Information & Communication Technologies in Earthquake Engineering

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Abstract

This chapter focuses on the recent advances in Information & Communication Technologies (ICTs) and their applications in the seismic design and assessment of modern structures, with emphasis on buildings and bridges. It aims to review and critically demonstrate new software applications, web-based engineering tools, decision-making systems, collaborative on-site and remote research tools, frameworks for hybrid simulation (coupled experimental and numerical modules), open source applications, data and metadata dissemination and archiving, applications for mobile devices and remote computing, as well as earthquake-specific GIS applications; all developed and implemented recently, in order to enhance the reliability of our prediction for the structural response under earthquake loading and contribute in mitigating the effects of earthquakes on structures. The chapter concludes with the current research needs and challenging opportunities related to the application of advanced Information & Communication Technological tools towards the enhancement of structural safety.

Keywords: information & communication technologies, earthquake engineering.

1 Introduction

Earthquake-induced strong ground motion causes complex interactions among the components of the built environment, inclusive of the subsurface materials, building foundations, and the structures themselves. These interactions can take place at a local (i.e., site specific) or at a global level leading to multiple network interdependencies. Given the current complexity of the economy and the flourishing social activity, it is of paramount importance to be able to reliably assess and predict the behaviour of the above systems under earthquake excitations, as a means to limit the seismic risk to socio-economically acceptable levels.

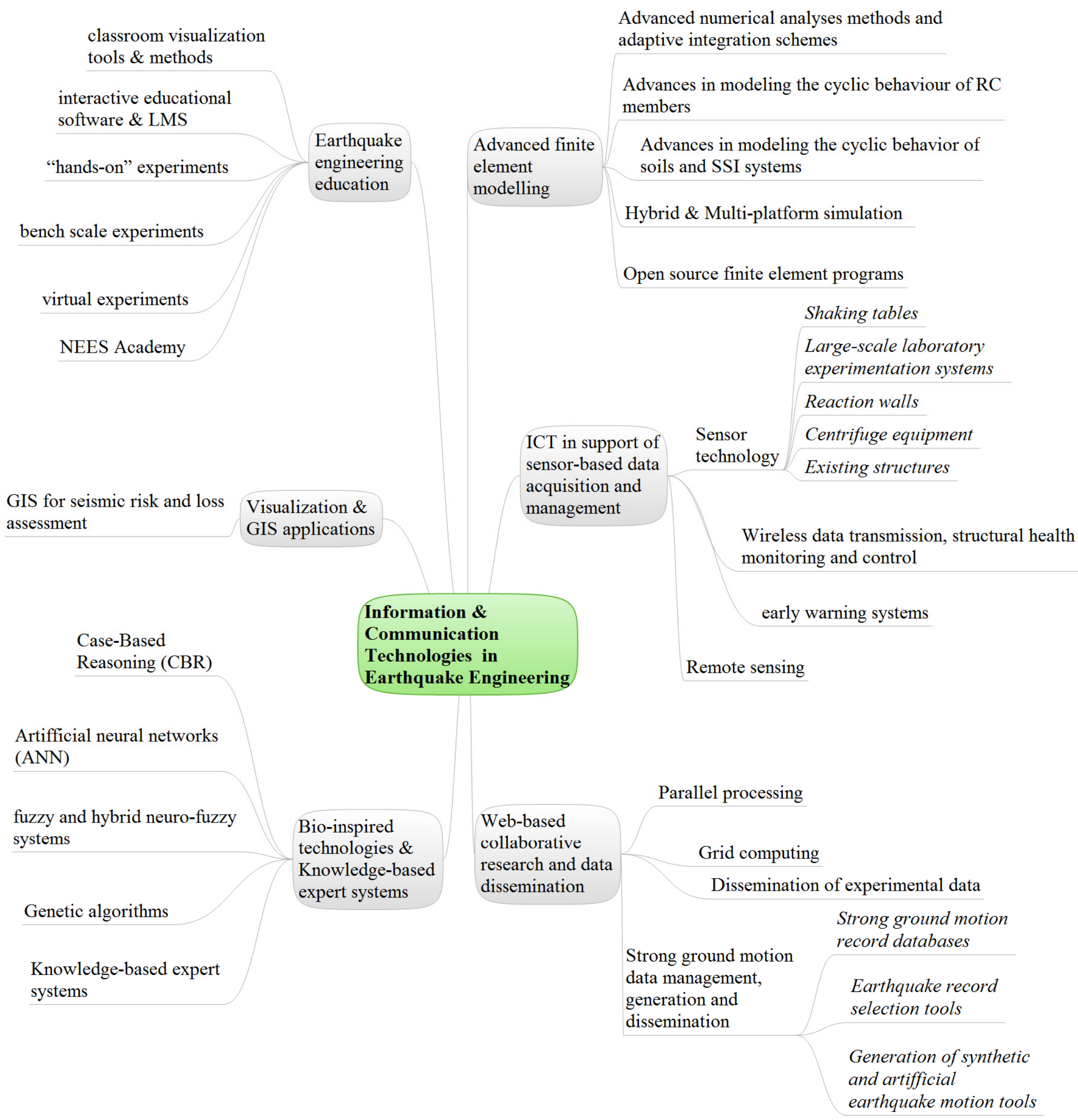

Figure 1. Overview of major ICT fields of application

Major advancements have been made during the last decades towards a better understanding of the structural and geo-structural behaviour under seismic loading, however, the development of computer tools and the evolution of computational power has only recently made feasible to study problems at the micro scale or large systems as a whole, thus providing a completely new perspective to earthquake engineering physical problems that was not available just a few years earlier.

Moreover, the revolution in Information and Communication Technologies (ICTs) that resulted from the rapid increase of internet speed, as well as the increasing access to IMT-2000/3G networks worldwide, has drastically reformed the way engineers work but most importantly, the way in which structural vulnerability and exposure to seismic hazard is assessed. Along these lines, the scope of this review chapter is to map the recent advancements and applications of Information and Communication Technologies in the field of earthquake engineering, in order to investigate possible synergies for integrated and multi-disciplinary research. It is apparent that as ICTs refer to all technical means used to handle information and aid communication, including computer and network hardware, communication middleware as well as necessary software [1], it is indeed quite difficult to conduct a comprehensive review study covering every single technological advancement and application made in earthquake engineering.

