Chapter 2
Seismic Design Criteria

2-1. Stability

a. Resultant location and sliding. RCC dams shall satisfy the overturning and sliding stability requirements for gravity dams using inertia forces calculated by the seismic coefficient method as set forth in EM 1110-2-2200 and ETL 1110-2-256. The seismic coefficients shall be as shown on the seismic zone maps provided in ER 1110-2-1806.

b. Extreme stability conditions. When intense ground shaking causes serious tensile cracking at the dam-foundation interface, a nonlinear time history analysis shall be performed to evaluate cracking, potential permanent displacements, and the effect these have on sliding stability. Certain stipulations regarding nonlinear analyses are covered in paragraph 2-2*g*.

2-2. Response to Ground Shaking

RCC dams shall be capable of resisting the strong motion ground shaking associated with design earthquakes within the allowable tensile stress design criteria specified in Chapter 4. Dynamic stress analysis methods and procedures are described in Chapter 8. The dynamic analyses shall incorporate the dynamic characteristics of the dam, foundation, reservoir, and backfill or silt deposition when applicable.

a. Defining ground motion. The free field ground motions are used to define the ground motion that would be felt at the site due to two design earthquakes. Free field ground motion associated with each shall be represented by design response spectra and, when required, design acceleration time histories. The design earthquakes are operating basis earthquake (OBE), and maximum credible earthquake (MCE). Both are discussed in detail in Chapter 4.

b. Propagation of cracks in RCC. Most dams with earthquake resistant provisions will probably survive the most severe earthquake shaking possible at the site with little or no damage, although high dams located near major faults have experienced extensive cracking during major earthquakes (Chopra and Chakrabarti 1973). Concrete cracking due to ground shaking combined with cracking due to foundation fault displacement could propagate to an extent where a failure mechanism is formed thus impairing the ability of the dam to contain the pool. Criteria defining an acceptable response of the dam to design earthquakes are based on initiation and propagation of tensile cracking within the RCC.

c. Analyzing response to ground shaking. The process of cracking and the propagation of the cracks result in nonlinear behavior of the dam. There are also nonlinearities associated with dam-foundation interaction and dam-reservoir interaction which are difficult to assess. Approximate linear relationships account for some of the nonlinear dynamic behavior and allow the response of the dam to the design earthquake ground motion to be determined using a linear-elastic analysis method. Tensile stresses can then be evaluated based on tensile strength parameters adjusted to be compatible with linear-elastic analysis methods.

d. Analysis methods. The simplest of the linear-elastic methods uses a response spectrum to define the ground motion as outlined in Chapter 5. Most RCC dams will be found adequate using this method. For the few exceptions, the next level of refinement in determining the dynamic response is the linear-elastic time history method, and in rare cases a nonlinear time history finite element analysis may be required.

e. Allowable tensile stress. The tensile strength of the RCC is the single concrete material property used to evaluate cracking, and to establish acceptable response. Allowable tensile stresses are defined in paragraph 4-2*c* and paragraph 4-3*c* for the OBE and MCE, respectively.

f. Evaluating time-history response. When dynamic response is determined by the linear-elastic time-history method, the allowable tensile stress is the principal criterion for evaluating acceptable response, but additional criteria are also required to qualify other response characteristics such as the number of stress cycles approaching or exceeding the allowable stress, and the magnitude and pattern of these excursions beyond the specified limits.

g. Evaluating nonlinear analyses. When dynamic response is determined by the nonlinear time-history method, criteria for evaluating acceptable response are based on the theory of fracture mechanics. This type of analysis should only be undertaken in consultation with and as approved by CECW-ED.

2-3. Foundation Fault Displacement

a. General. Most RCC dam sites are not subject to any significant differential displacement of the ground surface at the dam-foundation interface during a seismic event. Dam sites should always be avoided when located near a major active fault system with the potential to trigger sympathetic foundation displacements at the site. Occasionally it is not possible to avoid these sites, and it becomes necessary to evaluate the response of the dam should such a foundation fault displacement occur.

