

RECORDING AND INTERPRETING EARTHQUAKE RESPONSE OF FULL-SCALE STRUCTURES

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ABSTRACT

Earthquake resistant design (or retrofit) of structures requires realistic and accurate physical and theoretical models. Validation and further improvement of these models can be done only by comparison with full-scale, in situ measurements of the response to earthquake excitation. This paper presents (a) a review of the principles this validation process is based on, (b) discussion of selected examples of past contributions to modeling of structures, and (c) an outline of some of the current research needs. It is concluded that, in the education of future engineers, the art of modeling full-scale structures, and breadth of knowledge in classical mechanics have been neglected, and that this trend should be reversed.

1. INTRODUCTION

To proceed with design of earthquake resistant structures, or to analyze the existing structures, the engineer begins by creating a model representation of the prototype. This model will form the basis for all subsequent analyses. It will be used to write the governing equations, to describe the structure by discrete or continuous parameters, and to compute the quantities required for design. Thus, this model must have the properties which will describe the response of the prototype as completely and as accurately as possible. The search for a *good model* is therefore the first and the most important step preceding the analysis and design processes. After the model has been specified, the engineer will analyze, design and test only that part of the real world which the adopted model is capable of representing.

The difficult task of selecting the model is compounded by the lack of attention the modeling process receives in our educational system. Too often we approach the modeling task backwards, choosing the model configuration and its properties so that we can accommodate the methods of analysis. We then complete the loop of appearances by experimental verification procedures which involve measurement of the most elementary (often incomplete) aspects of the response. Having accepted the simplified experimental program, which usually does not produce adequate constraints, we finally ignore the nonuniqueness of our solution. Of course, the critique will arrive eventually in the form of a careful and detailed analysis of a full-scale experiment, but often too late to correct the original design.

Is detailed modeling necessary for many engineering design tasks? After all, many design methods continue to rely on empirical and ad hoc procedures, many of which have been shown to be practical and adequate. The answers to these questions require considerations of the criteria defining the occupant safety and economic consequences, which both change with time. For example, thirty to forty years ago, analyses of earthquake losses focussed mainly on the replacement value of structures [43]. Today, and more so in future, with the growth and intricate interdependence of technologically advanced societies, which will live in dense metropolitan areas, reduction of indirect losses will govern in the selection of the required levels of safety [24, 25]. These new priorities will require

development of advanced design principles and criteria which will be aimed towards reducing losses from business interruptions, and will provide answers to the above questions. To prepare for the required changes in the design codes, we must initiate systematic development of advanced modeling techniques. This is feasible only through the use of the full-scale experimental measurements, which will guide us on how to single out the important phenomena and how to develop representative modeling and analyses.

The availability of representative dynamic models, and of carefully tested methods of analysis, will set the stage for realistic consideration of base-isolation methods, and of passive control techniques. Structural health monitoring will also become feasible, because the availability of representative models will enable selection of proper variables for real time monitoring. To implement the current and future advanced analyses, design, and control techniques, we must first solve the modeling problem, and to do that we must learn how to interpret better and document the actual response of structures to strong earthquakes. This can be accomplished by analyses of past recordings, and by continued but more advanced and detailed monitoring of response during future strong shaking.

The first key step towards creation of representative dynamic models of structures is to include the effects of soil-structure interaction. Soil-structure interaction has a profound influence on the form and on the solution of the governing equations of motion, and on the wealth of physical phenomena that accompany transfer of energy from the ground to the structure, and back to the ground. It offers advantages in the form of absorption and scattering of incident wave energy, before this energy enters the structure. These advantages must be brought to the attention of designers, and exploited fully before other more expensive and complex layers of protection, such as base-isolation or passive control are considered. Neither base-isolation, nor various ideas on structural control can be designed or implemented without including the soil-structure interaction effects in the controlling motions [46, 52–54].

In the following, we discuss the iteration steps in the learning process for development of representative models of structures. We illustrate these steps by examples from our past and current work on full-scale experimental studies. Finally, we summarize our view of priorities for future work. The mentioned full-scale experimental studies are only for illustration purposes, and do not represent a general and comprehensive review of literature on this subject.

2. SELECTED MODELING CONSIDERATIONS

The steps of the learning process (with the feed-back loops) which describe how to select representative models of engineering structures for dynamic response analyses are summarized in Fig. 1. The forward analyses include only the first three steps: (1) idealization of real structures, (2) mathematical representation and modeling and (3) analysis of response. The iterative learning process involves two additional tasks: (4) full-scale experimental verification and (5) revision of the previously adopted models. In the following, we discuss selected aspects of these steps and illustrate their role by reviewing examples from our previous work.

2.1 Idealization of Real Structures

This step constitutes the most important and the most difficult first step in any dynamic response analysis. Here the aim is not to overlook the importance of maintaining clarity and simplicity, while developing the model on the basis of deep understanding of the physical problem [4].

2.2 Simple Versus Detailed Models.

A tall structure, responding to long period (long wave) dynamic loads mainly in its first mode of vibration, could be represented by a single-degree-of-freedom (SDOF) system (Fig. 2a). The same structure, excited by high frequency (short wave) dynamic loads, will have to be represented by a detailed (continuous or discrete, two- or three-dimensional) model which is capable of representing relative deformations and the associated forces within the structure (Fig. 2b). A structure supported on “rigid” base (which deforms due to passage of earthquake waves, but does not deform due to forces caused by the structure), can be represented by a one-, two- or three-dimensional continuous shear beam model (Fig. 3a,b). Such representation can describe relative deformations within the structure and the way these depend on the internal distribution of rigidities [47–50]. In another example, the NS motions of a nine-storey reinforced concrete building, vibrating in its first mode during forced vibration tests (the effects of soil-structure interaction were included), could be represented by a bending beam model (Fig. 4a).

Forced vibration response of the same building in EW direction leads to large deformations of the foundation and floor slabs, and must be modeled in detail by the finite element method [31]. Structures with rigid floor slabs and flexible columns can be modeled via lumped mass models, where the mass of the floor structure and bottom half of the columns above, and top half of the columns below, are lumped at each floor level. The lateral shear stiffness can be represented by massless springs representing the total stiffness of all columns between adjacent floors (e.g. Fig. 3c) [69]. Such models are very common in both theoretical [15, 16] and forward engineering analyses [27].

In the example shown in Figure 4a, the deformation of the model (structure) can be specified by only one coordinate and can be described by one-dimensional wave equation. For structures with smaller height-to-width ratio, and with nonuniform distribution of stiffness (e.g. Fig. 3a and b), the use of two- or three-dimensional models and wave propagation analysis may offer advantages over vibrational description of the response [55].

