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Technical Letter
No. 1110-2-301

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Engineering and Design
INTERIM PROCEDURE FOR SPECIFYING EARTHQUAKE MOTIONS

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INTERIM PROCEDURE FOR SPECIFYING EARTHQUAKE MOTIONS

1. Purpose. This letter provides interim guidance on procedures to be used in specifying earthquake motions for design analyses of new civil works structures and in the assessment of existing civil works structures.

2. Applicability. This letter is applicable to all field operating activities having civil works responsibilities.

3. References. See Inclosure 3 for a list of references.

4. Background. ER 1110-2-1806 is currently being revised. As part of that revision, the technical guidance portions of the ER are being deleted; the ER will contain direction only. The necessary technical guidance on earthquake design and analysis will be provided in Engineer Manuals. During the period of preparation of these manuals, interim guidance will be provided by a series of Engineer Technical Letters. This ETL on specifying earthquake motions is the first of the series. Other topics to be discussed in subsequent ETLS include field investigations, laboratory testing, and analytic techniques for embankments, concrete dams and appurtenant structures.

5. Discussion. The interim guidance presented in this letter is contained in two Inclosures. Inclosure 1 is a list of definitions of terms used in the practice of engineering seismology. Some have slightly different meanings from agency to agency. The list is not complete but should serve to assure that the use of important terms is consistent within the Corps. Inclosure 2 contains a procedural checklist with guidance on the method and philosophy of approaching the problem. Actual data to be used in specifying earthquake motions are not included but are contained in the cited references. Included in Inclosure 2 is a general discussion concerning the circumstances requiring the specification of earthquake motions, the use of "deterministic" and "probabilistic" methods, the sequence of procedures necessary to select the design earthquakes, project site ground motions, and a discussion of the use of response spectra and accelerograms.

FOR THE COMMANDER:

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Definitions in Engineering Seismology

1. Active Fault. A fault, which has moved during the recent geologic past (Quarternary) and, thus, may move again. It may or may not generate earthquakes.

2. Amplification. Modification of the input bedrock ground motion by the overlying unconsolidation materials. Amplification causes the amplitude of the surface ground motion to be increased in some range of frequencies and decreased in others. Amplification is a function of the shear wave velocity and damping of the unconsolidated materials, its thickness and geometry, and the strain level of the input rock motion.

3. Attenuation. Decrease in amplitude of the seismic waves with distance due to geometric spreading, energy absorption and scattering.

4. Bedrock. Any sedimentary, igneous, or metamorphic material represented as a unit in geology; being a sound and solid mass, layer, or ledge of mineral matter; and with shear wave velocities greater than 2500 feet per second.

5. Capable Fault. An active fault that is judged capable of producing macroearthquakes. It is defined as a fault that can be shown to exhibit one or more of the following characteristics:

a. Movement at or near the ground surface at least once within the past 35,000 years.

b. Macroseismicity (3.5 magnitude or greater) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.

c. A structural relationship to a capable fault such that movement on one fault could be reasonably expected to cause movement on the other.

d. Established patterns of microseismicity that define a fault and historic macroseismicity that can reasonably be associated with that fault.

6. Design Earthquakes. Design earthquakes define the ground motion at the site of the structure and form the basis for dynamic response analyses. Usually, several design earthquakes for both the maximum credible earthquake and the operating basis earthquake, as applicable, are investigated.

7. Dispersion. Distortion of the shape of a seismic-wave train because of variation of velocity with frequency.

8. Duration of Strong Ground Motion. In Inclosure 2 "bracketed duration" is used as the time interval between the first and last acceleration peaks that are equal to or greater than 0.05 gravity.

9. Epicenter. Point on the Earth's surface vertically above the earthquake forcus or hypocenter.

10. Fault. A fracture or fracture zone in the earth along which there has been displacement of the two sides relative to one another parallel to the fracture.

11. Free Field. A ground area which is not influenced by topography or man-made structures and boundary effects are not significant.

12. Ground Motion Parameters. Numerical values representing vibratory ground motion, such as particle acceleration, velocity, and displacement, frequency content, predominant period, spectral intensity, and duration.

13. Hypocenter. The location within the Earth where the sudden release of energy is initiated. Also, the focus of an earthquake.

14. Intensity. A numerical index describing the effects of an earthquake on mankind, on structures built by mankind and on the earth's surface. The scale in common use in the U. S. today is the Modified Mercalli Intensity Scale of 1931 with grades indicated by Roman numerals from I to XII.

