AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

PREPRINT 83-501 $2.00

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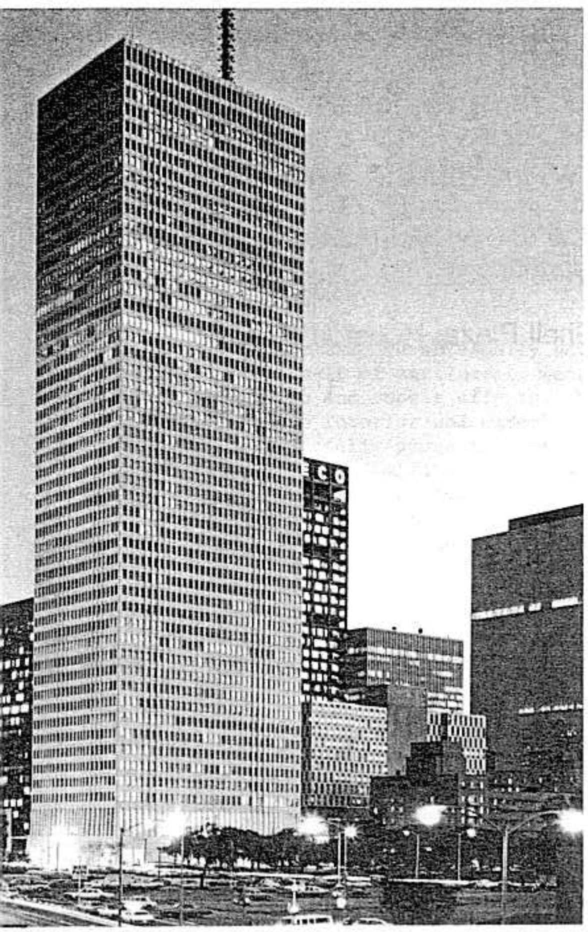

ASCE

Houston, Texas

October 17-19, 1983

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VIBRATION CRITERIA FOR HISTORIC AND SENSITIVE OLDER BUILDINGS

by Walter Konon[1], M. ASCE and John R. Schuring[1], M. ASCE

Introduction

Ground vibrations caused by construction operations such as blasting, pile driving and compaction have a potential to cause damage to adjacent structures. During the period from approximately 1950 to 1980, the most common damage criterion for safe vibration levels advanced by most researchers has been that the peak particle velocity at the point of concern should not exceed 2 in/sec (50 mm/sec). It was believed that if the peak resultant ground particle velocity was maintained below this level, there should be no damage caused in a structure as a result of construction induced ground vibrations. Many states and some government agencies such as the U.S. Corps of Engineers and the U.S. Bureau of Mines adopted the 2 in/sec (50 mm/sec) ground particle velocity damage criterion level during this period.

With the publication of the Bureau of Mines Report #RI 8507 (12) and in light of other recent publications (1, 3, 10), it became clear that the 2 in/sec (50 mm/sec) criterion was in fact not a safe limit for all types of structures. The 2 in/sec (50 mm/sec) "no damage" vibration criterion may be especially non-conservative when historic and older structures are involved.

A building that has been designated a landmark has, by decree, been given an extended useful life beyond what the original builders may have intended. As such, these special buildings deserve special protection if they are to be preserved for posterity. Part of this special treatment should be the selection of conservative vibration limits when these buildings are affected by construction induced ground vibration.

Older landmark structures usually have residual strains in their components as a result of settlement, weather cycles, poor maintenance, and past renovation and repair efforts. Many historic buildings have extensive elaborate interior and exterior ornamentation and surface detail that is especially prone to vibration damage. Strict construction vibration control limits for these buildings serve not only to eliminate the possibility of immediate damage, but also to reduce future fatigue damage that may be caused by the cumulative effects of both man and the environment.

This paper will briefly discuss the relevant parameters which must be considered in establishing vibration damage criteria for historic and sensitive older buildings. Existing criteria will be reviewed, and a new criterion is recommended.

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Characteristics of Ground Motion

Although experience has shown that particle velocity is a useful measurement criterion for construction vibrations, this parameter alone cannot predict damage levels in structures. Ground vibrations are complex sinusoidal-type wave forms, with several other wave characteristics that affect their damage potential. The more significant of these characteristics include frequency, particle displacement, and total duration(2).

