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ORIGINAL ARTICLE

Towards specific T–H relationships: FRIBAS database for better characterization of RC and URM buildings

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Abstract

FRIBAS database is an open access database (https://doi.org/10.5281/zenodo.6505442) composed of the characteristics of 312 buildings (71 masonry, 237 reinforced concrete and 4 mixed types). It collects and harmonizes data from different surveys performed on buildings in the Basilicata and Friuli Venezia Giulia regions (Southern and Northeastern Italy, respectively). Each building is defined by 37 parameters related to the building and foundation soil characteristics. The building and soil fundamental periods were experimentally estimated based on ambient noise measurements. FRIBAS gave us the opportunity to study the influence of the main characteristics of buildings and the soil-building interaction effect to their structural response. In this study, we have used the FRIBAS dataset to investigate how the building period varies as a function of construction materials and soil types. Our results motivate the need of going beyond a 'one-fits-all' numerical period–height (T–H) relationship for generic building typologies provided by seismic codes, towards specific T–H relationships that account for both soil and building typologies.

Keywords Soil-structure interaction · Period–height relationship · Ambient noise measurements · Building behavior

1 Introduction

The fundamental vibrational period of the building is a key parameter needed both in the design of new buildings and in the assessment of the dynamic behavior of existing ones. In engineering practices, fundamental periods are involved either explicitly (linear methods

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of analysis) or implicitly (non-linear methods). There is extensive literature concerning the crucial role of the vibrational periods on the seismic behavior of structures, and thus on their seismic response and design. For this reason, in recent decades, a significant number of studies have been carried out (e.g. Jiang et al. 2020) and different procedures have been proposed to evaluate the fundamental period (i.e. Gallipoli et al. 2009; Hatzigeorgiou and Kanapitsas 2013; Al-Nimry et al. 2014; Asteris et al. 2017). Furthermore, while some studies have focused only on the fundamental period, others have also estimated the damping and modal shape in order to assess the expected damage and validate the results with documented ones. Building periods can be affected by many factors; for Reinforced Concrete (RC) buildings the main factors are: (1) building height; (2) structural type (i.e. Moment Resisting Frame—MRF or Structural Walls); (3) regularity in plan and in elevation; (4) infill walls; (5) RC member cracking due to permanent actions (e.g. gravity loads); (6) earthquake resistant design level (mainly gravity-load design or anti-seismic design); (7) soil-structure interaction. For unreinforced masonry (URM) buildings, the fundamental period can be affected by parameters such as masonry type, regularity in plan and in elevation, geometric and mechanical parameters, which are rarely accounted for (Bayraktar et al. 2015; Zini et al. 2018; Spina et al. 2019). For URM buildings, the analysis of the expected seismic response, in particular the fundamental period, has historically been based on simplified methods (Block et al. 2006; Snoj et al. 2020), and is still a common approach (i.e. Portioli et al. 2021; Calò et al. 2021; de Felice et al. 2021). At the European scale, URM buildings represent a high share of the residential building stock (Crowley et al. 2020); in addition, they encompass a wide range of typologies depending on the local characteristics. However, no specific studies have highlighted the influence of their specific characteristics (e.g. floor type, shape, presence of basement) on their fundamental period.

The fundamental building periods can be determined using simplified empirical relationships (e.g. period–height expressions, Crowley and Pinho 2006), numerical simulations for different structural types (refer to Kwon and Kim 2010 for an extensive review) and through experimental measurements (e.g. Gallipoli et al. 2010; Michel et al. 2010a). The existing codes generally provide empirical formulas or various approximations for the fundamental periods, either excluding or including the effects of infill walls (Eurocode 8 2003; CEN 2004). The Eurocode 8 (EC8) provides simplified expressions for estimating the fundamental period T as a function of the building height and a specific coefficient for each typology. The use of empirical formulas allows an easy estimation of the building period in order to verify the applicability of simple methods (e.g. as prescribed in EC8) for lateral force analysis. An overview of the different numerical approaches for the estimation of period–height (T–H) relationships applied to RC buildings, and widely represented in the European built environment, is reported in Masi and Vona (2010) and Hatzigeorgiou and Kanapitsas (2013), where the role of some structural characteristics (cracking, masonry infills, elevation irregularities, etc.) was carefully examined. According to Kose (2009) and Michel et al. (2010a), the building height and the distribution of structural walls are the most important factors controlling the fundamental period of RC buildings, reflecting the limited influence of the plan dimension of a building.

In the design and evaluation of existing structures, structural models are usually based on simplified assumptions and commonly disregard the phenomena of interaction between soil, foundation and structure (SFS). This hypothesis is to be considered realistic only for structures built on very rigid soil, while neglecting this effect on soft ground could cause an incorrect evaluation of the dynamic response of the structure (Paolucci 1993; Mylonakis and Gazetas 2000; Piro et al. 2020). Veletsos and Meek (1974) and Luco et al. (1988) already pointed out that the interaction between structures and the foundation soil may have significant effects on the response due to three principal factors: (1) a flexibly supported structure has more degrees of freedom and, consequently, different dynamic characteristics than a rigidly mounted structure; (2) a significant part of the vibrational energy of a flexibly supported structure may be dissipated by radiation of waves into the supporting medium (e.g. Petrovic and Parolai 2016; Petrovic et al. 2018a) or by damping in the foundation material; (3) the deformation of buildings associated with the yielding of the foundation soil leads to a rigid-body motion of the superstructure that may account for a significant portion of the total response (Veletsos and Meek 1974).

Currently, the estimation of experimental T–H relationships is possible since the number of Ambient Vibration (AV) measurements on buildings is increasing. After the development of a standard procedure for AV measurements in the free-field (SESAME 2004; Bonnefoy-Claudet et al. 2008), some international projects were devoted to comparing different AV techniques for the fundamental period estimation of RC buildings ("Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data" NATO project; Mucciarelli et al. 2009). Hans et al. (2005) and Gallipoli et al. (2009) showed that forced vibration and ambient vibration yield the same values for the fundamental periods of buildings as long as they remain in their elastic field, i.e. excited at low strain. Therefore, the dynamic behavior of buildings can currently be assessed using earthquake recordings (e.g. Snieder and Safak 2006; Celebi et al. 2016; Petrovic et al. 2018b), forced vibration (e.g. Hans et al. 2005) or ambient noise measurements (e.g. Michel et al. 2008; Bindi et al. 2015).

In contrast to building periods estimated through empirical formulas, which only take into account the structural system, those experimentally determined at the top of a building are representative of the linear elastic behavior of the entire dynamic system (structure-foundation-soil). Thus, they account for the presence, position and characteristics of infill panels, structural member stiffness (dimensions, extent of concrete cracking) and soil-structure interaction. AV recordings can easily be carried out in a large number of buildings because these surveys are cost-effective, non-invasive and non-destructive. Nowadays, AV monitoring is a worthwhile alternative to permanent building monitoring: to determine modal frequencies and mode shapes, and the damping ratio (e.g. Mikael et al. 2013; Ivanović et al. 2000 and references therein); to estimate variations of modal parameters before and after major earthquakes (Snieder and Safak 2006) or before and after retrofitting (Çelebi and Liu 1998; Gallipoli et al. 2020a); to update linear numerical models (Skolnik et al. 2006) and non-linear models of structures (Michel and Guéguen 2010b).

In recent decades, several authors have performed AV measurements on a large number of buildings and proposed experimental T–H relationships for RC-MRF buildings. For instance, the following authors performed studies in specific countries: Hong and Hwang (2000) in Taiwan; Navarro et al. (2007) in Spain; Güler et al. (2008) in Turkey; Oliveira and Navarro (2010) in Portugal, Chiauzzi et al. (2012) in Canada; Pan et al. (2014) in Singapore; Al-Nimry et al. (2014) in Jordan; Salameh et al. (2016) in Lebanon; Kaplan et al. (2021) in Turkey. Studies have also been deployed at European level e.g. by Gallipoli et al. (2010) for 244 RC buildings. Other studies combined the experimental data collected on both RC and masonry buildings, such as Gallipoli et al. (2009, 2020b) in Italy and Michel et al. (2010a) in France.

