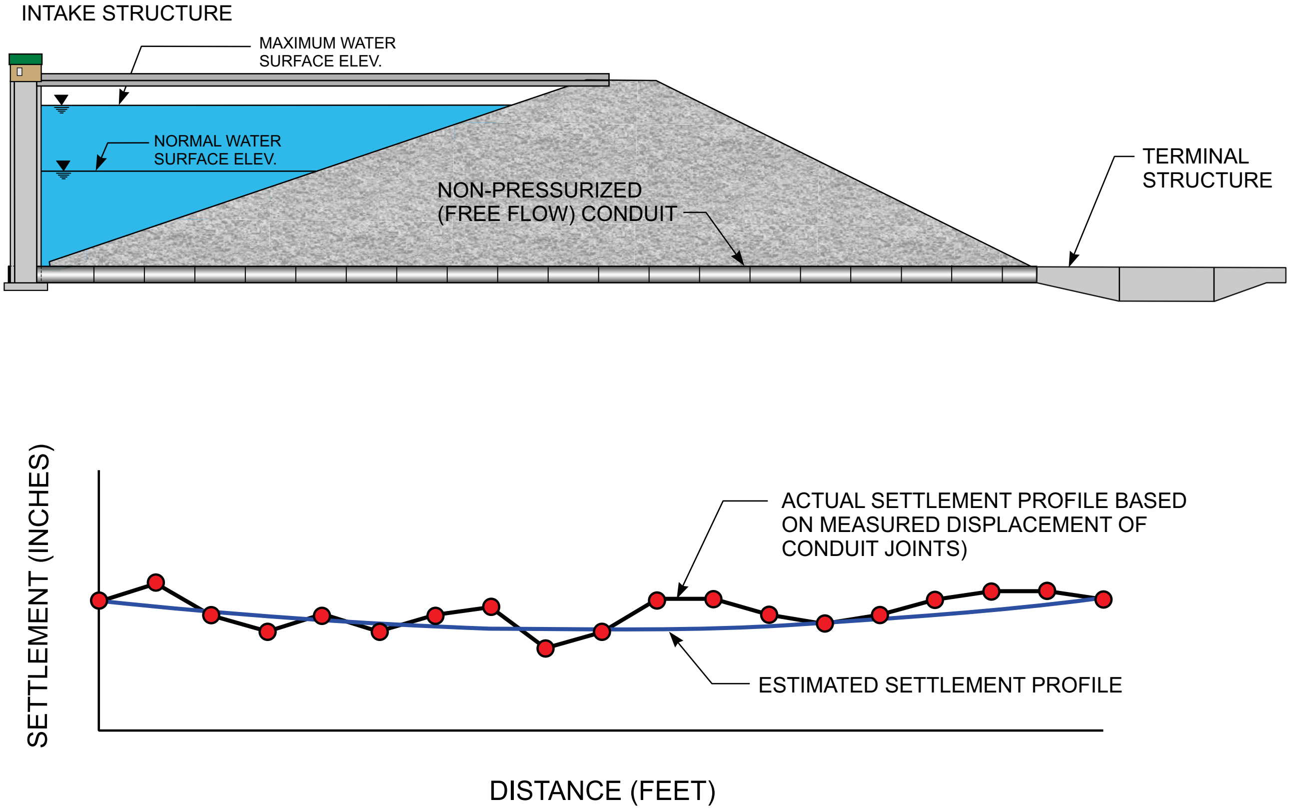



(FEMA, 2005a)

FIGURE 6.65 COMPARISON OF PREDICTED AND OBSERVED CONDUIT SETTLEMENTS

disparity in the weights and foundation conditions between the two structures. If both structures are constructed over relatively soft materials, the intake structure will tend to settle much more than the conduit. If the intake structure is constructed over engineered fill of low compressibility or on deep foundation elements, the conduit may tend to settle more than the intake structure. Either situation can lead to excessive deformation of the conduit joints in the vicinity of the intake structure. Under such circumstances, provisions to allow for relative movement may need to be incorporated into the design.

### 6.6.7 Blasting Impacts

Blasting must be conducted in such a manner as to prevent injury to site personnel and unacceptable impacts to structures associated with a coal refuse disposal facility, including refuse or earthen embankment dams and their impoundments. Impacts to off-site structures and properties must also be limited in accordance with applicable guidelines. Typically, embankment dams have very low natural frequencies (on the order of 1 hz) and thus are not particularly susceptible to damage due to blast vibrations, which have a much higher frequency range. If it is believed that blast effects could have a deleterious effect on site structures (such as for embankments developed by the upstream construction method), the impact of ground motion for the anticipated magnitude and frequency range of blast vibrations can be considered using the procedures for seismic stability described in Chapter 7. Some structures associated with fresh water dams, such as large concrete spillway channels, tall riser intake structures or pipelines under low confinement could possess natural frequencies similar to blast frequencies and thus be impacted by blasting. However, typical concrete structures and pipelines used at coal refuse facilities are normally not very susceptible to damage from blasting vibrations.