(1) Considerable judgment is required in the evaluation process. At best, analysis methods for foundation fault displacement are approximate and are generally unsupported by past observations of the response of existing dams to fault displacements occurring at the dam foundation. Furthermore, considerable judgment is required in the prediction of future fault movement and in the magnitude of the fault displacement. For example, the estimate of the magnitude of potential fault displacement provided by different experts for a specific site could vary from a few inches to several feet. This necessitates consulting several geotechnical firms to provide site-specific fault displacement estimates, and then carefully scrutinizing these estimates before finally establishing the design fault displacement.

(2) Experts in plate tectonics, geology, seismology, and finite element analysis techniques should be consulted to provide guidance for any dam located on a site subject to foundation fault displacement. Because of the many uncertainties and the risk involved, approval by CECW-ED is required for any RCC dam which is located on a site subject to foundation fault displacement.

b. Types of faults. Fault slip is the relative displacement of two adjacent tectonic plates with respect to each other. This refers to large active fault systems such as the San Andreas or Hayward faults in California. On a smaller scale, the foundation rock mass beneath a dam contains various discontinuities, joint sets, and shear and fault zones. Normally this is a system of historically inactive discontinuities; however, there is a potential for fault slippage particularly when triggered by a great earthquake on a nearby large active fault. The three general types of fault slips are strike-slip, normal-slip (dip-slip), and reverse-slip (thrust-slip). Refer to Figure 2-1 for illustrations of the various types of faults and how the magnitude of slip is measured. The strike of the fault is the trace the fault makes with respect to the ground surface, and it may be at any orientation with respect to the dam axis.

c. Design fault displacement. The design fault displacement (DFD) is defined as the maximum possible free field fault slip movement that could reasonably occur in the dam foundation as measured at the ground surface. The return period that would be associated with the DFD is similar to that of the MCE. Therefore, the DFD and the free field ground motion together specify the site-specific seismic activity associated with the MCE. To fully describe the DFD, three factors must be specified: magnitude, type of slip, and strike of the fault.

(1) The geology of the dam foundation is complex, and the foundation may be crossed by a number of discontinuities with fault displacement potential. Experts in the fields of geology and seismology should be consulted to study the foundation fault system, determine which faults are capable of surface displacement, and finally recommend which faults are critical and specify the DFD for each critical fault.

(2) Normally, foundation fault displacements are not considered to occur concurrently with strong motion shaking associated with the OBE. The active fault near the dam site that produces a seismic event of OBE magnitude is not likely to trigger sympathetic slippage in the fault system in the dam foundation. The probability of sympathetic foundation fault displacement is normally several orders of magnitude less than the recurrence rate for the strong motion shaking associated with the OBE; therefore, the probability of the OBE being accompanied by significant foundation displacement is usually considered negligible.

(3) On rare occasions, the probability logic discussed above may not apply when considering if it is appropriate to combine foundation fault displacement with ground shaking in specifying the OBE. For example, unusual geology of the foundation could make it susceptible to a reservoir-induced foundation fault displacement or to other

