FHWA Recommendations for Seismic Performance Testing of Bridge Piers

by

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ABSTRACT

The demand on seismic performance data of structural components and systems increases rapidly as a result of multiple level performance requirements introduced in latest design methodologies. Seismic performance data need to be produced in consistent condition and presented in forms that can be compared to each other. The current practice of seismic performance testing of bridge piers employs diverse testing conditions. Some of the variations are due to a lack of consensus-based testing guidance. Such unnecessary variation impedes the data comparison with other research and reliable engineering application of the testing results. This paper reports the current problems and resolutions recommended in a Federal Highway Administration (FHWA) document on seismic performance testing methodologies of bridge piers. This document contains information on specimen preparation, loading, and documentation of bridge pier seismic performance testing. This document is purported for use with both scientific experiment and engineering validations. It provides elaborate description on an assembly of practical testing procedures while alternatives are offered for special testing needs. Procedures are provided for testing piers made of conventional or advance material. Requirements on test records, which are consistent with the needs in establishing or expanding seismic performance databases, are given to enable user access and verification on the test results. Technical terms used in seismic testing and seismic design are clarified. An expert panel including members from academia, state highway agencies, and federal government, was assembled to advise the development and to review the product.

KEYWORDS

Seismic performance, testing, experiment, pier, protocol

1.0 INTRODUCTION

1.1 Seismic Performance Testing and Seismic Design Criteria

The advancing of seismic design methodology and specifications is closely associated with findings and verifications produced by laboratory testing. The accumulation of seismic performance data can support both engineering practice and development of performance-based seismic design criteria. Since a simple static horizontal earthquake load was introduced to the Standard Specifications for Highway Bridges in 1961, the seismic design for bridges has become more sophisticated as a result of the persistent experimental and theoretical studies on bridge systems and bridge components over the years.

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The latest version of the recommended LRFD design (ATC/MCEER, 2003) is composed of multiple definitive performance objectives and associated design criteria. Bridge components are required to maintain specified service and damage level under corresponding earthquake events. Seismic performance testing is often necessary to verify compliance with multiple performance objectives of new or existing bridges.

Most pre-1980 seismic performance testing of structural systems and components targeted building structures. The results were extrapolated for use with bridge seismic design. Organized experimental projects and performance data accumulation for bridge components have been carried out since the early 1980s (Stone and Cheok, 1989). The National Institute of Standards and Technology (NIST) produced a collection of pier testing data in 1993 as an attempt to assist utilization of the limited amount of bridge pier testing data. This collection included a reference, digital top force-displacement histories, key material properties, as well as a description of the test geometry for 199 concrete column tests dating back as far as 1973. The database was later expanded in a Pacific Earthquake Engineering Research Center (PEER) project (Hose et al., 2000), providing additional details of the tests, including the P-Δ configuration and the maximum column deflection imposed before reaching various damage states.

1.2 Deficiencies in Practice of Seismic Performance Testing

Many early seismic performance tests of structural components were custom designed and executed for individual use. Such practice can be characterized by having

1. Intuitive loading program
2. Diverse definitions on limit states
3. Insufficient data for error analysis
4. Limited measurement records

Structural components exhibit different service performance and damage propagation under different cyclic loading programs. Results from using one program can hardly be translated to those from the other programs. An intuitively designed cyclic loading program does not well represent a reasonable seismic demand in a real earthquake. The variation of intuitively determined cyclic loading programs can introduce difficulties in verifying seismic design or developing seismic design criteria.

Loading programs and testing results are often presented in terms of some limit states. For example, amplitudes of cyclic loading programs for bridge pier testing are often given in terms of displacement ductility, which is directly related to yielding displacement. Two testing results cannot be compared to each other if the yielding limit state is not defined consistently.

Error control is critical in combining or comparing existing testing results. Testing for specific purpose may adhere unique error tolerance in specific part of testing setup or execution. Information regarding error control is easily discarded after the immediate purpose of the testing is fulfilled. The addition of P-Δ configuration to the NIST-PEER column testing database clearly demonstrates the demand of error-control parameters from the users of testing data.

