NCHRP 25-25/Task 72

CURRENT PRACTICES TO ADDRESS CONSTRUCTION VIBRATION AND POTENTIAL EFFECTS TO HISTORIC BUILDINGS ADJACENT TO TRANSPORTATION PROJECTS

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Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACHP	Advisory Council on Historic Preservation
ADC40	Committee on Transportation Noise and Vibration
APE	Area of Potential Effect
APTA	American Public Transit Association
BART	Bay Area Rapid Transit
BETP	Built Environment Treatment Plan
Caltrans	California Department of Transportation
CFR	Code of Federal Regulation
CIDH	cast-in-drilled-hole
DOTs	Departments of Transportation
EIS	Environmental Impact Statement
FHWA	Federal Highway Administration
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
NCHRP	National Cooperative Highway Research Program
NHL	National Historic Landmark
NHPA	National Historic Preservation Act
NRHP	National Register of Historic Places
PHA	Project Historical Architect
PPV	Peak particle velocity
SHPO	State Historic Preservation Officer
THPO	Tribal Historic Preservation Officer
TRB	Transportation Research Board

1. INTRODUCTION

NCHRP identified a need for a comprehensive compilation of current and successful practices that address construction vibration impacts on historic buildings adjacent to roadway construction projects. The goal of this compilation is to help historic preservation resource agencies and organizations, departments of transportation (DOTs), and the public understand the technical aspects of vibration impact studies.

To prepare the compilation of current and successful practices, the research team conducted a review of literature authored in the United States and abroad to identify the current state of the art for assessing the fragility of historic structures and their susceptibility to damage, for monitoring vibration transmission from construction projects, and for mitigating potentially damaging vibration.

The research team also surveyed state DOTs and other agencies to understand how they currently address this issue and to identify several case studies that illustrate how construction vibration effects on historic buildings have been recently evaluated.

This report summarizes the results of the literature search and the survey of transportation agencies and provides a detailed discussion of seven informative case studies. A recommended guideline approach for addressing construction vibration effects on historic buildings has also been provided.

2. BACKGROUND ON VIBRATION AND DAMAGE

2.1 Terminology

The following discussion provides basic information on how construction-induced vibration is generated and measured. More information on terminology is provided in Appendices A and B.

Operation of heavy construction equipment, particularly pile drivers and other impact devices such as pavement breakers, creates seismic waves that radiate along the surface of the earth and downward into the earth. These surface waves can be felt as ground vibration. Vibration from operation of this equipment can result in effects ranging from annoyance of people to damage of structures.

As seismic waves travel outward from a vibration source, they excite the particles of rock and soil through which the waves pass and cause the particles to oscillate. The actual distance that these particles move back and forth is usually only a few ten-thousandths to a few thousandths of an inch. The rate or velocity (in inches/sec) at which ground particles oscillate varies from low values that are barely measureable (0.001 inches/sec) to values that can be more than 5 inches/sec. This maximum velocity value, referred to as the peak particle velocity (PPV), is a commonly accepted descriptor for ground vibration amplitude.

2.2 Construction Activity

Construction that can result in significant levels of ground vibration generally falls into two categories that best are characterized by the cause of the vibration and its duration. Vibration that is steady-state and more or less continuous can be caused by vibratory compaction of soil, vibratory pile driving, movement of large equipment, and other sources. In contrast, vibration that is much more transient in nature and intermittent due to impulsive forces can be caused by pile driving and blasting. Researchers on vibration and its effects on older, more fragile buildings generally indicate which type of vibration they are evaluating, but often do not distinguish between the two nor indicate that the type of vibration can have different effects on a structure. It is important to keep the two types of vibration in mind when setting vibration limits.

2.3 Vibration Propagation

Vibration travels through the ground from the point at which energy is imparted (e.g., blast), spreading out and getting reflected from different soil layers. As it travels, vibration attenuates because of the spreading and damping properties of the soil or rock through which the vibration travels. Consequently the process of vibration propagation is often complex and difficult to predict for any given site. However, some sites have enough empirical data available for use in predicting vibration away from the source.

2.4 Building Response and Damage

The manner in which a particular building will respond dynamically to strong ground vibration depends on many factors, among which are the soil on which the building is founded, the building's foundation (e.g., spread footing, piles), the building's mass, and the stiffness of the building's main structural elements. Whether dynamic motion will damage the building's structure and its architectural features (e.g., interior surface finishes) depends in large part on the type of construction (e.g., masonry) and the elastic behavior of the building material at higher levels of strain. Wood and steel are more elastic than masonry, such as brick and stone. Interior finishes that are more susceptible to damage are those such as lath and plaster. The condition of a building and its maintenance are important factors when assessing susceptibility to vibration damage and must be taken into account when setting vibration limits.

A modern categorization of damage, which is contained in BS Standard 7385: Part 1: 1990 (BSI, 1990) and ISO 4866-2010 (ISO, 2010), follows. Note that dusting of cracks may occur even when no cosmetic damage has been observed.

- Cosmetic: The formation of hairline cracks on drywall surfaces or the growth of existing cracks in plaster or drywall surfaces; formation of hairline cracks in mortar joints of brick/concrete blocks.
- Minor: The formation of large cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.
- Major: Damage to structural elements of the building, cracks in support columns, loosening of joints, splaying of masonry cracks, etc.

In these documents, the term "threshold damage vibration level" is defined as the highest vibration level at which no cosmetic, minor, or major damage occurs.

2.5 Building Settlement

The study conducted by the research team is focused on the direct shaking effects of construction-generated ground vibration on historic buildings. In a situation where the soil has high liquefaction potential, construction vibration can cause ground settlement or shifting that significantly reduces support provided by the soil. Rather than vibration itself, this ground settlement or shifting of the ground can cause damage to the building. This situation requires a geotechnical engineer and a review of analysis, mitigation, and monitoring processes that is beyond the scope of this study.

3. SECTION 106 PROCESS

3.1 Section 106 and Vibration

The National Historic Preservation Act (NHPA) establishes a process to evaluate potential effects on historic properties that may be caused by federally-funded or approved projects. This process would apply to potential damage to historic properties caused by construction vibration. The following discussion summarizes the NHPA process and how the process might apply to damage caused by construction vibration.

3.2 The Section 106 Process in General

The process to minimize potential harm and damage to historic properties outlined in the NHPA is commonly referred to as the Section 106 process. Section 106 mandates that each responsible federal agency "take into account the effect" of its project on historic properties. An "historic property" is any property that is listed in or qualifies for listing in the National Register of Historic Places (NRHP). Most commonly, these properties are buildings or archaeological sites.

The NHPA also creates the Advisory Council on Historic Preservation (ACHP) and empowers it to administer the Section 106 process. The ACHP published detailed regulations in 36 Code of Federal Regulation (CFR) Part 800, which lays out the Section 106 process. The NHPA also established the position of State Historic Preservation Officer (SHPO) and created the NRHP. Each SHPO is primarily responsible for implementing the Section 106 process in their state. The law also creates a position of Tribal Historic Preservation Officer (THPO), who has SHPO-like duties and powers on tribal lands.

The ACHP regulations lay out a four-step process for "taking into account" impacts on historic properties:

1. Initiating the process.
2. Identifying the area of potential effect and historic resources therein
3. Assessing effects.
4. Resolving adverse effects.

These steps are discussed in detail below. Most projects typically involve only the first three steps. It is only when there is an adverse effect that all four steps will be taken. The agency responsible for the undertaking leads the process. The SHPO or THPO is consulted during all four steps.

3.2.1 Initiating the Process

The first step is the simplest of the four. The agency must decide whether its project, or "undertaking," is subject to Section 106. Certain types of activities, such as planning efforts, are not subject to Section 106 because they have no potential to cause harm to an historic property. It can be assumed, however, that any construction-related activity that is federally permitted or funded is subject to Section 106.

3.2.2 Identifying the Area of Potential Effects and Historic Resources

The second step involves determining whether there is an historic property within the area that might be affected by the project. The Part 800 regulations use the term "area of potential effects," commonly called the Area of Potential Effect (APE), to refer to the impact zone.

The first step in the identification process is defining an APE, which is usually delineated on a map. The APE can differ from one type of project to the next depending on the undertaking. Defining the APE can be especially critical in assessing effects associated with construction-related vibrations. The regulations define an APE as "the geographic area or areas within which an undertaking may directly or indirectly cause alterations in the character or use of historic properties" (36 CFR 800.16 (d)). The APE for a highway construction project typically encompasses the actual construction zone plus adjacent buildings, recognizing that construction may cause visual and auditory impacts beyond the actual construction zone. In many cases, those adjacent buildings could also be subject to damaging construction vibration impacts. It is possible, however, that the APE for vibration impacts would be different than the APE for visual impacts. The vibration-related APE should be defined on the basis of good science for predicting the area in which such impacts would likely occur.

A second sub-step within the identification process is to determine whether any of the properties within the APE meet the definition of "historic property" under Section 106. With many projects, there are properties that qualify for listing in the NRHP but which have not been formally evaluated. In such cases, the project proponent typically hires a preservation consultant or relies upon qualified staff to determine whether these properties meet the eligibility criteria necessary for listing in the NRHP.

In the many cases, the process ends at this point because there are no historic properties within the APE. When it is known that an historic property is located within the project's APE, however, the agency would move to the third step, assessing effects.

3.2.3 Assessing Effects

In this step, the responsible agency must make a finding as to whether the project will have an effect on an historic property. Effect is defined as "alteration to the characteristics of an historic property qualifying it for inclusion in or eligibility for the National Register" (36 CFR 800.16 (i)). The regulations allow for three types of findings: no historic properties affected; adverse effect; and no adverse effect.

A finding of no historic properties affected is used in two ways: there are no historic properties within the APE; or the historic properties within the APE will not be affected in any manner.

A finding of adverse effect is a conclusion that the project will cause an adverse effect on an historic property within the APE. Adverse effect is defined as an action that would "alter, directly or indirectly, any of the characteristics of an historic property that qualify the property for inclusion in the National Register in a manner that would diminish the integrity of the property's location, design, setting, materials, workmanship, feeling, or association" (36 CFR 800.5 (a) (1)).

A finding of no adverse effect is used in situations in which an effect will occur but the effect is not so severe that it meets the definition of an adverse effect. This finding is common in projects that involve repair or rehabilitation to an historic property. The rehabilitation work will "affect" the historic building but that effect will not be adverse if the rehabilitation is consistent with accepted historic preservation standards, as stated in the Secretary of the Interior's Standards for Treatment of Historic Properties (36 CFR part 68).

Potential effects from vibration could be determined to be adverse depending upon the projected severity of damage to an historic building. If an engineering analysis indicated that vibration from highway construction would have a high likelihood to cause a building to suffer structural damage, that result would obviously be an adverse effect. However, the vibration projected by the engineer as likely to cause cracking (cosmetic damage changing the building's appearance), but not weakening the structure might be seen as a lesser, but still adverse, effect. The resolution of potential adverse effects depends on many factors, which are discussed next.

3.2.4 Resolving Adverse Effects

This step is taken only when there is a finding of adverse effect. In this step, the responsible agency consults with the SHPO, the ACHP (if the ACHP chooses to participate), and with other consulting parties to arrive at steps that would reduce the adverse effect to an acceptable level or would mitigate for the adverse effect. Following this consultation, the various parties will memorialize the terms of their agreement in a Memorandum of Agreement (MOA).

There is an almost limitless range of terms for an MOA, depending upon the nature of the potential adverse effect. In a situation where construction of a project would require removal of an historic building, the MOA might specify that the building be recorded photographically prior to its destruction. This is one of the most commonly utilized options for mitigation of adverse effects on historic properties. However, because construction activity that causes vibration severe enough to destroy a building would be necessary only in an extremely rare case, it is unlikely that this mitigation measure would ever be applicable to vibration impacts.

Although damage to an historic building would be considered an adverse effect, this could be mitigated through a commitment to repair the damage in accordance with the Secretary of the Interior's Standards. A responsible agency, for example, could make a finding that the project would likely cause minor damage to an historic building, but the agency would commit itself to using the Secretary of the Interior's Standards in repairing that damage.

It might also be possible to move the building out of harm's way. However, this may not be desirable because a building that is susceptible to vibration damage could be damaged through a move as well. Moreover, most preservationists do not approve of moving historic buildings because relocation removes the buildings from their context. In addition, moving a building automatically delists it from the NHRP, unless the move was previously approved by the Keeper

of Register. One of the case studies discussed herein involved an historic building that was eventually moved, but for reasons unrelated to construction of the transportation project.

In a situation where damage could occur, the MOA might specify appropriate repair work, using the Secretary of the Interior's Standards. In a situation where potential damage can be avoided by implementing alternative construction methods, the MOA could specify the use of the alternative methods and require monitoring during construction to ensure that vibration does not exceed acceptable levels.

3.3 Section 106 as it Applies to Highway Construction Vibration

There are several conclusions that may be drawn about how Section 106 applies to highway construction-related vibrations. First, the Section 106 process applies to most highway construction projects because a high percentage of highway work is federally-assisted. If a project is not federally-assisted, it may nonetheless be reviewed under state or local historic preservation laws.

Second, there is a need for good science in helping to establish the vibration APE for a project. In other words, how wide is the geographic area in which vibration damage would likely occur? The answer to this question should be provided by technical experts and be based upon sound scientific analysis. In this respect, it is generally easier to analyze vibration impacts than visual impacts because visual analysis will always involve a degree of subjectivity and is not amenable to scientific analysis. Vibration impact analysis, on the other hand, can be based primarily on a quantitative, objective analysis. However, given the state of the art, determining vibration impact significance and mitigation still involves some subjectivity.

Third, the complexity of the Section 106 process will be in direct proportion to the severity of potential vibration impact. If the impact is so severe that the building may suffer structural damage, the SHPO and others may extend consultation and request that the project be redesigned to avoid the impact. Lesser impacts, however, could be resolved through a commitment to use alternative construction methods that generate less vibration or to use the Secretary of the Interior's Standards as a guideline to repair or reinforce the building. Qualified preservation professionals will be required to assist in identifying historic properties, evaluating potential effects and developing mitigation or repairs to affected historic properties.

4. LITERATURE REVIEW

The research team conducted a literature search to gather the most recent information available on the subject. Using the information contained in a recent document as a starting point, further research was conducted using various on-line search engines (e.g., Google Scholar). The follow-up phone calls to certain individuals who responded to the questionnaire survey (described in Section 5) also produced additional reference material. A memo, summarizing the results of the literature review, is contained in Appendix A. A brief summary of the literature review is provided below.

During the literature search, the research team obtained several references that were published subsequent to the 2002 document (HNTB Corporation and Wilson, Ihrig and Associates). Including previous literature and newly obtained literature, the research team assembled 64 reference documents, including published journal articles, project reports, national and

international standards, government guidelines, government regulations, and books related to the subject.

After reviewing existing reference lists and conducting an on-line search, the Team reviewed the material obtained for the level of relevance to the research topic. To assist with this task, the research team devised a rating scheme that focused on the relevance of the material. This rating can also serve as a simple guide to users of this document who desire to go beyond the summary provided herein and read the full text of the reference literature for additional details.

In order to focus the review of the literature, a list of general subject matter was developed. The list consisted of essential elements of the research. The Team members identified fourteen (14) relevant areas or content categories for characterizing the material found in the literature. The categories are:

- Historic, old or fragile buildings or other such structures are discussed
- Construction (general and blasting) vibration effects are discussed
- Damage is discussed
- Protection from construction vibration (mitigation) is discussed
- Ambient vibration effects are discussed
- Vibration limits to protect structures are presented
- A formal or structured process (government or otherwise) to evaluate and protect historic structure is discussed
- A detailed case study is presented
- Actual damage (or no damage) correlated to vibration is presented
- Detailed construction vibration mitigation measures are presented
- The fragile nature of structures is discussed (what makes a structure damage prone)
- Prediction of vibration from construction is presented
- Blasting vibration effects are discussed
- Discussion of the potential for soil settlement

Using the above categories it was possible to systematically review the documents obtained and evaluate their applicability to the subject matter based on how thorough each one was in covering the identified areas of interest.

From the research team's literature review, it has been concluded that there is consensus on many issues relating to protecting historic structures. The research team also concludes that there is no consensus concerning appropriate vibration limits. Most of the research in the field of building damage comes from blasting vibration and its effect on modern structures. The research team observed that blast effect researchers tend to recommend higher levels of vibration than researchers whose studies involve lower levels of vibration such as that associated with roadway traffic. There is very little research pertaining to the subject of common construction vibration.

It is unlikely that additional government research on construction vibration will happen any time soon. In the meantime it will probably be necessary to adopt a cautious approach to setting limits and allow for flexibility on a case-by-case basis. This seems like the most viable approach to take and seems to have some support based on the literature reviewed. The procedures for documenting the existing condition of buildings and monitoring vibration are well established and generally there is universal agreement on these procedures.

Many state DOTs have procedures for controlling and monitoring blast vibration. Aside from this, the State of California is the only DOT which has produced a set of detailed procedures for controlling general construction vibration associated with transportation projects. Neither the survey of state DOTs nor the follow-up phone calls revealed procedures similar to those of California. The details of the literature search and review can be found in a summary memo in Appendix A.

4.1 Vibration Criteria

Table 1 summarizes the range of vibration limits recommended by researchers, practitioners, and government standards for avoiding damage to historic buildings as obtained from the generally available literature. Only those limits that are unique and originated with the reference document are indicated.

Clearly there is a wide range of opinion on appropriate vibration limits for historic buildings and structures. At one end of the range is a conservative limit of 0.10 inches/sec except in the case of ancient ruins where 0.08 inches/sec is considered appropriate by some. At the other end of the range, some would consider 0.50 inches/sec or even 2.0 inches/sec to be appropriate.

Much of the research indicates that as the vibration frequency increases, building elements are better able to withstand higher levels of vibration. A full explanation of this phenomenon would require a rather lengthy discourse on structural dynamics. Suffice it to say that the reason has to do with the movement of main building elements (primarily walls) when subjected to base excitation. At lower frequencies, walls tend to deform more (the relative movement of different points on the wall), thus subjecting the brittle materials (in the case of masonry construction) from which they are made (such as brick and mortar) to higher stresses and strains. Based on the research, it would appear that using a frequency-based limit is probably the most reasonable approach. The German standard DIN 4150-3 is a good example of this approach.

Some case studies suggest that it is possible to set conservative vibration limits and still allow for some flexibility in modifying those limits based on detailed engineering investigation and analysis done on a case-by-case basis prior to award of the construction contract. Alternatively, the transportation funding agency could adopt conservative criteria and allow for flexibility after the award of contract based on detailed investigations to be conducted by the contractor, who would need to demonstrate based on an engineering analysis the appropriateness of higher limits.

Table 1. Summary of Vibration Limits

Reference Source	Remarks on Vibration Source	Remarks on Building or Structure	Remarks on Type of Damage	Vibration Limit - PPV (inches/sec)
British Standards Institute (1993)	All (including blasting)	Unreinforced or light framed structures	Cosmetic	0.6 to 2.0† (historic buildings may require special consideration)
Sedovic (1984)	All	Historic buildings in good state of maintenance	--	0.5
City of New York City (1988); Esrig and Ciancia (1981)	Blasting, pile driving and vehicular traffic	Structures which are designated NYC landmarks, or located within an historic district or listed on the NHRP	--	0.5
Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Architectural damage and risk of structural damage	0.4 to 0.6
Rudder (1978)	Traffic	All	Structural damage possible	0.4
City of Toronto (2008)	All (blasting not mentioned)	All buildings	--	0.3 to 1.0† (lower limits may be identified by professional engineer)
Konon and Schuring (1985)	Transient	Historic buildings	Cosmetic	0.25 to 0.5†
Swiss Standards Association (1992)	All (blasting, construction equipment, and road traffic)	Historic and protected buildings	--	0.2 to 0.5†
Federal Transit Administration (2006)	All	Non-engineered timber and masonry buildings	--	0.2
Sedovic (1984)	All	Historic or architecturally important buildings in deteriorated state of maintenance	--	0.2
Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Threshold of risk of architectural damage	0.2
Feilden (2003)	All	All buildings	Threshold for structural damage	0.2
Rudder (1978)	Traffic	All	Minor damage possible	0.2
Konon and Schuring (1985)	Steady state	Historic buildings	Cosmetic	0.13 to 0.25†
Deutsches Institut für Normung DIN 4150-3 (1999)	All	Buildings of great intrinsic value	Any permanent effect that reduces serviceability	0.12 to 0.4†
Federal Transit Administration (2006)	All	Buildings extremely susceptible to vibration	--	0.12
American Association of State Highway and Transportation Officials (2004)	All	Historic sites and other critical locations	Threshold for cracks (cosmetic)	0.12
Esteves (1978)	Blasting	Special care, historical	--	0.1 to 0.4††
Rudder (1978)	Traffic	All	Threshold of structural damage	0.1
Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Virtually no risk of architectural damage	0.1
Feilden (2003)	All	All buildings	Threshold for plaster cracking	0.08
Whiffin and Leonard (1971)	Traffic	Ruins and ancient monuments	--	0.08

† frequency-dependent criteria
†† depending on soil type and frequency

4.2 Current Practices

Current practices for controlling construction vibration affecting historic structures vary considerably. Most jurisdictions recognize a need to document the condition of the affected buildings prior to starting construction. This can be accomplished with still photo and video documentation. Where vibration limits are specified, vibration monitoring is required. Some agencies require warning thresholds to indicate when vibration levels are approaching the allowed limit. With current monitoring instrument technology, exceeding a threshold can be used to trigger a visual or audio alarm as well as an email notification of the event.

Incorporating a Project Historical Architect (PHA) into the process allows a professional trained in building preservation to work with the resident engineer in the decision making process when vibration limits are exceeded. Most mitigation measures included in project contract documents tend to be generic but do provide some means and methods that contractors can follow when vibration limits are exceeded.

4.3 Procedures

There is general agreement on the procedures to follow when dealing with construction vibration. The following are generally recommended steps to follow:

- Consultation between historic building owner, development team and reviewing agencies, such as SHPO and local planning departments, to identify potential risks, negotiate changes, and agree on protective measures.
- Documentation of building conditions prior to commencement of adjacent work, including a detailed photo survey of existing damage.
- Establishment of vibration limits based on building conditions, founding soil conditions, and type of construction vibration.
- Implementation of vibration mitigating measures on the construction site and/or at the historic building, which could include specific means and methods or protective measures.
- Vibration monitoring during construction using seismographs, with notification by audible and/or visual alarms when limits are approached or exceeded.
- Regular condition surveys and reviews during construction to identify damage, to evaluate the efficacy of protective measures already in place, and to identify and implement additional corrective steps.

4.4 Human Perception of Vibration

Although it was not the intent of this project to explore human reaction to construction vibration, it is important to address if only briefly. The potential effect of vibration on occupants of an affected building can have a substantial effect on the public's reaction to a project. The vibration criteria presented by researchers discussed herein deal exclusively with the effects on buildings. However, a few documents included in the literature search also address human perception as well. Examples can be found in Caltrans (2004) and Whiffin and Leonard (1971). In addition the research team has relied on its experience from previous projects. Note that vibration measured at ground level can sometimes be lower than vibration inside the building due to amplification of vibration caused by resonances in building floors.

For continuous (steady state) vibration (e.g., vibratory compaction, vibratory pile driving):

- PPV that exceeds 0.035 inches/sec is generally considered to be distinctly perceptible.
- PPV of 0.10 inches/sec would be strongly perceptible and, according to Whiffin and Leonard (1971), begins to annoy.
- PPV of 0.2 inches/sec is definitely annoying.
- PPV between 0.4 and 0.6 inches/sec would be unpleasant, according to Whiffin and Leonard (1971).

Consequently, if one adopted a vibration limit of greater than 0.1 inches/sec for continuous vibration, a reaction from building occupants should be expected. The greater the limit, the greater the reaction would be.

Humans are generally considered to be less sensitive to transient (generally impulsive) vibration (e.g., impact pile driving, blasting), than to similar vibration from continuous sources. Kelly, et al. (1998) and Wiss (1981) present data that relate human perception to transient vibration as well as steady state vibration. For transient vibration (e.g., pile driving, blasting):

- PPV between 0.04 and 0.2 inches/sec is considered to be barely perceptible.
- PPV between 0.2 and 0.8 inches/sec would be distinctly perceptible.
- PPV between 0.8 and 2.0 inches/sec should be strongly perceptible.

Comparing the two sets of data (continuous and transient), it can be seen that there is approximately a factor of eight difference in the sensitivity to the nature of the vibration.

Figure 1 provides a comparison between typical vibration levels at 25 feet from various common sources and the response of humans (annoyance) and the potential for damage to historic buildings. The sensitivity of humans makes them aware of vibration at levels much lower than those that result in damage to most contemporary structures, although older historic buildings can be at risk in the transition range of vibration that is just barely perceptible (0.02 inches/sec) to vibration that most people would find definitely annoying (0.2 inches/sec).