2.3 Reduction of the Degrees-of-freedom.

The number of the degrees of freedom, which must be considered in the analysis, will depend on the type of the model (e.g. model in Fig. 2a versus model in Fig. 2b), and on the band-widths of the excitation. For a given model (e.g. in Fig. 3c), it may be desirable to further reduce the number of degrees-of-freedom. For example, two adjacent floors could be lumped into one mass, thus reducing the order of the linear system of differential equations by a factor of two. Such condensation of the degrees of freedom will lead to a reduction of computer time and may give adequate results as long as the outcome depends only on the low order modes of vibration (long wave lengths). Relative to the original model, the intermediate modes of vibration will have only approximate frequencies and mode shapes, while the higher modes and frequencies will be absent [9].

2.4 Linear Versus Nonlinear Analyses

In addition to the geometrical description of the model, the specification of the maximum amplitudes of response, and of material properties, the following needs to be defined:

(i) *Force displacement relationships.* These can be modeled, e.g. as linear elastic (Force, F , and displacement, x , are related by $F = k_0x$, where k_0 is a constant), nonlinear elastic (e.g. $F = k_0x + k_1x^3$, where k_1 is a positive or negative constant, this leads to Duffing equation), nonlinear hysteretic (e.g. F is defined by bi-linear hysteric spring) and so on.

(ii) *Amplitudes of response.* For large deflections, differential equations of dynamic equilibrium will involve nonlinear transcendental functions (e.g. sines and cosines).

(ii) *Stability.* For large amplitudes of response, simultaneous action of vertical and of horizontal inertial forces, in the presence of gravity, will lead to dynamic equilibrium equations which will result in time dependent excitation term influencing the stiffness term in the differential equations. The effective stiffness then may oscillate between positive and negative values, and for response amplitudes beyond the static stable deflections, the structure will enter the dynamic instability region and may collapse. This feature of the models is rarely considered in earthquake engineering studies [19], but should be included in every analysis dealing with large deflections and nonlinear response. The contribution of the soil-structure interaction to this dynamic instability is rarely investigated, even though it may be very important for “stiff” structures on “soft” soils.

2.5 Various Forms of Dynamic Coupling.

Many models of structures are symmetric and, for linear response, this makes the superposition principle applicable, and excitation in two orthogonal horizontal directions can be analyzed separately. For nonlinear response, the yielding members will cause sudden migration of the centers of stiffness, this will lead to strong coupling of the two horizontal translations with the torsional response, and the superposition principle does not hold. For nonlinear response of foundations, it is also usually assumed that the nonlinear response of symmetrically arranged piles, for example, does not lead to significant migration of the center of rigidity of the soil-structure interface. When this does occur, it can cause strong coupling of the torsional and the translational components of excitation [66].

2.6 Soil–structure Interaction

This describes a complex family of phenomena which are caused by the flexibility of the foundation soils. Analysis of soil-structure interaction requires consideration of additional degrees-of-freedom and, depending on the model, it may call for methods of solutions based on wave propagation. In general terms, the soil-structure interaction will lengthen the apparent period of the system, will increase the relative contribution of rocking excitation of ground motion to the total response, and will usually reduce the maximum base shear [53]. The advantages of including soil-structure interaction in the design of structural systems result from the scattering of incident waves from the foundation, and from additional radiation of structural vibration energy into the soil. When the soil surrounding the foundation experiences small to modest levels of nonlinear response, the soil-structure interaction will lead to significant loss of the available input energy. Since this energy loss occurs outside the structure, it will be one of the important challenges for future design of safe structures to quantify this loss and to exploit it in design.

The simplest way to consider soil-structure interaction effects is to assume that the building is supported by a rigid foundation. This results in minimum number of additional degrees-of-freedom (three translations and three rotations), but may lead to restrictive and too simple representation. Studies which model flexible foundations are rare [21, 30] and difficult to evaluate in absence of strong motion records. As far as we know, there exists no strong motion program to document distortions and warping of foundations of structures during passage of seismic waves [66].

The extent to which soil-structure interaction alters the apparent frequencies of the system response and changes the nature of the time functions of absolute and relative displacements, rotations, shear forces and bending moments in the structure ranges from negligible to profound, and depends mainly on the relative stiffness of the soil and the structure [53]. Recordings of strong motion in structures show that destructive shaking is usually accompanied by nonlinear response of the foundation soils [31, 64, 66], and that the time dependent changes of the apparent frequencies of response are usually accompanied by significant contribution of soil structure interaction [68]. Since the success of base-isolation systems, control of structural response, and of health monitoring depends on accurate representation of the anticipated and of recorded motions, it is clear that the nonlinear soil-structure interaction phenomena must be included in the analysis.

Experimental studies of soil-structure interaction are best conducted in full-scale, in actual buildings during microtremors [57–59], forced vibrations [5, 18], and earthquake excitation [32]. It is difficult to conduct soil-structure interaction tests in laboratories, not only because of the constraints imposed by the need to satisfy to similarity laws, but mainly because it is almost impossible to model the half space boundary conditions for the soils.

2.7 Dissipation Mechanisms

Modeling the dissipation of energy of a vibrating structure is constrained by the mathematical methods of analysis, and by the lack of comprehensive measurements which would show the physical nature of this dissipation [36]. Many linear response analyses use normal mode representation and, to maintain the advantages of working with decoupled equations, approximate the damping matrix by a linear combination $\alpha[m]+\beta[k]$ of the mass and stiffness matrices, $[m]$ and $[k]$, where α and β are constants. For an n degree-of-freedom system, this allows one to choose the damping only for two modal frequencies, ω_i and ω_j , and the remaining $n-2$ modes then have equivalent damping ratios $\zeta_k=0.5(\alpha/\omega_k+\beta\omega_k)$, which are not realistic. A common practice is to use constant damping ratios for all mode-shapes in the response analyses. This, of course, ignores the fact that the solution then violates the original differential equation.

In the presence of soil-structure interaction, the system damping depends on the damping in the building and in the soil, and on the scattering of wave energy from and through the foundation [31]. Design of foundations to scatter efficiently high frequency (short) waves can increase the apparent system damping and can reduce the amplification of the system response near the first mode of vibration [53].

In nonlinear response, the energy dissipation (damage) results from the work required to break structural components, to create plastic hinges and in nonlinear deformation of the soil supporting the foundation. For each

structure and excitation, this energy can be quantified by computing the work dissipated by the equivalent hysteretic forces, but it will be different for each case.

3. MATHEMATICAL REPRESENTATION AND MODELING

Mathematical modeling of full-scale structures, for the purpose of performing response analyses, aims to find those representations which will satisfy all the modeling requirements and the constraints of the available analytical tools. For analytical representation of the incident waves, and for linear response analyses, the foundation soil (or rock) has to be geometrically simple. With the analytical approach, it is practical to consider only simple topographic irregularities [28, 29] and simple soil and alluvium layers [33, 34]. More complicated surface topography and layering must be represented by finite element or finite difference models.

