Taiwan Recorded Ground Motion Database for Structural Response History Analysis

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Abstract

Nonlinear response-history analysis is beneficial for obtaining inelastic structural responses that resemble reality, especially for high-rise, long-span, damping, or base-isolated structures. However, to obtain reliable responses, one of the key issues is proper input excitation selection. In this study, we develop the Taiwan recorded ground motion database for structural response history analysis, which is based on ten target response spectra, local recorded ground motions, and the mean-squared error (MSE) of the major selection index. Target spectra for seven general sites, with corner periods ranging from 0.4 s to 1.0 s, and three Taipei Basin seismic microzonation sites were chosen, all of which have a return period of 475 years. A total of 30 records were selected for each target spectrum to provide an initial reference for choosing input excitations before executing time-history analysis. The ground motion selection fitness index was based on the MSE. This study concludes by providing suggestions for addressing practical issues in database applications, such as methods for selecting reference scale factors (SFs) for bidirectional ground motions, SF and MSE thresholds, and principles for selecting multiple records.

Keywords: recorded ground motion database, response history analysis, Taiwan Building Code, Taiwan general sites, Taipei Basin sites

Introduction

Time-history analysis studies the behavior of a structure to obtain detailed displacement and internal force information at specific time steps and thus gain a better understanding of structural nonlinearity. This approach is widely used for dynamic structural analysis. Input excitations are extremely important elements impacting the reliability of structural responses, and this stability of solutions of structural analysis is mainly influenced by two requirements: the number of recorded time-histories and the characteristics of recorded response spectra. The first requirement, for design purposes, is that a sufficient number of records with sufficient variability is selected in order to achieve unbiased structural response results. For the second requirement, recorded spectral shapes should reflect the site-specific characteristics generated by seismic hazards and site effects.

The motivation for this study was to provide an initial reference and proper data source for dynamic time-history analysis in engineering practices. Using basic principles for generic applications and the Taiwan Building Code (TBC) regulations, we developed the Taiwan recorded ground motion database for structural response history analysis. A total of ten datasets are grouped in this database. Seven datasets are for general sites, which do not incorporate consideration of near-fault effects (Liu et al., 2020), and three datasets are for Taipei Basin sites. Each dataset includes 30 selected ground-motion records based on a target design spectrum that reflects one of the representative site characterizations in Taiwan.

For generic applications and to ensure equivalence to shape characteristics of recorded response spectra, the observed range of target spectral periods and modified decay of spectral acceleration (S_a) after certain corner periods (T_0) were applied. For general sites, the period ranges from 0.03 s to 3 s and S_a is proportional to T^{-1} after T_0. For Taipei Basin sites, the period range is 0.01-8.0 s, and S_a is proportional to T^{-1} and T^{-2}, respectively, after T_0 and a period of 4.0 s. The corner period T_0 is defined as the intersection of regions

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of the spectrum where spectral acceleration is constant and where spectral velocity is constant, which is highly dependent on site condition.

Target Design Spectra

Under the current seismic design code regulations in Taiwan, a site can be classified into one of three categories according to regional characteristics: general sites, near-fault sites, and Taipei Basin sites. In this study, which does not consider near-fault effects, the target design spectra for developing the Taiwan recorded ground motion database include seven sets for general sites (Figure 1) and three sets for Taipei Basin sites (Figure 2).

General Sites

If all combinations of S_s^D and S_1^D for general sites with a return period of 475 years are considered, a first class site (a hard site) without near-fault effects, can be categorized into three groups depending on the distribution of T_0 for code-based normalized design spectra (with an effective peak acceleration (EPA) of 0.4 g): T_0 equal to 0.5, 0.6, and 0.7 s. The T_0 range can be extend to 0.4-1.0 s if the site amplification factors (F_a and F_v) follow a semi-logarithmic empirical model (Jean, 2020), which is formulated in terms of V_{s30} and designed ground motion intensities (S_s and S_1). Rather than setting a constant S_a (e.g., $0.4S_{DS}$ or $0.4S_{MS}$) after a spectral period larger than $2.5T_0$, as is done for a conservative consideration of seismic design force in the current TBC, in this study, the S_a after T_0 is assumed to continue to be proportional to T^{-1} for general sites so that real ground motion characteristics are reasonably approximated.