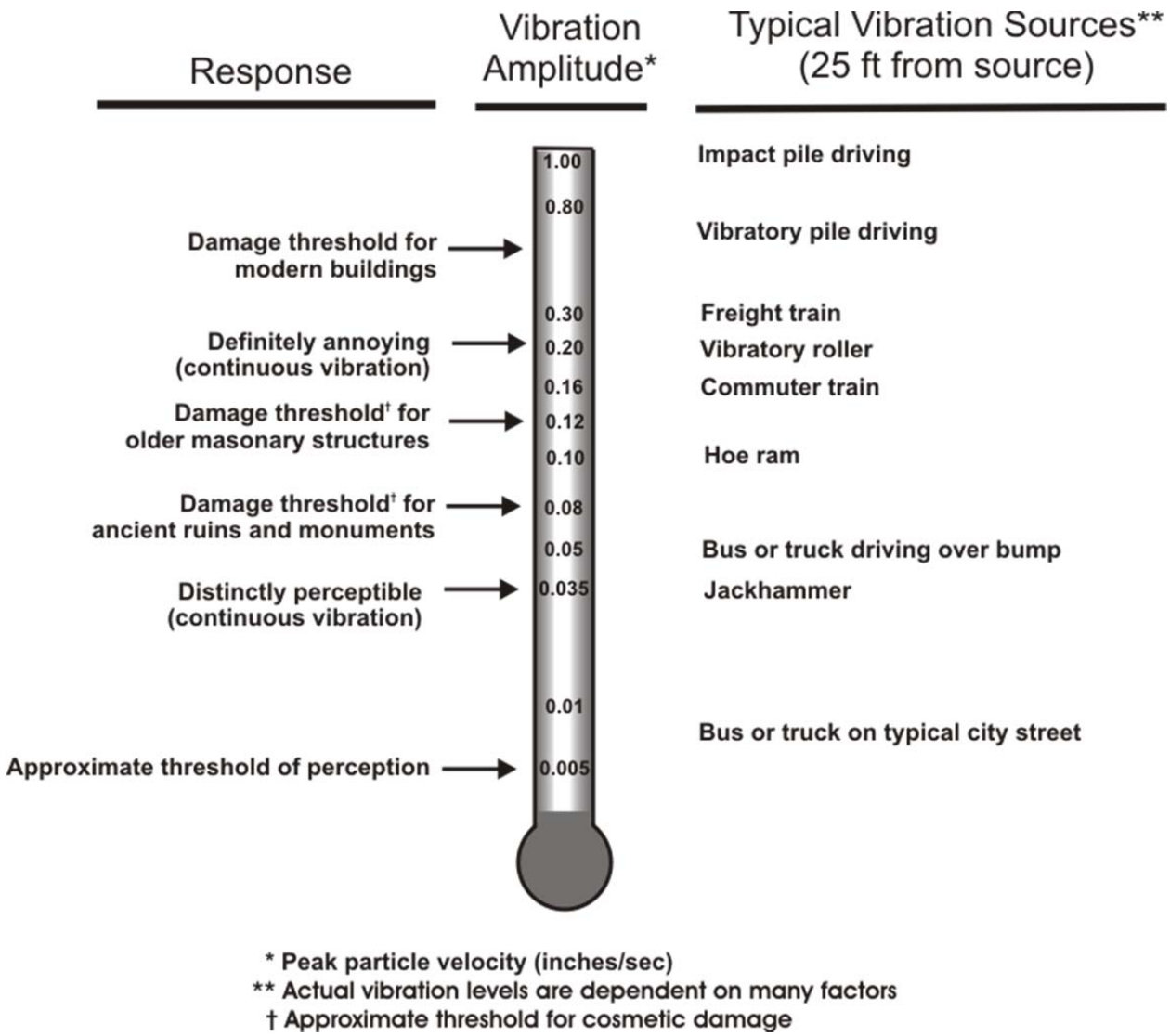

Figure 1. Typical Vibration Amplitudes and Thresholds

Agency staff and consultants who interact with the public and building owners in particular should be aware of potential human reaction to vibration. They should be prepared to explain in terms that can be understood by the average person that just because a person can feel vibration does not automatically mean that damage is occurring, They also should be prepared to explain that even though older buildings tend to be more susceptible to vibration, adequate measures can be implemented that protect against damage.

4.5 Summary

Recommended vibration limits tend to vary considerably within the published literature and national standards. The research team attributes this to the viewpoint of the researcher preparing the recommendation. The primary variables affecting the recommendation appear to be whether the field research was focused on blasting (at the high end of vibration) or motor vehicle traffic (at the low end of vibration), with the differences between these two types of vibration being the time history of the vibration (i.e., transient vs. continuous) and the number of vibration cycles to which a building is subjected.

The background of the researcher also appears to have some effect on the recommended limits as well. Researchers from the preservation profession tend to adopt a more conservative approach than researchers in the engineering profession, which is not unexpected. While some older buildings may be more susceptible to damage than new construction, the determining factors are the construction type and condition, not whether the building is historic. Human reaction to construction vibration might also be a consideration when setting limits or at least taken into account when conducting public meetings and outreach.

Aside from the vibration limits adopted for a specific project, general procedures—including building preconstruction condition surveys, clearly specified agreements between stakeholders, and monitoring during construction—are generally accepted procedures to follow to ensure protection of historic buildings. Stakeholders should also involve both experienced preservation professionals and engineers, especially in critical situations where the risk of damage is higher and/or the possibility of mitigating it after the fact is less acceptable.

5. TRANSPORTATION AGENCY SURVEY

The research team conducted a survey of state departments of transportation, other public agencies, and acoustical consultants to collect and synthesize successful practices currently in use. A memo summarizing the results of the survey and a copy of the survey are contained in Appendix B. A brief summary of the survey is provided below.

The following is summary of participants that were approached for the survey.

State DOTs. State DOT staff members were contacted through the membership lists of the American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Construction and the Transportation Research Board (TRB) Committee on Transportation Noise and Vibration (ADC40).

Transit Agencies. The American Public Transit Association (APTA) did not respond to requests for assistance in contacting members. The research team contacted individual agencies throughout the country.

Turnpike and Toll Road Authorities. Thirty-eight members of the International Bridge, Tunnel and Turnpike Association were contacted.

Federal Highway Administration (FHWA). Stephanie Stoermer at FHWA was contacted. She did not identify any staff in FHWA Division Offices that would be appropriate to contact.

State Historic Preservation Officers (SHPOs). The research team contacted SHPO staff members through the membership list of the National Conference of State Historic Preservation Officers.

Members of TRB ADC40 Committee on Transportation-Related Noise and Vibration. Members of ACD40 were contacted through the ADC40 membership list.

Members of TRB ADC50 Committee on Historic and Archaeological Preservation in Transportation. The research team contacted members of ACD50 through the ADC50 membership list.

The research team used the on-line survey service Survey Monkey to implement the survey. The survey was distributed via e-mail and asked respondents to reply within 2 weeks.

5.1 Survey Response

Response Numbers

The following is a summary of the survey responses:

- 506 requests sent
- 138 total responses received (27.9%)
- 59 participants completed the entire survey (22.7%)
- 6 consultants
- 45 State DOTs
- 34 unique states (several states had multiple responses)
- 5 SHPO staff
- 2 Canadian provinces

The survey results indicate that none of the responding agencies has formal processes (i.e., adopted guidelines or official policy documents) in place for evaluating the potential effects of construction vibration on historic buildings. California appears to have done the most work in this regard with the development of a guidance manual on the effects of construction vibration, including a discussion of historic buildings.

In general, if the issue arises, the agencies' approach varies depending on the perceived and actual sensitivity of the historic building, the nature of the construction vibration (i.e., impact pile driving vs. grading), ground conditions, and the level of concern by the public and public agencies. Although many respondents offered elements of good approaches, no single best approach was obtained from the survey results. The survey identified several case studies that are discussed later in this report. The details of the survey can be found in a summary memo in Appendix B.

5.2 Follow-Up Calls to Survey Respondents

The research team called selected survey respondents to obtain additional information. The respondents directly contacted represent both the historical preservation side of the issue as well as the engineering side. The information obtained in this follow-up effort provided more insight into the process and procedures that State DOTs follow to protect historic buildings from construction vibration damage.

In many cases individuals who were contacted had either not been in their position a long time or worked in a state where the issue does not come up frequently (e.g., less populated states and/or states without large urban areas). In spite of that, the research team was able to obtain useful information. A very informative conversation was conducted with a preservation specialist in New Mexico who has worked in this area for many years and was involved in evaluating the impacts on very old structures in historic monuments. Not only did the preservation specialist tell us of several projects, but she also provided useful contact information for engineers with

more specific details. In addition, the specialist provided a few more reference documents that had not been discovered in the literature search.

The research team contacted 16 survey respondents by phone, interviewed them using a focused set of questions, and then discussed specific examples in which historic buildings were considered to be potentially impacted by a transportation construction project. The research team was provided with examples of project documentation, including MOA's, specifications, and technical studies.

In summary, the responses obtained in the follow-up calls were as follows:

- Most states address historic buildings and protection from construction vibration damage on a case-by-case basis.
- The issue generally arises during an environmental review process and is identified by the SHPO during the Section 106 process.
- In some instances, the issue is raised by the public or a building owner.
- Generally, the type of construction (e.g., blasting, pile driving, use of heavy construction equipment) and its proximity to historic buildings are what determines whether a building is considered to be potentially impacted by the project.
- A consultation between SHPO and DOT engineers is used to determine the potential for impact and what contract requirements are necessary. Occasionally, SHPO has disagreed with DOT staff.
- When necessary, but infrequently, stakeholders bring in an expert to assist to determine a building's susceptibility and what protection is needed, including setting vibration limits and developing a monitoring plan.
- Where a building or group of buildings is determined to be possibly impacted by vibration, the procedure adopted generally requires vibration monitoring at a minimum.
- In some instances, a visual pre- and post-construction survey has been required to document the existing condition of the building (specifically existing cracks).
- Where vibration limits are set in contract bid documents, the type of construction is typically considered in setting the limits.
- In some instances, where vibration limits on the low side of the range were adopted, it was determined before or during construction that the existing ambient vibration was greater than the vibration limit. This resulted in an increased vibration limit. This situation could have been avoided by measuring ambient vibration prior to setting the contract limit.
- Some contracts have included a "stop work" order when vibration limits are exceeded. However, this appears to be the exception rather than the rule.

6. CASE STUDIES

The research team selected several candidates for cases to illustrate the various aspects of the process of protecting historic buildings from construction vibration damage. The possible cases were drawn from the research team's project experience and from project information obtained in the literature review. Unfortunately, the agency survey and follow-up calls produced no cases with sufficient information to be included. Although agency staff with whom we spoke were always willing to help, the people who were directly involved with a project had often left the

agency or retired. Another challenge for the research team as well as agency staff is the availability of project files, which after more than a few years are no longer easily accessible.

Once the cases to be included were selected, a major challenge faced by the research team was locating persons who were directly involved in each of the projects to provide relevant information even for those projects in which a research team member participated. In many cases, one agency staff member is involved in the planning phase, another is involved during the engineering phase, and a third may be involved during construction. Another reason for the fragmentation of information is that very few projects result in a summary report on their completion. One case (Doyle Drive) is an exception to the rule and provides a fairly complete picture of the process from beginning to end.

The main aspects illustrated by these cases are:

- Identification of potentially affected historic buildings.
- Importance of preconstruction survey of affected buildings.
- Determination of a building's susceptibility to vibration damage.
- Selection of vibration limits to be imposed during construction.
- Mitigation by monitoring to control the level of vibration at the building.
- Supplementary vibration mitigation measures.
- Success of the mitigation measures in preventing damage.

6.1 Case Study #1: Sacramento Railyards Central Shops (Carman, et al.)

We include this project as a case study even though the main concern was not construction vibration, but, rather, long-term vibration from freight railroad activity. We include the project because the issues were similar to those encountered when dealing with construction vibration and historic buildings and because the approach taken to determine an appropriate vibration criterion was innovative and informative.

The Railyards property, adjacent to the Amtrak station in Sacramento, contains eight massive, historic masonry buildings originally used to construct and maintain locomotive engines. The buildings are referred to as the Central Shops. The Railyards property is adjacent to the current Amtrak Station and was the western terminus of the First Transcontinental Railroad when the Central Pacific Railroad connection with the Union Pacific Railroad was completed in 1869. The Central Shops Historic District is a City of Sacramento historic and cultural resource. The city is in the process of nominating the district for listing in the NRHP.

The Intermodal Transit Facility Track Relocation Project on this site involved relocation of the existing railroad tracks that carry freight and Amtrak passenger trains. The track relocation, just recently completed, brought the tracks within 32 feet of the Central Shops. These buildings are all constructed of multi-wythe brick masonry with lime mortar joints. In general, the masonry walls are in a deteriorated condition due to weathering over many decades, and, in part, foundation settlement. Some building walls have been repointed and are in relatively good condition.

The environmental impact study performed as part of the Environmental Impact Statement (EIS) for the Sacramento Railyards Project recommended investigating vibration from freight operations and its potential effect on the Central Shops. The recommended criterion of the

Federal Transit Administration (FTA) to avoid damage to older buildings "extremely susceptible to vibration" is 0.12 inches/sec. Based on a detailed analysis of expected vibration levels from trains operating on the new tracks, the project's vibration consultant recommended that a vibration mitigation measure be implemented underneath the new tracks to reduce vibration. The recommended vibration mitigation measure was an underlayment of tire-derived aggregate (shredded motor vehicle tires) below the track. However, because of engineering concerns involving flammability, this mitigation measure was not implemented.

The project's vibration consultant predicted vibration from freight traffic to be in the range of 0.13 to 0.32 inches/sec under a worst case scenario of "severe wheel flats" on freight rail cars. Because the predicted vibration exceeded the FTA criterion of 0.12 inches/sec, there was concern. The engineers recommended further investigation with more detailed analyses and site-specific measurements in the project's design phase.

During the project's design phase, the owner engaged a structural engineer to evaluate the condition of the buildings and the effect of future train vibration. The engineer concluded from a visual review that even though the maximum predicted vibration exceeded the FTA criterion, the vibration was not expected to cause any risk to the existing masonry walls (structural or cosmetic), with the exception of one building (Car Shop), which had a large cantilevered wall (i.e., unsupported laterally). Figure 2 shows the outside of the Car Shop's unsupported wall.

Figure 2. Car Shop within the Sacramento Railyards Central Shops Historic District

The structural engineer conducted a detailed finite element analysis to evaluate the Car Shop wall and its susceptibility to ground vibration. The vibration consultant made additional vibration measurements for freight and passenger trains and characterized the site-specific soil conditions at the Car Shop. The additional data from measurements were used to refine the predicted vibration levels expected at the base of the cantilevered wall of the Car Shop.

The structural engineer used the refined vibration predictions as input to the finite element model to determine maximum stresses and strains in the wall at critical points. The structural engineer was able to evaluate whether the strains from vibration were a structural risk by considering strains from wind loading. Using the finite element model, the structural engineer simulated wind loads the wall would have been subjected to over its lifetime based on historical data of nearby recorded maximum wind loads. Comparing strain levels in the wall due to freight train vibration with strain levels due to recorded maximum wind loading, the structural engineer concluded the wall was stable for the anticipated train-generated vibrations predicted for the site once remedial structural work was done to meet the local building code.

This case demonstrates that it is possible through site-specific and detailed engineering analysis to determine with more certainty the effects of vibration on an historic building and to develop a building-specific criterion to protect the building. Although this case is unique, it demonstrates the steps and procedures that can be taken (possibly on a lesser scale) to arrive at a more definitive assessment for a specific building, rather than taking a more generic approach.

6.2 Case Study #2: Cypress Lawn Cemetery – Entrance Archway and de la Montaña Mausoleum

This case involved the construction of a new subway line to the San Francisco International Airport for the Bay Area Rapid Transit (BART) system. The right-of-way used for the construction was the original railroad alignment for Southern Pacific Railroad circa 1870, which provided rail access to San Francisco during the late 19th Century. The old railroad alignment, which fell out of use during the 1940's, passes through several cemeteries developed over the last century on both sides of the right-of-way. Although the cemeteries had encroached on the alignment over time, California law gave them certain easement rights requiring BART to reach an agreement with the cemeteries on several issues.

Most of the cemeteries, including Cypress Lawn Cemetery, are a NRHP historic district. Cypress Lawn has 21 historic resources, including a chapel, columbarium, and numerous tombs and mausoleums. The portion of Cypress Lawn Cemetery through which the subway was built is considered to be one of the last grand rural garden cemeteries built in the West and is the final resting place for such luminaries as Charles De Young (newspaper), Charles Crocker (railroad), George Hearst (newspaper), and Wyatt Earp (lawman).

Two historic buildings, an historic archway, and an historic family mausoleum were relatively close to the subway tunnel construction, causing concern they might be damaged by construction vibration. As a result of the Memorandum of Understanding (MOU) between BART and the various affected cemeteries, including Cypress Lawn, vibration monitoring during construction was conducted at several buildings and structures. The Cypress Lawn entrance archway (Grand Gateway) and the de la Montaña Family Mausoleum were among those monitored.

Subway construction involved a cut-and-cover excavation technique called soil mix wall. The soil mix wall (one on each side of the subway box) provides support for the surrounding soil during excavation of the trench within which the concrete box for the subway structure is built. A soil mix wall is constructed by drilling several rows of holes into the ground and inserting soldier piles (H-shaped beams) in each of the holes. The holes are then filled with a soil mix (cement-based binder slurry). Once the soil mix has hardened, forming a wall underground, the soil in between the two walls is excavated and the concrete structure is constructed between the two walls. All of these activities generate vibration.

The most significant vibration generated during the subway box construction occurred during what is called “bond break” between the soldier piles and the soil mix, 24 hours after pouring of the soil mix and prior to its reaching full hardened strength. The bond break is achieved by vibrating the piles with the same vibratory hammer that is used to drive them a short distance into the ground below the drilled hole. The purpose of the bond break is to minimize the vibration generated when the piles are later extracted. Extraction of the soldier piles allowed the contractor to reuse the piles in subsequent sections of the construction. Excavation also generated vibration levels that were substantial, as did the movement of equipment used for excavation when in close proximity to the monitoring locations adjacent to the two historic structures.

The contract construction specifications developed by BART specified that cemetery structures and buildings in weakened condition (as determined by a preconstruction visual survey) would have a vibration limit of 0.08 inches/sec. For structurally sound buildings, the vibration limit was specified as 0.2 inches/sec. The archway is a granite masonry structure constructed in 1892 and one of the earliest examples of Mission Revival-style architecture. The vibration limit adopted for the archway was 0.08 inches/sec based on its age, even though it was a well maintained structure. As agreed to in the MOU and as a protective measure, BART had the archway repointed at its expense. BART documented the condition of all potentially affected structures with still and video photographs prior to start of construction.

Figure 3 shows the archway and a seismograph used for monitoring vibration. In addition to the seismograph at the base of the archway, there was an alarm system with warning lights (yellow for caution and red for exceedance) and an audible alarm. The warning system provided a direct feedback to the equipment operators when vibration limits were being approached or exceeded and allowed equipment operators to adjust their activity. After an initial learning stage of trial and error, the system became a reasonably successful tool to control vibration.

Figure 3. Cypress Lawn Cemetery Grand Gateway

The implementation of the alarm system was somewhat unusual, but the cost was inconsequential because the seismograph was configured to allow for an alarm. The alarm's main advantage was that it allowed for real-time feedback to the equipment operator, thus increasing the chances of successful compliance with the vibration limit. In general, the response of the equipment operator to having an alarm was positive, and he was able to modify the activity of his equipment to stay within the vibration limits.

Although not implemented on this project, current seismograph technology allows phone numbers to be dialed every time a threshold is exceeded (i.e., either warning or limit). Generally, such a call would be made to at least the Resident Engineer or a representative who would then assess the situation and decide what changes in activity or equipment were necessary.

Vibration levels measured at the archway during construction of the BART project ranged from 0.09 to 0.12 inches/sec. The higher vibrations occurred during excavation and by movement of a small Caterpillar approximately 15 feet away from the archway. Although these levels were above the limit of 0.08 inches/sec, engineers found no damage to the archway during inspections during and after construction.

Figure 4 shows the de la Montaña Mausoleum. The mausoleum was constructed in 1907. The lower part of the structure is steel framed with sandstone cladding, while the upper part is a stone finial that sits on four stone arches atop four large granite blocks. At the time of BART subway construction, the de la Montaña Mausoleum was in a deteriorated condition due to lack of maintenance.

Figure 4. Cypress Lawn Cemetery de la Montaña Mausoleum

Based on the structure's age and condition, the vibration limit for the mausoleum was set at 0.08 inches/sec. To avoid any serious damage to the mausoleum and to protect its structural integrity, BART had the contractor install temporary interior shoring using scaffolding to support the structure at critical points. A structural engineer re-evaluated the vibration limit of 0.08 inches/sec and determined the limit could be raised to 0.138 inches/sec with the interior supports.

In addition, the contractor was not allowed to break bond between the slurry wall and soldier piles in a "no pull zone" closest to the historic structures. Construction vibration levels measured at the mausoleum ranged from 0.09 to 0.11 inches/sec (less than the vibration limit of 0.138 inches/sec) during the bond break of piles in the soil mix wall at the closest point to the mausoleum (approximately 135 feet away).

In spite of these precautions, Cypress Lawn filed a lawsuit after construction was complete claiming construction vibration damaged the de la Montaña Mausoleum. BART retained an engineering team, which analyzed the damage in two ways:

1) The team reviewed the preconstruction videos and photographs, including historic photographs in local archives, and found that all the claimed damage existed before construction.

2) The engineers performed calculations comparing construction vibration energy and frequency content with that from earthquake ground shaking. They found that earthquakes in 1957 and 1989 had peak velocities 20 and 120 times greater, respectively, than the vibrations caused by the construction. They found that the energy (measured as a function of ground velocity squared) of the 1957 and 1989 earthquake ground shaking was 85 and 10,000 times greater, respectively, than the energy generated during the soldier pile extraction and bond breaking. The earthquakes were sufficient to have caused much of the observed stone displacement.

The lawsuit was settled during arbitration in accordance with the findings that the BART construction did not cause damage to the mausoleum.

This case demonstrates several aspects of the process of evaluation, agreement, monitoring and settlement of issues with construction vibration and historic buildings and structures. Although BART had to defend its actions and the activities of its construction contractor, it was able to show that it had taken reasonable and appropriate efforts to avoid damage to the historic cemetery buildings. The preconstruction photos and videos taken by BART were a critical component in proving that the BART construction had not damaged the mausoleum.

This case illustrates how a warning system could be provided as a real-time interface between the vibration monitoring and the contractor, thus facilitating better control over vibration and better adherence to vibration limits. A warning system is not a commonly used measure and would usually be implemented only when high levels of vibration were expected to occur during construction in close proximity to the historic building. However, the expense of an alarm system is minimal, and a system can easily be constructed from commonly available material. The other unique feature on this project was scaffolding installed inside the mausoleum structure. This approach is uncommon, but could be used where deemed necessary for protection and minimizing the risk justifies the cost. This case also emphasizes the importance of a pre-construction survey.

6.3 Case Study #3: Gipfel Brewery Building, Milwaukee (HNTB Corporation and Wilson, Ihrig and Associates)

An evaluation was prepared by a vibration consultant for the Wisconsin DOT and the City of Milwaukee for the effects of freeway demolition (Park East) on three historic buildings in

downtown Milwaukee. One of the buildings (Gipfel Union Brewery) was built in 1853 in the Federal style and was the oldest brewery building still standing in the city, although Gipfel ceased operation in the 1890s. The Gipfel building was designated a city landmark in 1985 and determined by the Wisconsin Historical Society to be eligible for the NRHP in 2000. The Gipfel building was the only remaining resource from the historic Kilbourntown, one of the original communities that became Milwaukee.

The Gipfel Union Brewery (a three story brick building) was 100 feet from the nearest freeway structure to be demolished. A second building (Gugler Building) in the same area was built in 1896 in the German Renaissance Revival style. The Gugler Building (composed of a one story and a two story brick building) was 95 feet from the freeway structure. The third building (WEPCO Switch House) was built between 1903 and 1912. The Switch House (a two story brick building with a reinforced concrete foundation, ca. 1942) was the city's primary source of electricity until the middle of the 20th century. The Switch House was located 20 feet from the freeway structure.

The Park East Study (HNTB-) contains an extensive review of vibration criteria. In the evaluation of the buildings and derivation of recommended criteria, the vibration consultant used the classification system for buildings contained in the British standard BS 7385, Part 1. Under this standard, each structure is rated according to four categories: the type of construction, the foundation, the soil, and political importance. As a result of the analysis, the consultant recommended a limit of 0.15 inches/sec for the Gipfel Union Brewery, 0.40 inches/sec for the Gugler Building, and 1.2 inches/sec for the WEPCO Switch House.

The activity expected to generate the greatest vibration was the dropping of large portions of freeway structure during demolition. According to the project manager, vibration monitoring was conducted during demolition of the freeway structure with no apparent damage to the buildings. Unfortunately specific vibration monitoring data were not available.

An interesting if sad footnote to this story, according to a 2009 newspaper article, was that, unrelated to the Park East project, the City of Milwaukee deemed the Gipfel building unstable and ordered the building owners to raze the building because it posed a threat to the safety and welfare of the public. The owners previously had moved it from its original location one block away with the intent of incorporating the brewery building into another development. However, the lead developer of the new project rejected this plan. The building owners still had hopes of saving the building, but, unfortunately, time ran out and the building was demolished in 2009. Figure 5 shows the building in the process of being moved.

This case demonstrates that by using an established classification system, it is possible to tailor the specified vibration limits to individual buildings. It also provides an example of how a smaller building could be moved to save the building if no other means were available to avoid damage, even though removing the building from its original surroundings and historical context might nullify the building's historical status.

Figure 5. Gipfel Brewery building being moved

6.4 Case Study #4: Fraunces Historic District, New York City (Esrig and Ciancia)

Although this was not a transportation project, it involved construction adjacent to historic buildings and provides a good example of steps used in evaluation and determination of vibration limits. The structural engineers (Esrig and Ciancia) were retained to address the effects of vibration from construction of a 29 story office tower adjacent on buildings in an historic district in lower Manhattan. The construction of the office tower involved blasting of the underlying granite and pile driving.

