Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
©2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

REDUCTION OF SEISMIC RISK OF ROMAN AND HINDU TEMPLES

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ABSTRACT

In the last decades, the devastating effects of seismic events in India have been raising the awareness about the high exposure of the population, especially in crowded urban areas. The daily gathering of believers in temples has been indeed identified as one of the most risky conditions, especially because of the high vulnerability of these historical temple structures. This paper presents the first outcomes of a joint project between EUCENTRE (Pavia, Italy) and IIT Madras (Chennai, India), aiming to reduce the seismic risk of selected architectural heritage structures both in Italy and India, by means of post-tensioning. Two sites were selected and recognized as cultural heritage both for their architectural features and their historical value, as representative of the respective structural typologies. The results of this study can be hence directly applicable to many other similar structures. The paper describes the characteristics of the two temples, in terms of geometry and material, identified based on literature data and results of in-situ investigations on both structural and soil properties. The results of a probabilistic seismic hazard analysis, which was combined with fully stochastic site response analyses at the Indian site, in order to define the expected seismic input, are also presented. The results of this preliminary study are necessary for the design of representative prototype specimens that will be tested on shaking table within this joint project. The numerical model of the temples will be validated against experimental results and will allow future studies on similar structures and improved retrofitting techniques.

Keywords: *Temples, post-tensioning, Multi-body dynamics, Shake-table tests, Strengthening*

1. INTRODUCTION

Monumental structures, as well as historical city areas, are essential and fundamental assets of the cultural heritage. In particular, in countries like Italy and India, the existence and maintenance of such precious heritage not only are endangered by the usual aging but they are also jeopardized by the seismic hazard of these areas. Potentially destructive events may cause losses in human lives, in regional economies and also in the culture and historical heritage to be handed down to the future generations. Recent events, such as Bhuj (2001) and Kashmir (2005) in the India region, or Umbria-Marche (1997) and L'Aquila (2009) in the Italian peninsula raised again the delicate issue of the

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seismic vulnerability of their huge architectural heritage. Therefore, in these particular areas, especially for the structures which are the objective of this study, the seismic risk is not mainly dominated by the hazard, although still significant, but by the convolution of a relevant vulnerability and a high exposure, enhanced by the combination of crowding of sites and, again, value of the architectural heritage.

The mitigation of this seismic risk is the scope of a multidisciplinary project that integrates aspects of seismic hazard, vulnerability and exposure, aimed at predicting the damage in selected monumental structures. Seismic consolidation and strengthening interventions using new materials and techniques would then be defined. The scientific research titled "Reduction of Seismic Risk of Architectural Heritage in Italy and India" was submitted to Regione Lombardia and approved in June 2010. This research project is being conducted as a collaboration between the Indian Institute of Technology Madras (IIT Madras) in Chennai, and the European Centre for Training and Research in Earthquake Engineering (EUCENTRE Foundation) of Pavia (Italy) and it is the ideal continuation of a previous joint project between researchers from the two institutions [1, 2].

The study is focused on the evaluation of the seismic vulnerability and the identification of appropriate techniques for reducing the seismic risk of a typology of monumental structure, representative of diffused architectonic and construction typology, which is of significant heritage value for the two countries. Two case study sites have been selected, one in each country, such that their seismic response is comparable and, to some extent, also the two selected structures may share a similar response behavior under lateral loads.

In order to improve the level of confidence in the outcomes of the research project, the numerical models developed for the selected structures will be verified against an experimental campaign of shake table dynamic tests, which will be performed at EUCENTRE. The specimens to be tested will be representative of both the real structures and the proposed strengthening solution studied for the specific archaeological sites.

The general results of this study, as well as the refined assessment and strengthening methodology, can be exported and applied to other similar sites or structures all over the two countries. A similar approach could be eventually used also in similar architectural heritage structures elsewhere.

2. AIM AND STRUCTURE OF THE RESEARCH PROJECT

The research project presented here is meant to develop a complete methodology for evaluating the vulnerability of selected monumental structures and defining a risk mitigation retrofitting strategy, applicable especially in specific country as India and Italy. The methodology, as well as the research program, will be characterized by subsequent phases spanning from the assessment of hazard and vulnerability to the design of the strengthening solutions.