To compensate this, an effort was made to present those ICT developments that have *already been applied* in the real-world or have resulted to *ready-to-use* research tools. The chapter is organised in eight sections which cover different fields of ICT applications (Figure 1), starting from aspects of computational mechanics to the computational support of physical testing and structural health monitoring, collaborative on-site and remote research, data dissemination and management, decision making systems, bio-inspired technologies for assessing or optimizing the structural performance and new visualization methods. The chapter concludes with a short review of modern tools that are used nowadays for transferring knowledge to the next generation of engineers and a critical discussion is made on the challenging opportunities that are currently opened and the priorities that need to be set.

Figure 2. ICT applications for mitigating seismic risk

2. Advanced finite element modeling for seismic design and assessment of structures

2.1 Advanced numerical analyses methods

Structural design in earthquake prone areas is a continuous process that aims to strike a balance between the demand imposed to the structures by earthquake ground motion and the capacity that has to be provided both at the member and structure level. As such, the reliable estimate of actions, action effects (member forces and displacements) and structural resistance is a key factor to ensure that the structures designed will meet specific performance objectives. To this end, finite element tools have been widely used for decades, primarily (though not exclusively) for the prediction of demand both in the framework of the design of new structures and the assessment of existing ones.

It was only few years ago that the capabilities available at that time for predicting the earthquake loading and modeling the cyclic response of all important elements of the three-dimensional soil-foundation structure system to seismic excitation, were deemed as simply inadequate [2]. Thirteen years after, significant advances have been made and a number of alternative methods are now available for nonlinear static or dynamic analysis of structures. Admittedly, limitations still exist and none of these methods can be globally used for all structural systems, materials, boundary conditions and performance levels, but the picture is clearly that the epistemic uncertainly, that is, the uncertainty associated with modeling decisions and assumptions is tends to be gradually reduced. The methods most commonly used nowadays for nonlinear seismic analysis can be summarized as follows (it is noted that linear analysis methods are not reviewed herein as they are deemed as rather straightforward):

- *Nonlinear Static (Standard Pushover) Analysis (SPA)*: this is a modern variation of the classical 'collapse' analysis [3] as it aims to predict the hierarchy of structural damage up to the onset of collapse. In principle, monotonically increased lateral loads are statically applied to the structure, in an invariant pattern that aims to resemble the distribution of the fundamental mode forces that the structure is subjected to, when excited seismically along a given direction [3-4]. Under the increasing load application, a series of plastic hinges develop at critical sections of the structure, leading to force redistribution and gradually to a failure mechanism. Through this analysis, it is possible to obtain the non-linear relationship between the lateral force applied and the deformation of the structure as it is monitored at a specific location; a relationship which is usually expressed in the form of the pushover curve, or else, of a "base reaction versus control node displacement".
- *Modal Pushover Analysis (MPA)*: is an extension of the above method [5] initially applicable for buildings only, where the total seismic demand of the inelastic system is computed as a combination of individual "modal" demands. With a series of adaptations and further assumptions, the method was extended

for the assessment of the inelastic seismic response of bridges [6-7]. An alternative Incremental Response Spectrum Analysis (IRSA) framework has been proposed by Aydinoğlu [8] while an interactive front-end has also been developed using the new SAP2000 open Application Programming Interface [9] to reduce the time required for post-processing the multi-modal results.

- *Displacement-based Adaptive Pushover Analysis (APA)*: another alternative to the "standard" pushover analysis which permits the redistribution of loading based on the stiffness degradation, period elongation and higher mode contribution that takes place with the increase of the lateral load. This is achieved by continuously updating the system stiffness and the corresponding loading vector using either discrete or distributed [10-11] plasticity models.
- *Pseudo-Static Response History Analysis (SRHA)*: is a method where the applied displacements can vary independently in the pseudo-time domain, while the inertia of the structure is ignored. It is particularly used for cases where the pseudo-static component of system response is of interest.
- *Nonlinear response history analysis (NRHA)*: involves direct integration of the equations of motion in the time domain for a given ground motion input after appropriate modeling of the nonlinear cyclic behaviour of the materials (i.e., concrete, steel, rubber, soil etc) and any potential geometric nonlinearity arising from the presence of gaps, discontinuities, friction and other contact issues.
- *Incremental dynamic analysis (IDA):* is a method, primarily used in the framework of Performance-Based Earthquake Engineering (PBEE), that requires multiple nonlinear response history analyses with a given, incrementally scaled suite of ground motion records, to provide a performance assessment from the early elastic limit-states to the onset of collapse [12]. To account for other sources of uncertainty, the IDA approach can be combined with reliability analysis methods such as the Monte Carlo simulation, either in conjunction with Latin Hypercube Sampling (LHS) [13] or a response surface approximating method [14]. Approaches to reduce the computational effort have also been proposed and involve approximate, moment-estimating methods [15] and utilization an estimate of the response statistics based on preliminary static pushover analyses [16].

2.2 Advances in modeling the cyclic behaviour of reinforced concrete members

The cyclic response of reinforced concrete (R/C) members is typically considered by assuming either distributed (fiber) or lumped (discrete) plasticity models. The lumped plasticity model is a long established approach, which involves a combination of an elastic beam with point plastic hinges located at the member's ends, the latter being represented by inelastic rotational springs which are connected to the elastic beam element in a series system. It is noted that in contrast to the case of nonlinear static procedures, where the moment-curvature relationship required for the definition of plastic hinges can be derived rather easily [17-18] by conventional fiber model analysis (presented below) given a reasonable estimate of the member axial load, in the case of nonlinear dynamic analysis, the designer needs to make a set of assumptions which are often associated with non-negligible uncertainty. The length the plastic hinge is one controversial issue; typically, this is to some extent compensated by either using analytical expressions from the literature [19] or by discretizing the element representing the member, to a series of multiple smaller elements with adequately closely spaced rotational springs; however, depending on the earthquake intensity and characteristics, the dispersion of structural response can still be high.

Another subjective issue related to the use of lumped plasticity models is the adoption of an appropriate hysteresis law. Currently, numerous hysteretic material laws are available for modeling the behavior of reinforced concrete members under cyclic loading, most of them being able to capture complex phenomena such as stiffness degradation, strength deterioration and pinching effect. Table 1 summarizes the most widely used software options [20-27] available to the designer; some of them offering additional advantages to run multiple analyses in a batch mode and access to the original code quite often at zero cost. It has to be noted though, that such advanced material models are hardly ever used in the design of ordinary structures. On the contrary, they are extensively used for research purposes and the assessment of important structures. In many cases, these advanced material models are combined with equally refined (linear, 2D or 3D) element types.