Structures are affected by blasting in relation to the peak particle velocity and frequency content of the ground motion induced by a blast. Simplified relationships are commonly used to determine the charge size relative to the horizontal distance to the monitoring point in order to meet acceptable motion (velocity) criteria. One such relationship for the peak particle velocity $V$ resulting from a blast is (ISEE, 1998):

$$V = K(D/W^{0.5})^{-1.6} \tag{6-33}$$

where:

$K$ = site-specific constant determined from calibration test

$D$ = distance to blast (length)

$W$ = weight of charge (force)

Topographic and geologic variations between the blast location and observation point and the position of the blast horizon relative to the foundation of the structure can significantly affect the attenuation or amplification of blast-induced ground motions.

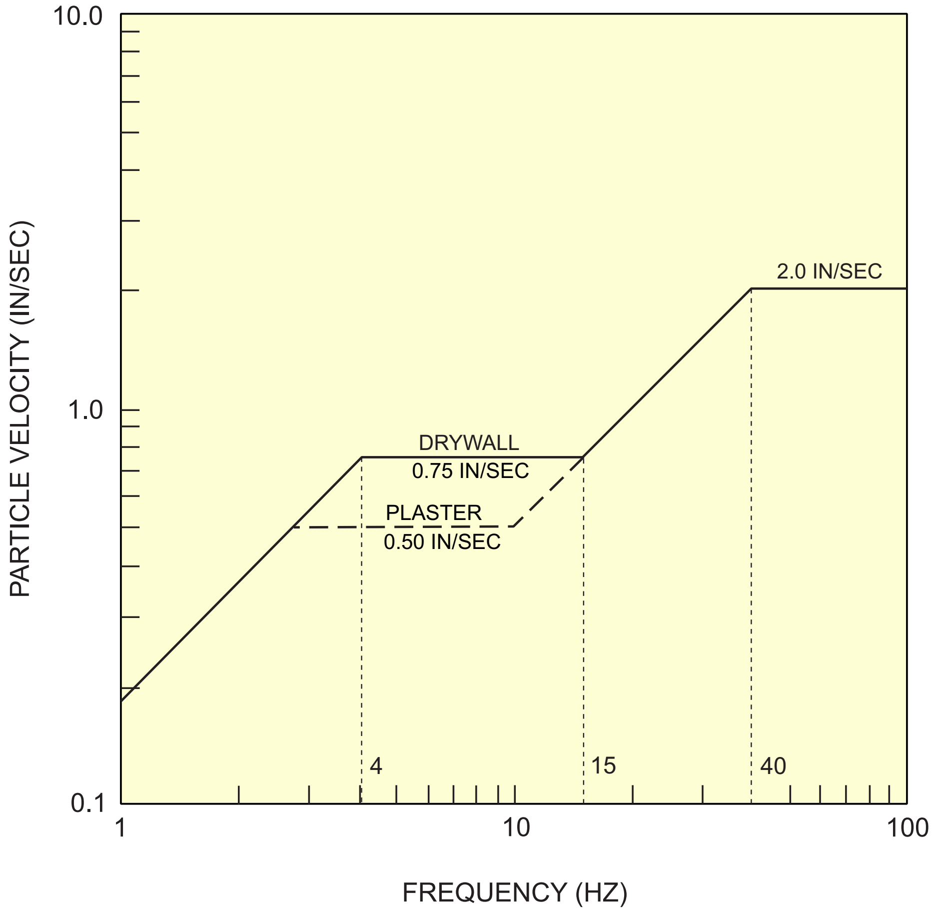
Acceptable vibration criteria are published in a number of sources: state regulatory programs typically provide guidance for peak particle velocity for common structure types, and general guidance can be found in Nichols et al. (1971), Siskind et al. (1980), ISEE (1998), and Hartman (1992). Blasting for excavation of rock materials is generally controlled to a peak particle velocity (PPV) of 4 inches per second for mass concrete structures (Hartman, 1992) and to 2 inches per second for typical steel and concrete superstructures. Notably, these PPV thresholds are generally very conservative and correlate to the possible onset of visible cosmetic damage. The noted structure types can typically tolerate much higher PPVs before structural damage occurs. Table 6.57 provides additional information on levels of damage to houses for specific particle velocities, and Figure 6.66 shows acceptable limits of vibration for houses, as recommended in Siskind (1980).

When blasting is planned within 500 feet of an active underground mine, the Surface Mining Control and Reclamation Act of 1977 requires approval of an operator's blasting plan by OSM, or the appropriate state agency, and MSHA. Blasting regulations are provided in 30 CFR § 780.13 and 30 CFR §

