METRO VENTILATION SYSTEM IN SEISMIC AREAS

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ABSTRACT

Globally more people live in urban areas than in rural areas. By 2050 67% of the world's population is projected to be in urban areas. This demographic datum clearly shows that future megalopolis will have to face a challenge in the urban traffic and surely the underground metro network will expand. The paper analyzes the main Countries in the world that have seismic risk and their codes/standards that are locally used. The analysis is carried out where a full document is available. Major attention lwill be placed on Europe where a common approach is available with Eurocode 8 (EN 1998-1 Design of Structures for Earthquake Resistance). The focus will be on the Italian Code NTC 2018, which is in line with Eurocode 8. The paper focuses on non-structural components and analysis of the equipment of the ventilation system concerning the seismic forces. Comments on the seismic forces in underground soil and analysis of data. General information regarding seismic tests on the vibration table is given to understand the feasibility of a seismic qualification of equipment. Where seismic requirements are limited to stability a static analysis is sufficient or a dynamic one still feasible, conversely where a functionality or operational status is required the preferred route leads to a seismic test.

Keywords: Seismic codes, Seismic areas, Underground, Seismic qualification

1. INTRODUCTION

Globally, more people live in urban than rural areas: in 2014, 54% of the world's population lived in urban areas (in 1950, 30% of the world's population was urban). In 2050, 67% of the world's population will be urban [1]. Of course, today's figure of 54% is not constant worldwide: North America 82%; Latin America and the Caribbean 82%; Europe 73%, conversely Africa 40% and Asia 48%. All regions are expected to urbanise further in the coming decades. Africa and Asia will urbanise faster than the other regions and are expected to reach 56% and 64% by 2050. These demographics clearly show that future megacities (> 10 M people) will face an urban mobility challenge: new vehicles powered by environmentally friendly engines and the metro network will expand for public transportation. Additional attention must be addressed and placed in seismic areas. The seismic design approach certainly focuses on the structural elements, but attention must also be paid to the "non-structural elements" that are sometimes crucial to the operation and safety of structures. Indeed, in the event of an earthquake, the functionality of facilities and equipment is a major issue. Ventilation systems for subways in earthquake zones fall into this context, especially because of the large number of people involved and located in confined spaces.

2. SEISMIC AREAS

2.1. Non-EU Countries

A global view provides an overview of the technical approach to seismic design. Each country has its own "Seismic Code" that guides how to approach seismic design. A focus on the non-European level is given in the following table:

Table 1: Seismic codes for non-EU Countries

Country	Code	Notes
USA	ASCE/SEI 7-10 [2]; ASCE/SEI 7-05[3]; ASHRAE-2019 Handbook Application Chapter 56 (see comments) [4]; International Building Code IBC (ICC 2009) [5]; SMACMA 2008 [6]; FEMA 412-413-414 (Federal Emergency Management Agency) [7–9]	
CANADA	NRC-IRC 2010 [10]	National Building Code for Canada
CHILE	NcH 2369-Of2003 [11]	Diseño Sismico de Estructuras e Installaciones Industriales
AUSTRALIA, NEW ZEALAND	AS 1170.4-2007 [12] and NZS 1170.5-2004 [13]	Common base AS/NZS 1170.2-2002
JAPAN	kyu-taishin building codes [14]	
CHINA	GB 50011-2010 [15]	Chapter 14 (Underground Buildings), Section 14.1.1, states that this chapter does not apply to urban subways and highway tunnels; this means that there is a separate document covering subways.

This global overview is not exhaustive but shows only examples from some Countries; it should be noted that sometimes these codes in the preamble and/or in the initial part of the text refer to other standards, consequently, a complete analysis is extremely complex and beyond the scope of the paper. Structural components are primarily discussed and refer to building construction and thus are outside our scope. The focus is on non-structural elements, in our case HVAC equipment used in subway ventilation systems. The following table provides a brief comparison of the various Codes and the technical requirements that must be adopted to meet the application of the standard. The equipment and its fixings are analysed in the Codes where it is possible to have the complete document and thus be assured of a correct view and interpretation.

