Theme Report on Topic 12
EARTHQUAKE RESISTANT DESIGN OF EQUIPMENT AND SERVICE FACILITIES

by

Erik H. Vanmarcke[I]

INTRODUCTION

This theme report deals with a very wide spectrum of engineered systems which have not, until recently, received much attention within the earthquake engineering community. In fact, the attention of most contributors to this Session is directed to systems which lie at opposite ends of this spectrum. At one end are so-called secondary systems supported by or appended to primary structures. Nonstructural components of buildings (ceiling assemblies, non-bearing walls (3))*, elevators (2), mechanical and electrical systems (4 - 7) fall into this category. Other specific secondary systems dealt with are: sensitive equipment located in nuclear facilities (5,14), computers (12) and telecommunication equipment (10,21) within buildings, porcelain insulators attached to power transmission facilities (6), and circuit breakers in a pumping plant switchyard (9). At the other end of the spectrum of systems of concern in this Session are large "lifeline" systems providing for the needs in energy, communication, and transportation. The following specific lifelines are considered: pipelines, both buried and above-ground (1,8,11,15,23), railway tracks (17), and high-voltage transmission lines (22). In addition, the following components of lifeline networks are examined: liquid storage tanks (20), telephone communication centers (10,21) and transmission towers (22).

In view of the great diversity of topics covered, this theme report is primarily an attempt to serve an integrating function, that is, to identify common threads in individual contributions and to relate these contributions to the state-of-the-art (exemplified by Ref. 28) in seismic design of equipment and service facilities.

SECONDARY SYSTEMS

Importance of Secondary Systems

By definition, a secondary system is appended to, attached to, or supported by, a primary structure. The latter has received far more attention than the former in the earthquake engineering community. Secondary systems may be components of utility systems (water, transportation, communication and energy), industrial systems (e.g., oil refineries, computer data processing facilities) or building systems (residential, commercial, hospitals). Past major earthquakes have amply demonstrated the vulnerability of secondary systems to earthquake damage. Continued function of these systems during and after earthquakes is often critically important. Moreover, they must withstand seismic effects which may be adversely affected by the dynamic characteristics of the primary system or by the interaction between the primary and the secondary systems.

Dynamic Properties: Testing

Guha et al. (4), Sugimoto and Sato (21), Liu (10) and Muto et al. (12) consider methods and requirements for testing of important pieces

* Numerals in the brackets are the numbers of references at the end.

[I] Associate Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 of (electro-mechanical) equipment. The goal of the testing is to verify functional capability during strong shaking and to establish damage and failure thresholds. Several authors (6,9) emphasize the importance of considering the nonlinear character of the dynamic response. Many of these papers (4,6,9,21) provide new information on the dynamic properties (periods, damping values) of specific secondary systems.

Active Devices for Seismic Protection

Two papers (2,14) deal with active devices which utilize a seismic trigger to initiate controlled shutdown in the event of an earthquake. Benuska et al. (2) provide information on an active system for elevators in buildings, while Peyrot and Plautz (14) report on the cost-effectiveness of such a device for nuclear particle accelerators. Active devices have seldom been used for earthquake protection because they require maintenance (to insure reliable operation) and they are often too costly.

Seismic Analysis of Secondary Systems

Several papers at this conference (5,16,28) focus on the methodology to predict the seismic response of secondary systems. Analysts of nuclear facilities have pioneered the practice of predicting floor response spectra (i.e., response spectra at the point of support within the primary system), and then using the response spectrum method to predict the secondary system peak response. Hadjian (5) examines in detail the implications of and the errors inherent in modeling the combined primary-secondary system as a "decoupled" system. The "decoupled system" model has obvious practical advantages in that it permits one to evaluate the support acceleration prior to having information about the precise configuration or the dynamic properties of the equipment. Hadjian (5) concludes that presently used criteria for decoupling are both arbitrary and conservative.