TABLE 6.57 COMMON RESIDENTIAL VELOCITY CRITERIA AND EFFECTS

| Velocity | Damage Level |
|---|---|
| 0.5 in/sec | Recommended limit to prevent threshold damage in plaster-on-lath construction near surface mines due to long-term, large-scale blasting operations (USBM, 1980). |
| 0.75 in/sec | Recommended limit to prevent threshold damage in sheetrock construction near surface mines (USBM, 1980). |
| 1.0 in/sec | Office of Surface Mining (OSM) regulatory limit for residences near surface mine operations at distances of 300 to 5,000 ft (long-term, large-scale blasting). |
| 2.0 in/sec | Widely accepted limit for residences near construction blasting and quarry blasting. Also allowed by OSM for frequencies above 30 hz (USBM; 1971, 1980). |
| 5.4 in/sec | Minor damage to the average house subjected to quarry blasting vibrations (USBM, 1971). |
| 9.0 in/sec | About 90 percent probability of minor damage from quarry blasting. Structural damage to some houses, depending on vibration source, characteristics and house construction. |
| 20.0 in/sec | For close-in construction blasting, minor damage to nearly all houses, structural damage to some. For low-frequency vibrations, structural damage to most houses. |

(ADAPTED FROM ISEE, 1998)




(ADAPTED FROM SISKIND ET AL., 1980)

FIGURE 6.66 ACCEPTABLE LIMITS OF VIBRATION FOR HOUSES

816.61 through 816.68 and 816.79. State criteria may also be applicable. The blasting plan should be prepared by a professional licensed in the state where the blasting is to be performed. Potential concerns when an impoundment is present include fracturing of abutments, impacts to pipes and other rigid structures, and possibly impacts to upstream construction. The potential impacts should be evaluated, and monitoring of particle velocity with a seismograph may be appropriate. Monitoring of specific structures and features may be warranted and could include inspection of impounding embankment crests and slopes for evidence of cracks or displacements, review of piezometer data for evidence of water level fluctuations, and observation of concrete joints or crack apertures to verify the general integrity and to note any movements.

# Chapter 7

# SEISMIC DESIGN: STABILITY AND DEFORMATION ANALYSES

## 7.1 GENERAL

### 7.1.1 Design Approach

Under certain conditions, seismic loadings from an earthquake or other source can cause embankment or foundation materials to lose strength, potentially causing a structure to become unstable. Coal refuse embankments constructed using the upstream construction method may be particularly susceptible to instability from an earthquake because a portion of the dam is constructed on soft or loose saturated, hydraulically-placed material. Designers should perform an evaluation (commensurate with the hazard potential of the structure) to confirm that dam and embankment designs provide an adequate margin of safety against seismically-induced instability.

The methods of exploration, testing, and analysis presented in this chapter are based on research and practice, publications, and experience on a variety of projects. They provide a variety of options for design. These methods, ranging from basic to sophisticated, have generally been applied on coal refuse disposal sites. Commentary is provided in the text to help explain the basis for the methods and the applicability of the methods to specific situations. It is recognized that refinements in the methods, as well as new methods, may be developed in the future. Designers are encouraged to evaluate such refinements, new methods, and other approaches that are technically sound, particularly if they better address site-specific materials or conditions. Designers are also cautioned that this subject is complex and that refinements of existing methods and development of new methods can require substantial research and investigation, as well as input from geologists, seismologists, geotechnical engineers, and other professionals.

This chapter refers to dams and embankments interchangeably. Also, references to “soil” or “material” encompass soils and coal refuse materials (e.g., fine coal refuse or tailings, filter cake, combined coal refuse, mixed refuse, coarse coal refuse, and amended refuse). As there have been no reported failures of coal refuse embankments due to seismic loading within the U.S. coalfields, the various studies of strength loss due to seismic loading are predominantly from sites that contain natural soils or other mine tailings. Thus, the physical behavior of coal refuse materials must be inferred from correlations, supported by laboratory testing.

The following published papers, studies and ongoing research on coal refuse materials and seismic design of disposal sites provide an overview of information specific to slurry impoundments and potential information on testing and parameters that may be available:

- Gardner and Wu (2002) present an overview of challenges in evaluating strength loss at coal refuse disposal facilities from MSHA's perspective. They summarize the available pore-pressure-based empirical methods (field standard penetration testing and cone penetration testing) and strain-based laboratory methods (undrained steady-state shear strength approach based on triaxial compression tests) for evaluation of potential strength loss at coal refuse disposal impoundments.
- Castro (2003) presents the undrained peak strengths and undrained steady-state strengths derived from cone penetration testing, field vane-shear tests, laboratory tests on undisturbed samples and laboratory-consolidated slurry samples. These strength data show that strength loss of fine tailings is noticeable and the undrained steady-state strength values are typically between one-half and one-fourth of the peak undrained strength. The paper also provides cyclic-triaxial test data for undisturbed samples of natural clayey silt of low plasticity, similar to fine tailings, to show the degradation of peak undrained strength with strain during cyclic loading.
- Genes et al. (2000) present the undrained steady-state shear strength approach for evaluation of strength loss at five coal refuse disposal facilities in West Virginia. Isotropically-consolidated, undrained triaxial compression tests of undisturbed and remolded samples of fine coal refuse from five different disposal sites are presented to show undrained steady-state shear strength variation with void ratio and effective vertical stress.
- Ulrich et al. (1991) present a pore-pressure-based evaluation using cyclic-triaxial tests on samples of fine coal refuse from sites in Kentucky, Ohio, and Tennessee.
- Cowherd and Corda (1998) discuss pore-pressure-based empirical methods for triggering of strength loss at coal refuse dams and provide standard penetration tests data along with the measured seismic shear wave velocities for fine coal refuse, with a summary of cyclic-triaxial test results from four disposal sites.
- Hegazy et al. (2004) presents engineering properties for northern Appalachian coal refuse, including a summary of results of seismic piezocone testing and field vane-shear testing used for determining undrained shear strength.
- Kalinski and Phillips (2008) present a progress report on research being conducted at the University of Kentucky concerning development of dynamic properties of coal refuse. When completed, it will include field and laboratory testing on the dynamic behavior of coal refuse materials. Field standard penetration testing, cone-penetration testing, field vane-shear testing, seismic surface-wave testing, and downhole-seismic testing are to be performed. Complementary laboratory cyclic-triaxial testing and resonant-column testing are also proposed for determining dynamic properties of coal refuse materials.
- Zeng and Goble (2008) present the results of laboratory testing (resonant-column and cyclic-triaxial tests) for determining dynamic properties (damping ratio and shear modulus) performed on Appalachian coal refuse at Case Western Reserve University.