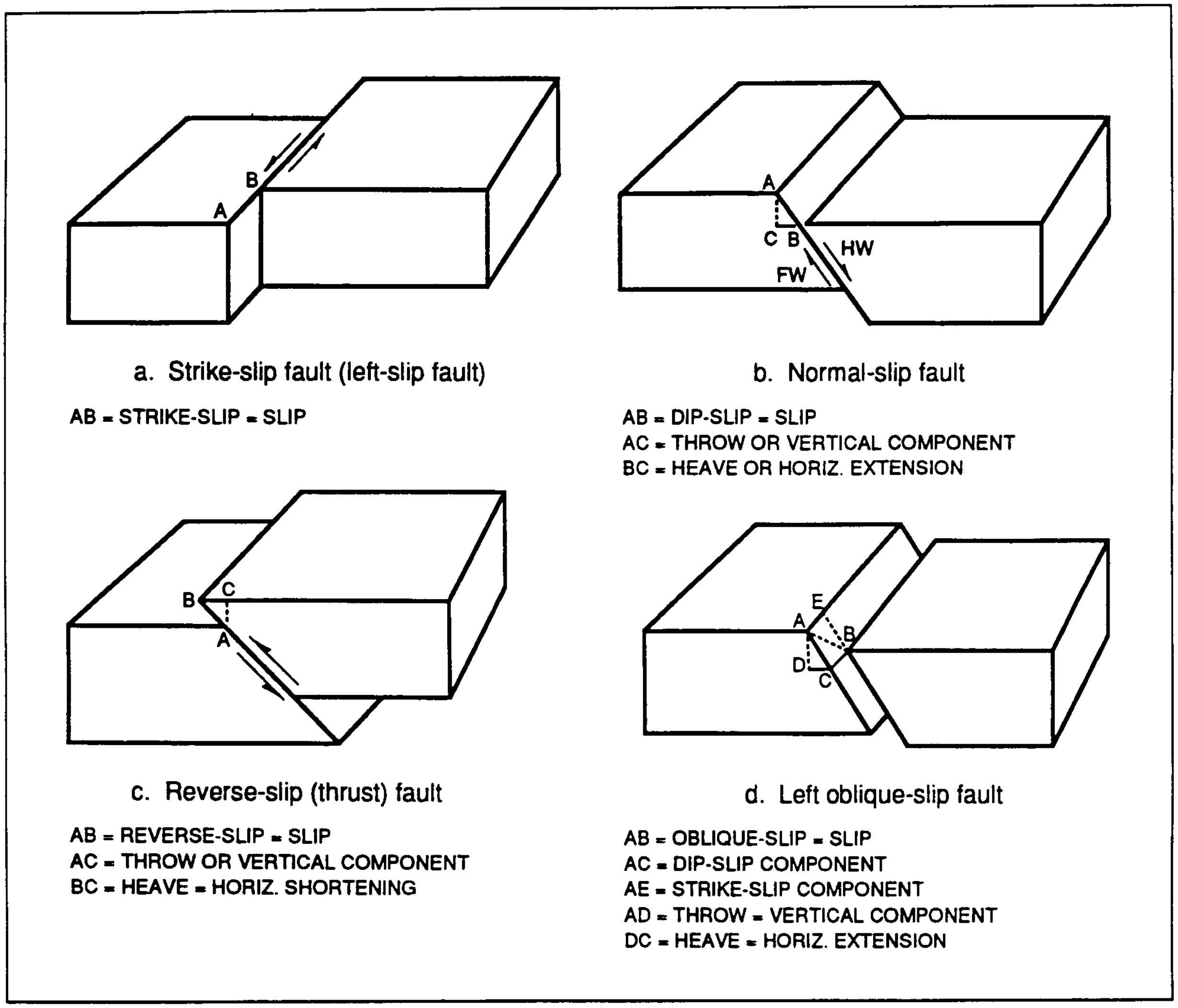

Figure 2-1. Types of fault slips

unusual causes of foundation fault displacement discussed later in this chapter. In these situations the strong motion shaking accompanying the local fault slip may be nearly as intense or even more intense than the gound motion shaking associated with an OBE produced by a major active fault slip occurring some distance from the site. When this is the case, a reduced value of the DFD would be included with free field ground motion to describe the OBE.