The first phase consisted in the definition of the seismic input on rock for different levels of ground motion intensity at the selected sites. As presented in the following sections, the definition of local seismicity, through site specific studies and geophysical investigations, has been used for the definition of different loading scenarios for the structures. After evaluating the structural capacity of the monuments under analysis, it will be possible to understand the expected level of damage for the different ground motions associated to the different levels of seismic intensity. These vulnerability models will be the basis of the final part of the study, consisting in the proposal of site-specific strengthening and retrofitting interventions, eventually with innovative technologies that will integrate the traditional systems for seismic damage prevention.

A series of non-destructive tests have been performed on the two selected structures to investigate the state and constitution of materials and building techniques, as well as the preservation of the structures and their dynamic properties. This information is relevant not only for assessing the structural vulnerability but also for finding retrofitting solutions able to enhance the seismic resistance of the monuments by improving their response, without altering the nature of the structural systems or jeopardizing the heritage preserved in the monument. All the knowledge collected about the sites, the structures and the possible strengthening techniques will be of fundamental importance to design and carry out a series of dynamic shake table tests. These tests would help defining the peak ground accelerations that could initiate damage or collapse mechanisms. The results of the shake table tests would allow one to compare, verify and improve the numerical models of the selected sub-systems. They would also assess the effectiveness of the seismic strengthening interventions.

The project has been therefore articulated in the following phases:

I. Identification of the two archaeological sites in Italy and India.
II. Definition of the seismic input within a probabilistic framework for the two sites.
III. Execution of geophysical and geotechnical investigation campaigns at the two sites.
IV. Execution of ground response analyses to quantify possible amplification effects at the two sites.
V. Identification of architectonic sub-systems vulnerable to seismic loads followed by analytical and numerical studies for evaluating the seismic vulnerability of these sub-systems.
VI. Identification, design and implementation of seismic strengthening techniques for the vulnerable sub-systems.
VII. Experimental testing campaign using dynamic shake table tests.

3. SELECTION OF THE CASE STUDY SITES

According to the conclusions of a previous study at the Kanchipuran temple [2, 3], which was part of a previous research bi-lateral project (Progetto MAE [1]), among the many architectural heritage structures, the typology of the Hindu Temple was considered as one of the most exposed to the seismic risk in the southern Indian area. These temples are usually characterized by three main structural and architectural systems: the entrances to the temple, often built as multi-storey pyramidal towers (*gopuram*), the shrines were the gods representations are kept and worshipped, and pillared structures (*mandapam*) were all other rituals are performed. The latest resulted to be the most vulnerable structures of the whole temple [3], mainly due to their complete lack of lateral resisting systems and the slender configuration that easily determines a complete loss of equilibrium of the colonnade.
The vulnerability, the materials used and the fragility of the colonnades as resisting systems are typical characteristics also of the Greek-Roman temples erected in Italy. This direct comparison was a key parameter for the selection of the two sites for the current project, which are described in the following sections. At the end, one particular mandapam of the main Hindu temple in Chennai was selected for the Indian case, whilst, for the Italian case study, the remains of the Marte Ultore temple were identified as a prototype of the architectural heritage to be preserved against main seismic events.

3.1. The Parthasarathy temple – INDIA

The Parthasarathy Temple is an 8th century Hindu Vaishnavite temple dedicated to Lord Krishna in four of its incarnations. Mentioned by the Azhwars in their sacred hymns in Tamil (the language of the actual Tamil Nadu), the Parthasarathy temple located in Tiruvallikeni or Triplicane (Chennai, India), as the Britishers called it, happens to be the oldest temple in the city. It is one among the 108 divya desams or holy abodes of Lord Vishnu. The story of the temple is directly linked with the existence of the Tiruvallikeni village, seen in records dating back to the Pallava period (8th century, during the reign of king Narasimhavarman) and earlier. The village's name itself is derived from the Lily pond in front of the temple, where it is said that Goddess Vedavalli, consort of Lord Ranganatha, one of the five main deities, was born in a Lily flower. This tank is said to consist of five sacred wells, and its waters are holier than Ganges. Thus the temple forms the core of the area's history, attracting pilgrims from all over the state and the country.
Apart from the religious prestige related to the holy site, the temple holds some of the finest architectural features of the Pallava style. The gopuram (towers) and mandapam (pillars) are decorated with elaborate carvings, a standard feature of South Indian temple architecture and therefore listed in the monuments protected by the Archaeological Survey of India (ASI). The Mahamandapam and the Thiruvoimozhi Prabanda Mandapam show clear architecture of Pre Pallava period; the perceptible differences seen in the structures in the main shrine and the mandapam in front indicate that the mandapam is a later annexure to the original shrine and the Dwajatohana Mandapam of Sri Parthasarathy swamy is even older. Many are also the figures and sculptures typical of the Vijayanagara Art.
The exposure of this cultural site is even increased by the many events capable of gathering together thousands of pilgrims within the temple perimeter. 12 main festivals are celebrated here during the year, most of them lasting for days. Furthermore, at least 11 rituals (pooja) are daily performed in the temple, creating an almost constant massive presence of people.