The potentially affected buildings in the historic district were constructed between 1820 and 1970 on fill placed in the area during the 17th Century. The historic buildings included 16 three and six story buildings located on one city block. The engineers indicated in their investigation that some of the buildings had undergone extensive renovations. Figure 6 shows Fraunces Tavern, one of several historic buildings within the Fraunces Historic District.

Figure 6. Fraunces Tavern.

As part of an earlier renovation of one of the buildings, test pits were dug in some basements to determine the foundation type and condition. The engineers recommended grouting the soil to

provide additional support for the foundation. For the office tower project, characterization of the soil was determined by digging test pits within some of the historic building's basements. The soil type was used to help determine appropriate construction vibration limits.

The engineers were tasked with arriving at permissible vibration levels and with other issues concerning movement of temporary restraining systems and movement of the buildings. The engineers list various limits for peak particle velocities ranging from 0.2 to 1.0 inches/sec. The New York City Department of Environmental Protection limit was 0.2 inches/sec for old brownstone buildings, according to the journal article. The engineers decided to recommend a limit of 0.5 inches/sec with the requirement that if either building movement or additional cracking during blasting and/or pile driving occurred, the limit would be reduced.

Monitoring of ambient conditions before construction indicated vibration that was generally less than 0.1 inches/sec, with only one level that reached 0.2 inches/sec. Monitoring during pile driving detected a maximum vibration level of 0.18 inches/sec. Based on visual inspection, it was determined that the historic buildings showed no measureable signs of distress or movement during the vibratory driving of the sheeting (sheet piles). Monitoring performed during blasting indicted vibration of less than the limit of 0.5 inches/sec, and no measureable distress was evident.

6.5 Case Study #5: Fort Point – San Francisco

After the Loma Prieta earthquake in 1989, the Golden Gate Bridge District evaluated the vulnerability of the Golden Gate Bridge in the event of an earthquake of even greater magnitude occurring in the vicinity of the bridge. The Bridge District's consultants determined that there was a risk of major damage if an earthquake with an epicenter near the bridge and a magnitude of 7.0 occurred, and that the bridge could collapse if the magnitude were 8.0. The consultants also determined that retrofitting the bridge to improve its resistance to an earthquake would be less expensive than replacing the bridge after a major earthquake.

Directly underneath the south end of the bridge is the historic Fort Point a masonry structure built in 1854. Figure 7 shows the inside of Fort Point with the bridge above. The contract specification for the bridge retrofit required vibration to be limited to less than 0.1 inches/sec for continuous activities and 1.0 inches/sec for single-event activities occurring near Fort Point.

Figure 7. Fort Point and Golden Gate Bridge

During Phase 1 remediation, cast-in-drilled-hole (CIDH) piling and pile caps were added around the perimeter of the original bridge foundation pedestals. The interface of new concrete to existing concrete was strengthened with post-tensioning of monostrands, clamping the new footings to the pedestals of the existing foundations. The existing grade beams between the foundation pedestals were also substantially strengthened, and additional grade beams were constructed. After the existing towers supporting the bridge were removed, the second stage of the foundation retrofit proceeded. First, the remaining upper portions of the existing pedestals were demolished. Then, new upper pedestals were constructed and closure pours placed to incorporate these elements into the entire foundation system. The erection of a new tower followed.

The most visually dramatic Phase 1 work was the complete removal and replacement of the four steel support towers with footprints of 50 feet by 75 feet and heights of up to 150 feet. The contractor sequentially replaced the existing towers with new ones that very closely imitate the appearance of the original towers. Each of these construction activities involved the generation of groundborne vibration.

Vibration monitoring was performed inside and outside the fort at points closest to the construction activity. Ambient monitoring indicated vibration levels that were quite low (i.e., less than 0.01 inches/sec) except during isolated events that could be attributed to people walking in the vicinity of the seismograph. Ensuring that non-construction vibration from activity of a local nature, which occurs next to the vibration sensor, is properly identified and not erroneously attributed to construction activity is always an issue for vibration monitoring. The person performing the monitoring must often query building occupants, review construction activity records, or undertake other analysis to determine the cause of the vibration.

The most significant activity for vibration was the driving and removing of sheet piles. The maximum recorded vibration for sheet pile activity was 0.17 inches/sec. Other vibration generating activities involved drilling for CIDH piles and excavation for new foundations at the towers. For the drilling, the maximum vibration recorded was less than 0.09 inches/sec.

6.6 Case Study #6: Historic District, New York City (Hammarberg, et al.)

Hammarberg and others involved in this project are structural engineers engaged to assess two construction projects in New York City that were in close proximity to historic buildings. The engineers recommended vibration limits and developed detailed plans for monitoring prior to and during construction.

In a paper published after the projects were complete, the engineers explain in clear terms the fragile nature of historic structures, which was typically due to the brittle materials (brick masonry, terra cotta, and plaster) and construction methods. The difficulty in minimizing construction impacts on historic structures, especially in urban areas, is explained. In addition to the effects of vibration on buildings, this paper also discusses the effects due to excavation adjacent to older buildings and the need to underpin to prevent soil settlement. Soil settlement caused by nearby excavation is a phenomenon similar to vibration caused settlement and equally as important.

Hammarberg distinguishes, as do most others, the difference between structural damage (that which affects the capacity of the primary or secondary load bearing members in the building) and cosmetic damage (that which affects the appearance of the building, but not the structural capacity). As the paper notes, the envelope of the building is the most likely to suffer cosmetic damage due to cracking of exterior finishes and growth of existing cracks, especially in older buildings that are often heavily ornamented. The weakening of building elements as a result of the aging process caused by weathering, temperature variation, freeze-thaw and long-term settlement of the structure is also a concern. A building that has suffered from what might be called the ravages of time is more likely susceptible to additional damage.

The paper provides a good description of the nature of construction vibration and how it interacts with structures, and the paper lists the most common types of vibration producing construction activity. Vibratory installation of sheet piles, pile driving, and vibratory compaction of soil are examples of long-term activity. Of a more short-term nature is the vibration associated with blasting and dynamic soil compaction.

In a discussion on setting vibration limits, the authors indicate that the generally adopted values come from empirical data that address vibration source, soil type(s), and condition of the structure and that there is no single, widely recognized standard for allowable vibration limits for historic structures. In spite of this lack of standards, the authors say it may be possible to predict a particular project's "probable damage" to an historic structure adjacent to construction when determining a "rational" vibration limit. Hammarberg indicates that the most appropriate standards for protection of historic structures are the standards that were developed for the protection of older, damaged or, in other words, more vulnerable structures.

The authors indicate that the Swiss, German and Central/Artery Tunnel (Boston) vibration standards were found to have prevented damage during construction in urban areas. In New York City the limit for historic buildings is 0.5 inches/sec, which Hammarberg et al. point out may not be sufficient to avoid damage to fragile historic buildings. Hammarberg discusses the need to determine a balance between providing safe vibration limits without precluding cost-effective construction. Of importance, the authors note the vibration limits derived from research

conducted by the U.S. Bureau of Mines on the effects of blasting on residential structures are the least appropriate standards for protection of historic structures.

Hammarberg emphasizes the importance of requiring a preconstruction survey of the historic building that includes:

- Description of the building
- Type of building construction
- Age of construction
- Foundation type
- Condition of the building
- Location, width and orientation of visible defects and/or cracks
- Location of loose material
- Location of previous repairs
- Distance to construction operations.

The mitigation measures applied to the building could include securing loose materials prior to construction to keep them from falling and supplemental support for equipment that might sway. Routine visual surveys during construction are recommended to observe if changes are occurring and to evaluate if new damage has occurred. The most important mitigation measure is to monitor vibration using proper instrumentation, according to Hammarberg. Existing cracks should be monitored to observe whether changes occurred during adjacent construction activity. A simple visual or electronic gage can serve as a monitor.

Hammarberg present two case studies involving historic buildings in New York City dating from the late 19th century. The unique features of two buildings (early sky-scrapers of 15 and 21 stories) in the first case that make them susceptible to vibration are explained in detail. An interesting recommendation was to include a gas leakage monitoring system.

The second case study involved an historic district of buildings dating from the early 19th Century. In this study, the foundations of buildings in this district were determined to be particularly susceptible to vibration damage due to their construction with loose material (stacked stone and rubble). Four vibration threshold levels were recommended by the engineering team. With each level, there were recommended reporting, engineer action and contractor action requirements, with the latter ranging from no action to cessation of all work.

6.7 Case Study #7: Presidio Buildings – Doyle Drive, San Francisco (ICF International)

Doyle Drive is located in the Presidio, in the northern part of the City of San Francisco. Doyle Drive, the southern approach of State Route 101 to the Golden Gate Bridge, is l.5 miles long with six traffic lanes. Doyle Drive passes through the Presidio on an elevated concrete viaduct (low viaduct) and transitions to a high steel-truss viaduct (high viaduct) as it approaches the Golden Gate Bridge toll plaza. The Presidio was designated a National Historic Landmark (NHL) in 1962. In the 1993 NHL update, Doyle Drive was determined to be a contributing element to the Presidio National Historic Landmark District.

A vibration study was conducted to evaluate the potential for damage to historic buildings at the Presidio that could result from construction activity (ESA 2004). With regard to potential damage criteria, the report states:

> *"[A] ground vibration PPV of 2 mm/sec (0.08 inches/sec) would be a conservative, but appropriate limit for the historical buildings that are more susceptible to damage, including those in a poor structural condition and those of masonry construction. The buildings in the Main Post area of the Presidio are mostly of masonry construction and would therefore fall into this category. In addition, visual observation of the buildings under consideration in this study indicates some existing differential settlement and cracks in the facades of the brick buildings. However, most of the other historical buildings in the Presidio are wood-framed structures which are substantially less susceptible to damage from vibration. For most of these buildings, a higher PPV of 5 mm/sec (0.2 inches/sec) would be an appropriate, conservative limit for construction vibration. The exterior facades of some of these wood-framed buildings (such as the Mason Street warehouses) are in a poor condition, although it is understood that these buildings are structurally sound."*

Figure 8. Buildings at the Presidio

Impact pile driving and dynamic compaction were identified as the activities that would typically generate the highest vibration level. Pile driving was required along much of the route. The tunnel road structure needed to be supported by piles, and sheet piling was installed during the excavation of one the tunnels. Dynamic compaction of the road surfaces using vibratory rollers was also required along much of the route.

The report indicates that the expected worst-case ground vibration velocity from impact pile driving would be less than 0.08 inches/sec PPV at a distance of 200 feet and less than 0.2 inches/sec PPV at 100 feet, even allowing for soil conditions that tend to assist the vibration propagation.

The report states that alternate means of pile driving would be used within a 200-foot buffer zone around the Presidio's historic buildings. These alternate measures would include vibratory piling, use of drilled piles, and pile jacking (where the piles are pressed into the ground by means of a hydraulic system, resulting in far less vibration). The report further states that although vibratory pile driving generally produces less vibration than conventional impact pile driving, vibratory pile driving could still generate ground vibration levels exceeding 0.08 inches/sec within about 100 feet and could exceed 0.2 inches/sec within about 50 feet. Where drilled piles are utilized because of vibration considerations, the report recommends that the steel casings be put in place by jacking rather than a standard vibratory process.

The report states that vibratory rollers can generate relatively high levels of ground vibration and that the maximum expected levels range up to about 0.08 inches/sec at a distance of 70 feet. The report further states that no damage would be expected due to a medium-to-heavy roller at distances greater than approximately 70 feet.

The report states that there would be minimal risk of damage to the historic buildings within the Presidio due to construction-induced building vibration provided that appropriate vibration limits are incorporated in the construction contracts and the vibration levels are controlled to within those limits by utilizing alternate demolition and construction procedures where necessary.

The viaducts are in close proximity to historic buildings; therefore, the method of demolition will not involve simply dropping the structures to the ground. Alternative approaches include lowering demolished viaduct structures by crane or the use of earthen cushions. If earthen cushions are used, their effect in reducing vibration will first be evaluated in less sensitive areas of the project site but within the project's archaeological APE (the area in which there will be ground-disturbing activity). To reduce potential vibration impacts on historic buildings from breaking up reinforced-concrete structures on the ground, the components will be placed as far as is feasible from the buildings, but still within the archaeological APE, before they are broken up. The vibration levels will be monitored. If blasting for either demolition or construction is permitted, the blast weights and blast design will be based on achieving compliance with conservative ground-vibration limits at the closest buildings. The Built Environment Treatment Plan, an addendum to the multi-agency MOA, adopted the conservative vibration limits specified in the vibration study (ICF International 2009).

The first phase of project construction is close to completion. Vibration monitoring was conducted by a vibration measurement firm retained by the construction contractor. Monitoring reports are now available. Monitoring alarms were triggered at three neighboring World War I-era warehouses. However, it is understood that there were issues with ambient vibration triggering exceedance warnings, which made monitoring of construction-induced vibration difficult. There were some instances where a building's changed condition may or may not have occurred as a result of vibration. The California Department of Transportation (Caltrans) made the decision to make repairs to the buildings rather than contest causality.

7. RECOMMENDATIONS

7.1 Assessment Approach

The flow chart provided in Appendix C provides a suggested guideline approach for addressing construction vibration effects on historic buildings and measures to avoid damage. This approach is a distillation of approaches based on information gathered from the literature review, the results of the agency survey, follow-up calls, and the experience of the research team.

The approach entails a screening procedure assuming a conservative APE due to vibration, use of conservative thresholds for potential damage, and simple vibration prediction methods indicated in FTA's Transit Noise and Vibration Impact Assessment (Federal Transit Administration 2006) and Caltrans' Transportation- and Construction-Induced Vibration Guidance Manual (California Department of Transportation 2004). The FTA's simple prediction method is based on the following equation:

$$PPV_{equip} = PPV_{ref} \times (25/D)^{n}$$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet

D is the distance in feet from the equipment to the receiver

n is the attenuation exponent

n = 1.5 for *competent soils:* most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with a shovel)

n = 1.1 for *hard soils:* dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock (cannot dig with a shovel, need a pick to break up)

Table 2 shows typical source levels reported in FTA guidance document.

Table 2. Vibration Source Levels for Construction Equipment

Equipment	PPV at 25 feet
Pile driver (impact)	0.644 to 1.518
Pile drive (sonic/vibratory)	0.170 to 0.734
Vibratory roller	0.210
Hoe ram	0.089
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003

Source: Federal Transit Administration 2006.

As an example the predicted vibration level at 500 feet from pile driving in hard soils would be calculated as follows:

$$PPV_{equip} = 1.518 \times (25/500)^{1.1} = 0.056 \text{ in/sec}$$

The recommended screening distance for potential vibration effects is 500 feet for all but blasting activity. Where adopted, state agencies commonly use a distance of 200 feet within which potential vibration effects from construction (except for blasting) are evaluated, although one state indicated it will consider distances of 500 to 1,000 feet in some cases. The example calculation above also shows that vibration from pile driving would typically be less than 0.1 in/sec, which is a conservative threshold for potential damage. Accordingly, 500 feet is considered to be a reasonable and conservative threshold for the screening for non-blasting sources. If blasting is involved, no maximum distance is recommended. It would be advisable to conduct the screening calculation where historic buildings will be located within a few thousand feet of the blasting.

The screening process uses thresholds of 0.2 in/sec for blasting and impact pile driving, and 0.1 in/sec for continuous vibration. These values are at the lower end of thresholds commonly used for fragile buildings. If vibration is anticipated to exceed these thresholds, then feasible measures for reducing vibration should be evaluated. These measures may include alternate construction or demolition methods, such as those described in the FTA and Caltrans guidance manuals. If exceedance of these thresholds is still anticipated, the process moves into a higher level of analysis involving a detailed evaluation of the buildings for fragility, development of more refined project-specific damage thresholds, and a more detailed vibration prediction analysis.

7.2 Research and Approach to Disseminate Research Findings

To disseminate the findings of the study, the research team recommends that notifications concerning publishing the final report on the TRB website site be sent to all of the survey respondents and all individuals who were contacted to participate in the survey (see the survey summary above). In addition, where feasible, the principal authors will give presentations on the report findings at TRB ADC40 and ACD50 winter or summer meetings.

8. CONCLUSION

This report summarizes the results of a literature search, a survey of transportation agencies, and follow-up calls with selected state DOT staff on the topic of construction vibration effects from transportation projects on historic buildings. A detailed discussion of seven informative case studies has also been provided.

There is no standard or commonly accepted approach for assessing the effects of construction vibration from transportation projects on historic buildings. Recommended vibration limits tend to vary considerably within the published literature, in national standards, and in practice. However, general procedures, such as building preconstruction condition surveys, clearly specified agreements between stakeholders, and monitoring during construction, are widely followed to ensure protection of historic buildings.

This report also provides a suggested guideline approach for addressing construction vibration effects on historic buildings and measures to follow to avoid damage. This approach is a

distillation of approaches based on the literature review, the results of the agency survey, follow-up calls, and the experience of the research team.

9. REFERENCES

American Association of State Highway and Transportation Officials. 2004. *Standard Recommended Practice for Evaluation of Transportation Related Earthborne Vibrations*. AASHTO R8-96. Washington, DC.

British Standards Institute. 1993. *Evaluation and Measurement for Vibration in Buildings, Part 2: Guide to Damage Levels from Groundborne Vibration*. BS 7385, Part 2.

California Department of Transportation. 2004. *Transportation- and Construction-Induced Vibration Guidance Manual*. June. Prepared by Jones & Stokes, Sacramento, CA. Prepared for Noise, Vibration and Hazardous Waste Office, Sacramento, CA.

Carman, R. A., G. M. Glickman, and C. H. Reyes. 2009. *Sacramento Intermodal Transit Facility and Track Relocation Project; Findings and Recommendation on Groundborne Vibration Mitigation*. April 22. Prepared by Wilson, Ihrig & Associates, with appendix by C. Searls and R. Mayes of Simpson, Gumpertz & Heger. Prepared for TranSystems.

City of New York. 1988. Technical Policy and Procedure Notice No. 10/88. June 6. New York, NY.

City of Toronto. 2008. Bylaw No. 514-2008. Toronto, Canada.

Deutsches Institut für Normung. 1999. *Structural Vibration, Part 3: Effects of Vibration on Structures*. DIN 4150-3.

ESA. 2004. *Noise and Vibration Study, Doyle Drive, South Access to the Golden Gate Bridge*. Final. December.

Esrig, M. I., and A. J. Ciancia. 1981. *The Avoidance of Damage to Historic Structures Resulting from Adjacent Construction*. May. American Society of Civil Engineers, New York, NY.

Esteves, J. M. 1978. *Control of Vibrations Caused by Blasting*, Laboratorio National De Engenharia Civil, Memoria 498. Lisboa, Portugal.

Federal Transit Administration. 2006. *Transit Noise and Vibration Impact Assessment*. May. Prepared by C. E. Hanson, D. A. Towers, and L. D. Meister, Burlington, MA. Prepared for Office of Planning and Environment, Washington, DC.

Feilden, B. M. 2003. *Conservation of Historic Buildings*. Third Edition. Architectural Press: London, England.

Hammarberg, E., K. Kesner, and D. Trelstad. 2009. Protection of Historic Urban Structures During Adjacent Construction. *Proceedings of the First International Conference on Protection of Historical Buildings*. Vol. 2, pp. 1393–1398. Rome, Italy.

HNTB Corporation and Wilson, Ihrig and Associates. 2002. *Park East Vibration Study*. February. Prepared for Wisconsin Department of Transportation and City of Milwaukee.

ICF International. 2009. *Built Environment Treatment Plan*. South Access to the Golden Gate Bridge, Doyle Drive Project. Prepared for San Francisco County Transportation Authority, California Department of Transportation, and Federal Highway Administration.

International Organization for Standardization. 2010. *Mechanical Vibration and Shock; Vibration of Buildings: Guidelines for the Measurement of Vibrations and Evaluation of their Effects on Buildings*. Second edition. ISO 4866-2010.

Kelley, P. L., S. J. DelloRusso, and C. J. Russo. 1998. Building Response to Adjacent Excavation and Construction. *Proceedings of the American Society of Civil Engineers Annual Convention*. Boston, MA. Pp. 80-97.

Konon, W. and J. R. Schuring. 1985. Vibration Criteria for Historic and Sensitive Older Buildings. *Journal of Construction Engineering and Management* 111(3): 208–215.

Rudder, F. F. 1978. *Engineering Guidelines for the Analysis of Traffic-Induced Vibration*. FHWA-RD-78-166. February.

Sedovic, W. 1984. Assessing the Effect of Vibration on Historic Buildings. *Association for Preservation Technology Bulletin*. Vol. XVI, Nos. 3&4.

Swiss Standards Association. 1992. *Effects of Vibration on Construction*. SN 604 312a.

Whiffin, A. C., and D. R. Leonard. 1971. *A Survey of Traffic-induced Vibrations*. Road Research Laboratory Report LR418. Crowthorne, England.

Wiss, J. F. 1981. Construction Vibrations: State-of-the-Art. *Journal of the Geotechnical Engineering Division* 107(2): 167–181.

APPENDIX A
(LITERATURE REVIEW)

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NATIONAL HIGHWAYS COOPERATIVE RESEARCH PROJECT

25-25 TASK 72

CURRENT PRACTICES TO ADDRESS CONSTRUCTION VIBRATION AND POTENTIAL EFFECTS TO TRANSPORTATION PROJECTS

LITERATURE REVIEW

27 June 2012

Prepared by:

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List of Acronyms

AASHTO	American Association of State & Highway Transportation Officials
ANSI	American National Standards Institute
BSI	British Standards Institution
Caltrans	California Department of Transportation
CA/T	Central Artery Tunnel (Boston)
CCP	Construction Protection Plan
CEQA	California Environmental Quality Act
DIN	Deutsches Institut für Normung
DOT	Department of Transportation
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
IBMS	Institute for Building Materials and Structure (Netherlands)
ISO	International Standards Organization
MOA	Memorandum of Agreement
NEPA	National Environmental Protection Act
NHPA	National Historic Preservation Act
NPS	National Park Service
NYC	New York City
OSMRE	Office of Surface Mining Reclamation and Enforcement
PANYNJ	Port Authority of New York and New Jersey
PATH	Port Authority Trans Hudson
PHA	Project Historic Architect
RPP	Resource and Protection Plan
SHPO	State Historic Preservation Office
SN	Schweizer Norm
TRRL	Transport and Road Research Laboratory
USBM	United States Bureau of Mines

List of Technical Terms

accelerometer	mechanical transducer that responds to acceleration of motion
crack gage	measuring device to monitor width of cracks in brittle material (e.g., plaster, concrete)
damage	as used herein a permanent defect in a structure or building finish caused by either environmental or human activity
differential settlement	non-uniform movement of ground under building foundation, which has propensity to cause structural damage
fragile	as applied to a building it is meant that the structure and/or its finishes (both interior and exterior) are possibly weakened due to the method of construction (e.g., stone masonry, lath and plaster) and deterioration with age and/or lack of adequate maintenance
failure strain	level of strain (displacement over reference length) that causes visible, permanent damage, typically a crack
geophone	mechanical transducer that responds to velocity of motion
ground settlement	permanent displacement of the ground underneath building foundation
Hz	Hertz (frequency of vibration in cycles per second)
in/sec	inches/second
liquefaction	saturated, unconsolidated sediments that are transformed into a substance that acts like a liquid
model	mathematical characterization of a physical phenomenon
natural frequency	frequency at which a structure will continue to vibrate once set in motion
non-cohesive	refers to soil that is loose and not bonded together very well
micron	10^{-6} meters (0.000039 inches)
PPV	peak particle velocity measured in inches per second in the USA
RMS	root mean square
shear movement	deformation of a material substance in which parallel internal surfaces slide past one another
sheet pile	underground pile system that is composed of interlocking sheets of steel
slurry wall	excavated trench that is typically filled with mixture of soil and bentonite or cement when excavation is to occur
vibration	oscillatory movement of ground or structure in response to mechanical energy that may be random or periodic in nature

vibration monitoring	automatic recording of vibration using a transducer (typically a geophone) connected to a seismograph
wythe	a continuous vertical section of masonry one unit in thickness (e.g., brick)

1. EXECUTIVE SUMMARY

The primary goal of NCHRP 25-25 Task 72 research is to obtain current practices used to address construction vibration and its potential effects on historic buildings adjacent to transportation projects. The main tasks of this research are to conduct a literature review, a survey of transportation agencies and SHPOs and recommend a best practices approach. This memorandum provides a summary of findings from the literature review, an annotated bibliography for the most relevant references and a bibliography of all the literature deemed relevant to the subject at the time of publication.

The team of ICF International, Wilson, Ihrig & Associates, and Simpson Gumpertz & Heger (Team) conducted a literature search with the goal of obtaining the most recent information available on the subject. The Team was able to build on recent documents that thoroughly summarized the subject matter as of the date of their writing, the last of which was 2004. Using the information contained in these documents as a starting point, the Team conducted a search using various on-line search engines (e.g., Google Scholar). The follow up phone calls to some of the individuals who responded to the questionnaire survey also produced additional reference material.

The current literature search obtained several references published subsequent to 2004 as well as a few references that had not been identified previously. Including previous literature and newly obtained literature, a total of approximately sixty-four reference documents including published journal articles, project reports, national and international standards, government guidelines, government regulations, and books were identified as having sufficient relevance to the subject.

