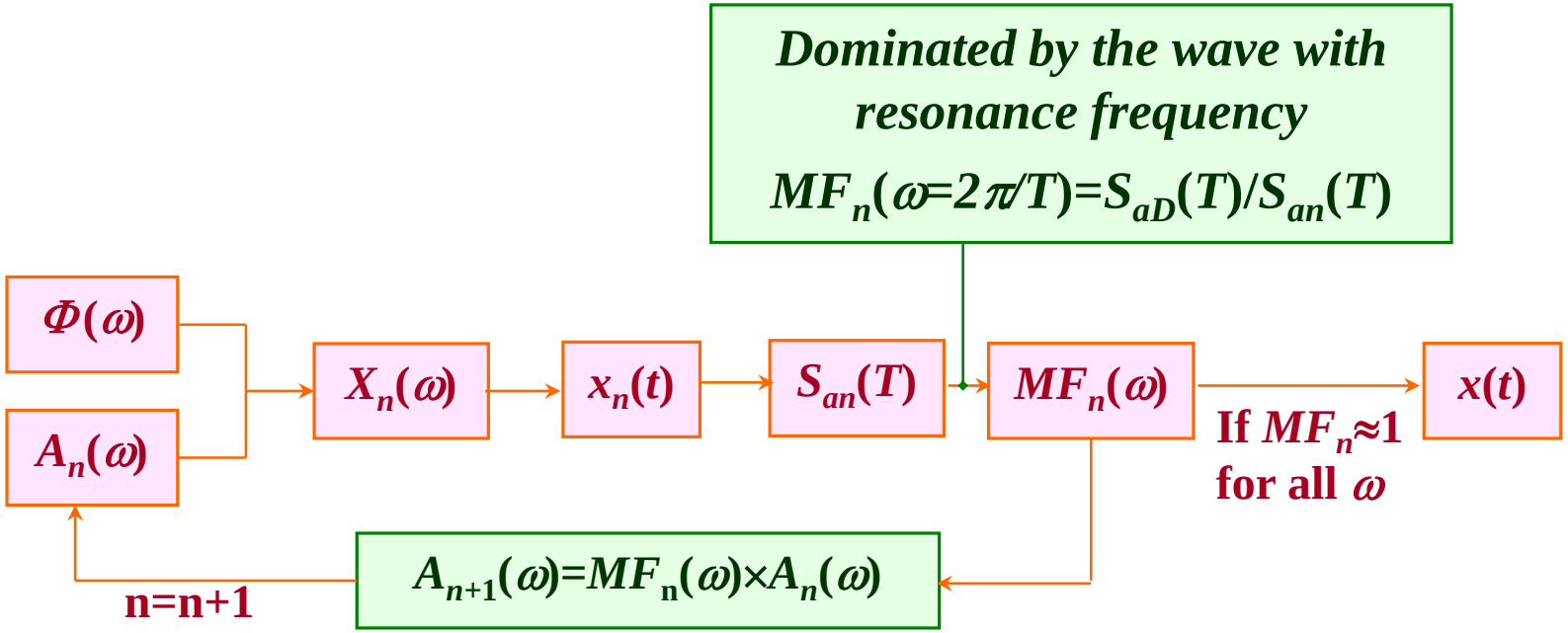
- General Requirements
  - Time history analysis
    - No fewer than three ground motions
    - All seismic response parameters shall be calculated for each time history analysis, and the maximum value of each response parameter is used for design
  - Input ground motions
    - Each input ground motion shall have magnitude, fault distance, and source mechanisms that are consistent with the design earthquake.
    - Compatible with the design response spectrum

- Input ground motions scaling (observed earthquake)
  - The 5%-damped spectral response acceleration for each period between 0.2*T* and 1.5*T* (where *T* is the fundamental period of the building) can not fall below 90% of the value specified by the design response spectrum.
  - The averaged value during this period range shall be larger than or equal to the value averaged from the design response spectrum.
- Spectrum compatible ground motions (synthetic earthquake)

