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ANR Research Project IM-SURF: Impact and mitigation of seismic surface waves on large 3D structures

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Abstract (Times New Roman 10pt, Bold)

IM-SURF is a research project funded by the French Research Agency. The project runs from 01/10/2024 to 30/09/2028 and is focused on the study of impact and mitigation of seismic surface waves (Rayleigh, Love) on large 3D structures. The project consortium comprises 3 academic partners (ENSTA, CentralSupelec, UC Davis), 1 public research entity (BRGM) and 1 specialized engineering consultancy (Géodynamique & Structure). The objectives of the research project are : a) enhance existing strong-motion databases with signals in which both the body wave and the surface wave components are fully characterized, b) further develop existing tools for the identification and extraction of surface waves from recorded signals, c) develop numerical techniques for obtaining full 3D wave regimes from the geological to the geotechnical scale, d) develop advanced numerical techniques for seismic soil-structure interaction analyses with complete 3D wave regimes that may reach a structure founded on the ground surface. Emphasis is given on the Domain Reduction Method which can be further developed with an emphasis on surface wave generation and on mechanisms of nonlinear response at the vicinity of the foundation, e) for specific types of structures (emphasis is given on large industrial buildings and critical facilities), investigate the impact of surface waves on overall dynamic response and structural design and identify those cases in which the consideration of a full seismic wavefield would be required for a safe seismic design or probe the margins obtained by using normative seismic motions with respect to more realistic complete seismic wavefields, f) finally, establish a set of guidelines and tools that can be introduced in engeering practice (benchmarking, validation, numerical tools, recommended practices etc.) The present paper is intented to present IM-SURF project to the research community and motivate discussions with other researchers working on this field.

Keywords: soil structure interaction, surface waves, numerical methods, Domain Reduction Method, wave propagation.

1- INTRODUCTION

Recent devastating earthquakes (Turkey 2023, Morocco 2023) have yet again underlined the need for reliable modelling and quantification of the impact of strong seismic motions on structures in general and specifically on critical infrastructure. It is known that strong motions arise via the propagation of seismic waves in complex geological domains, are intrinsically 3D and result from the combined effect of both body waves (P, S) and surface waves (Rayleigh, Love, Stoneley). Nonetheless, state-of-the-art engineering practice still privileges a simple method for dynamic Soil-Structure Interaction (SSI) calculations based on the assumption of vertically propagating body waves through simplified 1D soil columns. The merit of this approach is that the complicated geometry of the soil domain is modelled as a horizontal stratification of soil layers of infinite extent. This leads to 1D site response models that can be easily solved and are sufficiently accurate for conventional seismic studies.

However, this simplified method does not allow modelling the generation/propagation of surface waves, which can strengthen wave amplification and be detrimental for structures of large dimensions (~100m) and/or for long-period structures. Recent research ([1] to [3]) has shown significant discrepancies in the seismic

response of certain classes of soil-structure systems when subjected to wave fields obtained via simplified 1D and via explicit 3D site response analyses.

Within this context, the recently completed ANR project MODULATE (https://modulate.brgm.fr/) has investigated the effects of surface waves on several types of structures that are characterized by long periods of vibration. Scientific partners of IM-SURF project have developed within MODULATE a rich inventory of tools allowing to identify and extract surface wave components from recorded signals. The main outcome of MODULATE ([4] to [6]) is to show that the seismic response of such structures can be significantly amplified (up to a factor ~3 for linear response and up to an order of magnitude for nonlinear response) when surface waves are incorporated in the analyses. The analyses performed in MODULATE are based on a dedicated strong motion database providing signals in which it is possible to identify and extract the surface wave component. This allows us to perform and compare structural analyses with full motions (body waves + surface waves) and motions without surface waves components. Additionally, MODULATE has shed light on the mechanisms of surface wave generation in sedimentary basins using realistic and canonical geometries and a variety of numerical techniques (SEM, BEM) for solving the problem of seismic wave propagation.