If the equipment can be modeled as an uncoupled linear one-degree system, then floor response spectra suffice for the purpose of seismic design of the equipment. Iwan (7) presents an approximate method to use the (floor) response spectrum to predict the response of an isolation system with nonlinear motion limiting constraints. Muto et al. (12) also propose a calculation method based on floor response spectra to be used in the design of a new installation device for computers in buildings.

At present, time integration analysis is the most common method for obtaining the floor response spectra corresponding to a set of specified design ground response spectra. The procedure calls for selecting (and in many cases computer-generating) one or more earthquake accelerograms which are compatible with the prescribed ground response spectra. Time-integration analysis is then used to evaluate the (primary system) acceleration response at the point of equipment support. Finally, the "floor response spectrum" is calculated and suitably smoothed or enveloped for use in equipment selection. The support point acceleration response may also be used as input loading in tests of the equipment. The frequency content of the acceleration response will be concentrated at the important eigenfrequencies of the primary structure. (For this reason, the test loading used to check equipment capability is often just a sequence of sinusoidal pulses at the different natural frequencies of the dominant primary system modes.) Proposals have recently been made to eliminate the need for time-integration analysis to predict floor response spectra when the ground response spectra and the normal modes (frequencies, dampings, shapes) of the primary structure are known. Semi-empirical procedures are proposed by Biggs (24) and by Sato et al. (16). Other recent proposals (25,26,29,30,31) are based directly on random vibration theory. In this analysis, the earthquake ground motion is modeled as a limited duration segment of a stationary random process with a spectral density function, usually of the Kanai-Tajimi type (see, for example, Ref. 31).

Codes

Code provisions for non-structural building components and systems are discussed by Goldberg and Sharpe (3). These provisions are being developed in the United States by the Applied Technology Council under contract with the U.S. National Bureau of Standards. The primary objective in developing the criteria is to assure life safety in the event of an earthquake. For mechanical and electrical systems, the criteria include provisions for fixed and resiliently mounted equipment. For architectural components, the requirements involve force resistance and provisions for inter-story drift and out-of-plane deflections. Shibata (19) discusses the requirements of an aseismic design code for components of oil refineries and petro-chemical industrial facilities. He proposes an "open form" of code which leaves considerable freedom to the designer. The specifications should be related to the concepts of "factor of importance" and "mode or mechanism of failure" which evolved during the early stage of development of aseismic design procedures for nuclear facilities. Specific failure modes and mechanisms relevant to equipment are: brittle fracture in vessels and pipings, failure due to acceleration response (including pipe whip), failure attributable to sloshing of liquids. Finally, several authors (4,10,11,12,21) make recommendations with regard to methods and standards for testing of equipment, on shaking tables or in situ, and at low or high levels of excitation.

"LIFELINE" SERVICE SYSTEMS

Importance of Lifelines

Many papers in this session are concerned with the seismic design of large utility networks and with "links" and "nodes" thereof, whose function is to fulfill society's needs for energy, communication and transportation. The systems include, for example, pipelines (1,8,11,15,23), railway tracks (17) and telephone communication systems (10,21). These long, linear facilities, whose continued operation during and after earthquakes is often vital, have heretofore received relatively little attention. Yet, they pose many new problems to engineers concerned with seismic safety. Failure of a component or a segment of a "lifeline" implies costs which go much beyond those associated with repair or replacement of the failed component or segment. Katayama et al. (8) summarize in quantitative terms the seismic damage to buried utility pipelines caused by past earthquakes and they attempt to relate the seismic damage to ground conditions. Sato and Miura (17) survey the damage to trains and railway tracks resulting from ten recent strong earthquakes in Japan.

Seismic Risk; Performance Evaluation

Seismic risk of extended facilities must be approached much differently than for "point" targets. A larger number of potential sources of earthquakes must be considered. A major earthquake close to a lifeline will generate a range of potentially damaging levels of ground motion within a large section of the lifeline. Damage or failure will occur where the local induced response exceeeds the available resistance. It follows that weak components (i.e., with low seismic resistance) of the lifeline as well as points closest to active seismic sources will be of most concern.