The frequency of ground vibration is an important factor since it determines how much resonance can be established in the receiving structure. Ground vibrations with frequencies close to the natural frequency of the structure are the most damaging due to resonance effects. It should be noted that individual structural components, i.e., walls, floors, etc., usually have natural frequencies which differ from that of the overall structure. The critical frequencies for a structure are therefore a range, and not just a single number. Most building structures and their components have natural frequencies between 5 and 40 Hertz, with historic structures tending towards the lower end of the range owing to their typically more massive construction.

Some investigators have demonstrated that damage levels generally increase as vibration frequencies decrease (5, 12). This can be explained in part by the normally low natural resonance frequencies exhibited by most structures. An additional reason for the greater damage potential of low frequency vibrations is that they are typically associated with large particle displacements. Large particle displacements are damaging in their own right, since they produce high levels of strain on the structure.

Total duration of the vibration is another key element in predicting damage potential. For equivalent wave characteristics, long lasting, steady state vibrations such as those produced by vibration compaction devices and vibratory pile drivers tend to cause more damage to structures than impulse or transient vibrations such as those produced by blasting. Once again, resonance is involved since long duration construction vibrations afford more opportunity for the development of sympathetic vibrations in the receiving structure. Structural fatigue of the building materials also becomes a factor with steady state vibrations of long duration. Wiss (14) has suggested that the safe level of intensity for a steady-state vibration should be between one-half and one-fifth the safe level for transient vibration.

It is important to recognize that the vibration wave generated at the construction source does not maintain the same wave characteristics, i.e., particle velocity, frequency, and particle displacement, as it is transmitted away from the source. Many site conditions tend to either attenuate, amplify or otherwise change the vibration. They include: 1) distance between the source and the receiving structure; 2) geology of the transmitting medium; 3) response characteristics of the receiving structure. The effects of each of these factors is briefly described below.

For a given energy at the source, the magnitude of the vibration energy at any point is inversely proportional to the distance from the source. This is due to geometric attentuation of the wave front, and is the basis for the "scaled distance" relationship which is commonly expressed as (13):

$$V = K \left(\frac{D}{\sqrt{E}} \right)^{-n}$$

in which V = peak particle velocity; D = distance; E = energy for impact vibrations, or charge weight per delay for explosives; and K and n are constants associated with the transmitting media and other variables. Hendron and Oriard (9) have suggested that the above expression be modified to include the cube root of energy, E, instead of the square root.

Some building codes permit the use of the scaled distance relationship for blast vibration control in lieu of seismic instrumentation of the blasting. However, when dealing with historic or sensitive structures, seismic monitoring with both particle velocity and frequency measurement capabilities should be used along with a construction control program consisting of a preconstruction survey, settlement controls, and strain telltales.

The effects of the geology of the transmitting media on the wave form can be significant. As the wave form travels through the ground, the frequency, and to a lesser extent the particle velocity, are reduced by frictional damping at varying rates depending on the type of soil and rock present. The arrangement and structure of the subsurface strata also affect damping as vibrations pass from one interface to another. The infinite variations encountered from site to site usually make exact anaylsis of the effects of geologic media impractical, although a general trend is worth noting. The firmer or more competent the transmitting geologic strata, the lower the rate of frequency damping. For example, close-in rock blasting with little or no soil overburden will produce high frequency ground vibrations which tend to be less damaging to structures. In contrast, ground vibrations which travel long distances through thick soil overburden will have low frequencies with higher damage potential.

The dynamic response characteristics of a structure determine its tolerance to vibration. As mentioned previously, each structure and its components have natural frequencies which, if excited, will produce resonance. It is well known that structures can actually amplify a vibration, which complicates damage prediction. The response characteristics of a particular structure will depend on its general dimensions and type of construction, e.g., wood frame, masonry, concrete frame, as well as its present condition.

It is important also to distinguish between structural and cosmetic damage. Some structures can tolerate surprisingly high levels of vibration without any noticeable change in structural integrity. The threshold

(2) Particle velocity (V), frequency (f) and displacement (D) are related variables. For simple harmonic motion, the relationship between the peak values is:

$$V = 2\Pi f D$$

Actual ground variations have a more complex mathematical form, but the variables remain proportional.

for cosmetic damage, i.e., cracking, spalling, etc. is usually much lower, especially for structures with interior wall finishes and exposed masonry. In historic structures, it is often of paramount importance that cosmetic damage be avoided.

Existing Criteria

A review of existing criteria pertaining to historic and sensitive structures was undertaken, and the results are summarized in Table 1. Although there are differing opinions about maximum permissible levels, there is general agreement that peak particle velocity should be less than 2.0 in/sec (50mm/sec). The criteria in Table 1 cover a variety of structural types and conditions, and some investigators have correlated allowable particle velocity with other dynamic variables and subsurface conditions.