IM-SURF project comes as a step forward with respect to MODULATE. The main objectives are the following:

- To enhance the MODULATE strong-motion database with signals in which the high-frequency content is fully described. Most of the signals in the MODULATE database are discretized with large time steps implying that their high-frequency content has been truncated in the available signals. If these signals are to be used for seismic analyses, it is necessary to complete the missing part of the frequency content, and this can be done using stochastic or AI methods and by post-processing additional signals from recent earthquakes.
- To investigate advanced numerical techniques for seismic wave propagation that allow performing the transition from the geological scale to the geotechnical scale while preserving the complete 3D wave regime that may reach a structure founded on the ground surface. Among these techniques, the Domain Reduction Method ([7], [8]) is efficient and already available in structural analysis programs. This method can be further developed with an emphasis on surface wave generation and on mechanisms of nonlinear response at the vicinity of the foundation. H-matrix accelerated Boundary Element Method is also an advanced modelling strategy allowing to combine low frequency surface wave generation/radiation and higher frequency local response ([9], [10]).
- To extend the study of the seismic response of structures subjected to surface waves to the case of massive structures of large dimensions. Indeed, the analyses carried out in MODULATE concerned long-period structures with simplified foundation geometries. Structures to be studied in IM-SURF project will concern large industrial buildings. As an example, such structures can present significant rotational motions because of the incidence of Rayleigh waves, and this is a feature that cannot be captured if 1D site response analyses are carried out. Therefore, 3D physics-based simulations containing the source and the structures are essential to quantify the response of large-scale structures. Additionally, for structures of large dimensions the effects of spatial variability of seismic motion may be significant and will need to be integrated in the analyses.
- To assess several mitigation methods to reduce the rotational components generated from surface waves which can drastically enhance the destructive capacity of moderate earthquakes in urban areas located over sedimentary basins. In practice, to decrease the vulnerability of existing structures to seismic risk, upgrading the structure is not always possible or cost-effective. An alternative solution is the retreat of the foundation, which aims to either reduce the earthquake motion transferred to the structure through the foundation or, in the case of surface waves, eliminate this risk. In fact, solutions such as periodic wave barriers could be used to mitigate low-frequency seismic waves and surface waves.
- The ultimate goal will be to enrich the state-of-the-art engineering practice by defining the validity domain for the conventional 1D site response analysis and by identifying specific cases (source characteristics, geological setup, geotechnical conditions, structural configuration, source-to-site and source-to-structure directions) that require adopting rigorous and efficient 2D/3D approaches for site response to capture the significant effects of surface waves.

2- PROJECT OBJECTIVES AND STATE-OF-THE-ART

To this day, state-of-the-art engineering practice for dynamic SSI analyses of critical industrial facilities (including nuclear power plants) is globally based on the following simplifying assumptions ([3], [11]):

- The soil domain can be represented as an idealized horizontal stratigraphy of infinitely extending horizontal viscoelastic soil layers (1D profile)
- The horizontal component of seismic motion is modeled as vertically propagating SH waves
- The vertical component of ground motion (whenever included in the analyses) is modeled as vertically propagating spatially coherent P waves

The adoption of the above assumptions leads to the definition of the so-called "3×1D" seismic motion (3 orthogonal translational components obtained via the propagation of body waves through a representative 1D soil column) which is an approximation of the "3D" seismic motion that excites a structure founded on soil surface. Some basic aspects of the exact "3D" seismic motion that are ignored in the "3×1D" approximation are the following:

- Real geological setups may have features that do not comply with the 1D approximation of infinitely extending horizontal layering. Such features are the presence of a sedimentary basin, layer folding, steep topography, extended fault configurations *etc*.
- The translational components of seismic motion (especially the vertical component) are not exclusively obtained via the vertical propagation of body waves but they result as a combination of inclined P- and S-waves and also of surface waves
- The seismic waves present spatial variability and incoherence
- The superposition assumption that is implied in the "3×1D" approximation may be an issue for strong motions

Despite the above points, state-of-the-art practice has been justified up to now by using design response spectra that are considered sufficiently envelope to cover the aspects of exact 3D motions that are ignored in adopting the "3×1D" motion approximation. For conventional structures of small to moderate dimensions (<100m), the impact of surface waves and spatial incoherency can be considered reasonably negligible whereas consideration of vertically propagating waves with respect to inclined waves generally produces more conservative results [11]. However for structure-foundation-soil systems that do not comply with the basic assumptions of the "3×1D" seismic motion approximation (*e.g.,* structures exhibiting large foundation dimensions or a significant aspect ratio or a geotechnical profile that cannot be modeled sufficiently by a horizontal stratification *etc.*) there is a growing need for a better understanding and quantification of the "error" when the "3×1D" approximation is adopted.