Schiff et al. (18) propose a computer simulation approach to evaluate the seismic response of lifelines, in particular electric power networks. The computer simulates seismic event times, sizes and locations; ground motion parameters at each support point of the system; seismic resistance levels for each system component; post-earthquake power demand; and so on. System performance is thus evaluated by extensive Monte Carlo simulation. Information gained from the simulation enables the designer, in principle, to evaluate the siting and seismic specification of individual system components in the context of overall system safety.

Seismic Response Analysis

The degree of spatial correlation between earthquake ground motion parameters and the phasing and the velocity of propagation of different frequency components of the ground motion are matters of great concern in lifeline seismic analysis. They also greatly complicate the analysis of soil-structure interaction of "spatially extended" systems (such as pipelines) which rest on multiple supports or which are buried underground. Powell (15) presents a procedure for computing the seismic response of cross-country pipelines. The procedure accounts for the effects of initial static loads, support nonlinearity, and out-of-phase ground motions at different points along the pipe. Takada (23) observes that underground pipelines are usually connected to structures such as manholes, buildings, etc., which have large masses and act in the same way as the surrounding ground during earthquakes. The occurrence of relative displacement between the pipe and the ground would therefore induce concentration of stress or strain at the points of connection. Takada (23) concludes that flexible joints which absorb the relative displacement are necessary to harmonize the motion of the pipeline with that of the surrounding ground.

System Design and Optimization

In his effort to mitigate the seismic hazard to lifeline systems, the designer must consider, in addition to more conventional protective measures through component design, opportunities for providing redundant links[+], for "optimal" siting of weaker or more critical components of the system, and for allocating protective measures (i.e., added seismic resistance) to optimize overall system seismic safety. Formal optimization is

---

[+] Aggour and Miller (1) develop a constraint on the distance between redundant underground pipelines at a nuclear facility. The requirement is that, if a rupture occurs in one pipeline, the resulting large volume of pressurized fluid discharged into the surrounding soil should not destroy the bearing capacity and hence, the functional capability, of the second (redundant) system.

practically very difficult, however (27). The seismic loading is only one of several potentially hazardous external loads and environmental conditions which the designer must consider, in addition to operating loads and functional requirements. Moreover, a clear "objective function" guiding the designer's effort to optimize the system can never be fully agreed on. Human suffering, environmental damage, and other intangibles as loss of professional reputation, are all components of a vector of losses associated with strong earthquake occurrence. These loss components cannot easily, if at all, be expressed in monetary terms (39). Nair and Kulkarni (13)[2] propose a formal multi-attribute decision analysis approach to the problem of siting of facilities.

In some situations, economic considerations largely dominate the total expected loss picture, and formal expected cost minimization becomes possible. S.C. Liu (10) proposes such an approach to the seismic design of communication facilities. An alternate interpretation is to say that the system designer "sub-optimizes" the system based on the monetary component of the seismic losses alone. It may then be argued that the resulting level of protection is a minimum justifiable on the basis of monetary considerations alone.

REFERENCES

Session XII Papers Referenced in the Theme Report

1. Aggour, M.S., and Miller, R.P., "Separation of Category I Pipelines in Granular Soil"

2. Benuska, K.L., Aroni, S., and Schroll, W., "Elevator Earthquake Safety Control"

3. Goldberg, A., and Sharpe, R., "Provisions for Seismic Design of Non-Structural Building Components and Systems"

4. Guha, S.K., Wedpathak, A.V., and Desai, P.J., "Aseismic Tests on Some Electro-Mechanical Systems"

5. Hadjian, A.H., "On the Decoupling of Secondary Systems for Seismic Analysis"

6. Hashimoto, K., and Tsutsimi, H., "Earthquake Resistance of Porcelain Insulator Electric Power Equipment"

7. Iwan, W.D., "Predicting the Earthquake Response of Resiliently Mounted Equipment with Motion Limiting Constraints"

8. Katayama, T., Kubo, K., and Sato, N., "Quantitative Analysis of Seismic Damage to Buried Utility Pipelines"

9. Kircher, C.A., "Forced Vibration Analysis of 230 KV Air Blast Circuit Breakers: Energy Dissipation Parameters Calculated for Different Excitation Levels"