While several experimental T–H relationships were developed for RC buildings, there are very few studies on URM buildings, the most relevant being Bal et al. (2008) for Turkey, Gosar (2012) for Slovenia and Scaini et al. (2021) for Italy. Furthermore, most of the studies proposing T–H relationships for RC-MRF buildings did not take into account the foundation soil conditions of the buildings, neglecting the effect of soil-structure interaction. Only a very few studies proposed T–H relationships for RC-MRF buildings on different soil conditions (e.g. Pan et al. 2014; Salameh et al. 2016).

In this study, we have collected the main characteristics of 312 buildings (237 RC-MRF, 71 masonry buildings and 4 mixed-material) and their relative foundation soils located in the Basilicata (Southern Italy) and Friuli Venezia Giulia (Northeastern Italy) regions. All data have been organized in the FRIBAS open access database (available at https://doi.org/10.5281/zenodo.6505442) constituted by 37 fields including the key characteristics associated with each building and the corresponding soil conditions (e.g. location, main typological, geometrical, structural and foundational soil characteristics, and geological and seismic context). FRIBAS sets the stage to study the influence of each parameter on the building behavior. In this study, we show how interaction effects between buildings of different construction materials and soil types influence the building behavior. In detail, we propose experimental T–H relationships for the two main building construction materials, RC-MRF and URM located on two soil types: rigid and soft soil.

2 The dataset: FRIBAS database

Currently, building classification is mostly focused on structural elements and assessed, based on external and internal building inspections with the use of forms. There are global building databases (e.g. WorldHousingEncyclopedia - WHE, https://www.world-housing.net/) and global-scale taxonomies defined for the classification of buildings (e.g. Global Earthquake Model—GEM taxonomy, https://storage.globalquakemodel.org/). Building taxonomies for Europe have been proposed by the Risk-UE project (Mouroux et al. 2006) and adopted in subsequent vulnerability and risk analyses (e.g. SYNER-G Reference report 2, 2013). Specific forms have been developed at national scale, for example the Aedes form (Baggio et al. 2007) and the Cartis form (Zuccaro et al. 2015) in Italy. However, none of these is intended to be used in combination with experimental measurements or geological/geotechnical information of the site where the building is located. To our knowledge, the combination of forms and AV measurements has not yet been used for building classification.

The FRIBAS database was compiled to study how the main characteristics of a building and its foundation soil can influence the structural behavior. To this end, we collected data from different surveys on buildings and soil in the Basilicata and Friuli Venezia Giulia regions (Southern and Northeastern Italy, respectively, Fig. 1). The main characteristics of the buildings have been collected by: (1) visual inspection with the help of local residents and practitioners (e.g. engineers, architects), using information available in national and regional databases (regional spatial data infrastructure of the Basilicata Region, 2015; open-data Matera; General Population and Housing Census); (2) performing AV measurements on buildings and relative foundation soil or using existing measurements; and (3) using geological details from microzonation studies. In the Friuli Venezia Giulia region, it was also possible to inspect the plans of a number of surveyed buildings. FRIBAS contains also the main building characteristics and the main fundamental structural parameters (vibrational periods of buildings and its foundation soils estimated by experimental measurements).

All data were harmonized in order to achieve an optimal trade-off between level of detail and generalization. In addition, we included simplified classes in order to support the

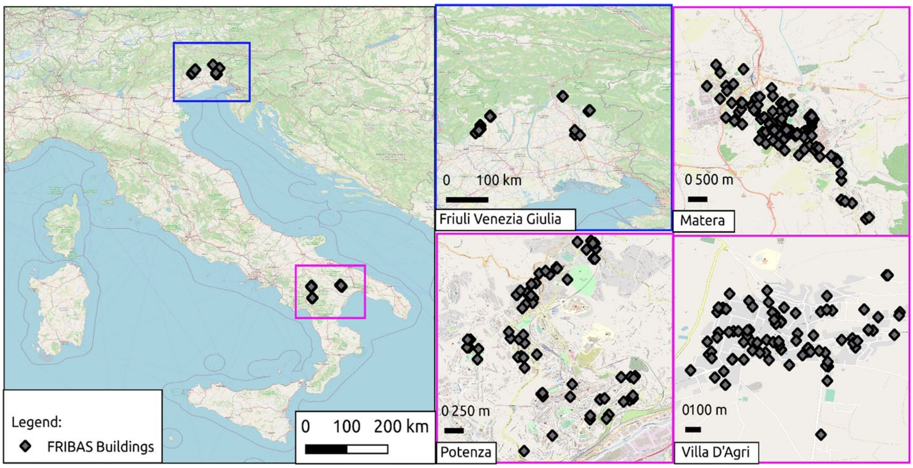

Fig. 1 Location of the FRIBAS buildings in Italy (left) and detail of Friuli Venezia Giulia region and the three considered towns in Southern Italy (Matera, Potenza and Villa D'Agri)

statistical analyses of different types of buildings and soils. Table 1 reports the 37 parameters (columns in the FRIBAS database, available at https://doi.org/10.5281/zenodo.6505442) specifying their main characteristics.

Additional information on parameter definitions (Table 1):

- ID_GIS: Unique identifier for each building.
- ID: Unique identifier for each building (string with reference to the location, MT=Matera, PZ=Potenza, VdA=Villa d'Agri, FVG=Friuli Venezia Giulia).
- COD_COM: Municipality code according to the national institute of statistics (ISTAT).
- LAT, LONG: Coordinates of the building in the WGS84 Universal Transverse Mercator (UTM)—zone 33N (EPSG:32633).
- Construction material: Information about the material of vertical load-bearing structure (obtained from building inspections): reinforced concrete, masonry and 'mixed' category (refers to buildings with both reinforced concrete and load-bearing masonry elements).
- Soft story: Presence of a soft story, i.e. a floor that can activate a weak-floor failure mechanism. Intermediate soft stories were also considered, as well as ground floors containing garages or commercial activities.
- Building use: Residential, Public, Industrial, Touristic.
- Age of Construction: Age intervals were defined according to the AEDES form (Baggio et al. 2007). The decade 1972-1981 is split into two classes (1972–1975 and 1976–1981) to account for the strong modifications of the building stock characteristics in Friuli Venezia-Giulia after the 1976 Friuli earthquake. Two classes were added after 1996 (1997–2001 and 2002–2008) to account for the adoption of new building codes in 2001 and 2009. For the eight buildings belonging to the "< 1988" class, a more precise assignment could not be provided because the available information was insufficient.

Table 1 List of the parameters, including a description, the available options (if applicable) and the data type

Parameter	Description and options	Count	Data type
ID_GIS	Unique identifier	312	Integer
ID	Unique identifier	312	String
Municipality	Municipality name	312	String
COD_COM	Municipality code	312	Integer
LONG	Longitude (WGS84/UTM33N)	312	Float
LAT	Latitude (WGS84/UTM33N)	312	Float
Construction material	Unreinforced Masonry (URM)	312	String
	Reinforced Concrete Moment Resisting Frame (RC-MRF)		
	Mixed (RC-URM)		
Soft story	Yes/no	312	String
Building use	Residential	310	String
	Public		
	Industrial		
	Touristic		
Age of construction	< 1919	312	String
	< 1988		
	1919–1945		
	1946–1961		
	1962–1971		
	1972–1975		
	1976–1981		
	1982–1991		
	1992–1996		
	1997–2001		
	2002–2008		
	> 2008		
# Floors	Value	312	Integer

Table 1 (continued)

Parameter	Description and options	Count	Data type
Presence of basement	Yes/no	304	String
Building height from the ground to the top of the roof	Value in m	312	Float
Building height from the basement to the top of the roof	Value in m	312	Float
Building width (B)	Value in m	307	Float
Building length (L)	Value in m	307	Float
B/L	Shape factor, dimensionless quantity	307	Float
B/H	Shape factor, dimensionless quantity	307	Float
Floor area	Value in m^2	308	Float
Polygon area	Value in m^2	305	Float
Area ratio	Floor area/polygon area, dimensionless quantity	305	Float
Building shape	R (rectangle), S (square), T (T-shape), L (L-shape), C (C-shape), H (H-shape), Tr (trapezoid)	307	String
Seismic provisions (masonry)	Free text with description of seismic provisions, if any (masonry only).	17	String
Masonry openings (%)	Percentage of openings with respect to the building lateral surface	25	Integer
Masonry type	Description of masonry type (e.g. stone, bricks), layout (regular/irregular) and quality	21	String
Slab	flexible/rigid	27	String
Roof type	Wooden/Other	35	String
Additional floors	Yes/No	312	String
Foundation type	Shallow/deep	32	String
Position of the building	single block/inside block/far end block	312	String
F1_building	Value in Hz	312	Float
F2_building	Value in Hz	240	Float
F0_foundation soil	Value in Hz	306	Float