For such structures, the following questions may become of major importance in quantifying seismic response:

- For a given soil-structure configuration at a given location, is it possible to verify that the "3×1D" motion approximation will provide conservative results for all relevant seismic scenarios and for all significant aspects of structural response (global stability, uplift ratio, structural integrity of the bearing system, in-structure response spectra)?
- Are there any aspects of the response that are underestimated with the "3×1D" motion approximation implying an unsafe design?
- Provided that the "3×1D" motion approximation provides conservative results, is it possible to quantify the available margin with respect to the more realistic "3D" motion?

The first two questions are essential in the design phase of critical facilities. The third question may be crucial for the reassessment of existing structures. Analytical and calculation tools that are available today provide the necessary ingredients for answering the above questions:

- In terms of wave regime characterization (wave radiation and polarization), tools developed in MODULATE can be used to identify and quantify all components of the full "3D" wave regime and in particular the presence of surface waves;
- At the geological scale, available numerical techniques (SEM, H-matrix accelerated BEM, SEM-FEM coupling, …) can provide accurate models for source mechanisms and seismic wave propagation in realistic and/or canonical setups for obtaining the complete wave regime (with seismic motion incoherence) that reaches the near field domain of the structure;
- At the geotechnical scale, the Domain Reduction Method and other alternatives can be used for injecting full "3D" motions on typical structures with consideration of nonlinear effects at the near field;
- At the structural scale, available models of for several types of buildings can be exploited for investigating all major aspects of dynamic response that may be found under- or over-estimated because of the "3×1D" approximation.

Within this context, the objectives of IM-SURF project with respect to state-of-the-art engineering practice is to make a systematic use of the above ingredients and present a set of guidelines defining the validity domain of the "3×1D" approximation with an emphasis on the impact and mitigation strategies for surface waves, while allowing to move forward to more realistic fully "3D" dynamic SSI analyses. Accordingly, Figure 1 presents the global flowchart of IM-SURF project with the role of each partner of the research consortium.

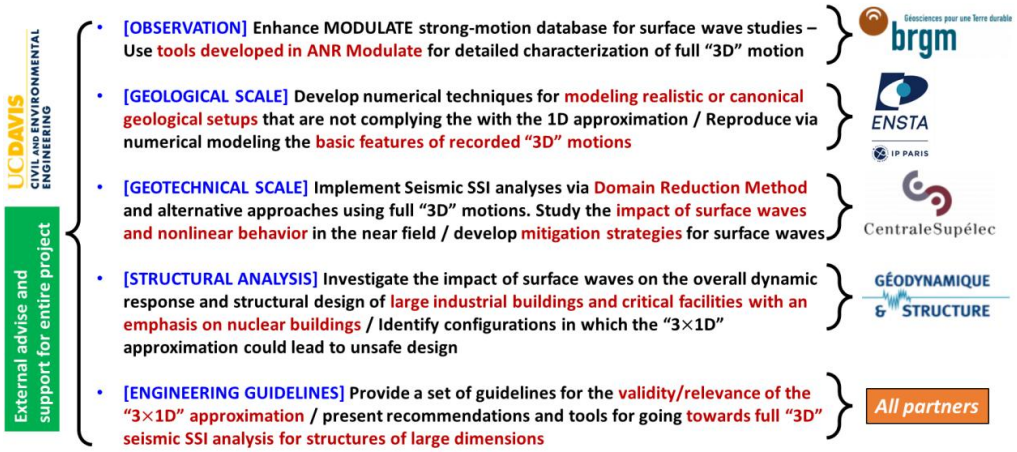


Figure 1- Global flowchart of IM-SURF project

3- PROJECT ORGANIZATION

IM-SURF project is divided into 4 technical Work Packages (WP) that are briefly described in the following sections.