3.1.1. Selected 4-pillars mandapam

The selected mandapam has been erected over a granite podium with 4 pillars in a square geometry of 3.5 m per side. Each column is a monolithic block of local granite (as confirmed by in-situ sonic tomography tests) with a significant slenderness, having a square cross section of only 0.3 m for 3.1 m height. One of the main characteristics is the heavy roofing system sitting on these four pillars (almost 70% of the whole mass is concentrated at the top). The whole structure has only dry flat connections between each element, relying only on the self-weight to accommodate any possible lateral load. Although the in-situ sonic tests performed have shown very well preserved materials, the peculiar building system (Fig. 1) makes the structure quite sensitive to any lateral displacement.

Fig. 1 Schematic representation of the 4-pillars mandapam, with clear distinction between the resisting and the roofing systems (left) and front view of the real structure at Triplicane, Chennai, India (right)

3.2. The Marte Ultore temple – ITALY

The archaeological site known as *Foro di Augusto* is part of a wider dense historical area called *Fori Imperiali* in the heart of the modern city of Rome. The forum was the commercial, religious and political center of the roman city and the one built under the emperor Augustus was the second erected in Rome after that ordered by Caesar, located next to it. The forum was 118m wide and 125 m long and it was dominated by the Marte Ultore temple (Fig. 2), unveiled in the 2 B.C. Along the three millennium of history since its construction, many alterations have occurred, leaving a permanent mark on the present ruins of this majestic architectural heritage. The forum itself was rearranged several times until the VI cent. a.C., when the main temple was demolished except for the colonnade.

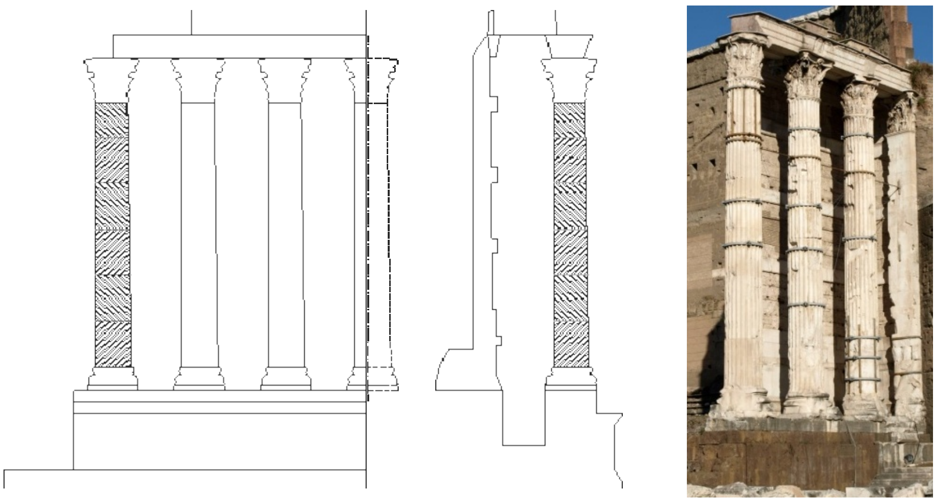


Fig. 2 A sketch (left) and a recent picture (right) of the colonnade of the Marte Ultore temple in Rome

In the IX cent. the San Basilio church was there erected and the columns integrated in the external walls. In the XV cent., an adjacent convent was built and the whole complex was renovated. Some of the finest architects of the history as Baldassarre Peruzzi and Andrea Palladio explicitly referred to these columns in their works. Less than one century later, the area was almost fully covered to leave space for a residential urbanization demanded by the current pope Pio V. The modern archaeological studies were started in the 1825 by Francesco Saponieri and then Rodolfo Lanciani, leading in 1924 to the demolition of the convent and annexed church, followed by the final restoration that modified the columns to their current aspect. The relevance of the monument is not only written in its history but also in the more specific architectural traits, which have been the inspiration for many following temples erected in the Roman Empire, becoming soon a prototype. For these reasons, it was selected as a reference model for this project.

