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# SEISMIC BEHAVIOR STUDY OF LIFELINES IN THE OCCIDENTAL REGION OF MEXICO

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## SUMMARY

In this work a study of the seismic behavior of lifelines in the Occidental region of Mexico is presented. Lifelines are those systems necessary for the functioning of an industrialized society as well as for the emergency response and recovery after a natural disaster. In recent years, strong earthquakes have struck the Mexican Pacific coast, causing severe damages in lifelines. This Region is located in a zone with a high seismic activity, where at least nine major earthquakes have been recorded. In this paper the results of the analysis of lifeline damage due to the last major earthquake (Tecoman, 2003) is presented, identifying and clasifying the most common damages, as well as identifying the main and secondary effects of these damages and the most affected lifelines. The paper also analyses and compares the Manzanillo and Tecoman seismic records and their response spectra. Furthermore, a comparison between the response spectra with the obtained design spectra as per seismic design recommendations is presented. In order to carry out this study, a team of the IIE visited the disaster area, collecting damage information of the main lifelines. In view of the extensive damage of these earthquakes, Mexican authorities are interested in further developing seismic risk studies in order to improve the seismic performance of lifeline infrastructure in the future.

## INTRODUCTION

Mexico is located in one of the seismic most active regions of the world, which is the result of the Cocos tectonic plate subducting beneath the North American plate. Such subduction in the Pacific coastal region is usually the cause of large destructive earthquakes in Mexico (Figure 1), including the great Mexican Earthquake of 1985. The subduction region extends along the Pacific coastline from the South of the State of Jalisco to the southern end of Mexico, past the states of Michoacan, Guerrero, and Oaxaca including the Isthmus of Tehuantepec.

Last decade two major earthquakes have struck the Colima coast causing serious damage. On January 21, 2003 an earthquake of magnitude 7.6 in the Richter scale occurred on the Pacific coast, and was felt in other parts of Mexico as well [1]. Its epicenter was located near the state of Colima (18.84N 103.82W), where previously (October 9, 1995, 09:35 AM) another earthquake of magnitude 8.0 had occurred

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(epicenter 18.79N 104.47W) [2]. Both earthquakes caused important damage in urban infrastructure as well as in lifelines. The damage was extensive in power, water, and highway systems due to their high vulnerability. Lifelines are of major concern due to their economic impact and will be discussed in this paper, as well as proposed changes in current design practice in Mexico to mitigate earthquake effects.

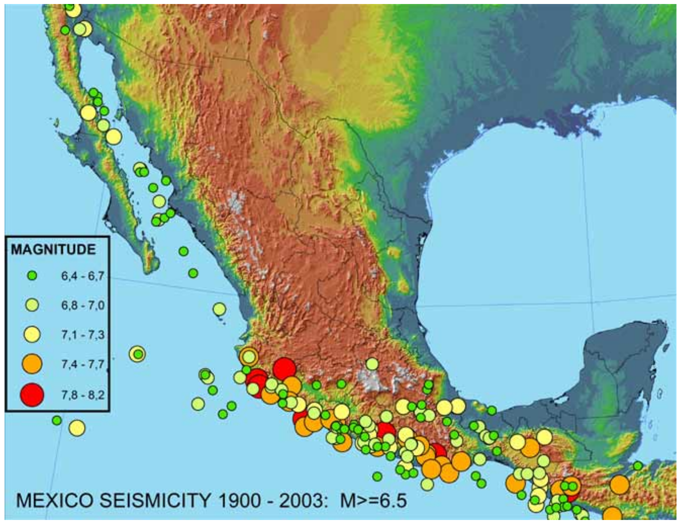


**Figure 1**. Seismicity for Mexico, 1900 – 2003: M>= 6.5 was created by using the Geographical Information System ARCGIS with the seismic database of National Seismological Service [1].

