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Review

Review of Methodologies for Displacement Checks in Modern Seismic Design Codes

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Abstract: This review paper discusses the procedures for evaluating the design displacement given in various design codes from seismically prone countries around the world (the United States, New Zealand, Chile, Japan, Greece, Italy, Iran, India, Turkey, and Romania). The limit displacements and the corresponding limit states are also presented and analyzed in this study besides the importance class factors considered in the selected seismic design codes. A presentation of the behavior factors necessary for evaluating the design value of the seismic action is also shown in this study. One of the observations of this review paper is that there are significant similarities in terms of the approach to the displacement check in the analyzed codes. In addition, it was observed that the displacement check is generally associated with the serviceability limit state (e.g., damage limitation). However, differences in terms of the mean return period for the serviceability check action were observed among the analyzed seismic design codes. Several aspects which have to be further adapted in the future versions of seismic design codes are also discussed in this review paper. One of the main aspects which must be further discussed is the enforcement of displacement limits, which are dependent on the structural system and on the importance of the class/height regime for the ultimate/serviceability limit state. In addition, the dependence of the T_D control period on the probabilistic seismic hazard ordinates should be further discussed. Moreover, the pulse effects, which can affect both the acceleration and the displacement design of response spectra, should be accounted for as well in future generations of seismic codes. Finally, it appears necessary to perform a harmonization of the behavior factors employed in seismic design codes.

Keywords: pulse effects; fault mechanism; control period; elastic displacement; amplification factor; limit displacement; limit state; importance class

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1. Introduction

This review paper is focused on a discussion regarding the displacement checks required by various design codes from the United States, New Zealand, Chile, Japan, Greece, Italy, Iran, India, Turkey, and Romania. These countries were selected mainly because they have been affected by significant earthquakes in the past 40 years and because their design codes have been updated using both local and global knowledge in the field. Besides the strength checks of the elements, displacement checks are performed in order to ensure a specified level of stiffness to structures and to control the likely nonstructural and structural damage. Finally, a structure designed according to modern seismic design codes should have enough ductility to have sufficient deformation capacity during strong ground shaking. This paper provides a review of the methodologies and parameters applied to the displacement checks of structures from the selected seismic design codes.

Three approaches to this check can be found: (i) displacement check for a serviceability limit state; (ii) displacement check for the ultimate limit state; and (iii) displacement checks for both the serviceability and ultimate limit states. Depending on the limit state used for the displacement check and on the mean return period of the seismic action employed, a quasi-elastic or inelastic behavior can be inferred for the structure. The correspondence between the limit states used for the design of structures in Europe and in the United States can be found in the paper by Fardis [1]. In most cases, the equal displacement rule ([2,3]), which means that the displacement of an inelastic system is equal to that of the same system behaving in an elastic manner, is applied. Various research studies have investigated the applicability of this rule to buildings (e.g., [4–12]), bridges (e.g., [13–16]), or structures with various types of dissipative systems (e.g., [17–20]).

The inelastic displacement demand of a multi-degree-of-freedom (MDOF) system is computed from that of the corresponding single degree-of-freedom system (SDOF), which is amplified considering the characteristics of the MDOF system, the ratio between inelastic and elastic displacements (displacement amplification factor), and other parameters. The displacement amplification factor depends in its basic form on the ductility level (μ), overstrength factor (R_S), and hysteretic model [21].

Within the scope of this study, a characterization of the main design requirements given in some modern seismic design codes (not necessarily the versions still in use) can be found in [22]. Recently, a discussion focused on the role of seismic design codes in risk perception and seismic risk reduction in Europe has been presented in a paper by Pavel [23].

In this review paper, the provisions related to displacement checks from various design codes (including design relations) in the selected seismically prone countries are briefly discussed and analyzed. Key parameters necessary for displacement checks are also presented in this paper. The parameters necessary for defining the soil conditions and the design response spectrum (including importance factors and behavior factors) are also presented in this study. Finally, some aspects which should be considered for introduction in future versions of seismic design codes are highlighted.

2. Evaluation of Displacement Demand in Structural Design Codes

In this section, basic provisions related to the design of seismic action and displacement checks from various design codes in seismically prone countries around the world are presented and briefly discussed.

