TELECOMMUNICATIONS LIFELINES IN A SEISMIC ENVIRONMENT

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SUMMARY

The present paper reviews the current understanding of the seismic performance of telecommunications networks, primarily based on field data derived from the damage experienced in past earthquakes, outlines the analytical procedures to be developed for a risk analysis for telecommunications systems, and indicates the specific empirical and experimental information that must be further gathered for the same analysis to be able to generate credible and reliable results.

INTRODUCTION

Urban telecommunications systems are recognized as essential lifelines whose continued serviceability following a major earthquake is indispensable to implementing emergency operations to mitigate the immediate consequences of severe earthquakes. Continuity of service is also a significant factor in maintaining the morale of citizens in a disaster area, which is important to smooth and efficient recovery efforts. Also, utilities have vast amounts of capital equipment exposed to seismic risk. Mitigation of these hazards through improved design and retrofitting is a high priority.

Knowledge of the seismic performance of urban telecommunications systems has improved since the 1971 San Fernando earthquake, where equipment in central dialing offices suffered significant damage. A program of damage interpretation, laboratory testing and analysis has resulted in new procedures for the design of individual components and support structures. Also, considerable effort has been expended by Japanese engineers and researchers to examine the impact of the 1978 Off-Miyagi-Ken earthquake, not only on the equipment and facility failure, but also on the functional performance of the telecommunications system that generally serves a wide area, including and surrounding the city of Sendai.

The purpose of the proposed paper is (1) to review the current understanding of the seismic performance of telecommunications networks, primarily based on field data derived from the damage experienced in past earthquakes, (2) to outline the analytical procedures to be developed for a risk analysis for telecommunications systems, and (3) to

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indicate the specific empirical and experimental information that must be further gathered for the same analysis to be able to generate credible and reliable results.

SEISMIC PERFORMANCE OF TELECOMMUNICATIONS NETWORKS

Central Dial Offices

As documented in more detail by Isenberg (Ref. 1), significant damage to facilities and equipment belonging to the General Telephone Company was sustained in the February 9, 1971 San Fernando earthquake. The main damage suffered by equipment in this earthquake was buckling and swaying of frames and, in the case of the Sylmar central office, toppling of the frames and switching equipment. Similar observations were made in the 1968 Hachinoe, Japan earthquake, in which batteries were also jolted out of place. In the 1972 Managua, Nicaragua earthquake, microwave equipment anchorages failed and equipment shifted but did not topple; exchange equipment fell.

In other instances, such as the 1979 Imperial County, California earthquake, there was no significant damage to telecommunications structures or equipment, but the system became overloaded by callers seeking aid or reassurance.

In addition to damage actually observed in earthquakes, shaker table tests of equipment and frames have been performed by Liu and De Capua (Ref. 2). In these tests, frames were subjected to synthesized earthquakes which populate an upper bound design spectrum. Various frame assemblies were subjected to the synthesized earthquakes with the peak acceleration increasing gradually from 0.1g to 1.0g. Among observations of interest are the peak acceleration levels corresponding to initial damage and to total failure. The initial damage level is defined as the input acceleration level that causes a permanent frame distortion or loosening of the anchor bolts. Total failure corresponds to buckling of the frame uprights or pullout of the anchor bolts. Weight of equipment attached to the frames was a parameter in the tests, ranging from 690 lbs. to 884 lbs. The main findings of the study were summarized as follows: (1) More heavily loaded frames fail at lower ground shaking intensity; and (2) For frames supported on the ground floor, the minimum level of acceleration for initial failure is 0.3g and for total failure is 0.5g.

An independent study of the natural frequency of a loaded frame (875 lbs. of equipment; 175 lbs. of frame) bolted to the floor and unbraced at the top was carried out by Wolmer (Ref. 3) and indicates that the fundamental mode is a cantilever-type with a natural frequency of about 1.9 Hz. Presently, however, nearly all frames in seismically active areas are braced.

With respect to the 1978 Off-Miyagi-Ken earthquake, Miwa and Okumura (Ref. 4) and Okamoto et al. (Ref. 5) reported that there was no damage to office buildings and equipment observed, at least not serious

enough to interfere with the normal operation of exchange functions. Most of the damage sustained by building structures and equipment was in the category of loosening and breaking of the anchor bolts.

Field Facilities

Again, speaking of the 1978 Off-Miyagi-Ken earthquake, the field facilities for telecommunication systems sustained some earthquake damage, particularly in those areas where the ground conditions were soft and susceptible to liquefaction and also where the land had been reclaimed. For example, transmission poles suffered excessive displacement causing aerial cables to snap, although few poles actually fell. Also, some of the damage was due to such secondary causes as a collapsing building striking the poles and aerial cables in its vicinity thus producing failure in the communications system. As for underground pipes protecting the cables inside, failure was often observed at pipe joints and at the locations where the pipes are joined to manholes or above-ground structures. Pipe failures were also observed at the location of bridge expansion joints when the pipes were attached to the bridge in order to shortcut physical obstacles. It is generally observed that the incidence of these physical failures tends to be more frequent when ground conditions are weak and more susceptible to liquefaction. Needless to say, the same observation can usually be made with respect to other underground lifeline systems such as water transmission pipeline networks.