Table 1: Software most widely used for nonlinear response history analysis

Software	LP	DP	Hysteretic models	Batch mode	Free-ware	Open-source
Zeus-NL	yes	yes	shear & flexure for constant & varying axial force etc	IM	yes	yes
OpenSees	yes	yes	Kent-Scott-Park etc	yes	yes	yes
Seismo-struct	yes	yes	Takeda, SSI, Ramberg-Osgood model, etc	IM	yes	no
IDARC	yes	no	multi-linear (Park et al.), smooth hysteretic model	IM	yes	UR
DRAIN	yes	yes	numerous models	yes	yes	IM
RUAU-MOKO	yes	IM	60 hysteresis rules	yes	no	UR
SAP2000	yes	no	multi-linear plastic-kinematic, Takeda, Pivot	yes	no	API
Fedias-Lab	yes	yes	various models	yes	yes	no

DP: Distributed plasticity, LP: Lumped plasticity, IM: implicitly, UR: upon request, API: available through Application Programming Interface

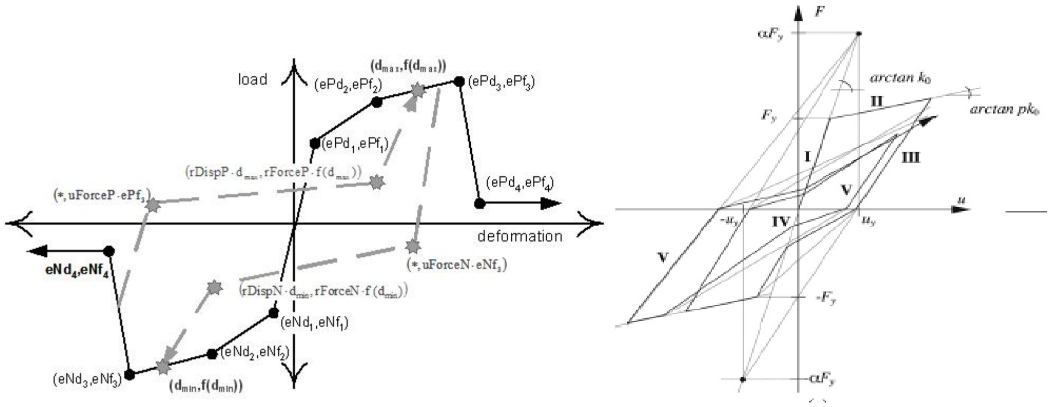

Figure 3. Indicative example of hysteresis rules used for R/C members [20], [27]

An alternative to the lumped plasticity approach is the so called, distributed (fiber) plasticity models, in which the member section is discretized into a set of fibers, each one associated with a nonlinear uniaxial stress-strain relationship [e.g., 28-29], the integration of which leads to the desired stress-strain relationship of the entire section. An advantage of this approach is that the hysteresis of the section is implicitly derived, based on the inherent material constitutive relationships, while the variation of the axial load of the member is also accounted during run time. A critical review of the latest advancements in fiber modeling of reinforced concrete sections can be found in [30].

2.3 Advances in modeling the cyclic behaviour of soils and the response of complex soil-structure interaction systems.

It is now widely accepted that the seismic response of structures may be strongly affected by the properties of their foundation, the supporting soil profile and the overall topographic conditions, hence, the importance of the so called, "Soil-Structure-Interaction" (SSI) is recognized as a key factor in numerous research studies. Despite the extensive research over the last 30 years though, common practices and codified approaches still remain approximate while the problem is often treated as a conditionally beneficial phenomenon [31] on the basis of the anticipated period elongation of the structure (and the monotonic decrease of spectral accelerations of the design spectra), as well as on the energy dissipation at the foundation level caused by wave radiation and hysteretic damping, thus leading to a common assumption that any structure can be conservatively assumed to be fixed at its base.

In fact, this perception has been long proven to be misleading since the foundation is flexible, dissipates energy and interacts with the surrounding soil and the superstructure in such a way, that it filters seismic motion (*kinematic interaction*) while it is subjected to inertial forces generated by the vibration of the superstructure (*inertial interaction*). This phenomenon is very complex and its beneficial or detrimental effect on the dynamic response of a structure is dependent on a series of parameters such as [32-35] the intensity of ground motion, the dominant wavelengths, the angle of incidence of the seismic waves, the stromatography, the stiffness and damping of soil as well as the size, geometry, stiffness, slenderness and dynamic characteristics of the structure itself [36].

Given the physical complexity of the problem, advanced numerical models have been developed to numerically predict the cyclic response of soil materials inclusive earthquake-induced liquefaction [37] and the dynamic interaction between the soil and the structure, the latter typically approached using the aforementioned kinematic and inertial interaction decoupling [33] or dynamic macro elements [38]. Efforts have also been made to model the entire soil domain surrounding and supporting the structure through the simulation of the (non-linear) dynamic subsoil-foundation-superstructure interaction [39], the simultaneous shear deformation and flexural failure of RC members (i.e. beams and columns and shear walls for buildings and piers for bridges) [40], as well of any potential geometric non-linearity that commonly arises under large seismic forces (i.e., closure of gaps or joints at the deck level in the case of bridges). Nevertheless, the literature related to such a 'holistic' finite element modeling is still limited for two main reasons: (a) due to the fact that the coupled modeling of all these systems still requires extensive computational effort and (b) that the uncertainty associated with the reliable identification of the (spatially variable) material properties seems to be still considerably higher than the epistemic uncertainty associated with the assumption of simpler finite element models.

