7 ANALOG EARTHQUAKES

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7.1 ABSTRACT

Analogs are used to understand complex or poorly understood phenomena for which little data may be available at the actual repository site. Earthquakes are complex phenomena, and they can have a large number of effects on the natural system as well as on engineered structures. Instrumental data close to the source of large earthquakes is rarely obtained. These rare events for which measurements are available may be used, with modifications, as analogs for potential large earthquakes at sites where no earthquake data are available. In the following, several examples of nuclear reactor and liquified natural gas facility siting are discussed. A potential use of analog earthquakes is proposed for a high level nuclear waste repository.

7.2 THE CONCEPT

The use of analogs is the first stage toward a better understanding of complex phenomena. Analogs are used to predict future happenings when too little is known about the phenomena being predicted or when theories are not completely accepted. Analogs may be used to add credibility to a theoretically derived prediction. A characteristic of an analog is the lack of a mathematically described variability. Often there is only one analog to an anticipated event or condition, and it is not likely to be a perfect match.

Among dictionary definitions, an analog is: something that is similar to something else. Definition of the word "analogy" yields further insight, e.g.: if something is similar to something else in some respect, it is likely to be similar in others. That the words "initial" or "all" did not appear in any definition encountered, is notable. An analog may be a model as inferred by the definition of "model" in Bates and Jackson (1980), "A working hypothesis or precise simulation, by means of description, statistical data, or analogy, of a phenomena or process that cannot be observed directly or that is difficult to observe directly."

Geological phenomena are generally observable only at the surface of the earth or in a one dimensional bore through the earth's surface to a limited depth. However, a more complete understanding of a particular geologic feature may be obtained in regions of great topographic relief or in regions where geologic features have been turned on their side, and erosion has produced a natural cross section. Limited exposures of a geologic feature, that are similar to a feature of one of these relatively rare natural cross sections, may be used to infer that which cannot be seen. On-going depositional processes produce features reminiscent of those seen in sedimentary rocks. Therefore, by analogy, these processes are presumed to have occurred in the past. Alteration products of active hydrothermal regions, likewise, by analogy, are used to infer the cause of alteration products in geology elsewhere.

That earthquakes are observed to accompany fault movements implies that fault offsets observed elsewhere were also likely to have been accompanied by earthquakes. Instrumental recordings of earthquakes accompanying certain types of faulting at specific distances, by analogy, are attributed to earthquakes which have a similar origin but for which no instrumental recordings are available.

Much of the subject of geology has its origins in analogs which were often referenced, although not necessarily with the word "analog", by early writers such as Hutton (1795). In a sense, all of geology is based upon analogs.

A past recorded earthquake whose characteristics or effects are sufficiently similar to those expected at a new facility site may be used to predict design loads or the consequences of potential structural degradation. Ideally, a strong motion record to be used as an analog should have been recorded from an earthquake having similar characteristics as that expected at the new site, e.g. :

- nature of the fault and the dynamics of its movement
- distance from fault to facility
- nature of the tectonic stress field and stress drop during an earthquake
- fault orientation to the facility and stress field, (Rogers et al., 1977; Boatwright and Boore, 1982)
- earthquake magnitude
- path geology
- depth of earthquake focus and depth of facility
- fault parameters, e.g., length, width, and offset
- location, number, and size of asperaties or barriers

Usually, not all variables will be identical or available. Consequently, modifications, based on other incompletely analogous earthquakes, will be required.

Predictions of earthquake ground motion are based upon:

- direct analogs
- interpolation or extrapolation from near or partial analogs
- formulae or computer codes which reproduced ground motion of analogous or nearly-analogous earthquakes.

7.3 SOME EXAMPLES

Example 1: The Diablo Canyon Nuclear Power Plant.

In the initial license application, a magnitude 6.75 aftershock was proposed at a 6 to 12 mile depth, caused by a magnitude 8+ main shock on the San Andreas fault about 40 miles distant. The assignment was made largely on the supposition of an unknown but possible fault at depth. Also, a magnitude 7.25 on the Naciemento fault, about 20 miles distant was proposed. This earthquake was a scaled up analog to the magnitude 6.3 Long Beach earthquake. Modified Mercalli Intensities of damage were documented for the 1933 earthquake. An equivalence between Modified Mercalli Intensities and peak ground acceleration compiled from many earthquakes provided a design basis.

