COMPARISON OF FACTORS TO DETERMINE DESIGN SEISMIC ACTIONS OF ISO, JAPAN, EUROCODE AND U.S.

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Abstract

Seismic codes are summarized, i.e. ISO 3010 “Bases for design of structures - Seismic actions on structures”, Building Standard Law (BSL) of Japan, Eurocode 8 and International Building Code (IBC) & ASCE 7 of U.S. Then the factors to determine design seismic actions included in these codes are compared. Requirements for seismic design and analysis are also compared.

Comparison of factors to determine design seismic actions

Factors	ISO 3010	BSL of Japan	Eurocode 8	IBC & ASCE 7 of U.S.
Load (importance) factor	$\gamma_{E,u}$	None (1.0)	γ_I	I_e
Zoning factor	k_Z	Z	Maps of a_g	Maps of S_S & S_1
Ground motion intensity*1	$k_{E,u}$	C_0/2.5*2	a_g	S_S/2.5*2
Return period		500 years*3	475 years	2,500 years*4
Site factor	k_{SS}	Three curves of R_t*5	S	F_a, F_v
Structural design factor	k_D	D_S	$1/q$	$1/R$
Design response spectrum	k_R	$2.5R_t$*2	Same as k_R	Same as k_R
Seismic force distribution factor	$k_{F,i}$	See below	Fundamental mode	Inverted triangle – parabolic distribution
Seismic shear distribution factor	$k_{V,i}$	A_i	See above	See above

*1 Intensity of severe earthquake ground motions for Ultimate Limit State (ULS) in terms of peak ground acceleration normalized by the acceleration due to gravity.

*2 “2.5” is the assumed elastic acceleration response amplification ratio for short period structures.

*3 Return period of “ZC_0” for C_0=1.0 can be approximately estimated 500 years.

*4 Spectral acceleration is multiplied by 2/3 for design, so that the return period is approximately 500 years.

*5 Three curves of R_t indicate that k_S=1.0 for hard soil, 1.5 for medium soil and 2.0 for soft soil.

Keywords: Seismic action; ISO 3010; BSL of Japan; Eurocode 8; IBC & ASCE 7 of U.S.

1. Background of seismic codes

1.1 ISO 3010

The first edition of International Standard "ISO 3010 Bases for design of structures - Seismic actions on structures" was published in 1988 through the activity of the working group in ISO/TC98. TC98 deals with "Bases for design of structures." The aim of TC98 is to create a coherent design system of International Standards in the field of building and civil engineering works. The system forms a basis for regional and national standard bodies which prepare their standards for particular types of structures and structural materials. The second edition of ISO 3010 was published in 2001 and the latest third edition in 2017. It includes principles for the determination of seismic actions on structures and seismic design.

1.2 BSL of Japan

The first building code of Japan was the Urban Building Law (UBL) in 1919 that had no seismic provisions. After the 1923 Great Kanto Earthquake, the provision that "the horizontal seismic factor shall be at least 0.1" was added in 1924 to the UBL. After World War II, the Building Standard Law (BSL) replaced the UBL in 1950. And the concept of "permanent" (long term) and "temporary" (short term) was introduced to load combinations and allowable stresses. Since the temporary allowable stress became twice of the old allowable stress (equivalent to the permanent allowable stress), the horizontal seismic factor became 0.2. The fundamental revision of the seismic design method became necessary because of severe damage caused by several earthquakes. Then a five year national research project for establishing a new seismic design method was carried out from 1972 to 1977. The BSL Enforcement Order was revised in 1980, and the new seismic design method has been used since 1981 that introduced two levels of earthquake motions, i.e. severe and moderate earthquake motions. Since then, minor revision has been made, but the basic concept remains the same.

1.3 Eurocode 8

In 1975, the Commission of the European Community decided on an action program in the field of construction. The objective of the program was the elimination of technical obstacles to trade and the harmonization of technical specifications. The Commission took the initiative to establish a set of harmonized technical rules for the design of construction works which would serve as an alternative to the national rules in the Member States and would replace them. For fifteen years, the Commission conducted the development of the Eurocodes program. In 1989, the Commission decided to transfer the preparation and the publication of Eurocodes to CEN (European Committee of Standardization) that is the official European standards body. Now Eurocode becomes the European standard for the design of construction works. It is used not only in European countries but also in some other countries. Eurocode consists of 10 standards, and one of them is Eurocode 8 "Design of structures for earthquake resistance".