Table 1 (continued)

Parameter	Description and options	Count	Data type
Outcropping geology	Gravina Calcarenite (coarse-grained carbonate sandstone)	312	String
	Calcari M.te Viggiano (Limestones and carbonate sandstones)		
	Marsicovetere Breccia (massive calcareous breccias)		
	Subappennine clay		
	Conglomeratic deposits		
	Sands and sandstones		
	Clean gravels		
	Silts and clays		
	Sand		
	Silty gravels		
	Gravels and sands, with silt and clay		
	Alluvial deposits		
	Colluvial deposits		
	Eluvial and colluvial deposits		
	Anthropic deposits		
Soft soil/rigid soil	Mechanical characteristic of foundation soil	312	String
Seismic soil class	Seismic design code (A, B, C, D, E)	312	String
Topographic class	Seismic design code (T1–T2–T3…)	312	String

The count refers to the number of buildings for which the parameter was collected or available

- # Floors: The top floor was included when its estimated volume was comparable with those of other floors in the building (e.g. habitable attic).
- Presence of basement: All floors that are partially or totally below ground are considered. This information was obtained from inspection and/or residents.
- Building height from the ground to the top of the roof (m): If the building is located on a slope and is not separated by the uphill side through a retaining wall, the ground floor is considered to be the one at the higher side of the slope.
- Building height from the basement to the top of the roof (m): Total height, including both the basement and the structures present at the top of the building (e.g. lift shafts).
- Building width B: The shorter dimension of a circumscribing polygon.
- Building length L: The longer dimension of a circumscribing polygon.
- B/L: Ratio between building width and building length, which is a proxy of the plan regularity (Bertero 1996).
- B/H: Ratio between building width and building height (from the ground level to the top of the building).
- Floor area: Building area calculated based on building footprints (e.g. from openstreetmaps or available national/regional digital maps).
- Polygon area: Area of the circumscribing polygon.
- Area ratio: Ratio between floor and polygon areas (Bertero 1996).
- Building shape: Geometric shape of the building; R (rectangle), S (square), T (T-shape), L (L-shape), C (C-shape), H (H-shape), Tr (trapezoid).
- Seismic provisions (masonry): Description of any seismic provisions (e.g. additional pillars, ring beam, walls reinforcement, tie-rods). Most of these were observed in the Friuli Venezia Giulia region during building inspections or mentioned by residents, and were performed as a consequence of the Friuli 1976 earthquake.
- Masonry openings (%): Percentage of openings with respect to the building lateral surface.
- Masonry type: Type of load-bearing masonry, including material (e.g. stone, bricks, concrete blocks), layout (regular, irregular) and quality. Masonry type and layout was identified by inspection and/or asking the residents. We did not gather information on masonry quality.
- Slab: Slab type (rigid or flexible). The floor type was inferred from inspection and/or information collected from residents. Rigid floors often consist of reinforced concrete and hollow tiles.
- Roof type: The roof type was assessed from inspection and/or information collected from residents. The most common types are: wood (with or without hollow tiles), reinforced concrete (with or without hollow tiles). In some cases, it was not possible to survey the roof. The presence of thrusting elements was surveyed only for a few inspected buildings and was not included in the database or used for roof classification.
- Additional floors: Presence of floors added to the building after its construction, but not included in the original project.
- Foundation type: Type of foundation (shallow or deep) based on the information collected from residents and/or from the building plans inspected during the data gathering process.
- Position of the building: We distinguish between buildings that consist of a single unit (single block) or are composed of multiple blocks. In particular, when constituted by multiple blocks (e.g. in the case of attached buildings), we distinguish between internal buildings (attached to two or more buildings) and buildings located at the edge (far end

blocks attached only to one building). The presence of seismic joints or staircases is specified in the text field.

- F_1_and F_2 building (Hz): The fundamental vibrational frequencies for all buildings and soils reported in FRIBAS have been experimentally estimated performing single station AV measurements analyzed with the Horizontal-to-Vertical Spectral Ratio technique (HVSR; Chavez-Garcia et al. 1990; Field and Jacob 1995; Mucciarelli 1998; Castro et al. 2004) following the SESAME (2004) criteria and the standard procedures proposed by Albarello et al. (2011). This technique immediately achieved resounding success as it is allowed to evaluate some geo-mechanical subsoil characteristics by making simple, low-cost and expeditious measurements. The theoretical principles have been the subject of in-depth studies for more than 30 years, at present there are thousands of papers dedicated to the HVSR technique, both from a theoretical and applied point of view (last review in Molnar et al. 2022). The SESAME project (2004; Bonnefoy-Claudet et al. 2006) was dedicated to investigating and standardizing a series of aspects for the acquisition, analysis and interpretation of data. A few years later, the "Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data" NATO project (Mucciarelli et al. 2009) was dedicated to validate the HVSR technique to estimate the main frequencies and relative damping on buildings. During this project, it was established how many measurements are needed, how to carry out the measurements on buildings according to the requested degree of precision, the conditions to fulfill during measurements and the reliability of the technique was discussed (last review in Castellaro 2016). In buildings, it is possible to make different measurement arrangements depending on the requested degree of precision. In our study, at least one measurement was performed on the top floor of the building. For each RC building, the measurement was carried out by posing the sensor on the top floor near the column-beam junction; for the masonry ones, close to the load-bearing wall. Measurements were accomplished using four different instruments (Tromino, Lunitek Sentinel GEO, Lennartz 3D-Lite 1s connected to Reftek or Titan dataloggers), aligning the sensor along the two building directions (longitudinal and transversal direction), acquiring data between 10 and 30 min.

  The HVSRs have been estimated following the subsequent procedure: each component was divided into non-overlapping windows of 20 s; each window was detrended, tapered, padded, Fast Fourier Transformed and smoothed with triangular windows with a width equal to 5% of the central frequency. For each of the 20 s windows, the spectra for longitudinal, transverse and vertical components have been computed and subsequently the two HVSR curves (longitudinal and transverse spectrum over vertical one) in order to estimate the main vibrational frequencies in the two horizontal components. Finally, the average HVSR spectrum was obtained, providing also the relative ±2σ confidence interval. Through this analysis procedure, the fundamental frequencies in the two directions of the buildings (longitudinal and transversal) are defined here as F1_building (lower value) and as F2_building (higher value); these frequencies have been evaluated in the elastic domain, thus we always refer to elastic periods. In this study, we have considered only F1_building.

- F_0_Foundation Soil (Hz): Measurements on free-field were performed with the aim to estimate the main resonance frequency (Hz) of the building foundation soil (F0_Foundation soil). In urban areas "pure free-field" condition does not exist because the wavefield is characterized by the contribution of different sources and it is impossible to separate/eliminate the contribution of the free-field waves due to geological conditions from those of buildings (Ditommaso et al. 2010). However, particular attention was paid to select locations where the influence of buildings, industrial facilities, and traffic on urban soil was reduced as much as possible. Measurements were carried out using two different instruments, Tromino or Reftek datalogger equipped with Lennartz 3D-Lite 1s sensors. The recording time varied between 10 and 30 min. For data analysis, see “F_1 and F_2 building (Hz)” field. For some cases, the resonance frequency has been deduced from HVSR of microzonation studies. For the validation of HVSRs, the SESAME (SESAME 2004; Bonnefoy-Claudet et al. 2006) criterions and suggestions by Parolai and Galiana-Merino (2006) and Albarello et al. (2011) have been applied.