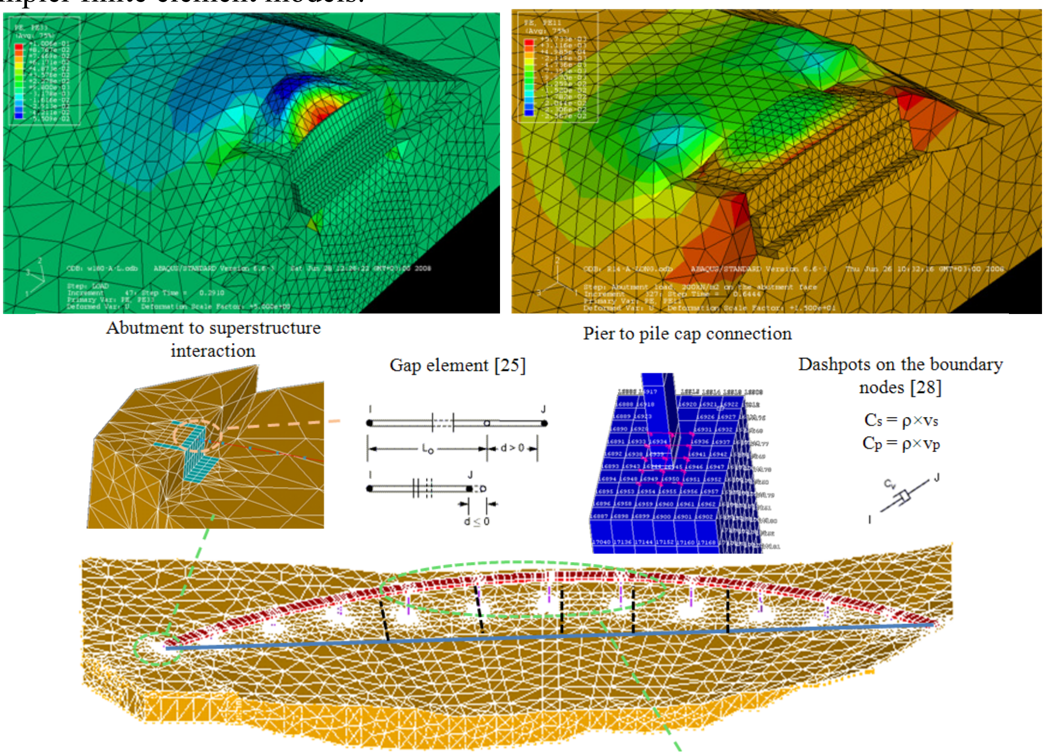

Figure 4. Indicative examples of 3-Dimensional modeling of the entire soil-foundation-superstructure system [41-42]

2.4 Hybrid and Multi-platform simulation

Given the above limitations as to model the entire soil subspace, a system by which a number of laboratories could combine their capabilities to undertake a set of integrated component tests of structural and geotechnical elements seems to be an exceptionally attractive option. In fact, this multi-site, *Real Time Hybrid Simulation* (RTHS) approach has already been developed in the United States for the assessment of complex interacting systems. It is supported by NSF through the Network for Earthquake Engineering Simulation (NEES, www.nees.org) scheme [43-46] and it aims to raise the limitations related to the size of the SSI problem and the laboratory capacities. In this framework, there is no need for using a single experimental facility neither there is need for physical proximity of the multiple sub-components tested. Moreover, since communication is solely web-based, using the same protocols, some components of the system can be analyzed numerically while others can be physically tested. The dynamic response of full scale specimens that are discretized into sub-structures is properly controlled with the use of purpose-specific coordination software. Two such specialized software platforms exist to date, i.e. the OpenFresco [47-48] and UI-SimCor [49]. The latter, developed by the research group of the University of Illinois, is the first platform that has been used for multi-site testing of bridges including SSI phenomena: it concerns an enhanced Matlab based script which coordinates either software or hardware supporting NEESgrid Teleoperation Control Protocol (NTCP) as well as TCP-IP connections outside of the NEES system. The basic concept of UI-SimCor is that analytical models of some parts of the structure or experimental specimens representing other parts of the same structure are considered as super-elements with many DOFs. The elements – analytical or experimental - are treated on different networked computers and, can thus be located anywhere in the world. Specially developed interface programs allow the interaction with different analysis software such as Zeus-NL [21], OpenSees [20], FedeasLab [23], and ABAQUS [50]. Another major advantage of hybrid simulation is that it removes a large source of uncertainty compared to pure numerical simulations, by replacing structural elements that are not well understood with physical specimens on the laboratory floor. Apparently, the drawbacks also exist and are related to the necessity for in-depth knowledge of specialized experimental and analytical tools as well as for considerable programming effort and computational cost.

The concept of Hybrid Simulation has been also applied in Korea [51] and Taiwan [52] for earthquake engineering research purposes. In Europe, it was first introduced at the ELSA-JRC laboratory [53]. A similar to the NEES initiative is the UK Network for Earthquake Engineering Simulation (UK-NEES), comprising the research laboratories at the Universities of Bristol, Oxford and Cambridge and aiming to provide the main UK earthquake engineering experimental laboratories with the necessary equipment to become nodes of the NEES network. Hybrid experiments have also been already performed by University Patras, Greece, for a multi-span bridge structure.

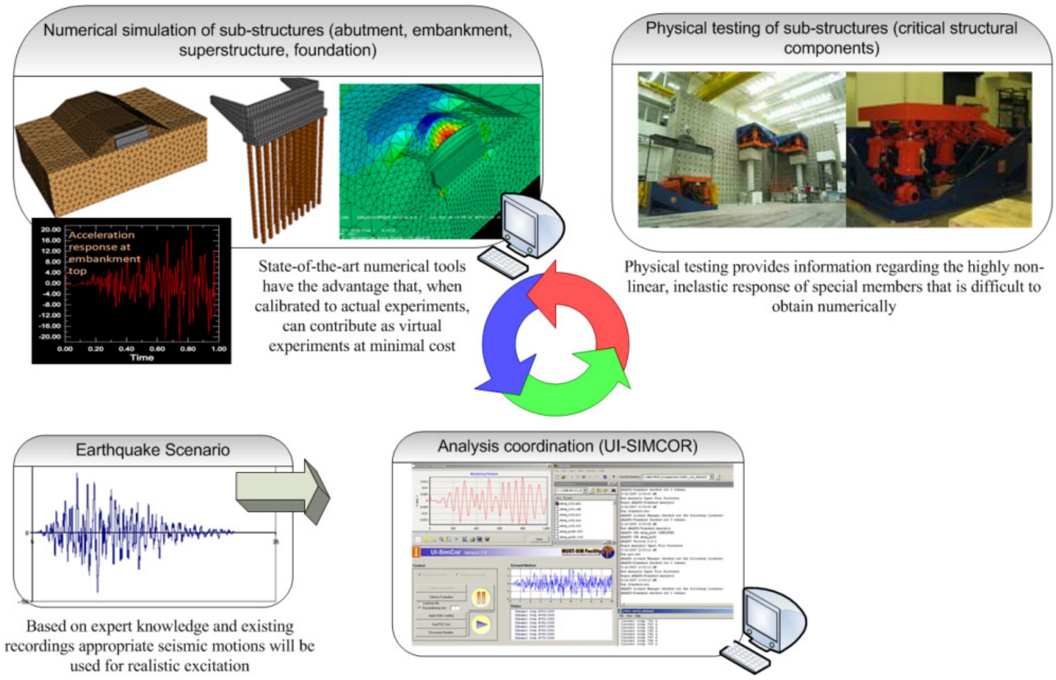

Figure 5. Overview of the multi-platform analysis and/or hybrid experimentation scheme [54]

The same concept has also been successfully applied [55] for the coordination of purely numerical analysis modules (where no physical testing is performed, in contrast to the hybrid simulation application) in the framework of the assessment of real bridges in the U.S. for various soil conditions, as well as for the study of the potential impact of liquefaction susceptibility [56]. This so called, "*Multi-platform simulation*" is another promising alternative to the aforementioned Hybrid simulation approach primarily because it permits the sub-structured analysis of a complex system using purely analytical tools, similarly physically distributed as was the previous case.