1.4 IBC & ASCE 7 of U.S.

International Building Code (IBC) is the building code currently used in the U.S. and also used internationally in some countries or on some international projects. The first draft of IBC was prepared in 1997, combining mainly previous three model codes that had been used in U.S., i.e. Uniform Building Code (UBC) which had been used in western part, National Building Code (NBC) in eastern and northern parts and Standard Building Code (SBC) in southern part. The first published IBC was the 2000 edition, since then the IBC is revised every three years. It includes principal requirements, and the detailed requirements are referred to ASCE 7 "Minimum Design Loads and Associated Design Criteria for Buildings and Other Structures". IBC also references other standards such as American Concrete Institute (ACI) standard 318 for design and detailing procedures for concrete buildings and American Institute of Steel Construction (AISC) standards 360 and 341 for design and detailing procedures for steel buildings.

2. Comparison of design seismic shear factors

This section summarizes the procedures to determine design seismic forces/shears of ISO 3010, BSL (Building Standard Law) of Japan, Eurocode 8, IBC (International Building Code) and ASCE 7 (American Society of Civil Engineers). Then, the seismic base shear factors are calculated for a given condition, i.e. (1) most ductile reinforced, (2) regular, (3) short period structures for (4) normal use on (5) firm soil at (6) seismically most active area.

2.1 ISO 3010

The design lateral seismic force $F_{E,u,i}$ of the i-th level of a structure for ULS (ultimate limit state) may be determined by

$$F_{E,u,i} = \gamma_{E,u}\, k_Z\, k_{E,u}\, k_S\, k_D\, k_R k_{F,i} \sum_{j=1}^{n} F_{G,j} \tag{1}$$

or the design lateral seismic shear $V_{E,u,i}$ may be used instead of the above seismic force:

$$V_{E,u,i} = \gamma_{E,u}\, k_Z\, k_{E,u}\, k_S\, k_D\, k_R k_{V,i} \sum_{j=i}^{n} F_{G,j} \tag{2}$$

where, $\gamma_{E,u}$ is the load factor as related to reliability of the structure (it is similar to an importance factor); k_Z is the seismic hazard zoning factor; $k_{E,u}$ is the representative value of earthquake ground motion intensity; k_S is the soil factor; k_D is the structural design factor to be specified for various structural systems (it is similar to D_s of Japan, $1/q$ of Eurocode or $1/R$ of U.S.); k_R is the ordinate of the normalized design response spectrum; $k_{F,i}$ is the seismic force distribution factor of the i-th level to distribute the seismic base shear to each level, where $k_{F,i}$ satisfies the condition $\sum k_{F,i} = 1$; $k_{V,i}$ is the seismic shear distribution factor of the i-th level which is the ratio of the seismic shear factor of the i-th level to the seismic shear factor of the base, where $k_{V,i} = 1$ at the base and usually becomes largest at the top; $F_{G,j}$ is the gravity load at the j-th level of the structure; and n is the number of levels above the base.

There are similar formulae for SLS (Serviceability Limit State), in which the subscript "u" of the above two formulae is replaced by "s" and k_D is eliminated.

ISO 3010 includes principals for determination of seismic actions on structures and seismic design, but it does not give any specific values for factors to determine seismic loadings. Its annexes, however, give useful information to determine the values for those factors.

2.2 BSL of Japan

The design seismic shear Q_i of the i-th story is determined as follows.

$$Q_i = C_i\, W_i \tag{3}$$

where, C_i is the seismic shear factor of the i-th story, and W_i is the weight of the building above the i-th story.

C_i for moderate earthquake motions is given by

$$C_i = Z\, R_t\, A_i\, C_0 \tag{4}$$

where, Z is the seismic hazard zoning factor, R_t is the normalized spectrum, A_i is the seismic shear distribution factor, and $C_0 = 0.2$ is the standard shear factor for moderate earthquake motions.