After conducting a review of existing reference lists and an on-line search, the material obtained was reviewed for the level of relevance to the research topic. To assist with this task, a rating scheme for the relevance of the material provided was devised to provide focus. This rating can also serve as a simple guide to readers who desire to go beyond the summary provided herein and read the full text of some of the literature for additional details.

From our review of the literature, we conclude that there is consensus on many issues relating to protection of historic structures, but not on one of the most important subjects, that of appropriate vibration limits. This appears to be due to the background of those making recommendations on what limits are necessary to avoid damage. Most of the research in the field of building damage comes from blasting vibration and its effect on typically more modern structures. Those that come from this background tend to argue for higher levels of vibration than those that have done research on lower levels of vibration such as that associated with roadway traffic. There is very little research pertaining to the subject of common construction vibration such as that associated with moving equipment and even pile driving.

It is unlikely that additional government research on construction vibration will happen any time soon. In the meantime it will probably be necessary to adopt a cautious approach to setting limits and allow for flexibility on a case-by-case basis. This seems like the most viable approach to take and seems to have some support based on the literature reviewed. The procedures for documenting the existing condition of buildings and monitoring vibration are well established and generally there is universal agreement on the need to do this. Many state DOTs have procedures for controlling and monitoring blast vibration, but aside from this only the State of

California has produced a set of detailed procedures for controlling general construction vibration associated with transportation projects. The survey of state DOTs did not turn up any similar procedures not did follow phone calls. However, there may be states with such procedures.

2. INTRODUCTION

2.1 Aims and Objectives

The primary purpose of the current project is to provide guidance to historic preservation professionals, transportation agencies responsible for the Section 106 process or other environmental processes, and the general public when evaluating risk to historic structures prior to construction of transportation projects. The goal of this work is to establish a summary of best practices that provide protection and at the same time do not unnecessarily hamper or constrain the construction of important infrastructure.

The research conducted for this project includes a literature review to obtain the most up to date information available on construction vibration and its effects on historic structures in particular those that may be in a fragile state due to age and/or method of construction, and the practices for mitigation of vibration. In order to get a more thorough survey of the practices followed by state DOT's and other transportation agencies; a questionnaire was prepared and disseminated to a list of transportation agencies and SHPOs. The research project report will combine the results of the literature review and the agency survey and provide a summary of the best practices.

2.2 Background

Building large scale transportation infrastructure typically involves the use of heavy earthmoving equipment and other activity such as pile driving, all of which can impart significant energy to the ground. Sometimes construction requires use of blasting where rock is encountered. The resulting ground motion propagates as spreading waves of vibration into the surrounding earth in a complex manner. The intensity of motion at a distance from the source depends on the amount of energy transmitted into the ground, the manner in which the ground responds and the internal damping within the ground as vibration travels through it. The dynamic response of a building or structure to ground motion is dependent on the unique characteristics of the structure and often on the site on which the structure sits. These factors make it challenging to predict ground vibration and the corresponding response of structures with a high degree of accuracy.

Occasionally, construction must be conducted in relative close proximity to older historic structures or buildings, particularly in dense urban areas. The public and many engineers perceive these structures as fragile and susceptible to vibration damage in large part due to their age. In addition, historic structures (or landmarks) are deemed worthy of preservation because of their importance to society. The historic integrity of landmarks is important, and they have a lower tolerance for acceptable damage than a modern structure. A specific structure's susceptibility to vibration damage is due to a number of factors including the method used in its construction, a lifetime of deterioration caused by weather, previous vibrations such as earthquakes, and proper maintenance or lack thereof. Without unique information about a structure, it is difficult to assess fragility based on age alone. However the type of building construction (e.g., stone masonry) and age of building are sometimes good indicators of fragility.

The National Historic Preservation Act (NHPA) requires that historic properties (including buildings, structures, and archeological sites) potentially affected by transportation projects receiving federal funding must undergo the "Section 106 Review Process" before construction can be approved. Any property listed on or eligible for the National Register of Historic Places is considered "historic" for Section 106. In addition, many states have additional environmental review processes, such as California's Environmental Quality Act (CEQA). All "adverse impacts" on the historic structure must be evaluated and, if possible, mitigated. The Section 106 process is led by the agency proposing the work in consultation with the State Historic Preservation Office (SHPO). The Advisory Council on Historic Preservation must approve the final review and Memorandum of Agreement (MOA).

Avoiding damage to historic structures is of utmost importance. However, the potential for damage to historic structures should be evaluated based on scientific principles, not the perception that any vibration near any historic structure could be a problem. Misplaced concerns regarding the effect of vibrations on historic structures can lead to unnecessary delays in the Section 106 process and other environmental reviews.

Current Status of Practice

The range of possible damage from vibration to any built structure is quite broad, ranging from minor cosmetic changes to an extreme situation of damage that endangers structural integrity. Obviously, when dealing with historic structures, the overriding goal is to avoid any damage. A key factor is proximity of the vibration producing activity to a structure. The question to be answered is: "When is a structure close enough to be of concern?" The answer depends on many factors. Some agencies, including the Federal Transit Administration (FTA), have published guidelines that address vibration and older more fragile structures. However, currently there is no widely accepted, uniform, and systematic procedure that historic preservation professionals can employ during the environmental assessment phase of an infrastructure project to quantify an historic structure's susceptibility to damage and thus design mitigation that appropriately minimizes this risk.

A complicating factor is that the term "historic structure" can encompass a wide variety of structure types, including free standing monuments, buildings, and existing older infrastructure such as bridges and even underground structures (e.g., brick sewer lines) and archeological sites. The spectrum of structural types includes several different construction methods, such as wood frame and unreinforced masonry, which affect a structure's response to vibration and complicates the task of determining its susceptibility to damage. Even more modern structures of concrete and steel may now be eligible for the National Register if they are over 50 years old and historically significant. Thus, a combination of factors makes individualized risk assessment difficult. There is a tendency to adopt what can be categorized as generic limits for construction vibration that are, by nature, conservative to cover the wide range of structures.

The primary means for controlling construction vibration in general practice today typically consist of requirements for the construction contractor to develop and submit for agency approval vibration control and monitoring plans that will adhere to the vibration limits imposed by the contract specifications. How the contractor is to demonstrate that will occur is not always made clear. Although it is necessary that an experienced professional be employed to project

(i.e., predict) vibration levels at historic structures to be protected, most specifications do not spell out how that experience is to be evaluated to ensure relevancy.

To demonstrate that vibration limits are being adhered to during construction, the contractor is required to monitor vibration at each of the affected historic structures. Typically the manner in which the vibration is to be measured and reported is also prescribed. However, specifications often lack methods to make the contractor aware of activity that causes vibration, which approaches a limit, such that remedial action can be taken before a limit is exceeded. In some project warning alarms (both visual and audio) have been installed to address this with relatively good success by giving real-time feedback to equipment operators. Monitoring vibration is necessary but not sufficient to ensure compliance and avoid damage. Monitoring without some form of feedback to equipment operators in real-time only allows for a reactive response (i.e., knowledge that vibration limits have been exceeded after the fact), whereas by adopting a proactive approach the chance for success can be increased and has been found from experience to provide equipment operators a certain amount of control over the vibration they produce.

The lack of a clear and widely accepted means of describing the effects of ground vibration on structures can cause concern among private building owners and, frequently, the public. Under the circumstances, public officials charged with making decisions are faced with a daunting task of ensuring that not only are the historic structures not damaged, but also educating the public about the expected vibration impacts to avoid unnecessary delays in approval and construction of needed infrastructure. There is clearly a need to develop a concise synthesis of the issues of potential vibration effects on historic buildings so that historic preservation professionals and building owners can better understand the issues and what means and methods are available to avoid damage. This project will address that need.

3. OUTLINE OF THE LITERATURE SEARCH METHODOLOGY

3.1 Defining the research topic

The topic of this research is construction vibration and its potential effects on historic buildings and current practices to mitigate its adverse effects. To properly address this topic it is necessary to define construction vibration, how it might affect buildings which are historic and therefore often in a fragile state, what constitutes damage to buildings, and how to adopt and successfully implement mitigation measures to avoid damage. Knowing a-priori that the subject still remains to be more thoroughly studied, it was decided to expand the search to include as much relevant material as could be obtained and draw conclusions by extrapolation where possible.

Based on past research on this subject it was known that other sources of ground vibration could possibly be relevant to the effects of construction vibration on historic buildings. Consequently the literature search included material relating not only to conventional construction (e.g., pile driving and soil compaction), but also to blasting which although less common is a major concern in some urban areas. Ground vibration that is generated by transportation operation (rail or motor vehicle) is also relevant to addressing the potential for low level vibration effects on buildings and has been the subject of several research studies.

Although the focus of this research is on historic buildings, the literature search also included historic structures such as bridges and hydraulic works knowing that the methods of construction

are sometimes similar (e.g., unreinforced masonry) and may therefore be relevant to potential for damage in historic buildings.

The subject of damage is broad and although there are definitions covering two very general levels of damage (structural and cosmetic) it is difficult to apply these definitions in a quantitative manner to modern structures let alone buildings whose conditions are only poorly defined if at all. Mitigation measures to avoid damage to historic buildings typically consists of setting vibration limits and monitoring with thresholds set to trigger warnings and stop work orders. Other mitigation measures have been tried and these are discussed.

3.2 Search Methodology Used

The literature search began with the list of related papers, books, and reports that were already listed in bibliographies in the Team's possession from previous similar projects involving environmental vibration and its effect on historic buildings and structures. The assembled reference lists in these resources were reviewed to get an idea of what types of sources were good candidates for searching. The initial review also produced relevant phrases that could be used as search terms for additional sources.

Using these search phrases in Google Search and Google Scholar, an initial batch of potentially relevant sources were obtained. The material found in the initial search was reviewed for the degree of and the search was refined. It was discovered, for example, that "threshold damage vibration" was a useful search phrase in Scholar, while something like "building fatigue" was less productive. The Team also used www.dialog.com and searched the OSMRE and various DOT websites.

Several iterations were conducted refining the search in response to the relevance of material obtained. From the reference lists of the newly acquired papers, other publications were selected that appeared relevant. With those specific titles, a search through Google and Dialog Information Services thus producing additional literature. Finally conference websites and preservation societies were researched for relevant material.

As a subsequent step in the questionnaire survey, follow up phone calls were made to selected individuals who had responded to the survey. The selection of who to call was based on the additional information provided in the survey. The follow up phone calls were fruitful in providing additional reference material including published papers, which for whatever reason, did not come up in the on-line literature search. The calls also produced examples of projects reports and other material such as example MOA.

4. IDENTIFICATION, SELECTION AND REVIEW OF THE LITERATURE

The literature search included the following sources:

- Published journal articles
- Project technical reports
- Government research reports

- National and international standards
- Government guidelines
- Government regulations
- Books

Other sources of information were also pursued such as personal communication with other professionals in the field.

4.1 Method of Selection of Literature

The literature search was conducted using the following general categories:

- Technical documents relating to vibration effects on older buildings and structures
- Technical documents relating to vibration criteria for older buildings and structures
- Policy documents relating to the effects of vibration on older buildings and structures
- Documents relating to the evaluation of environmental effects on historic or heritage structures
- Government documents on preservation of historic buildings and structures

By "older buildings" it is meant buildings of historic nature that are not contemporary and presumably in a structural state that they could more easily sustain damage than buildings that are of modern construction when subjected to the same vibration. Several documents did not include construction vibration in the research, but are considered relevant because they concern low level vibration from traffic as it relates to the potential for damage to historic structures. Consequently these were included as well because of the information contained in them that would not otherwise be included.

4.2 Method of Literature Review

In order to focus the review of the literature, a list of general subject matter was developed. The list consisted of essential elements of the research. The Team members identified fourteen (14) relevant areas or content categories for characterizing the material found in the literature. The categories are:

- Historic, old or fragile buildings or other such structures are discussed
- Construction (general and blasting) vibration effects are discussed
- Damage is discussed
- Protection from construction vibration (mitigation) is discussed
- Ambient vibration effects are discussed
- Vibration limits to protect structures are presented
- A formal or structured process (government or otherwise) to evaluate and protect historic structure is discussed
- A detailed case study is presented
- Actual damage (or no damage) correlated to vibration is presented
- Detailed construction vibration mitigation measures are presented
- The fragile nature of structures is discussed (what makes a structure damage prone)
- Prediction of vibration from construction is presented

- Blasting vibration effects are discussed
- Discussion of the potential for soil settlement

Using the above categories it was possible to systematically review the documents obtained and evaluate their applicability to the subject matter based on how thorough each one was in covering the identified areas of interest.

5. SUMMARY OF LITERATURE REVIEW

We discuss in detail only the most relevant literature. The literature selected for the annotated bibliography was based on the completeness of the reference material in the content areas presented in Section 4. Not all the literature in this review specifically addresses construction vibration, but it has been included due to its coverage of a specific subject matter that is important to understanding vibration and/or older buildings and structures and what makes them susceptible to vibration. We have included material that addresses the effects of traffic vibration on historic structures due to its relevance to low level construction vibration and the amount of research that has been conducted studying low level vibration effects from traffic.

5.1 Published Journal Articles

Several published articles that were identified in the literature search address construction vibration and in particular address historic structures and the potential for damage. We now present an annotated bibliography of a few of the more comprehensive journal articles and a website article. The articles discussed below are presented generally in descending order of the thoroughness of the content presented.

5.1.1 Hammarberg, et al. (2009)

This paper is one of five most comprehensive papers, the others being Henwood and Haramy (2002), Sedovic (1984), Esrig and Ciancia (1981), and Kelly et al. (1998). Hammarberg and his fellow authors are structural engineers who were engaged to provide an assessment for two construction projects in New York City that were in close proximity to historic buildings. They recommended vibration limits and developed detailed plans for monitoring prior to and during construction.

The authors explain in clear terms the fragile nature of historic structures, which is typically due to the brittle materials (brick masonry, terra cotta, and plaster) and methods used in their construction. The difficulty in minimizing construction impacts to historic structures especially in urban areas is explained. In addition to the effects of vibration, this paper also discusses the effects of excavation adjacent to older buildings and the need to underpin to prevent soil settlement a phenomenon similar to but unrelated to vibration caused settlement, however equally as important.

Hammarberg distinguishes, as do most others, the difference between structural damage (that which affects the capacity of the primary or secondary load bearing members in the building) and cosmetic damage (that which affects the appearance of the building, but not the structural capacity). As the paper notes, the envelope of the building is the most likely to suffer cosmetic damage due to cracking of exterior finishes, growth of existing cracks especially in older

buildings that are often heavily ornamented. The existing condition of historic structures is also of concern due to weakening of building elements as a result of the aging process caused by weathering, temperature variation, freeze-thaw and long-term settlement of the structure. A building that has suffered from what might be called the ravages of time is more likely susceptible to additional damage.

The paper provides a good description of the nature of construction vibration and how it interacts with structures and the most common types of vibration producing construction activity are listed. Vibratory installation of sheet piles, pile driving, and vibratory compaction of soil are examples of long-term activity. Of a more short-term nature, there is the vibration activity associated with blasting and dynamic soil compaction.

In a discussion on setting vibration limits, the authors indicate that the generally adopted values come from empirical data that address vibration source, soil type(s) and condition of the structure and that there is no single, widely recognized standard for allowable vibration limits for historic structures. The authors do point out that, in spite of this, for a particular project it may be possible to assess the "probable damage" to a historic structure adjacent to construction when determining a "rational" vibration limit. Hammarberg indicates that the most appropriate standards for protection of historic structures are the standards that were developed for the protection of older, damaged or in other words more vulnerable structures.

Of importance, the authors note the vibration limits derived from research conducted by the USBM on the effects of blasting on residential structures are the least appropriate standards for protection of historic structures. They indicate that the Swiss, German and Central/Artery Tunnel (Boston) vibration standards were found to have prevented damage during construction in urban areas as reported by Kelly et al. (1998) and Glatt et al. (2004). The specific limits reported in Kelly et al. (1998) paper depended on the frequency of the vibration and the building. In New York City the limit for historic buildings is 0.5 in/sec, which Hammarberg et al. point out may not be sufficient to avoid damage to fragile historic buildings. The authors discuss the need to determine a balance between providing safe vibration limits without precluding cost-effective construction.

The authors emphasize the importance of a preconstruction survey of the historic building and that it should be required and would include:

- Description of the building
- Type of building construction
- Age of construction
- Foundation type
- Condition of the building
- Location, width and orientation of visible defects and/or cracks
- Location of loose material
- Location of previous repairs
- Distance to construction operations.

A thorough survey can be used for comparison in the case of reported damage.

The mitigation measures discussed include securing loose materials prior to construction to keep them from falling and supplemental support for equipment that might sway. Routine visual surveys during construction are recommended to observe if changes are occurring and to evaluate if new damage has occurred. The most important mitigation measure is to monitor vibration using proper instrumentation. Where there are pre-existing cracks they should be monitored to observe whether changes have occurred. This can be done by a simple visual gage or electronically.

Two case studies involving historic buildings in New York City dating from the late 19th century are presented. The unique features of two buildings (early sky-scrapers of 15 and 21 stories high) in the first case that make them susceptible to vibration are explained in detail. An interesting recommendation was to include a gas leakage monitoring system.

The second case study involved an historic district of buildings dating from the early 19th Century. In this study, the foundations of buildings in this district were determined to be particularly susceptible to vibration damage due to their construction with loose material (stacked stone and rubble). Four threshold levels were recommended by the engineering team. With each level, there were recommended reporting, engineer action and contractor action requirements, with the latter ranging from no action to cessation of all work.

Unfortunately, the authors apparently published their paper before the construction work was started or at least completed. It would be important to follow up with how well this plan and the vibration limits worked in practice.

5.1.2 Sedovic (1984)

Sedovic comes to the subject from the perspective of a historic preservation architect. His article presents a very comprehensive discussion of the effects of vibration on historic buildings and the process necessary to minimize and ideally eliminate likelihood of damage. Sedovic provides a concise and easy to understand explanation of what causes vibration and the types of activity that result in the different temporal aspects of construction vibration (e.g., impact, steady state). He describes the basic aspects of vibration (frequency, amplitude, velocity, acceleration, distance and time) and why they are important in terms of the negative effects they can have on structures.

Sedovic discusses four classifications of damage: damage to a structure's contents, structural deterioration, architectural damage, and structural damage. The first two classifications are not often discussed by others. The identification of structural deterioration as a classification implies that damage can occur after time has passed from when the vibration occurred. Damage to contents can occur to objects that are not permanently fastened to the structure (e.g., furnishings, artifacts) that move or break.

Sedovic rightly points out that vibration limits developed for contemporary structures are not appropriate for older historic structures. He discusses the problem of developing limits from test data in the context of a statistical process that may be unacceptable even though damage might only be 15% likely if the building contained historically important, delicate plaster moldings. In this case he points out that vibration limits must be based on levels at or approaching 100%

avoidance of damage. The lack of research data to prevent content damage and structural deterioration complicates this process.

Maintenance of the structure is emphasized as a good indicator of a buildings ability to successfully withstand the forces of vibration. By this it is meant that a well maintained building constructed with traditional masonry walls has been shown to withstand even severe vibration such as from earthquakes. By conducting a thorough inspection of a building's condition (i.e., crack survey) it is possible to determine how well the building has been maintained over its life from which an assessment of its potential susceptibility to external vibration can be made. He points out old cracks (even hairline cracks) should be mapped and that old cracks re-open at lower levels of vibration than that need to form new cracks.

Limits for preventing damage are discussed including the need to avoid unduly stringent restrictions. Based on research from the effects of blasting, Sedovic suggests that 0.2 in/sec would be a safe limit for "structures that exhibit significant levels of historic or architectural importance or that are in a poor or deteriorated state of maintenance." For all other historic sites, he indicates a safe limit of 0.5 in/sec. However he also states that "it is important to reiterate that it is superficial to define safety in terms of peak particle velocity alone." A discussion of vibration monitoring instrumentation and its use is also provided.

5.1.3 Esrig and Ciancia (1981)

The authors of this paper are structural engineers. They address the effects of vibration from construction of a 29 story office tower adjacent to buildings in an historic district in lower Manhattan (New York City). The potentially affected buildings in the historic district were constructed between 1820 and 1970 and were built on fill placed in the area during the 17th Century. The historic buildings included sixteen 3 and 6 story buildings located on one city block. The authors indicate that some of the buildings have undergone extensive renovations over their lives sometimes after fires.

As part of the renovation of one of the buildings, test pits were dug in some of the basements to inspect the type and condition of the foundations. Grouting of the soil was recommended and undertaken to provide additional support for the foundation. For the office tower project, characterization of the soil was determined by digging test pits within some of the historic building's basements.

The authors were tasked with arriving at permissible vibration levels and limits for other issues concerning movement of temporary restraining systems and movement of the buildings. They list various limits for peak particle velocities ranging from 0.2 to 1.0 in/sec. NYC Department of Environmental Protection limit was 0.2 in/sec for old brownstone buildings. The project decided to use a limit of 0.5 in/sec with the requirement that if either building movement or additional cracking during blasting and/or pile driving occurred, the limit would be reduced.

Monitoring before construction of ambient conditions indicated vibration that was general below 0.1 in/sec with only one level that reached 0.2 ins/sec. Monitoring during construction indicated that the maximum vibration was 0.18 in/sec and that "the historic buildings showed no measureable signs of distress or movement during the driving of the sheeting" (sheet piles).

Monitoring performed during blasting indicted vibration below the 0.5 in/sec limit and no measureable distress evident.

5.1.4 Henwood, et al. (2002)

This paper does not deal with vibration from construction equipment, but does address the effects of vibration from construction traffic and addresses most of the areas of concern. The authors are FHWA staff. The authors discuss the nature of vibration generated by heavy haul trucks involved in a resurfacing of a roadway and how vibration can affect historic buildings constructed in the mid to late 19th century from "soft brick."

The project involved an investigation with controlled testing using a test truck carrying a known load and travelling at different speeds (10, 20 and 30 mph) during which vibration was measured at two relatively close distances (3 and 5 ft) from the roadway. During monitoring of construction truck traffic vibration the monitors were between 10 and 20 ft from the roadway shoulder. Apparently not all of the monitored locations involved historic buildings.

Ambient vibration from mostly automobile traffic ranged from 0.02 to 0.19 in/sec, whereas truck traffic vibration ranged from 0.02 to 0.15 in/sec or roughly similar to ambient vibration. The authors mention the Swiss standard SN 640 312 (1992) for "objects of historical interest" of between 0.12 and 0.20 in/sec depending on the frequency range. Only one truck produced vibration higher than the 0.12 in/sec standard at a historic building, but frequency analysis indicated that the vibration was within "acceptable" limits because of the associated high frequency. It is noted that the controlled testing produced higher levels of vibration than the typical ambient and the monitored construction traffic.

The authors note that the vibration form the monitored construction traffic was less than the Swiss standard of 0.12 in/sec and although it is not stated presumably there was no damage observed for the historic buildings.

5.1.5 Abdel-Rahman (2002)

This article deals with a historic structure (a pier on the Dammietta Branch of the Delta Barrage in Egypt) rather than a building, but is sufficiently detailed and comprehensive in its treatment of the subject to be considered worth inclusion since it addresses many of the areas of interest. A bridge and navigation lock was constructed using impact and vibratory hammers next to this structure. A crack in the pier was observed to have formed during pile driving operations at a distance of 10 ft away.

A study was undertaken to prevent further damage and assess the potential for damage to the Barrage structure and buildings in the area. This paper details the measurement program and analysis performed to determine how to drive piles safely so as not to affect the Delta Barrage structures. Although many of the structures were located at relatively safe distances a thorough monitoring program was conducted.

Data are provided for vibration levels associated with driving sheet piles in soft and hard soils at various distances. The author mentions construction of a trench as a means of control ground vibration and seems to believe that it was successful contrary to what other research has shown.

Vibration levels detected on the Barrage structure were typically 0.03 in/sec and due mainly to motor vehicle traffic on the surface of the Barrage. There is a list of conclusions one of which is "It is important to assess the dynamic effect before beginning construction."

5.1.6 Kelly, et al. (1998)

The authors are structural engineers and report on construction vibration associated with the Central Artery/Tunnel (CA/T) project in Boston. The focus of their work was on two historic structures one a seven story building constructed in 1899 and the other an eleven story building constructed that same year. Both buildings use brittle material in their construction. The first building has a façade of multi-wythe brick and granite cladding on the lower floors and a granite cornice. The façade was observed to have mortar erosion, regions of loose brick and moderate brick cracking. The second building had structural floors framed by steel beams and girders with a tile-arched infill supported on steel columns and exterior brick piers. The façade of the second building is similar to the first and includes terra cotta pillars and arches and an ornamental terra cotta parapet. The façade on this building also exhibits cracking prior to construction of the CA/T project.

The authors explain the steps by which the effects of construction were evaluated during the environmental impact statement (EIS) process for the CA/T. The EIS referenced the Swiss Standard SN 640312 vibration limits for historic structures, but expressed concern that criteria cannot account for long-term fatigue that may occur over many years of construction vibration. Consequently the EIS selected the German Standard DIN 4150 criteria for historic structures instead as more conservative criteria to use, but taking into account the frequency of the vibration. The paper indicates that criteria ranging from 0.12 in/sec to 0.30 in/sec were used.

Instrumentation for monitoring vibration is presented as are the locations appropriate for monitoring at the two historic buildings. Monitored vibration data are presented. Although uncommon the vibration was not only measured at the ground level, but also at higher levels in the two buildings to address human response to the vibration. The monitored vibration levels reported were less than the German DIN 4150 criteria.