The advantage of this approach is that the appropriate selection and combination of different analysis packages, enables the concurrent use of the most sophisticated constitutive laws, element types and features of each package for each corresponding part of the system. In other words, different software can be used for different system components (i.e. abutments, superstructure and supporting pile groups for instance in the case of a long bridge), depending on the foreseen inelastic material behaviour, level and nature of the seismic forces and the geometry of the particular problem. It is believed that this approach leads to combined capabilities that no finite element program currently provides, nor is probable to provide in the near future. On the contrary, it has the minimum assumptions possible and permits the best available option to simulate each component using the most appropriate analytical model, while integrating the various contributions into a fully interacting system. As for the case of Hybrid Simulation though, the computational cost and level of expertise is high.

2.5 Open-source finite element programs and collaborative framework for seismic applications.

The open-source finite element programs available for seismic analysis are summarized in Table 1. OpenSees [20], is an open-source, object-oriented general-purpose code written in C++ specifically developed for earthquake engineering analysis. It is the official simulation platform of the Pacific Earthquake Engineering Research (PEER) Center and has been adopted as the simulation platform of NEES, the NSF-sponsored George E. Brown Jr. Network for Earthquake Engineering Simulation. Zeus-NL [21] is another commonly used computer program which has recently gone open-source, while SAP2000 [24] has introduced an open application programming interface permitting, during run-time, a direct bind to be established, between a third-party application and the analysis software itself [9]. Various robust and versatile frameworks have been developed around the above platforms [57-59] thus introducing a new culture of open programming languages that promote collaborative research.

3 ICT in support of sensor-based data acquisition and management.

3.1 Sensor technology.

Thanks to the rapid ICT developments, significant advances have been also made during the decades in laboratory testing for assessing the nonlinear seismic response of structures. Nowadays, advanced research is conducted all over the world, primarily in U.S., Europe (i.e., ELSA-JRC and EU-CENTRE [60] in Italy, BLADE in the U.K. among others) and Japan (E-DEFENCE, [61]) where numerous large scale facilities operate. The NEES infrastructure in the U.S. in particular, utilizes web-based tools, state-of-the-art instruments, laboratory and measuring equipment, computational resources and a digital library for sharing and retrieving data from past experiments in order to facilitate the operation of a geographically distributed network that permits shared use of equipment sites among 15 universities throughout the US. The test equipment available through the Network for Earthquake Engineering Simulation NEES includes *Shake Table Research Equipment* **(**University of Buffalo, State University of New York; University of Nevada, Reno; University of California, San Diego), *Large-Scale Laboratory Experimentation Systems* (University at Buffalo, State University of New York; University of California, Berkeley; University of Colorado, Boulder; University of Minnesota-Twin Cities; Lehigh University; University of Illinois, Urbana-Champaign), *Centrifuge Research Equipment* (University of California, Davis; Rensselaer Polytechnic Institute), *Tsunami Wave Basin* (Oregon State University, Corvallis, Oregon), *Large-Scale Lifeline Testing* (Cornell University), *Field Experimentation and Monitoring Installations* (University of California, Los Angeles; University of Texas, Austin; Brigham Young University).

The improvements in sensor and data-acquisition technologies and the use of non-contact (wireless) measurement systems, permit high quality concurrent measurements of the displacements or stresses at thousands of points on the structures that are physically tested. As the traditional methods of data management cannot handle such enormous amount of data, new data-visualization and analysis tools have been developed [62] that can integrate in real time the details of the test structure with measured strains, displacements, and cracking data.

3.2 Wireless data transmission, structural health monitoring and control.

Sensor technology can also be used for the assessment of the structural "health" and the vibration characteristics of buildings and bridges by providing information such as displacements, velocities, accelerations, forces, temperatures, acoustic signals, etc. [63] through permanent or temporary instrumentation deployments. Typically, the excitation used for monitoring structural response is ambient vibrations and less often, controlled, man-made, excitations or even actual ground motions. Based on output measurements, various *System Identification* (SI) techniques have been developed for the identification of modal properties, both in the time and frequency domain. Important information also can be derived by the comparative assessment between the results of the measured response and those of advanced numerical analysis that consider the entire soil domain [64]. Recent developments are also reported in Peeters and De Roeck [65] and Basseville et al. [66] using time domain stochastic subspace identification methods, in Beck et al. [67] using time domain least-squares methods based on correlation functions of the output time histories, in Verboven [68], Gauberghe [69] and Brincker et al. [70] using frequency domain least-squares methods based on full cross-power spectral densities (CPSD), and in Peeters and Van der Auweraer [71] based on half spectra. Bayesian and maximum likelihood statistical methods have also been proposed, for example, in Katafygiotis and Yuen [72], Guillaume et al. [73]. System Identification (SI) of structures is also used as a tool to back-evaluate the design assumptions of existing structures and to monitor the changes of structural systems through time.

3.3 Early warning systems.

In many cases, on-board computing capabilities and systems connected in networks with fast Internet based telemetry can extend the applicability of system identification methods by feeding their data directly into rapid response systems assessing in real time the structural condition of critical facilities [74-77], geostructures [78] and life lines before, during and after a large earthquake [79]. Existing tools range from passive, web-based post-earthquake information content requiring no pre-event configuration, to sophisticated damage-assessment and active notification systems (e.g, ShakeCast, described below) that require pre-event set up and IT expertise. Such services include [80] Recent Earthquake Maps, Earthquake Notification Service (ENS) customizable alerts, earthquake magnitude and location notifications), ShakeMaps (a tool used to portray the extent and distribution of potentially damaging shaking following an earthquake by combining recorded seismic shaking levels with state-of-the are shaking estimates [81]), ShakeCast (an automatic use of ShakeMap for Critical Facilities and Utilities [82]), and a system called PAGER (which adds population exposure and vulnerability to the above maps [83]). Similar early warning systems have been developed in other parts of the world such as Taiwan [84].

Another use of wireless technology and mobile devices is the collection of pre- and post earthquake data by trained engineers on site. Typically the data are gathered using mobile phones, they are automatically processed and the geographical distribution of the results is visualized either in specific GIS maps (e.g., [85]) or directly on public maps such as Google Earth [86].