3-1- ENRICHMENT OF EXISTING STRONG MOTION DATABASES FOR SURFACE WAVE STUDIES

Starting point for this WP is the strong-motion database developed in ANR MODULATE. Previously, we have worked on the basin-induced surface waves, focusing on the known basins where there are sufficient recorded datasets such as Los Angeles, Mexico City, Kanto and Nobi basins (Japan) [12], [13]. The basin-specific parameters such as relative delay time, amplification coefficient and central frequency were characterized for the mathematically extracted surface waves, while the source effects (magnitude, azimuth, etc.) were always recognized. The frequency band of the analyses was also limited (e.g. 0.25 to 0.5 Hz in Mexico City case), and this represents a part of the total energy of full waveforms. Thus, in IM-SURF, we intend to extend our database towards two axes: Firstly, the recent earthquakes in the last years will be analyzed for the further enrichment of the database. We need to analyze the surface waves in terms of the near-source effect differently from the site conditions. Then, we adopt stochastic and AI techniques ([14], [15]) for realistic predictions of the high-frequency components so as to be coherent with the surface waves. Any hybrid method has been rarely applied in the presence of surface waves. It is necessary to understand the 3-component full waveforms over a long duration of ground motions.

Case study on recent earthquakes. Recent earthquakes, in particular, the 2023 Turkey earthquakes can feed our knowledge and database. There were more than ten stations at a short distance (a few kilometers) from the causal fault, allowing the complete analysis on the wave field at any distance. A preliminary analysis [16] has shown that the pulse-like low-frequency signals (0.3-0.4 Hz in some stations during the 2023 Pazarcik earthquake) are very visible in the near-field from Turkish strong-ground motion network. It is a question how to quantify the generation and propagation of such waves in a 3D medium. We are going to analyze the acceleration data, aiming to distinguish the near-source effects from the sites. One hypothesis to explore is that low frequency signals may be generated due to the near-fault low velocity zone. We first aim to spatially characterize low-frequency ground motions from the data. Next, we are going to distinguish the origin with help of the numerical modellings.

Another case is the 2024 Noto (Mw7.6, Japan) earthquake. The data is of high-quality from the Japanese strong-motion networks K-net and Kik-net. This earthquake is very energetic (at least more energetic than the 2004 and 2007 events studied in [17]) and it is thus worth evaluating the surface waves at the known stations that we already studied once.

***Hybrid ground motion generation in the presence of surface waves*.** In parallel, we aim at providing the full waveforms over broadband frequency range under the existence of the surface waves. We first adopt stochastic methods for high-frequency contents ([14], [18]) to carry out a hybrid ground motion generation. It is a question how the three components of ground motion can be consistently generated. Low frequency parts are calculated deterministically according to the known earthquake scenario and crustal structure using numerical modelling. Next, we try to produce stochastically the entire waveforms ([19]). The basic idea is to use the middle frequency range (corresponding to the body waves) to predict the low frequency part (surface wave) as well as the high frequency part. Surface waves are not always generated, so we need to determine a priori at which site and at which condition, the surface waves may be generated.

3-2- OBTAINING FULL 3D WAVE REGIMES (FROM THE GEOLOGICAL TO THE GEOTECHNICAL SCALE)

This WP focuses on the study of numerical techniques that are necessary to couple the source characteristics, the geological scale, and the geotechnical scale in order to obtain realistic 3D wave regimes that preserve the potential surface wave components already present at the geological scale that can be used as incoming wave regimes at the geotechnical scale. The Spectral Element Method and the H-matrix accelerated Boundary Element Method ([10]) are considered. Variability in the near-surface soil properties can also be considered in simulating the 3D wave fields propagation using physics-based numerical simulation. Weak coupling approaches (SEM-FEM, or a SEM-SEM-FEM, or BEM-FEM) will allow to produce a realistic input excitation for the structural response considering soil–structure interaction (SSI).

From source radiation and directivity to basin impinging. One basic aspect to consider concerns source radiation and directivity effects in the incident wavefield impinging alluvial basins. It is fundamental to assess the seismic wavefield polarization before and after the interaction with the large-scale alluvial deposits. The features of the incident wavefield radiated from the source and the properties of the alluvial basin govern the seismic wavefield propagating up to the surficial geotechnical structure. The Spectral Element Method and the H-matrix accelerated Boundary Element Method will allow efficient and accurate numerical simulations of such coupled effects with the aim to quantify the detailed polarization of the seismic wavefield in the various stages of generation, propagation and scattering. This task is also focused on the implementation of accurate predictors for the interactions between seismic waves and basin geometry. The proposed methodology will integrate several computational techniques, such as the Fourier Continuation-based solvers ([20], [21]) with Spectral Element or Finite Element method to simulate accurate predictions of seismic response in scenarios involving complex basin settings from regional to local scales. The effectiveness of the coupling framework in accurately simulating seismic scenarios in basin environments will be assessed.