From the point of view of the design of ground motion amplitude metrics, two categories of design codes can be inferred: (1) seismic design codes using peak ground acceleration and (2) seismic design codes using spectral accelerations. From the subsequent review, it can be observed that the majority of the analyzed seismic design codes employ peak ground acceleration as the ground motion amplitude metric. In some design codes, site amplification factors that are amplitude dependent are provided besides specific spectral shapes.

2.1. Europe

The current version of Eurocode 8 [24] employs a two-limit state design approach, one for strength checks (no collapse) and the other one for the stiffness requirement (displacement limitation), which corresponds to the damage limitation limit state. The selected ground motion amplitude parameter is the peak ground acceleration (PGA) corresponding to a mean return period of 475 years. Soil factors are proposed as a function of the soil class in order to adjust the design of the peak ground acceleration for the corresponding site conditions. The control periods T_C and $T_{D,}$ which represent the border between the constant acceleration and constant velocity branch and the constant velocity and constant displacement branch of the design of the response spectrum, respectively, are pre-defined for each site category. Since the displacement check is associated with a serviceability limit state, the displacement check consists basically of a reduction in the design of the displacement with a reduction coefficient υ, which considers the lower mean return period of the seismic action associated with this check. The values of υ are 0.4 or 0.5, depending on the importance class of the structure.

The proposed future draft of the Eurocode 8 [25] proposes a different approach for the evaluation of the design of seismic action involving two spectral accelerations, for the short period range S_{α} and medium period range S_{β}. The site-specific design of spectral accelerations is computed by amplifying the rock spectral ordinates with the corresponding site amplification factors. The control periods T_C and T_D are computed based on the spectral ordinates and site conditions and will not have pre-established values. In addition, the proposed future draft of the Eurocode 8 [25] also contains some information related to the evaluation of the displacement proposing two limit states for this check, namely the fully operational and the damage limitation, as applicable.

2.2. United States

The most recent version of the American seismic design code, ASCE 7-22 [26], considers a mean return period for the maximum considered earthquake (MCE) of 2475 years (probability of exceedance of 2% in 50 years). The design of spectral accelerations (adjusted for the corresponding site conditions) is considered as 2/3 of those corresponding to the maximum considered earthquake. The displacement check is performed considering the design of earthquake ground motion amplitudes. The control period T_C is computed based on the design of spectral accelerations at 1.0 s (S_{D1}) and the design of spectral acceleration in the short-period range (S_{DS}), while the control period T_D (or T_L) is taken from zonation maps. It has to be mentioned that the ASCE 7-22 code [26] includes specific conditional probabilities of failure (target reliability levels) for structural stability due to earthquake action as a function of the structure risk class, thus allowing for a full performance-based design. The interstory drift limit at the ultimate limit state is dependent on the height regime of the structure and on the importance class (risk category).

2.3. New Zealand

The design of spectral acceleration evaluated according to the seismic design code from New Zealand NZS 1170.5 [27] is based on the design of peak ground acceleration and site-dependent spectral shapes (normalized by the peak ground acceleration for rock conditions). In the evaluation of the design of seismic action, an additional parameter, namely the near-fault factor, which depends on the position with respect to a known fault and on the structural eigenperiod, is also employed. If applicable, the shortest distance from the site to the nearest fault is also given in the code. The displacement check is performed for both the serviceability and the ultimate limit states, as well. A drift modification factor denoted as k_{dm} is employed for the computation of the design of interstory drifts. The coefficient k_{dm} is height dependent, and the values are between 1.2 and 1.5 for structures having heights in excess of 30 m.

2.4. Chile

The Chilean seismic design code [28] was updated in the aftermath of the destructive Maule earthquake of 2010. The design of peak ground acceleration adjusted for the corresponding site conditions is employed for the evaluation of the design of seismic action. Some key requirements of the current seismic design code of Chile are given in the paper by Lagos et al. [29]. An important observation regarding the Chilean approach is that the code employs two different levels of earthquake actions for structural design, namely one for strength design and a new one using a larger earthquake for structural damage control, calibrated for the roof displacement demands observed in the 2010 Maule earthquake. A displacement amplification factor dependent on the soil class and structural eigenperiod is employed for the evaluation of the displacement design for the maximum considered earthquake. The displacement check is performed in the Chilean seismic design code [28] for both serviceability limit state and the ultimate limit state.

