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Evolution of Seismic Site Classification According to the Criteria in Chilean Design Codes

Edgar Giovanny Diaz-Segura

Faculty of Engineering, Escuela de Ingeniería Civil, Pontificia Universidad Católica de Valparaíso, Av. Brasil 2147, 3tr Floor, Valparaíso 2340000, Chile; edgar.diaz@pucv.cl

Abstract: Design codes establish seismic site classifications to determine the seismic demand of a structure according to the response of the soil foundation under the action of earthquake ground motions; the site classification can even condition the feasibility of a project. The occurrence of great earthquakes in Chile has tested its design codes, generating much information and experience regarding the seismic design of structures that have allowed researchers to identify variations in seismic demands according to the kind of ground foundation and to propose seismic site classification methods in Chilean regulations since the 1930s; countries in the vanguard of seismic design, such as the USA, Japan, and New Zealand, proposed methods even earlier. In this document, the evolution of methodologies for seismic site classification according to the criteria in Chilean codes is analysed from their implementation in the 1930s to the most recently proposed design code NCh 433, 2018–2021. Although the distinctive features of each country shape the criteria in their design codes, clear knowledge of the evolution of established criteria from their origins is considered an important tool that contributes to the better understanding, interpretation and application of the seismic site classification methodologies contained in a design code with better criteria. Likewise, the review indicates a distinct need to conduct a continuous evaluation of the classification criteria supported by records of new earthquakes, as well as by physical and numerical models that allow incorporating variables which condition the response of the terrain such as topography, lateral heterogeneities, and basic effects.

Keywords: seismic site classification; seismic design codes; earthquake resistance design; design criteria; soil response

1. Introduction

The current main objective of seismic site classification is to assign design response spectra or to define parameters for its establishment according to the non-linear response of the soil foundation to shear waves generated from the bedrock upward to the ground surface by the action of earthquake ground motions.

Parameters to carry out seismic site classification remain objects of study and analysis. Despite the discrepancies generated by the geological, geomorphological and laws of each country, some consensus has been achieved at an international level, sometimes indirectly, with respect to parameters that must be applied for such seismic classification. An example of the latter is the known parameter Vs30 proposed by Borcherdt and Glassmoyer [1] and Borcherdt [2], which incorporates many design codes as the main classification parameter [3]. Although it has been the subject of some debate [4–6], the Vs30 parameter is accepted internationally. Note that some questions also arise due to the complexity and nature of the variables that intervene in the non-linear seismic response of the ground, which has hindered the definition of absolute or unified criteria at the normative level. Given the uncertainties generated in the analysis, perhaps in the future it could be convenient to incorporate complementary data analysis tools based on the neuro-fuzzy logic technique into design code committees [7].
On the other hand, the high seismic demand to which the Chilean infrastructure has been subjected because of great earthquakes during the last 100 years, especially recent large-magnitude earthquakes (Mw 8.8, 8.4, 8.3), has demanded that Chilean engineering be able to define ad hoc characterization parameters. This situation has allowed the response of the ground foundation for a structure to be categorized, which is required to establish the seismic demand for its seismic resistance design. Currently, the Chilean seismic resistance design code, named NCh 433, in its most recent modified proposal (version 2018–2021), contains important advances with respect to the methodology of seismic site characterization and would be a pioneering proposal at the international design code level. This position is not unprecedented for Chile, as the country has developed normative regulations for construction according to its investigations and experience and had integrated qualifying factors for almost 90 years before similar developments by other countries, such as the USA, Japan, and New Zealand. The objective has been to make a difference in seismic requirements according to ground conditions and has produced the seismic classification criteria recorded in different proposed design codes.

In this document, a review and an analysis of the evolution of methodologies for seismic site classification according to Chilean regulations are performed, from their implementation in the 1930s to the most recent proposal in 2018–2021, which considers some limitations of the use of Vs30 as the only dynamic parameter of soil for classification [3–5]. These methodologies incorporate the fundamental period measured by the H/V spectral ratio method (HVR), $T_g$, as a complementary parameter of seismic classification. Having distinct knowledge of the evolution of ruling criteria from their origins is considered an important tool that contributes to understanding, interpreting and applying better criteria for ground classification methodologies contained in a design code.

2. Brief Historical Context of Chilean Construction Regulations

For the Chilean territory, from colonial times, urban planning regulations, such as the Discovery Ordinances, New Populations and Pacifications of 1573, were issued to regulate the conformation, growth or reforms of cities, mainly motivated by demographic growth and for reasons of health [8].

In Chile as a republic, the first approach to regulations related to urban subjects was decreed in 1854, which assigned to city halls the responsibility for defining urban development guidelines about construction or urbanism. Between 1874 and 1912, urbanism laws were enacted by different city halls in Chile; these laws were collected during the reform of the city halls law in 1915 [8]. Although Chile has historically recorded more than 10 earthquakes with great magnitude since achieving independence in 1810 (today, earthquakes are catalogued with magnitudes higher than Mw 8.0 [9]), laws or regulations issued prior to 1927 did not include any type of seismic consideration for construction. As an international context for this decade, the first regulation of seismic design in the world was decreed in 1924 in Japan.