15. Magnitude (Earthquake). A measure of the strength of an earthquake, or the strain energy released by it, as determined by seismographic observations. C.F. Richter first defined local magnitude as the logarithm, to the base 10, of the amplitude in microns of the largest trace deflection that would be observed on a standard torsion seismograph at a distance of 100 km. from the epicenter. Magnitudes determined at teleseismic distances are called body-wave magnitude and surface-wave magnitude. The local, body-wave and surface-wave magnitude of an earthquake do not necessarily have the same numerical value.

16. Maximum Credible Earthquake (MCE). The earthquake(s) associated with specific seismotectonic structures, source areas, or provinces that would cause the most severe vibratory ground motion or foundation dislocation capable of being produced at the site under the currently known tectonic framework. It is determined by judgment based on all known regional and local geological and seisomological data.

17. Operating Basis Earthquake (OBE). The earthquake(s) for which the structure is designed to resist and remain operational. It may be determined on a probabilistic basis considering the regional and local geology and seismology and reflects the level of earthquake protection desired for operational or economic reasons. The OBE is usually taken as the earthquake producing the maximum motions at the site once in 100 years (recurrence interval).

18. Particle Acceleration. The time rate of change of particle velocity.

19. Particle Displacement. The difference between the initial position of a soil particle and any later temporary position during shaking.

20. Particle Velocity. The time rate of change of particle displacement.

21. Predominant Period. The period(s) at which maximum spectral energy is concentrated.

22. Response Spectrum. The maximum values of acceleration, velocity, and/or displacement of an infinite series of single-degree-of-freedom system subjected to an earthquake. The maximum response values are expressed as a function of natural period for a given damping. The response spectrum acceleration, velocity, and displacement values may be calculated from each other assuming a sinusoidal relationship between them.

23. Scaling. An adjustment to an earthquake time history or response spectrum where the amplitude of acceleration, velocity, and/or displacement is increased or decreased, usually without change to the frequency content of the ground motion. There are other methods to scale earthquakes and, if used, they should be clearly defined. The earthquake time history or response spectrum can be scaled based on ground motion parameters of peak acceleration, peak velocity, peak displacement, spectrum intensity, or other appropriate parameters.

24. Seismotectonic Province. A geographic area characterized by a combination of geology and seismic history.

Specification of Earthquake Motions for Use in Engineering Design

General Discussion.

1. ER 1110-2-1806, Reference 1, provides guidelines for the seismic design and evaluations of Corps projects. As a minimum, a geological and seismological evaluation should be performed for all projects in seismic zones 2, 3, and 4. A detailed field investigation should be conducted on foundation and embankment materials to determine their susceptibility to liquefaction and deformation for all projects in zones 3 and 4 and selected projects in zone 2 where materials sensitive to earthquake shaking exist in the foundation or embankments. The results of these field investigations coupled with the results from the geological and seismological evaluation will determine the appropriate dynamic response and/or deformation analyses. Seismic coefficient analyses are no longer performed on embankments. They are performed to determine the sliding and overturning stability of all concrete structures. In addition a dynamic response type of stress analysis should be performed for concrete structures in zones 3 and 4 and in zone 2 where the predicted peak ground acceleration is 0.15 gravity or greater.

2. The seismic coefficient analysis is commonly known as the pseudostatic analysis. This method of analysis treats the earthquake loading as an inertial force applied statically to a structure. The magnitude of the inertial force is the product of the structural mass and the seismic coefficient. The seismic coefficient is a ratio of the earthquake acceleration to gravity. It is a dimensionless unit and in no case can be related directly to acceleration from a strong motion instrument. The seismic coefficients to be used in the pseudostatic analysis of Corps concrete structures in the various seismic zones are contained in ER 1110-2-1806.

3. A dynamic analysis tests a structure by applying a cyclical load approximating that of an earthquake. The shaking may be applied as a wave traveling vertically from bedrock through soil and into a structure. The objective is to test for possible structural damage. Examinations are made of such factors as failure in concrete from excessive peak stresses, the buildup of strain in soils beyond acceptable limits, and, in the case of saturated granular soils, the possibility of failure by liquefaction.

4. There are two general approaches to doing dynamic analyses. They determine the way earthquake motions are specified and used.

5. One approach begins with acceleration values which may be modified by factors for given structural components and are then entered directly into standard curves for smoothed response spectra. The other approach begins by selecting appropriate accelerograms, commonly known as time histories, for a site. Values are specified for peak horizontal acceleration, velocity, and displacement, and a duration of strong shaking is assigned. The motion must

be identified as representing a free field ground surface, for either rock or soil. These values are then used as input to a number of numerical analyses that examine stress, strain, or displacement in the structure (e.g., finite element analyses).