C_i for severe earthquake motions is given by

$$C_i = D_s F_e F_s Z R_t A_i C_0 \tag{5}$$

where, D_s is the structural characteristic factor (D_s = 0.3 for most ductile reinforced concrete buildings), F_e is the shape factor as a function of stiffness eccentricity, F_s is the shape factor as a function of lateral stiffness, and C_0 = 1.0 for severe earthquake motions. Therefore, for the given condition, the base shear factor C_B = 0.3 is given from the above equation, substituting D_s= 0.3, F_e = 1.0, F_s = 1.0, Z = 1.0, R_t = 1.0, A_i = 1.0 and C_0 = 1.0.

Since for severe earthquake motions, non-linear analysis is used in BSL of Japan, the C_B value derived above should be reduced when it is compared with other values that are derived using linear analysis. Therefore it may be estimated that C_B = 0.25-0.3 in BSL of Japan.

2.3 Eurocode 8

The base shear F_b is determined as follows:

$$F_b = S_d (T_1)\, m\, \lambda \tag{6}$$

where, $S_d (T_1)$ is the ordinate of the design spectrum at period T_1, T_1 is the fundamental period of vibration of the building, m is the total mass of the building; and λ is the correction factor, λ = 0.85 if $T_1 \leqq 2T_c$ and more than two stories or λ = 1.0 otherwise.

$S_d (T)$ is given by

$$S_d(T) = \begin{cases} a_g \cdot S \left[\frac{2}{3} + \frac{T}{T_B} \left(\frac{2.5}{q} - \frac{2}{3} \right) \right] & (0 \le T \le T_B) \\ a_g \cdot S \cdot \frac{2.5}{q} & (T_C \le T \le T_B) \\ a_g \cdot S \cdot \frac{2.5}{q} \left[\frac{T_C}{T} \right] \ge \beta \cdot a_g & (T_C \le T \le T_D) \\ a_g \cdot S \cdot \frac{2.5}{q} \left[\frac{T_C T_D}{T^2} \right] \ge \beta \cdot a_g & (T_D \le T) \end{cases} \tag{7}$$

where, $a_g = \gamma_I a_{gR}$ is the design ground acceleration on type A ground, γ_I is the importance factor that is 1.0 for ordinary buildings, a_{gR} is the reference peak ground acceleration on type A ground. S is the soil factor that is 1.0 for ground type A (rock), 1.2 for ground type B (very dense sand, gravel, etc.) and 1.15 for ground type C (dense or medium dense sand), etc. $q = q_0 k_w$ is the behavior factor where the basic value of behavior factor q_0 = $4.5\alpha_u/\alpha_1$ and α_u/α_1 = 1.3 for multistory, multi-bay frames or frame-equivalent dual structures, and k_w=1.0 for frame and frame-equivalent systems.

In most seismically active area in Europe, a_{gR} = 0.4-0.5g. Then, for the given condition, a_{gR} = 0.4-0.5g, S = 1.15, q = 4.5×1.3. Therefore the base shear factor $C_B = S_d (T)/g$ = (0.4-0.5)×1.15×2.5/(4.5×1.3) = 0.20-0.25.

2.4 IBC & ASCE 7 of U.S.

According to the equivalent lateral force procedure (ASCE7 12.8), the seismic base shear V is determined as follows.

$$V = C_s W \tag{8}$$

where, C_s is the seismic response coefficient, and W is the effective seismic weight.

C_s is the base shear factor C_B itself and is determined as follows.

$$C_s = \frac{S_{DS}}{(R/I_e)} \tag{9}$$

where, S_{DS} is the design spectral response acceleration parameter in the short period range, R is the response modification factor, and I_e is the importance factor.

The response modification factor R of most ductile structure is 8, and the importance factor for Risk Category II (normal use) is 1.0.

C_s need not exceed the following:

$$C_s \le \begin{cases} \frac{S_{DS}}{T(R/I_e)} & \text{for } T \le T_L \\ \frac{S_{DS}T_L}{T^2(R/I_e)} & \text{for } T \ge T_L \end{cases} \tag{10}$$

C_s shall not be less than

$$C_s = 0.044 S_{DS} I_e \ge 0.01 \tag{11}$$

In addition, where $S_1 \ge 0.6g$,

$$C_s \ge \frac{0.5S_1}{(R/I_e)} \tag{12}$$

where, S_1 is the mapped maximum considered earthquake (MCE) spectral acceleration parameter.