Simple symmetric structures can be modeled by analytical methods and can be analyzed via wave propagation approach. Geometrically irregular structures and those which are expected to experience nonlinear response must be modeled by lumped masses, finite elements or by other discrete representations [72]. Simple surface or embedded foundations can be approximated by rigid slabs, when the soil is relatively soft and when the foundation and the structure are expected to experience only small relative deformations. However, it is difficult to predict intuitively how realistic is such an assumption and the decision should be guided by data and experience from full-scale tests on similar structures. Soft (flexible) foundations can be represented by discrete lumped mass interconnected foundations [74], and this can be combined with finite element representation of the structure.

4. ANALYSIS OF RESPONSE

The method which will be used for estimation of response will depend on whether the response will be linear or nonlinear. For linear response, the analysis can be formulated in terms of transfer functions, which express the quantity of interest (e.g. displacement of a point, bending moment, stress) in the frequency space. When response time functions are required, inverse transforms can be used to obtain the results, and when only the estimates of the peaks of response are required, spectrum superposition methods, coupled with probabilistic estimation of peak values, will give the final results [14–16].

For nonlinear response, numerical integration of the system of governing equations must be carried out. This used to lead to lengthy calculations, but with modern computers it is becoming easier and faster [75].

5. FULL-SCALE EXPERIMENTAL VERIFICATION

For forward modeling, the above described three steps will produce the end result (Fig. 1). To verify the accuracy of this modeling, full-scale experiments can be carried out. The type of these experiments, the scope of measurements and the analysis of measured data will depend on the available sources of excitation, instrumentation and the specific purpose of the experiment. Components of full-scale structures may be tested in the laboratory, but evaluation of complete structures should be performed in full-scale. This limits the experiments to completed or to similar existing structures, and cannot be performed before the structure is built. However, systematic testing of the existing full-scale structures and careful interpretation and documentation of the results can go a long way towards creating a body of intuitive understanding, deep physical insight, and experience on how to extrapolate, and which essential steps to take leading to the core of complex new problems.

It should be noted that the laboratory tests can be very useful, but can never be as complete as full-scale experiments. Even the most carefully and completely planned laboratory work will represent only those aspects of the problem which the experiment designer chose to study and had incorporated into the model. That is, the best and the most complete laboratory tests can be used to verify and quantify mainly those aspects of the problem which the investigator knows. Except when fortunate accidents occur, we do not know how to model what we are not aware of and what we do not understand. The full-scale tests present a completely different set of practical problems, and the as built environment contains all the physical properties of reality. We only have to find ingenious ways to discover, record and interpret the reality.

Another point to be made is that the physical completeness and the reality of the full-scale structures is necessary but not sufficient to guarantee correct end results. The discovery and understanding of the true nature of response tend to be born by the difficult labor involving reconciliation between our imperfect theories, modeling and analyses, with often incomplete data from measurements. Experienced experimentalists know that the first test rarely produces results, as we inevitably forget to measure something, or what we measure does not turn out to be useful. Thus, iterations are almost a rule, in both experiments and in the analyses.

Often, the difficulty lies in nonunique features of our starting models and assumptions. For example, the transfer functions of horizontal roof displacement of a fixed-base building, and of the same building on flexible soil, have very similar appearance near the peak of the first fixed-base frequency, or near the apparent frequency of the soil-structure system. Using a simple identification technique, it is easy to estimate the “frequency” and the associated “fraction of critical damping” from full-scale measurements during an earthquake, but it is not easy to identify the factors which contribute to the formation of these peaks. Separation of the fixed-base frequency of the structure from the rocking and translation frequencies associated with soil-structure interaction is less straight forward and can be performed only if special purpose instrumentation and records are available. The list of investigators who overlook this nonuniqueness is so long that it seems that this problem is ignored in most published work. Along the same lines, it is common to find papers presenting analyses of nonlinear response of structural components with discussions of structural ductility and how it relates to the observed changes in the response period, without including in their analyses the fact that, shortly after the earthquake, the apparent period of the soil-structure system was back at or near its pre-earthquake value, indicating that the main source of nonlinearity was not in the structure, but in the soil supporting it.

Most of the above mentioned nonuniqueness can be eliminated by placing additional instruments to measure the rotation of the building foundation [31, 36], but so far this is not possible with most of the data recorded in the buildings in California. It is interesting to note that in spite of the fact that transducers which recorded rotational acceleration and velocity have been constructed and tested [39, 42, 73], essentially no buildings are equipped with such instruments, and so far the earthquake engineers do not seem to request such data.

Rotation of the foundation about a horizontal axis (rocking) can be calculated from the difference of recorded vertical motions at two points on a line perpendicular to the axis of rotation. The result represents the average rotations between the two points. To evaluate the actual point rotations, it is necessary to map the pattern of deformations of the building foundation, associated with the apparent frequency of the system prior to and following the earthquake (provided no damage occurred), using forced vibration tests, for example. This requires detailed full-scale testing and is not available for most buildings.

The experience shows that full-scale testing of structures, before and after significant earthquake shaking, must be very detailed if one is to find the location and the extent of changes (failures) in the material properties, and to identify differences with respect to the previous models, assumptions and analyses. The next generation of improved models and theory will be developed through reconciliation of differences with the current experimental results. This is clearly a difficult and time consuming work, and it is therefore not surprising that it is rarely carried out. Nevertheless, this is the only way we can learn how to measure what, where and how much to record. Before this work is completed, it is difficult (1) to see how to improve the full-scale observational programs, and (2) impossible to implement (correctly) various new ideas involving base-isolation, structural control, and structural health monitoring.

6. EXAMPLES OF FULL-SCALE TESTING AND ANALYSES

In the following, by way of examples, we illustrate the nonuniqueness associated with forward modeling, and some results on measurements of flexibility of foundations and iterations in modeling.

6.1 Forward Modeling Without Model Revision.

Empirical evaluation of fundamental vibration periods of buildings is used in building codes to calculate lateral earthquake design loads. For a building on flexible ground, the period of vibration of the soil-structure system [23] is

$$T = [T_t^2 + T_r^2 + T_{fs}^2]^{1/2}, \quad (1)$$

where T_t is the period of horizontal translatory vibration of the rigid building, T_r is the period of rocking motion of the rigid building, and T_{fs} the period of the first mode of vibration of an elastic building fixed at its base. Thus, the fundamental period of the system, T , compared to the period of the same structure on rigid base, T_{fs} , is longer.

Many empirical studies of T analyze the functional form of the dependence of T_{fs} , in terms of the type of lateral resisting system (e.g. moment resistant frames, shear walls), but ignore the contributions of T_r and T_t . For example Housner and Brady [17] refer to “foundation yielding” as a “second order effect”, while Goel and Chopra [13] ignore it [61].