3.2.1. The colonnade

The temple was standing on a 3.5 m height podium, 40 m by 30 m in plan, built with roman concrete and tuff blocks under the external walls, while the colonnade was supported by tuff and travertine marble. This podium, covered by marble pavements and decorations, was supporting the main shrine and 8 Corinthian columns on three sides, while the fourth side was characterized by the huge walls still visible at the end of the forum. The columns were constituted by Carrara marble, used also for the many sculptures that enriched the temple and that nowadays are either lost or preserved in museums (none of them was left on the site).

The remaining three standing columns are linked together by an architrave that enhances the in-plane lateral resistance of the system, despite being poorly connected to the capitals. The out-of-plane capacity of the colonnade is instead left to the single column resistance, which has been weakened by aging and plundering of the lead keys between the blocks. Apart from a recent jacketing of the fractured elements, no other strengthening or retrofitting has been developed on these columns, that are considered among the few columns in Rome to which no anastilosis was applied.

3.3. Comparison of the two selected sites

Although apparently very different, the two selected sites share many common features. Apart from the cultural heritage that makes both monuments more precious than many others, also the expected seismicity is somehow similar. Both areas are considered of moderate seismicity, with a long return period for the considered destructive event (which has not occurred yet since their construction). Both structural sub-assemblies, i.e. the mandapam for the Hindu temple and the colonnade for the Roman one, are very well designed for gravity loads but poorly, if not at all, resisting to lateral loads. The two structures rely on dry-flat connections within the elements, and nothing but friction prevents the sliding at the joint level. Thus both systems dissipate energy by rocking of the elements. Although the good quality of the materials used for these specific monuments, granite and marble respectively, the capacity of the structures is probably insufficient for the expected seismic demand and a more redundant resisting system is recommended. The very likely occurrence of a rocking mechanism and the high compressive strength of the material suggest a common retrofitting technique, consisting in a post-tensioning unbounded (reversible) solution, capable of enhancing the overall capacity and redundancy of the system (by creating a reliable resisting system under lateral loading) and, at the same time, preserving the original response of the monuments and maintaining unaltered the historicity of the structures.

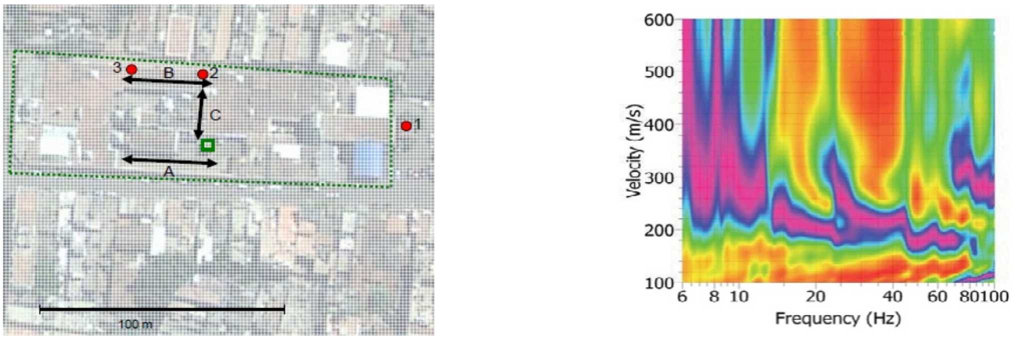
The two monuments still present many peculiarities that make unique their response. The pillars of the mandapam are monolithic elements, while the roman colonnade is constituted by multi-block elements, with a significantly different slenderness and spacing. The colonnade shows a significant variation in the three dimensions, with a week out-of-plane response and a negligible applied axial load, except for the self-weight. On the contrary, the mandapam is almost perfectly symmetric in the two orthogonal directions and it has a heavy roofing system that increases the stability of the structure in case of an overturning mechanism.

4. IN SITU INVESTIGATION CAMPAIGNS

The geotechnical characterization of the sites under investigation was performed taking into account the results of in-situ geophysical tests and geological and geotechnical information from the literature.