The 5% damped design spectral response acceleration parameters at short period S_{DS} and at 1(s) period S_{D1} are determined from

$$\begin{cases} S_{DS} = \frac{2}{3} S_{MS} \\ S_{D1} = \frac{2}{3} S_{M1} \end{cases} \tag{13}$$

where, S_{MS} and S_{M1} are adjusted MCE spectral response acceleration parameters for short period and 1(s) period, that are determined as follows.

$$\begin{cases} S_{MS} = F_a S_S \\ S_{M1} = F_v S_1 \end{cases} \tag{14}$$

F_a and F_s are the site coefficients. Both are 1.0 for Site Class B soil (rock). S_S and S_1 are the MCE_R ground motion response accelerations of 0.2(s) spectral acceleration and of 1(s) spectral acceleration, respectively, both for 5% of critical damping on the Site Class B. Counter lines for S_S are from 0.05g to 2.0g, and those for

S_1 are from 0.02g to 1.0g. S_s and S_1 are based on the 2,500 year return period. Then, it may be considered that S_{DS} and S_{D1} are approximately based on 500 year return period.

Therefore, for the given condition, the base shear factor is given as follows: S_S=2.0, F_a = 1.0 (for site classes B, C and D, F_a =1.0 in case $S_S \geqq 1.25$), $S_{MS} = F_a S_S$= 2.0, S_{DS} = (2/3)S_{MS} = 4/3, $C_s = S_{DS}/(R/I_e)$ = (4/3)/(8/1) = 1/6 = 0.17, i.e. C_B = 0.17.

3. Comparison of factors

The factors to determined design seismic forces/shears are summarized in Table 1. The base shear factors C_B for (1) most ductile reinforced, (2) regular, (3) short period structures for (4) normal use on (5) firm soil at (6) seismically most active area, are C_B = 0.25-0.3 in Japan, C_B = 0.20-0.25 in Europe, and C_B = 0.17 in U.S.

Table 1 – Comparison of factors to determine design seismic actions

Factors	ISO 3010	BSL of Japan	Eurocode 8	IBC & ASCE 7 of U.S.
Load (importance) factor	$\gamma_{E,u}$	None (1.0)	γ_I	I_e
Zoning factor	k_Z	Z	Maps of a_g	Maps of S_S & S_1
Ground motion intensity*1	$k_{E,u}$	C_0/2.5*2	a_g	S_S/2.5*2
Return period		500 years*3	475 years	2,500 years*4
Site factor	k_{SS}	Three curves of R_t*5	S	F_a, F_v
Structural design factor	k_D	D_S	1/q	1/R
Design response spectrum	k_R	2.5R_t*2	Same as k_R	Same as k_R
Seismic force distribution factor	$k_{F,i}$	See below	Fundamental mode	Inverted triangle – parabolic distribution
Seismic shear distribution factor	$k_{V,i}$	A_i	See above	See above

*1 Intensity of severe earthquake ground motions for Ultimate Limit State (ULS) in terms of peak ground acceleration normalized by the acceleration due to gravity.

*2 “2.5” is the assumed value of elastic acceleration response amplification ratio for short period structures.

*3 Return period of “ZC_0” for C_0 = 1.0 can be approximately estimated 500 years.

*4 Spectral acceleration is multiplied by 2/3 for design, so that the return period is approximately 500 years.

*5 Three curves of R_t indicate that k_S = 1.0 for hard soil, 1.5 for medium soil and 2.0 for soft soil.

4. Comparison of analysis methods

4.1 ISO 3010

In ISO3010, equivalent static analysis, nonlinear analysis, and dynamic analysis are accepted as analysis methods. The standard states "ordinary and regular structures may be designed by the equivalent static method using conventional linear elastic analysis”. But it also states "Structures where nonlinear sequence of behavior is difficult to predict should utilize nonlinear static analysis to determine the sequence".