- Geology: The geological classification was inferred from field surveys or the detailed geological maps of microzonation studies at the scale of 1:5000 or 1:10.000, if available. Otherwise the geological map at the scale 1:50.000 was considered.
- Soft soil/rigid soil: This classification was introduced to simplify the geological classification. Soils with Vs > 360 m/s have been considered as rigid soils. This class is mainly composed of outcropping concrete bedrock (limestones, sandstones and breccias of the South-Appennine Units) and clean coarse gravels of the Upper Friulian Plain. Loose sediments (silts, clays, sands, gravels and their mixture) of different origin (alluvial, colluvial, eluvial or anthropic) with Vs < 360 m/s have been considered as soft soil.
- Seismic soil class: This classification refers to the national building code (NTC 2018 § 3.2.2) based on Vs30. The Vs profiles have been measured nearby the studied buildings. If deduced by microzonation studies, they are marked by a star (*).
- Topographic class: The topographic class refers to the national building code classification (NTC 2018 § 3.2.2). 4 classes are recognized: T1, Flat surface, isolated slopes and cliffs with average slope angle $i < 15°$ or elevation difference H<30 m; T2, Slopes with $i > 15°$ and elevation difference H>30 m; T3, Relief with ridge top width much smaller than the base, $15° < i < 30°$ and elevation difference H>30 m; T4, Relief with ridge top width much smaller than the base, i > 30° and elevation difference H > 30 m.

2.1 Exploratory data analysis

The vast majority of the buildings of FRIBAS are built on soft soil (247), only 65 are built on rigid soil (Fig. 2a). This net imbalance is clearly visible also when the construction materials are considered. 43 URM buildings are located on soft and 28 on rigid soils; 200 RC-MRF buildings were built on soft and 37 on rigid soils (Fig. 2a). In addition, 4 RC-URM mixed type buildings were constructed on soft soils. In Italy, sites characterized by real rigid soils, i.e. class A soils with Vs30 greater than 800 m/s (NTC 2018 § 3.2.2), are quite rare. Rigid sites are generally affected by topographic amplification and their site response is often due to the presence of weathered/fractured bedrock (Rovelli et al. 2002; Martino et al. 2006; Pileggi et al. 2011) which causes unexpected amplification (Gallipoli and Mucciarelli 2009). In FRIBAS, the sites classified as rigid soils are those located on outcropped Gravina Calcarenite (coarse-grained carbonate sandstone), Mount Viggiano’s limestone (limestones and carbonate sandstones) and on clean coarse gravels of the Upper Friulian Plain with flat HVSR functions. The soft soils are loose sediments (silts, clays, sands, gravels and their mixture) of different origin (alluvial, colluvial, eluvial or anthropic) with Vs < 360 m/s. The buildings included in FRIBAS range from a minimum of two floors up to fourteen floors (Fig. 2b). As expected, URM buildings are mostly low and mid-rise: most buildings have less than 5 floors, with a prevalence of 2 and 3-story buildings (about 66% of all URM buildings) and only two 6-story buildings. For the RC-MRF class, 4 and

5-story buildings are the most frequent, constituting about 32% and 18%, respectively, of the total RC buildings.

The analysis of the distribution of construction material classes as a function of the age of construction (Fig. 3) shows that (i) the oldest (< 1919) and the most recent construction-age classes (>2008) are the least represented (5% in total); (ii) the most numerous class (about 30%) is that of the 1972–1981 decade; (iii) each of the remaining construction age classes contains about 10% of the buildings. The URM buildings in FRIBAS were built approximately from the early 1900s up to the 70s, while after 1982 almost all buildings were constructed in RC. For 8 buildings it was not possible to assign the construction period more accurately than '<1988'.

For all analyses that are described below, the fundamental period refers to the elastic frequency of the first mode (F1_building). The distribution of the fundamental frequencies (Fig. 3b) is asymmetric (right-tailed). The vibrational periods of most buildings (95%) are below 0.4 s and only for a few buildings they are higher, up to 0.83 s. The lower mean value (median) of the period for URM (0.17 s) compared to RC buildings (0.26 s) reflects the fact that the former are, on average, lower than the latter. Furthermore, the comparison between the coefficients of variation (ratio between standard deviation and mean) of the fundamental vibrational period (0.38 RC vs 0.35 URM) confirms the fact that the sample of RC buildings present in FRIBAS is characterized by a greater typological variability than the URM buildings.

As expected, for both construction materials, the average fundamental vibrational period increases according to the number of floors (Fig. 4). The fundamental period of URM buildings shows an increasing trend up to 4 story buildings; although there are very few URM buildings with more than 4 stories in FRIBAS, the sample of URMs is representative for the building stock of the two regions. The RC-MRF buildings show a stronger increasing trend reaching values greater than 0.4 s for buildings with more than 9 stories. It can also be seen that the T–H relationship seems to grow faster up to 6 stories than it does from 7 stories and up. This suggests that both a linear and a power law might be applicable to describe the T–H relationship.

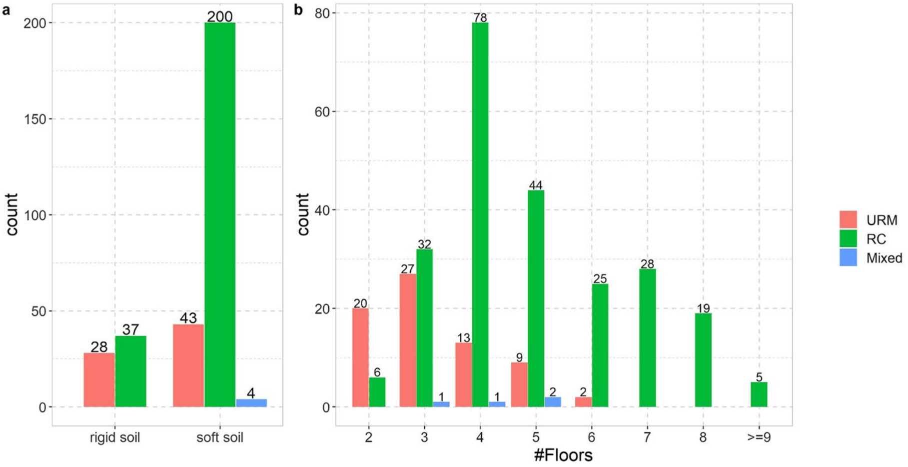

Fig. 2 Distribution of the number of buildings as a function of **a** the construction material and the soil type and **b** the construction material and the number of floors

To evaluate how much the foundation soil characteristics affect the building response, we analyzed the relationship of the fundamental vibrational periods as a function of the number of floors and the foundation soil characteristics. Figure 5 shows that the fundamental periods of buildings built on soft soil are slightly greater than those of buildings located on rigid ones for almost all the number of floors. Further, the observations suggest a slightly higher increasing trend of the main vibrational period on soft soils compared to rigid soils. Despite the small number of buildings constructed on rigid soil for some height classes (> 5 floors), this analysis highlights the necessity to introduce distinguished T–H relationships taking into account the construction material and soil mechanical characteristics.

3 Results: experimental period–height relationships

In codes, standards, and guidelines, relationships for estimating periods are generally based on building height, which is a parameter that can be simply estimated. For this reason, it was decided to focus on the period–height relationship. Moreover, in this study, it is evaluated how adequate the linear and power laws were to describe our dataset. This choice is also in line with many published papers so that results can be directly compared. Experimental relationships between fundamental periods T, and building heights H have been obtained through a regression analysis by comparing two different models (linear with zero intercept and power-law) defined as follows:

$$T = aH \tag{1}$$

$$T = aH^b \tag{2}$$

To choose the most suitable model, we first analyzed residuals to check for the presence of any trend not captured by the model, and to estimate the accuracy of the fitted model by