From basin effects to local geotechnical response variability. From the seismic wavefield generated by the source/basin coupling, the transmission to the surficial geotechnical structure is another the main goal in this Work Package. The combination of lower and higher frequency components generated at different scales is an important computational challenge. The interaction between the complex wavefield traveling in various types of alluvial basins and the local heterogeneous soil layering is the main target. After a verification phase, the numerical models will have to be validated from the seismic motion database in realistic alluvial basins. A sensitivity analysis will then be performed to assess the basin/soil features leading to the largest amount of surface waves and seismic motion variability. Both weak and strong seismic motions must be computed and compared to quantify the influence of soil nonlinearities on such effects.

3-3- SSI CALCULATIONS WITH COMPLETE WAVE REGIME AND STRONG NONLINEARITIES IN THE NEAR FIELD

This WP is focused on investigating basin-induced surface waves in realistic basins and on improving the forward fault-to-structure simulation tools used in ANR MODULATE.

First, important aspects of the seismic wave propagation problem can be explicitly taken into consideration (such as the earthquake source, the propagation path, the local site effects, the nonlinear soil behavior) in a high-fidelity predictive numerical model. Physics-based simulations can be used to tackle large-scale earthquake simulations from seismic faults to sites of interest. Thus, this WP will investigate and develop numerical models to represent the spatial correlation of soil properties, both directivity pulse and near-fault pulses caused by earthquakes and propagate the underlying uncertainties to the hazard and risk metrics to the study of the structural response. In this part, using realistic sources as input motion, the effect of the source type and position on the generated surface waves is assessed. Surface wave parameters are expected to vary due to a combination of source and basin geometry effects. The earthquake scenarios will present a near field

effect, where velocity pulses in the fault normal direction are observed, increasing spectral accelerations at large periods. The effects of long period ground motions would be then a combination of near field ground motion and basin generated surface waves.

SSI calculations will be performed with incident motions that preserve the characteristics of the complete 3D wave regime. To this end, we mainly work with the Domain Reduction Method and develop new methodologies for handling incident surface waves and strong nonlinearities in both the structure and at the foundation level. Uncertainty in the source-to-site azimuth and distance, source mechanisms, underlying velocity structure, and near-surface soil properties will be reflected in the analysis inputs for the Domain Reduction. Surface waves are particularly important among the various seismic waves due to their potential to cause building damage at great distances from the earthquake epicenter. Specific tasks in this WP include the following:

Improvement of 3D FEM dynamics analysis of large-scale structures including SSI. This task is related to the improvement of full 3D soil-structure models to capture the dynamic characteristics of studied structures, including the aspects of the nonlinear response of both soil and structure. The superstructure and the soil foundation will be modelled with the Finite Element Method (FEM). On the other hand, the surrounding bedrock will be discretized with the Spectral Element Method (SEM), which has proven to be more efficient for simulations of wave propagation, given their low numerical dispersion.

The dynamic behavior will be studied for a selected, limited set of signals that account for the presence of basin and near-fault generated surface waves and the results will be compared with analyses using conventional signals. It will thus be possible to reconfirm and validate the conclusions drawn from the ANR MODULATE and get a more detailed appreciation of the impact of surface waves on structural response. Working with a complete model will allow examining more targeted aspects of the response such as the transferred spectra at characteristic points of the structure, the reinforcement demand or ductility demand in critical sections, the evolution of specific performance criteria, *etc*.

Mitigation of low-frequency seismic waves and surface waves. This task is related to the assessment of soil reinforcement methods for reducing the associated seismic structural damage due to surface waves. We study soil improvement methods that locally treat the subsoil to modify its mechanical characteristics and therefore reduce the amplitude of the shaking arriving at the base of the structure. To decrease the vulnerability of existing structures to seismic risk, upgrading the structure is not always possible or cost-effective. An alternative solution is the treatment of the foundation, which aims at either reducing the earthquake motion transferred to the structure through the foundation or, in the case of surface waves, to eliminate this hazard. This can be done either by increasing the inertia of the foundation with respect to the soil or by creating a dynamic altering system in the soil. Vertical rigid materials could be envisaged to create such an altering system. In fact, solutions such as periodic wave barriers could be used to mitigate low-frequency seismic waves and surface waves [22]. They work by exhibiting bandgaps that prohibit the propagation of elastic waves and produce seismic wave attenuation.