An experimental study of the effects of soil-structure interaction in 1966 and 1967 concluded that the rigid body motion of the superstructure due to compliance of the soil contributed less than 1 percent to the total roof motion [20]. Repeated tests in the same building, in 1973 and in 1974 [11, 32], found that the rigid body motion contributes about 30 percent to the total roof motion (Fig. 5). While errors in data reduction cannot be ruled out [32], it has been argued [10] that this change is real and that it corresponds to degradation of the foundation system as a result of San Fernando Earthquake in 1971. That apparent periods of response, T , can change by factors approaching 2, during shaking by strong earthquakes, has been reported by Udawadia and Trifunac [68], but further systematic studies identifying the primary sources of these changes have not been carried out. Papers have been written describing these changes, and often ascribing them to the nonlinear response of structural components [20], but field evidence and later tests suggest that these changes are associated mainly with nonlinear soil response.

The above illustrates that verification and revision of the models of analysis followed by improvement of the original models and governing equations are more of an exception rather than customary in comprehensive and complete analyses. The consequences for the future research are serious. With so many past studies opting for simplified and only forward modeling, it will be increasingly difficult in future to convince researchers who work with base-isolation, identification, control and health monitoring that to test these ideas and to make them work in real buildings, all aspects of soil-structure interaction must be included in the analysis.

6.2 Nonunique Representation

A weakness of many past and present instrumentation programs, which contribute data on actual earthquake response of full-scale structures, has to do with lack of adequate number of transducers, and lack of minimum data required to describe motion and deformation of foundations of buildings. Even in most carefully instrumented structures, the transducers have been installed on the basis of intuitive expectation rather than detailed measurements and analysis. A classical example of counter intuitive outcome is provided by the problem of optimal placing of two horizontal transducers into a one-dimensional lumped mass model of a tall building with n stories, on fixed ground and deforming in shear (Fig. 3c). Intuitively, with only two recording instruments, one would choose ground level (A) and roof (B) to record future shaking, as we have done to instrument many tall buildings during the past 65 years. This however leads to $n!$ possible models which would be consistent with recorded motions at A as input and at B as output. A unique solution (i.e. one unique set of masses and springs) is possible, but the second instrument must be on the first floor (C), not on the n -th [67].

The lack of ideal physical access in buildings to the centers of mass, rigidity, and torsion results in placement of the recording instruments at some distance from these “ideal” locations. This results in recording a mixture of the desired components of motion. From the point of view of performing simplified identification analyses, such “contaminated” data may rule out the possibility for any meaningful interpretation. It is possible, however, to incorporate actual recording eccentricities for each position of the transducers into a linear representation of the recorded time series [36], and in this way separate translations from rocking and from torsion. Unfortunately, the recorded data is usually not accompanied by information on the exact location of the instruments (e.g. within the plan of each floor of the building). Information on the centers of rigidity and of mass requires analyses and interpretation, but could be verified via full-scale experiments prior to strong motion instrumentation in a building. The lack of reports with such information forces researchers to work with simplified models and assumptions. This limits the quality and quantity of possible inferences and often results in problems associated with nonunique representation.

The above incomplete information is further complicated by the lack of documentation on the accuracy of the transducer orientations, accuracy of relative timing of digitized data from individual transducers, and on transducer characteristics. It is, of course, difficult and may not be practical to place the sensitivity vectors of all transducers exactly along specified directions. It is possible, however, to describe their relative orientations with sufficient accuracy and to perform the required corrections [45, 56]. Data can be processed with very accurate relative time for different components [65]. Sufficient detail on measured transducer constants (sensitivity, damping, natural frequency, and electrical frequency and damping parameters for force balance accelerometers, for example) could be provided, so that advanced instrument correction algorithms can be used. Most modeling and identification analyses will benefit immensely from data which incorporates all these corrections and instrument parameters [37, 38].

At present, the digitized data is distributed without information on how the origin time of the traces has been identified, and it is not known how accurate the time coordinates are, and whether corrections for nonuniform film speed have been performed. It is further not clear what transducer corrections have been used. All this creates obstacles for knowledgeable investigators and limits the scope of possible inferences which otherwise they could extract from the recorded data.

Organizational efforts associated with maintenance of instrument arrays, data retrieval, data archiving, digitization, processing and dissemination are considerable. Therefore, it is difficult to suggest that instruments should be recalibrated at certain time intervals (and certainly following every strong shaking), and that important data should be digitized and processed again using advanced methods, followed by rigorous quality control [65], especially when unknown, but abundant recorded data has never been digitized and processed. The Strong Motion Instrumentation Program of the California Division of Mines and Geology (CDMG), the United States Geological Survey (USGS) and several private organizations have large volumes of excellent data which has not been processed (particularly data recorded in buildings). These data already contains invaluable information for improvement and modification of the earthquake design codes, and can be used to teach us how and what to instrument and record in the future.

6.3 An Example of Engineering (Forward) Modeling Analyses

The Imperial County Services Building in El Centro (Fig. 3d) almost collapsed during the 1979 earthquake in Imperial Valley, California. We have studied this building and the data recorded in it to find how successful a typical engineering analysis would be in predicting such response [27]. We found that, in the first iteration, we were not able to predict the actual response, and that the reasons for this were complex and in some instances beyond the state of the art at that time. Perusal of more recent attempts to do the same today, will show that we would probably have the same difficulties at present. It is still difficult to model foundations on piles, and to describe realistic distribution of stiffness in the soil-pile-foundation-structure systems. Almost 20 years later, little has changed. It is still an art to model structures by simplified commercially available computer programs, and we still do not have adequate number of such studies to have gained good understanding of how to improve our ability to model.

6.4 Rigid Versus Flexible Foundation Model

When soil-structure interaction is considered in the dynamic analysis of soil-structure systems, it is convenient to assume that the foundation is rigid. This assumption simplifies the analysis and reduces the required number of additional degrees-of-freedom to model soil-structure interaction, and thereby the number of simultaneous equations which must be solved. Whether such assumption can be made must be carefully investigated, and the outcome does not depend only on the relative rigidity of the foundation and of the soil, but can be influenced also by the overall rigidity of the structure, its lateral load resisting system and its orientation. As we already noted, this can be illustrated by comparison of NS versus EW vibrations of a nine-storey reinforced concrete structure which was studied by Luco et al. [31]. Even though the foundation system of that building is relatively flexible, for NS vibrations, two symmetric shear walls at each end (east and west) of the building act to stiffen the foundation slab, and this allows one to proceed with “rigid” foundation representation (Fig. 4a). For EW vibrations, the building carries lateral loads by an elevator core, which deforms the foundation slab in the middle, while the shear walls act as membranes providing axial constraints, but little bending stiffness (Fig. 4b). For EW vibrations, the foundation slab cannot be approximated by a “rigid” foundation model. These three-dimensional deformation shapes, which showed how this structure deforms while vibrating in NS and EW fundamental modes of vibration, were measured during forced vibration tests, and were essential for this interpretation.