## THE COLIMA EARTHQUAKES

The Manzanillo and Tecoman earthquake were both superficial. The 1995 earthquake had an origin located at a depth of 33 km, whereas the 2003 one was 10 km deep. After the main event, in both cases aftershocks of magnitudes as high as 5.8 were felt, causing concern in the nearby areas. Both earthquakes were felt in the states of Jalisco, Nayarit, Michoacán, Guerrero, Zacatecas, Hidalgo, Colima, Querétaro, Morelos, Puebla, Tlaxcala, Guanajuato and in Mexico City (495 km from the epicenter), where several buildings were reported as damaged. However, the majority of the damages were concentrated in nearby towns and cities such as Manzanillo and the state capital, Colima (Figures 2A and 2B).

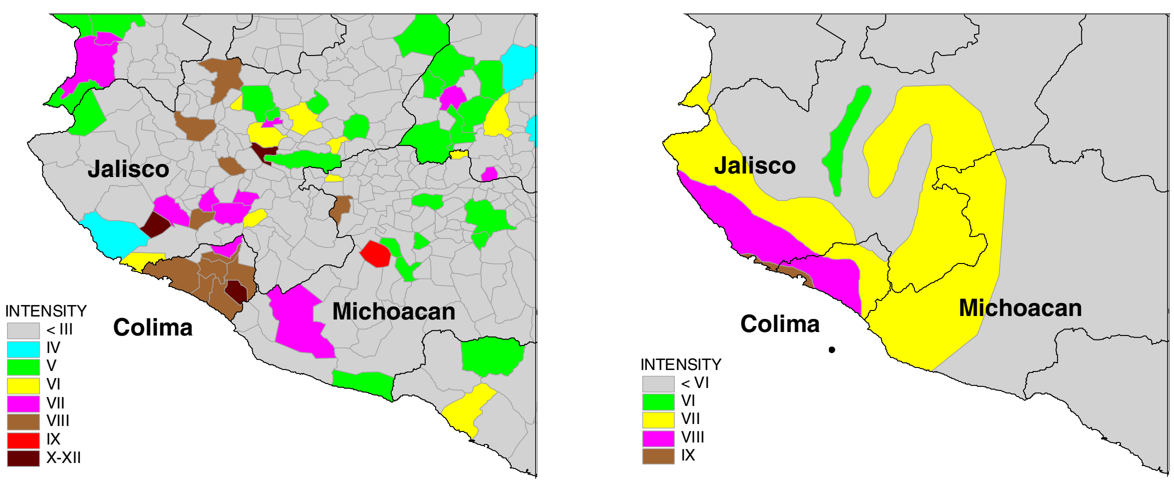


**Figure 2**. The earthquakes were felt in several region of Mexico as shown in these intensity maps. A) Manzanillo Earthquake October 19, 1995 [3] and B) Tecoman Earthquake January 21, 2003 [1].

## DAMAGE IN LIFELINES

### Electric power system in Colima

Figure 3 shows the location of all the substations of different voltages, that CFE (Federal Commission of Electricity) operates in the state of Colima (11 in total) [4]. Four of these substations were inspected after the 1995 and the 2003 earthquakes, namely: Manzanillo I-II, Colomo, Tapeixtles and Colima II.