3.4 Remote sensing.

The remote sensing techniques that are most applicable to earthquake science/engineering are optical satellite imagery, synthetic aperture radar (SAR), and light detection and ranging (LIDAR) [87]. Satellite remotely sensed images have wide applications in pre-event, rapid post-earthquake, and long-term post-event activities; however, so far, they have been primarily used for assessing the seismically-induced damage. In particular, damage that has occurred as a result of the earthquake is detected based on comparative image processing. Examples are the cases of the 2001 Gujarat Earthquake [88], the Bam earthquake in Iran in 2003 [89], the Boumerdes in Algeria in 2003 [90], the Central Java, Indonesia earthquake in 2006 [91] and the L'aquilla earthquake in Italy [92] in 2010.

4 Web-based collaborative research and data dissemination.

4.1 Parallel processing.

Most seismic problems carry an inherent parallelism since many large physical problems can be decomposed into a set of smaller (and actually quite small) tasks. For structural problems characterised by a large number of degrees of freedom, numerous software packages offer the capability to utilize multiple CPUs or processor cores. Alternatively, instead of solving a single large-scale problem by partitioning it to several CPUs, specific types of seismic analysis methods (i.e. IDA) can also be, by definition, split among various CPUs that can run independently in parallel, thus providing results that can be combined and interpreted by an appropriate post-processor [93]. Parallel processing can also be used for engineering seismology purposes and seismic data processing (e.g., [94]).

4.2 Grid computing.

Grid computing can be thought of as a distributed system with *non-interactive* workloads that involve a large number of files. What distinguishes grid computing from conventional high performance computing systems, such as cluster computing, is that grids tend to be more loosely coupled, heterogeneous, and geographically dispersed. Although a grid can be dedicated to a specialized application, it is more common that a single grid will be used for a variety of different purposes. An example of large scale grid computing for Earthquake Engineering and geoinformatics purposes is the San Diego Supercomputer Center (SDSC), an organized research unit of the University of California, San Diego (UCSD).

4.3 Web-based collaborative research and large scale dissemination of experimental data.

The management of research data is emerging as a central issue in an growing number of engineering domains. Thanks to the continuously improving sensor equipment, today one is able to instrument almost any imaginable object, no matter its size, thus being able to collect vast amounts of information that can be preserved for future study or can be processed in real time. NEEShub (http://nees.org) is currently considered as the most integrated web-based service-focused organization worldwide as it links earthquake researchers (primarily being activated within the framework of NEES) with leading edge computing resources and research equipment. This permits the participating research teams to plan, perform, and publish their experiments. NEEShub comprises of the following web-based groups of tools: data management software for organizing and sharing data through the hub, telepresence tools for enabling remote participation in experiment planning and execution, visualization capabilities for viewing pre-recorded sensor data and corresponding videos with common time, collaboration services for promoting joint research and simulation software for computational modeling. NEEShub (Figure 6) has also pursued education and outreach strategies to promote learning and communication amongst the IT and earthquake engineering communities [95].

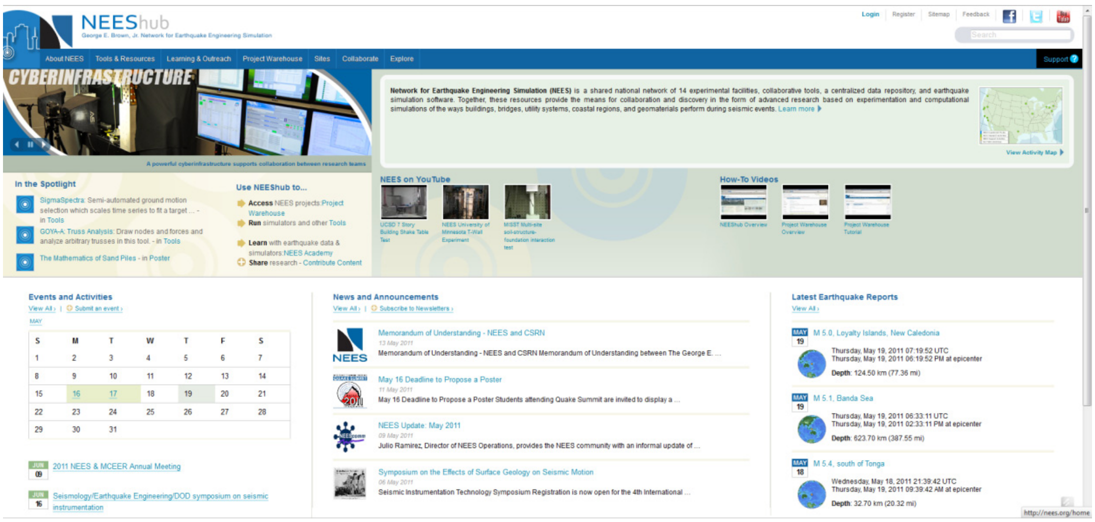

Figure 6. NEEShub web-portal for collaborative research on earthquake engineering

4.4 Strong ground motion data management, generation and dissemination.

As the concept of performance-based design heavily relies on the realistic definition of the earthquake input motion, numerous computational tools have been developed for (a) selecting suites of earthquake records from available strong ground motion record databases (b) generating synthetic and artificial ground motions (c) generating spatially variably time histories, primarily for the assessment of long structures.

4.4.1 Strong ground motion record databases

Among numerous strong ground motion databases in Japan, Taiwan and Europe (European Strong Ground Motion database, www.isesd.hi.is), the PEER-NGA Next Generation Attenuation strong-motion database [96-97] (peer.berkeley.edu/peer_ground_motion_database) is a continuously developing project consisting of 3551 publicly available, three-components seismic records (i.e., about 10650 individual earthquake acceleration time series) that have been recorded during 173 shallow crustal earthquakes from active tectonic regions world-wide. The corresponding seismic events, which have been recorded primarily in California, range in magnitude from 4.2 to 7.9 and cover epicentral distances in the range 0.2km-600km. Apart from the magnitude and the distance, the earthquake database contains basic information about the seismic source including date and time of the event, hypocenter location, faulting mechanism, seismotectonic environment and others. Detailed data about 1600 strong-motion stations are also provided (i.e. site characterizations, surface geology, shallow subsurface conditions, the location of the instrument inside the structure's installation place). Furthermore, each acceleration time-history has been corrected for the response of the strong-motion instrument itself and filtered out the noise included while it can also be automatically scaled online.