In 1928, the Mw 7.6 earthquake in Talca greatly damaged structures, which emphasized the urgent need to regulate building construction while considering the seismic demands of the country. From the previous background, in 1929, a law project was decreed that authorized developing a general ordinance to establish regulations to which building construction must conform in the different districts of Chile. These regulations would consider criteria to prevent collapse, for the first time indicating that construction must “avoid, as much as possible, the risks coming from an earthquake”. Thus, between 1930 and 1931, the First Law and Ordinance of Construction and Urbanization (OGCU), began seismic resistance regulation for construction in Chile [10], joining countries with normative design criteria, such as Japan, 1924 [11], the USA, 1927 [12], and New Zealand, 1935 [13]. Note that criteria and definitions with respect to seismic design are contained mainly in the version of the OGCU established in 1936, OGCU-1936 [14].

Between 1936 and 1971, the main regulation with seismic design criteria was the OGCU, which underwent different changes motivated by the large seismic events that
occurred in the country. In 1972, the first Chilean seismic design code, referred to as NCh 433, was promulgated, the most recent version of which corresponds to the proposal evaluated between 2018 and 2020, which is in the process of being approved.

3. Seismic Site Classification Methodologies According to Chilean Design Regulations or Seismic Codes

3.1. Construction and Urbanism General Ordinance (1930–1936)

As indicated above, the first seismic regulations were established in OGCU-1936 [14], which set criteria for seismic design by referring to a variation in seismic solicitation according to ground conditions. This regulation shows the first approximation to seismic site classification, which is an aspect of design codes that was not considered during this period.

OGCU-1936, similar to the Japanese model [11], considered seismic action an equivalent force applied to the centre of gravity of a structure; the magnitude of the horizontal component was equal to the building weight multiplied by a seismic coefficient, while the vertical component was considered to be 50% of the horizontal component. This standard was based on a criterion proposed in the Japanese code of 1924, with a seismic coefficient equal to 0.1, i.e., 10% of the structure’s weight. However, the OGCU defined seismic coefficients between 0.05 and 0.1 according to the seismic and geologic characteristics of the zone where the construction was to be located and the quality of the foundation ground. These coefficients were categorized with the expression “allowable resistance of ground”, as shown in Table 1. Considering this criterion, the “allowable resistance of ground” would be one of the first parameters for seismic site classification; starting from this point, the expected seismic solicitation magnitude for design was defined. In addition to that indicated in Table 1, Art. 152 of the OGCU-1936 also established conditions for “seismic action” based on the kind of ground, assigning for its consideration the factor shown in Table 2. However, the ambiguous statement of Art. 152 does not allow us to identify the use or application of such a factor in a settled way; whether it involved a balance of seismic coefficients (del Canto, et al., 1940) is also not indicated, but if it did consider a balance, this method could generate a solicitation for more than 10% of building weight for low-quality ground.

| Allowable Resistance of Ground Foundation | Horizontal Seismic Coefficient, $k_h$ | Vertical Seismic Coefficient, $k_v$ |
|------------------------------------------|--------------------------------------|-----------------------------------|
| ≤300 kPa                                  | 1/10                                 | 1/10                              |
| >300 kPa                                  | 1/20                                 | 1/40                              |

| Class of Ground Foundation                | Factor      |
|-------------------------------------------|-------------|
| Sandstone ground                          | 1.0–2.4     |
| Loose sand ground                         | 2.4–4.4     |
| Loose and fill soils                      | 4.4–11.0    |

In a complementary way, the OGCU also included an analogous criterion that today could be considered a place effect, indicating that “Departments of Construction of City Halls would be able to require that the effect of resonance is studied in special cases”. However, according to the reported precedents, this statement was more likely intended to analyse a possible place effect because at this time, engineers lacked the power to consider variable acceleration effects during a seismic event, as OGCU-1936 suggested a constant acceleration magnitude for design [15].
3.2. Construction and Urbanism General Ordinance, OGCU-1940

As a consequence of the devastating earthquake in Chillan on 24 January 1939, which caused more damage and the highest number of fatalities reported in Chile, the government requested the creation of a technical government commission, which submitted an evaluation of the current ordinance with the damage report, highlighting mistakes and ambiguities, proposing new seismic factors and incorporating the first approach to design using a dynamic method; the commission recommended “... reinforced concrete buildings to be calculated in a more rational way (that is, taking into consideration not only the maximum acceleration of earthquakes as established by the Ordinance but also the amplitude and period)” [15]. This document is the basis of the main changes related to seismic design and generated a new OGCU that was approved in 1940 [16]. The new OGCU included an adjustment with respect to seismic action, which is now considered a harmonic movement, and followed the use of a static method equivalent to that defined in OGCU-1936, which would subsequently depend on the type and period of a structure. Thus, for structures with the period $T_e$ less than 0.4 s, the seismic action was determined using the static method defined in OGCU-1936. If $T_e$ was greater than or equal to 0.4 s, “... the action of the earthquake will assimilate to a horizontal vibration in any direction, of a simple harmonic movement, with the following characteristics: Acceleration 0.1 g to 0.2 g (g gravitational acceleration); amplitude 4 to 6 cm, period 1 to 2 s ... ”. For this last case, the OGCU-1940 established the possibility of using an approximate method to determine the seismic action, which due to the absence of more precise methods suggests that the government commission utilized such a method [15,17]; based on this reasoning, the provision is interpreted as a seismic classification method, as listed in Table 3.