2.5. Japan

The approach from the Japanese seismic design code is presented by Ishiyama [30] and Narafu et al. [31]. The shape of the Japanese design response spectrum, as in the case of the design of response spectra from Chile, is particular and does not follow the format common to other seismic design codes in the world. The design involves two limit states (moderate and severe earthquakes). The mean return period of the seismic hazard coefficient involved in the evaluation of the design of seismic action is around 500 years [31]. The reduction in the design of seismic action considering the inelastic behavior of the structures is much smaller in the Japanese seismic design code as compared to other codes applied in seismically prone countries.

2.6. Italy

The current Italian seismic design code [32] employs a two-limit state (serviceability and ultimate) approach for the design of structures. The design of peak ground acceleration is evaluated considering the site-specific soil factor (amplitude dependent). The control period T_C is computed based on the rock peak ground acceleration and the corresponding site condition. The control period T_D is also computed based on the peak ground acceleration for rock conditions. The current Italian seismic design code [32] specifies mean return periods and specific limit states which are dependent on the importance class of the building (e.g., damage limitation vs. fully operational for the serviceability limit state).

2.7. Greece

The seismic design code EAK 2000 [33] employs a similar approach, consisting of two limit states as in Eurocode 8 [24]. The design of peak ground acceleration is employed in the code for the evaluation of seismic action. Distinct spectral shapes (without site amplification factors) are provided for each site category. As in Eurocode 8 [24], the displacement check is applied for the serviceability limit state.

2.8. Iran

The peak ground acceleration is employed as a ground motion parameter. Soil amplification factors are given for each site class besides the spectral shape. The Iranian seismic design code, Standard 2800 [34], employs a displacement check for both the serviceability and ultimate limit state. The interstory drift limit at the ultimate limit state is dependent on the first eigenperiod of the structure.

2.9. China

The seismic design code of China [35] employs the design of peak ground acceleration as a ground motion parameter. Three levels of seismic hazard, namely frequent earthquakes, moderate earthquakes, and rare earthquakes are considered in the design. The mean return period of the peak ground acceleration corresponding to a moderate earthquake is 475 years, while for the frequent earthquake, it is 50 years. The design of seismic forces is based on the peak ground acceleration for a frequent earthquake multiplied by a load factor. Height limitations are introduced in the Chinese seismic design code as a function of the seismic zone, construction material, and structural system. The displacement check is performed for frequent and rare earthquakes. Displacement limits for both limit states given in the code are a function of the structural system.

2.10. India

The Indian seismic design code [36] employs the peak ground acceleration for the estimation of the design of seismic action. The design of spectral shapes corresponding to each site class does not include site amplification factors. The displacement check required by the code is related to serviceability purposes considering the action of the earthquake design.

2.11. Turkey

The Turkish seismic design code was recently updated in 2018 [37–39]. A discussion related to the provisions for RC buildings given in the 2018 version of the Turkish seismic design code can be found in [40], Four different levels of earthquake ground motion are specified in the 2018 code, namely service level, frequency, design, and maximum considered. The design of seismic action is based on the same approach as in ASCE 7-22 [26], employing the design of spectral accelerations at 1.0 s (S_{D1}) and the design of spectral acceleration in the short-period range (S_{DS}) amplified corresponding to the site conditions. The displacement check is associated with the frequent or the design earthquakes and is related to the limitation of damage. Different interstory drift limits are imposed as a function of the construction material. The target performance objectives depend on the importance class and height regime of the structure.

2.12. Romania

The current Romanian seismic design code P100-1/2013 [41] uses the peak ground acceleration (PGA) as the design of the ground motion amplitude parameter. The design of the PGA and the design of the control period T_C (considered as a proxy for soil conditions) are taken directly from zonation maps, without the need for further amplifications due to site conditions. The inelastic displacement demand as a function of the construction material (RC or steel) is obtained by multiplying the elastic demand with the displacement amplification coefficient for both the damage limitation and life safety limit states. This approach was introduced for the first time in the 2006 version of the code [42]. The control periods, T_C and T_D, proposed in the code were computed using the ground motions recorded during the significant Vrancea intermediate-depth earthquakes of 1977, 1986, and 1990 using the procedure proposed by Lungu et al. [43]. It has to be mentioned also that the displacement check was introduced in the Romanian seismic design code [44] in the aftermath of the destructive Vrancea intermediate-depth earthquake of March 4, 1977. A discussion regarding the impact of the relations proposed in the future draft of the Eurocode 8 [25] for the computation of the control periods T_C and T_D for some sites in Romania (including Bucharest) can be found in the study by Pavel et al. [45].