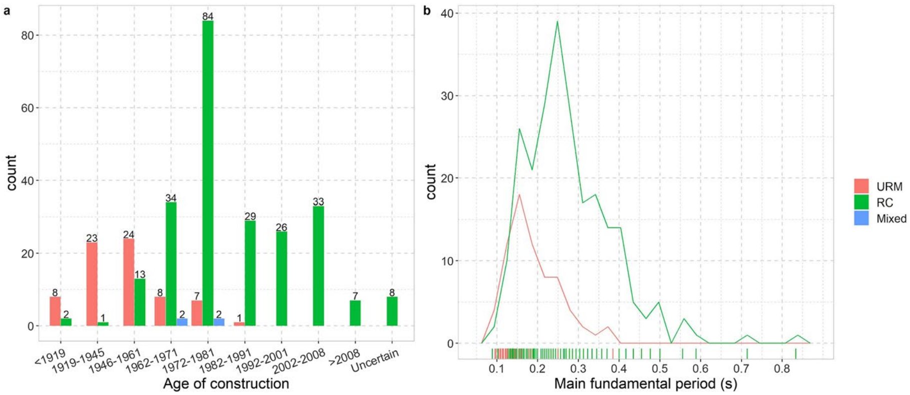

Fig. 3 **a** Distribution of the number of buildings for different construction ages. Some age-of-construction classes having very few buildings have been merged whenever possible: the classes "1972–1975" and "1976–1981" have been joined in the class "1972–1981"; the classes "1992–1996" and "1997–2001" have been joined in the class "1992–2001"; the class 'Uncertain' contains the buildings belonging to the '<1988' class. **b** Empirical distributions of the main fundamental periods for URM and RC buildings

using two indicators, the root-mean-squared error (RMSE), and the mean absolute error (MAE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(T_m - T_f\right)^2}{n - m}} \tag{3}$$

$$MAE = \frac{\sum_{i=1}^{n} \left|T_m - T_f\right|}{n} \tag{4}$$

where T_m and T_f are the measured and fitted fundamental periods, respectively, n is the sample size and m represents the number of estimated parameters (one for the linear model and two for the power model).

The 4 RC-URM mixed type buildings were excluded from the analysis. We show here the T–H relationships for four different cases: case A) the entire dataset is analyzed without any distinction of construction material or soil types (308 buildings); case B) the dataset is split according to construction materials, i.e. URM and RC-MRF (71 and 237 buildings, respectively); case C) the dataset is split according to soil types, i.e. soft and rigid soils (243 and 65 buildings, respectively); case D) the dataset is split according to both construction material and soil type, i.e. URM buildings on soft soils (#43), URM buildings on rigid soils (#28), RC-MRF buildings on soft soils (#200) and RC-MRF buildings on rigid soils (#37).

Case A The T–H relationship has been estimated for all FRIBAS buildings (#308). The residual analysis (Fig. 6b, c) and the performance indices of the models, evaluated through RMSE and MAE (Table 2), suggests that the more complex non-linear model does not improve the description of the T–H relationship. This is also confirmed by the graphical analysis of the residuals where the residuals of the linear and power-law models exhibit very similar patterns when plotted against heights (Fig. 6b) and very similar univariate

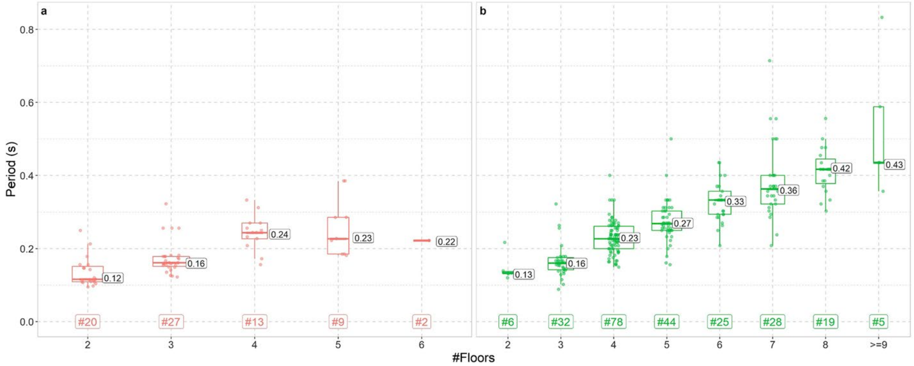

Fig. 4 Empirical distribution of the first vibrational periods of buildings estimated through HVSR as a function of the number of floors and construction material **a** URM, **b** RC-MRF. Boxplots report the first and third quartiles (lower and upper hinges) and the second quartile (the median, whose numerical value is reported in black). Whiskers extend 1.5 times the interquartile distance (3rd—1st quartile). Boxplot width is proportional to the square-root of the number of measurements for each group (reported below in white). Dots represent period values of single buildings. A small amount of color transparency and random variation to the location of each dot has been added to improve visualization

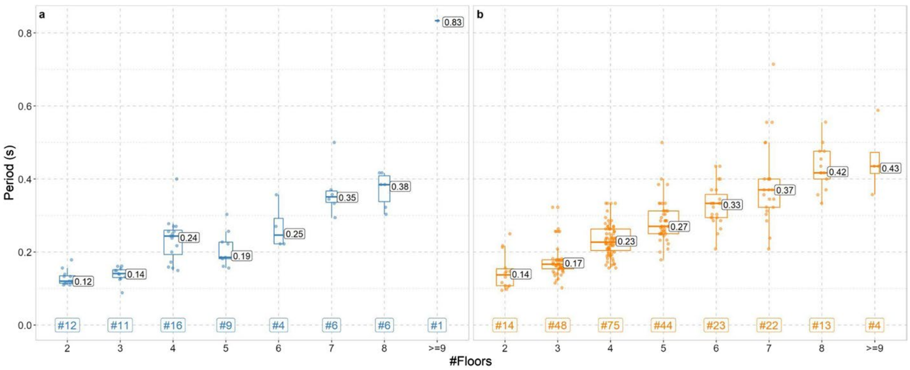

Fig. 5 Empirical distributions of the HVSR first vibrational period of buildings as a function of the number of floors and the soil type **a** rigid soil, and **b** soft soil. Boxplots and dots as in Figure 4. Please note that 4 buildings belonging to the 'mixed class', which are located on soft soils, have been excluded from this analysis

distributions (Fig. 6c). Since this is valid for all four cases (see Table 2), we assume hereinafter that the simpler linear model is a sufficiently accurate approximation of the T–H relationship for the FRIBAS datasets. We note, however, that for the six buildings higher than ~ 30 m the linear model gives a systematic overestimation of T with slightly higher residuals compared to the power-law model.

Fig. 7 shows the comparison between the linear T–H relationship obtained for all FRIBAS dataset ($T=0.0161*H$, solid violet line), with those from other authors obtained performing AV recordings (colored lines) and the EC8 relationships (CEN 2004) for RC-MRF and URM buildings (black/gray line). Although the ambient noise measurements have been acquired with different instruments on buildings constructed after different seismic codes, with different age of construction, presence and position of infilled panels and site conditions, the comparison shows a very good agreement between all experimental T–H relationships, whereas the EC8 relationships return much longer theoretical periods for both RC-MRF and URM buildings. The EC8 relationship differs even more than 120% from the experimental ones for RC-MRF and about 50% for URM buildings.

Case B Studying URM and RC-MRF buildings separately does not have a significant influence on the T–H (linear and power-law) relationships as can be seen by comparing the estimated parameters and their confidence intervals (Table 2). The slope of the linear model is 0.0161 *s/m* for all buildings (case A), 0.0158 *s/m* for URM and 0.0161 *s/m* for RC-MRF buildings (case B). Comparing the confidence intervals (95% probability) of the estimated T–H slopes, we see that that for RC (0.0157–0.0165 s/m) is completely contained in that for URM (0.0150–0.0165 s/m). From this we see that, with the data available in the database, the estimated empirical models for RC and URM do not show significant statistical differences. This could be due to several factors, such as the difference in size of the RC and URM datasets, the significant differences in building heights present in the two classes of building materials, and to the ranges of building heights considered. A deeper understanding of these interdependencies, however, would require further in-depth investigations that are beyond the scope of this paper and will be carried out in the future.