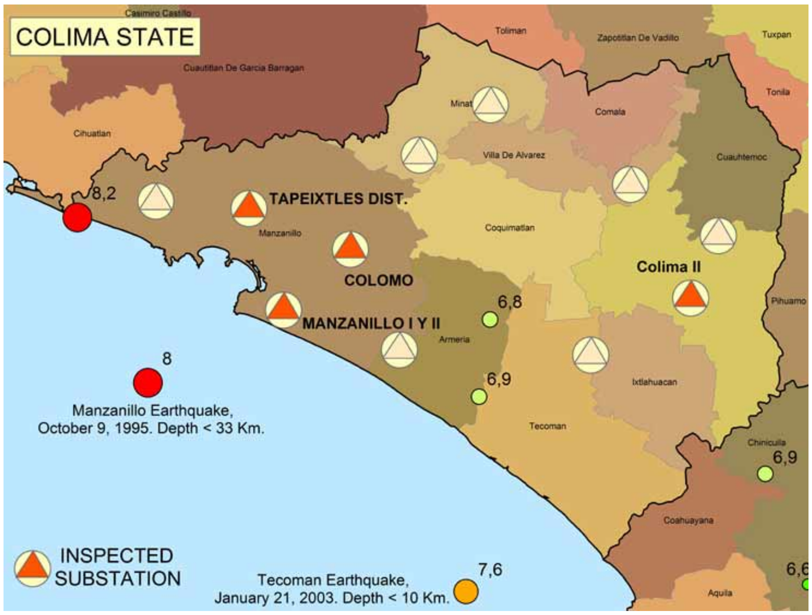


**Figure 3**. Two major earthquake have struck the Colima Cost in last decade.

*System performance and damage*

Power system performance, as measured by the extent and duration of power disruptions, was relatively good. Shortly after the earthquake occurred (20:06:36 Mexican central time), power was disrupted over a broad area including Manzanillo and extending to the state capital, Colima. While there is no information on when the substation buses were re-energized, there are reports indicating that the power was restored between 1 and 8 AM, although there were frequent disruptions of varying length. Undoubtedly many small areas were disrupted by damage in the distribution system from fallen distribution transformers or the collapse of adobe houses that also damaged power distribution lines. Extensive damage was inflicted by the earthquake in the Manzanillo I-II transmission substation and there are reports from the CFE that this substation was not put back in operation for at least three weeks after the earthquakes at a considerable cost.

While power was restored quickly, the system did experience significant equipment damage in the generating station switchyard, lesser damage at two 400 kV substations, at two 230 kV and one 115 kV distribution substations. Severe damage was inflicted by the earthquake to Potential transformers, Circuit breakers, Transformer bushings and other installations like Control houses in the substations. Manzanillo I-II and Colima II were the substations that suffered the most important damage.

Figure 4 depicts the collapse of two 400 kV Potential transformers in the Manzanillo I-II substation. As can be seen, transformers are mounted on single concrete columns (as high as 3 m tall) with an enlarged upper end; this, coupled with the geometric characteristics of the equipment and the fact that they are of porcelain material, makes them very vulnerable to earthquakes, becoming very unstable due to ground motion.

**Figure 4**. Partial view of damage in the Manzanillo I and II substation during the Tecoman earthquake.

Figures 5 and 6 show failure of several circuit breakers due to the Tecoman earthquake. As shown in the first of these figures (see Figure 5a), circuit breakers were installed on a steel frame, about 1.5 m high and 4 m long. It can be seen in Figure 5b, that these circuit breakers had an original "T" shape, made up by a group of 4 porcelain vertical elements and another 4 horizontal elements of the same material.

Another type of arrangement is shown in Figure 6; here each circuit breaker rested on a steel tripod base (see Figure 6a). This type of arrangement did not behave any better than the one just described, and most of them collapsed. This type of failure was observed on the 1995 Manzanillo earthquake (Figure 6b), thus it is apparent that such arrangements for this type of equipment is highly vulnerable to the earthquake action.

**Figures 5**. A) Circuit breaker collapsed ; B) Original set up of circuit breakers (far end)

**Figure 6**. Circuit breakers on isolated supports. A) 2003 earthquake B) 1995 earthquake

It is worth noting that after the failure of circuit breakers during the 1995 earthquake, CFE installed damping devices of the type shown in Figure 7, in many such pieces of equipment for several of the Manzanillo area substations. Most of the circuit breakers with such protection behaved well and survived the 2003 earthquake, as can be seen in Figures. 5b (near end) and 7. These pictures were taken after the January Tecoman earthquake.