Later, an offshore fault, the Hosgri fault, was determined to be of licensing significance. A magnitude 7.3 offshore earthquake in 1927 had caused rock slides, sand boils, water spurts, a tsunami of six feet and some fallen chimneys in the vicinity of Lompoc, California (Coffman and von Hake, 1973). The U.S. Geological Survey (USGS) and the Nuclear Regulatory Commission (NRC) concluded that there was sufficient uncertainty in the location of this earthquake 60 km offshore that it was possible that this earthquake might have occurred on the Hosgri fault.

The Lompoc earthquake, therefore, became an analog for a 7.5 magnitude earthquake located offshore, five miles from the plant. There were no strong motion records for the Lompoc earthquake or from any other earthquake of this magnitude at this distance. Considerable effort was expended in extrapolating the effects of other earthquakes to this magnitude and distance. Dr. Robert Page of the USGS applied prior research on the number of cycles of strong motion at various levels for the Alaskan pipeline to this site. Dr. Nathan Newmark, consultant to the NRC, interpreted Dr. Page's information in terms of design criteria. Again, the analog earthquake was based on a past earthquake on what might have been a similar fault. The analogy was imperfect, however, because all desired data concerning the analog was not available. Consequently, extrapolations from the data of other imperfectly analogous earthquakes were employed to complete the necessary design criteria.

Continued research on this project has resulted in additional proposals including earthquake source computer modeling to obtain or confirm adequacy of design criteria.

Example 2: NRC Task Action Plan A46 regarding the seismic qualification of nuclear power plant components for old plants.

The requirement for seismic qualification of some components was imposed after construction of the plants. These components had been used in conventional fossil fuel power plants throughout the world. Studies by the Brookhaven, Lawrence Livermore, and Sandia National Laboratories, Southwest Research Institute (SwRI), EQE Inc., and others documented that many of these plants had been subjected to earthquake shaking and that the components had not failed (Yanev, 1984; Smith and Dong, 1983; Chang, 1987; and Kana et al., 1983). The magnitudes and distances of the earthquakes to the plants, and some records, were available. These earthquakes became analogs for seismic shaking table input and, in turn, verified that the test shaking levels were analogous to real earthquake ground motion.

This example differs from the previous ones and suggests a somewhat different use of analogs. It is to directly support the performance of structural or mechanical elements by using analog exposures to vibratory ground motion without the use of an intermediate approximate relationship or model.

This type of procedure eliminates the necessity of constructing approximate models of earthquake shaking, e.g. peak acceleration as a function of distance and magnitude and appropriate spectral envelopes for test shaking or accepting a white-noise spectral shape for such test shaking. The method depends upon many analogs. Therefore, a statistical distribution of parameters may be possible which might add credibility to the result. A possible negative aspect is that the details of the analogs may not be well investigated and compared to the site or sites in question. The question of whether foundation types, fault types, stress drops, etc. are similar to the site in question may not be possible to answer or may be largely ignored.

Example 3: The planned Grassy Point, British Columbia, liquified natural gas compression and storage facilities, and seaport.