Recent ambient vibration tests in a seven storey, reinforced concrete, moment resistant frame building have shown that the foundation supported by piles deforms during passage of microtremor waves. It was then inferred that the same happens during passage of much larger strong motion waves. Detailed ambient vibration survey of this symmetric structure, on symmetric pile foundations, showed that the center of torsion for this structure is outside the building plan, close to its south-eastern corner. Subsequent reexamination of the strong motion records in this building has shown that this eccentricity may have been present in all post 1971 excitations and that it is associated with some asymmetry in the soil-pile system, since the date of its construction, in 1966, or that it was caused by some partial damage during the 1971 San Fernando earthquake [66].

Differential motion of building foundations [60] may reduce the translational response at the upper floors, but leads to large additional shear forces and bending moments in the columns of the first floor. The response spectrum method can be modified to include the consequences of such differential motions [62], but it is necessary to document this via full-scale measurements during future strong earthquakes, and to correlate the theory with observations.

The assumption that foundations can be represented by rigid slabs seems to be implicit in most full-scale instrumentation programs for the buildings where strong motion was recorded so far. Technically, it should be easy to supplement the existing instrumentation to provide data on differential motion of building foundations. Ideally this should be done first in instrumented buildings where strong motion has already been recorded during many past earthquakes, so that additional value can be added to the existing data, interpretation and analyses.

6.5 An Example of Iteration in Modeling Soil-structure Interaction

Following many ambient, forced vibration, and earthquake recording experiments in a nine storey reinforced concrete building, and apparent inconsistencies in the data and its interpretation, we decided in mid 1970's to develop a comprehensive model, which includes soil-structure interaction, so that we could use it in interpretation of all the recorded data [31]. When this model was completed, comparison of the theoretical predictions with the recorded motions showed that the theory for computation of compliances available at that time (for rigid surface foundations) was not adequate to interpret the results. Our analysis and writing of the report were interrupted, and we started to work on refinement of compliance functions, so that the embedment could be considered explicitly. After new compliance equations were developed and tested, the original full-scale tests of the building could be explained, now resulting in excellent agreement between the theory and the measurements. Finally, the report could be finished, almost ten years after it was started.

Not every iteration of an experiment verification will take ten years to complete. With more focus and effort, our work could have been completed earlier, but it should be understood that complicated subjects take more time to understand and to master. The nature is full of fascinating examples showing that the time from conception to complete delivery is proportional to the complexity of the product. Clearly, there exists an upper bound on the time rate of creation and realization of technologically advanced ideas.

Finally it must be remembered that many valuable discoveries tend to be accidental, and so their production rate can be measured only in probabilistic terms. We may approach more advanced levels sooner by designing more ingenious experiments, processing and analyzing more recorded data in many different full-scale structures, all these over a longer period of time and focussing our attention on how to explain even innocent and small inconsistencies between the data and the theory. Focused initiatives and organized five or ten year programs may be counter productive, because the education of new experts and the time they need to produce significant new results are increasing with the complexity of the new challenges, and the time to delivery may be significantly longer than five to ten years.

7. SUMMARY, GENERAL COMMENTS AND SELECTED PRIORITIES FOR FUTURE RESEARCH

Successful and lasting contributions to advanced modeling require: (1) comprehensive gathering and preparation of representative databases, (2) education of young generations in modeling and analysis, and (3) development of general nonlinear theory to guide future data gathering, interpretation, modeling and education. The following discussion and presentation of selected priorities for future work may help initiate some efforts towards these goals.

7.1 Digitization, Processing and Dissemination of Response Data in Buildings and Other Structures

The ultimate tests of earthquake resistant design provisions came from recorded response and from observation of the performance of full-scale structures during severe earthquake shaking. Following the introduction of the first strong motion accelerographs to record ground motion in early 1930's, gradually instruments were placed also in buildings, dams and bridges to record their response. Following many organizational changes, today many cities in California still have local provisions requiring one or three accelerographs to be installed in buildings over six stories high (when the floor area is greater than 60,000 feet²) or over 10 stories high. At least several hundred buildings in the Los Angeles metropolitan area are believed to have recorded the 1994 Northridge earthquake. A fraction of these records is processed and distributed to researchers, but most of these data eventually end up in various archives, never to be seen or used in engineering analyses. Also, the United States Geological Survey (USGS), the California Division of Mines and Geology (CDMG), and several private and public organizations maintain recording stations in selected buildings. Following the Northridge earthquake, USGS collected records from over 30 high-rise buildings, 7 hospitals, 12 dams, 6 fire stations and 7 water and power distribution facilities [40]. CDMG recorded motion in 77 structures, including 57 buildings, 12 dams, 5 freeway interchanges, a toll bridge, an airport tower and a power plant [41].

In the former Soviet Union, various strong motion transducers and recorders were developed, mainly by the laboratories associated with the Institute of Physics of the Earth, in Moscow [12]. The lack of modern digitization systems for processing of analog records, and the emphasis on direct recording rather than computing the derived quantities (e.g., computing velocity and displacement from recorded acceleration) resulted in a series of transducer-galvanometer combinations which could be paired to measure directly acceleration, velocity and displacement [12, 37]. Buildings were instrumented systematically and in detail with many channels of simultaneous acceleration, velocity and displacement recorders (e.g. [3]). Most of the recorded data is still archived in various laboratories of the newly formed independent countries (Armenia, Uzbekistan, Tajikistan, Kazakhstan), has never been processed, and soon may be lost due to the lack of support or local wars.

Our goal should be to digitize and process these data, and then to analyze it so that we can be guided by the results, in formulation of future instrumentation and recording needs.

7.2 Analysis of Data Recorded in Buildings and Other Structures

All the data recorded so far should be analyzed and interpreted, so that systematic work on linear and nonlinear response and modeling can be initiated without delay. This analysis will also provide sound basis for future selection of recording techniques and for better coverage of recorded motions through design of more advanced recording systems. Finally, it will help by leading towards wiser deployment of the available transducers.

For many years, typical building instrumentation consisted of two (basement and roof) or three (basement, roof and an intermediate level) self contained tri-axial accelerographs interconnected for simultaneous triggering. The early studies of recorded motion [31] noted that such instrumentation cannot provide information on rocking of building foundations, and that this information is essential for identification of the degree to which soil-structure interaction contributes to the total response. Beginning in the late 1970's, new instrumentation was introduced, based on central recording of individual, one component transducers (usually force balance accelerometers). This instrumentation provided greater flexibility to adapt the recording systems to the needs of different structures, but budget limitations and lack of understanding of how different structures would deform during earthquake response, often resulted in recording incomplete information [27]. The outcome is that the recorded data is used rarely in advanced engineering research, and usually only to provide general reference for the analyses.