4.2 BSL of Japan

In BSL of Japan, linear static analysis is accepted to confirm that buildings withstand moderate earthquake (rare earthquake) motions, which would occasionally occur during the service life of the buildings with almost no damage. Non-linear static (pushover) analysis or joint distribution method to evaluate the ultimate capacity of buildings are accepted to confirm that buildings do not collapse nor harm human lives during severe earthquake (extremely rare earthquake) motions, which would rarely occur during the service life of the buildings. Non-linear response history (dynamic) analysis can be used by obtaining the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) certification.

4.3 Eurocode 8

In Eurocode 8, four types of seismic analysis methods, i.e. (1) lateral force method of analysis, (2) modal response spectrum analysis, (3) non-linear static (pushover) analysis, and (4) non-linear time (response) history (dynamic) analysis, are accepted depending on the structural irregularity. Nonlinear analysis is described as "Alternative to a linear method".

4.4 IBC & ASCE 7 of U.S.

In ASCE 7, three types of seismic analysis methods, i.e. (1) equivalent lateral force (ELF) procedure, (2) modal response spectrum analysis (RSA), and (3) linear response history analysis, are accepted. This standard does not accept non-linear static (pushover) analysis, but nonlinear response history analysis is accepted. In the latest revision, description of nonlinear response history analysis has been changed from "Alternate procedure to ELF, RSA" to "Supplementary procedure to ELF, RSA, or linear response history" procedure.

Table 2 – Comparison of analysis methods

	ISO 3010	BSL of Japan	Eurocode 8	IBC & ASCE 7
Linear elastic analysis Lateral force method analysis Equivalent lateral force procedure	A	A	A	A
Modal response spectrum analysis	A	A*	A	A
Non-linear static (pushover) analysis	A	A	A	NA
Linear response history analysis	A	NA	NA	A
Non-linear response history analysis	A	A	A	A

A : Accepted, NA : Not Accepted
* It can be used to calculate the seismic shear distribution factor in lieu of A_i in Table 1.

5. Comparison of analysis models of structure

In ISO 3010 states "The two horizontal and the vertical components of the earthquake ground motion and their spatial variation, leading to torsional excitation of structures, should be considered". Similar to ISO 3010, BSL of Japan, Eurocode 8, and ASCE 7 also stipulate to take into account torsion. In ASCE 7 there are constraints not only on the amount of torsional deformation but also on the irregularities of shear walls and floor diaphragms.

There is also a difference in the evaluation of concrete stiffness. In Japan, the models of the fundamental period and the first phase design do not consider the effects of cracks and other factors on concrete stiffness. Eurocode and ASCE 7, on the other hand, consider the effects of cracks on concrete stiffness.

6. Comparison of limit state

6.1 ISO 3010

In ISO 3010 states that to give complete protection against all earthquakes is not economically feasible for most types of structures, and there are two design limit states, i.e. serviceability limit state (SLS) and ultimate limit state (ULS). BSL of Japan and Eurocode 8 have similar philosophy to ISO 3010, while IBC & ASCE 7 of U.S. do not have concept of two limit states, and it may be considered that only ULS is included (see 6.4).

6.2 BSL of Japan

In BSL of Japan, there are two design phases. The concept of first phase design is to design the structure such as the stresses in structural members should not exceed allowable stress due to moderate earthquake motions which the structure may experience several times during its service life. The second phase design is to ensure that the structure should not collapse nor reach to similar forms of structural failure due to severe earthquake motions which may be experienced only once in its service life.

6.3 Eurocode 8

In Eurocode 8, there are two states to be verified, i.e. ultimate limit state and damage limit state. As to the ultimate limit state, structural system is verified for its resistance or its energy dissipation capacity under design seismic action where the reference return period is 475 years. As to the damage limit state, deformations of structures should be less than the limits for the seismic action of the 95 year reference return period. The reference return periods that are given in the code are recommended values, and local authorities are allowed to change them.

6.4 IBC & ASCE 7 of U.S.

The philosophy of two limit states is not clearly stated in IBC & ASCE 7. Since the design seismic force is based on 2,500 year reference return period for stress verification and deformation limitation, the verification may be for ULS.