The German standards (12) are the strictest but are reportedly not always enforced. Rudder's (11) threshold of structural damage was developed for traffic induced vibrations which tend towards the steady state condition. Esteves (7) of Portugal presents criteria for three generically different kinds of subsurface conditions. The Swiss standards (5) are frequency dependent, and also distinguish between steady state and transient vibrations.

Ashley's (1) recommended criteria are for blasting related to tunnel construction in urban areas. Esrig and Cancia's (6) criterion was successfully used for the protection of 100+ year old historic buildings in New York City. Chae's (3) recommended blast design criteria included a scaled-distance relationship. Siskind, et al (12) base their criteria on an extensive study of blast effects on residential structures, and like the Swiss, have made it frequency dependent.

Recommendations

In order to predict the damage response of structures to construction vibrations, it is desirable to perform a dynamic mathematical analysis of the structure. However, due to the numerous structural and environmental variables involved, even approximate analyses are difficult and expensive. Such analyses can seldom be accomplished within the scope of normal projects. Older structures are especially difficult to model dynamically because the building components are typically in varying states of deterioration, and previous settlements and movements in the structure often have redistributed the loads and stresses into unknown patterns.

When historic or landmark designated buildings are involved the cultural, social, economic, political and architectural importance of such buildings must also be considered in setting vibration limits. The possibility of damaging a unique historic building must be weighed against the increased cost of construction operations when low maximum permissible vibration limits are specified. As such, the selection of the proper vibration criterion for a historic structure becomes an economic decision as well as a technical one.

It, therefore, becomes apparent that for the majority of historic and sensitive structures, the establishment of vibration damage criteria must be largely empirical, tempered with experience and judgment. Based on the authors' experience and the work of other investigators, the vibration criteria shown in Figure 1 are recommended. The allowable maximum peak particle velocity, which provides the primary field control,

TABLE 1
Existing Vibration Criteria for Historic and Sensitive Structures

Reference	Maximum Peak Particle Velocity (in/sec)	(mm/sec)	Vibration Type	Type and Condition of Structure	Comments
German Vibration Standards (12)	0.08	2	Unspecified	Ruins, ancient and historic buildings	
	0.16	4	"	Buildings with visible damage and cracks in masonry	
Rudder (11)	0.10	2.5	Traffic	All	Threshold of structural damage
Esteves (7)	0.10	2.5	Blasting	Special care and historical monuments	Loose and soft soils and rubble mixtures
	0.20	5	"	"	Medium to hard soils, uniform and well-graded sand
	0.40	10	"	"	Hard soils and rock
Swiss Association of Standardization (5)	0.12	3	Machines, traffic	Objects of historic interest and other sensitive construction	Frequency, 10 to 30 Hertz
	0.12-0.2	3-5	"	"	Frequency, 30 to 60 Hertz
	0.3	8	Blasting	"	Frequency, 10 to 60 Hertz
	0.3-0.5	8-12	"	"	Frequency, 60 to 90 Hertz
Ashley (1)	0.3	8	Blasting	Ancient and historic monuments	
	0.5	13	"	Housing in poor repair	
Esrig and Ciancia (6)	0.5	13	Blasting and impact pile driving	Historic buildings in poor condition	Approximately 30 feet of soil cover over bedrock
Chae (3)	0.5	13	Blasting	Old residential structures in very poor condition	Scaled distance criterion: 50 ft/ $\sqrt{lb}$
	1.0	25	"	Relatively old residential structures in poor condition	Scaled distance criterion: 30 ft/ $\sqrt{lb}$
Siskind, Stagg, Kopp and Dowding (12)	0.5	13	Blasting	Older residences, plaster on wood lath construction for interior walls	Frequency less than 40 Hertz
	2.0	50	"	"	Frequency greater than 40 Hertz

is shown to vary according to the frequency of vibrations. The recommended plot is for transient vibrations, and the limiting values shown should be reduced by about one-half for steady state vibrations.

The criteria shown in Figure 1 are intended to represent the damage threshold for historic and sensitive buildings. Specific site conditions may warrant some adjustment, and each application of the criteria should be reviewed carefully with regard to the characteristics of the vibration source, transmitting media, and receiving structure.