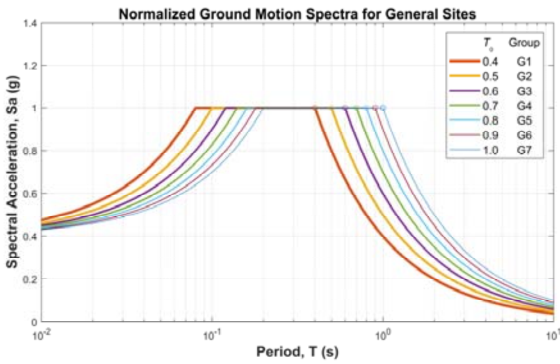

Fig. 1 Seven normalized target design spectra for general sites (EPA of 0.4 g).

Taipei Basin Sites

For Taipei Basin seismic microzonation sites 1, 2, and 3 (TAP1, TAP2, and TAP3) with a return period of 475 years from the current TBC, all S_{DS} values are 0.6 and the T_0 values are 1.6, 1.3, and 1.05 s, respectively. In addition, with reference to past earthquake data, in this study the corner period defined by the intersection of regions of constant spectral velocity and spectral displacement is designated as T_L, which is the cut-off point for S_a being proportional to T^{-1} and T^{-2}. T_L is chosen to be 4.0 s in accordance with seismic hazard analysis results (Jean et al., 2020).

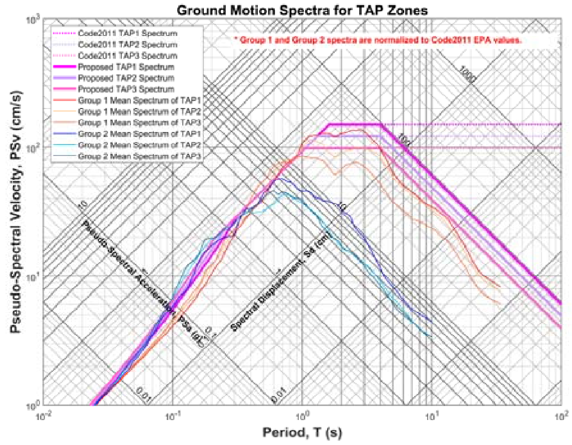

Fig. 2 Three target design spectra for Taipei Basin sites (thick solid lines).

Ground Motion Selection Approach

In accordance with the above-mentioned ten target design spectra, TBC regulations, and application limits of target design spectra at long period ranges, we propose the following methodology for recorded ground motion selection (after Liu et al., 2020):

1. The recorded response spectrum is presented as the geometric mean of both horizontal spectra, which is the basis for spectral amplitude scaling and spectral shape goodness-of-fit testing of horizontal components. S_a is computed at 50 points, which are uniformly spaced over the log period scale from 0.01 s to 10 s.

2. The period range for the spectral shape goodness-of-fit estimation is 0.03 s to 3 s for general sites; this range avoids celebrated earthquake events (e.g., 921 and 331 severe earthquakes) that dominate selection results and have unrealistic target spectral shapes at long periods. The period range for spectral shape goodness-of-fit estimation is 0.01 s to 8.0 s for Taipei Basin sites; this reflects the actual spectral trends after T_L, including those at long period ranges.

3. The ranking method for recorded response spectra uses a scale factor (SF) and mean-squared error (MSE). The calculation process for the rank index is as follows:

(a) Calculate SF_0 from:

$$SF_0 = \exp\left(\frac{\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i)\right)\right]}{N}\right) \quad (1)$$

where T_i is the i^{th} spectral period in a specified range, N is the total number of points of the specified periods, Sa_{target} is the target S_a, and Sa_{record} is the recorded S_a, which is defined as the geometric mean spectrum of both horizontal components.