As shown in Table 3, OGCU-1940 removed the parameter for classifying the admissible resistance of the ground, reducing it to a general characterization of the ground without main specifications. This lack of a main decree with respect to the ground could be attributed to the effects of the 1939 earthquake, which was uniformly devastating throughout the whole area of influence. These effects would make it more difficult to refine particular aspects associated with the ground. Considering the limited geomechanics exploration that was conducted during this period, the normative analysis was centred more on the identification of the characteristic seismic wave, temporarily and partially disregarding the influence of the ground. Nevertheless, participants in the government commission suggested that geological aspects were required to continue investigation [15].

Considering bibliographic antecedents available at the time, the OGCU commission in charge of revision observed that at an international level, prominent investigators concurred, indicating that the evidence of earthquakes, such as those in San Francisco in 1906 or Tokyo in 1923, demonstrated that the destructive aspect of earthquakes was attributed to waves whose periods varied between certain defined limits [17] (p. 87). Therefore, with this assumption, the ordinance adopted a criterion to restrict construction, whose $T_e$ period would range between 1.0 and 2.0 s. The simplified method, previously indicated and suggested by OGCU-1940, did not explicitly include factors for other periods, such as for $T_e$ between 0.75 and 1.0 s and between 2 and 3 s. Therefore, in Table 3, values of seismic action in these period ranges correspond to an interpretation, based on the report of the commission, to complete the analytical range for an accepted $T_e$ in OGCU-1940. The maximum values reported for factors $\alpha$ and $\beta$ are extrapolated for different site classes.
Table 3. Interpretation of seismic classification criteria according to OGCU-1940.

| Ground Foundation | Structure Period, $T_e$, s | Static Method | Amplitude of the Seismic Action as Simple Harmonic Motion |
|-------------------|-----------------------------|---------------|----------------------------------------------------------|
|                   | $k_h$ | $k_v$ | $a_{h\gamma}$, g | $\delta_{h\delta}$, m |
| Rock              | 0.10  | -    | -              | -              |
| Sandstone or conglomerate | <0.4 | 0.12 | 0.15           | -              |
| Gravel or loose sand | 0.15 | -    | -              | -              |
| Fill              | 0.20  | -    | -              | -              |
| Rock              | -     | -    | 0.10 $\times \alpha$ | -              |
| Sandstone or conglomerate | $0.4 \leq T_e \leq 0.75$ | -    | 0.15 $\times \alpha$ | -              |
| Gravel or loose sand | -     | -    | 0.15 $\times \alpha$ | -              |
| Fill              | -     | -    | 0.20 $\times \alpha$ | -              |
| Any type of ground | 1.0–2.0 | -   | Constructions are not allowed |
| Rock              | -     | -    | 0.040 $\times \beta$ | -              |
| Sandstone or conglomerate | $2.0 < T_e \leq 3.0 - \beta = 2.0$ | -    | -              | 0.052 $\times \beta$ |
| Gravel or loose sand | $T_e > 5.0 - \beta = 1.0$ | -    | -              | 0.060 $\times \beta$ |
| Fill              | -     | -    | 0.060 $\times \beta$ | -              |

*1. For $0.4 \leq T_e < 1.0$ s, according to the modification of the OGCU-1940, the seismic action is considered a uniform acceleration, $a_h$, which is equal to the maximum of the seismic event multiplied by the coefficient, $\alpha$.  
*2. For $T_e > 2.0$ s, the design must consider applying the horizontal displacement, $\delta_h$, to the centre of gravity of the structure, which is equal to the maximum amplitude of the seismic wave multiplied by the coefficient $\beta$.

3.3. Construction and Urbanism General Ordinance, OGCU-1949

In 1949, a new version of the OGCU was promulgated; however, with respect to seismic design, it contained criteria similar to those in OGCU-1940, which had the government commission’s report as technical backup [15].

For seismic action, the recommendation of using the approximate dynamic method proposed by Del Canto et al. [17] was retained, and it was also declared directly that the determination of “... seismic and fatigue solicitation that they produce in materials will be done, in general, by the dynamic equations.” This last point represents the ratification of the need to establish a design criterion, the dynamic method, considering dynamic solicitation as the action of waves that spread with amplitude, acceleration and displacement from the ground to the foundation and building.