Table 2: Comments on the codes for non-EU Countries

ASCE/SEI 7-10	(i)Table 1.5-1. Buildings and other structures that failure of which could pose a substantial hazard to the community (similar to NTC 2018 later shown). All chapter 13 (Seismic Design Requirements for non-structural components) gives precise information on action to be taken. (ii)Paragraph 13.1.3 Numbers 1 and 3. Essential components for safety, continuous operation purposes. (iii)Paragraph 13.1.6. Letter c. Fixings of components. (iv)Table 13.2.1. Applicable requirements for mechanical and electrical components. (v)Paragraph 13.2.2. Components for continuous operation after earthquake. Qualification by analytical approach. (vi)Paragraph 13.2.5 &6. Certification of component as alternative to analytical approach. (vii)Paragraph 13.6.1. Mechanical and electrical components fixings. (viii)Paragraph 13.6.3. Critical mechanical components (grade I_p>1)

ASHRAE 2019 Handbook Application Chapter 56	(i)in the preamble equipment that is to be restrained must also have the necessary strength to remain attached to the restraint. (ii)Paragraph 1. The importance of the equipment and system affected should be understood for code application to include those items that must be functional after the seismic event
AS 1170-4 2007	(i)Paragraph 8.1.4-part (b) letter (viii). Reciprocating or rotating equipment. (ii)paragraph 8.2 & 3. Non-structural components and their attachments shall be designed to resist the earthquake forces. The Acceleration method or the simple method is used.

2.2. EU Countries

If we now look at Europe, we can see that seismic zones are limited to five areas with significant seismic risk: Italy, Greece, Turkey, the northern Balkan area (Romania) and Iceland, see the following figure.