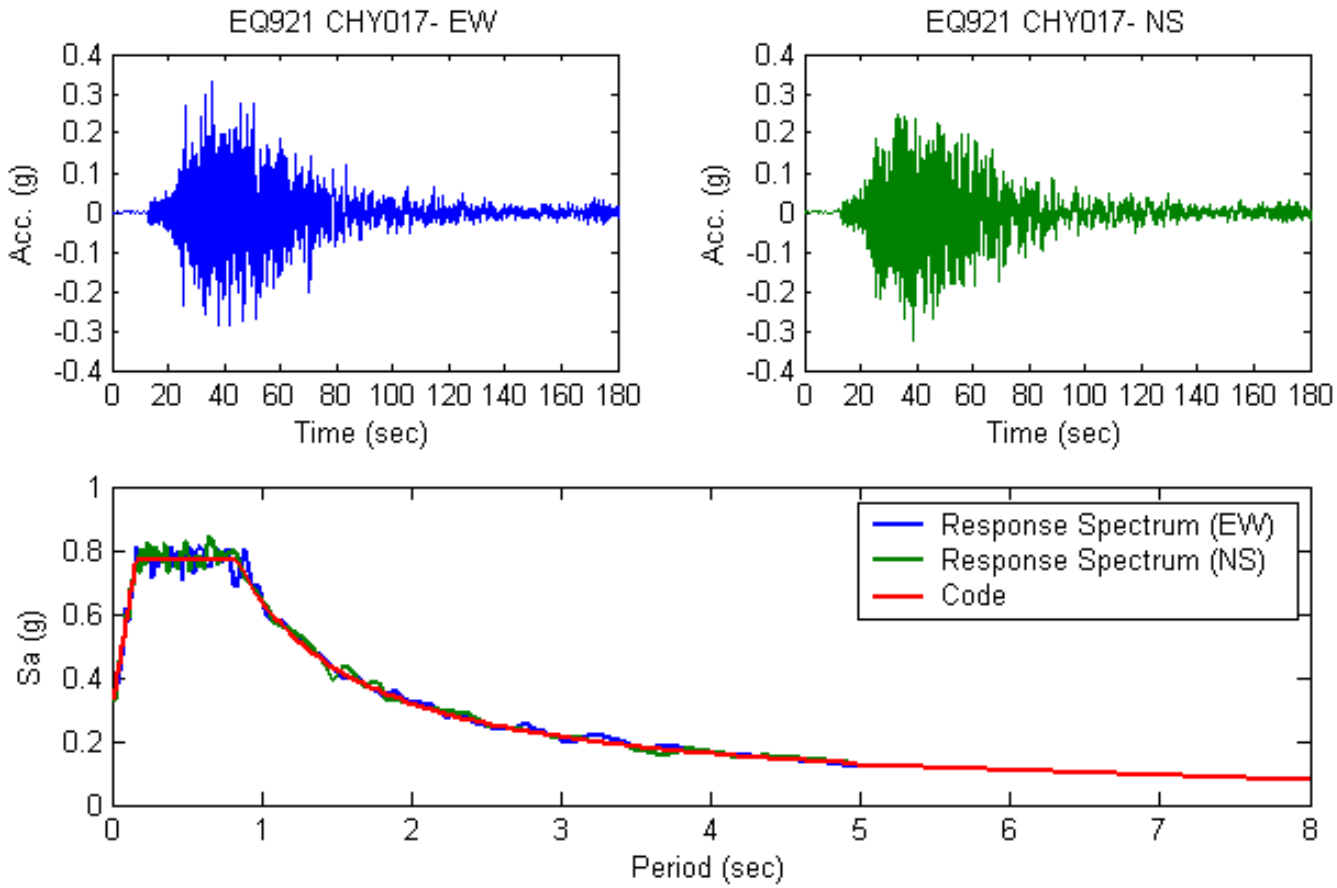
- Simulation of Spectrum Compatible Ground Motions
  - Phase spectrum
    - Phase characteristic of earthquake motion strongly controls the non-stationary nature of earthquake motions, the most important issue for simulating the input ground motion is to model the phase spectrum.
    - For an interesting site, the phase spectrum can be obtained from the earthquake data observed at nearby observation stations while the selected earthquake being similar to the design earthquake in magnitude, fault distance, and source mechanisms.