Based on the previous description, Table 4 shows the classification interpreted according to criteria in OGCU-1949 [18], which still permitted the use of the approximation method and was compatible with the classifying method shown in Table 3. One difference is that the new OGCU-1949, in addition to the period of a structure, incorporated the stiffness of the foundation as a distinguishing parameter of seismic action. In relation to restricted structures with periods between 1.0 s and 2.0 s, OGCU-1949 did not specify; however, to make the approximate method valid, indirect restrictions were retained. Factors $\alpha$ and $\beta$ shown in Table 3 were deleted, and the values were held constant for cases with periods of $0.75 < T_e < 1.0$ s and $2.0 < T_e < 3.0$ s as the criteria for the approximate method [17].
### Table 4. Interpretation of seismic classification criteria according to OGCU-1949.

| Ground Foundation                  | Structure Period, $T_e$, s | Foundation Rigidity                     | $k_h$ *1 | Amplitude of Seismic Action, m |
|-----------------------------------|---------------------------|----------------------------------------|----------|-------------------------------|
| Rock                              |                           | -                                      | 0.08     | -                             |
| Conglomerate or very dense ground | $<0.4$                    | -                                      | 0.12     | -                             |
| Loose soils or sand               |                           | with raft foundation or similar rigidity | 0.10     | -                             |
|                                   |                           | without raft foundation                 | 0.12     | -                             |
| Rock                              |                           | -                                      | 0.05     | -                             |
| Conglomerate or very dense ground | $0.4 \leq T_e \leq 0.75$ | -                                      | 0.10     | -                             |
| Loose soils or sand               |                           | with raft foundation or similar rigidity | 0.12     | -                             |
|                                   |                           | without raft foundation                 | 0.15     | -                             |
| Any type of ground               | 1.0–2.0                   | Constructions are not allowed           |          |                               |
| Rock                              |                           | -                                      |          | 0.020                         |
| Conglomerate or very dense ground | $T_e > 3.0$ *2            | -                                      |          | 0.040                         |
| Loose soils or sand               |                           | with raft foundation or similar rigidity |          | 0.050                         |
|                                   |                           | without raft foundation                 |          | 0.060                         |

*1 The vertical component of the seismic wave will only be considered in cases where the nature of the work requires it. Its acceleration and amplitude will be equal to 50% of the horizontal seismic action. *2 Interpretation and limit of the period taken from the approximate method proposed by Del Canto, et al. [17], which the OGCU authorizes can still be applied for the determination of seismic action.

#### 3.4. Earthquake Building Resistance Code NCh 433Of72

Following the modification of OGCU-1949, during the 1950s, there were no changes in seismic regulations, although at least five earthquakes of magnitude Mw higher than 7.5 occurred, culminating with the mega-earthquake in Valdivia in 1960, which reached Mw 9.5. Nevertheless, by the end of the 1950s and prior to the great earthquake in 1960, the National Institute of Investigations, Inditecnor (which in 1973 became the National Institute of Standardization, INN), was requested in 1959 to start developing seismic design criteria independent from OGCU. A committee was created with professionals and academic experts.

During the 1960s, different proposals were formulated; in particular, the work of Arias and Husid [19] had great influence. With respect to the ground effect, they had already indicated that the designer could modify the spectrum shape to consider selective amplifying cases for types of ground. Starting with models and spectrum analyses of real earthquakes, Arias and Petit [20] subsequently presented a theoretical basis to define relationships between the response spectrum and ground properties, directly expressing for the first time the need for seismic site classification analogous to the system employed today.

An antecedent in the form of a 1968 preliminary regulation denoted NCh 433Of68 [21], which was not officially published but accepted the incorporation of the static method and dynamic method. The former is applicable to short structures with simple construction, while the latter is applicable to taller and more morphologically complex buildings. Starting from this basis, a seismic coefficient was defined, and an acceleration spectrum was categorized for different site classes to which the fundamental vibration period, $T_0$, was assigned. The equations applied for each method are listed as follows:

Seismic coefficient for the static method:

$$C = 0.10 \text{for } T < T_0$$

(1)
\begin{align*}
    C &= 0.10 \cdot \frac{2T T_0}{T^2 + T_0^2} < T_0 \\
    \text{Acceleration spectrum for the dynamic method:} \\
    a_g &= 0.10 K_1 K_2 \text{for} T < T_0 \\
    a_g &= 0.10 K_1 K_2 \frac{2T T_0}{T^2 + T_0^2} < T_0
\end{align*}

where \( C \) is the seismic coefficient; \( T \) is the period of the corresponding vibration mode; \( T_0 \) is the fundamental vibration soil period; \( K_1 \) is a coefficient relative to the intended use of the structure (factor between 0.8 and 1.2); and \( K_2 \) is a coefficient relative to the structural form (factor between 0.8 and 1.2).

Taking as references the unpublished proposal from 1968 and recommendations proposal by Saragoni [22] regarding earthquake spectra from Chile, Peru, Japan and the USA, which provided clear knowledge of the foundation ground type where these spectra were recorded, a seismic site classification was proposed. This scheme is shown in Table 5 and was included in the new regulation. All previously indicated criteria were finally consolidated and included in the regulation that was made official as “NCh 433Of72, Earthquake resistance of buildings 1972” [23], which combined with the Argentine code [24], constituted together the first official codes of seismic design at the South American level that incorporated design spectra.