7.3 Full-scale Testing and Upgrading of the Existing Instrumentation

In addition to the analyses of earthquake records in buildings, it will be necessary to document further the three-dimensional deformations accompanying the principal modes of vibration of instrumented buildings. This will facilitate the work on advanced modeling tasks.

Full-scale forced vibration and ambient vibration tests will help demonstrate how important it is to consider soil-structure interaction. Simplified soil-structure interaction provisions are included in NEHRP [6] and Applied Technology Council [2] codes, but these provisions are voluntary and are often neglected in design. At present, there is a common perception that ignoring soil-structure interaction results in conservative design. The factors which have contributed to this situation could be related, in part, to a common belief, prevailing up to the early 1970's, that the contribution of soil-structure interaction to the observed response is small. By late 1970's, it became clear that soil-structure interaction effects cannot be ignored, but neither code design provisions nor the principles governing the decisions on how to instrument the buildings seem to have recognized this. A simple and useful "standard" approach would have first performed detailed three-dimensional ambient vibration tests in the buildings [22, 31, 57–59]. Next, based on the three-dimensional deformation and mode shapes from these tests, a knowledgeable committee could have selected the optimum number, location and orientation of sensors for future recordings. When necessary, subsequent repetition of ambient vibration surveys could have compared the results with the previous "finger-print" of the structural system, thus documenting the state of the structure preceding the earthquake and the subsequent changes. This approach would have created numerous possibilities for new studies and better understanding of the response of actual structures, and would have acted in a positive way towards quality control for all forward calculations of response [27].

The Northridge earthquake of 1994 provided, so far, the most valuable and abundant data on strong ground motion and on response of structures. However, it seems that little will change, in spite of the fact that many experts have started to recognize the discrepancies between what we perceive and what the nature does. In contrast, looking back more than 60 years ago, it is remarkable with how much foresight and how energetically the researchers of that time set out to measure and understand the phenomena associated with the response of full-scale structures. In the introduction to a report entitled "Vibration Observations" (by Carder [7]), referring to instrumentation and testing of full-scale structures, L. Jacobsen wrote: "The work done by the United States Coast and Geodetic Survey is of such fundamental importance to the engineering profession that it makes a distinct milestone in our quest for better knowledge of how to build earthquake resistant structures." Then he continues to say that "without these and similar tasks, we should be in the dark as to whether or not certain proposed theories have experimental confirmation." In the same issue of "Earthquake Investigations in California, 1934–1935," after introducing another article (by Blume [5]) which describes an early model of a "centrifugal force agitator," Jacobsen states: "An experimental study of periods of vibration of buildings may be made by observing free transitory vibrations set up in the structures by impulsive external agencies, as for instance, wind gusts. Under these conditions a building will vibrate in a number of its natural modes" It will take forty years for this idea to be revived and fully affirmed as a useful tool for full-scale in situ testing of engineering structures [8, 59, 71].

7.4 Instrumentation Development and Deployment

Transducers which measure rotation have been developed and used to record the response of soils and structures to strong shaking, but the measurements of angular accelerations and velocities did not gain popularity so far. Except for a few isolated cases, such instrumentation is generally not available and there are no significant databases to study strong motion rotations [39, 42, 73].

The traditional view has been that strong motion instruments should be designed to have high dynamic range, proper sensitivity and recording accuracy in as broad frequency band as possible. What we tend to overlook is that many problems in engineering can be understood and interpreted only by capturing the spatial variations of response, and that this calls for dense array type measurements, with small inter-station separation, to be able to record "short" wave lengths. Simple estimates call for deployment of many small aperture arrays, with each array containing hundreds to thousands of transducers, all working together. In the framework of the currently available instrumentation costs and the budgets which can be expected for such projects, the initial purchase and maintenance costs, immediately rule out such experiments. We must take advantage of the new technology to develop such systems, deploy such dense arrays, and maintain them in operation for 30-50 years.

7.5 Education

It seems that, at present, the earthquake engineers are not properly trained in mechanics. Paraphrasing Biot [4], both scientists and engineers working in the field may have "become victims of narrow specialization... Many are almost

totally ignorant in classical mechanics and are not able to understand the formulation of even simple problems unless it can be reduced to the solution of..." a differential equation of single-degree-of-freedom viscously damped oscillator.

Perhaps it is difficult to find another topic in earthquake engineering which has grown and matured so well, and for which so much has been accomplished as has been the case for soil-structure-interaction. Furthermore, there is hardly any other topic which is more central and fundamental to the response analysis, and which offers so many powerful possibilities for implementation of passive energy dissipation, and which is at the same time less used, less understood and less considered in engineering design. There is no doubt that the principal reasons for this lie in our educational programs. Most universities just do not offer adequate number of lectures on soil-structure interaction, and so cannot build up the students understanding to the required mathematical level, which would allow professors to teach the intricacies of the physical nature of this problem. Timoshenko wrote "...a student should be taught, of course, *how* to use the method, but this is not enough. He should also understand *why* it works..." [44]. Since all advanced concepts of response control, such as base-isolation, active and passive control, and use of smart materials, all depend on our ability to write correct and representative differential equations describing the response, it is essential to initiate systematic and rigorous education of the future researchers and engineers in soil-structure interaction.

7.6 Full-scale Tests and Modeling Studies

Following a brief and productive period, from about 1965 to 1975, when many useful force vibration and ambient vibration experiments were conducted, the earthquake profession seems to have converged toward small-scale laboratory experiments. From 1984 to 1992, perusal of papers published in the proceedings of World Conferences on Earthquake Engineering, will reveal about 100 to 150 papers (per conference) describing various experimental investigations. Only ~6 percent of these papers in 1984 (8WCEE, San Francisco), ~8 percent in 1988 (9WCEE, Tokyo-Kyoto) and ~3 percent in 1992 (10 WCEE, Madrid) were related to experiments with full-scale structures. In 1996, "Earthquake Spectra" [1] published a theme issue entitled "Experimental Methods" which contains nine papers. These papers neither discuss nor reference full-scale tests of structures. An uninitiated reader might conclude that we are dealing with an anachronistic subject, but the time will show that systematic gathering and processing of strong motion data recorded in buildings, combined with comprehensive full-scale tests of the same structures, is the best and the only real laboratory where scaling and similarity laws do not pose problems, and where the boundary conditions are never approximated. By contrasting and combining the full-scale ambient vibration tests of a building with what the available records of earthquake response can show, we may influence those who decide where and how many transducers to use in instrumenting the full-scale structures, and what and how many records to digitize for engineering research applications. With this paper, we wish to contribute towards initiating a new phase of rational full-scale measurements for future earthquake engineering research and design.

Analyses and interpretation of experimental measurements are difficult because the recording resolution may not be adequate or the location or type of the instruments are not suitable for the structure being tested. Most successful experiments require a series of tests where the preceding tests and their interpretation serve as a guide on how to perform the next test. This may require far more work than what is feasible for most commercial analyses, but the results are always invaluable and always teach us how to model the structure for computer simulation [22, 26, 35, 70].