3. Comparisons of Seismic Action Parameters

Two important parameters considered in both the strength and stiffness checks are the building importance class factor, which basically increases or decreases the reference seismic action (the mean return period) considering the likely consequences of the failure of the analyzed structure and the behavior factor q or R (which depends on the construction material, structural system, or ductility class). In Table 1, a comparison of the importance class factors and of the behavior factors (the maximum values corresponding to ductility class High) given in the analyzed seismic design codes is shown.

The Japanese seismic design code employs building categories as a function of the height, based on which the design procedure is selected. The Romanian seismic design code P100-1/2013 [41] also uses as an extra criterion for assigning a particular importance class, the building height (all the buildings of more than 45 m in height are assigned to importance class I; all the buildings with heights in between 28 m and 45 m are assigned to importance class II).

It can be noticed from Table 1 that the values of the behavior factors have a very large range of values, with the differences between the smallest values and the largest ones being of the order of 200–300%. In addition, it can be observed that in the majority of the analyzed seismic design codes, the values of the importance factors are consistent.

Table 1. Comparison of the importance class factors and behavior factors given in various seismic design codes.

Seismic Design Code	No. of Importance Classes	Importance Class Factors	Behavior Factor q
Eurocode 8 [24]	4	0.8–1.4	RC frames: 5.85 RC shear walls: 5.4 Confined masonry: 3.0 Steel frames: 6.5
ASCE 7-22 [26]	4	1.0–1.5	RC frames: 8.0 RC shear walls: 8.0 Confined masonry: 4.0 Steel frames: 8.0
NZS 1170.5 [27]	5	0.75–1.8	RC frames: 6.0 RC shear walls: 5.0 Confined masonry: 3.5 Steel frames: 6.0
D.S. 61 [28]	4	0.6–1.2	RC frames: 7 RC shear walls: 7 Confined masonry: 4 Steel frames: 7
Japanese seismic design code	4 categories based on the building height	1.0	RC frames: 3.3 RC shear walls: 2.5 Confined masonry: 2.0 Steel frames: 3.3
Italian seismic design code [32]	4	0.7–2.0	RC frames: 5.85 RC shear walls: 5.2 Confined masonry: 3.9 Steel frames: 6.5
EAK 2000 [33]	4	0.85–1.3	RC frames: 3.5 RC shear walls: 3 Confined masonry: 2 Steel frames: 4
Standard 2800 [34]	4	0.8–1.4	RC frames: 10 RC shear walls: 7 Confined masonry: 4 Steel frames: 10
GB 50011-2010 [35]	4	0.9–1.1	-
IS 1893: 2016 [36]	3	1.0–1.5	RC frames: 5.0 RC shear walls: 4.0 Confined masonry: 3.0 Steel frames: 5.0
TBEC 2018 [37]	3	1.0–1.5	RC frames: 8.0 RC shear walls: 7.0 Confined masonry: 3.0 Steel frames: 5.0
P100-1/2013 [41]	4	0.8–1.4	RC frames: 6.75 RC shear walls: 5.75 Confined masonry: 2.8 Steel frames: 6.5

4. Evaluation of Design Displacement and Recommendations

The limit design displacements and the corresponding limit states for which the displacement check is performed are analyzed in this section. Table 2 shows the mean return period of the seismic action design, the mean return period of the seismic action for which the displacement check is performed, and the limit drift ratio as well as the corresponding limit state. It can be noticed that there are significant differences in terms of the mean return period considered for the displacement check. As such, the inter-story drift limits also have a wide range of values, and thus they cannot be directly compared. It can be also observed that the displacement check is generally associated with the serviceability limit state.

Table 2. Characterization of the design of seismic action given in various seismic design codes.