5.1.7 Konon and Schuring (1985)

These authors investigate the criteria traditionally used as of the date of their writing to protect historic and older buildings. The authors are civil engineering professors. They provide an easy to understand discussion of ground vibration and how it is measured. It is mentioned that older buildings usually have residual strains as well as settlement and other age related issues. They point out as others have that elaborate ornamentation both exterior and interior is prone to damage and that strict limits on construction vibration can not only eliminate possibility of immediate damage but also reduce the possibility of fatigue damage due to cumulative effects.

The authors discuss summarize the particulars of eight different criteria including that of the German standard DIN 4150, Swiss standard SN 640 312, Rudder, Esteves of Portugal, Whiffin and Leonard, Ashely, Esrig and Ciancia, the City of New York, and that of Chae some of which are discussed below. The criteria for historic structures in these references range from 0.10 to 0.50 in/sec. Rudder recommends 0.10 in/sec. The German standard 4150 recommends from 0.12 to 0.40 in/sec for short term vibration depending on the frequency range. Swiss standard SN 640

312 recommend 0.12 in/sec for continuously occurring vibration (machines and traffic) and 0.30 in/sec for blasting unless the frequency of the blasting vibration is between 60 and 90 Hz. The higher criteria are in general for impulsive type vibration such as from blasting and pile driving.

The authors indicate that the possible damage to a unique historic building should be weighed against the increased cost of construction associated with using a low maximum permissible criterion. They recommend a limit for transient vibration that is 0.25 in/sec for frequencies less than 10 Hz and a varying limit between 10 and 40 Hz, above which the recommend limit of 0.5 in/sec. For steady state vibration they recommend reducing these limits by one-half.

5.1.8 Wiss (1981)

This paper written by a civil engineer evaluated the state of the art of construction vibration in 1981. There is a very good discussion of the nature of construction vibration with examples of the different types of equipment associated with each. For example, steady-state vibration can be generated by vibratory pile drivers, large pumps, and compressors. Transient vibration is caused by blasting, impact pile driving, demolition and wrecking balls. Another category of vibration is labeled pseudo-steady-state in that the vibration is random in nature or caused by a series of impacts of short intervals. Examples of the latter are jackhammers, pavement breakers, trucks, bulldozers, cranes and scrapers.

The author provides a discussion of vibration and the effects of distance and a chart of typical levels of vibration for different sources as a function of distance. The latter can be useful as an approximation of expected levels of vibration, but should be used with caution keeping in mind that source strengths and soil properties will affect the actual vibration level.

Wiss also presents criteria for limiting vibration. He presents the newly published Swiss standard at the time SN 640 312 (now SN 640 312a), which is discussed in more detail below. Most of the paper is focused on other than historical structures (residences and human perception). He indicates a need to obtain fatigue data for buildings subjected to transient and steady-state vibration.

5.1.9 Svinkin (no date)

Svinkin, a vibration consultant, focuses mainly on pile driving and discusses in detail the mechanics of driving piles. For those that want details on pile driving there is ample information, which would be useful. He reviews and presents a summary of the work of several researchers addressing monitoring and control of construction vibration. Unfortunately historic structures are only mentioned in passing and there is no mention of criteria for these types of structures. Svinkin does talk about soil settlement and how it might affect buildings, but only qualitatively. He does emphasize a preconstruction survey as do others.

5.1.10 Gutowski (1978)

Gutowski, a vibration consultant, also focuses on pile driving vibration and includes details on slurry wall construction both which can be encountered when there is large excavation. Most of this papers emphasis is on the measurement of vibration for sheet pile driving, pile augering and slurry wall construction. Although the latter is often thought to produce less vibration, the author

points out that to construct a slurry wall a trench is dug first and that the "clam shell bucket" on the excavator is often dropped from a height of 10 ft to ensure an adequate bite. The energy of this activity can be four to six times greater than the typical pile driving energy although pile driving energy can also be higher than this. There is useful data presented for typical levels of pile driving vibration that has been normalized to a nominal energy of impact from the pile driver.

Gutowski explores the human response to vibration which can often determine how people perceive the potential for building damage. He also discusses the USBM criteria for damage, however there is no discussion of historic structures. His concludes that pile driving vibration can lead to major complaints from nearby neighbors, but based on the USBM criteria would not likely lead to building damage. Were the paper to be written today and address historic structures, his second conclusion might be different.

5.1.11 Crockett, J.H.A. (1963)

Crockett is a structural engineer who examined the issue of damage from traffic vibration in medieval cathedrals in the UK. His paper is widely cited by other researchers. The paper provides a very good explanation of the construction process used in cathedrals in the 12th and 13th century and what would make them fragile. It could be argued that this may not be that applicable to structures in the USA, but there is enough similarity between older construction using brittle materials in the USA such that the concepts if not the results of vibration measurements and their correlation with damage observed are worth considering.

Crockett explores the phenomenon of aging due fatigue due to cycles of temperature variation comparing that to the cycles of traffic vibration, which are much greater in number. Unfortunately he does not present any quantitative data (although some measurements were apparently made), but does describe in great detail the mechanics of building deformation in particular with respect to foundation settlement as soil compacts. His primary conclusion on vibration effects are deduced from the statistics of the data on damage observed in forty cathedrals and their proximity to roadways, which ranged from about 10 ft to 180 ft. His conclusion was that traffic (vibration) damages these buildings.

5.1.12 Greene (2010)

The subjects of this paper involved a historic church (Calvary Baptist Church) and a historic bridge (Cyprus Avery Route 66 Memorial Bridge), which could be affected by highway construction in Virginia. The author discusses the possible vibration limits which could be applied with the most stringent being 0.08 in/sec. The paper primarily focuses on the importance of obtaining ambient vibration data before the start of construction to ensure that the specified vibration limits are not inconsistent with the existing ambient conditions. The other point the author makes is the importance of a pre-construction evaluation of the structures.

The ambient vibration measurements and a detailed on-site review of the Calvary Baptist Church sanctuary determined that vibration of 0.4 in/sec and 0.2 in/sec for transient and continuous vibration respectively would be appropriate as limits to protect the church. For the Memorial Bridge, which is closed to both vehicular and pedestrian traffic due to the bridge's deteriorated

condition, the appropriate vibration limits were determined to be 0.12 and 0.08 in/sec for transient and continuous vibration respectively,.

5.1.13 Dowding (1987)

Dowding is a professor of civil engineering. His paper focuses specifically on the vibration criteria for historic buildings and is a discussion of the Konon and Schuring (1985) paper and is interesting for that if for no other reason. He takes issue with this paper in several ways. Dowding says "Historic status does not automatically imply higher-than-usual sensitivity." He refers to a recent evaluation (with no specific citation) where historic structures were found to be less sensitive typical structures. He also says "All structures should be evaluated on their own physical condition, rather than a status determined by historic and cultural considerations." In principle we would agree with this statement, however in practice it may not be feasible or practical to adequately assess a structures physical condition in a quantitative manner.

Dowding, who obviously has much experience in the subject matter of vibration from blasting and construction (see section on books), also discuss at length the concept of damage as it relates to cracks. This is useful if one is to understand the process of vibration induced damage. His main focus is on blasting and he refers to research work on older buildings' response to blasts. Quite interesting is his comparison of strains measured in walls caused by daily changes in temperature and humidity compared to those caused by exterior vibration. He seems to take issue with the German standards (presumably DIN 4150), implying that political considerations may have trumped science.

5.1.14 Medearis (1977)

Meaderis is a consultant whose paper deals with damage criteria for low-rise structures subjected to ground vibration from blasting related to underground nuclear blast research. His research work involved residential structures some of which were 96 years old and constructed with masonry walls. This makes his work somewhat relevant to the subject of historic buildings although none were apparently involved. Most of the paper is focused on the mechanics of ground and building motion from blasting. The data presented is somewhat unique in that it was measured inside the buildings. Meaderis contends that "structural damage" must take into account the frequency response of the ground to blast motion. He also concludes that damage threshold criteria must take into account the frequency response of the structure. The main result of his research was that structural damage could be avoided for one to 2 story residential structures when the vibration was less than about 0.75 in/sec. This value could possibly be seen as something of an upper limit for all historic structures to avoid damage, but presumably only those in very good condition.

5.1.15 Ashley (1976)

Ashley indicates a vibration limit of 0.3 in/sec for ancient and historic structures.

5.2 Project Reports

The following reviews are for technical reports prepared in general by consulting firms (engineering and vibration specialists) for government agencies. At least two or three of these

project reports contain sufficient information and data to provide examples of representative case studies to be presented in the Task 72 project report.

5.2.1 Gutowski, et al. (1977)

The authors (vibration consultants) of this report provide a very detailed analysis and assessment of the potential for vibration damage during construction for I-38 in Baltimore. They also evaluate vibration effects from traffic. The authors mention the following potentially affected historic buildings: St. Phoenix Shot Tower, Carroll Mansion, the Star Spangled Banner Flag House, 9 Front Street, St. Vincent de Paul Roman Catholic Church, and the President Street Station.

They provide a clear discussion of the sources of construction vibration and how it can be controlled with emphasis on pile driving and augering of piles, which would be used in slurry wall construction. Other construction activities producing vibration that would not necessarily come to readily to mind are “clam bucket” drop and chisel drop.

Representative vibration data are provided from prior measurements for various construction activities. Of note the authors point out that the horizontal motion of the ground may well be the largest component as indicated by previous investigations. Details of mitigation measures that can be employed to reduce vibration are discussed. The vibration limit adopted in this report to assess cosmetic damage to historic buildings is 0.20 in/sec. This report also discusses a concern for soil settlement due to vibration.

5.2.2 Shaw (2000)

This report deals in extensive detail with vibration effects from blasting at a surface mine near a historic house (Meason House) in Pennsylvania. The report was prepared by a vibration engineering consultant (D. E. Shaw). The Meason House, constructed in 1802 is a 2½ story ashlar sandstone house representing the English Palladian villa-type style and the most sophisticated example for this region from this early period. Shaw’s work includes a detailed statistical analysis of measured vibration data and engineering analysis of the response of the building’s major structural elements (walls) to ground motion from the blasting.

A thorough investigation of the building was conducted to document its condition. There is a detailed description of these observations and an engineering assessment as to stresses and strains probably existing in the main building structural elements and in some instances the possible cause. The observations relate the existing condition (e.g., cracks) to the potential for increased damage due to vibration. A detailed description and discussion is also provided for the internal condition of the house with its lathe and plaster walls and ceilings.

From his dynamic analysis, Shaw conducts a stress assessment to determine the probability of additional damage due to on-going blasting at the surface mine. He examines mortar cracking, block sliding, plaster damage, and subsidence (of support pillars). His probability analysis examines the effects of a single blast and the effect of numerous blasts (100) over a two year period. Using the measured vibration data for blasting at various distances he determined that there was a high probability of damage in terms of mortar cracking and plaster damage for the two year period of blasts. Further assessment of lower vibration limits led him to conclude that

the Department of Environmental Review limit of 0.5 in/sec was too high based on the limit of 0.20 in/sec to avoid extension of existing cracks. We quote from Shaw:

"However the historic and architectural nature of the house do create special circumstances in the evaluation of potential damage. These circumstances dictate that such an evaluation go beyond simple criteria designed for protection of structures adjacent to mine blasting operations, criteria which are geared to providing optimal protection for average structures for which economic damage can be recompensed."

5.2.3 Nykamp (2008)

This report details the results of vibration and crack monitoring for two historic buildings in the Pioneer Square Historic District of Seattle. The two buildings (Western and Polson) are industrial buildings built in the early 1900s. The construction work involved retrofit stabilization of the Alaskan Way Viaduct foundations nearby. The Washington DOT contract required limiting vibration at the closest points of the two buildings to 0.5 in/sec. Prior to construction a crack survey was performed to document existing damage to the two buildings. Based on the recommendations of the geotechnical and environmental subcontractor Shannon & Wilson a total of 25 crack gages were installed in the two buildings on existing cracks to monitor movement. The results of the vibration monitoring indicated levels never exceed 0.1 in/sec and the majority of crack gages indicated no significant changes in crack widths.

5.2.4 King and King (1994)

This report does not address construction vibration but is considered relevant due to its detailed field research on very fragile structures and the effects of vibration from exiting ambient sources (e.g., motor vehicles). The authors investigated the risk to free standing, stone wall structures (building ruins) dating from 11th to 13th Century at the *Aztec Ruins National Monument*. They used a unique method to excite the structures and determine natural frequencies of the structures and monitored existing ambient vibration.

Knowledge of a structure's natural frequencies is important for understanding how it will respond to vibration. The walls are generally 8 to 15 ft high and constructed of stacked stones. To excite the wall, a person moved back and forth at the approximate natural frequency of the wall. After the person stopped moving, the wall continued to vibrate while measurements were done at the top of the wall to determine the frequency of free vibration. The investigation determined primary (lowest) natural frequencies of the walls to be in the range of 12 to 25 Hz.

Sources of nearby vibration include maintenance vehicles (pickup truck) as close as 20 ft and whose natural frequencies are in the range of 14 to 17 Hz. More distant sources include visitor traffic on *Monument* roads (approximately 100 ft away from walls). The pickup truck at 20 ft produced vibration between 0.01 and 0.03 in/sec.

The authors recommended a restriction on heavy vehicles to be at least 50 ft from any ruin wall, one of the roads was in rough enough condition to be of concern, basic vibration monitoring during any heavy restoration work, a 0.2 in/sec maximum except near rooms with "pertinent mud coating," for which a maximum of 0.08 in/sec should be used.

5.2.5 Crockett and Wilson (1995)

The report was prepared by a vibration engineering consultant (Wilson, Ihrig & Associates). Crockett and Wilson investigated the effects of high speed trains operating on a historic viaduct structure in Connecticut. The viaduct is on Amtrak's Northeast Corridor. The viaduct is an unreinforced structure which had significant visible damage and mortar in poor condition and there was concern about increased vibration from higher speed trains traveling at up to 150 mph. As part of the authors' analysis on the viaduct, a literature search was conducted to collect threshold of damage standards and criteria for vibration. Twenty-one references were obtained and summarized. Only four of these references are relevant to historic structures and the rest deal with more modern structures. Of the criteria for historic structures the vibration limits range from 0.08 to 0.40 in/sec.

Crockett and Wilson evaluated all of the criteria the collected and recommended a limit of 0.10 in/sec for the viaduct in its current condition. Based on the structural reinforcements that were to be implemented, they recommended that the limit be 0.20 in/sec.

5.2.6 HNTB and WIA (2002)

A vibration evaluation was prepared for WisDOT and the City of Milwaukee for the demolition of a freeway (Park East) adjacent to three historic buildings in downtown Milwaukee. The report was prepared by a vibration engineering consultant. The Park East Vibration Study covers most of the essentials of construction vibration and historic buildings and is a good case study.

One of the buildings (Gipfel Union Brewery) was built in 1853 in the Federal style and is the oldest brewery still standing in the city. The Gipfel Union Brewery (a three story brick building) was 100 ft from the nearest freeway lanes. A second building (Gugler Building) was built in 1896 in the German Renaissance Revival style. The Gugler Building (comprised of a one story and a two story brick building) was 95 ft from the nearest freeway lanes. The third building (WEPCO Switch House) was built between 1903 and 1912. The Switch House (a two story brick building with a reinforced concrete foundation, ca. 1942) was the city's primary source of electricity until the middle of the 20th century. The Switch House was located 20 ft from the nearest freeway lanes.

The Park East Study also contains an extensive review of vibration criteria that builds on the Crockett and Wilson (1995) study with seven additional references with criteria. In their evaluation of the buildings and derivation of a recommended criteria, the authors used the classification system for buildings contained in the British standard BS 7385, Part 1, in which each structure is rated according to four categories: the type of construction; the foundation; the soil; and political importance. As a result of their analysis, the authors recommended a limit of 0.15 in/sec for the Gipfel Union Brewery, a limit of 0.40 in/sec for the Gugler Building and a limit of 1.2 in/sec for the WEPCO Switch House.

5.2.7 Carman, et al. (2009)

The report was prepared by a vibration engineering consultant. In 2002 the authors prepared a technical analysis for the Sacramento Railyards project in Sacramento, California. The project involved a massive redevelopment plan for an area (244 ac) formerly used by the two railroads

for storage and maintenance of their freight cars and locomotives. The Railyard property is adjacent to the Amtrak station and was the original western terminus of the First Transcontinental Railroad when the Central Pacific Railroad connection with the Union Pacific Railroad was completed in 1869.

The specific project for which this report was prepared involves the relocation of the current tracks that carry freight and Amtrak passenger trains. The track relocation will bring the nearest track within 32 ft of one of the historic buildings. The environmental impact analysis for the Sacramento Railyards Project recommended investigating the predicted vibration levels from freight operations and their potential effects on the remaining historic railroad buildings in more detail.

There are eight historic buildings all of brick construction that are associated with the Southern Pacific Railroad shops known as the Central Shops. The Central Shops buildings are slated to be redeveloped for use as a public market, museum and performing arts space. The construction of the buildings is multi-wythe brick masonry with lime mortar joints. In general, the masonry walls were in a deteriorated condition due in part to foundation settlement. Other walls had been repointed in were relatively good condition.

The FTA recommended criterion to avoid damage to older buildings is 0.12 in/sec. Based on their detailed vibration analysis the authors recommended that a vibration mitigation measure be implemented underneath the new tracks to reduce vibration to the surrounding ground. The vibration mitigation measure consists of a tire derived aggregate (shredded motor vehicle tires) underlayment below the rails. The authors predicted vibration with mitigation for freight traffic for all of the historic buildings to be in the range of 0.13 to 0.32 in/sec for a worst case scenario of “severe wheel flats” on freight rail cars. There was still some concern on the part of the engineers regarding the effects of vibration on the historic buildings even with this mitigation measure.

One of the authors, a structural engineer, conducted a visual review of the existing condition of historic buildings and concluded that even though the maximum predicted vibration with mitigation exceeded the FTA criterion, the vibration would not be expected to cause any risk to the existing masonry walls (structural or cosmetic), except possibly one building (Car Shop), which had a large cantilevered wall (i.e., unsupported laterally).

A more detailed investigation was conducted using a numerical analysis modeling procedure (finite element analysis) to model the Car Shop wall in conjunction with the predicted foundation level, lateral vibration from freight activity. Based on the existing condition of the Car Shop wall the structural engineers concluded that the cantilevered wall of the Car Shop would obviously require considerable remedial structural work to make the building safe for occupancy aside from vibration considerations. Once the remedial work was done to meet local building codes, the structural engineers were able to conclude based on their detailed analysis that the wall would not risk additional esthetic cracking of the upgraded masonry walls.

5.2.8 HGC Engineering (2011)

This report addresses a construction vibration assessment prepared for a project at the Royal St. Georges College in Toronto, Ontario. The report was prepared by a vibration engineering

consultant for the project as required by the City of Toronto. The project involved construction of underground and at-grade parking, at-grade outdoor recreation areas, various underground teaching and utility spaces, and an extension to one of the campus buildings on campus. The campus has two heritage-designated buildings that could be affected by construction vibration (Church of St. Alban the Martyr and Ketchum Hall). The construction work would include excavation using excavators and trucks, but no "percussive" demolition. No impact or vibratory pile driving or vibratory sheet pile installation was anticipated. Soil compaction was expected using vibratory rollers and plate tampers. Also a vibratory roller was anticipated. Percussive, vehicle-mounted hammers would be necessary for foundation demolition

The report lays out the formal process required by the City of Toronto (Toronto By-Law 514) for assessing and controlling vibration from construction. The German (DIN 4150) and Swiss (SN 640 312) are referenced with the emphasis placed on avoiding cosmetic damage. For the historic buildings, a limit of 0.12 in/sec over the frequency range of 10 to 30 Hz is indicated in both standards. We quote from the authors.

"*Although listing a structure as a heritage-designated building does not necessarily indicated that the building is more sensitive to vibration than its neighbors, heritage-designated structures are often assigned a lower criteria due to their importance or for other reasons.*"

An interesting aspect of the author's recommendations is for "cautionary limits" for vibration. Often this means setting a warning limit of less than the damage threshold to warn the construction contractor and resident engineer when the damage threshold is being approached. In this particular instance the cautionary limit for the historic buildings is the limit of 0.12 in/sec.

A preconstruction survey and vibration monitoring program is specified by the authors that includes both "attended" (monitoring live with a technician present) and unattended (automated monitoring). The location for vibration monitors is indicated in the report. The frequency of vibration monitoring reporting is delineated as well as when monitoring should start during different phases of the project. Monitoring reports are to be supplied to the City. At the completion of excavation, a final report is to be submitted summarizing all vibration measurements made.

For mitigation (aside from monitoring) the authors specify:

If excessive vibration levels were to be found, modifications to the construction techniques, potentially utilizing lighter or smaller equipment or less aggressive usage would be required."

5.2.9 PANYNJ (2006)

This report prepared for the Port Authority of New York and New Jersey (PANYNJ) address a protection plan and monitoring program for historic properties adjacent to the new permanent World Trade Center (WTC) PATH Terminal in New York City. The protection plan indicates there are seven historic buildings adjacent to the terminal construction project that could be affected by construction vibration. The Historic Properties are: Vesey Building, Federal Post Office, 20 Vesey Street, former East River Savings Bank, Beard Building, 114 – 118 Liberty Street and St. Paul's Chapel and graveyard.

The plan is part of the Construction Protection Plan (CCP) prepared for PATH, which will:

- Provide for inspection and reporting of existing conditions at these Historic Properties
- Establish protection procedures
- Establish a monitoring program to measure vertical and lateral movement and vibration
- Establish and monitor construction methods to limit vibration
- Incorporate the commitments made in the Project MOA and Resource Protection Plan (RPP)

A Project Historic Architect (PHA) is to be retained throughout the period of design and construction. The CPP provides for the PHA to meet the professional qualifications standards of the Secretary of the Interior. The CPP empowers the PHA, in consultation with the chief engineer or their designee to issue "stop work" orders to prevent any unanticipated damage to Historic Properties. Work shall only be permitted to resume when chief engineer and PHA determine appropriate modifications have been made to construction techniques to assure no damage to Historic Properties.

A very clearly delineated set of management controls are specified, which include CPP awareness, incorporation of all applicable MOA and RPP requirements in project design specifications, construction planning and construction contract documents. Procedures, responsibilities and accountability for project-wide compliance and problem resolution are to be established. The vibration limit adopted for protecting the Historic Properties is that recommended by the FTA of 0.12 in/sec for a vibration damage threshold for "buildings extremely susceptible to vibration damage."

A list of types of vibration mitigation measures include:

- Use of deep saw-cuts to minimize vibration transmission from pavement breaking operations
- Use of concrete cutters on pavement instead of pavement breakers (where practical)
- Use of vibratory rather than impact pile drivers (where feasible)
- Routing of truck traffic and heavy equipment to vibration impacts
- Properly securing street decking over cut-and-cover excavations
- Minimization of duration of vibration impacts

The report also details procedures to deal with alleged damage to Historic Properties including a 12 month period for property owners to file claims with PATH, advising property owners of their rights, response to damage claims within 45 calendar days, and after investigation, if PANYNJ determines damage to a property was caused by the Project construction, after consultation with SHPO, PANYNJ will repair damages reasonably attributable to the Project vibration activities.

5.2.10 Sierra Blanca Constructors (2002)

This report presents a noise and vibration monitoring plan prepared for the New Mexico DOT. The concern of the project was vibration from roadway improvement construction and the effects it could have on concrete and masonry structures such as acequias (community waterways used for irrigation, which are often 200 years old) and walls. The goal was to avoid threshold

cracking. Although no limits are given for vibration it is stated that threshold limits that are 3 to 8 times lower than the values recommended for the materials that make up the acequias will be used. The specifications for the vibration monitor indicate a data range of 0.75 to 10 in/sec. Consequently it would be reasonable to assume the thresholds used are within this range. For the purpose of monitoring, the acequias are assumed to be lined with aged concrete and mortar materials. Vibration monitoring will be done whenever there is construction within 200 ft of the historic irrigation ditches. Immediately after blasting a field engineer and environmental monitor will visually inspect any historic retaining walls to determine if damage has occurred.

5.2.11 Siskind (2000)

Siskind's report addresses potential damage to residential buildings prepared for Dade County, Florida addressing concerns about blasting at quarries in the area. Although this investigation does not address historic structures it is of some interest in that residences have concrete block walls, which tend to be brittle. Siskind investigated strains in building walls considering typical structural responses. He also discusses normal environmental forces that can also be responsible for cracking such as temperature, humidity and soil moisture cycles. The author points out that crack damage is usually due to "racking" (shear movement) of walls and that floors are not exposed to this type of motion from ground vibration.

5.3 Government Research Reports

Government sponsored research over the past 40 to 50 years has produced most of the detailed vibration data pertaining to building damage. The research work has investigated two types of activity (blasting and motor vehicle traffic) that generates ground vibration.

5.3.1 Whiffin and Leonard (1971)

Although this report does not address construction (although it does mention blasting in passing), it is important because of its coverage of low level vibration from road traffic (there is also mention of rail traffic vibration) and its effects on historic buildings. The report provides a general discussion of vibration, its transmission through the ground, and the response of structures. The report basically reviews the general state of knowledge and opinion on the subject with many references as of the date of its writing.

The human emotional factor relating to vibration and building damage is mentioned by the authors. In their discussion of damage, the authors quote M. W. Jackson (1967),

"Recognition of damage to buildings depends on people. Minor damage may be tolerated if caused by hurricane, tornado, thunderstorm or other suprahuman cause. An owner may endure stoically all the problems of differential settlement, expansion and contraction due to temperature and humidity and natural deterioration of his property if there is no obvious human cause. However, an owner who sees any possible human cause for the smallest defect or minor damage may have an associated emotional factor that can magnify any claimed damage by several orders of magnitude."