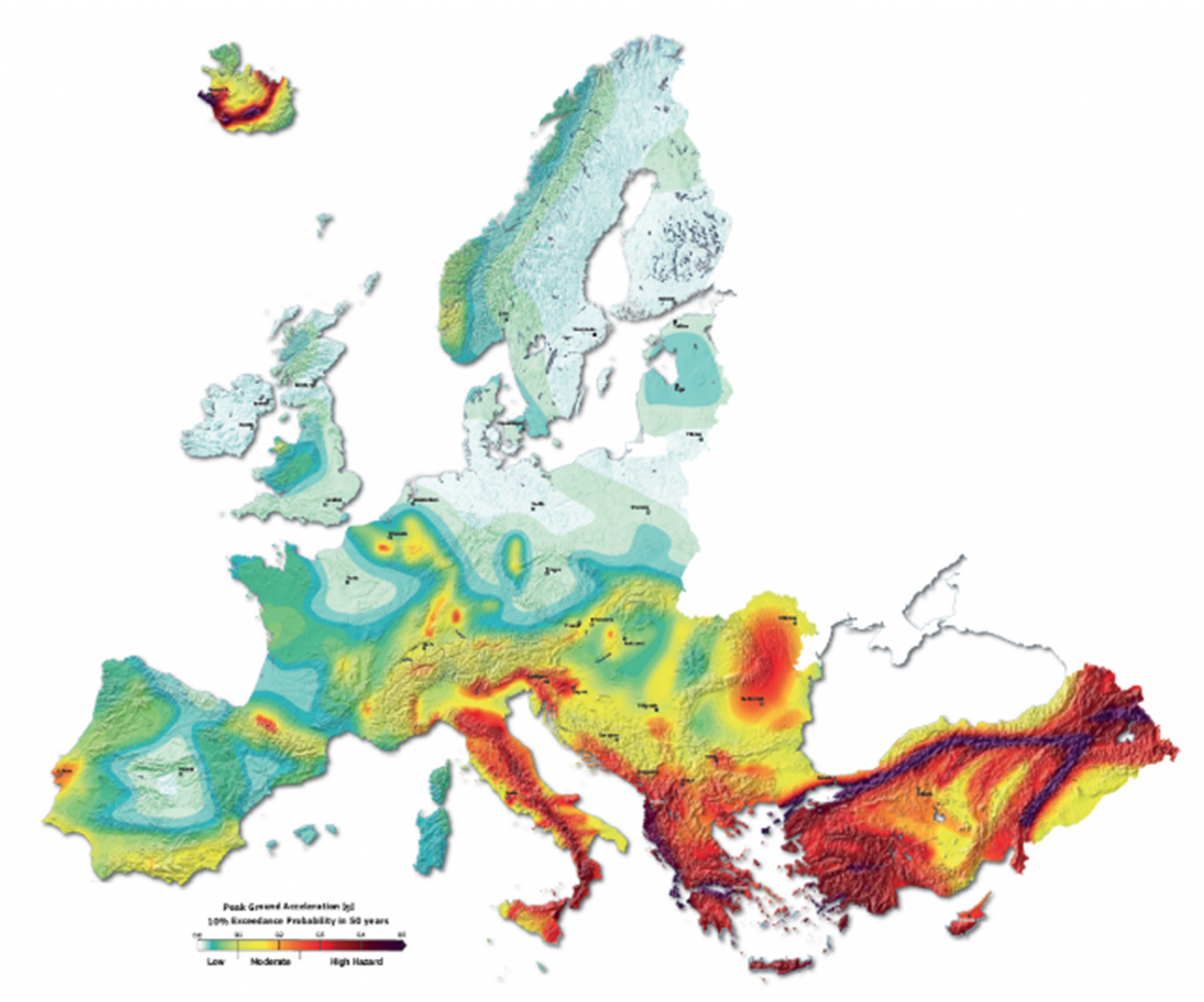

Figure 1: European seismic hazard map [16].

A common code called the Eurocode was issued in Europe in early 2000; the structural Eurocode program includes the following standards, generally consisting of several parts:

- EN 1990 Eurocode: Basis of structural design
- EN 1991 Eurocode 1: Actions on structures
- EN 1992 Eurocode 2: Design of concrete structures
- EN 1993 Eurocode 3: Design of steel structures
- En 1994 Eurocode 4: Design of composite steel and concrete structures
- EN 1995 Eurocode 5: Design of timber structures
- EN 1996 Eurocode 6: Design of masonry structures
- EN 1997 Eurocode 7: Geotechnical design
- EN 1998 Eurocode 8 Part 1: Design of structures for earthquake resistance
- EN 1999 Eurocode 9: Design of aluminium structures

The following table shows the essential elements of Part 8 and the "Basis of structural design (EN 1990)", document from which the National Standards are derived.

Table 3: Comments of the EN1998-1 [17] and EN 1990 [18]

EN 1990	(i)Paragraph 1.5.1.1 Construction works define not only building but also civil engineering work. "It refers to the complete construction works comprising structural, non-structural and geotechnical elements." (ii) Paragraph 1.5.1.2 gives some examples related to buildings and civil works (iii) Annex B. Table B1. Construction classes. Metro should be in CC3. In any case, EN 1998-1 under 4.2.5 Table 4.3 is clearer.
EN 1998-1	(i)Eurocode 8. Design of structures for earthquake resistance. (ii)Paragraph 1.1.1. Letter (1) P. Structures important for civil protection remain operational. Note every EU Country can define different seismic risks. (iii)Paragraph 1.1.2. Norm applies to buildings and civil engineering works in seismic regions. (iv)Paragraph 2.1.1(P). Structures in seismic regions shall be designed and constructed with the requirements of no-collapse and damage limitation. (v)Paragraph 2.2.2.6(P). The ultimate limit state is designed. It shall be verified that under the design seismic action, the behaviour of non-structural elements does not present risks to persons and does not have a detrimental effect on the response of the structural elements. (vi)Paragraph 4.2.5. It is defined the importance class for buildings, and the underground train is in class IV. (vii)Paragraph 4.2. Table 4.3. Importance class for buildings. Class IV buildings whose integrity during earthquakes is of vital importance. (viii)Paragraph 4.3.5.1 Letter (1) P. Non-structural elements …… equipment that might, in case of failure, cause risk to persons or………. services of critical facilities, shall together with their supports, be verified to the design seismic actions. Letter (2)P……. the seismic analysis shall be based on realistic models. (ix)Paragraph 4.3.5.2. Verification of non-structural components.