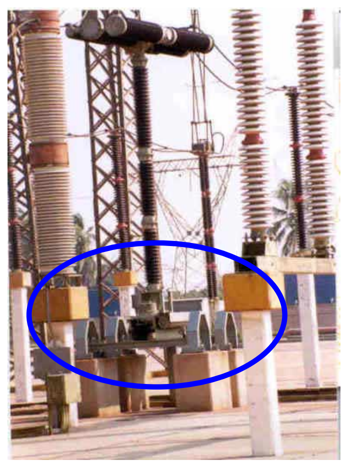

**Figure 7**. Circuit breaker with damping devices in  the Manzanillo I-II substation

*Earthquake Performance of Power Transformers*

Power transformers are one of the most critical items within a substation, because they cannot be bypassed to restore service, as can be done with most other substation equipment. There are five known features associated with power transformers that are related to their earthquake performance. These features are: a) Transformer anchorage,  b) Bushing  mounting configuration,  c) Bushing design, d) Conductor configuration and connection to bushings and e) Installation of surge arresters. In the course of the visits following the 2003 Tecoman earthquake, several power transformers were inspected including those at the power plant substation switchyard and those at the other substations visited. Several bushings of the transformers suffered damage and even collapsed, however, the transformers did not suffer damage.

**Water system in Colima**

Large urban water systems normally include a source, treatment, storage (reservoirs and tanks), and distribution. Following the 2003 Tecoman earthquake the Water National Commission (CNA) reported damage in both the storage and distribution systems. The Trojes (Figures 8A and 8B) and Basilio Badillo reservoirs suffered a slight damage, however none of these turned out to be in a danger situation and continued working normaly. Both reservoirs are used to supply the potable water to some towns of the region as well as for irrigation purposes.

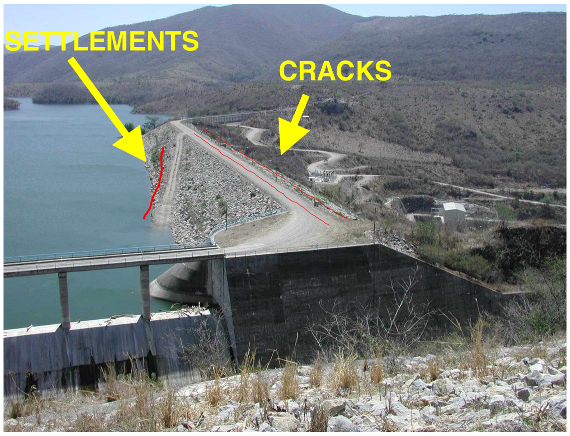

**Figure 8**. Trojes reservoir. A) An important cracks appeared in the top of gravity dam. B) The auxiliary road had a settlements of several centimeters.

Nevertheless, the earthquake inflicted extensive damage to eight water aqueducts. The bulk of the observed aqueducts damage was due to soil compaction at stream crossings (See Figure 9). The aqueducts' damage cut off the water supply to the region's populations. The repair time of all aqueducts to supply potable water to all towns which had such service before the earthquake was approximately a month and the cost of the repair work was more than 600,000.00 USD.


**Figure 9**. Extensive damage of aqueducts lines. The damage cut off the towns water supply.

**Bridges and Roads**

Bridges are very important elements in the modern transportation systems, and they are prone to suffer damage due to earthquakes. The damage induced in bridges can take many forms, depending on the ground motion, site conditions, structutal configuration, and specific details of the bridge. The Communications and Transports Secretary of Mexico (SCT) reported that several bridges suffered slight to moderate damage due the Tecoman earthquake. The Coahuayana bridge suffered an important damage, which cost of restoration ammounted to close to 700,000.00 USD. The slopes of Jiquilpa bridge had a settlement of 10 cm approximately. It was reported also that the bridges' columns had substantial movements, causing the total destruction of seismic stops on several bearings. Another kind of bridge damage was due the collision of bridge decks and lateral displacement between two decks (Figures 10 and 11). In spite of bridges' damage, all of them continued working normally.