6. The response spectra method is used in the analyses of concrete and steel structures. The accelerogram method is used for soil structures and foundations and for concrete structures under certain circumstances.

Deterministic and Probabilistic Methods

7. It is generally accepted that there are two procedures for estimating earthquake motions at a particular site; deterministic and probabilistic. In the deterministic procedure, the maximum earthquake is assigned on the basis of empirical knowledge, theoretical conceptualization, and professional judgment, and that earthquake motion is attenuated from its source to the site. For Corps structures it is assumed that the earthquake occurs at the closest point to the site from the causative fault or source region and that the earthquake magnitude is the maximum which can be expected for the fault or source region.

8. In conjunction with probabilistic methods, the Corps performs seismic hazard analyses which involve the probability of recurrence of given sizes of earthquakes. This is in contrast to the broader seismic risk analyses (i.e., the development of probability versus consequences for a given structure or site resulting from probabilistically determined earthquake motions).

9. For "seismic hazard analysis," as done generally in the profession, seismic source areas must be identified, frequency-magnitude relationships must be developed for each source area, attenuation relationships must be developed, and then the probability of exceeding a given ground motion at a particular site for a given exposure time can be calculated. There are a number of potential problems in using this probabilistic approach. The major problems are:

a. The common assumption that earthquake occurrence can be modeled by a Poisson distribution, a model which assumes that earthquakes are independent in time and space.

b. The considerable ranges of error that result from relating motions to sizes of earthquakes and projecting both from a historic record of 150 to 350 years in the United States to several thousand years.

c. The difficulties in arriving at a maximum earthquake from a magnitude-frequency of occurrence relationship.

10. Most of the practitioners working with the probabilistic method recognize these problems. Inevitably they must affix maximum events to their magnitude-frequency of occurrence curves. This act or procedure makes the decision deterministic.

Specifying Motions

11. The specification of earthquake ground motions for a particular site is a process in which there are many decision levels. Candidate maximum credible and operating basis earthquakes are selected and motions are specified based on the following relationships:

a. The presence or absence of identifiable faults capable of producing earthquakes.

b. Estimated maximum magnitudes for these earthquakes.

c. The boundaries for zones of seismic activity in which maximum credible earthquakes are assigned and floated throughout the zones.

d. The types of faulting that produce these earthquakes and the character of surface displacement.

e. The peak motions (particle acceleration, velocity, displacement), as well as duration and predominate period that are associated with these events.

f. The attenuation of motions from source to site.

g. The effects of site characteristic (soil, rock, topography, field conditions, etc.) on the resultant motions.

h. The selection of analogous strong motion records or synthetic seismograms for scaling to the specified motions at the site.

i. Alternatively, appropriate equivalent accelerations can be specified for entrance into available response spectra.

12. In addition, it may be desirable to:

a. Determine recurrence intervals.

b. Specify spectral density or other requirements.

c. Consider focusing of earthquake waves along a fault.

13. If the geologic and tectonic studies are performed in conjunction with a new project they would be part of the project regional geologic studies as described in EM 1110-1-1801 Reference 2. If performed for an existing project they would be more limited in scope and specialized. They should be aimed at delineating the geologic structural pattern in the region of interest, generally within 100 to 400 kilometers from the site depending on the seismotectonic province(s) involved. The tectonic setting and history should be determined to understand the stress fields and fault mechanisms associated with the region. Satellite imagery can assist in the development of the

regional geologic and tectonic setting. On a larger scale, review of available geophysical studies such as gravity and magnetic studies can assist in defining geologic structures and relating them to the local seismic history.

14. Airphotos and overflights are useful in locating faults and judging whether they are active or inactive. Slemmons and Glass (1978), Reference 3, provide a useful summary of guidance for the utilization of imagery. Generally, no fault can be accepted from imagery or overflights until it is located on the ground or "ground-truthed." A fault that is shown to be active must also be determined to be capable. The larger the capable fault, the greater the potential earthquake. Thus, relationships have been developed between dimensions of faults and magnitude of earthquakes. Dimensions include length of fault rupture, displacement during movement of the fault, whether the movement is on a primary fault or a branch fault or an accessory fault. Compilations have also included the types of faults, whether strike-slip, thrust or normal, and estimates of seismic moment. The latter may be calculated from the area of a fault plane involved in movement, the permanent displacement and the rigidity of the rock. A useful summary relating faults to earthquake magnitude is provided by Slemmons (1977), Reference 4.