The Eurocode standards recognize the responsibility of local authorities in each EU member country to safeguard their right to determine values according to national levels, as these may vary from time to time, based on seismic risk, and from state to state.

The following table shows the different standards or codes found in various European Countries:

Table 4: Seismic codes for EU Countries

Country	Code	Notes
Greece	EAK-2000 [19]	Greek Code for Seismic Resistance Structures
Turkey	TEC-2007 [20]	National norm recently updated in 2019
Spain	NCSE-02 [21]	National norm General y edificaćion (Norma de Construction Sismorresistente)
Portugal	National decreto Lei 235/83 (RSAEEP) [22]	National Decreto
Romania	P100 series [23]	National norm that follows also the ASCE standards of USA
Bulgaria	Regulation RD-02-20-2 of January 2012 [24]	the Regional Ministry approved a methodology for seismic risk assessment
Austria	The National Annex ÖNORM B 1998-1 (2017) [25] to Eurocode 8 (2004) was firstly introduced in 2009.	
Iceland	the Standardization Council of Iceland is preparing a National Application Document (NAD) in conjuction with adoption of Eurocode 8	
Switzerland	SIA Norms from 260 to 267 compliant to Eurocode 8; SIA 269,269-1, 269-8 the last one relevant to seismic conservation and seismic safety; ASTRA 13020-2021 V1.01 (mainly dedicated to energy supply in tunnels); ESTI 248 version 1220i (electrical plants and seismic fixings).	Even if is not part EU the approach is inspired by Eurocode 8.

2.3. Italian approach

The regulatory framework in Italy includes various documents such as Standards, Directives, Laws, L.D., Regional Laws, and Guidelines. They have been issued over the years and some of them refer to international documents. We can mention the Official Gazette No. 108 of May 11, 2006, which establishes the territory in four seismic zones (acceleration with a 10% probability of exceedance in 50 years ag):

- Zone 1 – 0.25 < ag < 0.35 g
- Zone 2 – 0.15 < ag < 0.25 g
- Zone 3 – 0.05 < ag < 0.15 g
- Zone 4 - <= 0.05 g