The column behavior under seismic loading is a combination of many local phenomena. Description using single load-deformation data series omits much valuable information that can be used in further study. For example, a curvature profile and reinforcement strain distribution can be very useful for developing numerical models of specific cross sections. A data series composed of force-displacement or moment-drift-rotation relationship is insufficient for such study.

1.3 Testing Protocols

One approach to remedy the above deficiencies is to establish a testing protocol for each specific type of testing to regulate the preparation, execution, and documentation of the testing. The Applied Technology Council (ATC) initiated an effort in 1988 to develop guidelines for seismic performance experiments of steel elements, and published the “ATC-24 Guidelines for Cyclic Seismic Testing of Components of Steel Structures” (ATC, 1992). The SAC program, a joint venture of the Structural Engineers Association of California (SEAOC), ATC, and the California Universities for Research in Earthquake Engineering (CUREe), published a testing protocol specifically developed for steel moment-frame connection testing (SAC Joint Venture, 1997). The ATC protocol and SAC protocol were developed for research purpose. The adoption of these protocols as acceptance criteria for steel building design by the "Seismic Provisions for Structural Steel Buildings" of the American Institute of Steel Construction (AISC) invested them with status of proof-test protocols. The American Concrete Institute (ACI) also adopted a similar acceptance testing protocol for concrete element since 1999 (ACI, 2001). In 2001, the Consortium of Universities for Research in Earthquake Engineering (CUREE) woodframe program published a series of loading protocols for cyclic testing of elements without clear yielding behavior under regular and near-fault earthquakes (Krawinkler et al., 2001). The above protocols have limited scopes in terms of material, types of structure, and testing methodology. All these protocols are developed for building structures. Each protocol targets steel, concrete, or wood structural components. The only testing methodology in all these protocols is cyclic loading testing. They are written in a provisional format that imposes requirements to the associated testing projects.

The Guide Specifications for Seismic Isolation Design (AASHTO, 1999) classifies the testing of isolation bearings into three types: system characterization tests, prototype tests, and quality control tests. Testing requirements are given in the guide specifications, NIST guidelines (Shenton, 1996), and Highway Innovative Technology Evaluation Center (HITEC) guidelines (HITEC, 1996). Other bridge components do not share these classification and testing methodologies. Bridge structural components such as bridge piers are massive and mostly cast on-site. Their seismic behavior includes non-recoverable damage. It is not practical to perform quality control tests on these bridge structural members. Even prototype tests are relatively rare for bridge piers.

In view of a lack of guidance document on seismic performance testing of bridge piers, the Federal Highway Administration (FHWA) initiated a study to summarize theories and current practice of pier testing and produced recommendations on preparation, execution, and documentation of pier seismic testing. A guidance document is produced to assist researchers and engineers to carry out pier seismic testing that produces data for multiple uses. This paper briefly summarizes the findings of the FHWA study and a preview of the guidance document produced in the study. Detailed discussion can be found in the FHWA report "Recommendations for Seismic Performance Testing of Bridge Piers" (in final preparation for publication as of March 2005).

A similar effort was made by the Public Works Research Institute (PWRI, Japan) to address seismic performance testing of bridge piers in Japan. Coordination between the Japanese and U.S. efforts on this subject was maintained by including joint members on the panel of each side. Documents produced by both sides will be compared and possibly synthesized upon completion.

2.0 CRITICAL ISSUES IN PLANNING A SEISMIC PERFORMANCE TESTING

The planning of a testing project needs to include considerations on:

1. Functions of the test within the scheme of the study
2. Performance objectives: clarifying unknown issues or verifying designated performance requirement
3. Subject and event: realistic response or general benchmark
4. Loading methodology by the research requirement and facility capability
5. Documentation requirements

2.1 Functions

Figure 1 shows the possible routes of a complete seismic performance research course. The optimal route can be determined by the consideration of research needs, cost/time consumption, and equipment availability. Analytical approach normally costs less but bears more uncertainty in the results. Figure 2 (Moncarz, 1981) shows a qualitative representation of effectiveness of analytical and experimental approaches with respect to the complexity of the engineering problem. The functions associated with experimental stages shown in figure have much influence on the experimental design and execution. Functions 1-a and 1-b represent functions of typical testing projects carried out in academia (scientific experiment) while function 2 represents the testing that validates immediate engineering application (proof-of-concept testing).