Nonetheless, compared to the T–H relationship estimated for all buildings (case A), there is a significant decrease of the average error in the estimation of URM periods,

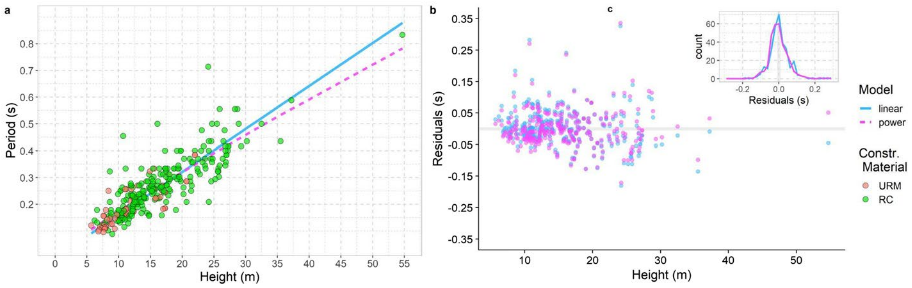

Fig. 6 **a** Experimental T–H relationship for FRIBAS buildings for the linear (blue solid line) and power-law models (red dashed lines); **b** scatterplot of residuals ($T_m - T_f$) vs building heights for linear and power-law models; **c** empirical distributions with frequency polygons of residuals ($T_m - T_f$) for linear and power-law models

RMSE: 0.039 versus 0.057 *s* and MAE: 0.028 *vs* 0.039 *s*. This error decrease is linked to the fact that URM points are closer to the modeled relationship compared to RC buildings (Fig. 6a, 8). The fact that the T–H data for RC-MRF buildings are, in general, much more scattered than the URM ones, reflects the greater variability of the construction characteristics of RC-MRF buildings compared to URM ones represented in FRIBAS. There are in particular three points very distant from the model, which have residuals > 0.2 s. These RC-MRF buildings differ significantly in their construction types from the others. By comparing our experimental relationships for each class of construction material with the ones suggested by the EC8 code, we see again that the latter returns much longer periods for given building heights.

Case C As regards the influence of soil characteristics on T–H relationships, the analysis shows significant differences between buildings built on soft compared to those built on rigid soils (Fig. 9, Table 2). In fact, while the slope of the linear T–H relationship for rigid soils is 0.0146 *s/m*, that for soft soils is equal to 0.0165 *s/m*. The comparison between the respective confidence intervals (at 95 %), 0.014–0.015 *s/m* versus 0.016–0.017 *s/m*, highlights the statistically significant difference of the T–H relationships for the two soil types. The higher slope of the T–H relationship for soft compared to rigid soils implies longer periods for a given building height. Moreover, buildings on rigid soils exhibit T–H points closer to the average estimated trend, which is reflected in the lower average estimation errors (RMSE: 0.04 s vs. ~ 0.06 s, MAE: 0.03 s vs. ~ 0.04 s).

Case D The analysis of buildings of different construction materials and on different foundation soil types shows that (Fig. 10):

1. For a given soil type, there are no significant differences in the T–H relationship between buildings built with the two different construction materials, e.g. on soft soils, the T–H slope for URM buildings is 0.0170 *s/m* (95% confidence interval: 0.016-0.018 *s/m*) and for RC-MRF buildings the slope value is 0.0164 *s/m* (0.016-0.017 *s/m).*
2. For buildings of a given construction material, the slope of T–H relationships estimated for buildings built on soft soil is significantly different from that for buildings on rigid soils, e.g. for URM buildings, the T–H slope for rigid soils is comprised in the interval 0.013–0.015 *s/m*, completely disjointed from the one on rigid soils (0.016–0.018 *s/m*).
3. The T–H relationships lead to significantly longer periods for buildings built on soft soils compared to those on rigid soils for both construction materials (Fig. 10, Table 2).

Table 2 Comparison of experimental T–H relationships (linear and power-law models)

Split by	Data	Model	Parameters	Conf. int. (95%)	RMSE (s)	MAE (s)	#
	All	Linear	a = 0.0161	0.0157–0.0164	0.057	0.039	308
		Power	a = 0.0224	0.0188–0.0267	0.056	0.039	
			b = 0.888	0.828–0.947			
Construction material	URM	Linear	a = 0.0158	0.0151–0.0165	0.039	0.028	71
		Power	a = 0.0212	0.0144–0.0310	0.038	0.028	
			b = 0.887	0.741–1.03			
	RC	Linear	a = 0.0161	0.0157–0.0165	0.061	0.043	237
		Power	a = 0.0243	0.0196–0.0301	0.060	0.042	
			b = 0.864	0.792–0.935			
Soil type	Soft	Linear	a = 0.0165	0.0160–0.0169	0.059	0.04	243
		Power	a = 0.0252	0.0202–0.0314	0.057	0.04	
			b = 0.855	0.779–0.931			
	Rigid	Linear	a = 0.0146	0.0141–0.0152	0.04	0.028	65
		Power	a = 0.0146	0.0113–0.0187	0.04	0.028	
			b = 1	0.922–1.08			
Construction material and soil type	URM-soft	Linear	a = 0.0170	0.016–0.018	0.038	0.029	43
		Power	a = 0.0181	0.0117–0.0278	0.038	0.029	
			b = 0.976	0.811–1.14			
	URM-rigid	Linear	a = 0.0141	0.013–0.015	0.029	0.018	28
		Power	a = 0.0284	0.0172–0.0454	0.025	0.021	
			b = 0.734	0.553–0.925			
	RC-soft	Linear	a = 0.0164	0.016–0.017	0.062	0.043	200
		Power	a = 0.0269	0.0206–0.0350	0.061	0.042	
			b = 0.834	0.744–0.924			
	RC-rigid	Linear	a = 0.0148	0.014–0.016	0.047	0.034	37
		Power	a = 0.0149	0.0103–0.0214	0.047	0.034	
			b = 0.998	0.886–1.11			

From top to bottom: all FRIBAS buildings, buildings split by construction material, buildings split by construction material and soil type;

RMSE root-mean-squared error, *MAE* mean absolute error. Both having units of seconds being estimated on the residuals = measured-fitted;

All regression parameters are significant with p-value < 0.001; Conf. int (95%) is the confidence interval of the estimated parameters with 95% of probability;

#Sample size

Moreover, for buildings of both construction materials, the precision of the estimated periods is higher on rigid soils, e.g. for linear models RMSE: 0.029 versus 0.038 for URM, and 0.047 versus 0.062 for RC buildings. On average, we observe a difference of about 20% of the vibrational period T for URM buildings on rigid with respect to those on soft soils and about 11% for RC-MRF buildings built on different soil types. In both cases, the differences are greater than 100% with respect to the EC8 formulas. These results highlight the importance of improving the code formulas by taking into account the main factors that can influence the building seismic response, including the effect of soil-structure interaction.

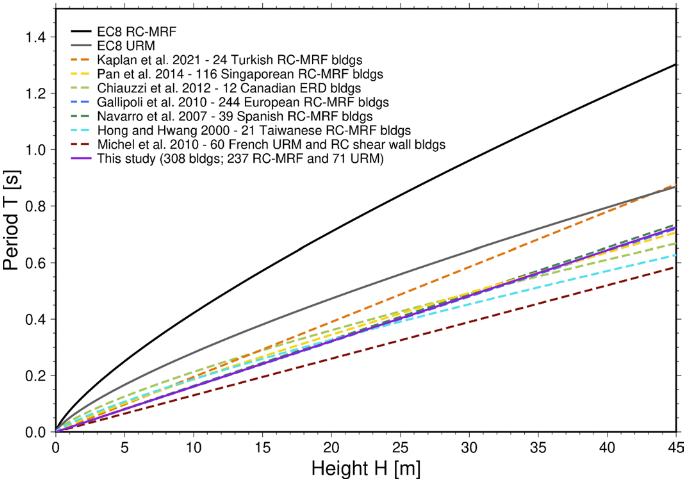

Fig. 7 Comparison between our T–H relationship (solid violet line) with those from other authors (colored dashed lines) and the European seismic design code EC8 (CEN 2004) for RC-MRF (solid black line) and URM buildings (solid gray line).