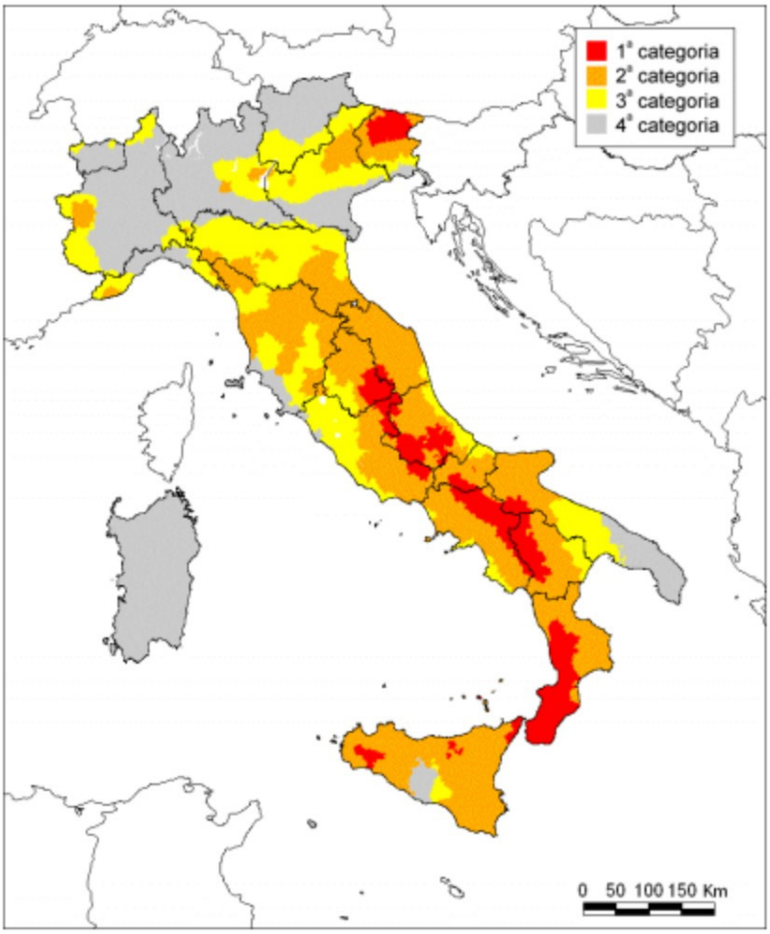

Figure 2: Peak ground acceleration According to "PCM Ordinance No. 3519-2006" [26]

Seismic acceleration ranges from 0.35 to 0.05 g. The main and essential document for seismic design is the NTC 2018 (Norme Tecniche per le Costruzioni) issued in "Gazzetta Ufficiale" No. 42 on February 20, 2018. This document is derived from EN 1998-1. This document is mandatory and currently in force, also used for the design of non-structural elements. To have a complete view, it is also necessary to consider the DM (Ministerial Decree) of October 21, 2015, which stipulates that fans for ventilation systems in subways must be certified for 400 °C/90 minutes. Therefore, the legislature considered the operation of fans essential for safety reasons during fires.

2.3.1. Focus on NTC 2018

Within NTC 2018 are the updated technical standards for construction. In Article 2, the scope, also provides for public works or public utilities, of course, subways fall within this context. The works and structural components must be designed, executed, tested, and maintained to enable the intended use with the expected level of safety. Requirements related to strength, durability, fire safety, safety against operating limit states, and safety against ultimate limit states are identified. The last two states refer to the construction, both considering structural elements, but also non-structural elements and systems. Buildings are divided into classes, the "metro" being in class IV, in which the use coefficient will be 2. This coefficient is used to obtain the reference period in which seismic actions on buildings are evaluated. Regarding the presence of structures within the metro, a static (to verify the stability) or dynamic analysis of them (to verify the functionality) can be carried out. This analysis is useful for determining the effects of seismic action. For all primary and secondary structural elements, non-structural elements and structures, it must be verified that the value of each design demand is less than the corresponding design capacity value. Thus, as can be seen from Table 7.3.III of the NTC text [27], verifications of facilities are carried out in terms of operation and stability, obviously depending on the class of use. It should also be remembered that the fans installed inside the subways, must be F400 certified, so they are considered vital for safety. Complexity in modelling easily leads to seismic testing.

3. METRO VENTILATION SYSTEMS

In the fan system the main equipment is the fan, and the other components are part of the system; all are described and discussed from sections 3.1 to 3.4. In seismic terminology, it is considered a "non-structural component," but this does not mean that it is not important. Non-structural seismic design, such as ventilation systems, cannot be forgotten or given less attention; it is not normally considered a priority like structural components. Typically, ventilation systems are push-pull in that they push fresh air in and suck out exhausted air to create a safe escape route for people. A general ventilation plant layout is shown in the following figures.