At this time, design codes at the international level, including the Uniform Building Code (USA), Building Law (Japan), and codes in New Zealand, had been continuously revised. However, for 1968, the year in which the seismic site classification criteria in NCh 433 were proposed, every design code proposed defining spectra according to the seismic zones of the country, but codes were not defined according to the type of ground; such criteria were incorporated in the USA in 1976 [25], New Zealand in 1976 [26], and Japan in 1971 [27]. Therefore, NCh 433, with respect to the influence of the ground, was one of the first design codes at the world level that incorporated the influence of ground foundations in the spectra for seismic design in buildings and assigned a seismic classification. Nevertheless, at that time, the Chilean code and international codes still did not have indications with respect to identification parameters to characterize the ground, as ground types for their classification were general and descriptive.

| Site Class                                | \( T_0, \text{s} \) |
|-------------------------------------------|---------------------|
| Rock, dense gravel, dense sandy gravel    | 0.20                |
| Dense sand, stiff cohesive soils          | 0.30                |
| Loose granular soils, soft or medium soft cohesive soils | 0.90                |

With code NCh 433, a great step was taken related to regulations for the design of structures considering seismic solicitations; these regulations incorporated not only the points previously indicated but also the first guidelines for design from a probability perspective.

### 3.5. Earthquake Resistance of Buildings, Codes NCh 433Of93 and NCh 433Of96

The earthquake on 3 March 1985, in the central zone of Chile represented a great test for the prevailing seismic laws in Chile, and as usual after a great seismic event, the National Institute of Standardization, INN, in 1986 constituted the Seismic Resistance Coordinator Code Committees. With input from these committees, the first modification to the code was proposed and then approved in 1993, and as a result, code NCh 433Of93 [28] was cancelled and replaced by NCh 433Of72 [23]. The 1993 version included different changes in the design code, highlighting the incorporation of a new system for the seismic
site classification of the ground and directly defining parameters to characterize the ground as well as the shear-wave velocity, $V_s$; SPT N-value; undrained strength, $s_u$; and the resistance to simple compression, $q_u$.

Considering the lessons learned after the earthquake of 1985 and great seismic events recorded around this time at an international level (Los Angeles, CA, USA, Mexico, and Peru), these regulations clarified for the first time the application range with respect to the geomorphological conditions of the ground. Parameters for seismic characterization and solicitation were defined considering horizontal surfaces and horizontal stratification and acknowledged that some structures are built on foundations that reveal geomorphological and topographic singularities. This last point was motivated by the effects of topographic amplification observed and categorized for structures built in the area of the Beagle channel, Viña del Mar, during the earthquake and aftershocks in 1985 [29]. Importantly, note that by the publication date of the document that contained the modifications to NCh 433Of72, 1989, no national or international codes had defined specific criteria for the identification of ground types that may suffer topographic effects, leaving their identification to engineers’ judgement. This procedure was generally applied in such cases as in regular professional practice, and topographic effects were not considered. Even today, most design codes at the international level still lack criteria for the consideration of topographic effects. Exceptions, such as the French code [30], Eurocode [31], and Italian code [32], share the same criteria.

In relation to special cases, for the first time, associated criteria were introduced for ground types with the potential to liquefy, identifying this phenomenon for sand ($N_1$) less than 20 blows/feet, which had been excluded from ground classification systems. In 1989, this point also represented a development, as different design codes, such as the USA [33], Japan [34] and New Zealand codes [35], did not include criteria that conditioned the seismic site classification in cases with possible liquefaction.

As a part of the revision process for the practical use of code NCh 433Of93, the Chilean Association of Seismology and Antiseismic Engineering (ACHISINA) proposed adjustments to the code based on the main conclusions registered by the professional community; in 1996, a second update became official, denoted NCh 433Of96 [36]. With respect to ground and seismic classification, the 1996 version did not involve any changes.

The seismic classification contents for NCh 433Of93 and NCh 433Of96 are presented in Table 6. In this case, four site classes were defined; they were identified starting with defined parameters and helped to reduce subjectivity, which could affect the characterization of ground types. This factor represented an important advance, considering for example, that code UBC 1991 [37] still did not include classification parameters but considered only the shear-wave velocity, $V_s$, employed to characterize rock. In 1997, when the UBC proposed a seismic classification system with direct classification parameters, the shear wave propagation velocity of the surface 30 m, $V_{s30}$, which corresponds to a parameter that many design codes worldwide later incorporated for the seismic classification. Although this system is still in force, in the case of the Chilean standard, it was not incorporated, and work continued until 2009, as shown in Table 6.

NCh 433Of93 also conditioned the classification to the thickness of the superficial strata using the criteria of 10 m and 20 m for site class types III–IV and II, respectively. Although there was no clear antecedent for the origin of criteria recently referenced by members of the code committee, an interpretation was obtained from the criterion defined by UBC 1985 [38] for seismic classification in a minor category corresponding to soft ground; $S_3$ (site class types III and IV in NCh 433Of93) ground types must have a thickness of 30 feet or approximately 10 m. On the other hand, related to measuring the shear-wave velocity in the uppermost 10 m to classify a location in site class type II, there was no clear justification for the criterion, which additionally applied to only this site class, since the shear-wave velocity for types III and IV was not specified. In terms of seismic site classification, NCh 433Of93 was not free of ambiguities, which were later exposed by the 2010 earthquake; consequently, this event led to changes in the seismic code.
Table 6. Seismic site classification NCh 433Of93/NCh 433Of96.