Seismic Design Code	Mean Return Period for Design of Seismic Action (yrs.)	Limit State for Displacement Check	Mean Return Period of Seismic Action for Displacement Check (yrs.)	Limit of Inter-Story Drift Ratio
Eurocode 8 [24]	475	SLS—Damage limitation	95	0.005–0.01 h_s
ASCE 7-22 [26]	2/3 * maximum seismic action (2475 years)	ULS–Design	2/3 * maximum seismic action	0.007–0.025 h_s
NZS 1170.5 [27]	500	SLS—Damage limitation	25	No limit provided
		ULS—Collapse prevention	500	0.025 h_s
D.S. 61 [28]	475	SLS—Immediate occupancy	475	0.005 h_s; 0.007 h_s
		ULS—Collapse prevention	950	At component level
Japanese seismic design code	500	SLS	500	0.005–0.008 h_s
Italian seismic design code [32]	475	SLS—Damage limitation	30–50	0.0025–0.01 h_s
EAK 2000 [33]	475	SLS—Damage limitation	-	0.005 h_s; 0.007 h_s
Standard 2800 [34]	475	SLS—Damage limitation	10	0.005 h_s; 0.007 h_s
		ULS—Collapse prevention	475	0.02 h_s; 0.025 h_s
GB 50011-2010 [35]		SLS—Damage limitation		0.001–0.0025 h_s
		ULS—Near collapse		0.008–0.033 h_s
IS 1893: 2016 [36]		SLS		0.004 h_s
TBEC 2018 [37]	475	SLS	72	0.004–0.016 h_s
P100-1/2013 [41]	225	SLS—Damage limitation	40	0.005–0.01 h_s
		ULS—Life Safety	225	0.025 h_s

In Table 2, h_s represents the story height, SLS means serviceability limit state, and ULS signifies ultimate limit state.

Some examples of the control periods T_C and T_D used in the selected design codes are given in Table 3 below. In addition, the soil class parameters employed for site classification are also given in Table 3.

Table 3. Comparison of the control periods T_C and T_D given in various seismic design codes.

Seismic Design Code	Soil Class Parameter	No. of Soil Classes	T_C (s)	T_D (s)
Eurocode 8 [24]	$V_{s,30}$	5 + 2	0.4–0.8	2.0
ASCE 7-22 [26]	$V_{s,30}$	8 + 1	computed	4.0–16.0
NZS 1170.5 [27]	T_0	5	0.4–1.2	3.0
D.S. 61 [28]	$V_{s,30}$	6	0.15–1.2	-
Japanese seismic design code	Geological/Geotechnical	3	0.4–0.8	-
Italian seismic design code [32]	$V_{s,eq}$	5	computed	computed
EAK 2000 [33]	Geological/Geotechnical	4 + 1	0.4–1.2	-
Standard 2800 [34]	$V_{s,30}$	4	0.4–1.0	-
GB 50011-2010 [35]	V_{se}	5	0.2–0.9	$5 \cdot T_C$
IS 1893: 2016 [36]	Geological/Geotechnical + N_{SPT}	3 + 1	0.4–0.67	4.0
TBEC 2018 [37]	$V_{s,30}$	5 + 1	computed	>4.0
P100-1/2013 [41]	T_C	3	0.7; 1.0; 1.6	2.0 or 3.0

In Table 3, $V_{s,30}$ is the average shear wave velocity in the upper 30 m of soil deposits, $V_{s,eq}$ is the equivalent shear wave velocity computed considering all the soil layers with shear wave velocities less than 800 m/s, T_0 is the site fundamental period computed based on the shear wave velocity through the soil deposits until the bedrock level, N_{SPT} is the number of blows in the standard penetration test averaged for all the soil layers up to a depth of 30 m, V_{se} is an equivalent shear wave velocity computed for soil layers with shear wave velocities less than 500 m/s. It can be observed from Table 3 that most of the analyzed seismic design codes use a shear wave velocity metric for characterizing the soil conditions.

One of the observations made based on Table 3 is that the smallest control periods, T_D, employed for design are found in Eurocode 8 [24] and in the Romanian seismic design code P100-1/2013 [41]. However, the Romanian seismic design code P100-1/2013 [41] also has the largest control period, T_C of 1.6 s, among the discussed seismic design codes.

A review of the amplification factors for the design displacements as a function of the considered limit state is shown for the selected seismic design codes in Table 4.