d. Combined DFD and ground shaking. Stresses associated with the DFD result from highly complex nonlinear behavior; however, simplified fault displacement analysis procedures, such as the one described below, are normally used to investigate concrete stresses that may occur due to fault displacement. Stresses due to ground shaking are determined by methods discussed earlier in this chapter. Thus, stresses due to fault displacement and stresses due to ground shaking are obtained from two separate, independent, and approximate analyses. The response to the design earthquake is then obtained by direct addition of the two sets of stresses without accounting for any interaction. Actually, the fault displacement may cause inelastic behavior at the dam-foundation interface, cracking within the RCC, or other inelastic response which changes the dynamic characteristics of the dam, which in turn interacts with and effects the ground shaking response. Because these simplified and approximate procedures have not been supported by nonlinear finite element analyses that properly combine the effects of fault displacement and ground shaking, they should be used with caution.

e. Simplified DFD analysis procedure. The simplified procedure described below was used to investigate concrete stresses due to fault displacement in the Auburn Dam in California (U.S. Department of the Interior, Bureau of Reclamation 1980). The dam and foundation are modeled with finite elements with the mesh geometry adjusted to allow the fault to be properly oriented. Refer to Figure 2-2. The foundation model consists of a fixed block with conventional boundary supports, and a movable block with special boundary conditions that allow forces to be applied at the boundary parallel to the fault to produce the DFD. The fixed and movable block are separated by elastic orthotropic elements which allow the sharp displacement discontinuity to take place as the movable block displaces upward.

(1) The finite element model is first loaded with the gravity loads followed by the hydrostatic loads, and finally the movable block is forced to undergo the DFD. Each loading is applied incrementally. After each loading increment, tensile stresses are evaluated and elements are softened in areas where the tensile strength is exceeded. Elements are softened by reducing their elastic modulus until the tensile stress is eliminated. Most elements requiring softening are located in the foundation because jointing and discontinuities in the rock prevent it from sustaining high tensile stress. When the DFD is reached, the extent of the tensile failure areas is evaluated. The dam tends to bridge over the fracture zone in the foundation. Resulting stresses induced in the RCC are obtained from the finite element analysis for the final increment of loading which produced the DFD.

(2) The method of incremental loading and softening of element properties allows the use of a simplified static, linear-elastic finite element analysis approach. Disadvantages of the procedure are that it gives only an approximation of the complex nonlinear behavior associated with fault displacement, it is time consuming, and it requires considerable judgment.

(3) The example shown in Figure 2-2 is typical for a normal or reverse fault where the fault strike is approximately parallel to the dam axis so a two-dimensional analysis is adequate. If the fault strike is not close to parallel to the dam axis, or for a strike-slip fault, a three-dimensional analysis is required. The three-dimensional analysis is even more time consuming and complex, but the principles and general procedure are similar to the two-dimensional analysis described.

f. Acceptable response to DFD. When the seismic activity associated with the design earthquake consists of both fault displacement and ground shaking, stresses for the combined response described in paragraph 2-3*d* must satisfy the allowable tensile stress criteria of paragraph 2-2*e*. Beyond these tensile stress requirements, additional consideration is required regarding general performance requirements of Chapter 4 related to dam safety and operations in the event of foundation fault displacement. The potential fault displacement and the effect it has on the dam must be evaluated on a case-by-case basis. The analysis procedures described above for evaluating the effect of fault displacement are rough approximations, but they do provide an indication of the extent of the fracture zones that could occur in the foundation or lower portions of the RCC dam. The analysis results must be coupled with considerable judgment to determine if this damage could lead to the erosion of the foundation or RCC materials to the extent that finally causes an uncontrolled release of the reservoir.

g. Dam failures caused by fault displacements. To help identify some of the judgment factors involved in evaluating sites with fault displacement potential, the following is a brief review of historical information on dams that failed directly or indirectly as a result of fault displacement. Differential displacements across a fault have been recorded due to: triggering of the fault by a seismic event; a difference in consolidation of materials on either side of the fault; a reduction in resistance to fault movement created by the lubricating effects of water, or the erosion of fault materials by flowing water; and increase in hydrostatic pressures along the fault.