| Site Class | Description |
|------------|-------------|
| I          | Rock: Natural material with in-situ $V_s \geq 900 \text{ m/s}$, or $q_u$ intact rock $\geq 10 \text{ MPa}$ and RQD $\geq 50\%$ |
| II         | (a) Soil, $V_s \geq 400 \text{ m/s}$ in the upper 10 m, and increasing with depth; or well,  
            | (b) Dense gravel, $\gamma_d \geq 20 \text{ kN/m}^3$, or relative density $\geq 75\%$, maximum dry density $\geq 95\%$; or well,  
            | (c) Dense sand, relative density $\geq 75\%$, $(N_1)_{60} > 40$, maximum dry density $\geq 95\%$; or well,  
            | (d) Stiff cohesive soil, $s_u \geq 0.10 \text{ MPa}$ (unfissured samples).  
            | Minimum thickness of the horizon layer on the rock, 20 m. If the thickness of the stratum on the rock is less than 20 m, the site class will be classified as type I. |
| III        | (a) Sand permanently unsaturated, $55 < \text{relative density} \leq 75\%$, $N_{60} > 20$; or well,  
            | (b) Unsaturated gravel or sand, maximum dry density $\geq 95\%$; or well,  
            | (c) Cohesive soil with $0.025 < s_u \leq 0.10 \text{ MPa}$, regardless of the water table; or well,  
            | (d) Saturated sand with $20 < (N_1)_{60} \leq 40$.  
            | Minimum horizon layer thickness: 10 m. If the thickness of the stratum on the rock or on the site class corresponding to type II is less than 10 m, the site class will be classified as type II. |
| IV         | Saturated cohesive soil with $s_u \leq 0.025 \text{ MPa}$.  
            | Minimum horizon layer thickness: 10 m. If the thickness of the horizon layer corresponding to certain types I, II or III is less than 10 m, the site class will be classified as type III. |

$V_s$: shear wave velocity; $q_u$: unconfined compressive strength; RQD: rock quality designation; $s_u$: undrained shear strength; $\gamma_d$: dry unit weight; $(N_1)_{60}$: normalized SPT N-value.

3.6. Resistance of Buildings to Earthquakes, Code NCh 433Of96mod2009

In 2009, a modification of the code denoted NCh 433Of96mod2009 [39], which did not include any changes with respect to seismic site classification, became official, and the criteria in Table 6 remained applicable. Notably, by the time the 2009 version of the code was made official, different countries had incorporated the shear-wave velocity in the upper 30 m, $V_{S30}$, as a seismic classification parameter. However, in Latin America, this parameter was not commonly employed in professional practice. The seismic code incorporated the seismic classification parameters from the 1996 version (NCh 433Of96), retaining a certain ambiguity with respect to obligatory measurement of the shear wave propagation velocity.

3.7. Emergency Supreme Decree 117, DS117-2011

Although code NCh 433Of96mod2009 had recently been approved, damage generated by the Mw 8.8 earthquake on 27 February 2010, in Maule, provided evidence for the urgent need to evaluate and adapt the code. The derived changes and immediate adjustments were included in Emergency Supreme Decree number 117-2011 issued by the Urbanism and Buildings Ministry, which modified NCh 433Of96mod2009 [40]. One of the points of special interest at the design code committee level was the seismic site classification, which at the time had undergone no changes for 17 years, as was evidenced from the damage recorded that was considered greater than acceptable; accordingly, the necessity of modifying the classification to incorporate the seismic requirements of the country according to its ground typologies was recognized.

Among the main changes in DS117-2011, new criteria were included for the seismic classification of ground types and associated new design spectra. Therefore, considering the international validation implied by the incorporation of parameter $V_{S30}$ proposed by Borcherdt [1,2], the parameter $V_s$, which included the previous version of the code for certain site classes, was modified to $V_{S15}$ and $V_{S30}$, considering the lesser value of the two velocities as a parameter for the classification of each type of ground. Here, $V_{Si}$ represents the velocity of shear waves that travel through the uppermost i metres of the ground. Because of the changes to the regulations, measuring the shear-wave velocity in the field became a professional procedure. At this time, there was not enough equipment to adequately measure the shear-wave velocity. Thus, for a temporary period of three years, the estimation of shear-wave velocity using indirect methods, data analysis or correlations...
with geotechnical exploration was authorized. Addressing this same point, the parameter \( V_{s15} \) would represent a conservative criterion of classification in some cases, which could simplify exploration in the short term.

In addition to the four types of site classes in NCh 433Of96, a fifth type, \( V \), which corresponds to ground types denoted “special” for which a special study was needed to define a local spectrum design, was incorporated. Furthermore, the classification shown in Table 7 excludes ground that may potentially liquefy (this class was retained with the criteria from NCh 433Of96 for its definition: sand, saturated sand or silt, \((N_1)_{60} < 20\)), which is susceptible to densification because of vibrations.