This planned facility was located 90 km east of the offshore Queen Charlotte fault. The Queen Charlotte fault is a strike slip fault which is analogous to the San Andreas fault in California. Both faults have experienced magnitude (M_s) 8+ earthquakes. There were no strong motion records from magnitude 8+ earthquakes. The location of the facility and the Queen Charlotte fault are in sparsely populated areas. Consequently, reliable Modified Mercalli Intensities of damage were also not available. The San Andreas $M = 8+$ earthquakes, however, had well documented damage intensities at distances of 90 km from the fault. Further, there was a strong motion record closer than 90 km to a $M = 7.7$ earthquake on the White Wolf fault near Bakersfield, California. An examination of seismic source theory indicated that for frequencies of vibration that could affect the facility, the vibrations of a magnitude 7.7 earthquake would be similar in amplitude to those of magnitude 8+. Therefore, the $M = 7.7$ Kern County (also known as the Arvin Tehachapi) earthquake of 1952 could be used as an analog to predict ground motion at the Grassy Point facility. The shaking recorded for the Kern County earthquake was scaled down to represent the greater distance. With modification, the Kern County earthquake strong motion record became an analog for a larger more distant earthquake on the Queen Charlotte fault. This value was checked against a correlation of Modified Mercalli Intensities for the $M = 8+$ earthquakes on the San Andreas fault in California (1872 and 1906) (Coffman and von Hake, 1973) and also against Canadian building code requirements. The analogs and the code requirements were in reasonable agreement (Hofmann, et al., 1982).

Example 4: The Gros Cacauna liquified natural gas receiving terminal in eastern Canada (Fenco Consultants Ltd., 1982).

The site was located in an area of past seismic activity where magnitudes had reached 7 or slightly higher. These earthquakes became analogs for an earthquake near the site. No strong motion records were available from these $M = 7$ earthquakes, however. Consequently, the record from the Kern County 1952 $M = 7.7$ (Coffman and von Hake, 1973) earthquake were slightly adjusted for distance and magnitude and used as design criteria for the facility.

7.4 LESSONS LEARNED

At times, only the occurrence of an analog earthquake is known and no strong motion records may have been available. The analogy is between the geologic conditions and the magnitude of the earthquake. Under these circumstances, a record is interpolated or extrapolated from other imperfectly analogous earthquakes or a record is derived from formulae or computer codes which were derived from the study of many earthquakes. It can be concluded that analogs of various types, some of them imperfect, are useful.

7.5 ANALOG EARTHQUAKES FOR A HIGH LEVEL NUCLEAR WASTE REPOSITORY

A number of variables affect earthquake shaking at a site. They can be categorized into source, path, site, and instrument variables. Source variables include those on the first page of this paper. Some of these variables also influence the displacement of faults possibly hidden at depth, that is inferred from the occurrence of an earthquake.

Path variables include:

- source to facility distance
- path geology
- effect of sedimentary wedges on surface waves (Herrmann, 1978)

Site and instrument effects include:

- depth of facility and depth of the strong motion instrument
- facility and instrument sites — foundation geology and geomechanics

Knowledge of all of these variables is not usually available or possible to obtain for either an anticipated earthquake near a site or for potential analog earthquakes to be used to predict effects at the site. Many of these variables are discussed by Hofmann (1991). This lack of knowledge may be translated into an expected variability in the effects at a site. Often there is insufficient information to determine the mathematical nature of this potential variability. It can be a limitation to the application of analogs if several of them are not available.

The qualities of an analog earthquake to be applied to any facility design should fulfill the following criteria:

- The analog should have occurred in an environment such that the effects to be predicted at the repository could have been observed.
- The analog earthquake should have occurred in a tectonic and geologic environment much like that of the repository.
- If the analog includes a strong motion seismic record, it should have been recorded at a depth and in material that are similar to that of the repository.

Vibratory ground motion effects which may be of concern to a deep repository are:

- Shaking of canisters in their boreholes causing stress cracks and accelerated corrosion
- Spalling of tunnel walls thereby enlarging the zone of higher permeability around tunnels and providing added avenues for groundwater or gaseous migration
- Shaking (or fault movement) may cause stress changes which squeeze groundwater from rock pores to higher elevations (Wood et al., 1985) which are closer or encompass formerly dry repository shafts, thereby providing faster radionuclide pathways to the biosphere.

Fault movement, which usually but not always causes earthquake shaking, may produce undesirable effects at a deep repository:

- Faults may move, increasing gouge thickness and decreasing permeability, thereby diverting groundwater from an aquifer to higher elevations and reducing the distance of radionuclide pathways to the biosphere.
- Faults or fault intersections may open, creating permeable pathways along which groundwater or gasses may migrate to the biosphere.
- Faults may intersect a waste package, thereby damaging this engineered barrier, causing leaks which, in turn, reduce the time of radionuclide migration out of the repository. Such faults may also provide a low permeability pathway directly from the waste to the surface or to moving groundwater which may carry radionuclides to the surface.