4.4.2 Earthquake record selection tools

Given the above extensive depository of earthquake records, the designer faces the challenge of defining, or selecting, a particular set of recorded earthquake ground motions that could be deemed “realistic” for the site of interest. As the most common earthquake record selection procedures involve spectral matching of the average response spectrum of the records to be used, with a target, code-prescribed or seismic hazard-defined elastic response spectrum [98-99], or even a conditional mean spectrum [100], recent work evolved to develop methods and computational tools for quantifying (e.g. [101-102]) and/or optimizing [103-104] this spectrum compatibility. Especially in case of the performance-based design approach, the selection of acceleration time series is considered with the goal of accurate prediction of the structural response at a specified ground motion intensity measure (IM). Most commonly, the Peak Ground Acceleration of the eligible records and some other characteristic parameters (i.e. the spectral acceleration, SA) have been used as suitable IMs (e.g. [105]). Nevertheless, advanced intensity measures, including information about the spectral shape and structural characteristics, are preferable for records selection and scaling procedures as they result in a more accurate and reliable estimate of the seismic demand [98], [106-108].

Despite the aforementioned state-of-the-art evolution in this quite recent research field, a rather rough framework is prescribed by most of the modern seismic codes and guidelines (inclusive of Eurocode 8 [109] and FEMA P-750 [110]) concerning the motions to be used for time history analysis. In fact, most of the aforementioned record selection methods proposed in the literature have not yet been incorporated in any seismic code worldwide, despite the fact that evidence exists that this leads to large dispersions of structural response [111]. Along these lines, numerous computational tools have been developed to raise the limitations imposed by the oversimplifying approach of the code-based, earthquake record selection procedures. REXEL [112], is the first software introduced for this purpose and facilitates the search for suites of waveforms compatible to target spectra that are either user defined or automatically generated according to Eurocode 8 and the recently issued Italian seismic code.

An alternative web-based software for earthquake record selection is SelEQ [113] offering various filtering options. More recently, a Matlab-based software ISSARS (Integrated System for Structural Analysis and Record Selection) has been developed [59] connecting through internet the selection engine to the aforementioned PEER-NGA ground-motion database, to form suites of records that comply with specific criteria (Figure 7). These suites of records are then ranked based on their compatibility with the design spectrum but also depending on the resulting level of dispersion of structural response quantities which is aimed to be kept as low as possible. This is made feasible by using the Applications Programming Interface (API) of the finite element program SAP2000 [24] to run numerical analyses at the background and quantify the produced discrepancy of structural response as a part of the earthquake record selection process.

4.4.3 Generation of synthetic and artificial earthquake motion tools.

Design and assessment of extended structures often requires the generation of spatially variable earthquake motions to be used as multiple-support inputs. A review of the methods most widely used can be found in [114]. Site effects and soil-structure interaction can also be accounted for in the signal generation process [115]. The use of existing, appropriately modulated, records to inherit prescribed target earthquake characteristics (i.e., nonstationarity in amplitude, frequency content, earthquake magnitude, local site conditions, duration etc) is another advantageous alternative [116]. Wavelets analysis [117], a powerful technique which extends the Fast Fourier Transformation technique by decomposing the signal into functions of a particular frequency content and limited length, has also been used for generating spectrum compatible synthetic accelerograms [118-119] for investigating the seismic response of both structures [120] and geotechnical systems [121].

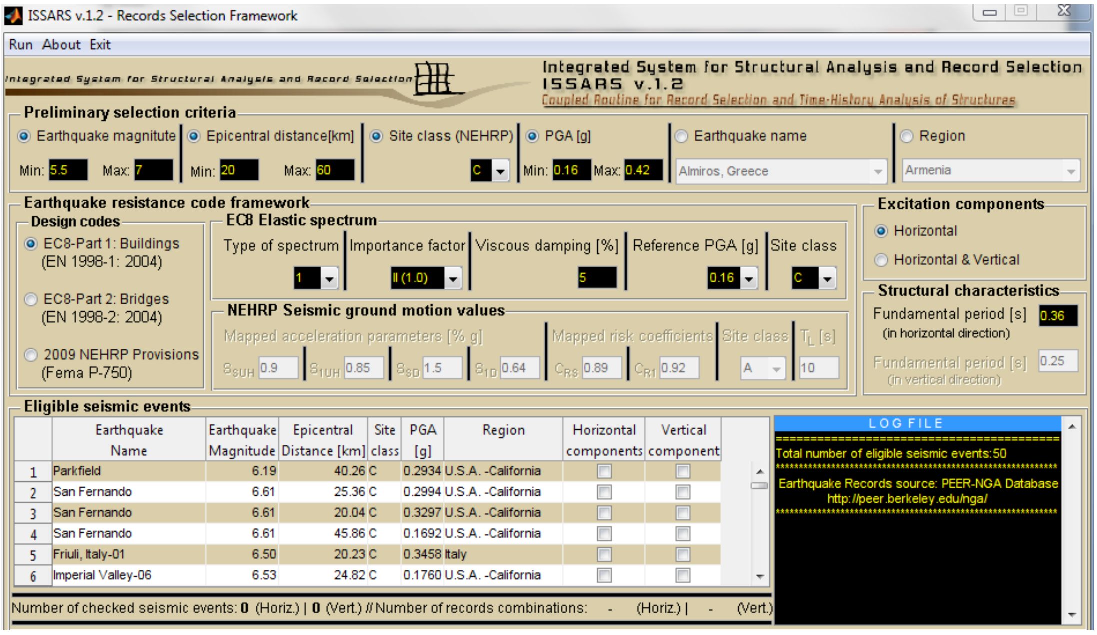

Figure 7. A Matlab-based tool for structure specific earthquake record selection [59]

5 Bio-inspired technologies & Knowledge-based expert systems.

During the last decades, various Artificial Intelligence (AI) techniques have been used to develop solutions for the design of problems where conventional computer-based approaches have been proved inadequate. Three are the main, widely used AI techniques applied to solve design problems: Case-Based Reasoning (CBR), Artificial Neural Networks (ANN) and Knowledge-Based Expert System (KBES). An overview of the available methods and application of the above methods can be found in two recently published works dealing with soft computing, ANN, genetic algorithms, [122] fuzzy [123] and hybrid neuro-fuzzy systems [124-125], as well as intelligent applications for structural and geotechnical engineering [126-129]. Despite the fact that a KBES typically lacks of intelligence, it can be considered effective for the explicit representation of both the knowledge base and the heuristic rule bases related to common civil engineering problems. Moreover, the explanation facility component that is inherently embedded in a KB expert system provides the advantage of gradual training of the user (instead of the system itself).