### Table 7. Seismic site classification—DS117-2011.

| Site Class | Description                              | Min \((V_{s30} ; V_{s15})\) m/s | RQD | \( q_u \) (MPa) | \((N_1)_{60}\) (For Sands) | \( s_u \) (MPa) (For Fines Soils) |
|------------|------------------------------------------|-------------------------------|-----|----------------|-----------------------------|----------------------------------|
| I          | Rock or cemented soil (not soluble in water) | \( \geq 900 \)               | \( \geq 50\% \) | \( \geq 10 \) \((\varepsilon_{qu} \leq 2\%)\) |                             |                                  |
| II         | Soft rock or very dense soil or very firm soil | \( \geq 500 \)               | \( \geq 0.4 \) \((\varepsilon_{qu} \leq 2\%)\) | \( \geq 50 \)                          |                             |
| III        | Medium dense or firm soils               | \( \geq 180 \)               | \( \geq 30 \)                          | \( \geq 0.05 \)                   |                             |
| IV         | Loose or soft soils                     | \( < 180 \)                 | \( \geq 20 \)                          |                             |                             |
| V          | Specials soils                          | -                             | -                           | -                            | -                            |

DS117-2011 had great impacts on practical engineering, confirming the importance of correct and consistent geotechnical exploration. This emergency decree was valid for a period of 9 months, during which analysis continued and whose results were subsequently included in Supreme Decree 61, approved in December 2011 [41].

#### 3.8. Supreme Decree 61, DS61-2011

Following the promulgation of emergency decree 117-2011, the committee on code NCh 433, having clarified the criteria that had been temporarily defined, proceeded to a proposal that included adaptations and adjustments to the seismic site classification system and the design spectra associated with each type of ground; these changes were contained in Supreme Decree 61, approved in December 2011 and known as DS61-2011 [41]. The newly proposed classification defined six types of ground, dividing the previous ground III into two types, defining the shear-wave velocity measured in situ, requiring \( V_{s30} \) as a parameter for the classification of ground types, and removing the criterion using \( V_{s15} \). The detailed seismic classification method is shown in Table 8.

DS61-2011 also specified with more detail cases that had previously not been classified and, therefore, that required special studies. These cases are described as follows: potentially liquefiable ground types such as sand, saturated silty sand or silt with \((N_1)_{60} < 20\) blows/foot; ground types susceptible to densification by vibration; collapsible and organic soils; saturated fine soils with liquid limit (LL) \( > 80 \) and thickness \( > 20 \) m; fine soils with sensitivity higher than 10; and ground types with irregular topography where local amplification phenomena can occur. Even given these additions, the classification system continued to classify “special cases” that are now categorized as site class type \( F \), which includes the previously indicated cases, except for topographic amplification.

As previously indicated, the regulations adopted a minimum exploration thickness of 100 feet, that is, 30 m, for classification and incorporated it in the International Building Code 1997 [42] and in many international codes; this value was incorporated as a site seismic characterization parameter. Additionally, considering that certain structures were built mainly in the city of Santiago, which had underground levels with depths greater than 15 m, DS61-2011 required the measurement of classification properties to a maximum between 30 m and \( D_f + 15 \) m, where \( D_f \) is the embedment depth. Thus, in cases with several basement levels, a minimum exploration depth of 15 m below the level of the foundation system should be guaranteed.
Note that the seismic classification of ground types defined from the response or characterization of the top 30 m has not been exempt from criticism; this depth can be an insufficient criterion for very stiff ground types [43] or for certain stratigraphic configurations, where two places may have the same Vs30 but different stiffness changes with stratum depth, generating a different seismic response for each case. This point will be the topic of a future ground study; thus, the analysis of information obtained from earthquakes and types of ground in the country will eventually incorporate some changes in the most recent proposal from NCh 433.

Table 8. Seismic site classification—DS61-2011.

| Site Class | Description | Vs30, m/s | RQD | q_u (MPa) (For Sands) | (N_1)_u (For Fines Soils) | s_u (MPa) |
|-----------|-------------|----------|-----|----------------------|---------------------------|-----------|
| A         | Rock or cemented soil (not soluble in water) | ≥900     | ≥50%| ≥10 (ε_q ≤ 2%)       |                           |           |
| B         | Soft rock or very dense soil or very firm soil | ≥500     | ≥0.4 (ε_q ≤ 2%) | ≥50                   |                           |           |
| C         | Dense or firm soils                          | ≥350     | ≥0.3 (ε_q ≤ 2%) | ≥40                   |                           |           |
| D         | Medium dense or firm soils                   | ≥180     |               | ≥30                   | ≥0.05                   |           |
| E         | Medium compactness or medium consistence soil| <180     |                | ≥20                   | <0.05                   |           |
| F         | Specials soils                               | -        | -              | -                     | -                       | -         |

3.9. Earthquake Resistance of Buildings NCh 433—Modified Proposal 2018–2021

After the validation of DS61-2011, members of the code committee continued their meetings with the objective of evaluating the large amount of data obtained and the new data generated by the practical application of DS61-2011. Additionally, two important earthquakes occurred in the northern part of the country with magnitudes of 8.2 and 8.3 in 2014 (Iquique) and 2015 (Illapel), respectively, which provided interesting complementary information for the seismic classification system.

The most recent proposal to code NCh 433 was presented in December 2018, and currently, it is in the final revision stage, which includes a period of public inquiry, where suitable professionals will deliver their observations. This process will enable the consolidation of the final version of the document, the application of which is expected to start during the next few years.

Verdugo [5], based on a rigorous analysis of the seismic site classification procedures identified from available data, including seismic records of earthquakes with a magnitude Mw greater than 8.0, discovered that the H/V spectral ratio (HVR) obtained via ambient vibrations reproduces the predominant periods shown by the response spectra and suggests its use as a complementary parameter for seismic site classification.