– Recursive procedures for simulation of spectrum compatible ground motions

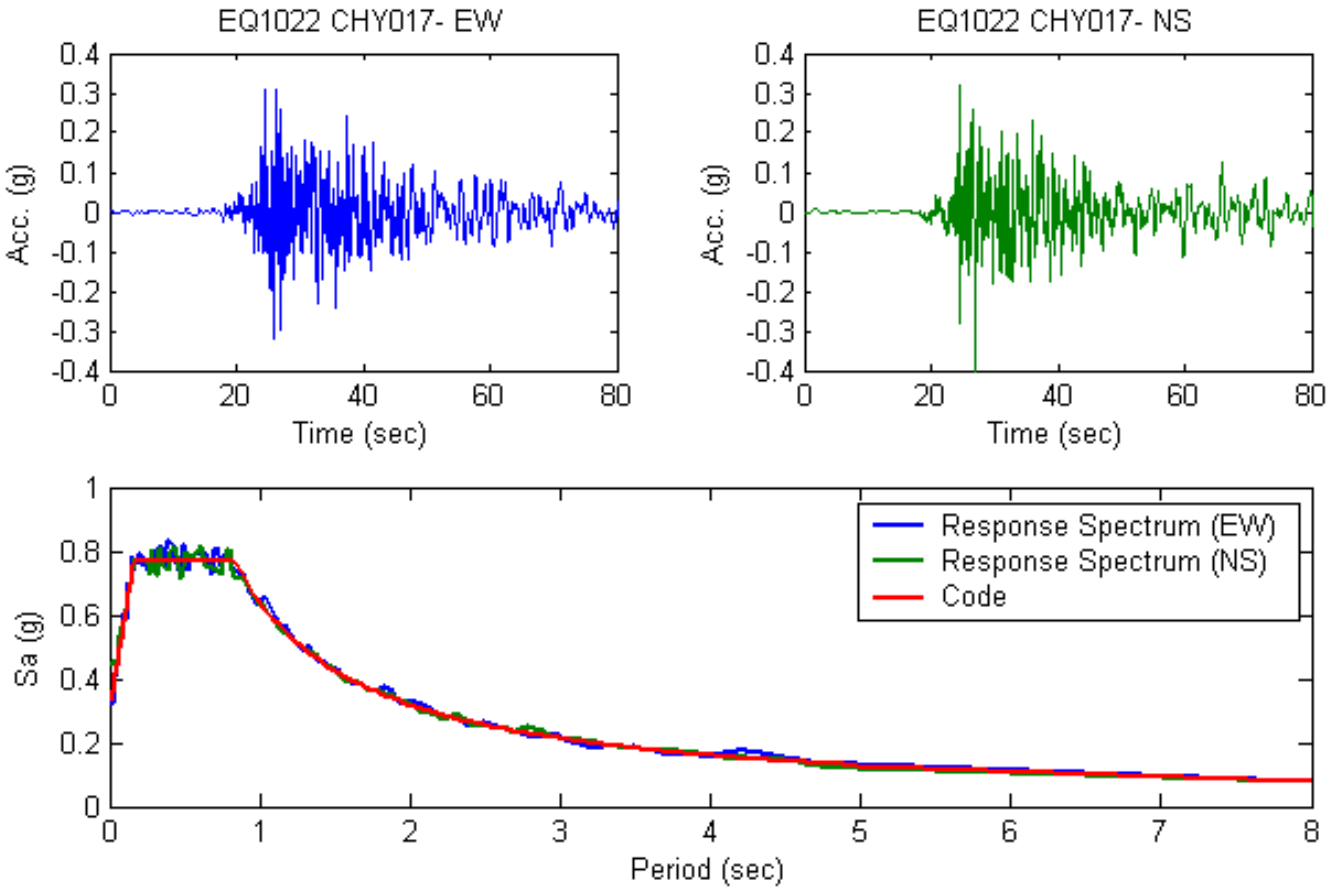
- Based on the phase spectrum at a site of interest, the input ground motion can be simulated by modifying the Fourier amplitude owing to the resonance effect