15. If not already available, historic earthquakes should be tabulated and plotted on the regional geologic map. The area for which the seismic history is compiled should be large enough to identify any geotectonic patterns that may be relevant to a site. The tabulation of historic earthquake events, though they are obtained from authoritative sources, should be examined critically. The epicentral intensity of earthquakes are sometimes overstated. The locations of epicenters may also be shifted on the basis of reinterpreting the available data. If the site is important, the historic records should be examined and the interpretations should be checked. The records include newspaper accounts, diaries, early scientific and historical works, etc.

16. Based upon the geologic structure, tectonics, and seismic history, seismic zones can be established. Each zone should be constructed so that it represents an area over which a maximum magnitude earthquake can occur anywhere or "float." In regions where causative geologic structures are not identified, the seismic zones should be based on seismic history. In areas where causative geologic structures are identifiable, the zones may be shaped to accommodate these structures.

17. Once seismic zones are defined, candidate maximum credible and operating basis earthquake motions are attenuated to the site. Recurrent relationships are developed as appropriate. (See Yegian (1979), Reference 5). The candidate design earthquake motions are attenuated to the site and the final design earthquakes are selected. The design earthquake motions are usually specified in terms of peak acceleration, velocity and duration. Three major problems must be kept in mind while assigning motions:

a. The paucity of strong motion records for large earthquakes.

b. The limited data near causative faults.

c. The spread in the available data.

18. The candidate earthquakes are specified in terms of intensity and/or magnitude depending on the sources of information available. Because it is instrumentally determined, magnitude would be the preferred parameter. However, in many regions intensity values comprise the majority of available information and intensity is a reliable means of earthquake assessment. The intensity scales allow for differences in types of construction and resulting damage. Present-day investigators generally come up with the same intensity for any given site. For most of the United States and the world, the historic data are available only as intensities. Intensities can be attenuated from a source to a site by any of a number of intensity-attenuation charts. Krinitzsky and Chang (1977), Reference 6, show a comparison of intensity attenuations in Western United States and Eastern United States. Attenuation differences in these two cases are greatly pronounced. The range in acceleration for Modified Mercalli (MM) Intensities obtained from representative worldwide data is several orders of magnitude. Also, there is a deficiency of data for MM VIII and greater. It is obvious from the dispersion of the values for acceleration that curves based on the mean or average do not reflect the spread in the data.

19. Krinitzsky and Chang (1977), Reference 6, presented charts that show an important difference in peak motions for the Near Field and Far Field. In the Near Field there is much focusing of waves from their source and there is reflection and refraction. There is a buildup of motions from resonance effects and there may be cancellation of motions. There are more high-frequency components of motion. Thus, there is a large spread in the peak motions for any given intensity. In the Far Field, the motions are less diverse, thus they are more orderly and predictable; their peaks are also more subdued. Krinitzsky and Chang (1977), Reference 6, devised sets of curves for Near Field-Far Field accelerations, velocities, and displacements. These curves also show the dispersion of the data, and values for the mean, the mean plus one standard deviation (σ), or 84 percentile, and the trend of peak observed values. The charts for accelerations and velocities have since been updated through the addition of nearly 400 records including a group from large earthquakes ($M \geq 7.0$) and many from soft or soil sites in Japan. A definition of a soft site was a bounding shear wave velocity of 2500 feet per second. The Krinitzsky and Chang revised charts, published in Reference 7, show accelerations, velocities and durations for hard and soft sites in the Near Field. For the Far Field, accelerations, velocities and durations are for hard and soft sites and for large earthquakes ($M \geq 7$) and moderate earthquakes ($M \leq 6.9$). Altogether there are 18 charts and they present the mean, mean + σ, and the limit of data for all relevant levels of Modified Mercalli Intensity.

20. The now classic work that established present day levels of peak motions for earthquakes in relation to magnitude and distance is that of Page and others (1972), Reference 8, for the Trans-Alaska Pipeline System. Their work had the benefit of the strong motion records derived from the San Fernando earthquake of February 9, 1971 in which accelerations greater than 1 g were recorded. A caution in using the table of motions that they specified for

various magnitudes of earthquakes is that they are for a frequency range of 1 to 9 Hz, suitable for the pipeline. Their filtering of the Pacoima record to eliminate high-frequency components of motion removed about 25 percent of the range in acceleration. Also, their specified motions are for the worst case situations where the pipeline is directly over capable faults. Thus, their tabulated values need to be assessed carefully for use in any other situation.