Seismic design of dams and embankments involves two separate requirements:

1. Prevention of seismic instability (slides)
2. Prevention of excessive deformations (translation, settlement, and cracking)

#### 7.1.1.1 Seismic Instability

The ground motion from an earthquake can result in a reduction in the shear strength of loose, saturated materials. Seismic instability may occur when post-earthquake shear strength is less than the pre-earthquake shear strength in one or more significant zones of an embankment or foundation. The driving force of the seismic instability is the static (gravity) weight of the embankment. Seismic instability is a particular concern for dams with substantial upstream construction because a portion of the dam is constructed on hydraulically-placed fine material. For seismic instability to occur, three conditions must develop:

1. The earthquake shaking must be strong enough to trigger undrained strength loss in one or more zones of material.
2. The strength loss must be significant enough that the post-earthquake shear strengths are less than the static driving shear stresses.
3. The location and amount of the material that experiences strength loss must be sufficient to generate instability.

Seismic stability is generally analyzed as a static (i.e., no seismic coefficient) limit-equilibrium, slope-stability problem, using post-earthquake shear strengths for the materials in the embankment and foundation. The earthquake shaking causes the material in the embankment or foundation to lose strength, but the static gravity shear stresses drive the failure. Some instability failures have been observed to occur after the earthquake shaking has stopped (Seed et al., 2003; Seed and Harder, 1990; Marcuson, Hynes and Franklin, 1992).

Experience has shown that when significant strength loss occurs in critical sections of a structure: (1) failures are often rapid, (2) they occur with little warning, and (3) the resulting deformations are often very large. Experience has also shown that the trigger events can be quite small. Hence, seismic design for significant- to high-hazard-potential dams and embankments should be carried out with caution and care.

#### 7.1.1.2 Excessive Deformations

If seismic stability analyses indicate that an embankment is unstable, then deformations should be considered to be unacceptably large. However, if seismic stability analyses indicate that an embankment is stable, then potential seismic deformations should be assessed. Seismic deformations occur primarily during earthquake shaking. The cyclic-shear stresses induced by the earthquake contribute directly to the deformations. This contrasts with the primary mechanisms of instability. In seismic instability, the earthquake shaking causes undrained strength loss, but the static gravity stresses drive the instability failure.

The material making up the dam or embankment, the fine coal refuse or tailings retained behind and sometimes underlying the embankment, and the natural soil below the embankment must all be evaluated as part of stability and deformation analyses.

The basic elements for seismic design and analysis require evaluation of:

- Susceptibility of materials to strength loss and post-earthquake strengths
- Seismic stability using post-earthquake strengths
- Whether the design earthquake will trigger strength loss
- Deformations

### 7.1.2 Seismic Design Considerations and Flow Chart

The following points were considered in developing the guidance and recommendations presented in this chapter:

- The levels of analysis that should be performed vary depending on the type of facility and the consequences of failure. So, for example, no seismic analysis is required for low-hazard-potential dams (provided static stability is satisfied), while seismic stability and deformation analyses are required for high-hazard-potential dams.
- Methods for evaluating the susceptibility of a material to strength loss during an earthquake and for evaluating the degree of strength loss depend partly on whether the material is sand-like or clay-like. Fine coal refuse within a structure, and natural soil deposits in the foundation, might include zones of both sand-like and clay-like material. Therefore, methods for evaluating both sand-like and clay-like material are provided. These methods apply to both coal refuse materials and soil.
- Straightforward screening methods should be available for differentiating zones that are potentially susceptible to seismically-induced strength loss from zones that are not susceptible. Further detailed investigation and evaluation can then be focused on the potentially-susceptible zones. This chapter presents screening methods for both clay-like and sand-like material that require only the basic information provided by Standard Penetration Test (SPT) or Cone Penetration Test (CPT) data, grain-size test results, and Atterberg-limit data.
- Relatively straightforward methods of analysis should be available to designers, as well as methods that are more sophisticated. The more sophisticated methods may allow for less conservatism in the design and might be worthwhile for achieving a more economical design. However, the more sophisticated methods are optional, not required. For example, relatively straightforward field testing methods can be used to estimate post-earthquake strength, as well as more sophisticated, optional, laboratory methods. Another example is that seismic-stability analyses can be performed by simply assuming that the design earthquake triggers strength loss in materials that are potentially susceptible to strength loss, or an optional triggering analysis can be performed to evaluate whether the design earthquake is in fact strong enough to trigger strength loss. The authors of this chapter note that triggering analyses are not considered to be appropriate for sand-like materials for design earthquakes that exceed certain criteria and therefore impose significant seismic stresses on the materials. In designing new structures, it is often prudent to design based on the relatively straightforward methods rather than using more sophisticated methods to justify a design.
- The level of detail required for evaluation of the seismicity of a site should depend on the level of seismic hazard at the site. Many coal mining regions in the U.S. are in areas of low seismic hazard. Minimum parameters for the design earthquake in these areas are provided, and a site-specific evaluation is not recommended. For sites in areas of higher seismic hazard, a site-specific seismicity evaluation is recommended.
- The various credible methods employed by geotechnical engineers experienced in the seismic design of dams should be available for use. Therefore, this chapter presents three methods for analyzing the triggering of strength loss in loose, sand-like material: (1) the pore-pressure-based approach developed by Seed and updated by Youd et al. (2001), (2) the strain-based approach developed by Castro (1994), and (3) the stress-based approach developed by Olson and Stark (2003). Several field and laboratory methods and correlations for estimating post-earthquake strength of materials that are susceptible to strength loss and several methods for performing deformation analyses are also presented.
- Structures should generally have a safety factor of at least 1.2 for seismic stability based on a static stability analysis using post-earthquake material strengths. This safety factor is intended to account for uncertainties in the geometry of the structure,

in the shear strength, and in the delineation of zones that are potentially susceptible to strength loss, and it also helps achieve designs for which predicted seismic deformations are within acceptable limits.

- There may be special cases involving existing facilities for which the recommended design criteria can be relaxed. Examples of these special cases include minor modifications made as part of closure activities in which the progress toward closure will eventually improve seismic stability, and interim improvements for addressing a specific existing deficiency (e.g., adding an interim stage to provide needed freeboard).

The recommended steps for a seismic evaluation or design are illustrated in the flow chart presented in Figures 7.1a, 7.1b and 7.1c. These steps are described in detail in Section 7.4.4. A relatively straightforward path through the seismic stability portion of the flow chart (in which triggering analyses, sophisticated laboratory testing, and seismicity evaluations are avoided) is described in Section 7.1.5.

The steps in the flow chart in Figure 7.1a can be summarized as follows:

1. Classify the structure and foundation based on type, size, downstream hazard potential, and anticipated performance under seismic loading, per the criteria indicated in Boxes 1, 2, and 3 of the flow chart.
2. Considering the classification in Step 1, and a conservative evaluation of post-earthquake stability (optional, Boxes 5 and 6), categorize the structure and foundation as either (1) further seismic evaluation is not needed (go to Box 4) or (2) potentially susceptible to seismic instability such that additional analysis is required (go to Box 7).
3. For those structures that are potentially susceptible to seismic instability, thoroughly characterize the soils and refuse in the structure and foundation (Box 7 of flow chart and Section 7.3 of text). This step generally requires a significant effort because the spatial distribution of the refuse materials can be variable. Identify zones in the structure and foundation that may be susceptible to strength loss due to earthquake shaking (Section 7.4.4.2).
4. Analyze the stability of the embankment using post-earthquake strengths (Section 7.4.3). Post-earthquake strengths will be lower than pre-earthquake (static) strengths for zones that are susceptible to strength loss. This analysis may be relatively straightforward based on field testing data and laboratory index testing (Boxes 7, 7A, and 8). At coal refuse disposal sites where the ratio of coarse to fine refuse is large enough to allow design of massive (wide) embankments with broad crests, employing the basic and more straightforward methods are recommended because of their relative simplicity in design and regulatory review and their conservatism. Alternatively, sophisticated laboratory testing can be used to provide better estimates of post-earthquake strength, and relatively complex triggering analyses can be performed to evaluate whether the earthquake shaking is actually strong enough to trigger strength loss in the materials that are potentially susceptible to strength loss (Boxes 9 through 16 and Sections 7.4.2 and 7.4.3.2). A seismic hazard evaluation (Section 7.7 and Figure 7.23) may be needed as part of these more sophisticated testing and analysis methods to define the magnitude and peak ground acceleration of the design earthquake and to obtain representative time histories of acceleration. These more sophisticated testing and analysis methods are often less conservative than the basic and more straightforward methods. The added costs of the more sophisticated testing and analysis may be justified by designs that are more economical or more efficient from an operational standpoint.