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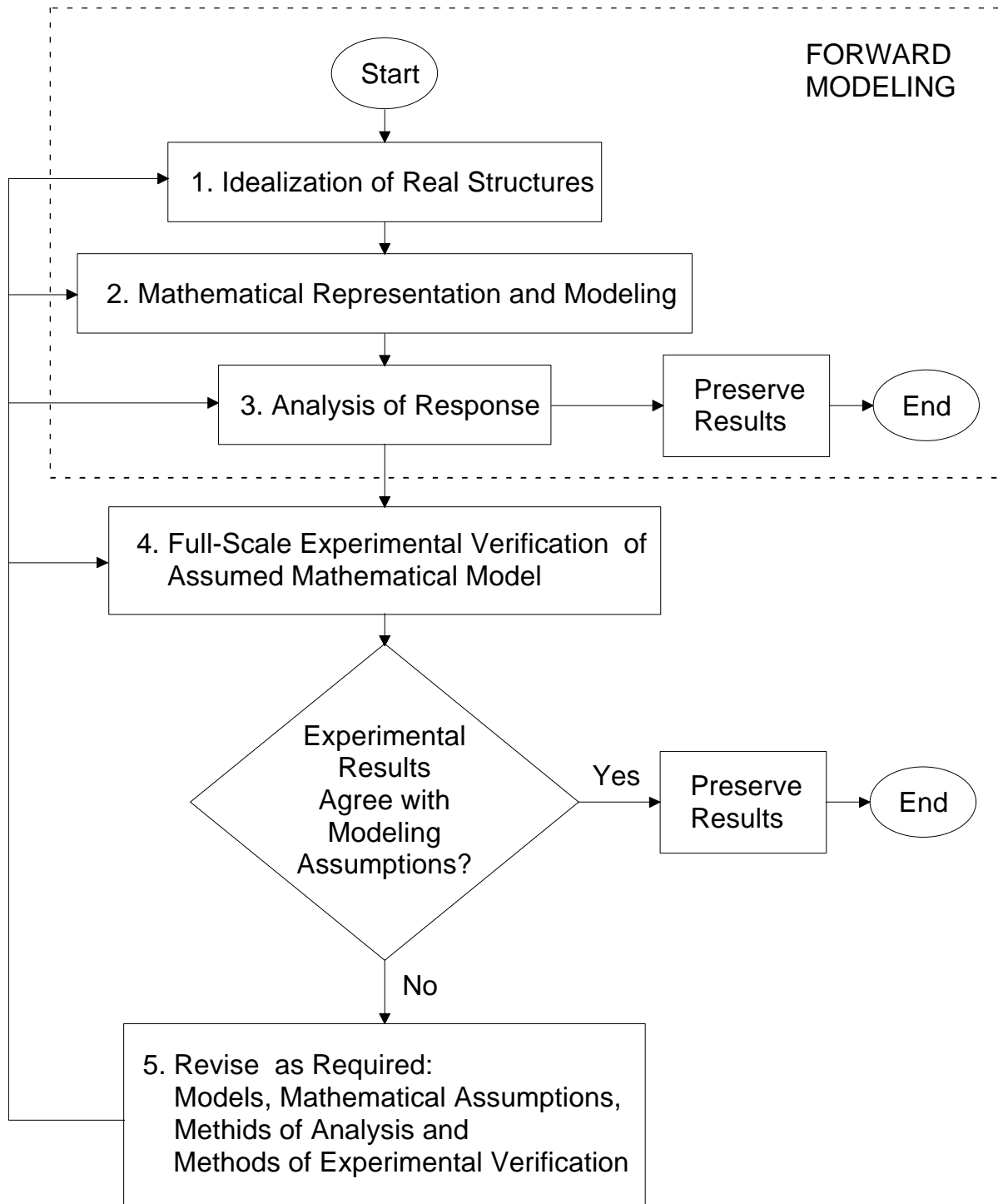


Figure 1. Steps in the learning process of selecting representative models of engineering structures for dynamic response analyses.

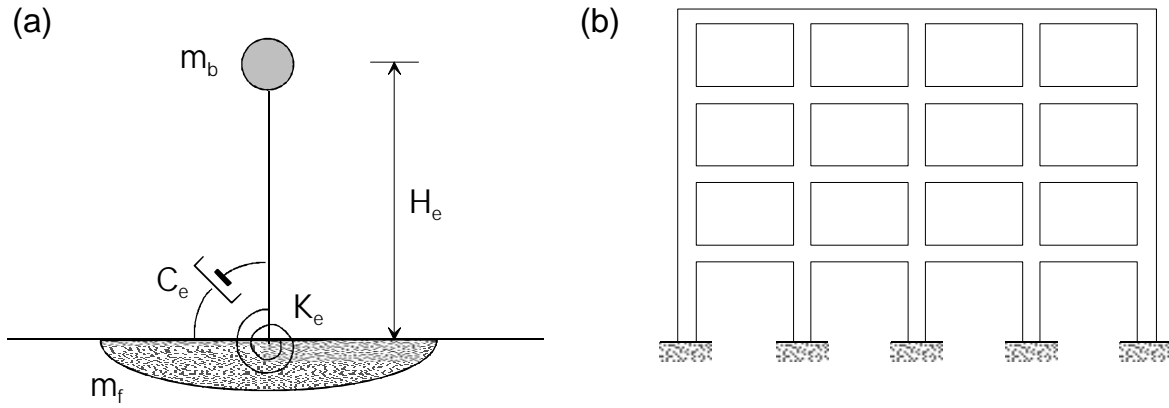


Figure 2. (a) Equivalent SDOF system (with damping C_e , rotational stiffness K_e , equivalent mass m_b , equivalent height H_e , on a rigid foundation with mass m_f) supported by flexible soil. (b) Multi-degree-of-freedom system (e.g., moment resistant frame) supported by independent spread footings on elastic soil.