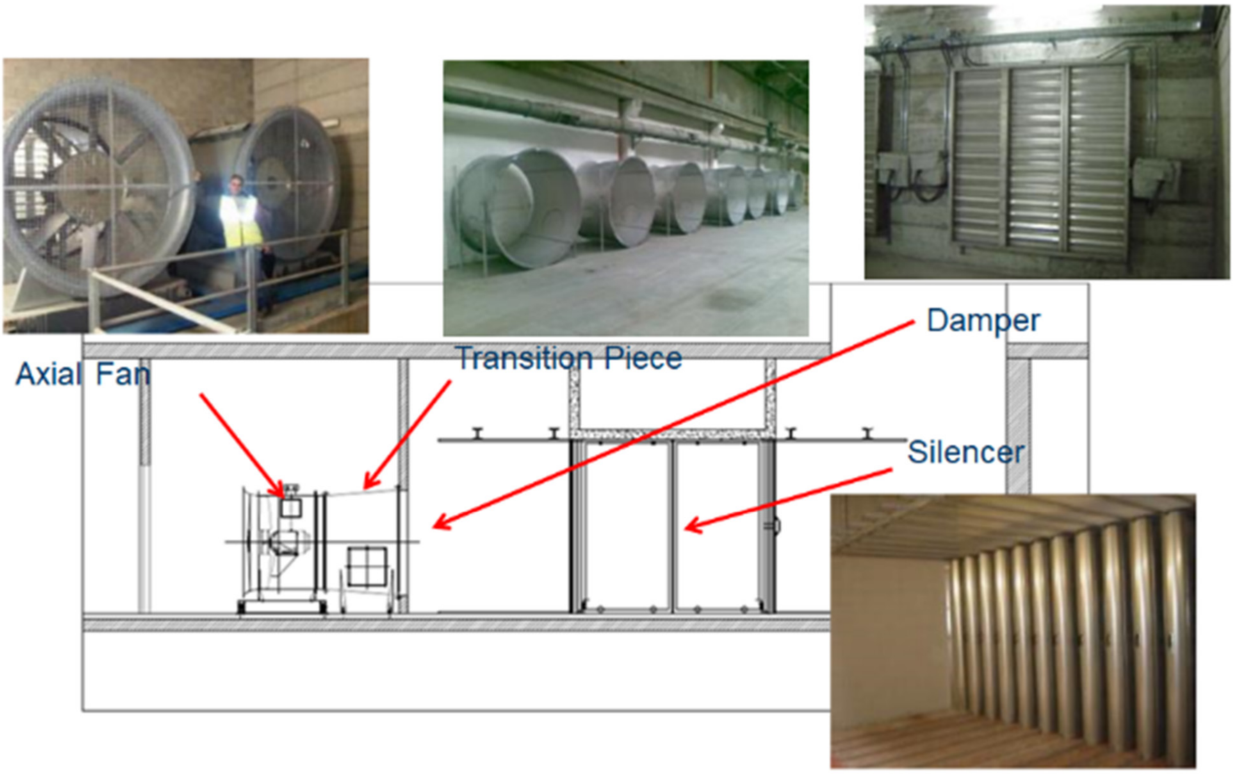

Figure 3: Typical ventilation chamber arrangement – courtesy of Systemair

3.1. Fans

The fans are mainly axial type horizontally installed in a plant room. They are also reversible and have a diameter of 1800 to 2500 mm with a motor power up to 350 kW. In Italy, they are also certified to operate as F400. The air volume is divided into 2 or more fans in parallel to have a safe redundancy. In some cases, jet fans in the metro tunnel are present to keep control the smoke spread. Fans can also be fixed on an inertial basement, which is intended to lower the centre of gravity and consequently achieve greater operational stability. Adding mass also results in less transmission of vibration to the surrounding ground. As a rule, adding mass reduces the natural frequency, while stiffening the structure increases the natural frequency.

Figure 4: Fan with seismic anti-vibrators – courtesy of Systemair and Mecanocaucho [28]

To complete the fan analysis, we can mention the natural blade frequencies are sufficiently higher than seismic normal frequencies (0.1 to 20 Hz). A typical fan of 2000 mm, 4 pole motor at 50 Hz shows a blades natural frequency of 46 Hz [29]. Furthermore, for an axial fan of 1600 mm (diameter) suitable for a 4-pole motor at 50 Hz, it was reported a casing natural principal frequency of 187 Hz with 1.927 m/s^2; with also two other frequencies at 237 Hz and 293 Hz [29].