Bridge piers differ from other structural components by their large dimensions, complexity of load combinations, low redundancy, and importance to public welfare. Due to a variety of functionality, safety, and aesthetic requirements, the design of bridge piers is greatly diversified. A large amount of experimental testing is required to provide a confident estimation of many parameters. In contrary with this demand, seismic testing of bridge piers is often carried out with a limited number of specimens due to high cost and time constraint for constructing and testing each specimen. One pier testing often carries partial functions of both scientific experiment and proof-of-concept testing. A protocol style document does not provide adequate aids to such testing. The FHWA guidance document uses a unique format that imposes less restriction while provides guidance. Options and alternatives are provided to each part of the testing along with explanations of advantages and limitations.

2.2 Performance Objectives

Performance objectives of a scientific pier experiment can vary in a wide range due to its academic origin. Performance objectives of a proof-of-concept pier testing are very specific in accordance with the requirements of the engineering problem in hand. It is, however, very common that one test can fulfill objectives required by proof-of-concept testing while providing abundant information for scientific research. This is especially beneficial for pier testing because of the need to retrieve maximum amount of information from limited specimen. For example, bridge design normally does not utilize the displacement capacity with significant decrease in lateral resistance. Pier behavior with decreasing lateral resistance is therefore not always required by tests for engineering application purposes. However, most pier tests, including proof tests, proceed beyond the required design performance objective in attempt to better understand the failure mechanism and to reveal the remaining capacity that possibly result in improvement of design criteria.

2.3 Subject and Event

The selection of testing subject (prototype) and seismic event unique for different testing purposes. In the matrix shown in table 1, the time-history simulation is the only type of testing that provides a demonstration of structural response under an earthquake. However, structural response can be completely different under two ground motions from the same process and similar parameters. Results from one or two of such testing may contain very special behavior that does not represent the general behavior of the respect subject under similar earthquakes. A general loading program (such as displacement-prescribed cyclic loading) can provide abundant information on the general performance and damage progression under a range of earthquakes although incapable of providing realistic detailed results for demonstration and verification. Same analogy applies to the generality of subject selection.

2.4 Loading Methodology

Seismic performance testing is often named after the loading methodology used in the test. Table 2 lists the names of testing by the source of load and loading speed. Each loading methodology inflicts unique assumptions and equipment requirement. For example, rate-dependent properties of material are assumed insignificant when slow testing is used. A displacement-prescribed loading program bears the assumption that the prescribed displacement history reasonably demonstrates the damage propagation in an earthquake. The shaking table testing with distributed load has the testing environment best resembling a bridge under earthquakes. However, most shaking table tests use relatively small scale specimen due to high equipment demand for large scale testing. Scale reduction also introduces additional possibility of errors. A sensible choice for loading method is one of the critical issues in test planning.

2.5 Documentation

Recording of testing results need to include the information needed immediately in the corresponding research project as well as some commonly demanded information to allow others to utilize the data. As more advanced seismic experimental facility become available and become integrated through network, data format and interchange protocol compliance are becoming more stringent.

3.0 TESTING PROCEDURE

An individual experimental project can be roughly divided into three stages: specimen preparation, loading, and measurement/documentation. Each type of testing inflicts unique requirements in every stage. Some typical issues in seismic performance testing are discussed in the following sections.

3.1 Specimen Preparation

Specimens must be designed with considerations of:

1. Resemblance to the subject: The specimen should resemble the subject of the test in all significant aspects, including geometric proportion, material behavior, and construction tolerance.
2. Generality over a group of subjects: If the objective is to study the general properties of a group of bridges or a class of bridge components, the specimens should well represent the group of bridges or the class of bridge components that the testing is designated for. Multiple specimens may be necessary when parameters of the subjects cannot be portrayed by a single specimen.
3. Practical for available resources: The testing facility must have sufficient space and load/displacement/velocity capacity to accommodate the specimen and carry out the loading programs associated with the specimen design.
4. Providing needed information: The specimen must provide access to desired measurements.

The specimen preparation comprises two steps: prototype determination and scaling. The prototype can be the structural system or component of a real bridge, a virtual bridge that represents a group of bridges, or a generic bridge. The size reduction and simplification introduced in scaling can produce various amount of unrealistic seismic behavior. Engineering professional judgment is needed to identify the dominant features of the prototype that need to be preserved.