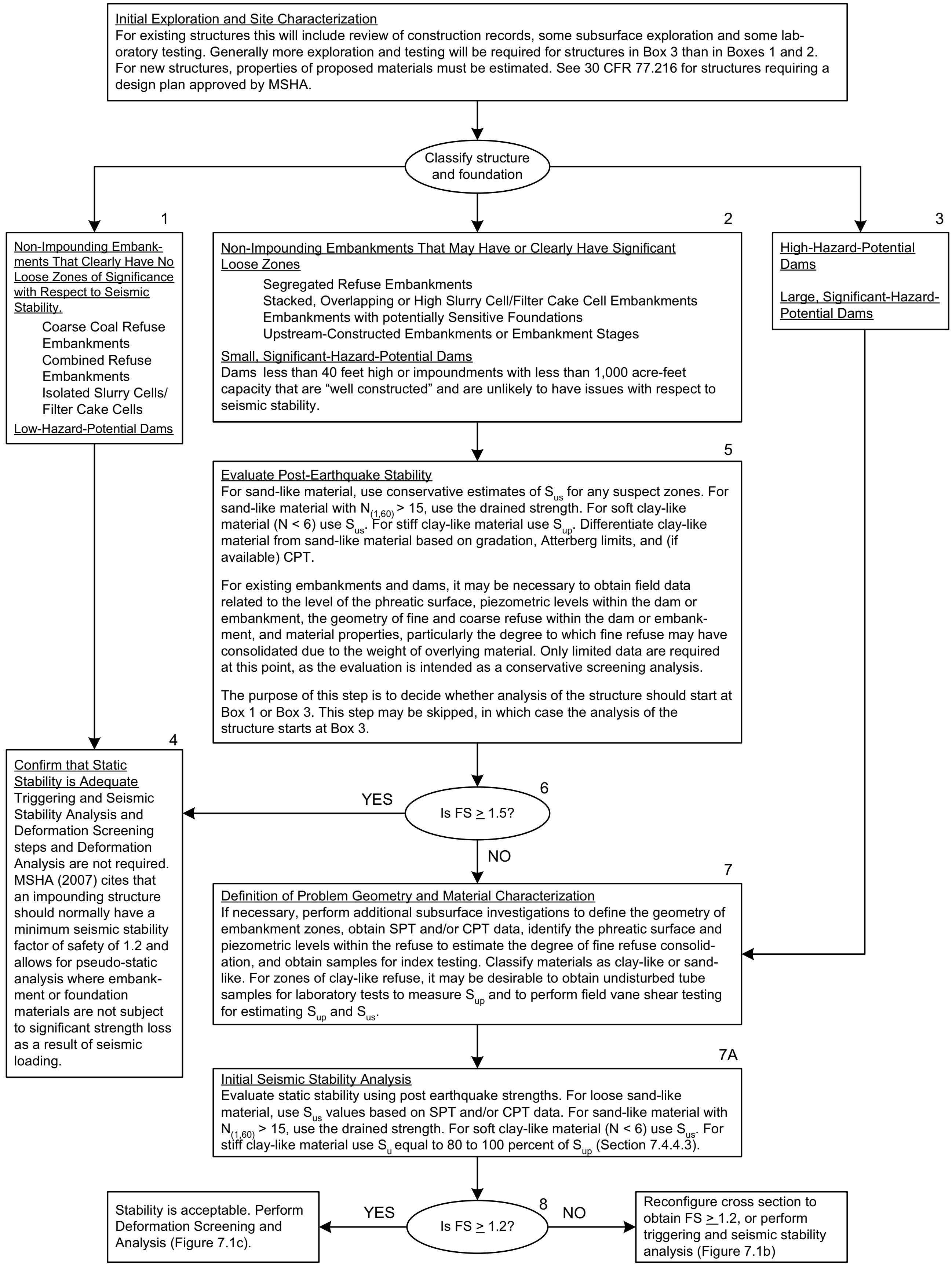



FIGURE 7.1a SEISMIC STABILITY SCREENING

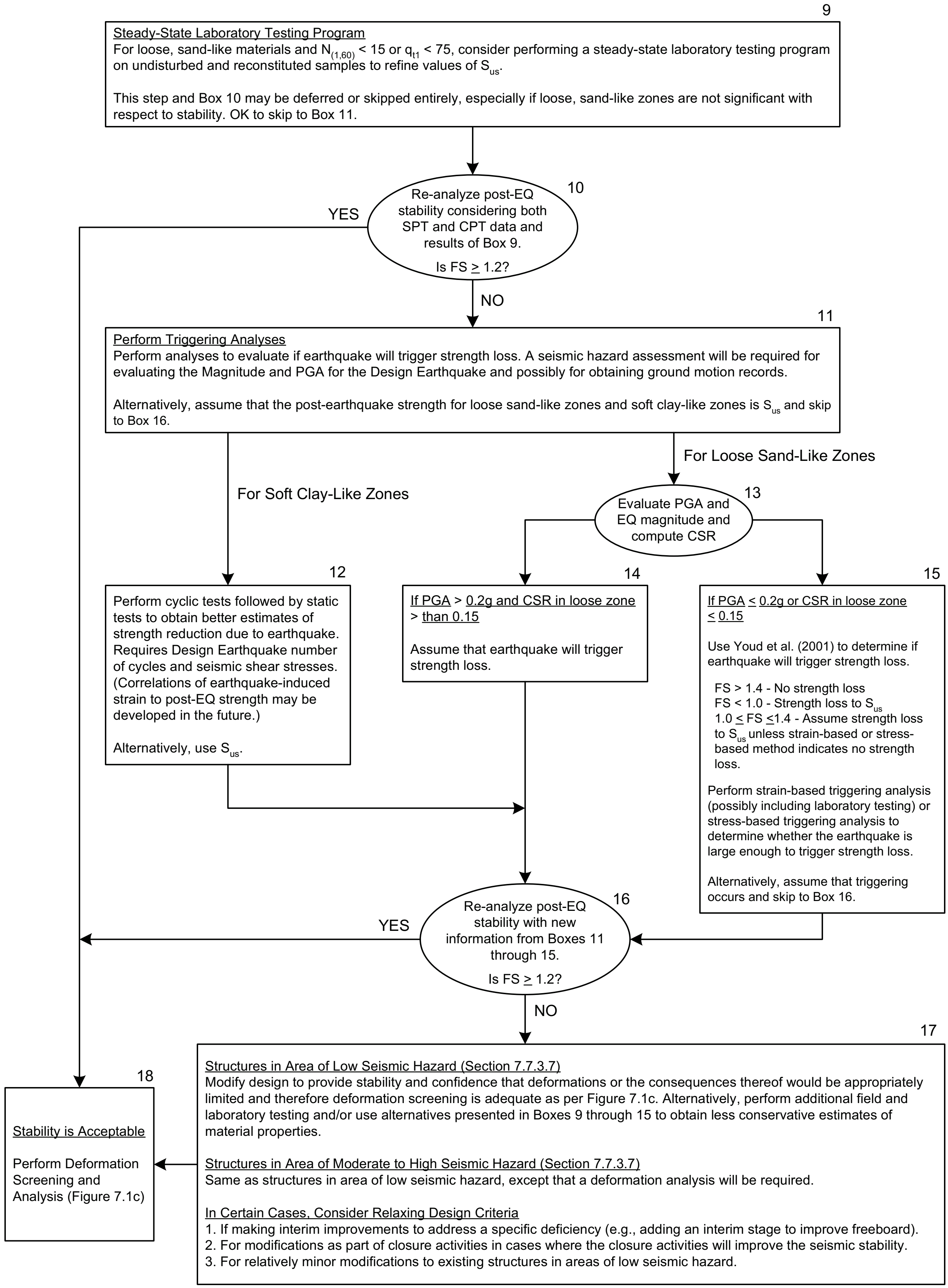



FIGURE 7.1b TRIGGERING AND SEISMIC-STABILITY ANALYSIS

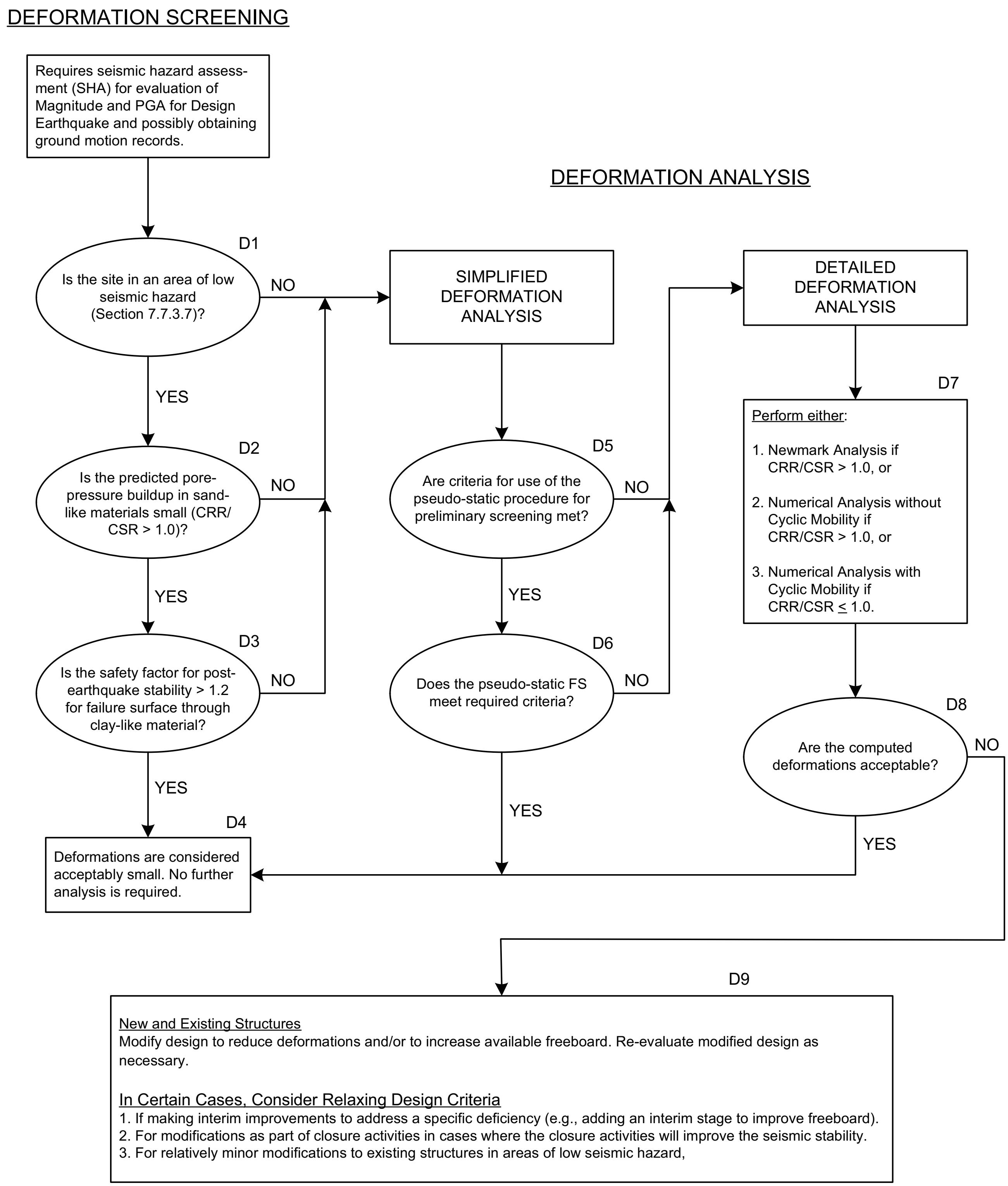



FIGURE 7.1c DEFORMATION SCREENING AND ANALYSIS

5. If stability is acceptable (safety factor of 1.2 or higher), evaluate potential deformations (Step 7).
6. If stability is not acceptable, redesign or modify the embankment until stability is acceptable (Box 17).
7. Evaluate potential deformations of the embankment caused by the earthquake shaking (Boxes D1 through D8 and Section 7.5). The deformation analysis may involve a

relatively simple screening analysis or may require sophisticated computer modeling. If not performed as part of Step 4, a seismic-hazard evaluation (Section 7.7 and Figure 7.23) will be needed as part of the deformation analysis.

8. If the estimated deformations are within an acceptable range, accept the design. Otherwise, redesign or modify the embankment (Box D9).

### 7.1.3 Sand-Like Versus Clay-Like Material

For many of the analyses described in this chapter, fine coal refuse and natural soils are referred to as sand-like or clay-like depending on whether they exhibit monotonic and cyclic undrained shear loading behavior that is fundamentally more similar to that of either sand or clay. The methods for evaluating susceptibility to strength loss, triggering, and post-earthquake strength are