Table 4. Amplification factors for the design displacements as a function of the limit state.

Seismic Design Code	SLS	ULS
Eurocode 8 [24]	$\upsilon \cdot q$ υ = 0.4 or 0.5 depending on the importance class of the structure	-
ASCE 7-22 [26]	-	C_d/I_e I_e—importance factor C_d—deflection amplification factor depending on the structural system
NZS 1170.5 [27]	1.0	$\mu \cdot k_{dm}$ μ—ductility coefficient k_{dm} = 1.2–1.5—drift modification factor

Table 4. *Cont.*

Seismic Design Code	SLS	ULS
D.S. 61 [28]	-	$(q/I_e)\cdot c_d$ c_d—deflection amplification factor depending on the soil class and period
Japanese seismic design code	1.0	-
Italian seismic design code [32]	q	-
EAK 2000 [33]	0.4·q	-
Standard 2800 [34]	1.0	0.7·q
GB 50011-2010 [35]	1.0	η_p η_p = 1.3–2.2—enhancement coefficient for elasto-plastic drift
IS 1893: 2016 [36]	1.0	-
TBEC 2018 [37]	$(q/I_e)\cdot\lambda$ λ = 0.4–0.5	
P100-1/2013 [41]	$\upsilon\cdot q$ υ = 0.4 or 0.5 depending on the importance class of the structure	$c\cdot q$ $1 \leq c = 3 - 2.3\frac{T_1}{T_c} < \frac{\sqrt{T_c\cdot q}}{1.7}$

It can be observed from Table 4 that various definitions of the amplification factors can be found in the analyzed design codes, with some codes employing various empirical amplification factors which account for the inelastic displacements. It can be observed that some design codes provide the response spectrum directly for the displacement check while other design codes amplify the design response spectrum using various coefficients (mainly related to the behavior factor q).

An important issue that has to be introduced in future versions of seismic design codes is the quantification of the pulse effects of ground motions on displacement demand. This issue has been studied in the literature by various researchers ([46–48]). The occurrence of pulse-like ground motions has also been observed for intermediate-depth earthquakes [49]. Another key problem regarding the design displacement check is the evaluation of the control period T_D and its values. In this context, Sozen [50] has proposed some upper bound limits on the nonlinear displacements of structures depending on the structural period and peak ground velocity.

5. Conclusions

This review paper presents an evaluation of the methodologies employed for the assessment of the displacement demands of structures in different seismic design codes from seismically prone countries around the world. A brief characterization of the design of seismic actions from different seismic codes is also presented. The main conclusions and observations of this study can be summarized as follows:

- From the analysis of the selected seismic design codes, it was observed that the displacement check is associated in most situations with the serviceability limit state (e.g., damage limitation limit state);
- Significant differences in terms of the mean return period for the serviceability (e.g., damage limitation) check action were observed among the analyzed seismic design codes;
- Similar displacement limits are observed in most of the analyzed seismic design codes for the damage limitation limit state. However, in the case of the ultimate

limit state, some seismic design codes (e.g., the U.S., China, etc.) provide limits that are dependent on the structural system and importance class of the building (risk category). A somewhat similar approach involving different performance objectives for the same limit state (serviceability or ultimate) as a function of the importance class can be found in the recent Italian seismic design code;

- The behavior factors have a very large range of values in the analyzed seismic design codes, with the differences between the smallest values and the largest ones being of the order of 200–300%;
- The design of spectral shapes from Chile and Japan are particular and do not follow the format commonly encountered in other seismic design codes in use around the world;
- Various definitions of the displacement amplification factors can be found in the analyzed design codes, with some codes employing various empirical amplification factors, which account for the inelastic displacements;
- The smallest control periods, T_D, employed for design are found in Eurocode 8 [23] and in the Romanian seismic design code P100-1/2013 [33].

The main aspects that have to be further investigated for possible adoption in future versions of the design codes are:

- The dependence of the T_D control period on the probabilistic seismic hazard ordinates and the use of such a period for design purposes;
- The inclusion of pulse effects in the assessment of the displacement demand of structures;
- Harmonization of behavior factors used for design;
- The inelastic amplification factors necessary for evaluating the design displacements for the ultimate limit state.

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