3.2. Antivibration mountings

They can be rubber or spring-loaded and selected to have maximum isolation efficiency at the rated rotational frequency of the impeller. In seismic zones, it is necessary to select components that limit horizontal displacement and have resistance to the seismic forces present. The market offers seismic constraints (bumpers) that limit movement in only one direction; there are also multidirectional seismic dampers (snubbers) that can be used in conjunction with vibration-damping mounts [4]. It is recommended to use anti-vibration mounts that include the ability to operate in a seismic environment and have a low natural frequency, in some cases close to 1 Hz (lower than the normal earthquake excitation frequency, e.g., 2-3 Hz); these can hold the displacement that is quite considerable and continue to function as a normal anti-vibration mount; seismic tests have shown a reduction of up to 25 percent of the seismic forces transmitted to the fan [30]. On the other hand, when you are forced to increase the natural frequency and go up to 25 Hz, the anti-vibration mounts are still in place, but as a last resort, as it is a poor vibration insulator. The component is not an accessory, but it is an important piece that ensures the stability and operation of the fan, so it is recommended that the manufacturer be involved from the beginning. Fasteners are normally designed using the equivalent static force method acting on the fan's center of gravity. For design in Italy, NTC 2018 applies, while in Europe, EN 1998-1 and EN 1992-4 apply.

3.3. Transformation ductwork and silencers

The fan/fans are connected via a round-to-square transformation diffuser to the on/off dampers. Silencers are generally installed after the dampers as shown in figure 3. These components are static ones so they can be statically designed to withstand the load of seismic forces, ground fixing is normally enough to reach the scope. As above NTC or EN are used.

3.4. On/Off dampers

The dampers consist of a frame (static part) and blades that open and close (dynamic part) via an actuator. The dampers are fixed on a partition wall which is certainly also a non-structural element, so care must be taken to check the seismic resistance of both. Dampers can be as much as 15 m^2 so an appropriate seismic evaluation should be performed.

The actuators can be of various types: electrical, pneumatic, electro-pneumatic, spring return etc. There are available types already certified in the seismic environment [31] the mentioned one should be connected to a one-quadrant gear. Also, actuators already suitable for dampers application as quarter turn are seismically approved [31]. Integral controls have to be evaluated in seismic applications.

4. SEISMIC ACCELERATION IN THE UNDERGROUND

The main data in the seismic design is PGA (Peak Ground Acceleration) and the Ground Elastic Response Spectrum; in the usual building with many floors the last one can increase up to 3 times with respect to the one measured at ground (should the building oscillate in the first mode e.g. upside-down pendulum); in case of the underground metro network we have a hypogeal construction (below the ground level) and it happens an opposite effect: acceleration decreases. Recently at a PIARC Conference it was presented a paper that for the first time, as far as we know, considers the seismic design in road tunnels [32], tunnels generally respond better during an earthquake than structures located at the surface. Ground seismic data are typically established at the ground surface. Tunnels, however, are located at some depth below the ground surface. For seismic evaluation of the tunnel construction and structure and non-structural components, ground seismic data must be obtained at the height of the tunnel. Since seismic data decreases with depth, the underground data is less than the surface data [33,34].

The ratio of tunnel depth/ground surface data is shown in the following table:

Table 5: Ground motion attenuation with depth [33]

Tunnel depth (m)	Ratio of ground motion at tunnel depth to motion at ground surface
≤ 6	1.0
6 -15	0.9
15 -30	0.8
≥ 30	0.7

Since the reduction is also influenced by soil type [35] a site depth-specific dynamic response analysis should be performed (1D response) or with spatial coordinates (2 or 3D response). Normally a 1D analysis is enough to have coherent data.