(1) Earth-fill dams, concrete gravity dams, and concrete arch dams have failed due to fault movements. Failures of the Baldwin Hills earth-fill dam, the Malpasset concrete arch dam, and the St. Francis concrete gravity dam (James et al. 1988) can all be attributed in part to forces and movements occurring along fault surfaces. Although these forces and movements were not triggered by seismic activity, it can be surmised that if a seismic event had occurred, it would have likely triggered similar failures. These examples show that fault movement can cause a

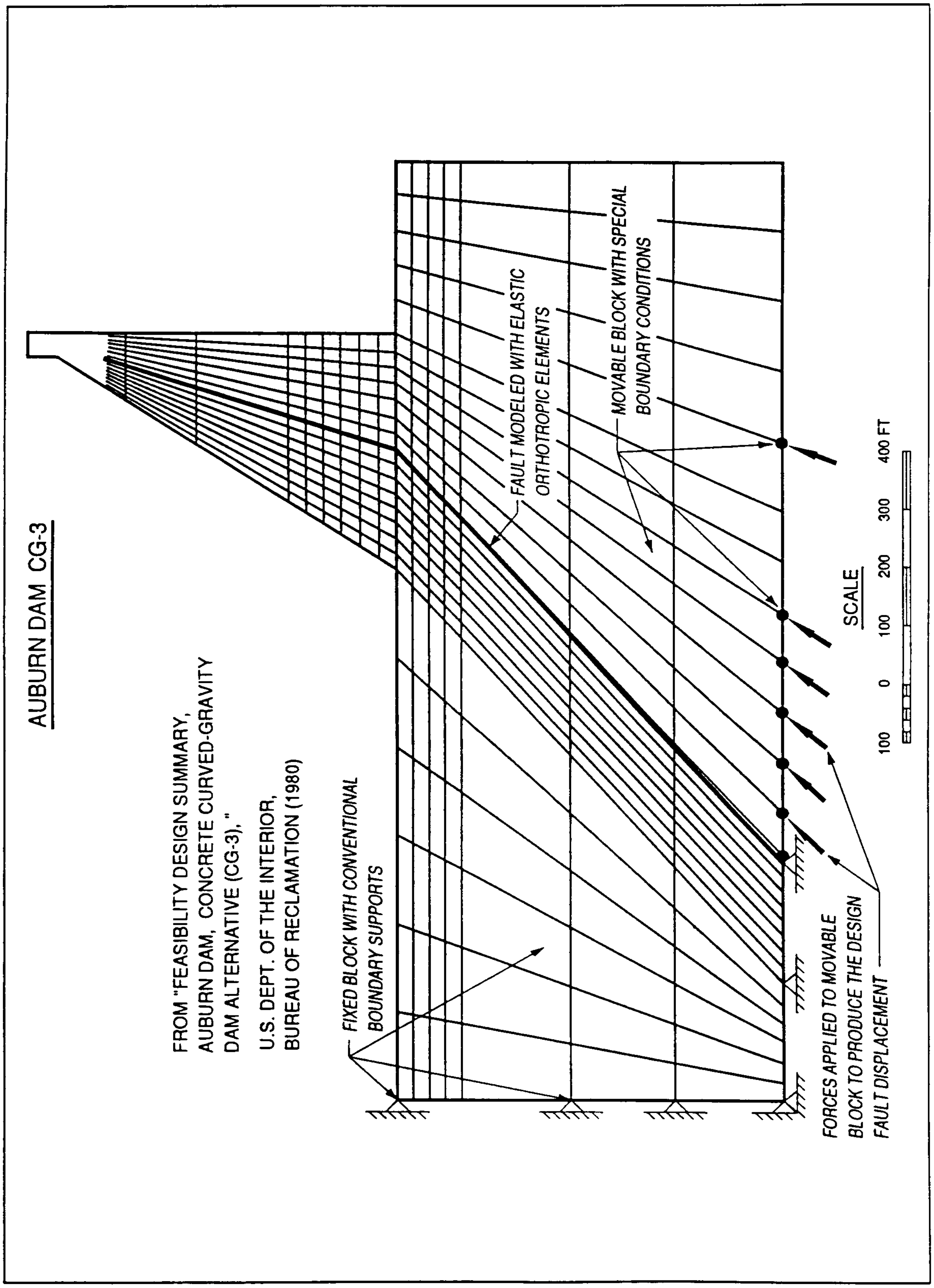

Figure 2-2. Finite element model for fault displacement analysis

failure mechanism to form in the dam structure which results in dam failure; however, it is more likely that the fault movement would create flow paths that could lead to a release of the impounded reservoir. Seepage can erode dam or foundation materials which eventually results in failure because capability for controlled release of the pool is lost.

(2) An earth-fill dam with a flexible core is normally considered less susceptible to failure due to foundation fault displacement because it would tend to conform to the displaced shape of the foundation. Although this flexibility of the dam material will reduce voids and flow paths in the dam and foundation it will not completely eliminate them. Thus, an earth-fill dam is susceptible to erosion of core or foundation material from water flowing through faults or through voids in the dam or foundation created by fault movements. For this reason, an earth-fill dam is not necessarily superior to a concrete gravity dam in resisting the effects of fault movement.

h. Defensive design features. Defensive design features which can be employed in the design of an RCC dam susceptible to foundation displacement are discussed below.

(1) The arching action provided by laying out the dam axis on a curve may better distribute the forces on a gravity dam due to foundation fault displacement, and reduce the tensile stresses and cracking of the RCC. This defensive feature is only effective if the heave of the foundation block is generally in a downstream direction, and providing the fault movement does not occur at either abutment.

(2) Special sliding joints may also be used to reduce cracking of the RCC due to fault displacement. For example, vertical joints may be located in the RCC to accommodate potential strike-slip fault displacements where the strike is generally in the upstream-downstream direction.