A geophysical characterization campaign was performed for the Parthasarathy temple by EUCENTRE, IIT Madras and SolGeo S.r.l. in January 2011, to determine dynamic soil properties via observation of the stress field of transient (active source testing) or steady-state (ambient noise testing) seismic waves. . A field geophysical campaign was also performed by EUCENTRE in the city of Rome at the Marte Ultore temple site in February 2012. The scope of this in-situ work was to determine the shear-wave velocity profile and the fundamental soil period at the location of the temples using rapid and non-invasive methods. The geophysical investigation included Multichannel

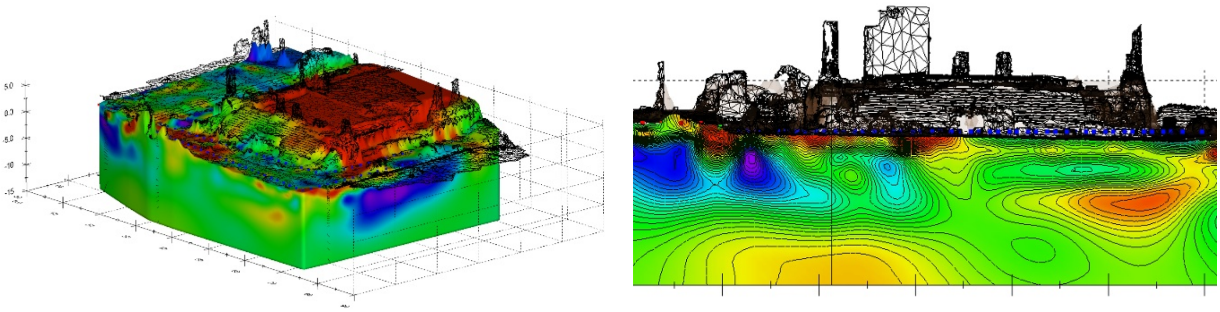
Analysis of Surface Waves (MASW), Refraction Microtremor (REMI) and Nakamura's technique. Fig. 3 and Fig. 4 show some pictures of the geophysical characterization for the Parthasarathy temple and for the Marte Ultore temple.



a) b)

Fig. 3 Parthasarathy temple (India): a) georeferenced feature map of the temple (green dotted lines), building analyzed with structural tests (green bold lines), seismic lines (black arrows, letters A to C) and Nakamura test locations (red dots, letters 1-3); b) MASW spectra showing phase velocity versus frequency for line A

At the Parthasarathy temple, site geophysical data was limited to seismic profiling using the MASW and REMI techniques, as well as Nakamura measurements in the vicinity of the Temple site. Due to the constraints of the Temple site, including pavement conditions and space restrictions, the profiles were limited in length and hence the depth of penetration of the seismic waves observed could not carry any information beyond 15m. However, making an assumption of continuity of the shear wave velocity profile to the bedrock and using the results obtained from the Nakamura method, an approximation to the bedrock depth was possible.



a) b)

Fig. 4 Marte Ultore temple (Italy): preliminary results of Electrical Resistivity Tomography, 3D and 2D view respectively (courtesy of G. Morelli, Geostudi Astier)

Proper interpretation of the acquired information led to the definition of a geotechnical model at the reference site to be used for ground response analyses. Since the site is characterized by a uniform soil deposit, without evidence of lateral heterogeneity, a mono-dimensional (1D) soil model has been assumed for the site under investigation. To define a 1D geotechnical model, it is necessary to define the number of layers and then, for each layer, the following parameters need to be specified: thickness, shear wave velocity mean density, shear modulus degradation curve and damping ratio degradation curve. Finally, a value of shear wave velocity for the half-space is required. As the evaluation of the above parameters involves some level of uncertainty, an interval of variation has been associated to each input parameter in the litho-stratigraphic model used to perform ground response analyses at the site.
Ground response analyses for the site in Rome are being carried out at the time of the preparation of this paper.

5. STOCHASTIC GROUND RESPONSE ANALYSES AT THE INDIAN SITE

The results of the Probabilistic Seismic Hazard Analysis (PSHA) proposed by Lai et al. [4] for Southern India were used as input to perform the site response analyses at the Parthasarathy temple site in the city of Chennai. The PSHA output is only valid for sites characterized as hard rock and without topographic irregularities.

To properly account for the uncertainty in the definition of the soil profile and the variability of the input motion, which strongly affect the reliability of the results of site response analyses, a fully stochastic procedure is necessary. For the Parthasarathy temple site, 1D linear-equivalent, fully stochastic site response analyses were carried out for the 475-year and 2475-year return periods, using a procedure developed at EUCENTRE [5, 6], based on Monte Carlo simulations associated with the Latin Hypercube sampling technique. Randomly generated geotechnical parameters varying according to properly defined probability distributions were assumed to generate 1000 soil profiles (Fig. 5) and hence calculate the seismic response by means of 1000 numerical simulations. The variability of the seismic input was also taken into account by considering an appropriate set of seismo- and spectrum-compatible natural records, selected using the code ASCONA [7]. The acceleration records were propagated through the soil profiles generated in the simulations.