Proper scaling is derived based on similitude theory. The primary concern in the derivation of scale factors is to prevent scaling the parameters that are difficult to change, e.g. elastic modulus, density, viscosity, and/or gravity. In structural testing, the restraining of the aforementioned parameters results in unavoidable distortion. Among the scale factors for Quasi-static testing shown in table 3, superstructural weight is scaled to S_L^2. If the superstructure is a geometrically proportional scale model, the weight would be scaled to S_L^3. The superstructure therefore cannot be a true replica of the prototype. The scaling for dynamic mechanical testing in general experimental theory is discussed under two different assumptions regarding gravity. If gravity is significant, the scaling of acceleration needs to be consistent with the scaling of gravitational acceleration, i.e. unscaled, except in a centrifuge. If gravity is negligible, the acceleration can be scaled independently to allow better control in specimen size. The significance of gravity in seismic performance testing depends on the proportion of gravity-induced stress and ground-motion-induced stress. Due to the massiveness of superstructure of bridges, self-weight of bridge piers is negligible in most cases (although mass of pier is not always negligible for the lateral inertia force it produces). Therefore, the scale factors provided in table 3 are <u>all based on the scaling methods that neglect gravity</u>. The difference in the two types of dynamic scaling shown in table 3 is the source of axial load on the pier specimen. For the case "superstructure not supported by specimen," the axial load in the specimen is provided by loading machines (e.g. hydraulic jacks). More possible configurations and corresponding scaling can be found in the FHWA guidance document.

3.2 Loading Programs

3.2.1 Limit States

Limit states are the primary link between testing results and practice in seismic design. Limit states are also used to define loading programs in seismic performance testing. Consistent definitions for limit states are crucial for both seismic performance testing and for seismic design. An example of inconsistent definition is found on the yielding displacement. This limit state is a critical parameter used in designate amplitude of cyclic loading programs. It is also extensively used in seismic design specifications in a form of displacement ductility. It needs to be defined accurately to ensure adequate translation from testing results to design criteria. However, the only available consensual definition for yielding displacement is the displacement at the elastic limit of the bilinear idealization. The method to obtain the bilinear idealization is diversified. ATC-24 protocol offers a method to identify yielding displacement before yielding occurs, which is inconsistent with the practice specified in Caltrans Seismic Design Criteria. It is currently difficult to determine a best definition. To avoid inaccurate interpretation, the FHWA guidance document discussed a few available methods and their relationship with design criteria.

3.2.2 Displacement-prescribed Loading

The displacement prescribed loading history has a wide range of complexity from the simplest monotonic increasing loading to sophisticated loading history resembling earthquake response. A sensibly selected loading history can provide a good basis for observing damage propagation and a benchmark performance measurement to compare different technology. However, a universally adequate and effective loading history does not exist. Attempts have been made to produce protocols suitable for various uses (such as ATC, SAC, ACI, and CUREE protocols. See introduction). The establishment of these protocols is based on combinations of statistical studies on seismic responses and consensus among users of the protocols. The critical factors of these protocols are the reference deformation used to define loading amplitude, the amplitude of loading cycles, and the number of cycles at each specific amplitude. For example, ATC-24 protocol uses yielding displacement as the reference deformation, amplitude with increment equal to the yielding displacement, and three cycles at each amplitude with a reduced number of cycles (two cycles) at larger amplitude. In order to address the issues related to steel moment frame performance after Northridge earthquake and to address difficulties in using ATC-24 protocol, SAC protocol made a number of changes to the three factors. The fixed drift rotation values, as a substitute for multiple of yielding displacement, is used to define amplitude. Increment of amplitude ranges from 0.125% to 1% drift rotation. Number of cycles at each amplitude ranges from two to six. The SAC program contains more cycles in lower amplitude to incorporate the findings in latest earthquakes. The difference between these protocols demonstrates the requirements in loading protocol for different earthquake characteristics and structural system behavior.
There is currently no universal method that generates adequate loading program for corresponding earthquake and structural system. Before a universal method becomes available, the consensus-based loading protocol practiced in each special application remains useful for keeping testing results comparable.
As a result of extensive discussion with experimental experts and user group, the FHWA guidance document includes several existing loading protocols that represent different earthquake characteristics (near-fault or far-field) and suitable for different pier types (concrete, steel, wood, or innovative material). Figure 3 gives an example that is suitable for reinforced concrete pier testing (based on the ACI protocol).