7. Comparison of lateral deformation due to seismic actions

7.1 ISO 3010

ISO 3010 states that the deformation of the structure under seismic actions should be limited, in order to restrict damage for moderate earthquake ground motions and to avoid collapse or other similar forms of structural failure for severe earthquake ground motions.

7.2 BSL of Japan

In BSL the story drift caused by lateral seismic shear for moderate earthquake motions shall not exceed 1/200 (0.005) of the story height. This value can be increased to 1/120 (0.0083), if nonstructural elements shall have no severe damage at the increased story drift limitation. There is no limitation for severe earthquake motions, however, it is usually required to limit it within 1/100 (0.01).

7.3 Eurocode 8

In Eurocode 8, the story drift caused by moderate earthquakes (recommended return period is 95 years) is adjusted multiplying a reduction factor to take into account the lower return period of seismic action associated with the damage limitation requirement. The adjusted story drift limitations are 1/200 (0.005), 1/133 (0.0075) or 1/100 (0.01) depending on the condition of non-structural elements.

7.4 IBC & ASCE 7 of U.S.

In IBC & ASCE 7, the assessment of deformation is based on story drifts that are derived from structural analysis caused by severe earthquakes. There is no clear notation whether the assessment of deformations is for ULS or SLS, but it should be for ULS. The allowable story drift is 1/40 (0.025) to 1/142 (0.007), depending on the structure and its risk category or importance factor.

8. Comparison of effect of site conditions

ISO 3010 states that site conditions should be evaluated, taking into account microzonation criteria such as vicinity to active faults, soil profile, soil behavior under large strain, liquefaction potential, topography, subsurface irregularity, and other factors including interactions between these. BSL of Japan, Eurocode 8 and IBC & ASCE 7 have clauses to evaluate actual soil profile at site including the subsurface irregularity and liquefaction potential, and consider them to seismic actions.

Eurocode 8 and IBC & ASCE 7 require evaluation based on soil investigation such as N-value by Standard Penetration Test, cohesion strength or shear velocity down to 30m deep below ground level.

Evaluation of liquefaction and design method against it are given in three codes except ISO 3010. Eurocode 8 does not include Tsunami actions, probably because the great disaster due to tsunami occurred after publication of Eurocode 8.

9. Comparison of consideration to non-structural members

9.1 ISO 3010

ISO3010 states that the structure, including non-structural as well as structural elements, should be clearly defined as a seismic force resisting system which can be analyzed, and the influence of not only structural system elements but also non-structural walls, partitions, stairs, windows, etc. should be considered when they are significant to the structural response.

9.2 BSL of Japan

BSL of Japan requires to pay attention to the stiffness of non-structural members. And whether the stiffness is evaluated in the analysis or not, non-structural members shall have enough capacity to follow the movement or deformation of the structure.

9.3 Eurocode 8

In Eurocode 8, non-structural members are required to be incorporated into analysis model. Certain structural members need not be considered in the analysis, if those secondary members do not form part of seismic action resisting system. Nonetheless those members and connections are deigned to maintain support of gravity loading when subjected to the displacement caused by the mot unfavorable seismic design condition.

9.4 IBC & ASCE 7 of U.S.

IBC & ASCE 7 require to include stiffness of non-structural members in the analysis. ASCE 7 has an independent chapter for nonstructural components.

10. Conclusions

Seismic codes, i.e. ISO 3010 “Bases for design of structures - Seismic actions on structures”, Building Standard Law (BSL) of Japan, Eurocode 8 and International Building Code (IBC) & ASCE 7 of U.S. are introduced. The factors to determine design seismic actions included in these codes are compared. Then the base shear factors C_B for (1) most ductile reinforced, (2) regular, (3) short period structures for (4) normal use on (5) firm soil at (6) seismically most active area, are calculated. The results are C_B = 0.25-0.3 in Japan, C_B = 0.20-0.25

in Europe, and C_B = 0.17 in U.S. The analysis and design methods are also compared. These seismic codes have similar concept and factors, but they are not identical. The differences are becoming smaller than decades ago. Hopefully we will have a unique seismic code in future.

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