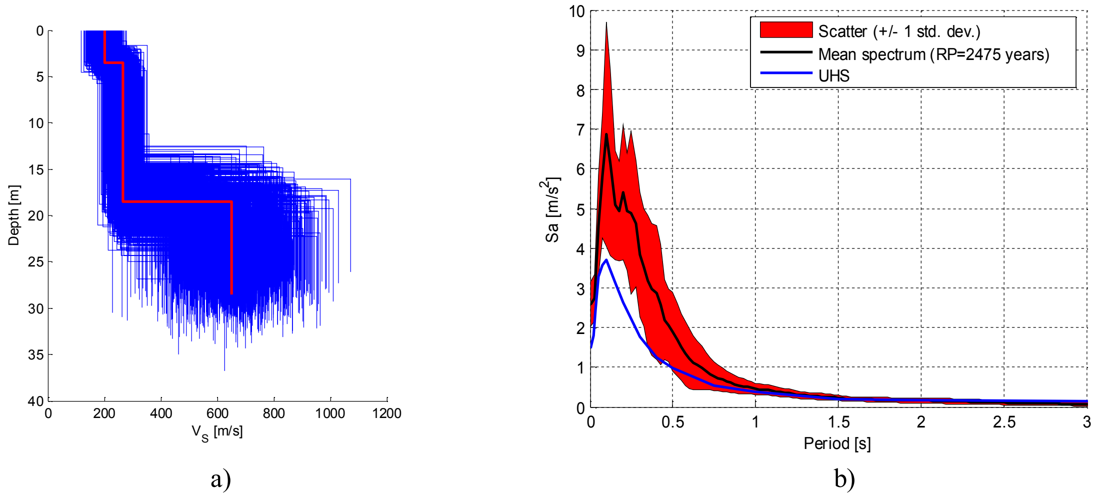


Fig. 5 Stochastic ground response analyses at the Indian site: a) random profiles obtained using the Latin hypercube sampling technique (the red line represents the mean profile) and b) mean spectrum (black line) plus/minus one standard deviation (red area) at the surface and the UHS obtained from the PSHA (blue line)

The mean acceleration response spectra and the mean plus or minus one standard deviation obtained at the surface after ground response analysis are plotted in Fig. 5 for the 2475-year return period. In the figure, they are compared with the Uniform Hazard Spectrum (UHS) obtained from the PSHA.

6. FINAL REMARKS

The expected outcomes of this research project are mainly related to the development of a multi-disciplinary methodology for the seismic risk assessment of historical structures, capable of integrating in a unique framework information related to different research environments. Two case study sites were identified (one in Italy and one in India) as representative of two selected monumental typologies, for which several results are already available:

- Definition of the reference seismic input, in terms of expected peak ground accelerations and uniform hazard spectra for horizontal and vertical components. for different selected return periods.
- Evaluation of site-specific amplification effects, by means of fully stochastic ground response analyses. The results are available in terms of expected PGA and response spectra for both horizontal and vertical components and accelerograms at the surface for different return periods, which could be used as input for dynamic analyses and shake table tests.
- In-situ characterization of historical building techniques and structural properties of the selected monuments.

These results are going to be integrated with a more comprehensive analysis on the following:

- Evaluation of the seismic vulnerability of the selected monuments by means of numerical studies with identification of expected collapse and damage mechanisms.
- Modeling of the seismic response of the analyzed structures, to extrapolate the results for more general studies on different geometries, materials and locations.
- Identification of suitable strengthening techniques or retrofitting procedures with traditional or innovative technological solutions.

The results of the dynamic shake table tests performed at EUCENTRE are expected to provide a significant level of confidence in the developed models and reliability in the results.

ACKNOWLEDGEMENTS

This project is funded by the Regione Lombardia, through the Direzione Centrale Programmazione Integrata, struttura Università e Ricerca. The contribution of SolGeo srl for the in-situ characterization at the Indian site and of Geostudi Astier srl for the in-situ characterization at the Italian site are gratefully acknowledged. In-situ tests were performed thanks to the help of qualified personnel from the TREES Lab of EUCENTRE. The authors also express their gratitude to Mr. Galimberti, formerly at ENEL-CRIS, for providing relevant information and results of past experimental tests carried out at the site in Rome. Finally, the contribution of Dr. Dodagoudar is gratefully acknowledged.

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