3.2.3 Inertia Loading

For a single-degree-of-freedom testing setup for a nonlinear pier column behavior, the equation of motion can be written as:

$$m\ddot{x} + R(\dot{x}, x) = -m\ddot{x}_g$$

in which m is the superstructural mass, x is pier top displacement, and x_g is ground displacement. The force R(.,.) represents a total reaction force from the specimen, which resists the sum of inertia force from the ground motion (right hand side of the equation) and inertia force from the structural response (first term on the left).With the same ground motion, the force applied to the specimen is greatly influenced by the structural property. The response data have significant value on the structural performance in entirety but rather limited information on the pier column performance benchmark.

3.2.4 Boundary Conditions

The properties of abutment and superstructure have significant influence on seismic loading to piers, bearings, and footings. For a number of reasons, most testing structures use simplified abutment and superstructure conditions. Certain simplification can be adequate for one loading method but inadequate for others. For example, specimens for cyclic testing often include the portion of a pier up to the flexural inflection point. Any seismic load inflicted by the mass above this point is simplified to the form of a few loading protocols. Such simplification does not introduce more uncertainties than those inherent in the protocols. On the other hand, shaking table testing is purported to faithfully reproduce seismic behavior of a specified structural system under specific earthquake. Accurate simulation of abutment and superstructure is critical for producing adequate seismic load.

3.2.5 Secondary Effect

The P-Δ effect produced by the large displacement at the loading point. This effect exists in both the loading machine (e.g. hydraulic jacks swaying) and the specimen. The combination of the two effects can produce a variety of different influence on the specimen response. When considering the effect of a specific cross section in a pier specimen, the P-Δ effect can be removed from the result data. However, the bending moment profile of P-Δ effect is inconsistent with bending moment profile of other force effect (see figure 4). The influence of P-Δ effect to the entire specimen may not be effectively separated from other force effects. This difficulty should be mitigated by both careful design of the loading apparatus and thorough documentation.

3.3 Measurement & Documentation

The desired types of records may have certain bearing on the selection of specimen design and loading methodology. For example, if detailed visual observation is necessary, quasi-static testing may be more desirable. As the knowledge of structural component behavior increases, more detailed observation on structural components and construction material during an earthquake is needed to make further progress in research. In the mean time, the information technology infrastructure has grown to be capable of accommodating large amount of data archiving and data query. Simple force-displacement relationship is not sufficient anymore. Figure 5 shows a basic configuration of instrumentation for pier dynamic testing. Some data are essential for describing the mechanical behavior of the bridge pier, which include load-deformation relationship and measurements for curvature and strain. Some additional data is critical for error control. Some examples are the measurements of slippage or deformation at fixture (a, b1, and b2 in figure 5). The NSF-funded research equipment project “George E. Brown Network for Earthquake Engineering Simulation (NEES)” is becoming operational. Interest in multiple site testing and need for an integrated database for earthquake simulation testing demand a consensus-based testing and documentation guidelines. The documentation methodology given in FHWA guidance document can serve as a reference and potentially assist in the development of a similar document for NEES.

4.0 SUMMARY

- Performance-based seismic design approach inflicts an increasing demand on seismic performance testing data.
- There is a lack of guidance document on seismic performance testing of bridge structural components.

- Without a guidance document, the comparison and interpretation of results from different testing project are difficult. Testing conditions of previous testing cannot be verified and results cannot be reused. Such deficiency in current practice leads to a waste of experimental resource and reduction of confidence in research conclusions.
- The FHWA recommendations on bridge pier testing procedures provide aids on selection of testing methodology, specimen preparation, loading, and instrumentation/documentation. Advantages and limitations of each testing methodology are provided. Critical issues and frequently encountered problems are discussed. Dynamic loading methods suitable for various purposes are collected and refined. Basic documentation requirements and format are given to allow reexamining and reusing of the testing results.
- The FHWA guidance document is not a protocol. It intends to define consistent testing condition without imposing excessive restraints that impedes scientific studies.
- The seismic testing technology is far from mature at this moment. Any guidance document is subject to revising periodically to maintain up-to-date.