The authors, as do others, emphasize the need to differentiate between structural and architectural (cosmetic) damage, such as cracking of plaster or other brittle materials. They point

out that environmental factors (temperature, material shrinkage, wind, snow and humidity) are natural causes of long-term damage. According to the authors, these factors probably result in fatigue damage if any from cyclic loading and unloading. With this background, the authors discuss ground vibration from motor vehicle traffic and the potential for architectural damage due to fatigue. The authors make reference to the German standard (DIN 4150) vibration limit of 0.08 in/sec for "ancient buildings" and the limit of 0.40 in/sec for residential buildings in good condition. They point out that most of the vibration data acquired in research has been in the vertical direction with little attention paid to vibration in a lateral direction. There is an extensive summary of the measurements made by the Road Research Laboratory (RRL).

The following table summarizes Whiffin and Leonard's view on traffic vibration and building damage.

Effect on Building	Limit PPV (in/sec)
Upper limit for ruins and ancient monuments	0.08
No risk of architectural damage to normal buildings	0.10
Threshold for risk for architectural damage to residential buildings with plastered walls and ceilings	0.20
Probable architectural damage and possibly minor structural damage	0.4 to 0.6

5.3.2 USBM (1980)

The authors of the government study for the USBM, Siskind, et al., present a very detailed study of building damage related to ground vibration due to blasting at surface mines. This report is an extension of previous studies carried out over roughly 10 years by the USBM involving building damage and blasting.

All of the buildings in the study were residences. In all 76 structures were included in the study. Although none were listed as historic buildings (most were of modern construction), based on the photos provided in the report, at least one was a wood frame structure (Test Structure #25) with lathe and plaster walls and another of brick construction (Test Structure #57) both of an early vintage.

Most of the residences did have plaster or gypsum wallboard interior wall construction, which would potentially be susceptible to vibration damage (cracking) of a high enough level. Although drywall damage is not directly related to the manner in which masonry walls could be damaged, there is some relevance in the data provided. Many of the residences did have basements with masonry or concrete foundations.

The report contains very detailed analysis of the dynamic response of the main building elements and relates their response to strain levels that could cause damage. Included is a discussion of laboratory tests that applied cyclic loading to gypsum wallboard in shear and relates that to "failure strain" over a range of vibration levels. The authors reference tests performed by Canadian researchers Edwards and Northwood (1963) and Crawford and Ward (1965) that examined dynamic strains in masonry and concrete walls. It is interesting to note that the latter

research found stain levels across mortar joints that were 10 times greater than those on the adjacent blocks.

The report concludes in part with the following:

- Damage potentials for low-frequency blasts (less than 40 Hz) are considerably higher than those for high-frequency blasts (greater than 40 Hz).
- Practical safe criteria for blasts that generate low-frequency vibrations are 0.75 in/sec for modern gypsum board houses and 0.50 in/sec for plaster on lath interiors. For frequencies above 40 Hz, a safe particle velocity maximum of 2.0 in/sec is recommended.

We emphasize that of course these conclusions and recommendations are being made for buildings of modern construction.

5.3.3 NCHRP (1997)

This research report prepared by R. D. Woods (University of Michigan) addresses pile driving and its effects on adjacent structures. It is very comprehensive in its treatment of pile driving and discussion of a program for mitigation and monitoring. Woods also discusses the human factor as does Wiffin and Leonard (1971) in discussing damage from ground vibration. He states that,

"Pile driving vibrations (and all construction vibrations, for that matter) present a two-pronged hazard: first, potential for "real" damage due to the construction activity, and second, potential for 'litigation' based on human perception."

He defines "real damage" as usually taking the form of structural damage, including cracking and breaking of structural elements or ground settlement. His main source of data appears to be primarily that obtained in USBM research on blasting. This follows to some degree because impact pile driving is impulsive in nature although vibratory pile driving is not. Woods makes passing reference to cosmetic damage (e.g., loosening of paint, small plaster cracks, lengthening of old cracks) but provides no specific guidance to limit it.

Woods states, "In Germany and Italy vibration amplitudes are limited to 25 mm/sec to protect historical structures and other antiquities." A limit of 25 mm/sec is the same as 1.0 in/sec. This seems to contradict other research and does not comport with DIN 4150 in its current form. As discussed below, DIN 4150-3 (1999) indicates that the limit for "structures that, because of their particular sensitivity to vibration, cannot be classified under Lines 1 and 2 and are of great intrinsic value (e.g., listed buildings under preservation order) have limits of 3 mm/sec to 10 mm/sec depending on the frequency of the vibration." These limits are equivalent to 0.12 in/sec and 0.40 in/sec respectively.

Granted the latest version of DIN 4150 was published after publication or Woods work, but earlier versions of DIN 4150 Part 3 (1975) recommended a limit of 0.16 in/sec for structures that are neither covered by Lines 1 or Line 2. That category of buildings is Line 3, which is the same as the description contained in DIN 415 Part 2 (1999). Woods statement on criteria to limit damage to historic structures is puzzling given his vast experience in the field of ground vibration and certainly warrants further investigation as to its basis.

The author provides a thorough but concise discussion of the mechanics of ground motion and pile driving with useful data to the practitioner on the latter. He also provides a detailed discussion of ground settlement with many case studies involving pile driving and recorded settlement.

Woods provides a discussion of one mitigation measure (ground trench) that has received limited testing, but continues to be mentioned as a potential measure. The research on ground trenches has shown that the depth of the trench must be substantial (40 to 60 ft) before it reduces vibration enough to be of value. He concludes that trenches are probably not cost effective. Other more promising mitigation measures for pile construction are: jetting, predrilling, cast-in-place or augered piles, non-displacement piles (like H-piles), vibratory instead of impact driving), and pile cushioning. Generally experience with vibratory pile driving has shown that it can produce levels of vibration comparable to impact pile driving.

A survey of state DOTs, consultants and contractors on how the status of pile driving is perceived was conducted as part of Woods research. It is noted that each of the three entities view pile driving from a different perspective. The results of the survey are useful in terms of providing guidance on how to minimize the hazards of vibrations from pile driving. Also of use is the procedural guidelines for a preconstruction survey and monitoring of vibration during construction in particular the instructions to contractors who will bid on work and the recommendation for a "susceptibility study" to evaluate buildings and structures in proximity to the project. The vibration criteria for the project would be based on such a study.

5.3.4 NPS Tech Note TPS #3 (2001)

This article is available from both the NPS website (www.nps.gov) and the Preservapedia website (www.preservapedia.org). Although the article is not quantitative in nature it covers almost all of the areas of interest and we consider it important enough to include it. It discusses a program for documenting building condition and monitoring of vibration, cracks and settlement that is quite thorough. The author (Chad Randl) an NPS employee emphasizes effective planning and protective measures to minimize the risk of damage. Mitigation measures that protect building elements such as windows include practical efforts such as encasing the windows to protect against dropped equipment, tools and materials are provided.

The author lists the following steps to provide protection:

- Consultation between historic building owner and development team to identify potential risks, negotiate changes and agreement on protective measures
- Documentation of the condition of the building prior to commencement of adjacent work
- Implementation of protective measures at both the construction site and the historic building
- Regular monitoring during construction to identify damage, evaluate the efficacy of protective measures already in place and to identify and implement additional corrective steps.

The benefit of early consultation is to build trust with the historic building owner, such that a foundation for a mutually beneficial relationship that is cooperative rather than adversarial. The building condition survey provides a well-documented baseline from which changes to the

building can be identified, monitored and assessed. The author also notes that "as with documentation, the historic building owner may want to hire an independent engineer to review both the monitoring process and the measurements." This paper provides useful checklists for both the historic property owner and the development team.

5.3.5 NRCC – Rainer (1982)

This work sponsored by the National Research Council of Canada provides an overview of the effects of vibration on historic buildings. The author notes:

"Vibrations are frequently blamed for deterioration of historic buildings while other detrimental effects are apparently being ignored."

He ascribes this to the fact that humans are very sensitive to vibration and will become alarmed at levels "generally well below the danger level for most buildings." He comes to the conclusion:

"that the additional dynamic loads imposed by traffic vibrations cause only a small fraction of the stresses already imposed by a structure's own weight, by wind forces and temperature changes."

However, he notes that the materials in older historic buildings are already in a deteriorated and weakened state "so that added stresses from low levels of vibration constitute a greater proportion of the available strength reserve." He concludes with "knowledge of vibration effects on historic buildings is rather incomplete." Rainer suggests that there may be in-situ methods of determining strength of existing structural components.

5.3.6 NRCC – Rainer (1986)

In this second work by Rainer, he explores the need for a standard approach to vibration and buildings. As with the first work this one is also an overview of the subject. The paper does not deal directly with historic buildings. It does discuss the need for verification of modeling and criteria.

5.3.7 TRRL 156 (1988)

This and the later companion report (TRRL 207) by Watts provide much useful data and damage information obtained from detailed case studies of four older historic buildings subjected to lower level, but high for traffic, vibration and damage. The author notes that the frequency of traffic vibration is generally greatest in the frequency range of 8 to 20 Hz. The sites were chosen by the TRRL in conjunction with the Civil Engineering Section of English Heritage. Worst case sites were chosen by virtue of a combination of high vibration levels (for traffic), soil and building conditions such that there was some risk of vibration related damage.

The buildings are all of masonry construction. Cracks were thoroughly documented and instrumented to measure growth during the study. The crack monitoring was accomplished with strain gauges that could resolve movement to within 1 micron (0.000039 in). Plumb lines were used to measure tilt of external walls. Vibration measurements taken at the building foundations

indicated that levels ranged as high as 0.14 in/sec at one site. At the other sites vibration was typically less than 0.04 in/sec with the highest being 0.05 in/sec. Compared to typical construction vibration these latter vibration levels are relatively low.

The well documented condition surveys provide ample photographs of damage in the form of cracks to external and internal walls. The crack measurements of dynamic movement due to all sources (traffic and internal activity such as doors slamming) demonstrated that the cracks moved as much and slightly more due to doors being slammed within 3 ft of the cracks compared to the movement due to traffic vibration.

The author concludes that "it appears that there are no compelling arguments to suggest that traffic vibration is causing structural damage to these buildings directly." However, he also concludes that it is not possible to determine whether traffic vibration is exacerbating settlement problems that were observed in the buildings.

One of the main conclusions is:

"Despite the relatively high vibration levels, crack movements were small being much lower than the movements observed for normal variations in temperature and humidity."

Finally he concludes that "the observed damage could be attributed more plausibly to other site factors than the exposure to traffic vibration." This would indicate that vibration levels below 0.14 in/sec are probably not responsible for damage to old buildings of masonry construction.

5.3.8 TRRL 207 (1989)

Similar to TRRL 156 (1988) this paper also has case studies of historic buildings subjected to traffic vibration. In these additional case studies the highest vibration level measured was 0.04 in/sec. Dynamic crack movements on the order of 1 micron were below the background and substantially less than the dynamic movement caused by door slams, which reached 22 microns (8.8×10^{-3} in) in one case. Watts reiterates his conclusion from the previous study in TRRL 156 (1988) that in all cases the main causes of damage were like to have been other site factors rather than exposure to traffic vibration.

5.3.9 HRR – WISS (1967)

This report has limited data on damage and none related to historic buildings. However it does provide data to use in modeling vibration generated by pile driving in different types of soil. Data on impact pile drivers and "sonic" pile drivers are presented.

5.3.10 Esteves (1978)

This document is in Portuguese, but it does provide numerical values for limiting vibration from blasting. Interestingly it combines both the ground type and the building construction (condition) in recommended vibration limits for a wide range of building types. In the table below we summarize the recommended limits for historical structures.

Type of Construction	Ground Type	PPV (in/sec)
Special care, historical	Hard soils and rock (c>6,600 ft/sec)	0.40
Special care, historical	Medium to hard soils (c=3,3000 to 6,600 ft/sec)	0.20
Special care, historical	Soft, loose soils (c<3,300 ft/sec)	0.10

The "ground type" refers to the ground on which a building's foundation rests. Esteves categorizes soil by its stiffness ("hardness") using the speed ("c") of a compression wave in the soil as measure of stiffness. Other researchers sometimes use the shear wave speed as an alternative. The two wave speeds are interrelated through inherent material properties of the soil. We can see that as the stiffness of the founding soil decreases Esteves considers an older building construction to have a lower ability to withstand vibration. We can interpret this to mean that softer soils will allow a building (regardless of its age) to react with greater response (i.e., movement), which in turn induces higher levels of strain in the building structure and finishes.

5.4 National and International Standards

There are national and international standards that provide specific vibration limits for historic structures. Three of these standards (DIN 4150, BS 7385 and SN 640 312) are often cited by researchers and investigators regarding vibration limits applicable to historic structures and prevention of damage. As any measurement standard would be expected to, the standards share commonality on procedures for measurement, definition of damage, and classification of buildings, if not vibration limits. They are all clearly indicated as being guidelines, which is to be expected. Unfortunately the research work that went into preparing these standards is apparently no longer available in particular since some of the standards were originally issued over 30 years ago.

5.4.1 DIN 4150-3 (1999)

This German standard was initially issued in 1975 and has undergone one or more revisions. It is provides general guidelines for measuring and evaluating the effects of vibration on structures. DIN 4150-3 defines damage as "Any permanent effect of vibration that reduces serviceability of a structure or one of its components." Three classes of buildings are defined:

- Line 1 – Buildings used for commercial purposes, industrial buildings, and buildings of similar design
- Line 2 – Dwellings and buildings of similar design and/or occupancy
- Line 3 – Structures that, because of their particular sensitivity to vibration, cannot be classified under line 1 and 2 and are of great intrinsic value (e.g., listed buildings under preservation order)

This standard provides for methods of determining stresses in building components either by measurement or by analysis, but indicates that these methods are not suitable for assessing "minor" damage. Minor damage (viewed as reducing serviceability in this case for structures in Lines 2 and 3) is defined as:

- Cracks form in plastered surfaces of walls

- Existing cracks in the building are enlarged
- Partitions become detached from load-bearing walls or floors

Vibration measurements are to be performed either at the foundation of the outer wall, on the outer wall, or in a recess in that wall, but no more than 1.6 ft above the ground when there is no basement.

As indicated in our discussion of NCHRP (1997) above, DIN 4150-3 recommends as a guideline for limiting vibration for Line 3 buildings (historic) a value ranging from 0.12 in/sec to 0.40 in/sec depending on the frequency (Hz) of the vibration.

DIN 41450-3 also provides a discussion on the potential for foundation settlement due to soil compaction. For this to occur, the soil needs to be "non-cohesive" such as in uniformly graded sand or silt. Another phenomenon mentioned is liquefaction of soil when sand or silt suddenly loses its bearing capacity as a result of dynamic effects. The German standard notes that the tendency to produce soil settlement is greater for vibratory pile driving than it is for impact pile driving.

5.4.2 BS 7385 Part 1 (1990)

Like the German standard, this British Standard covers characteristics of building vibration, factors to be considered in building response, measurement of vibration, classification of structures according to building and type of soil. A main element of this standard is a classification system taking into account:

- Group of structure with Group 1 being ancient and elderly buildings
- Category of foundation with different classes depending on the construction type
- Types of soil on which the foundation rests

A matrix relating Category of Structure (Category 8 is buildings in a delicate state) to Class of Building (with the highest number 14 needing the most protection) with the various combinations of foundation and soil types. Recommended vibration limits are contained in BS 7385 Part 2.

5.4.3 BS 7385 Part 2 (1993)

Like the German standard, this British Standard covers characteristics of building vibration, factors to be considered in building response, measurement of vibration, and assessment of vibration (basis for damage and criteria). The sources of vibration covered by this standard include: blasting, demolition, piling, ground treatments (soil compaction), construction equipment, tunneling, road and rail traffic and industrial machinery.

The standard states that "case-history data, taken alone, has not so far provided an adequate basis for identifying thresholds for vibration induced damage." Furthermore, BS 7385 states that "A building of historical value should not (unless structurally unsound) be assumed to be more sensitive." However "important building which are difficult to repair may require special consideration on a case-by-case basis." Not surprisingly then, unlike the German standard BS 7385 Part 2 (1993) does not have a special category for limits applied to historic buildings.

The most restrictive category (unreinforced or light framed structures) has a recommended vibration criterion for cosmetic damage of 0.59 in/sec at 4 Hz increasing to 0.79 in/sec at 15 Hz then increasing to 2.0 in/sec at 40 Hz and above. Clearly this is a much more liberal standard than the German standard. Interestingly there is no reference to the work contained in TRRL 156 (1988) and TRRL 207 (1989). Nor does Part 2 seem to incorporate Part 1 classification system in terms of assessing susceptibility to damage.

5.4.4 Swiss SN 640 312a

This standard is only available in German and French, hence we discuss the most relevant information and that are the recommended vibration limits for historic buildings. The recommended limits are indicated as a function of the duration of the vibration, its frequency and the class of building. Class 4 buildings include historic and protected buildings. The recommended vibration limits in this standard are as given in the following table:

Class 4 Building (Historic and Protected) Vibration Limits (in/sec)

	Vibration Frequency (Hz)		
Vibration Duration	<30	30 – 60	>60
Infrequent (<1,000 events)	0.59	0.79	1.12
Frequent	0.23	0.31	0.47
Permanent (>10,000 events)	0.12	0.16	0.29

The limits for permanent vibration are not too dissimilar to those recommended for very fragile buildings by some researchers. Since most construction vibration would probably fall in the range of 1,000 to 10,000 events, the recommended limits are in the mid-range of what has been recommended by others.

5.4.5 ISO 4886 (2010)

This international standard is similar in scope to the British standards BS 7385. There is a strong emphasis on measurement procedures and instrumentation including selection of transducers and position and mounting of transducers. There are two types of vibration transducers that are used: a) so-called velocity transducers (geophones) and b) piezoelectric accelerometers. The most generally used vibration transducers are geophones that measure velocity directly. When measuring acceleration to compare to vibration limits it is necessary to covert to velocity by integrating the signal in time.

There is also discussion provided in the collection, analysis and assessment of field data. Event types are defined as permanent (e.g., generator, heavy car traffic), intermittent, which is further divided into cyclic (piling), stable (refrigeration) and other (crushing mil, compactor) and isolated or single (blasting).

With respect to damage ISO 4886 describes three categories:

- Cosmetic – The formation of hairline cracks on drywall surfaces or the growth of existing cracks in plaster or drywall surfaces; in addition, the formation of hairline cracks in mortar joints of brick/concrete block construction.
- Minor – The formation of large cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.
- Major – The damage of structural elements of the structure, cracks in support columns, loosening of joints, splaying of masonry cracks, etc.

ISO 4886 also categorizes structures in the same manner a BS 7385 Part 1 (1990). Category 8 (the least resistant to vibration) is for ruins and near ruins and other buildings, all in a delicate state. No recommendations are made on limits to vibration.

5.5 Government Guidelines

The following government guidelines offer recommendations for how to measure and assess ground vibration from transportation and construction sources.

5.5.1 Caltrans (2002, 2004a)

This Technical Advisory prepared by R. Hendricks covers general principals of vibration from construction and operation of transportation facilities, criteria used by Caltrans, impacts, vibration study approaches, possible mitigation, and screening procedures to identify potential vibration problems in the field.

Predictive formulas and data are provided for trains and motor vehicles and most construction including pile driving. As of the date of its publication there were no FHWA or state standards for vibrations. This Technical Advisory adopted the TRRL criterion of 0.08 in/sec as a limit for historical buildings, or buildings in poor condition subjected to continuous vibration. Obviously this is a fairly restrictive criterion. The 2004a Technical Advisory does indicate that 0.08 in/sec for continuous vibrations may be used as a limit for historical buildings, or buildings that are in poor condition.

Data are provided for typical levels of vibration from impact pile drivers and maximum levels for vibration from trains. We note that based on this data, the limit of 0.08 in/sec is reached at about 25 ft from train tracks. Most of the mitigation suggestions have to do with improving roadway surfaces. We note that there was a 2004 update to this Technical Advisory expanding on the material including a detailed vibration monitoring report format.

5.5.2 Caltrans (2004b)

This document is an extension of the Caltrans (2002, 2004a) document providing in great detail the principals of vibration generation, propagation and effect on buildings. A wealth of information is provided dealing with soil properties and other factors that affect vibration. The guidelines cover all building uses and summarize the various criteria available, all of which are discussed above under the various authors and publishing agencies. This manual makes clear that Caltrans is not setting a standard for vibration limits, but rather providing a synthesis of the available criteria at the time of publication. We interpret this to mean that the limit indicated in the 2004a Technical Advisory was amended.

Prediction models are provided for pile driving vibration along with example calculations. Mitigation measures include all of those discussed above. The authors note that alternatives to hydraulic breakers include hydraulic crushers, saws or rotary rock-cutting heads, hydraulic splitters and chemicals can be used to break up concrete into smaller size pieces to be then hauled away for recycle.

Step by step details are provided for the general procedures that can be followed to deal with public concerns about construction activity that produces perceptible vibration. They include identifying potential problem areas, determining existing conditions, informing the public, scheduling work, designing to minimize vibration, notification of the public and property owners, monitoring and responding to complaints. The recommend contents of a vibration study reports is provided. An entire chapter on blasting is included.

5.5.3 AASHTO (2004)

This document is in the form of a standard recommended practice (for evaluating transportation-related earthborne vibration) and replaces AASHTO R 8-81 (1980). Much of the same material that has been discussed in other reference above is covered here. The document notes that the safe vibration limits recommended by standards are based upon the appearance of "threshold cracks" or cosmetic damage. To prevent damage to historic sites and other critical locations, AASHTO recommends a vibration limit of 0.12 in/sec (adapted from DIN 4150).

5.5.4 FTA (2006)

We include this reference, because it is often cited in environmental documents in particular those transit projects sponsored by the FTA. The limit for construction vibration for the protection of" buildings extremely susceptible to vibration damage" is 0.12 in/sec and for "non-engineered timber and masonry buildings" the limit is 0.2 in/sec. Depending on the construction and condition of an historic building, one could interpret either the 0.12 in/sec or 0.2 in/sec as applying.

5.5.5 Wisconsin DOT (2003)

This document includes information contained in one or more of the documents reviewed above. It is basically a synthesis of various other documents which address research on vibration and its impacts to buildings. Summarizing the policies of various state transportation agencies we see that:

- Florida mentions construction impacts but without reference to historic buildings
- Nebraska provides a case of vibration affecting a sensitive research center but nothing historic
- Michigan provides an environmental impact statement the recommends special consideration be given to historic structures
- Indiana and Kentucky provide a programmatic draft memorandum of agreement in which the agencies stipulate that special care be exercised to avoid damage to historic structures

The document provides additional references and links to websites that provide information on vibration.

5.5.6 FHWA-RD-78-166 (1978)

Although this document deals exclusively with traffic induced vibration it provides another perspective on building damage and vibration. The "threshold" of structural damage is indicated as 0.1 in/sec. These guidelines indicate that "the nature of alleged building damage from traffic-induced vibration is generally related to cracks in plaster, wall board and separated grout around ceramic tiles." By threshold of structural damage it is meant that damage is very improbable. At 0.24 in/sec "minor damage" is possible according to this document and at 0.39 "structure damage" is possible. Aside from these criteria, this document provides very detailed data on the effects of and prediction of traffic induced vibration. The author (Rudder) notes that "any potential for building damage, if at all possible, can result only in a long-term exposure to repeated vibration excitation." He also notes that "it does not appear that traffic-induced vibration can cause building damage on a single event basis."

5.6 Government Regulations

There are very few government agencies that have codified vibration limits in particular those dealing with issues such as damage to buildings and historic buildings in particular.

5.6.1 City of Toronto (2008)

This by-law (514) is part of the municipal code and regulates vibration from construction activity. The vibration limits adopted for all buildings are indicated in the following table.

Frequency of Vibration (Hz)	Limit on PPV (in/sec)
<4	0.31
4 to 10	0.59
>10	0.98

The above values are similar to but not exactly the same as any of the national or international standards. The existence within the zone of influence of any buildings that have been designated under the Ontario Heritage Act must be identified in the Vibration Control Form. Nothing specific is indicated for protecting historic buildings, but the prescribed vibration limits must be adhered to unless "lower levels as may be identified by the professional engineer as being prudent taking into consideration site specific conditions." The professional engineer is not clearly defined, but this may be the measure of protection for historic buildings.

5.6.2 New York City TPPN 10/88 (1988)

This regulation (Technical Policy and Procedure Notice) supplements the city's building code. It specifically addresses designated historic structures. It stipulates that the maximum permissible vibration from construction including vehicular traffic, blasting and pile driving shall not exceed 0.50 in/sec. It references Esrig and Ciancia (1981) and Wiss (1968). It also requires "a monitoring program to reduce the likelihood of construction damage to historic structures and to detect at an early stage the beginnings of damage so that construction procedures can be changes."

5.7 Books

There are numerous books published on the subject of groundborne vibration. The ones specifically dealing with construction vibration are discussed below. The most relevant book is Dowding's textbook dealing with construction vibration. Other books reviewed address historic buildings, their conservation and what makes them susceptible to damage from vibration and other environmental factors.