A number of KBES have been developed during the last years to solve various civil engineering problems. The most recent involve Expert Systems for the analysis and design of liquid-retaining structures [130], optimal selection of retaining walls [131], management of underground pipelines [132] and maintenance planning of highway concrete bridges [133-135] among others. The implementation of fuzzy logic into such civil engineering expert systems has quantified the uncertainty of various subjective factors as a part of the decision process [136-137]. Other Knowledge-Based Expert Systems that have been developed specifically for Earthquake Engineering applications) deal with decision support for reinforced concrete design buildings [138-141] and bridges [142-145], assessment of earthquake induced building damage [124], pre-earthquake assessment of buildings [85], soil-structure interaction [146] seismic assessment and conservation of historical buildings [147], and seismic retrofit [148]. More recently, a probabilistic performance-based proposal for seismic assessments of RC buildings based on the knowledge levels and the quantification of the uncertainty in the structural modeling parameters has been proposed by [149], while an optimization based computational framework for the life-cycle management of highway bridges has been presented by Okasha and Frangopol [150].

6 Visualization & GIS applications.

During the last two decades, many disciplines have embraced the power of Geographical Information Systems (GIS) for either visualizing spatially variable data obtained by conventional computing and manual methods or utilize the illustrated data for decision-making purposes. In a similar manner, GIS has also penetrated into the entire range of earthquake engineering applications, however, it is can be claimed that GIS is primarily used for seismic risk evaluation purposes (indicatively, [85-86], [151-153]).

Nowadays, a wide range of GIS tools are available as commercial (e.g., ArcView, ArcGIS, MapInfo) or public domain open source software (e.g., GRASS, SAGA, ILWIS, Quantum, GMT). Some loss estimation software tools are also interlinked to certain GIS platforms. An example is HAZUS-Multi Hazard [154] which is fully embedded into the ArcGIS software package (ESRI) and as such, although it is freeware itself, an ArcGIS license is required to fully function. HAZUS-MH developed and distributed by FEMA (www.fema.gov/plan/prevent/hazus) and it is both a software and a standardized methodology for estimating potential losses from earthquakes, floods, hurricanes and other natural hazards. It is probably the most widely used loss estimation software, at least in the U.S. A public-domain, GIS-based software package named REDARS2 (Risks from Earthquake Damage to Roadway Systems) [155] is another software for loss estimation that has been developed in the framework of a FHWA-MCEER Motorway Project in the US and includes, inter alia, post-earthquake congestion-dependent trip demands analysis, and a “decision guidance” model to guide seismic risk reduction decision making. The most recently released GIS-based tool for managing network risk is the open source code MAEViz [156].

In Europe, it is the International Centre of Geohazards (ICG; www.geohazards.no) that has been developing since 2004, through the independent geo-scientific research foundation NORSAR (www.norsar.no), an open-source software tool for seismic risk and loss assessment called SELENA [157]. A translator for this software has entitled RISe can be used to visualize the spatial data in Google Earth [158]. GIS-based seismic risk management systems have also been developed for New Zealnad [159].

For geotechnical earthquake engineering-related disaster management purposes, GIS has also been developed for spatially characterizing slope stability, evaluate the earthquake-induced landsliding susceptibility [160] and levee failures [161] as well as for the generation of “near-real-time” Slidemaps [162] utilizing the publicly available Shakemaps provided by the United States Geological Survey (USGS). A web-enabled geotechnical information system has also been developed on a GIS platform [163].

7 ICT applications in earthquake engineering education.

All the above advancements described in the previous sections have a common ground: the use of refined and sophisticated Information and Communication Technologies for enhancing the seismic safety of structures and infrastructure. Educators on the other hand, are faced with an ongoing challenge of creating engaging, student-centered learning situations that can relate classroom topics to both the tools developed and their pioneering applications. This is a critical step that not only reforms the traditional educational experience and procedure but prepares the students for complying with the new demands of their profession. Along these lines, ICTs are widely used for [164]: (a) improving the visualization and demonstration equipment in class, (b) developing interactive educational tools and software for distant and life-long learning related to structural, geotechnical and earthquake engineering applications [165-170], (c) utilizing “hands-on” experiments for demonstrating basic concepts in structural dynamics and earthquake engineering (i.e., portraying natural frequencies and mode shapes, studying the effect of earthquake input on the structural response), (d) setting up and executing bench-scale shaking tables at a lower scale, and (e) training students through “virtual” experiments in a self-learning environment [171].

Important role in the education of earthquake engineering through ICTs plays the NEES Academy for Education and Training of students, teachers and professionals which has been developed as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) operations. The Academy uses cyber-technology for delivering NEES-related resources such as complex computational simulations, learning modules, visualizations, multimedia presentations, video resources and interactive games, all serving the purpose of knowledge dissemination to the educational and professional community [172-173] and it is deemed that provides a continuous link between the students, educators and researchers.

8. Conclusions

This chapter is a review on the recent developments in Information & Communication Technologies (ICT) applications in the field of earthquake engineering. It covers a wide range of relevant topics, such as new software applications, web-based engineering tools, decision-making systems, tools for collaborative on-site and remote research, frameworks for hybrid simulation (coupled experimental and numerical modules), open source applications, tools for data and metadata dissemination and archiving, applications for mobile devices and remote computing as well as earthquake-specific GIS applications. Admittedly, the extent of the subject and the wide variety of the applications presented herein are prohibitive for an in-depth presentation and most importantly, for a critical evaluation of the tools and methods developed, hence the presentation is inevitably limited to a broad but still, rather superficial perspective.

Nevertheless, even in this framework, it is made clear that the future of research in earthquake engineering is inherently dependent on the Information and Communication Technological advances to be made in the years to follow and thus, it is not only the tools that will be developed based on specific needs of the engineering community, but the needs themselves will be transformed due to the rapid technological change. Along these lines, in a world that is changing more and more fast, it is evident that the threat of developing unrecoverable large technological gaps between generations, world regions and social classes, is *ante portas*. A framework for continuous knowledge transfer related to ICTs that could take place both horizontally (i.e., world-wise) and vertically (i.e., from the research to the professional community) is therefore deemed a prerequisite so as to ensure a uniform level of professional development, equal opportunities and after all, social cohesion. Education, collaboration, knowledge dissemination and life-long learning should be seen as priorities of equally high value with the primary investment in technology. After all, it is the human mind that drives evolution and as such it can control the direction of technological development so as to primarily serve humanistic values.

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