5.0 ACKNOWLEDGEMENTS

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Table 1 Types of subject and seismic event

	General	Realistic
Subject	Representative parameters for a large group of bridges (ex. mean, median, or popular parameters)	Replica of a specific bridge (ex. scale model for an existing bridge)
Event	Prescribed program (ex. cyclic testing, monotonic testing, harmonic loading testing)	Time history simulation (ex. earthquake simulation shaking table testing, pseudodynamic testing, or hybrid testing)

Table 2 Classification of testing by loading methodology

Loading / Speed	Prescribed displacement loading	Inertia loading	
		Distributed load	Point load
Slow	**(A)** Quasi-static Monotonic loading (A1), Quasi-static cyclic loading (A2)	N/A	**(D)** Pseudodynamic tests
Fast	**(B)** Fast monotonic loading (B1), fast cyclic loading (B2). (Not recommended)	**(C)** Distributed mass shaking table tests	**(E)** Lumped-mass shaking table tests (E1), effective force tests (E2), hybrid tests (E3)

Table 3 Scaling of seismic performance testing specimens

Variable	Quasi-static (A)	Dynamic and Pseudodynamic (C, D, E)	
		Superstructure supported by specimen	Superstructure not supported by specimen
Length ℓ	S_L	S_L	S_L
Time t	N/A	$S_L^{0.5}$	$S_L^{0.5}S_a^{-0.5}$
Stress σ	1	1	1
Strain ε	1	1	1
Elastic modulus E	1	1	1
Force P	S_L^2	S_L^2	S_L^2
Displacement U	S_L	S_L	S_L
Bending moment M	S_L^3	S_L^3	S_L^3
Curvature ϕ	S_L^{-1}	S_L^{-1}	S_L^{-1}
Acceleration	N/A	1	S_a
Superstructure mass	N/A	S_L^2	$S_L^2S_a^{-1}$
Superstructure weight	S_L^2 (axial force)	S_L^2	S_L^2 (total axial force)
Frequency	N/A	$S_L^{-0.5}$	$S_L^{-0.5}S_a^{0.5}$