5. SEISMIC QUALIFICATION

So far, as far as we can understand, there are no cases where seismic qualification by vibration test rig (shake table) have been done regarding the main components of the metro ventilation system. Most seismic Codes ask for a static or analytical approach, if modelling is required it is specified that has to be realistic. Case studies are not available and consequently no data can be evaluated as examples. In Italy the NTC 2018 asks for stability and operation so for the latter one only a modeling is applicable; but again, the mathematical net of elements is very heavy and practically leads us to consider the seismic test. There is exhaustive literature and documentation relevant to seismic test for nuclear application. For the considered case studied, the technical requirements are lower and therefore the approach should be easier. There are many norms for seismic testing but mainly focus on nuclear applications (e.g.IEEE 344 and IEC 60980). Currently, the Norms that should be applied to the ventilation equipmentss are: ICC ES AC 156 (2020) of the International Code Council and IEEE 693 (2018). The process is quite complex and not fully explained in this paper; the Laboratory will handle the horizontal and vertical seismic forces with relevant frequencies and with an appropriate mathematical manipulation will determine the required technical inputs to be used during the test. This part is the core of the seismic qualification.

The test is performed on a multi-axial shake table with the following main data

Table 6: multi-axial shake table / main data

Plate dimensions	4.8m x 4.8 m
Movements	longitudinal/transversal/vertical/yaw/roll/pitch
Stroke (X, Y, Z axes)	±500mm/±500 mm/+90 mm, -50 mm
Velocities (X,Y axes)	2 m/s
Velocity (Z axis)	0.5 m/s
Acceleration (X, Y, Z axes)	±15 m/s^2 ; ±15 m/s^2 ; ±12 m/s^2
Max. longitudinal/tranverse force	1400 kN static
Max. payload	30 t
Frequency range	0.1-50 Hz nominal

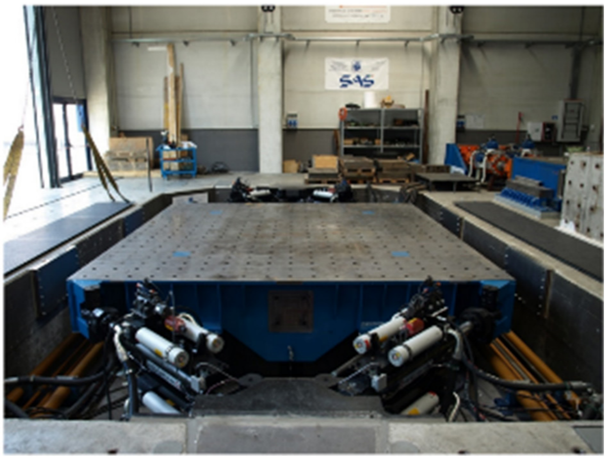

Figure 5: Multi axial shake table - courtesy of EUCENTRE [36]

6. CONCLUSION

Depending on the complexity, and the type of plant section, the designer, installer and supplier will have to find the best way to fit the plant and the tool identified. The choice of the best procedure to be able to comply with the regulations is linked to the type of component, whether a static analysis is sufficient or a dynamic analysis is also necessary. In this context, the possible alternatives are as follows: in the case of stability, static calculation, or modelling (static only) may be sufficient, whereas for functionality, dynamic modelling is very complex and, in any case, would then have to be validated with ad hoc tests, so the preferred route concerns the use of seismic testing. An example of structural and fatigue strength analysis for a tunnel damper (5650x3600x300 mm) can be cited to highlight the complexity. For the fatigue strength analysis alone for a passive component, 793622 elements with a high computational cost were used [37]. Another damper manufacturer approaches the problem in a different way: the number of elements changes during the process of modelling so the damper is divided into parts and consequently in sub-models to be separately calculated. This approach leads to reduce the modelling complexity [38].

7. ACKNOWLEDGEMENTS

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