Finding analogs for all these effects is not likely. For those that can be found, very site specific characteristics may be needed to reduce uncertainties. Modification of analog observations may be necessary to better reproduce the desired conditions at the site. Modifications for ground motion may be accomplished by determining the desired maximum magnitude for the site and the potential source distance from the site. Ground motion amplitudes may then be adjusted using standard curves. Compensation for records of the analog being at the surface and the repository being at depth may be modified by computer modeling or by determining ground motion amplitude ratios from seismic recordings on the surface and at depth in mines. This would be another analog. Groundwater movement from strain changes might be determined from scaling of near-analog effects to the earthquake magnitude and groundwater table at the site. An alternative is finite element strain groundwater flow modeling.

7.6 POSSIBLE EXAMPLE ANALOG EARTHQUAKES FOR YUCCA MOUNTAIN

The likelihood of strong shaking at or near Yucca Mountain, Nevada, has been estimated, for example by Sommerville et al. (1987) and Rogers et al. (1977). Additional work performed may use other boundary conditions. Rogers et al. (1977) limit their hazard estimates to magnitude 7 or lower earthquakes. Sommerville et al. (1987) assigned maximum magnitude potentials to a number of faults in or near the Yucca Mountain site. The maximum magnitudes were about 7.4. Higher magnitudes on longer but more distant faults were also considered in their hazard estimations. The estimates in Table 3 of Sommerville et al. (1987) correlate $M_s = 7.4$ with fault lengths of about 53 to 57 kilometers in this region. The nearest fault of that length, in their study, was the Rock Valley fault, 20 km or more from the site. The largest fault closer to the site was the Paintbrush Canyon with a presumed maximum magnitude of 7. Further field work may disqualify the maximum magnitude for particular faults. As field work at Yucca Mountain progresses, other faults may be found to be near 57 km long.

Observations of the effects of the potential example analogs below may be adjusted if the desired magnitudes for faults at Yucca Mountain differ. These are possible examples of analog earthquakes for effects that may be possible at Yucca Mountain.

- 1983 Borah Peak, Idaho, $M_s = 7.3$
  - Occurred in an extensional environment on the border of the Basin and Range Province
  - Dip slip faulting
  - Occurred in carbonate rocks
  - Groundwater effects observed
  - Shallow groundwater table must be modified for the Yucca Mountain site.
- 1980 Vieste, Italy, $M = 6.5$
  - Occurred in an extensional environment
  - Dip slip faulting
  - Occurred in a tuff sequence
  - Groundwater effects observed
  - Shallow groundwater table must be modified for the Yucca Mountain site.

Near-field ground motion records were not available for the 1983 Borah Peak earthquake. Rovelli et al. (1988) summarize scaled accelerations for earthquakes from extensional areas in Italy. They do not verify theoretical results with an analog earthquake, suggesting that no suitable strong motion records are available. Another analog may be required for ground motion effects.

7.7 CONCLUSIONS

Although the entire complexity of earthquakes is seldom utilizable from analog earthquakes, they remain good examples of natural analogs and their limitations. Analogs are a first step in a better understanding of complex natural processes. Partial analogs are useful but modifications may be necessary to apply analogs in some, perhaps many, circumstances. Analogs do not usually include knowledge of potential variations in observations caused by the statistical or chaotic nature of the processes involved, or from overlooked, unknown, or ignored variables.

Analog earthquakes need not be perfect to be useful. Perfect analogs are seldom found. The depth for which strong motion information is desired may differ from the depth of a strong motion seismograph which has recorded an earthquake of the proper magnitude and distance. The media within or upon which information is desired may be different from that on which a strong motion seismograph is located. The type of fault movement causing the earthquake may differ from that expected at the site of interest. A large number of differences degrades the utility of an analog, but one or a few differences can sometimes be accommodated.

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