S_L: length, S_a: acceleration

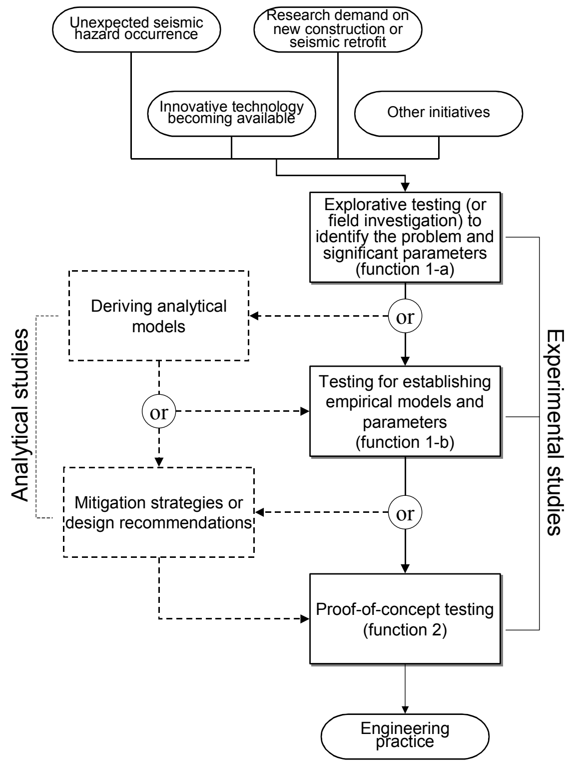

Figure 1 Seismic performance study

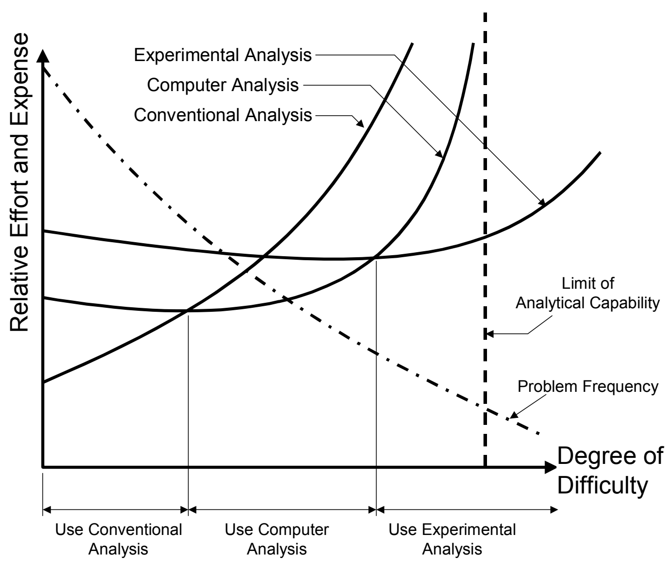

Figure 2 Effectiveness of analytical/experimental approaches

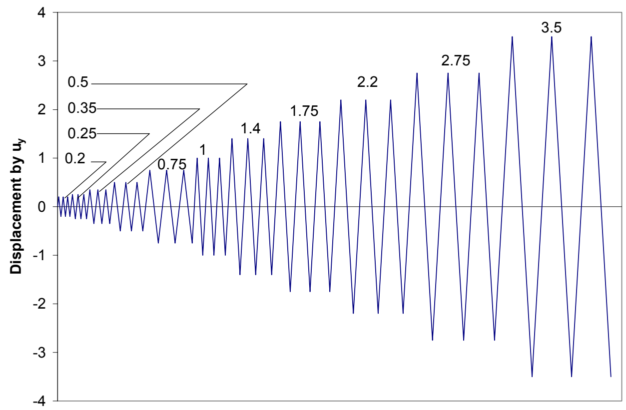

Figure 3 A loading program based on ACI protocol

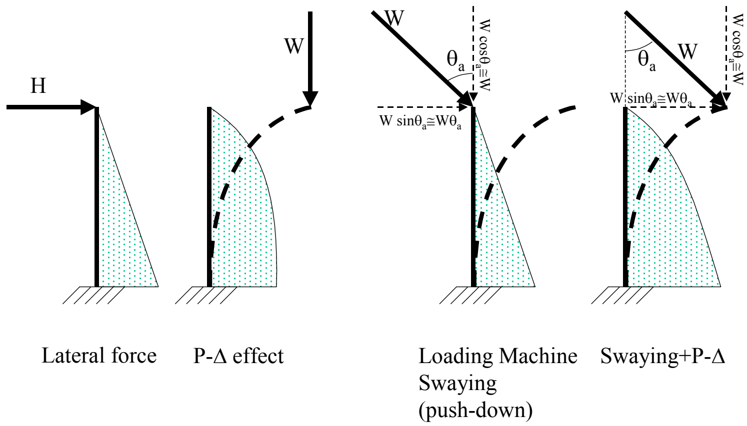

Figure 4 Breakdown of secondary effect

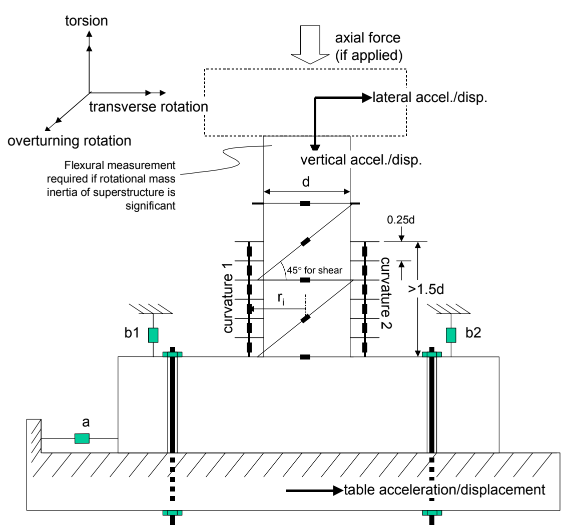

Figure 5 Basic measurements for bridge pier shaking table testing