- Example I
  - CHY017 / EQ921



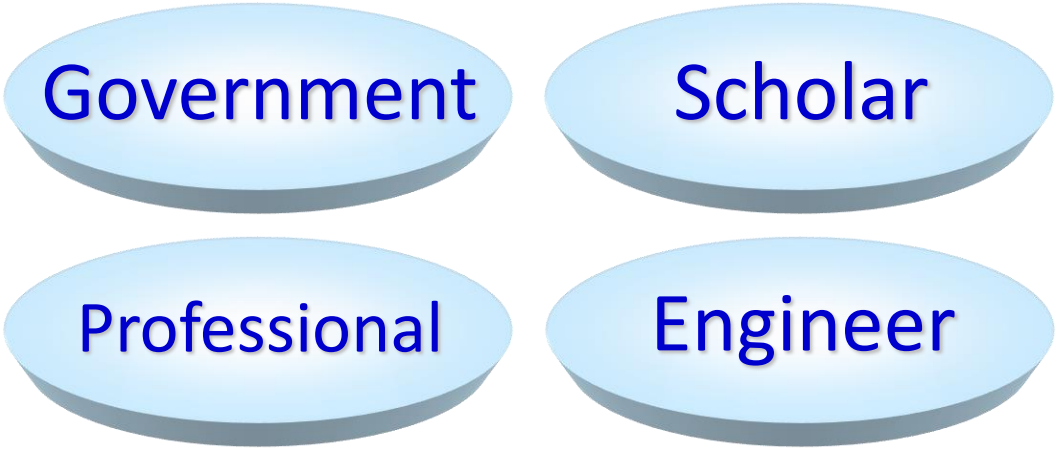
- Example II
  - CHY017 / EQ1022



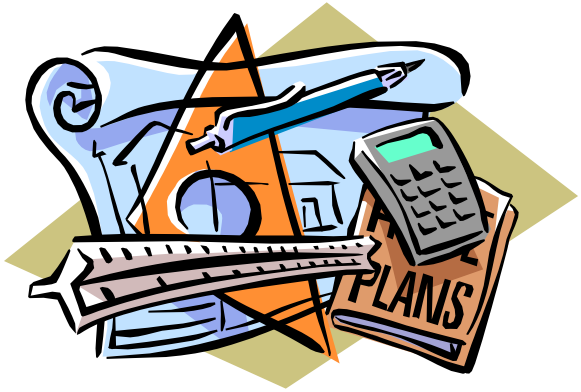
- Modification factors for the response
  - Linear time history analysis
    - Modification Factor = $\dfrac{I}{1.4\alpha_y F_u}$
    - Modification factors shall not be less than $\dfrac{I}{3.5\alpha_y}$ for Taipei Basin & $\dfrac{I}{4.2\alpha_y}$ for others
  - Nonlinear time history analysis
    - Nonlinear behavior should be modeled in the analysis
    - Modification factor =1.0

Research & Development Committee for Seismic Design Code

- Organized by NCREE in 2005



- Objectives
  - Modification of current seismic design code
  - Development of next version of seismic design code (PBD)

NARLabs

THANK YOU FOR YOUR ATTENTION !