**Figure 10**. Damage due to collision of bridge deck and the embankment.

**Figure 11**. Damage in the limit stops due to lateral displacement.

On the other hand, landslides triggered by the Tecoman earthquake were observed (Figure 12). This landslides obstructed the vehicular traffic during several hours. The most important landslide was on the Colima – Manzanillo highway with a cut of 18,000 $m^3$ of material closing the traffic temporarily. The total cost of cleaning and restoration was close to 900,000.00 USD.

**Figure 12**. Landslides on a federal road due the Tecoman earthquake.

## COMPARISON OF SEISMIC RECORDS FROM BOTH COLIMA EARTHQUAKES

Important seismic information has been gathered in the last 10 years mainly due to 7 instruments installed in the region, as part of the Seismic Monitoring Program on Large Industrial Plants in the Pacific Coast, implemented in Manzanillo by CFE and EPRI. In the case of the two Colima earthquakes, the closest accelerograph to the epicenters at ground level was the free field station in the Manzanillo Power Station.

Probably the most severe earthquake thus far registered is the one of October 1995. The maximum accelerations registered were 0.394 g (N-S direction) and 0.395 g (E-W direction) and 0.309 g (vertical direction). The duration of the earthquake was of some 150 sec. Figure 13 shows the first 100 sec. The destructive power of this earthquake was evidenced by the damage inflicted in the region, especially in the Manzanillo Power Station, which included substation equipment failures, damage to the intake, liquefaction affecting turbogenerator pedestals and other foundations, as well as severe damage to secondary structures in the plant. The January 2003 earthquake had a duration of 90 sec, and the maximum accelerations were registered by the same accelerograph in the Manzanillo Power Station as 0.378 g (N-S), 0.266 g (E-W) and 0.192 g (vertical) as shown in Figure 14.

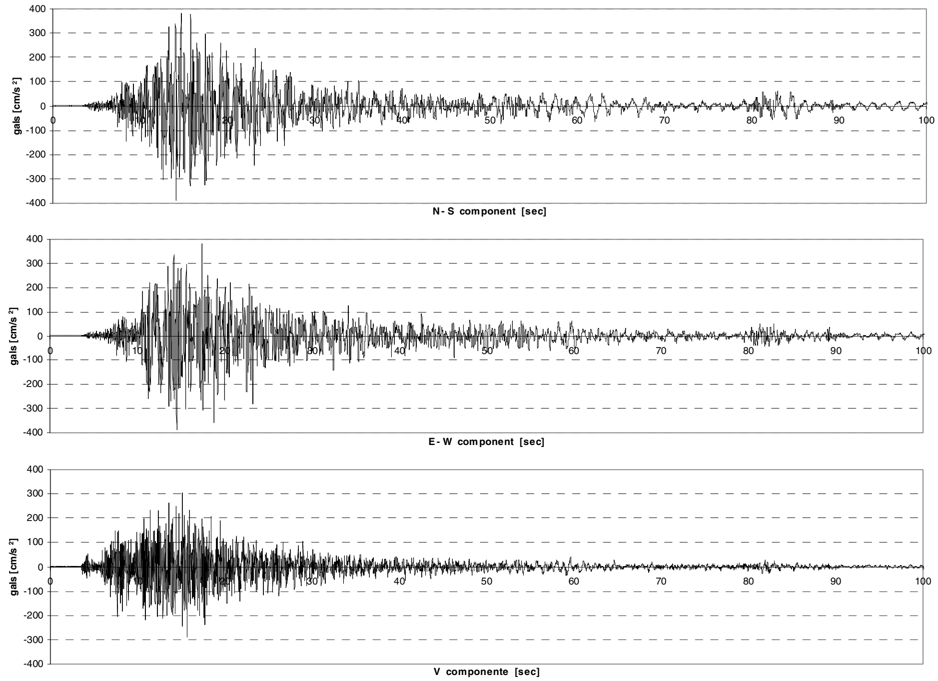


**Figure 13**. Acceleration components during the 1995 Manzanillo earthquake.

A comparison of these records shows that although the maximum accelerations registered for both events were almost the same, the other two components of the acceleration were substantially larger for the 1995 earthquake. With a larger energy liberated (8.0 vs 7.6 magnitudes) and a longer duration of the movement, this earthquake had a much larger destruction power.