In this task, numerical simulations will be performed to design such mitigation strategies and estimate their efficiency. Several coupled 3D SEM-FEM models will be developed using a non-linear elastoplastic model to describe both the soil and the structure behavior. Parametric dynamic analyses are carried out to reveal the beneficial or unfavorable effects of the proposed mitigation methods.

3-4- SEISMIC PERFORMANCE OF STRUCTURES SUBJECT TO THE INCIDENCE OF SURFACE WAVES

In this WP, the tools developed in the previous WPs are put together in order to study the seismic performance of specific types of structures of large dimensions subjected to the incidence of full “3D” seismic motions with a significant surface wave component.

First, we perform a parametric study of the impact of full “3D” seismic motions with significant surface wave component on structures of various typologies. For this, we select a set of representative structures of that are studied under a variety of incident wave regimes that pertain to full “3D” seismic motions and also to the equivalent “3×1D” approximations. The models are extracted and/or inspired from the rich inventory of structures studied and designed by Géodynamique & Structure (a member of the consortium) over the last decades. For these structures we perform several sub-tasks:

- We develop simplified models that allow performing parametric studies in an efficient way
- We identify configurations (structure, soil, earthquake) for which the incidence of surface waves can be particularly detrimental
- For a limited number of selected cases, we develop more detailed models and investigate the effect of “3D” incident motions, and surface waves in particular, on several aspects of seismic design such as global stability, design of structural members and the mat foundation, transfer of response spectra

within the structure *etc*. These analyses provide more insight into the relevance and the consequences of adopting a particular method for defining the incident seismic motion to the design outcome.

- Parameters to be investigated are the following: foundation dimension, structural configuration, intensity and characteristics of incident seismic motion, presence of nonlinearity in the near field zone and in the soil-foundation interface. Aspects of dynamic response to be explored are the following: uplift ratio as function of type and intensity of wave regime, reinforcement demand in several critical positions of the structure, and the mat foundation, in-structure response spectra and global displacements etc.

The results of this task will lead to the identification of parameters that are key for the structural response and their relations with the main characteristics of the wave regime that excites the structure. The objective of this task is to identify possible aspects of the response that are underestimated when using the "3×1D" approximation and also quantify the available margin when comparing the exact "3D" and the approximate "3××1D" approach.

The results of the performed tasks in all WPs are compiled into a concise set of rules and guidelines that define the validity range for conventional 1D site response methods for the definition of incident seismic motions for structures that are found to be particularly vulnerable to the effects of "3D" motions and the incidence of surface waves.

These guidelines provide the necessary instructions for identifying and treating those cases that require to go beyond the conventional approaches and define some simple rules for obtaining a preliminary quantification of surface wave effects on seismic response of structures, considering the effect of uncertainties in the source, velocity structure, and near-surface soil properties *etc*.

4- CONCLUSIONS

As the presence of significant infrastructure is steadily growing to cover the increasing societal needs of communities, there is a continuous demand for advanced methods of seismic design to optimize cost of large investments without compromising safety for the population. Research project IM-SURF has received funding from the French National Research Agency (ANR: Agence National de la Recherche) under grand agreement ANR24-CE22-2333 to study the "Impact and Mitigation of seismic SURFace waves on large 3D structures".

In terms of scientific impact, IM-SURF project is of theoretical and practical significance. The theoretical importance of the project lies on identifying the mechanisms that a full 3D wave regime with significant surface wave components can affect several types of structures. The implementation of advanced and efficient numerical tools and processing methods is also of great scientific interest. In terms of engineering practice, this project is important because it will provide a better appraisal of how structural behavior interplays with surface waves and will lead to the definition of the validity range of state-of-the-art methods for site response analysis.

In terms of societal and economic impact, authorities and stakeholders are expected to have interest in the results of IM-SURF project in regard to the applicability and relevance of current engineering methods for the effects of surface waves on several types of civil engineering structures. Moreover, the project findings can influence code development committees, while practitioner engineers will be able to access novel advanced methods for seismic modeling and assessment. Scientific outcomes will be published in journals and presented in conferences. The present paper is intended to present IM-SURF project to the Earthquake Engineering research community and motivate discussions with other researchers working on this field.

5- ACKNOWLEDGMENT

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