RISK ANALYSIS

Previous Work

In the face of these possibilities of damage, the purpose of seismic risk analysis for telecommunications networks is to provide information concerning the risks arising from the consequences of networks failing under specific earthquake loading conditions. Particular components may be determined to be critical in the sense that they have the highest probability of failure for specific magnitude earthquakes. Such information can be used for design and upgrading of the networks. It can also permit better crisis preparedness by management since it can now predict likely failure locations. References 6-12 represent some of the previous work performed in the general area of risk analysis, although, except for Ref. 12, they deal primarily with water transmission pipeline network systems. Highlights of these papers are briefly presented below. Among the major causal factors of seismic damage which include (i) ground motion associated with the wave propagation, (ii) fault movement, (iii) liquefaction, (iv) landslides, and (v) interference with other under- and above-ground structures, the first two were considered in the analysis. For the purpose of risk analysis, these papers

(a) defined system unserviceability;
(b) postulated correlations between unserviceability and physical damage;
(c) developed a method of evaluating the probability of unserviceability;

(d) indicated a method of estimating the costs accruing from system unserviceability; and
(e) recommended a method of system optimization.

It is noted that the system connectivity and serviceability are not necessarily synonymous. More specifically, in Refs. 7-11, a water transmission network modeled on the Los Angeles City system was analyzed, taking into account the existence of the major faults surrounding and penetrating the system, the topological and structural characteristics of the water transmission network, conditions of the soil and ground in which the system is embedded, and the probabilistic nature of the location, frequency, and magnitude of future earthquakes. The Monte Carlo technique was used to simulate a sample of damaged states of the transmission network. The Newton-Raphson method was then used to analyze each of these damaged states of the network for its flow characteristics. The result of this analysis determines whether or not the network remains serviceable under each simulated state of damage and hence leads to a Monte Carlo estimation of the probability of system serviceability. The system was judged to be serviceable as long as both the flow rates and water heads at prescribed demand nodes remained above certain minimum levels after an earthquake in order to fight possible post-earthquake fires. Finally, procedures were established for optimizing the design of new networks as well as for the optimum improvement of existing systems on the basis of seismic risk and cost-effectiveness considerations.

Dealing with the telecommunications system that extends over the area around Sendai City, Japan (Fig. 1), Miwa and Okumura (Ref. 4) performed a reliability analysis by means of the Monte Carlo simulation method. This area experienced strong ground shaking resulting from the 1978 Off-Miyagi-Ken earthquake. The analysis estimated the probabilities of connectivity between any pair of nodes to remain intact during and after an earthquake of intensity V (in the Japanese Meteorological Agency scale), which is approximately equivalent to an earthquake of intensity VIII in the Modified Mercalli Intensity (MMI) scale. The result of this analysis is shown in Table 1 in the form of a (symmetric) matrix whose i-j element indicates the probability that nodes i and j will remain connective during and after an earthquake of intensity V.

It appears, however, that the analysis in Ref. 4 did not take into consideration the possibility of nodal failure. Since all the nodes in Fig. 1, except for nodes 13 and 14, represent telephone offices, although of various kinds within the hierarchy (RC, EO, TP, TC), the analysis would have been more realistic if the probabilities of nodal failure had been incorporated into the Monte Carlo simulation. Such probabilities of nodal failure can be obtained by performing such analyses as those examplified by Isenberg (Ref. 1). In their concluding remarks in Ref. 4, Miwa and Okumura emphasized the importance of systematic collection of field data in order to determine, with more confidence, the reliability values of cables in various protective modes (see the legend in Fig. 1) under prescribed soil and seismic intensity conditions. To this, the present authors could not agree more, since it is these reli-

ability values that are used as input data for the Monte Carlo analysis.

FAST Code

Connectivity probabilities are being estimated by the present authors for typical urban telecommunications systems with the aid of the code known as Fast (Failure Analysis using Statistical Techniques) (Ref. 13). The code is powerful and flexible, permitting the user to exercise great latitude in the formulation of the input data, which consist of (i) environmental conditions (soil conditions, earthquake intensity, etc.), (ii) transfer functions, (iii) component fragilities, and (iv) network topology. The code utilizes a Monte Carlo computational scheme to evaluate the survival probabilities of components and then the network itself. The results are presented in the form of histograms and of tabulations of cumulative probabilities of survival with confidence estimates. Furthermore, the code is divided into two computational-loops to accommodate the systematic as well as random uncertainties involved primarily in the input data.