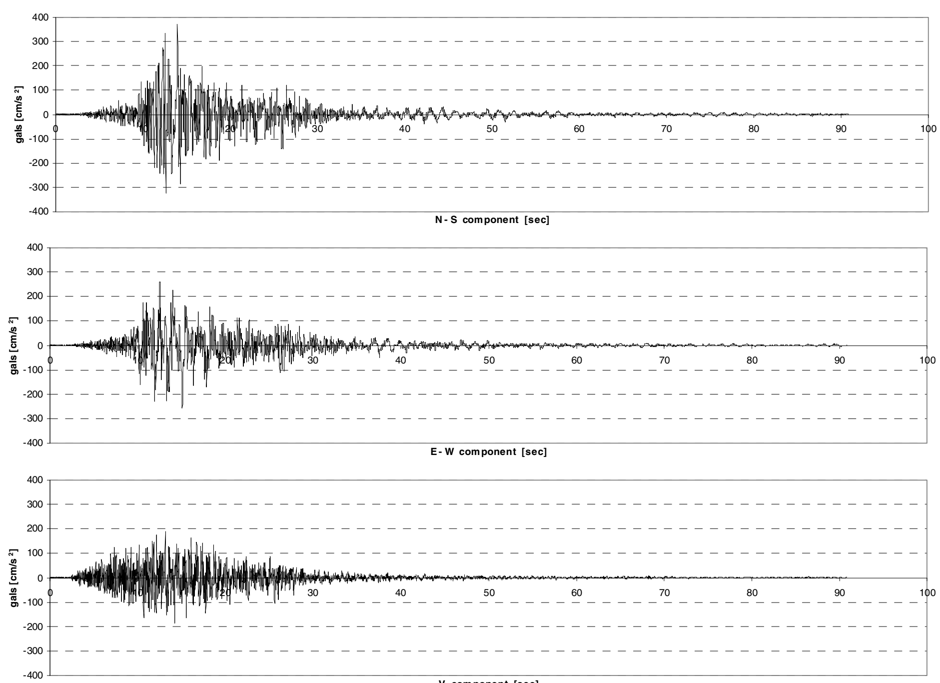


**Figure 14**. Acceleration components during the 2003 Tecoman earthquake.

Furthermore, response spectra for both earthquakes were obtained. In Figure 15, response spectra for the 1995 event for 5% damping and for soft soil are shown. Maximum values of 1.83 g (N-S), 1.68 g (E-W) and 1.15 g (vertical) of spectral ordinates were obtained, corresponding to periods of 0.23 s, 0.23 s and 0.12 s, respectively. Figure 16 shows the response spectra for the 2003 earthquake, also for a damping factor of 5%. In this case the maximum values calculated are 1.52 g (N-S), 0.85 g (E-W) and 0.67 g (vertical), for periods of 0.13, 0.15 and 0.05 respectively. A comparison between Figures 15 and 16 shows that although there are significant differences between response spectra from both earthquakes, maximum values occur for periods between 0.1 g and 0.3 g, where substation equipment is vulnerable.