(b) Calculate MSE_0 from:

$$MSE_0 = \frac{\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i) \times SF_0\right) \right]^2}{N} \quad (2)$$

(c) Calculate SF_m for reference scaling from:

$$SF_m = \begin{cases} SF_0 \times \left(0.9/RTR_{min}\right), & RTR_{min} < 0.9 \\ SF_0 & , \quad RTR_{min} \geq 0.9 \end{cases} \quad (3)$$

where $RTR_{min} = \min\left(Sa_{record}(T_i) \times SF_0 / Sa_{target}(T_i)\right)$ is the minimum record-to-target ratio in a specified spectral period range.

(d) Calculate MSE_m for rank index from:

$$MSE_m = \frac{\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i) \times SF_m\right) \right]^2}{N} \quad (4)$$

MSE_0 or MSE_m denote fitness index. The lower the MSE, the more similar the shapes between target and scaled recorded spectra. MSE_m is larger than MSE_0 because of the criteria restricting recorded spectra from falling more than 10 percent below the target spectrum at any one period. In addition, SF_0 or SF_m denote scaling index, which can be applied to scale the amplitude for both horizontal components of the accelerograms. The scaled recorded spectrum may present a certain design level and conforms to the TBC requirements. In general, lower MSE and SF values are preferable in practice.

Taiwan Recorded Ground Motion Database

The earthquake data used in this study are from the Taiwan Strong Motion Instrumentation Program (TSMIP) operated by the Central Weather Bureau (CWB) from January 1991 to June 2018. In accordance with the above ten target design spectra, ground motion selection approach, and data sources, Figure 3 shows the complete procedure and statistics for the construction of the Taiwan recorded ground motion database for structural response history analysis.

The purpose for recorded ground motion candidate selection is to set adequately relaxed restrictions and then collect as many records as possible. Regarding the strong-motion station criteria, for general sites, the V_{s30} level decreases while T_0 rises and the division points of the V_{s30} range are 270, 360, and 520 m/s. For Taipei Basin sites, the range of selected stations is extended to the group with next lowest T_0.

Each dataset corresponding to each group of target spectra contains the first 30 recorded ground motions with the smallest MSE_0. The number of earthquake events decreases with increasing T_0, which means that in Taiwan, few earthquake events with large magnitudes inducing long energy periods occurred. The number of stations in each group is greater than 24, which is sufficiently large to cover the range for strong-motion station distributions. In addition, the statistics for the MSE_0 range are within 0.038 for general sites and 0.079 for Taipei Basin sites, which are less than the

Target Spectrum Setting of Each Group

- ***For General Site:***

$$\begin{cases} S_a = S_S\left(0.4 + 3T/T_0\right), & T \leq 0.2T_0 \\ S_a = S_S & , \quad 0.2T_0 < T \leq T_0 \\ S_a = S_S T_0 / T & , \quad T_0 < T \end{cases}$$

- ***For Taipei Basin Site:***

$$\begin{cases} S_a = S_S\left(0.4 + 3T/T_0\right), & T \leq 0.2T_0 \\ S_a = S_S & , \quad 0.2T_0 < T \leq T_0 \\ S_a = S_S T_0 / T & , \quad T_0 < T \leq 4.0 \\ S_a = 4S_S T_0 / T^2 & , \quad 4.0 < T \end{cases}$$

- ***Target Spectrum Parameters of Each Group:***

Group	G1	G2	G3	G4	G5	G6	G7	TAP3	TAP2	TAP1
T_0 (sec.)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.05	1.30	1.60
T_L (sec.)	-	-	-	-	-	-	-	4.0	4.0	4.0
S_S	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6	0.6	0.6

Recorded Ground Motion Candidate Selection

- ***Data Sources:***
  - Taiwan Strong Motion Instrumentation Program (TSMIP)
  - Engineering Geological Database for TSMIP (EGDT)
- ***Time Period:*** Jan 1991 ~ June 2018
- ***Intensity Threshold:***
  - ***For general site:*** $PGA_{GM} \geq 100$ gal
  - ***For Taipei Basin site:*** $PGA_{GM} \geq 50$ gal
- ***Ground-Motion Station Condition of Each Group:***

Group	G1	G2	G3	G4	G5	G6	G7	TAP3	TAP2	TAP1
Station Condition	$360 \leq V_{s30}$	$360 \leq V_{s30}$	$270 \leq V_{s30} \leq 520$	$270 \leq V_{s30} \leq 520$	$V_{s30} \leq 360$	$V_{s30} \leq 360$	$V_{s30} \leq 360$	TAP3 & General Site	TAP2 & TAP3	TAP1 & TAP2