21. Donovan (1973), Reference 9, showed acceleration values with distance for worldwide earthquakes and for the San Fernando earthquake. The spreads are shown by the mean, mean plus 1 and mean plus 2 σ. The total spread of the worldwide data is seen to be several orders of magnitude. Algermissen and Perkins (1976), Reference 10, adjusted the Schnabel and Seed (1973) curves Reference 11, using attenuations for Central United States developed by Nuttli so that the Schnabel and Seed curves for acceleration could be used for any part of the United States. The curves, however, present problems in accommodating the range that exists in acceleration values and they do not provide guidance for specifying other critical components of motion such as velocity, displacement and duration. Nuttli and Herrmann (1978), Reference 12, provided curves for Central United States that give acceleration and velocity for magnitude and distance from source. These are useful curves but a few cautions are in order:

a. There is such a lack of data that most of the lines are simply interpreted.

b. The indicated motions, especially close to the source, do not show what is likely to be a large dispersion in the data.

c. The lines are not exactly peak values or means or mean plus ; they are not specified in these terms and probably vary over the graph.

d. There is no distinction between soil and rock because of a lack of data.

An important set of relationships between acceleration and velocity, magnitude and distance, and rock versus soil was developed by Joyner and Boore (1981), Reference 13. Their values are expressed as mean and mean plus σ. Their motions are very high for sites close to the source for large earthquakes ($M = 7.0$ to 7.5). The curves for these earthquakes are not based on observed data but on the patterns set by the 1979 Imperial Valley earthquake, of $M = 6.5$, for which there are excellent instrumental records. However, it may be that near a fault the peak motions for $M = 6.5$ will not continue to increase in the proportions that are interpreted to be the case for the larger magnitudes. Another caution is that these attenuations with distance are suitable for Western United States but are not suitable for other areas such as east of the Rocky Mountains.

22. Several investigators have proposed methods of measuring the duration of strong motion shaking. An important approach is an integration of the acceleration peaks with a duration that encompasses the inflection of the curve at the beginning of shaking and at the end. (See Arias, 1980, Reference

14, Vanmarcke, 1979, Reference 15). Probably, the method most widely used in engineering is that of Bolt (1973), Reference 16, called bracketed duration. It is the inclusive time in which the acceleration level equals or exceeds the amplitude threshold of 0.05 g, or 0.10 g, according to the selection. A comparison is made of bracketed duration for soil and for rock by Krinitzsky and Chang (1977), Reference 6, Page and others (1972), Reference 8, and Bolt (1973), Reference 16. A significant difference, roughly 100 percent, is indicated between soil and rock. Duration will always provide the greatest uncertainty in specifying earthquake motions. Very simply, a large earthquake may result from ruptures on several planes with their motions fused together in their effects at any one point so that they have the appearance of one earthquake rather than the sum of several.

23. Policy has not yet been established concerning the degree of conservatism to adopt when selecting ground motions from dispersed data. For most circumstances, the use of a mean plus one is sufficiently conservative. For floating earthquakes with no identified source, Far Field motions can be used. The decisions on the degree of conservatism are to a large extent subjective and depend on the needs of the project and the experience and judgment of the personnel performing the analyses. The spectral composition of strong motion records are likely to be affected by site conditions and by distance from earthquake source. The appropriate spectral composition will be obtained by selecting records for scaling from earthquakes that are as analogous as possible to the specified type of faulting, distance from source, attenuation and site conditions. Synthetic accelerograms are likely to contain appropriate spectra but may be somewhat conservative as they contain more spectral components than most natural events.

24. Seed and others (1976), Reference 17, presented a statistical analysis of response spectral shapes that show differences of soil and rock in the Western United States. Chang and Krinitzsky (1977), Reference 18, present predominant period characteristics that are related to magnitude and distance together with local geological conditions. Chang (1981), Reference 19, developed non-site-specific spectra based on geology of the sites and expressed as power density. He found close relationships among peak acceleration, duration and root mean square (rms) accelerations.

25. Chang (1978), Reference 20, provides a catalog of earthquakes of Western United States arranged by fault type magnitude, soil and rock, epicentral distance and peak acceleration, velocity, and displacement. Tabulations also list the duration, predominant period, and focal depth. This source, or the selection of representative earthquakes listed by Hays (1980), Reference 21, in his Table 16 to show appropriate earthquakes for soil and rock sites, may be used to select appropriate strong motion records either to use as they are or for scaling. Accelerograms from strong motion records chosen for design should be those recorded under comparable conditions of earthquake magnitude, distance from the earthquake source, and site (rock or soil). Other constraints may have to be added such as the type of faulting, focal depth, and regional geology. However, the more the constraints, the harder it will be to find the desired number of records without deviating too much from the specified site conditions. Vanmarcke (1979), Reference 15, indicates that scaling

must be restricted to a factor of two or less in order to avoid distortion of the spectral properties of the records. The time scale should not be altered unless there are definite spectral values that are desired. The time scale can be repeated or deleted in portions in order to obtain a desired duration.

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