The environment, transfer functions, and component fragilities can all be modeled to account for systematic and random uncertainties. The transfer function specifies a transformation between the free field response and the component response. This component response determines the components' probability of survival through the corresponding fragility curve, where the input to the abcissa (component response) yields a failure probability on the ordinate. The outer (systematic) and inner (random)-loop algorithm proceeds in the following way. The first stage, accomplished in an outer-loop of the code, selects bias values from the systematic variation distributions for the environment, fragilities, and transfer functions. The systematic information thus defined is passed to the inner-loop where the second stage of the sampling process is accomplished. Values are selected from the random variation distributions for the environments and transfer functions. After completing this selection, the response parameter is input to the fragility curve to obtain the component probability of failure. Next, all the component probabilities of failure are combined using network probability relations to obtain sub-system and system probabilities of failure. The inner-loop is repeated until the sample size or convergence criteria are satisfied and the process is repeated for many outer-loop iterations until the outer-loop sample size criteria are satisfied.

The environmental input format needed some modification since the current application of FAST is for earthquake responses rather than for responses under explosive ground motion conditions as it was originally intended for. However, more substantive revisions on the original FAST are being implemented. They consist of (1) the original FAST can only be used for a network topology reducible to a combination of parallel and series components. Under the revision, the original FAST will be used on the parallel system of proper tie-sets of the network, and therefore the revised version can be applied to any network topology; (2) The original FAST does not recognize the effect of the length of each physical component (branch) on its survival probability. The

revised version considers such an effect; (3) The original FAST does not consider the possibility of nodal failure (e.g., failure of a telephone office). The revised version will incorporate the failure probabilities of the nodes in order to reflect such possibilities in the analysis.

In order to complete such revisions, field data must be more carefully examined so that the failure probability of a cable per unit length is documented, and more research must be carried out to develop techniques for estimating the probability of a nodal (telephone office) failure, particularly that of a functional failure resulting from equipment malfunction due to earthquake effects.

CONCLUDING REMARKS

The current understanding of the seismic performance of telecommunications networks is briefly reviewed. Previous work pertaining to the seismic risk of telecommunications network systems is also reviewed. The use of a revised version of the FAST code has been suggested for the risk analysis with the contents of the revision being delineated.

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Table 1 Connectivity Between Nodes (Ref. 4)

	1	2	3	4	5	6	7	8	9	10	11	12	(13)	(14)
1	1,000	998	856	734	554	745	738	737	737	729	584	870	870	874
2		1,000	858	736	556	743	736	735	735	727	582	868	868	872
3			1,000	850	653	644	537	636	636	631	402	742	742	744
4				1,000	762	556	550	549	549	546	417	632	632	634
5					1,000	408	404	402	402	399	309	476	476	478
6						1,000	991	984	984	974	434	650	650	654
7							1,000	979	979	969	430	645	645	649
8								1,000	1,000	990	430	642	642	646
9				sym					1,000	990	430	642	642	646
10										1,000	426	634	634	630
11											1,000	664	666	664
12												1,000	997	996
(13)													1,000	995
(14)														1,000

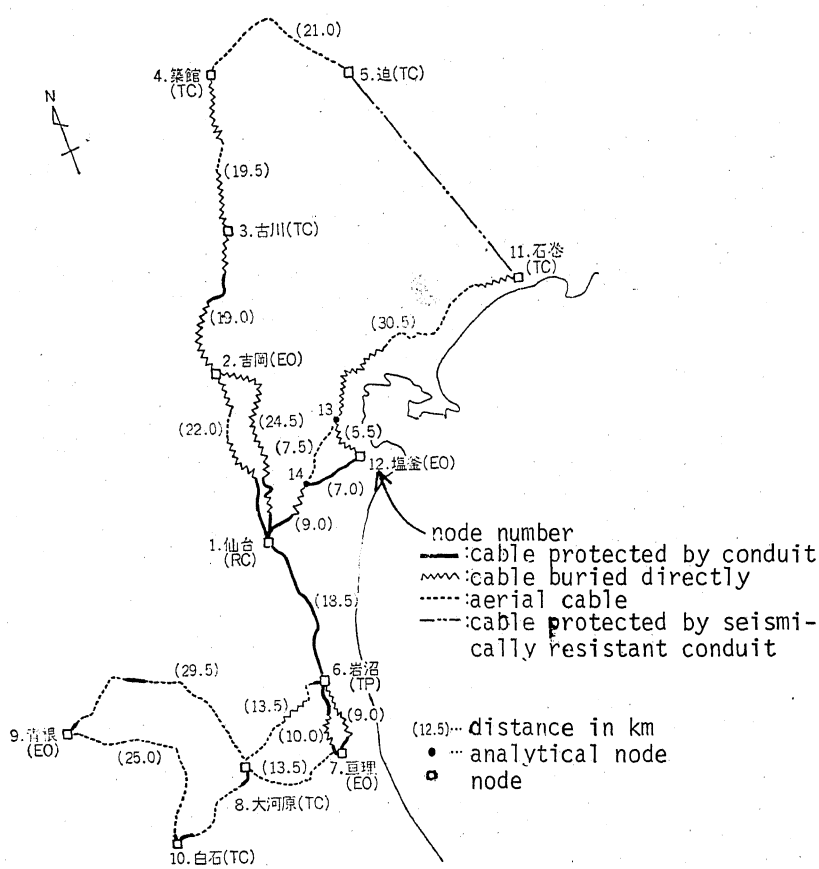

Fig. 1 Telecommunications Network Analyzed (Ref. 4)