- ***Statistics for Candidate Records of Each Group:***

Group	G1	G2	G3	G4	G5	G6	G7	TAP3	TAP2	TAP1
# of records	1,527	1,527	976	976	825	825	825	3,977	133	130
# of events	329	329	229	229	142	142	142	455	23	21
# of stations	279	279	186	186	206	206	206	403	49	51

Constructing the Taiwan Recorded Ground Motion Database for Structural Response History Analysis

- ***Recorded Spectrum Type:*** geometric mean (GM) of both horizontal components
- ***No. of S_a points:*** 50 points uniformly spaced over the log period scale from 0.01 s to 10 s
- ***Period Range for Goodness-of-Fit Estimation:***
  - ***For general site:*** 0.03 s ~ $3T_0$ s (total 26 to 30 period points)
  - ***For Taipei Basin site:*** 0.01 s ~ 8.0 s (total 48 period points)
- ***Recorded Spectrum Ranking Procedure:***

1. Calculate SF_0 – Compute the mean ratio between recorded S_a and target S_a in the specified period range:

$$SF_0 = \exp\left(\frac{\sum_i^N \left\{ \ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i)\right) \right\}}{N}\right)$$, which satisfies $\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i) \times SF_0\right) \right] = 0$

2. Calculate MSE_0 – Compute the mean-squared logarithmic error between recorded S_a after SF_0 scaling and target S_a in the specified period range:

$$MSE_0 = \frac{\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i) \times SF_0\right) \right]^2}{N}$$

3. Calculate SF_m – Evaluate the minimum record-to-target ratio (RTR_{min}) for recorded S_a after SF_0 modification and target S_a in the specified period range, and then determine SF_m after comparison of RTR_{min} and 0.9:

$$SF_m = \begin{cases} SF_0 \times \left(0.9/RTR_{min}\right), & RTR_{min} < 0.9 \\ SF_0 & , \quad RTR_{min} \geq 0.9 \end{cases} \quad \text{where } RTR_{min} = \min\left(Sa_{record}(T_i) \times SF_0 / Sa_{target}(T_i)\right)$$

4. Calculate MSE_m – Compute the mean-squared logarithmic error between recorded S_a after SF_m scaling and target S_a in the specified period range:

$$MSE_m = \frac{\sum_i^N \left[\ln\left(Sa_{target}(T_i)\right) - \ln\left(Sa_{record}(T_i) \times SF_m\right) \right]^2}{N}$$

5. Rank Seed Records – Rank the top 30 seed records in ascending order based on MSE_0

- ***Dataset Statistics of Each Group:***

Group	G1	G2	G3	G4	G5	G6	G7	TAP3	TAP2	TAP1
# of events	19	16	18	14	10	8	9	6	2	2
# of stations	28	25	24	26	28	28	28	26	24	28
MSE_0 range	0.015 ~ 0.034	0.017 ~ 0.038	0.015 ~ 0.034	0.013 ~ 0.033	0.013 ~ 0.031	0.008 ~ 0.029	0.012 ~ 0.031	0.018 ~ 0.035	0.017 ~ 0.079	0.029 ~ 0.071
MSE_m range	0.033 ~ 0.224	0.035 ~ 0.207	0.021 ~ 0.134	0.019 ~ 0.157	0.020 ~ 0.229	0.013 ~ 0.180	0.024 ~ 0.206	0.027 ~ 0.226	0.042 ~ 0.555	0.088 ~ 0.520
SF_0 range	0.76 ~ 5.30	1.12 ~ 4.85	0.81 ~ 4.62	0.98 ~ 5.01	1.34 ~ 4.85	0.87 ~ 5.12	0.89 ~ 5.15	0.76 ~ 5.61	3.05 ~ 5.96	2.52 ~ 5.81
SF_m range	0.93 ~ 6.50	1.36 ~ 6.51	0.95 ~ 5.68	1.17 ~ 6.99	1.601 ~ 6.49	1.13 ~ 6.09	1.13 ~ 6.40	1.09 ~ 7.50	4.00 ~ 9.92	3.55 ~ 9.48

Fig. 3 Procedure and statistics for construction of the Taiwan recorded ground motion database for structural response history analysis.