5.7.1 Dowding (1996)

Dowding's book written in textbook format (including problems to be solved) provides an extensive treatment of almost everything related to construction vibration. It is an indispensable resource for vibration data, prediction methodology and the understanding of what damage is and what causes it. Much of the data in the literature on the subject is contained in this book. Not surprisingly there is heavy emphasis on blasting since most of the research has been done in this area. Dowding provides over 250 references on the subject of wave propagation, construction vibration and its measurement. There are seven individual case studies involving the effects of ground vibration on buildings and test samples of building elements that are discussed in detail. Most of the case studies involve modern construction (gypsum wall board), but are useful to read for the detailed discussion provided on crack formation and propagation in a brittle material.

He provides a very detailed description of building damage relating the many environmental factors that occur naturally that cause damage over time. Dowding has an entire chapter that compares environmental factors that cause crack damage and those that are vibration-induced. The environmental factors include:

- Differential thermal expansion
- Structural overloading
- Chemical changes in mortar, brick, plaster and stucco
- Shrinkage and swelling of wood
- Fatigue and aging of wall coverings
- Differential foundation settlement

He notes that buildings expand and contract along existing weaknesses (i.e., cracks), distortions that caused the cracking also create stress concentrations, which may lower a wall coverings resistance to vibration cracking, and these cracks occur naturally over a period of time. He presents data from research that examined crack dynamics (growth and shrinkage over time). As others have noted, everyday activities of occupants (e.g., doors slamming) create vibration that affect cracks. There is a very detailed discussion on preconstruction crack surveys.

The vibration criteria presented by Dowding are those from the USBM research. These are in the form of frequency based criteria and they are on the high side of criteria. The frequency based criteria of OSMRE ranges from 0.20 in/sec to 2.0 in/sec over the range of 1 to 100 Hz. Dowding has virtually nothing to say about historic structures other than a preconstruction survey should be conducted for all buildings including historic buildings or structures.

5.7.2 Bachmann (1995)

Bachmann is the editor of this book written by several authors. Although there is only minor treatment of construction vibration in this book, there is other relevant information that some may find useful. There is a short section on construction vibration including criteria, but nothing is particularly said about historic buildings. The wavelength of the vibration is stated as having "great significance for the influence of vibration induced by construction work on different structures."

There is a summary of various frequency-based criteria that indicates a limit on vibration from various standard construction activities (i.e., piling, sheet piling, vibratory compaction, dynamic soil compaction and construction-site traffic) that ranges from 0.08 in/sec at about 3 Hz to 0.20 in/sec at 5 Hz and above. Several tables in an appendix summarize the various vibration criteria. Aside from the DIN 4150-3 criteria that addresses historic structures, there is a summary of the Swiss standard SN 640 312. The latter criterion indicates a limit on the "resultant" velocity of 0.12 in/sec from 10 to 30 Hz and an increasing limit from 0.12 in/sec at 30 Hz to 0.20 in/sec at 60 Hz for historical buildings. The limits on the vertical velocity are somewhat lower than these.

5.7.3 Feilden (2003)

This book provides an extensive coverage of the subject of conservation of historic buildings and a concise discussion of vibration and its potential to cause damage. Maybe most importantly Feilden's book explains in great detail the causes of environmental deterioration that building experience as they age, deterioration that can significantly affect the underlying structural elements supporting the building as well as the decorative elements, which give the building its unique character representative of a certain period and/or style of architecture. Deterioration is a consequence of many factors including solar radiation, temperature, moisture, wind, biological agents, insects and those that are man-made. Dowding's book (1996) and although not as technically oriented with regard to vibration Feilden's book both provide in-depth coverage of age related damage and are therefore valuable with regard to understanding building's condition prior to the start of construction.

The most damaging dynamic loading is that caused by earthquakes, whereas the most common dynamic loading is due to wind. As Feilden points out an important issue is whether there is an adequate reserve margin of strength and stiffening in all the structural elements of an historic building and their interconnections to resist live and dead loadings." And he adds this "is often a matter of judgement." He emphasizes the importance of ground settlement underneath a building as a primary mechanism that can weaken a structure if the settlement is uneven.

Feilden provides ample description of the variety of structural elements found in buildings with emphasis on the more ancient structures of Europe. His discussion of cracks in masonry structures with arches, domes and vaults is useful in understanding how they form and what can be done to strengthen structural members with cracks such as injection with epoxy resin and doweling with metal pins.

In discussing the damaging effects of vibration, Feilden mentions the wearing of joints in masonry structure and/or their opening which can cause load to be redistributed due to a weaken of a structural member. He states "that little research has been done" to understand vibration

damage to historic buildings and structures. Another problem Feilden mentions is the difficulty to measure vibration "to cover all the permutations of a massive indeterminate structure." He then goes on to state that "positive proof of damage resulting from a given incident is almost impossible to obtain, as it is very difficult to distinguish between damage from vibration and the inevitable aging of a building." Feilden makes a case for limiting vibration (presumably due to traffic) to considerably less than even the most stringent standard.

Feilden discusses the sensitivity of plaster ceilings (lath and plaster) to cracking and emphasizes that the "condition of the lath should be examined before any exposure to exceptional vibration such as piling." Other non-structural building elements that are susceptible to vibration damage are fragile glass, loose plaster mosaics or pieces of stone. He notes that the Institute of Building Materials and Structure in Holland suggests a velocity limit of 0.08 in/sec as the threshold for potential cracking of plaster.

5.7.4 Forsyth (2007)

We have included Forsyth's book not because it contains information on construction vibration, but because it is a useful reference on historic building conservation engineering. There is a brief qualitative treatment of vibration generated by traffic. There is a very useful discussion on the issue of safety versus conservation that some may find informative. "A safe structure may be defined as one that will withstand the designed loads without becoming unfit for use." This issue may have some implication for implementation of physical mitigation (secondary supports) during construction should that mitigation need to be permanent in order to provide adequate protection for structures in very delicate condition. A chapter is devoted to the issue of "movement" in old buildings and the resultant cracking in building elements that occur.

5.7.5 Ewing, Jardetsky and Press (1957)

This book is a classic reference on the subject of wave propagation in the ground. Although quite theoretical it does provide reference material for predication models.

5.7.6 Richart, Hall and Woods (1970)

This book is a classic reference on the subject of vibration of soil and foundations. It complements Ewing, Jardetsky and Press (1957) in that it is theoretical and provides practical examples of the dynamic interaction between the ground and building foundations. A discussion is provided of research performed to investigate the effectiveness of trenches on reducing groundborne vibration.

5.7.7 Barkan (1962)

Similar to Richart, Hall and Woods (1970) this book provides an extensive treatment on the subject of vibration in the ground and its interaction with structures. A detailed discussion of soil settlement is provided.

6. FINDINGS

While there is consensus on most of the issues involving construction vibration and the protection of historic buildings, there unfortunately is little agreement on the subject of criteria to limit vibration. This appears to be in part due to the focus of early research on damage to buildings caused by vibration and the development of essentially two perspectives on what levels of vibration are tolerable. In the United States, the research has focused almost exclusively on the effects of blasting, whereas in Europe in addition to research on blasting there has also been research on the effects of traffic vibration.

Not surprisingly blasting tends to occur in rural areas and affects mostly residential structures that are newer construction, whereas traffic vibration that may cause damage would occur in urban settings such as in Europe where traffic tends to be in closer proximity to older buildings than in the United States. These two sources of vibration tend to represent the extremes of vibration intensities to which buildings may be exposed with blasting producing high levels of vibration and traffic producing low levels of vibration. The nature of these two phenomena are also different in that blasting is impulsive in nature whereas traffic vibration is more continuous, although at times the latter can have a transient characteristic that approaches an impulsive vibration.

There apparently has been little research conducted to address the most common forms of construction vibration and its effect on older buildings. Consequently there are essentially two views of what are appropriate vibration limits for historic buildings, those that come from a blasting research background and those that come from a traffic research background without much in between. It is unlikely that government research on construction vibration will happen any time soon and in the meantime it will probably be necessary and prudent to adopt a cautious approach in setting limits and allow for flexibility on a case-by-case basis. This seems like the most viable approach to take and seems to have some support based on the literature reviewed in particular the published case studies.

6.1 Vibration Criteria

Early investigations into the effects of strong ground vibration on structures examined the suitability of a number of different vibration metrics, which could be used to characterize the potential for damage. The evolution of this area of study was, in part, determined by the type of measurement equipment available at the time. Currently vibration, when measured to assess damage potential, uses the “peak particle velocity” (PPV) motion of the ground surface measured in in/sec (USA) or mm/sec (elsewhere). The ground motion is typically measured along three (3) perpendicular axes, one of which is vertical.

The use of PPV as the basis for damage criteria involving blasting used in mines was persuasively demonstrated by the United States Bureau of Mines (USBM). Researchers examined a collection of damage data from several different studies and concluded that the PPV for different levels of damage remains constant over a significantly broad frequency range, whereas damage as a function of the ground acceleration and displacement vary. The USBM research determined that a safe damage threshold for blasting was 2.0 in/sec for residential buildings. For reasons that will be explained, this is not a valid vibration limit for historic

buildings and structures, except in a very few limited circumstances that have to do with the construction of the structure.

It should be noted that blasting causes a short term pulse to occur. Pile driving although producing less energy is similar in that it is impulsive whereas most conventional construction vibration is more of a continuous nature. This distinction is important and should be kept in mind when evaluating damage potential and vibration limits. It should also be noted though that proximity to the activity whether it be blasting or pile driving is most important.

There are other variables such as strain which may arguably be better measures to assess damage potential. However, the use of PPV has far received the most common usage, in part because of the ease by which it can be measured and partly because a preponderance of the existing measurement data indicates a strong correlation between vibration of the ground as measured in PPV and damage upon which many different systems of damage classification and criteria are based. Consequently there appears to be no good reason to use another metric other than PPV to measure and assess damage. There is a trend towards specifying PPV as a function of the vibration frequency (e.g., Swiss standard SN 640 312a, DIN 4150-3, and BS 7385 Part 2).

6.1.1 Classification of Damage

A modern categorization of damage follows which has been taken from BS Standard 7385: Part 1: 1990 (BSI, 1990) and ISO 4866-2010 (ISO, 2010). Note that dusting of cracks may occur, even when no cosmetic damage has been observed.

> *Cosmetic - The formation of cracks on drywall surfaces, or the growth of existing cracks in plaster or drywall surfaces, or cracks through breaks/concrete blocks.*
>
> *Minor - The formation of large cracks, loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.*
>
> *Major - Damage to structural elements of the building, cracks in support columns, loosening of joints, splaying of masonry cracks, etc.*

In these documents, the term “threshold damage vibration level” is defined as the highest vibration level at which no cosmetic, minor, or major damage occurs.

6.1.2 Vibration Limits

Clearly there is a wide range of opinion on appropriate vibration limits for historic structures. At one end of the range is a conservative limit of 0.12 in/sec except in the case of ancient ruins where 0.08 in/sec is considered appropriate by some. At the other end of the range, some would consider 0.50 in/sec or even 2.0 in/sec appropriate.

Much of the research indicates that as the vibration frequency increases, building elements are better able to withstand higher levels of vibration. Therefore, it would appear that using a frequency-based limit is probably the most reasonable, based on all the research. The German standard DIN 4150-3 is a good example of this approach.

Based on some case studies it would appear that it is possible to set conservative vibration limits in general and yet still allow for some flexibility in modifying those limits based on detailed engineering investigation and analysis done on a case-by-case basis prior to award of the construction contract. Alternatively the transportation funding agency could adopt conservative criteria and allow for flexibility after the award of contract based on detailed investigations to be conducted by the contractor, who would need to demonstrate based on an engineering analysis the appropriateness of higher limits.

The following table summarizes the range of vibration limits recommended by researchers, practitioners, and government standards for avoiding damage to older, historic buildings as obtained from the generally available literature. We have indicated only those limits, which are unique and originated with the reference document. The data from IBMS was obtained from Feilden (2003).

Reference Source	**Remarks on Vibration Source**	**Remarks on Building or Structure**	**Remarks on Type of Damage**	**Vibration Limit - PPV (in/sec)**
BS 7385 Part 2 (1993)	All (including blasting)	Unreinforced or light framed structures	Cosmetic	0.6 to 2.0† (historic buildings may require special consideration)
Sedovic (1984)	All	Historic buildings in good state of maintenance	--	0.5
New York City TPPN 10/88 (1988) (source: Esrig and Ciancia, 1981)	Blasting, pile driving and vehicular traffic	Structures which are designated NYC landmarks, or located within an historic district or listed on the NHRP	--	0.5
Whiffin and Leonard	Traffic	Buildings with plastered walls and ceilings	Architectural damage and risk of structural damage	0.4 to 0.6
FHWA-RD-78-166 (1978)	Traffic	All	Structure damage possible	0.4
City of Toronto By-law 514 (2008)	All (blasting not mentioned)	All buildings	--	0.3 to 1.0† (lower limits may be identified by professional engineer)

Reference Source	Remarks on Vibration Source	Remarks on Building or Structure	Remarks on Type of Damage	Vibration Limit - PPV (in/sec)
Konon and Schuring (1985)	Transient	Historic buildings	Cosmetic	0.25 to 0.5†
SN 640 312a (1992)	All (blasting, construction equipment, and road traffic)	Historic and protected buildings	--	0.2 to 0.5†
FTA (2006)	All	Non-engineered timber and masonry buildings	--	0.2
Sedovic (1984)	All	Historic or architecturally important buildings in deteriorated state of maintenance	--	0.2
Whiffin and Leonard	Traffic	Buildings with plastered walls and ceilings	Threshold of risk of architectural damage	0.2
IBMS Holland (according to Feilden)	All	All buildings	Threshold for structural damage	0.2
FHWA-RD-78-166 (1978)	Traffic	All	Minor damage possible	0.2
Konon and Schuring (1985)	Steady state	Historic buildings	Cosmetic	0.13 to 0.25†
DIN 4150-3 (1999)	All	Buildings of great intrinsic value	Any permanent effect that reduces serviceability	0.12 to 0.4†
FTA (2006)	All	Buildings extremely susceptible to vibration	--	0.12
AASHTO R 8-81 (1980)	All	Historic sites and other critical locations	Threshold for cracks (cosmetic)	0.12
Esteves (1978)	Blasting	Special care, historical	--	0.1 to 0.4††
FHWA-RD-78-166 (1978)	Traffic	All	Threshold of structural damage	0.1

Reference Source	Remarks on Vibration Source	Remarks on Building or Structure	Remarks on Type of Damage	Vibration Limit - PPV (in/sec)
Whiffin and Leonard	Traffic	Buildings with plastered walls and ceilings	Virtually no risk of architectural damage	0.1
IBMS Holland (according to Feilden)	All	All buildings	Threshold for plaster cracking	0.08
Whiffin and Leonard	Traffic	Ruins and ancient monuments	--	0.08

† = frequency dependent criteria
†† = depending on soil type and frequency

6.2 Current practices

Current practices vary considerably on how construction vibration affecting historic structures is controlled if at all. Most jurisdictions recognize a need to document the condition of the affected buildings prior to start of construction. Where vibration limits are specified, vibration monitoring is required. Some agencies require the setting of warning thresholds to indicate when vibration levels are approaching the allowed limit. Exceeding a threshold triggers either a visual and/or audio alarm as well as notification by email of the event.

Incorporating a PHA into the process allows for the assessment by a professional trained in building preservation to be involved in the decision making process along with the resident engineer when vibration limits are exceeded. Most mitigation measures included in project contract documents tend to be generic in nature, but do provide some means and methods that contractors can follow when vibration limits are exceeded.

6.2.1 Procedures

There is general agreement on the procedures to follow when dealing with construction vibration. The following are generally recommended steps to follow:

- Consultation between historic building owner, development team and reviewing agencies such as SHPO and local planning departments to identify potential risks, negotiate changes and agreement on protective measures
- Documentation of the condition of the building prior to commencement of adjacent work, including a detailed photo survey of existing damage
- Establishment of vibration limits not to be exceeded based on condition of building, founding soil conditions and type of construction vibration
- Implementation of protective measures at both the construction site and the historic building, which could include specific means and methods to be used and those that will not be used

- Regular monitoring during construction to identify damage, evaluate the efficacy of protective measures already in place and to identify and implement additional corrective steps.

7. HUMAN PERCEPTION OF VIBRATION

Although it was not the intent of this project to explore the aspect of human reaction to construction vibration, it is important to address if only briefly. The potential effect of vibration on occupants of an affected building can have a substantial effect on the public's reaction. The vibration criteria presented by researchers discussed herein deal exclusively with the effects on buildings. However, a few of the researchers covered in this literature also address human perception as well. Examples can be found in Caltrans (2004b) and Whiffin and Leonard (1971). In addition we can rely on experience from previous projects. It should be noted that vibration measured at ground level can sometimes be lower than that inside the building due to amplification of building floors.

For continuous (steady state) vibration (e.g., vibratory compaction, vibratory pile driving), a PPV that exceeds 0.035 in/sec is generally considered to be distinctly perceptible. At a PPV of 0.10 in/sec the vibration would be strongly perceptible and according to Whiffin and Leonard (1971) begins to annoy. A vibration level that reaches 0.2 in/sec is definitely annoying and between 0.4 and 0.6 in/sec the vibration would be unpleasant according to Whiffin and Leonard (1971). Consequently if adopting a vibration limit of greater than 0.1 in/sec for continuous vibration it should be expected that there would be a reaction from building occupants and the greater the limit the greater the reaction would be.

For transient (generally impulsive) vibration (e.g., impact pile driving, blasting), humans are generally considered to be less sensitive than to similar vibration from continuous sources. Kelly, et al. (1998) and Wiss (1980) present data that relate human perception to transient vibration as well as steady state vibration. Transient vibration that is between 0.04 and 0.2 in/sec is considered to be barely perceptible, whereas transient vibration between 0.2 and 0.8 in/sec would be distinctly perceptible. A transient vibration level between 0.8 and 2.0 in/sec should be strongly perceptible. Comparing the two sets of data (continuous and transient), we see that there is approximately a factor of eight difference in the sensitivity to the nature of the vibration.

8. CONCLUSIONS

One main conclusion from the literature review is that recommended vibration limits tend to vary considerably. We would attribute this most likely to the viewpoint of the researcher preparing the recommendation. The primary variable affecting the recommendation appears to be whether the field research was focused on blasting (at the high end of vibration) or motor vehicle traffic (at the low end of vibration) with the differences between these two types of vibration being the time history of the vibration (i.e., transient vs. continuous) and the number of vibration cycles to which a building is subjected. The background of the researcher also seems to have had some effect on the recommended limits as well, which is probably also reflects the field experience of the research. Another conclusion is that those from the preservation profession tend to adopt a more conservative approach compared to those in the engineering profession, which is not unexpected. The human reaction to construction vibration might also be a consideration in setting limits or at least taken into account when conducting public meetings and outreach.

Aside for the vibration limits that could be adopted to apply to a specific project, the general procedures including pre-construction, building condition surveys, clearly specified agreements between stakeholders and monitoring are generally accepted as good procedures to follow to ensure protection of historic buildings. Involving experienced professionals from both the preservation side as well as the engineering side should also be considered especially in critical situations where the potential for damage is higher and the possibility of mitigating it after the fact is less acceptable.

In addition to the data obtained from the literature search, information was also obtained through a survey questionnaire of numerous transportation agencies conducted as a separate task of this research project. The details of the survey can be found in a summary memo (Survey Summary for NCHRP Project 25-25/Task 72, 29 March 2012). One of the findings of the survey was that few agencies have formal policies in place to deal with construction vibration and fewer have policies to deal with historic buildings.

In general transportation agencies rely more on informal processes involving communication between the project development team and the cultural resources specialists. Direct follow up calls to specific respondents to the survey tended to confirm the general findings from the response to the questionnaire. The information contained herein combined with the results of the survey questionnaire will be summarized in a project report.

9. BIBLIOGRAPHY

Published Journal Articles

Abdel-Rahman, S.M., "Vibration Associated with Pile Driving and Its Effects on Nearby Historical Structures," Proceedings, 20th International Modal Analysis Conference, Los Angeles, California (2002), pp. 1251-1258.

Ashley, C. and D.B. Parkes, "Blasting in Urban Areas," Tunnels and Tunneling, **8**(6), (September/October 1976), pp. 60-67.

Binda, L., P. Condoleo, A. Saisi, P. Taranto, and L. Zanzi, "Combined Non-destructive Techniques to Assess the Structural Safety of a Medieval Tower," Proceedings, 1st International Conference on Protection of Historical Buildings, Rome, Italy, Vol. 2 (2009) pp. 827-833.

Boscato, G., S. Russo, F. Sciarretta, and V. Vanzo, "Comparisons Among Non-destructive and Micro-destructive In Situ Tests in Historic Masonry Structures: First Results and Reliability," Proceedings, 1st Int. Conf. on Protection of Historical Buildings, Rome, Italy, Vol. 2 (2009) pp.835-839.

Crockett, J.H.A., "Traffic Vibration Damage in Mediaeval Cathedrals," Proceedings of Symposium on Measurement and Evaluation of Dynamic Effects and Vibrations of Constructions, Rilem Budapest (1963), pp. 303-317.

Dowding, C.H., "Vibration Criteria for Historic Buildings," Journal of Construction Engineering and Management, Vol. 113, No. 3 (September 1987), pp. 533-536.

Edwards, A.T., and T.D. Northwood, "Experimental Study of Effects of Blasting on Structures," The Engineer, Vol. 210 (September 1960), pp. 538-546.

Esrig, M.I., A. J. Ciancia, "The Avoidance of Damage to Historic Structures Resulting from Adjacent Construction, American Society of Civil Engineers, (11-15 May 1981).

Glatt, J., J. Roboski, and R.J. Finno, "Sheetpile-induced Vibrations at the Lurie Excavation Project," Proceedings, Geo-Institute Conference on Geotechnical Engineering for Transportation Projects, Los Angeles, California, Vol. 2 (2004), pp. 2130-2138.

Green, R., "Construction Vibration Baseline Measurements for Historic Properties," paper presented at Noise-Con 2011, Portland, OR (25-27 July 2011).

Gutowski, T.G., "Ground Vibration from Cut-and-cover Tunnel Construction," Sound and Vibration, Vol. 12, No. 4 (1978), pp. 16-22.

Hammarberg, E., K. Kesner, and D. Trelstad, "Protection of Historic Urban Structures During Adjacent Construction," Proceedings, 1st Int. Conf. on Protection of Historical Buildings, Rome, Italy, Vol. 2 (2009), pp. 1393-1398.

Henwood, J.T., and K.Y. Haramy, "Vibrations Induced by Construction Traffic: A Case Study," Proceedings, Geophysics 2002, The 2nd Annual Conference on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure, Los Angeles, California (2002), p. 9.

Jackson, M.W., "Thresholds of Damage due to Ground Motion," Proceedings, International Symposium on Wave Propagation, and Dynamic Properties of Earth Materials, New Mexico (1967).

Kelley, P.L., S.J. DelloRusso, and C.J. Russo, "Building Response to Adjacent Excavation and Construction," Proceedings, Effects of Construction on Structures, American Society of Civil Engineers Annual Convention, Boston, Massachusetts (1998), pp. 80-97.

Konon, W., and J.R. Schuring, "Vibration Criteria for Historic and Sensitive Older Buildings," Journal of Construction Engineering and Management, Vol. 111, No. 3, (September 1985), pp. 208-215.

Medearis, K., "The Development of Rational Damage Criteria for Low-rise Structures Subjected to Blasting Vibrations," Proceedings, The 18th U.S. Symposium on Rock Mechanics (USRMS), Golden, Colorado (1977), pp. 1-6.

Northwood, T.D., R. Crawford, and A.T. Edwards, "Blasting Vibrations and Building Damage," The Engineer, Vol. 215, No. 5601, (May 1963), pp. 973-978.

Sedovic, W., "Assessing the Effect of Vibration on Historic Buildings," Association for Preservation Technology XVI, No. 3&4, 1984.

Svinkin, M.R., "Vibration Environmental Effect of Construction Operations," Vulcan Hammer, www.vulcanhammer.net (no date)

Wiss, J.F., "Construction Vibrations: State-of-the-Art," Journal of the Geotechnical Engineering Division, Vol. 107, No. 2 (February 1981) pp. 167-181.

Project Reports

Carman, R. A., G.M. Glickman, and C.H. Reyes, Sacramento Intermodal Transit Facility and Track Relocation Project; Findings and Recommendation on Groundborne Vibration

Mitigation, prepared by Wilson, Ihrig & Associates with appendix by C. Searls and R. Mayes of Simpson Gumpertz & Heger for TranSystems, (22 April 2009).

Crockett, A.R. and G.P. Wilson, Threshold Damage Vibration Criteria for the Canton Viaduct, Wilson, Ihrig & Associates (September 1995).

Gutowski, T.G., L.E. Wittig, and C.L. Dym, Assessment of Groundborne Vibration From Construction and Traffic for I-83 in Baltimore City, Report No. BNN-3466, Bolt Beranek & Newman, Inc. Cambridge, MA, (1977).

HNTB and WIA, Park East Vibration Study, Milwaukee, WI, prepared by HNTB Corporation and Wilson, Ihrig and Associates for WisDOT and City of Milwaukee (February 2002).

King, K. and E. King, "Vibration Investigation of Archaeological Structures - Aztec Ruins National Monument - New Mexico," report prepared by K. King consultant for National Park Service, US Department of Interior (27August, 1994).

McCabe, N., and B. Howe, Assessment of Construction Vibration Potential and City of Toronto By-law 514-2008 Vibration Control Form, prepared for IBI Group (July 2011).