10. Liu, S.C., "Earthquake Protection of Communications Facilities"

11. Merz, K.L., "Equipment Systems in the Seismic Environment"

12. Muto, K., Nagata, M., and Fuduzawa, E., "Earthquake Resistant Installation Device of Computers"

13. Nair, K., and Kulkarni, R.B., "Locating and Designing Facilities in Seismically Active Areas"

14. Peyrot, A.H, and Plautz, K.A., "An Active Device to Protect Nuclear Particle Accelerators from Earthquakes"

15. Powell, G., "Analysis of Earthquake Effects on Pipelines"

16. Sato, H., Suzuki, K., Komazaki, M., and O-Hori, M., "On a Simple Method for Estimating the Appended System Response Spectrum from a Statistically Simulated Spectrum"

17. Sato, Y., and Miura, S., "Deformation of Railway Track and Running Stability of Train in Earthquake"

18. Schiff, A.J., Feil, P.J., and Newsom, D.E., "Computer Simulation of Lifeline Response to Earthquakes"

19. Shibata, H., "The Way of Setting the Aseismic Design Code of Oil Refineries and Petro-Chemical Industries"

20. Sogabe, K., and Shibata, H., "Aseismic Design of Cylindrical and Spherical Storages for their Sloshing Phenomenon"

21. Sugimoto, Y., and Sato, Y., "Telecommunications Equipment Seismic Effect Study"

22. Syrmakezis, C.A., "Earthquake Resistant Design of Steel Towers of Electrical High Voltage Transmission Lines Subjected to Horizontal or Vertical Ground Motions"

23. Takada, S., "Earthquake Resistant Design of Underground Pipelines"

Other References

24. Biggs, J.M., "Seismic Response Spectra for Equipment Design in Nuclear Power Plants," Proceedings 1st International Conference on Structural Mechanics in Reactor Technology, Berlin, West Germany, September 1971, Paper K4/7.

25. Chakravorty, M., "Transient Spectral Analysis of Linear Elastic Structures and Equipment under Random Excitation," M.I.T. Department of Civil Engineering Research Report R72-18, April 1972.

26. Chakravorty, M.K., and Vanmarcke, E.H., "Probabilistic Seismic Analysis of Light Equipment within Buildings," Proc. 5th WCEE, Rome, Italy, 1973.

27. Cornell C.A., "Optimization: The Only Rational Way or Only a Rationalistic Way?", 6 WCEE, Contribution to the Panel Discussion on Design and Engineering Decisions.

28. Newmark, N.M., and Rosenblueth, E., Fundamentals of Earthquake Engineering, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1971.

29. Singh, M.P., "Generation of Seismic Floor Response Spectra," J. Eng. Mech. Division, ASCE, Vol. 101, No. EM5, Proc. Paper 11651, 1975, pp. 593-607.

30. Vanmarcke, E.H., "A Simple Procedure for Predicting Amplified Response Spectra and Equipment Response," 6 WCEE.

31. Vanmarcke, E.H., "Structural Response to Earthquakes," Chapter 8 in Seismic Risk and Engineering Decisions, C. Lomnitz and E. Rosenblueth, Eds., Elsevier Press, Amsterdam, Netherlands, 1976.

32. Whitman, R.V., et al., "Seismic Design Decision Analysis," J. Structural Division, ASCE, Vol. 101, No. ST5, May 1975.

DISCUSSION ON THEME REPORT

A.R. Chandrasekaran (India)

The specifications for testing equipment to withstand earthquakes as drawn out by some authorities specialising in Electrical Engineering are rather unrealistic. For example, in one case, they had specified that the equipments should withstand an acceleration of 0.5 'g' from 1 cps to 40 cps. I feel it is unrealistic to demand a constant acceleration amplitude over such a wide frequency range as strong grounds motions do not have predominant peaks over this frequency range. Would the theme reporter like to comment on amplitudes and associated frequency ranges in case steady state sinusoidal tests are carried out on equipments for the purpose of determining their performance due to earthquakes ?

Author's Closure

Not received.