0.164 required in the New Zealand structural design standard (NZS 1170.5:2004-A1, 2016). This comparison shows that the database developed in this study is appropriate for practical applications. Figure 4 presents scaled recorded spectra for the smallest MSE_0 compared with corresponding target spectra for group G4 (general site; T_0 = 0.7 s) and group TAP2 (Taipei Basin site; T_0 = 1.05 s).

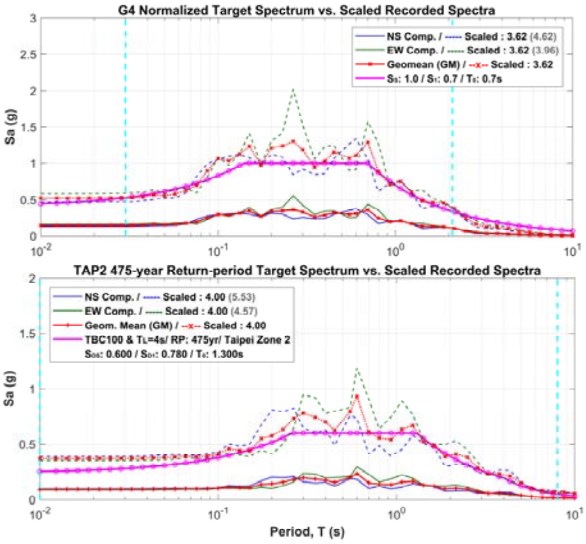

Fig. 4 Scaled and non-scaled recorded spectra of the smallest MSE_0 for group G4 (top plot) and group TAP2 (bottom plot).

Key parameters are classified into four categories listed in the metafile of each dataset in the Taiwan recorded ground motion database:

1. *Seismic Source*: earthquake time (UTC), epicentral coordinates (WGS-84), moment magnitude, focal depth, epicentral distance, and hypocentral distance.
2. *Strong-Motion Station*: station code, station coordinates (WGS-84), V_{s30} value, located seismic zone, component, and CWB record filename.
3. *Rank Parameter*: SF_0, MSE_0, SF_m, and MSE_m.
4. *Ground Motion* (after baseline correction): PGA (A), PGV (V), PGD (D), V/A, AD/V^2, cumulative absolute velocity (CAV), strong-motion durations (5%–75% and 95% Arias intensity), record length, and S_a at 50 specified periods.

Conclusions and Suggestions

This study describes the construction of the Taiwan recorded ground motion database, which contains seven datasets for general sites and three datasets for Taipei Basin sites. Each dataset includes 30 recorded time histories and information related to spectral fitness and scale factors (SFs), seismic source, strong-motion stations, and ground motion intensity. This database provides a useful reference for selecting input motions during practical response history analysis. We suggest the following for bidirectional dynamic analysis when utilizing this database:

1. Each record listed in the metafile contains both horizontal components, and its geometric mean has its own rank parameter. The SF in these parameters offers a reference for generating uni- or bi-directional input excitations. It is appropriate to use one SF from the geometric mean for bidirectional input excitations.
2. The criterion for better spectral fitness is an MSE less than 0.045 estimated from empirical observations. In practice, however, this could be relaxed to be less than 0.164, in accordance with the New Zealand standards. An SF less than 5.0, is recommended and an SF larger than 7.0 is regarded as inadequate.
3. When selecting multiple ground motions, all earthquake events should be unique and should consider a minimum of three ground motions. In addition, each earthquake event should not exceed two records when considering a minimum of seven or eleven ground motions. The SF determination for multiple ground motions can be compared with the k_1−k_2 approach outlined in New Zealand standards.
4. Structures with a longer predominant period (T_p) should be examined more carefully. If 1.5 times T_p exceeds the applicable limits (3T_0 or 8.0 s), the suitability of the specific spectral shape should be specially confirmed. It is worth noting that the SFs listed in the database for general sites are calculated via normalized target spectra with generic application purposes; these SFs should therefore be corrected depending on the actual demands.

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