Nykamp, M.A., ., "Results of Vibration and Crack Movement Monitoring for Polson and Western Buildings, Phase 2, Yesler Way Vicinity Foundation Stabilization Project, Alaskan Way Viaduct and Sewall Replacement Program, Seattle Washington," prepare by Shannon & Wilson for Washington DOT, 23 May 2008.

Park East Vibration Study, prepared for Wisconsin Department of Transportation and The City of Milwaukee (February 2002).

Port Authority of New York and New Jersey, Permanent World Trade Center (WTC) PATH Terminal: Construction Protection Plan for Historic Properties Adjacent to the Project, DRAFT (February 2006).

Saurenman, H.J., and S. McKenna, Vibration and Noise Management and Remediation Plan, prepared for Metropolitan Council (April 2010).

Shaw, D.E., Evaluation of Potential Blasting – Induced Damage to the Meason House, (2000).

Sierra Blanca Constructors, "Noise and Vibration Monitoring Plan," prepared for New Mexico DOT (16 October 2002).

Siskind, D.E., and M.S. Stagg, Assessment of Blast Vibration Impacts from Quarry Blasting in Dade County, prepared for The Miami-Dade County Blasting Task Force (May 2000).

Government Research Reports

Esteves, J.M., Control of Vibrations Caused by Blasting, Laboratorio National De Engenharia Civil, Memoria 498, Lisboa, Portugal, (1978).

Nicholls, H.R., C.H. Johnson, and W.I. Duvall, Blasting Vibrations and Their Effects on Structures, Denver Mining Research Center, Denver CO Report No. PB-231 971 prepared for U.S. Department of the Interior Bureau of Mines (BuMines B 656), Washington, D.C. (1971).

Rainer, J.H., Effect of Vibrations on Historic Buildings: An Overview, NRCC 21092, Ottawa, Canada (1982).

Rainer, J.H., An Approach to a Vibration Standard for Buildings, NRCC 26052, Ottawa, Canada (1986).

Siskind, D.E., M.S. Stagg, J.W. Kopp, and C.H. Dowding, Structure Response and Damage Produced by Ground Vibration form Surface Mine Blasting, RI 8507, Bureau of Mines Report of Investigations, U.S. Department of the Interior Bureau of Mines, Washington, D.C. (1980).

Stagg, M.S., D.E. Siskind, M.G. Stevens, and C.H. Dowding, Effects of Repeated Blasting on a Wood-frame House, RI 8896, Bureau of Mines Report of Investigations, U.S. Department of the Interior, Bureau of Mines, Washington, D.C. (1984).

Watts, G.R., The Effects of Traffic Induced Vibrations on Heritage Buildings – Further Case Studies, TRRL 207, Transport and Road Research Library, Department of Transportation, Crawthorne, Berkshire England (1989).

Watts, G.R., Case Studies of the Effects of Traffic Induced Vibrations on Heritage Buildings, TRRL 156, Transport and Road Research Library, Department of Transportation, Crawthorne, Berkshire England (1988).

Whiffin, A.C., and D.R. Leonard, A Survey of Traffic-induced Vibrations, RRL Report LR418, Road Research Laboratory, Crowthorne, England (1971).

Wiss, J.F., Damage Effects of Pile Driving Vibration, Highway Research Record, No. 155, (1967), pp. 14-20.

Woods, R.D., NCHRP Synthesis of Highway Practice 253: Dynamic Effects of Pile Installations on Adjacent Structures, Washington, D.C. (1997).

National and International Standards

BS 7385: Part 1: 1990, Evaluation and Measurement for Vibration in Buildings, Part 1. Guide for Measurement of Vibrations and Evaluation of their Effects on Buildings, British Standards Institute, British Standard (1990).

BS 7385: Part 2: 1993, Evaluation and Measurement for Vibration in Buildings, Part 2. Guide to Damage Levels from Groundborne Vibration, British Standards Institute, British Standard (1993).

DIN 4150-3: 1999, Structural Vibration – Part 3: Effects of Vibration on Structures, Deutsches Institut für Normung (1999).

ISO 4866: 2010, International Organization for Standardization, Mechanical Vibration and Shock - Vibration of Buildings -Guidelines for the Measurement of Vibrations and Evaluation of their Effects on Buildings (2010).

SN 604 312a, Effects of Vibration on Construction, Swiss Standards Association, Swiss Standard (1992).

UNI 9916, Criteria for the Measurements of Vibrations and the Assessment of their Effects on Buildings, Ente Nazionale Italiano di Unificazione (2004).

Government Guidelines

Construction Vibration and Historic Building, CTC & Associates LLC, prepared for Wisconsin Department of Transportation (WisDOT) (2003).

Engineering Guidelines for the Analysis of Traffic-Induced Vibration, F.F. Rudder, FHWA-RD-78-166, (February 1978).

Georgia Department of Transportation's Environmental Procedures Manual, Georgia Department of Transportation, Atlanta (2010).

Standard Recommended Practice for Evaluation of Transportation Related Earthborne Vibrations, American Association of State Highway & Transportation Officials, AASHTO, Designation R8-96, Washington, D.C. (2004).

Transportation-and-construction-induced Vibration Guidance Manual, Jones & Stokes, prepared for California Department of Transportation, California (June 2004b).

Transportation Noise and Vibration Impact Assessment, Hanson, C.E., Towers, D.A., and L.D. Meister, prepared for Federal Transit Administration, Washington, DC (May 2006).

Transportation Related Earthborne Vibrations (Caltrans Experience), Technical Advisory, Vibration, TAV-04-01-R0201, Rudy Hendriks, (23 January 2004a).

Transportation Related Earthborne Vibrations (Caltrans Experience), Technical Advisory, Vibration, TAV-02-01-R9601, Rudy Hendriks, (20 February 2002).

Government Regulations

City of Toronto By-law No. 514-2008, City of Toronto, Toronto, Canada (2008).

Technical Policy and Procedure Notice (TPPN) 10/88, New York City Department of Buildings, New York (1988).

Books

Bachmann, H., Ammann, W.J., Deischl, F., Eisenmann, J., Floegl, I., G.H. Hirsch, Vibration Problems in Structures: Practical Guidelines, Birkhauser Verlag, Basel (1995).

Barkan, D.D., Dynamics of Bases and Foundations, McGraw-Hill, New York (1959).

Dowding, C.H., Construction Vibrations, Prentice Hall, Upper Saddle River (2000).

Ewing, W.M, W.S. Jardetzky, Elastic Waves in Layered Media, McGraw-Hill, New York (1957).

Feilden, B.M., Conservation of Historic Buildings, 3rd Edition, Architectural Press, London, (2003).

Forsyth, M., Structures & Construction in Historic Building Conservation, Blackwell, Oxford (2007).

Richart, F.E., J.R. Hall, and R.D. Woods, Vibrations of Soils and Foundations, Prentice-Hall, Englewood Cliffs (1970).

APPENDIX B
(AGENCY SURVEY)

Memorandum

Date:	May 29 , 2012
To:	Nanda Srinivasan
From:	David Buehler, ICF International Richard Carman, Wilson, Ihrig & Associates
Subject:	**Survey Summary for NCHRP Project 25-25 (Task 72)**

Introduction

Purpose

The purpose of National Cooperative Highway Research Program (NCHRP) Project 25-25 (Task 72) is to research current practices that address construction vibration and potential effects on historic buildings adjacent to transportation projects. As part of this effort a survey of state departments of transportation and other agencies was conducted to collect and synthesize the successful practices currently in use. This memo summarizes the survey development, execution, and results and provides a recommended approach for addressing this issue.

Under Section 106 of the National Historic Preservations Act of 1966 and for the purposes of this study a "historic" building is a building that is listed or is eligible for listing on the National Register of Historic Places. Buildings that are listed or eligible for listing on a similar state or local historic register are included as well.

Terminology

Operation of heavy construction equipment, particularly pile driving and other impacts devices such as pavement breakers create seismic waves that radiate along the surface of the earth and downward into the earth. These surface waves can be felt as ground vibration. Vibration from operation of this equipment can result in effects ranging from annoyance of people to damage of structures. As seismic waves travel outward from a vibration source, they excite the particles of rock and soil through which they pass and cause them to oscillate. The actual distance that these particles move back and forth is usually only a few ten-thousandths to a few thousandths of an inch. The rate or velocity (in inches per second) at which these ground particles oscillate varies between 0 inches/sec and some maximum velocity value. This maximum velocity value referred to as the peak particle velocity (PPV) is a commonly accepted descriptor for ground vibration amplitude.

Table 1 summarizes typical vibration levels generated by construction equipment (FTA 2006).

Table 1. Vibration Source Levels for Construction Equipment

Equipment	PPV at 25 feet
Pile driver (impact)	0.644 to 1.518
Pile drive (sonic/vibratory)	0.170 to 0.734
Vibratory roller	0.210
Hoe ram	0.089
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Source: FTA 2006.	

Table 2 summarizes damage thresholds recommended by Caltrans (Caltrans 2004) for transient and continuous construction vibration. Equipment or activities typical of continuous vibration include: excavation equipment, static compaction equipment, tracked vehicles, traffic on a highway, vibratory pile drivers, pile-extraction equipment, and vibratory compaction equipment. Equipment or activities typical of single-impact (transient) or low-rate repeated impact vibration include: impact pile drivers, blasting, drop balls, "pogo stick" compactors, and crack-and-seat equipment (Caltrans, 2004).

TABLE 2. GUIDELINE VIBRATION DAMAGE POTENTIAL THRESHOLD CRITERIA

	Maximum PPV (in/sec)	
Structure and Condition	**Transient Sources**	**Continuous/Frequent Intermittent Sources**
Extremely fragile historic buildings, ruins, ancient monuments	0.12	0.08
Fragile buildings	0.2	0.1
Historic and some old buildings	0.5	0.25
Older residential structures	0.5	0.3
New residential structures	1.0	0.5
Modern industrial/commercial buildings	2.0	0.5

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

Caltrans has developed guidelines for the relationship between various vibration amplitudes and human perception. (Caltrans 2004). Table 3 summarizes this relationship and gives some sense as what various amplitudes mean in terms of human perception.

Table 3. Guideline Vibration Annoyance Potential Criteria

Human Response	Maximum PPV (in/sec)	
	Transient Sources	Continuous/Frequent Intermittent Sources
Barely perceptible	0.04	0.01
Distinctly perceptible	0.25	0.04
Strongly perceptible	0.9	0.10
Severe	2.0	0.4

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

Survey

Survey Content

The survey questionnaire was developed by Principal Investigator Richard Carman of Wilson Ihrig & Associates (WIA), David Buehler from ICF International (ICF), Carolyn Searls from Simpson Gumpertz & Heger (SGH), and Stephen Mikesell of ICF. The questionnaire was submitted to the NCHRP project panel for review and comment. Comments from the panel were addressed and the questionnaire was incorporated into an on-line survey format using the Survey Monkey website. A copy of the survey is attached for reference.

Target Survey Participants and Survey Distribution

The following is summary of participants that were targeted for the survey.

State Departments of Transportation (DOTs). We contacted State DOTs through the membership lists of the American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Construction and the Transportation Research Board (TRB) Committee on Transportation Noise and Vibration (ADC40).

Transit Agencies. The American Public Transit Association (APTA) has not responded to requests for assistance in contacting members. Selected agencies throughout the country were individually contacted.

Turnpike and Toll Road Authorities. Thirty-eight selected members of the International Bridge, Tunnel and Turnpike Association were contacted.

Federal Highway Administration (FHWA). We contacted Stephanie Stoermer at FHWA and she did not identify any staff in FHWA Division Offices that would be appropriate to contact.

State Historic Preservation Offices (SHPOs). SHPO staff members were contacted through the membership list of the National Conference of State Historic Preservation Officers.

Members of TRB ADC40 Committee on Transportation-Related Noise and Vibration. We contacted members through the ADC40 membership list.

Members of TRB ADC50 Committee Committee on Historic and Archaeological Preservation in Transportation. We contacted members through the ADC50 membership list.

The survey was distributed via e-mail and respondents were asked to reply with two weeks. A reminder was sent several days before the end of the two-week period.

Survey Response

Response Numbers

The following is a summary of the responses to the survey.

- 506 requests were sent.
- 138 total responses were received (27.9%)
  - 59 participants completed the entire survey (22.7%)
    - 6 consultants
    - 45 State DOT
      - 34 unique states (several states had multiple responses)
    - 5 SHPO
    - 2 Canadian provinces

Response Content Overview

Thirty agencies indicated that they have had to consider the effects of construction vibration on historic buildings, and the same number indicated that they have a process in place (either formal or informal) for addressing this issue. The responses generally indicated, however, that established, formal processes for addressing this issue are not in place and that informal processes involving communication between the project development team and the cultural resources specialists are typical. In many cases, respondents cited only one or two instances in recent history where construction vibration effects on historic buildings were a concern. Because the issue rarely arises, the respondents indicated that there has been little need to establish formal processes.

Process Trigger

Typically, compliance with Section 106 of the National Historic Preservation Act and with state and federal environmental laws triggers the need to investigate the effects of construction vibration on historic buildings. Several states indicated that they apply a "200-foot rule," which means that if vibration-generating construction activity will occur within 200 feet of a historic building, the potential effects on the building must be investigated. Michigan uses a 100-foot distance threshold. In Iowa eligible structures within 500 feet of a project that has known potential to generate low-

frequency vibrations are investigated. The 500-foot distance would be increased to 750 feet or on rare occasions 1,000 feet depending on subsoil conditions.

Once the need to investigate is established, a variety of the informal processes is typically employed depending on the perceived and actual sensitivity of the historic resource, the nature of the construction vibration (i.e., impact pile driving vs. grading), ground conditions, and the level of concern by the public including building owners, and public agencies. Engineering staff is typically responsible for managing and commissioning technical work, including preconstruction condition surveys, determining building sensitivity to vibration, determining effect thresholds, and monitoring during construction. SHPO staff typically serves in an oversight role and must concur with decisions and recommendations made by project sponsors relative to potential building damage from construction vibration.

Building Evaluation

Twenty-nine agencies responded that they have conducted or commissioned a technical survey of a historic building for the purposes of assessing its susceptibility to structural damage or to assess the building's architectural features for potential damage from construction vibration. Thirty-five agencies have conducted (or commissioned) a pre-existing condition survey of a historic building for the purposes of documenting existing cracks, foundation settlement, or other pre-existing damage (structural or architectural) prior to construction of a project.

Potential for Damage

With regard to vibration criteria used to assess the potential severity of effects, several documents were cited.

- Federal Transit Administration Transit Noise and Vibration Impact Assessment (FTA 2006).
- California Department of Transportation (Caltrans) Transportation- and Construction-Induced Vibration Guidance Manual (Caltrans 2004).
- U.S. Bureau of Mines blasting criteria.
- "Blasting Vibration Monitoring and Control" (Dowding 1985).
- Illinois Department of Transportation Bureau of Design & Environment Manual, – 2010 Edition.

Specific thresholds that have been applied include those listed below.

- Virginia DOT uses a "threshold velocity" of 0.5 inches/second. (This is a mining standard defined in state law. Discretion can be used to use lower (more sensitive) velocity limit depending on the circumstances.)
- A consultant applied "limiting" peak particle velocity values of 0.2 and 0.3 inches/second.
- Massachusetts DOT has applied a limit at structures of 2 inches/second from blasting.
- Oklahoma DOT has applied an "alert" criterion level of 0.08 inches/second peak particle velocity and a "stop work" criterion level of 0.12 inches/second peak particle velocity. When work is

stopped the activities are evaluated and alternative methods to reduce vibrations below alert levels are investigated.

- Ohio DOT has applied a peak particle velocity limit of 0.12 inches/second.
- Missouri DOT states that it has "limited the amount of vibration a contractor was allowed to make in the vicinity of a historic property to less than 2 inches per second of vibration."
- Eighteen agencies have determined that construction vibration from a project had the potential to cause damage to a historic building.

Monitoring and Mitigation

Thirty-one agencies have conducted or commissioned vibration monitoring for a historic building during project construction for the purposes of limiting or controlling vibration received at that building or to determine effects on that building. It may seem unusual that 31 agencies have conducted monitoring when only 18 have determined that vibration had the potential to cause damage. Based on responses this discrepancy is attributed to situations where damage was not necessarily indicated but where precaution through monitoring was needed as a result of community concerns or perceived high sensitivity of a building by the public and public agencies.

Agencies employed the following methods to reduce vibration.

- Requiring the use of oscillating rollers instead of vibratory rollers to compact pavement.
- Jetting of piles to reduce vibration from impact pile driving.
- Use of non-vibratory compaction methods.
- Prohibiting use of "certain equipment."
- Prohibiting blasting "in the vicinity of a masonry building."
- Shoring of buildings during construction.
- Limiting the energy on pile driving hammers, limiting the energy used to "rubblize" pavement, using drilled shaft foundations in place of driven piles, limiting demolition methods, packing up and moving fragile personal property off site.
- Construction of a trench between construction equipment and a building.

Sixteen agencies indicated that they have stopped work on a project as a result of complaints or exceedance of a pre-established threshold. Alternative construction methods were typically identified and employed.

Public Outreach

Nine agencies have conducted public outreach or education concerning the effects of construction vibration on historic structures. Eight agencies stated that they were successful in addressing concerns expressed by the public and project stakeholders regarding the effects of vibration. In the one case where outreach was not successful the public did not believe the DOT studies which showed that vibration effects would be minimal.

Conclusions Regarding Various Approaches

The results of the survey indicate that none of the responding agencies has formal processes in place for evaluating the potential effects of construction vibration on historic buildings. California appears to have done the most work in this regard with the development of a guidance manual that specifically relates to the effects of construction vibration and includes a discussion of historic buildings. In general, if the issue arises, the approach to addressing the issue varies depending on the perceived and actual sensitivity of the historic building, the nature of the construction vibration (i.e., impact pile driving vs. grading), ground conditions, and the level of concern by the public and public agencies. Although many respondents offered elements of good approaches, no single best approach was obtained from the results of the survey.

Recommended Approach

The following is a distillation of approaches based on the results of the survey and our personal experience. This recommended approach will be refined and presented in our final report based on applicable literature and follow-up contact with selected agencies and consultants. A flow chart decision tree will likely provide the best method for illustrating the varied phases of the recommended approach.

- Determine if the transportation project will involve use of equipment that will generate high levels of vibration, such as pile driving, vibratory rollers, hoe rams, and crack-and-seat operations. If yes, continue.
- Determine if buildings are located within 500 feet of vibration-generating activities. If yes continue.
- Determine if any of the buildings qualify as historic buildings per Section 106 of the National Historic Preservation Act, or state or local regulations. If yes, continue.
- Conduct an initial screening evaluation using methods recommended in FTA 2006 and a peak particle velocity limit of 0.2 inches/second as an initial criterion. If soil conditions may be conducive to vibration transmission, use the more detailed analysis approach in Caltrans 2004 based on site-specific conditions. If exceedance of 0.2 inches/second is expected, continue.
- Evaluate feasible measures for reducing vibration, such as alternative pile driving methods (i.e., cast-in-drilled-hole piles versus driven piles), alternative foundation types for the new construction (i.e., spread footings versus driven piles), alternative compaction methods, and physical measures (intervening trench, increased distance). If feasible measures cannot be identified to reduce vibration below 0.2 inches/second, continue.
- Evaluate potentially affected buildings to determine specific susceptibility to damage.
  A structural engineer should evaluate the building structure. An architectural historian and a licensed architect should evaluate architectural elements. As part of this process establish building-specific thresholds for structural and architectural damage. If damage potential is still indicated, continue.

- Conduct a more detailed analysis of potential vibration levels, including consideration of site specific soil conditions and measurement of strength of vibration source(s) using methods specified in Caltrans 2004 to examine how vibration is attenuated by local soil conditions.. Evaluate options in more detail for alternative construction methods and physical measures to reduce vibration. If damage potential is still indicated, continue.
- Consider implementation of vibration mitigation measures on or inside a building to protect architectural features. Such measures could include temporary supports or temporary removal of fragile building elements or contents.
- Conduct pre-existing condition survey of potentially affected buildings. This should be conducted by a structural engineer for structural elements and an architectural historian and licensed architect for architectural elements. The survey should include photo or video documentation.
- Require monitoring to be conducted at the building during construction. This monitoring can include crack gages on existing cracks and vibration amplitude monitoring. Establish warning and stop work thresholds for monitoring. Implement visual and audible signals that are triggered by a vibration monitor when exceedances of warning and stop work thresholds occur. If warning thresholds are exceeded routinely, consider alternative construction approaches.
- If stop work threshold is exceeded, evaluate the condition of the building for damage. If no damage is indicated consult with structural engineer and/or architectural historian to assess whether higher thresholds are possible and adjust as appropriate .
- If damage occurs determine if any other construction approaches are feasible to reduce vibration. If none is available examine the severity of the damage to determine if damage is minor and repair is feasible. If repair is feasible continue with construction, but monitor vibration and damage closely to ensure that damage remains repairable. Consider whether a lower stop work threshold is feasible.
- If damage approaches becoming unrepairable and vibration levels have approached or exceeded the stop work threshold repeatedly, reconsider construction of the project.
- Repair any damage that has occurred.

Monitoring at the building of concern as described above should be considered even if the initial screening process finds that damage is unlikely. Factors to consider would include the level of detail of the engineering information, the related confidence in the engineering analysis, and the level of concern by the public and public agencies.

References

Federal Transit Administration (FTA). 2006. Transit noise and vibration impact assessment. Washington, D.C.

California Department of Transportation (Caltrans). 2004. Transportation- and construction-induced vibration guidance manual. Sacramento, CA.

Dowding, Charles H. 1985. Blasting vibration monitoring and control. Prentice Hall.

APPENDIX C
(ANALYSIS FLOW CHART)

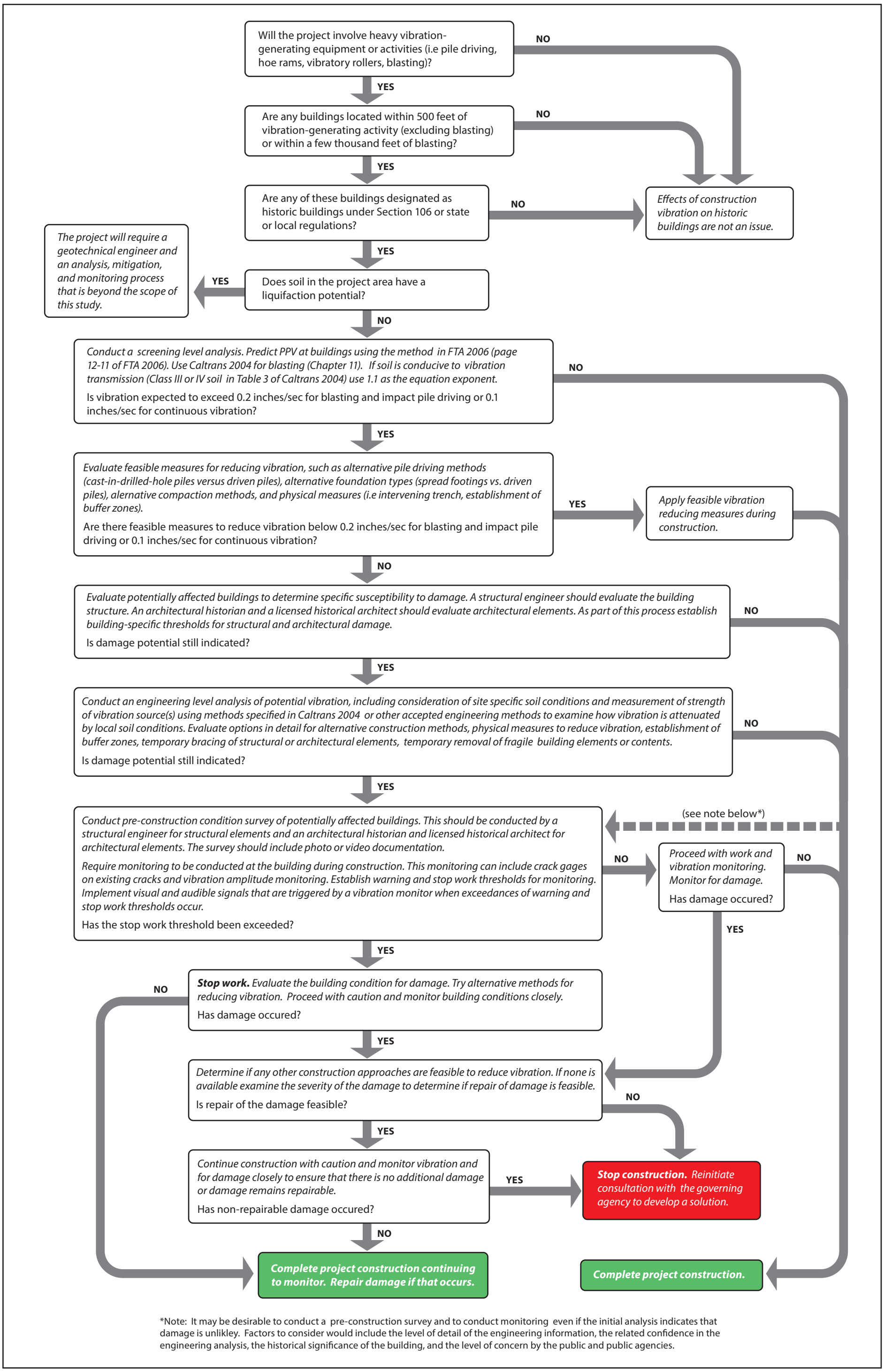

Figure C-1
Flow Chart for Recommended Approach for Addressing Construction Vibration Impacts on Historic Buildings