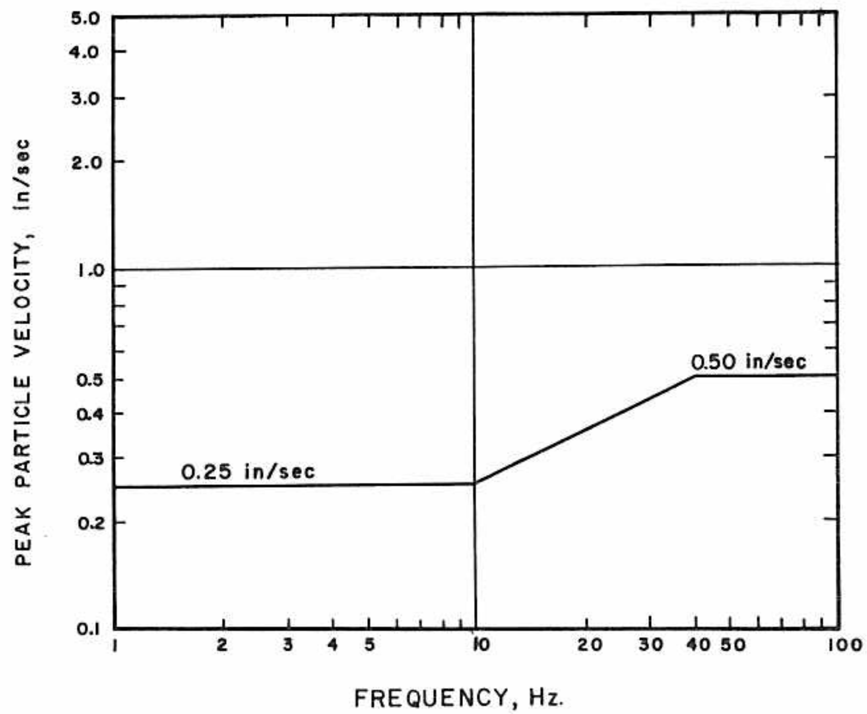

Fig. I — Recommended Vibration Criteria for Historic and and Sensitive Older Buildings

Conclusions

Historic and sensitive older buildings require special attention to protect them from construction induced ground vibrations. Damage level criteria for these structures are by necessity more conservative than the 2.0 in/sec (50 mm/sec) traditionally used for modern structures in good condition. When establishing a vibration damage criterion for a project, consideration must be given to the vibration wave characteristics, the conditions of the site and receiving structure, and the economic impact of the selected limiting value.

Appendix - References

1. Ashley, C., "Blasting in Urban Areas," Tunnels & Tunneling, Vol.8, No. 6, Sept. 1976, pp. 60-67.

2. Bata, M., "Effects on Buildings of Vibrations Caused by Traffic," Building Science, Vol. 6, 1971, pp. 221-246.

3. Chae, Y.S., "Design of Excavation Blasts to Prevent Damage," Civil Engineering, ASCE, Vol. 48, No. 4, April 1978, pp. 77-79.

4. Edwards, A.J. and Northwood, T.D., "Experimental Studies of the Effects of Blasting on Structures," The Engineer, Vol. 210, Sept. 30, 1960, pp.538-546.

5. "Effects of Vibration on Construction," Swiss Association of Standardization, Seefeldstrasse 9, CH8008, Zurich, Switzerland.

6. Esrig, M.I. and Ciancia, A.J., "The Avoidance of Damage to Historic Structures Resulting from Adjacent Construction," ASCE Preprint 81-052, 1981.

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

8. Heckman, W.S. and Hagerty, D.J., "Vibrations Associated with Pile Driving," Journal of the Construction Division, ASCE, Vol. 104, No. CO4, 1978.

9. Hendron, A.J.,Jr. and Oriard, L., "Specifications for Controlled Blasting and Civil Engineering Projects," Proceedings, North American Rapid Excavation and Tunneling Conference, AIME, Vol. 2, 1972, pp. 1585-1609.

10. Medearis, K., "Rational Damage Criteria for Low-Rise Structures Subjected to Blasting Vibrations," Proc. Instn. Civ. Engrs., Part 2, Vol. 65, September, 1978, pp. 611-621.

11. Rudder, F.F.,Jr., "Engineering Guidelines for the Analysis of Traffic-Induced Vibration," Federal Highway Administration Report No. FHWA-RD-78-166, February 1978.

12. Siskind, D.E., Stagg, M.S., Kopp, J.W., and Dowding, C.H., "Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting," United States Bureau of Mines Report of Investigation 8507, 1980.

13. Wiss, J.F., "Construction Vibrations: State-of-the-Art," Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. GT2, 1981.

14. Wiss, J.F., "Damage Effects of Pile Driving Vibrations," Highway Research Board Record 155, 1967, pp. 14-20.