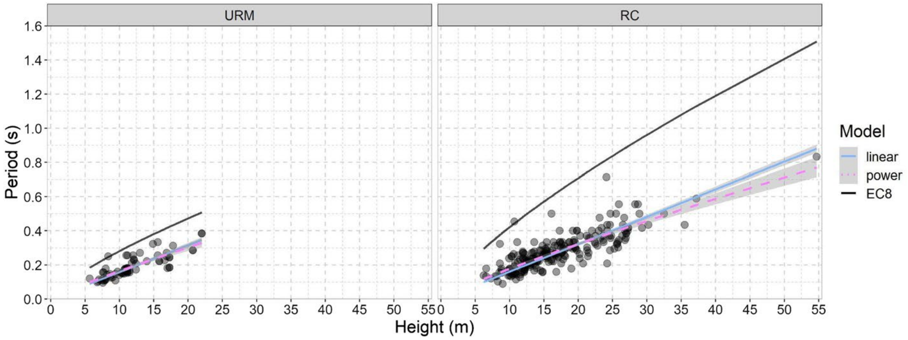

Fig. 8 Experimental T–H relationships for FRIBAS buildings (black dots with transparency) obtained with linear (blue solid line) and power-law models (red dashed line) fitted separately for URM (left) and RC buildings (right); the grey area around regression models represents their 95% confidence interval. The solid black lines represent the T–H relationships from the European seismic design code EC8. The transparency is set to the color of dots to visualize the overlapping of measurements, i.e. darker color represents a larger overlapping

In Fig. 11, we show the comparison of the building-soil specific T–H relationships (RC/URM buildings on soft/rigid soils) and the one considering all building types on all soil types. For a better comparison of the different T–H relationships, they are plotted up to 45 m building height. The T–H relationship for RC buildings on soft soil (green solid line) is very similar to the one for all buildings (violet solid line). This is mainly due to the fact that most of the buildings (around 64%) of FRIBAS are RC buildings constructed on soft soils, especially the tallest buildings. The T–H relationships for RC buildings on soft (green solid line) and rigid soils (green dashed line) do not differ as much as the ones for URM buildings on soft (red solid line) and rigid soils (red dashed

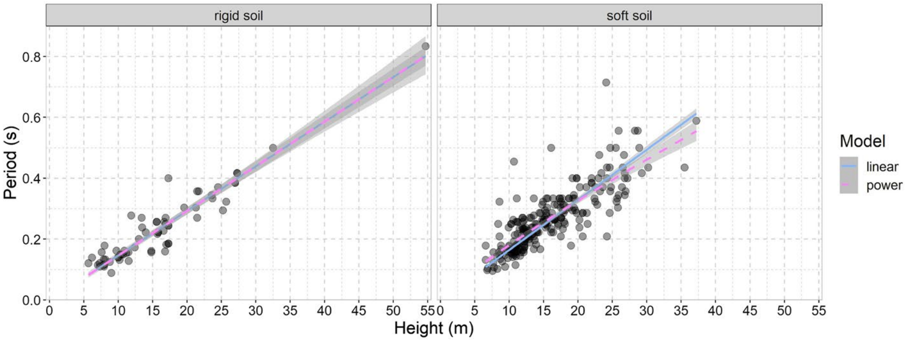

Fig. 9 Experimental T–H relationships for FRIBAS buildings (black dots with transparency) obtained with linear (blue solid line) and power law models (red dashed line) fitted separately for buildings built on (left) rigid and (right) soft soils; the grey area around regression models represents their 95% confidence interval. The transparency is set to the color of dots to visualize the overlapping of measurements, i.e. darker color represents a larger overlapping

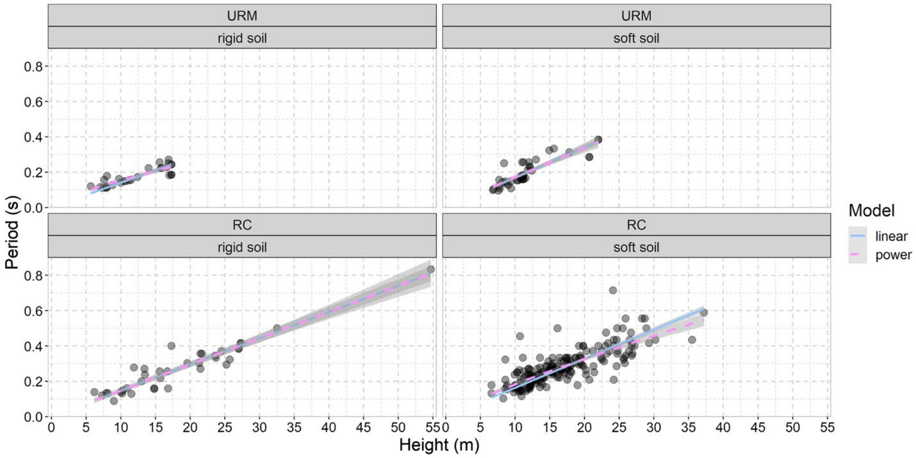

Fig. 10 Experimental T–H relationships for FRIBAS buildings (black dots with transparency) obtained with linear (solid blue line) and power-law models (red dashed line) for URM buildings on rigid soil (upper left), URM buildings on soft soil (upper right), RC-MRF buildings on rigid soil (lower left) and RC-MRF buildings on soft soil (lower right). The grey area around regression models represents their 95% confidence interval. The transparency is set to the color of dots to visualize the overlapping of measurements, i.e. darker color represents a larger overlapping

line). Buildings built on soft soils (both URM, red solid line and RC buildings, green solid line) have longer periods compared to buildings built on rigid soils (both URM, red dashed line and RC buildings, green dashed line) as was previously discussed. It is finally noted that on rigid soils the slope of the T–H linear relation for RC-MRF buildings is larger than the one of URM buildings. On the other hand, on soft soils the T–H linear relation for URM buildings has a slightly higher slope than for MRF-RC buildings. In our opinion these results have to do with the very different building-height distributions for URM and RC in the two classes of soil. On rigid soils, the number

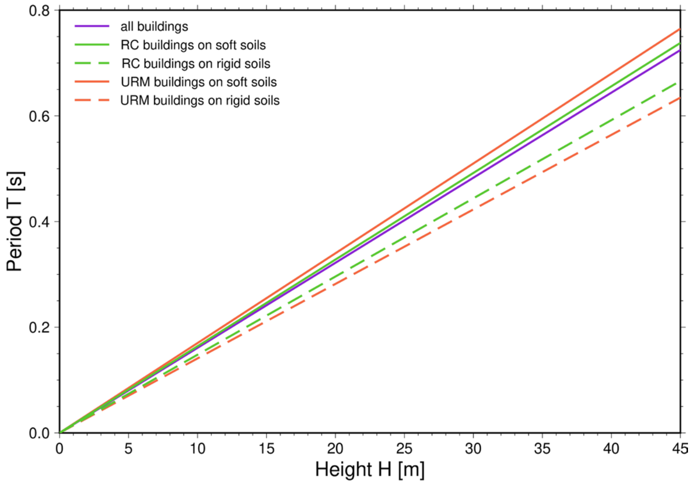

Fig. 11 Comparison of experimental T–H relationships obtained from FRIBAS considering buildings of both construction materials built on all soil types (violet solid line), RC buildings on soft soils (green solid line), RC buildings on rigid soils (green dashed line), URM buildings on soft soils (red solid line) and URM buildings on rigid soils (red dashed line)

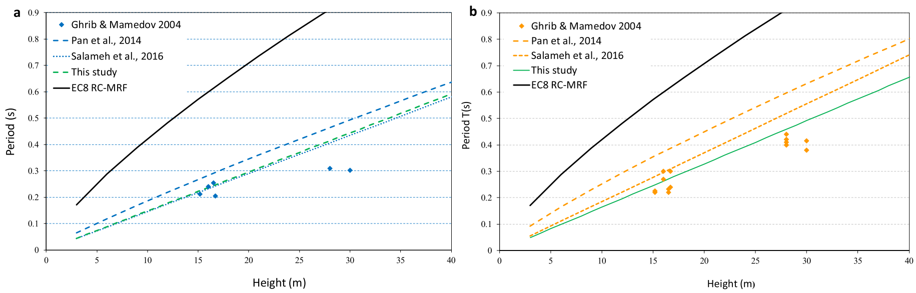

Fig. 12 Comparison of our T–H relationships for RC-MRF buildings on **a** rigid soil (green dashed line) and **b** soft soils (green solid line) with those of other studies and the European seismic design code (EC8)

of buildings for each class of height (expressed as number of floors) is quite balanced between URM and RC with only 13 RC buildings having more than 6 floors. The situation is markedly different in soft terrain where, with the exception of 2-story buildings, there are many more RC buildings in each height class (up to 5 stories). Most importantly, the presence of as many as 68 RC buildings with more than 5 stories contributes to the decrease of the slope of the linear T–H relation.