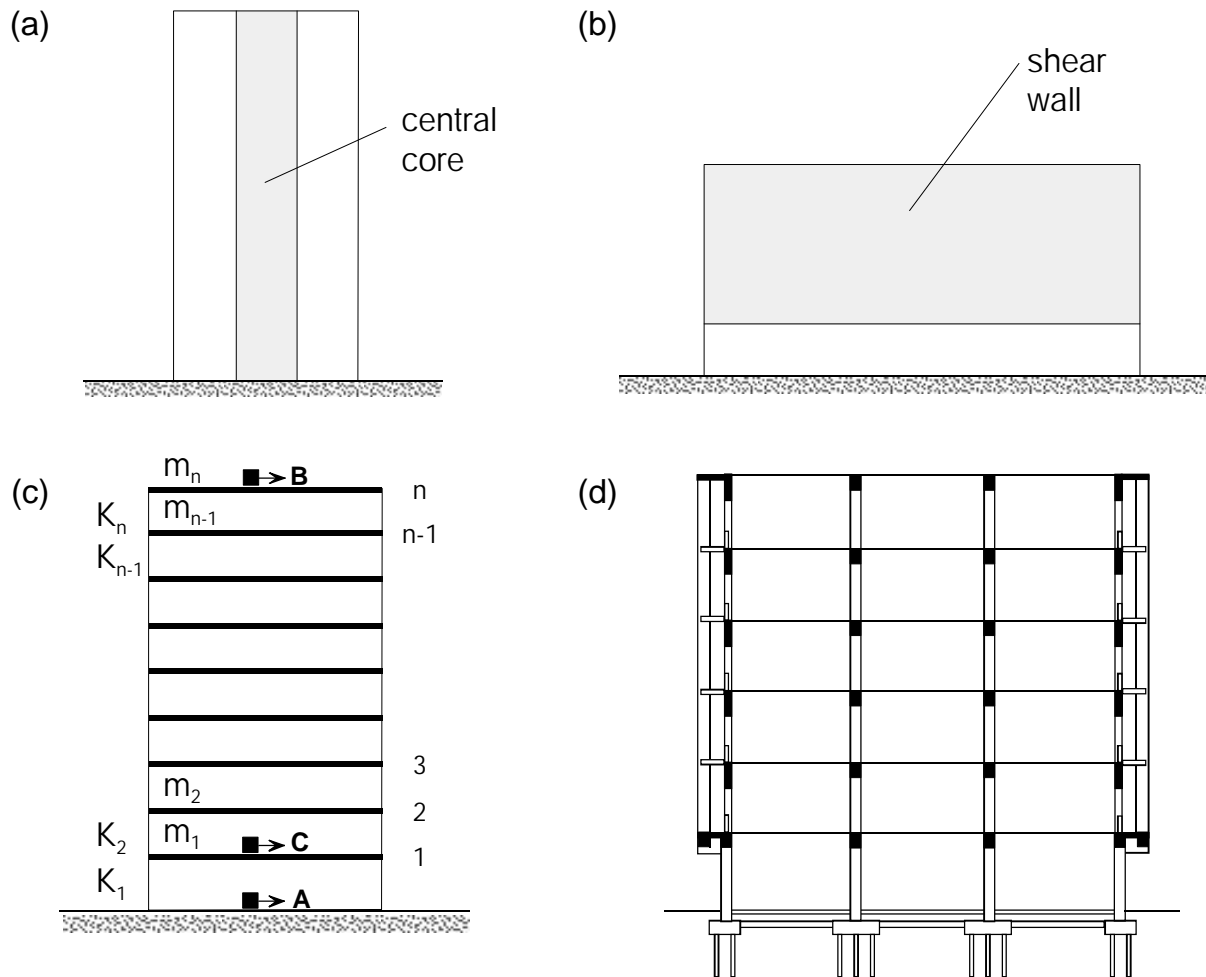


Figure 3. (a) Continuous model representation of a tall building with a stiff central core [55]. (b) Continuous model representation of a building with a soft first storey, on flexible soil [55]. (c) Discrete MDOF system of an n -storey building with rigid floors (m_i -floor mass, K_i -floor stiffness, A, B and C-strong motion instruments). (d) A section through a six-storey reinforced concrete structure supported by a foundation on piles [27].

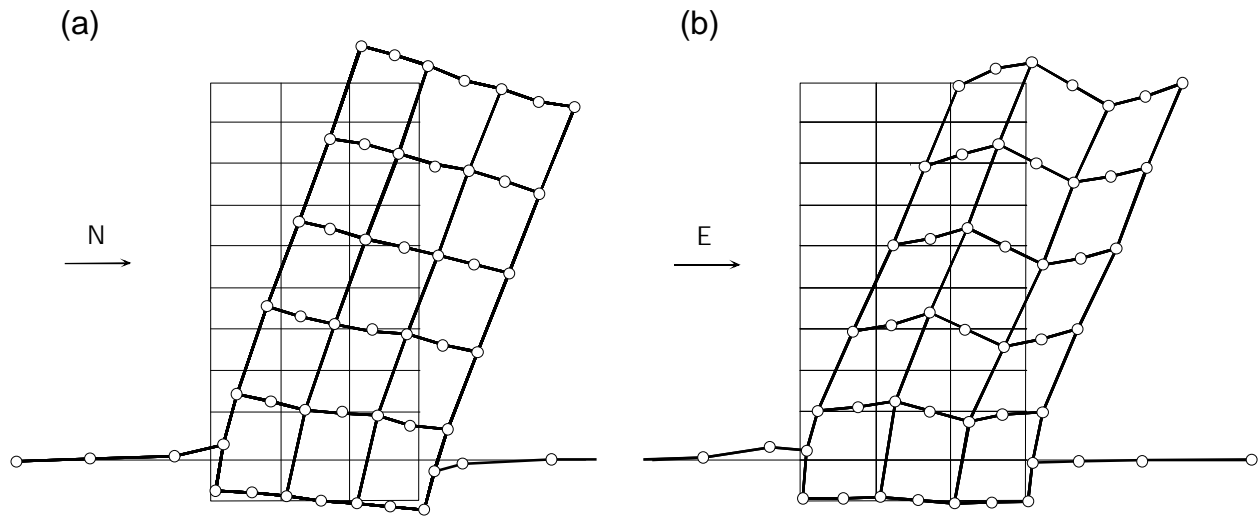


Figure 4. Deformation of a nine-storey reinforced concrete building excited at the roof by a shaker with two counter rotating masses [11] (a) along the west shear wall, and (b) along a section through the elevator core.

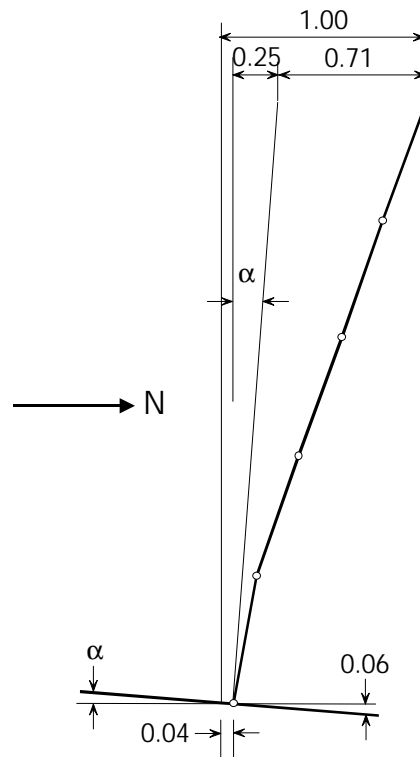


Figure 5. Contribution of foundation translation and rocking to the roof motion for N-S shaking of the nine-storey reinforced concrete building.