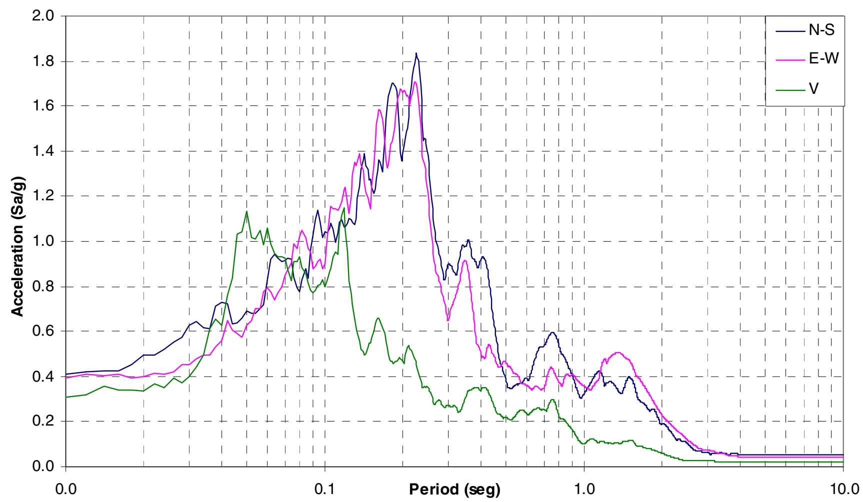


**Figure 15**. Site response spectra (5% damping) for the 1995 Manzanillo earthquake

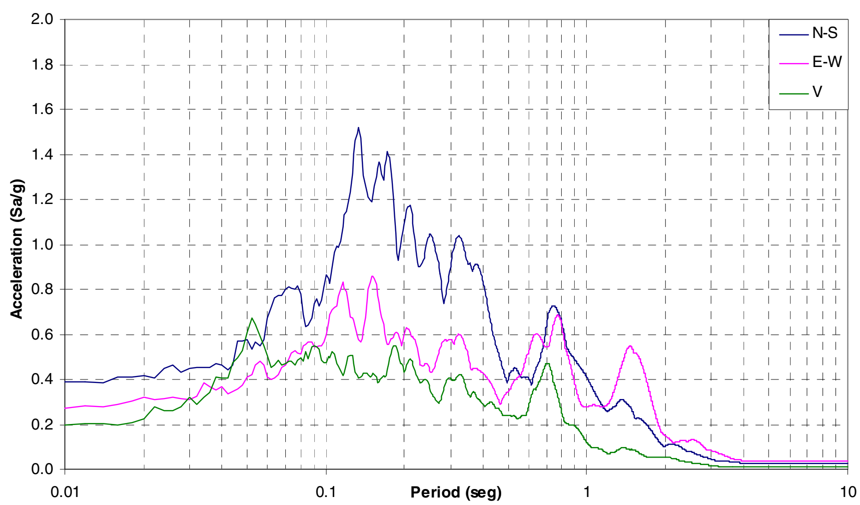


**Figure 16**. Site response spectra (5% damping) for the 2003 Tecoman earthquake.

Figure 17 presents a comparison of the response spectra from both Colima earthquakes (N-S component), with the design spectra obtained as per the Seismic Design Manual of the Handbook of Civil Works of CFE [5] and IEEE-693 Recommended Practice for Seismic Design of Substations [6].

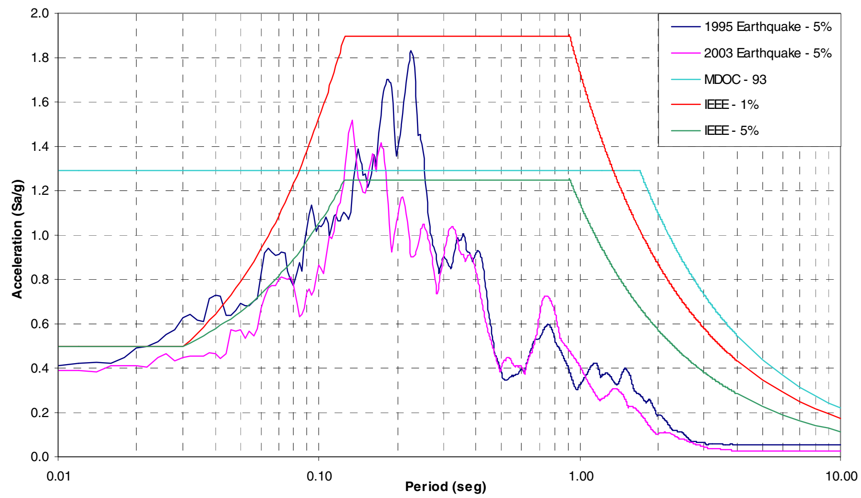


**Figure 17**. Comparison of the 1995 and 2003 earthquake response spectra with design spectra from recommended design manuals