(3) A design feature for controlling the reservoir release is to provide a buttress fill against the upstream face of the dam. This requires the reservoir water to pass through a succession of filters and crack stoppers in a manner analogous to the behavior of the transitions and filters in a zoned embankment dam. This defensive measure would be effective for flood-control projects where the reservoir pool elevation is low enough that the required height of the buttress fill is economically feasible, and does not impair the stability of the dam.

2-4. Refined Dynamic Analyses Methods

a. Need for refinement. When the simplified linear-elastic analysis methods described above for an existing RCC dam produce tensile stresses in excess of the allowables discussed in paragraph 2-2*e*, more refined analyses methods shall be pursued before the dam is judged unsafe. Also, if all practical and economical adjustments to the design of a new dam have been exhausted in the attempt to satisfy the allowables based on simplified linear-elastic methods, the more refined analyses methods may be pursued to better evaluate nonlinear structural behavior. Refined analyses consist of linear or nonlinear time history analyses as discussed in paragraph 2-2*d*, with some additional details of the nonlinear analysis provided below. The response produced by refined analyses shall be evaluated in accordance with the stipulations of paragraphs 2-2*f* and 2-2*g*.

b. Fracture mechanics. Nonlinear dynamic analysis is based on fracture mechanics theory which is presently in the research phase. It is also difficult to determine just what level of structural damage can be sustained safely by the dam and still consider it to satisfy the performance requirements. The nonlinear attribute requires this type of dynamic analysis be performed in a time domain (time history analysis) rather than a frequency domain (response spectrum analysis), and use a direct integration solution. The analysis accounts for: energy dissipation by cracking, strength of cracked concrete, changes in vibration characteristics caused by cracking, changes in damping, and changes in strength due to strain rate and loading history.

c. Nonlinear analysis requirements. Because it is very complex, costly, and requires a considerable amount of judgment to interpret the results, an expert in fracture mechanics and nonlinear analysis techniques should be consulted to provide guidance when pursuing a nonlinear analysis.