different for sand-like and clay-like materials. This differentiation is significant primarily if the material is loose enough (sands) or soft or sensitive enough (clays) that it is potentially susceptible to strength loss.

The key factors in differentiating loose sand-like material from soft or medium clay-like material, for the purposes of seismic stability and deformation analyses, are the strain at peak undrained strength and the abruptness of the drop-off in shearing resistance as strains increase beyond the strain at peak. Loose sands and highly sensitive clays can reach peak undrained strength $S_{up}$ at small strains, and experience abrupt drop-off in resistance at higher strains. Most clays tend to reach $S_{up}$ at higher strains, and tend to experience more gradual and limited drop-off in shearing resistance at higher strains. Fine coal refuse deposits often include materials falling within both classifications, and near the boundary of these two types of behavior.

Loose material with shear strain at peak strength of less than 2 percent in an undrained monotonic (non-cyclic) test, and a rapid drop-off in resistance after reaching peak strength, is generally considered sand-like (although highly sensitive clays may exhibit similar behavior). Loose or soft material with shear strain at peak strength of more than about 5 percent, and a gradual drop-off in resistance after reaching peak strength is considered clay-like. Figure 7.2 illustrates the associated stress-strain curves for these materials. Material with strain behavior between these descriptions is considered borderline. It should be noted that shear strain in an undrained triaxial test is 1.5 times axial strain. Peak strength refers to peak principal stress difference ($\sigma_1 - \sigma_3$).

For the analyses in this chapter, it is generally more conservative to assume that a borderline material is sand-like than to assume it is clay-like. It is very difficult to obtain or prepare samples of in-situ low plasticity material for strength testing at its in-situ void ratio. Therefore, Atterberg-limits tests, gradation tests, and, preferably, CPT data should be used first as an index of stress-strain behavior to categorize materials as sand-like or clay-like. Laboratory stress-strain testing should be used to help categorize borderline materials.

The following criteria are recommended:

- Atterberg limits and gradation – Material should be treated as sand-like if the plasticity index of the material (measured from the portion passing the No. 40 sieve) is 7 or less.

  Material should be considered clay-like if all of the following criteria are met:

  - The material has 35 percent or more by dry weight passing the No. 40 sieve.
  - The material has 20 percent or more by dry weight passing the No. 200 sieve.
  - The plasticity index of the material (as measured by the portion passing the No. 40 sieve) is 10 or higher.