As Figure 17 shows, the response spectra for both earthquakes are considerably larger than the design spectra obtained from the Mexican seismic design standard as well as the design spectra defined by the IEEE-693 document. This clearly shows that equipment was under designed in view of those documents. It should be noted that if the IEEE-693 design guidelines are used, considering a damping factor of 1% (see Figure 17), the design spectra obtained would envelope both Colima earthquake response spectra. However, it is not customary in practice to use design spectra for such low damping value.

## PROPOSED MODIFICATIONS TO CURRENT DESIGN PRACTICE

The Electrical Research Institute of Mexico (IIE) has been responsible for the development and edition of the Seismic Design Manual of the Handbook of Civil Works of CFE. A proposal of revision of this document is already underway, and some major changes will be introduced in view of recent experiences, such as the one reported in the previous section. These changes are outlined next.

- A new procedure to obtain the soil foundation characterization in terms of parameters that better represent the most relevant dynamic characteristics of subsoil, such as the vibration period and the effective propagation velocity of a site will be introduced.

- Seismic microzonification will be updated for soil classification, as a function of soil amplification properties.

- Seismic risk maps will be updated in view of recent engineering and seismological studies. Experience accumulated during the last 12 years in these disciplines will be included in the new recommended practice document.

- A continuous seismic zoning of Mexico will be developed, that will allow engineers to obtain a particular value of seismic risk directly, as a function of maximum ground acceleration and spectral ordinates for return periods of 100, 200 and 500 years.

- A revision of the procedure for obtaining response spectra based on the newly developed seismic risk maps and soil foundation classification will be made. These response spectra will not include reduction factors (transparent response spectra) thus representing actual seismic risk for elastic structures. These spectra could in turn be explicitly reduced to account for ductile behavior as well as inelastic behavior. These factors will be defined accordingly.

- Soil structure interaction effects will be revised, and new procedures for evaluating these effects will be included.

- New criteria for reclassification of structures will be presented, for conventional and industrial buildings. The new classification of structures will consider an actual group for structural systems as well as the importance of the construction.

- New structural analysis methods will be considered and the feasibility of using non-linear analysis will be included.

- In particular, with regards to electrical substations, appropriate seismic classification will be presented for all the electrical equipments used as well as methods for the seismic verification of such equipments.

## CONCLUSIONS

During the visit to substations after the 2003 Tecoman earthquake, it was found that damage was as extensive as the one observed after the 1995 strong motion, in spite of the fact that the epicenter was farther away and the earthquake originated at a deeper location. There is enough evidence that the lifelines are very vulnerable to earthquakes, particularly the power system. In this case, the earthquake damage was concentrated in the substation electrical equipment, like circuit breakers, surge arresters and bushings also sustained a great deal of damage, thus research to study the behavior of these pieces of equipment is mandatory. In addition, a thorough research program should be implemented for the installation of damping devices in electrical substation equipment, in view of the good behavior of such devices in the 2003 Tecoman earthquake. It is likely that the damage of electrical equipment in the Manzanillo I-II substation was originated by soil amplification. This was observed in both Manzanillo’s earthquakes. Thus, microzonification studies of the area are required.

In spite of earthquake damage in other lifelines, none of these generally turned out to be in a danger situation and continued working normally. That was the case of the roads’ systems and the reservoirs.

The response spectra of both earthquakes present maximum spectral accelerations for periods between 0.1 and 0.3 s, thus electrical equipment design must take this characteristic into consideration.

It is mandatory to review and update the Mexican earthquake engineering standards and attention should be given to substation electrical equipment.

## ACKNOWLEDGMENTS

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