Centring the analysis of the proposal only on those revisions related to seismic site classification, one of the main changes proposed by the code committee, taking into account all the antecedents, consists of the incorporation, as a classification parameter of the fundamental period of vibration of the ground, T_g, measured in situ using the HVR method, which is directly linked with the seismic response of the ground and is complementary to Vs30. This criterion allows differentiation of the cases that may present an equal Vs30 but may have stiffness variations with depth that condition the seismic response at the surface; the incorporation of T_g will allow each case to be distinguished. This proposal is innovative in global design codes; although the Japanese code [44] also uses the period as a classification parameter, it is estimated starting with the shear-wave velocity to the named engineering bedrock, and its direct in situ measurement is not required.

Considering the fundamentals of the previous code, the proposed code replaces properties and/or indices associated with the resistance of the ground formerly applied for seismic classification (its density q_u or N-value SPT) for parameters that represent the
dynamic stiffness properties of a location, which are correlated with the phenomenon of ground amplification (Vs30 and T\(_g\)). The classification system is shown in Table 9, in which Vs30 should be entered, and the T\(_g\) value measured in the field should be verified through the HVR method [45].

Table 9. Seismic site classification—NCh 433 proposed for public consultation in 2021.

| Site Class | Description | Vs30, m/s | T\(_g\), s | Note |
|------------|-------------|-----------|----------|------|
| A          | Rock or cemented soil (not soluble in water) | ≥900 | <0.15 (or plane HVR) | *1 |
| B          | Soft or fractured rock; very dense soil or very firm soil | ≥500 | <0.30 (or plane HVR) | *2 |
| C          | Dense or firm soils | ≥350 | <0.40 (or plane HVR) | *2 |
| D          | Medium dense or firm soils | ≥180 | <1.00 | |
| E          | Medium compactness or medium consistence soil | <180 | - | |

*1 Soil period, T\(_g\), measured in situ using the HVR method. *2 A flat measurement is considered when the HVR is less than 2.0.

With respect to the validity range or applicability of the classification, the code partially retains the recommendations from DS61-2011; however, special cases are now directly grouped in site class type F, which corresponds to different situations in which a study is required and requested. This provision allows a spectrum of local design to be defined as follows: potentially liquefiable soils corresponding to sandy or silty soils with (N\(_1\))\(_{60}\)-cs < 30 blows/foot, or q\(_c\)-cs < 17 MPa (updated criterion in this proposal, which should be confirmed or eliminated by means of a study of potential liquefaction); soils sensitive to vibrating densification; collapsible or organic soils, peat, and fine saturated soils with LL > 80 and thickness greater than 20 m; and fine saturated soils with sensitivity higher than 10.

The validity of the code is ratified only for ground types with topography and horizontal stratigraphy and for structures located outside of zones where local amplification phenomena occur or can be generated.

4. Conclusions

The seismic classification of foundation ground types has direct implications for the seismic design of a structure, impacting its construction costs and conditioning its feasibility. Therefore, a clear knowledge of the genesis of regulatory criteria allows engineers to better understand, interpret and apply professional criteria for classifying ground types and following the methodologies in a design code, which defines guidelines that are ultimately intended to safeguard the lives of those who will use the structure.

Great seismic events to which Chilean territory has been subjected have generated important information and experience in the seismic design of structures, which have allowed Chilean regulations to identify and include variations in seismic demand according to the type of ground since the 1930s, prior to most design codes worldwide. The main conclusions have been scattered among the different design codes proposed for Chile, generating seismic classification proposals that could be considered in the vanguard for each period. Along these lines, NCh 433 has recently proposed the replacement of properties associated with ground resistance that are usually applied in different design codes (ground density, q\(_u\), or N-value, SPT) by parameters that represent the dynamic stiffness properties of a specific location, which correlate more consistently with the ground amplification phenomenon. Thus, in addition to the commonly employed Vs30, the code proposes incorporating the fundamental period of ground vibration measured in situ, T\(_g\), as a parameter for seismic classification.
Regarding the predecessor Chilean design codes and homologous regulations at the international level, the most recent proposed version of NCh 433 presents an important advance regarding the selection of seismic site classification parameters in the process of performing a practical characterization that can better correlate with the phenomenon of ground amplification. Likewise, it is recognized that the Vs30 parameter, which is widely employed internationally, should not be substituted but rather should be complemented with dynamic parameters, such as the proposed $T_g$, which, according to the observations of the last earthquakes, was considered with suitable parameters.

Seismic engineering in its different disciplines has made important advances that have allowed the adjustment of seismic design codes. This review highlighted the clear need to undertake a continuous evaluation of the classification criteria, supported by records of new earthquakes, as well as physical and non-linear numerical models that allow incorporating variables that condition the response of the terrain, such as topography, lateral heterogeneities, and basic effects. Notably, the particularities of each country shape the criteria in their design codes. Nevertheless, acknowledging other criteria, such as those in Chilean codes gained by experience with respect to seismic site classification, allows the consolidation of similar criteria that could be common, at least, at the regional level.

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