We compared our results for RC-MRF buildings with those of the few available studies on RC-MRF buildings on rigid (Fig. 12a) and soft soils (Fig. 12b). As already observed for the entire database (Fig. 6a), the experimental T–H relationships give significantly lower period values than those of the EC8 (the differences reach 150% for rigid and are over 100% for soft soils). Our T–H relationships for RC-MRF buildings on both rigid and soft soils are in good agreement with the results of Ghrib and Mamedov (2004), Pan et al. (2014) and Salameh et al. (2016). Nevertheless, our T values are lower (around 35% and

25%) than those of Pan et al. (2014) and Salameh et al. (2016), respectively, for soft soils and lower than those of Pan et al. (2014) for rigid soils (around 20%), but almost identical to those of Salameh et al. (2016) for rigid soils. The differences may on the one hand be due to different construction types in different countries (our study: Italy, Pan et al. 2014: Singapore, Salameh et al. 2016: Lebanon), and on the other due to differences in soil conditions and the definition of soft and rigid soils.

4 Discussion and Conclusions

In this study, we present FRIBAS, an open access database (https://doi.org/10.5281/zenodo.6505442) made up of 312 buildings (71 URM, 237 RC-MRF and 4 mixed RC-URM), each characterized by 37 parameters (if applicable). To our knowledge, it is the first database collecting many characteristics (including the experimental fundamental periods of buildings and their foundation soils) for a large number of RC and URM buildings. At present there are few databases that provide the fundamental vibrational periods estimated through experimental measurements on both buildings and soils. Significant examples are those of Gallipoli et al. (2010) on 244 European RC buildings and the "Center for Engineering Strong Motion Data of the USGS." However, the former database is not public and that of the USGS provides only recordings but not the estimated fundamental periods. The FRIBAS attributes were defined to synthesize the main building characteristics in relation with the fundamental period. However, it was not possible to inspect all buildings internally, thus information on some characteristics may not be available for all buildings. In particular, the masonry type (regular or irregular, type of bricks/blocks) was retrieved only for a few buildings during inspection or by asking directly to residents. These aspects are difficult to gather during inspections, but can be crucial to assess the expected behavior of masonry buildings. In addition, future work is needed in order to investigate the correlation between masonry type and age, which might vary depending on the context of the study areas. Additional parameters could be also included in future versions of the database (e.g. mortar type and quality, presence of vaults, thrusting systems in roofs), especially if they have proven influence on buildings dynamic response.

FRIBAS is a starting point for analyses aimed at a better characterization of the soil-building interaction effect to improve the building design, the performance of existing buildings, and subsequently to estimate the expected damage caused by earthquakes. Having information on the structural characteristics is crucial to investigate the influence of each parameter on the building dynamic response (i.e. the fundamental frequency of the building-soil system) and subsequent damage caused by earthquakes (Crowley et al. 2020). This is particularly of interest for Italy, where historical URM buildings have suffered substantial damage in the last decades (e.g. Valensise et al. 2017; Sextos et al. 2018; Sorrentino et al. 2019; Penna et al. 2022). So far, most studies were devoted to assessing the dynamic behavior of individual buildings, without extending the results to assessing the behavior of buildings of a given construction material. A few studies focused on evaluating the dynamic behavior of a selected building typology (e.g. historical URM, low- or mid-rise) and the interaction with the foundation soil (Piro et al. 2020). Recent works showed that the correct estimation of fundamental vibrational periods for different building typologies can support near real-time seismic damage assessment (e.g. Scaini et al. 2021; Petrovic et al. 2022).

Nowadays, the fundamental vibrational period is derived from general relationships (e.g. Eurocode 8 2003; CEN 2004) with well-known limits (e.g. Hatzigeorgiou and Kanapitsas 2013; Michel et al. 2010a). As already demonstrated by several authors (e.g. Gallipoli et al. 2010) and confirmed in this work (Fig. 7), fundamental periods of RC-MRF buildings derived by numerical relationships (used in most building codes, including EC8) overestimate those based on experimental measurements (more than 120%). This is due to several factors which are often not accounted for in numerical modeling, including the cracking of the reinforced concrete components, the contribution of non-structural elements (e.g. infill walls, Masi and Vona 2010) and the soil-structure interaction effects (Kose 2009). For URM buildings, the mismatch is probably mainly related to the fact that they are often attached to other buildings, resulting in a change of the global stiffness. Further, there is a large variation in the material quality and connection of the elements which is not considered in the building codes. Moreover, the Eurocode 8 relationship was derived from the Goel and Chopra relationship, without considering in detail the specific characteristics of European buildings. Goel and Chopra (1997) advised in their study that "since these recommendations are developed based on data from buildings in California, they should be applied with discretion to buildings in less seismic regions of the US or other parts of the world where building design practice is significantly different than in California."

Here, we present the first results obtained from the correlation between some parameters of the FRIBAS dataset. It is widely recognized that the structural response of a building on soft soil may differ from the response of an identical one on rigid soil for the same excitation (Luco et al. 1988). Thus, we have estimated T–H relationships for buildings of different construction materials on different soil conditions. Our results highlight that, for a given building height, the main elastic vibrational period differs depending on the foundation soil type (simplified into two broad categories, soft and rigid). The interaction effects between buildings (both RC-MRF and URM) with their foundation soil influence the vibrational periods of the system: the periods of URM buildings located on soft soil increase by about 20% with respect to those located on rigid soil; for the RC-MRF buildings the soil characteristics increase the periods of about 11%. In this study, we evaluated the effect of soil-structure interaction in the linear elastic field; it is known that this effect can increase as the ground motion increases. In fact, Luco et al. (1988) estimated that the soil-structure interaction effect for a specific building can modify the ground motion by more than 30%.

These results motivate the need of going beyond a 'one-fits-all' numerical T–H relationship for generic building typologies, towards specific T–H relationships that account for both soil and building typologies. Considering the importance of soil-structure interaction effects on building dynamic response, these effects should be taken into account in the seismic code which returns much longer periods than those obtained experimentally.

In conclusion, we underline that:

1. FRIBAS is the first database of 312 buildings (327 RC and 71 URM buildings), characterized by a great number of parameters (37 attributes), including their fundamental experimental vibrational period and that of the relative foundation soil;
2. The FRIBAS open access database (https://doi.org/10.5281/zenodo.6505442) supports the analysis of how different building and soil parameters influence the soil-building dynamic response;
3. Specific T–H relationships for different typologies on different soil conditions are presented:
    a. $T = 0.0170H$ for URM buildings on soft soil;

b. T = 0.0141H for URM buildings on rigid soil;
c. T = 0.0164H for RC-MRF buildings on soft soil;
d. T = 0.0148H for RC-MRF buildings on rigid soil;

FRIBAS is a completely public database, which hopeful will be integrated with other data collected on other buildings around the world and thus, represents a great opportunity for the entire scientific community to investigate some issues related to the dynamic behavior of buildings and consequently update seismic codes.

Certainly, it will be essential in the future to further investigate some aspects, such as:

(1) Evaluate the correlation of the fundamental elastic period not only with height but also with other appropriately weighted parameters. In this regard, it will certainly be very interesting to compare these results with the numerical ones obtained by Verderame et al. (2010);
(2) Evaluate the T–H relationship in more detail, taking into account any effects related to the sample size of URM and RC buildings, the height ranges considered, and the distributions of building heights for each class of building materials.

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Author contributions MRG: Conceptualization, Data curation, Data analysis, Writing—Original draft preparation; BP: Data curation; Data analysis, Visualization, Writing—Original draft preparation; GC: Data curation; Data analysis, Visualization, Writing—Original draft preparation; NT: Data curation; CS: Data curation; Data analysis, Writing—Original draft preparation; CB: Data curation; Data analysis, Writing—Original draft preparation; MV: Data analysis, editing; SP: Supervision. All authors discussed the results and contributed to the final manuscript.

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Data availability The data that support the findings of this study are available at an open access database: https://doi.org/10.5281/zenodo.6505442.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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