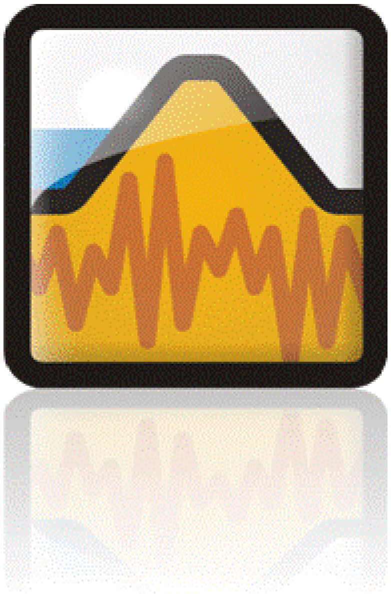

Dynamic Modeling with

QUAKE/W 2007

An Engineering Methodology

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1 Introduction

QUAKE/W is a geotechnical finite element software product used for the dynamic analysis of earth structures subjected to earthquake shaking and other sudden impact loading such as, for example, dynamiting or pile driving.

QUAKE/W is part of GeoStudio and is, consequently, fully integrated with the other components such SLOPE/W, SEEP/W, SIGMA/W for example. In this sense, QUAKE/W is unique. The integration of QUAKE/W and other products within GeoStudio greatly expands the type and range of problems that can be analyzed beyond what can be done with other geotechnical dynamic analysis software. QUAKE/W can be used as a stand alone product, but one of its main attractions is the integration with the other GeoStudio products.

The purpose of this document is to highlight concepts, features and capabilities, and to provide some guidelines on dynamic numerical modeling. The purpose is not to explain the software interface commands. This type of information is provided in the on-line help.

The remainder of this chapter provides a brief overview of the main geotechnical issues related to the response of earth structures subjected to seismic loading and how QUAKE/W is positioned to address these issues. The intent here is not to provide an exhaustive review of the state-of-the-art of geotechnical earthquake engineering. The intent is more to provide an indication of the thinking behind the QUAKE/W development.

The textbook, *Geotechnical Earthquake Engineering*, by Steven Kramer (1996) provides an excellent summary of the concepts, theories and procedures in geotechnical earthquake engineering. This book was used extensively as a background reference source in the development of QUAKE/W and is referenced extensively throughout this document. QUAKE/W users should ideally have a copy of this book and use it in conjunction with this documentation. It provides significantly more details on many topics in this document.

1.1 Key issues

The response and behavior of earth structures subjected to earthquake shaking is highly complex and multifaceted. Generally, there are the issues of:

the motion, movement and inertial forces that occur during the shaking, the generation of excess pore-water pressures,

the potential reduction of the soil shear strength,

the effect on stability created by the inertial forces, excess pore-water pressures and possible shear strength loses, and

the redistribution of excess pore-water pressures and possible strain softening of the soil after the shaking has stopped.

Not all these issues can be addressed in a single analysis, nor is it possible to address all the issues in the current version of QUAKE/W. Effects such as strain softening and re-distribution of excess pore-pressures will be perhaps dealt with in future version. The point here is that there are many issues and to use QUAKE/W effectively it is important to at least be aware of the multifaceted nature of the problem.

1.2 Inertial forces

Earthquake shaking creates inertial forces; that is, mass times acceleration forces. These forces cause the stresses in the ground to oscillate. Along a potential slip surface, the mobilized shear strength decreases and increases in response to the inertial forces. There may be moments during the shaking that the mobilized shear strength exceeds the available shear resistance, which causes a temporary loss of stability. During these moments when the factor of safety is less than unity, the ground may experience some displacement. An accumulation of these movement spurts may manifest itself as permanent displacement.

Figure 1-1 illustrates how the factor of safety may change during an earthquake. Note that the factor of safety falls below 1.0 five times during the earthquake. Subtracting the QUAKE/W computed stresses from the initial static stresses gives the additional shear stresses arising from the inertial forces. This information together with the Newmark Sliding Block concepts can be used to estimate the permanent deformation. In GeoStudio, SLOPE/W uses the QUAKE/W results to perform these calculations.

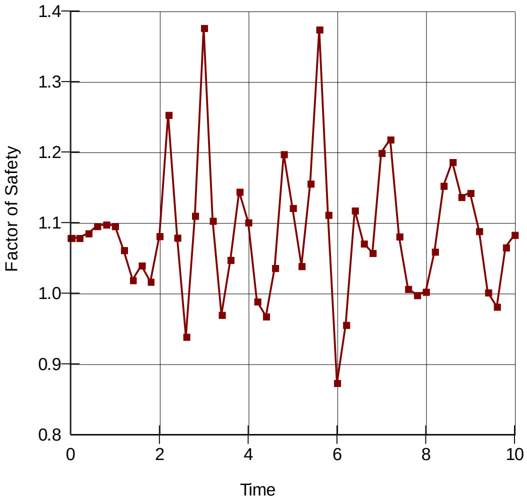

Figure 1-1 Factor of safety as a function of time during an earthquake

As discussed in more detail later in this book, examining the potential permanent deformations resulting from the dynamic inertial forces is applicable only to certain situations. It is only one aspect of earthquake engineering and does not provided answers to all to issues.

In the late 1990's an embankment was constructed in Peru at a mine site to control temporary flooding (Swaisgood and Oliveros, 2003). The embankment was constructed from mine waste with a concrete blanket on the upstream face to control seepage through the embankment. The embankment was very wide with 4:1 side slopes and a crest width of 130 m. The embankment materials were expected to remain essentially dry (unsaturated) most of the time since water would be ponded up against the dam only for short durations after heavy rainfalls. On June 23, 2001, a Magnitude 8.3 earthquake struck the southern portion of Peru. The newly constructed dam was heavily shaken by the tremors. The dam, however, endured the shaking without much damage. The downstream crest settled only about 50 mm.

The Peru Dam is a case that lends itself well to a Newmark-type permanent deformation analysis arising from the earthquake inertial forces. The unsaturated coarse material meant that there was no generation of excess pore-pressure and very little change, if any, in the shear strength of the fill, conditions essential to an analysis like this.

1.3 Behavior of fine sand

Loose contractive sand

As is well known, loose sandy soils are susceptible to liquefaction. There are many variables besides grain size distributions that influence the potential for the soil to liquefy. Two of the more prominent are the density or void ratio, and the stress state. Different starting stress states can have a profound effect on the soil behavior when subjected to monotonic or cyclic loading. The behavior can best be described in the context of a q-p´ plot (shear stress versus mean normal stress).

Consider the diagram in Figure 1-2. If a sample is isotropically consolidated (Point A), the effective stress path under undrained monotonic loading will follow the curve in Figure 1-2. Initially, the shear stress will rise, but then curve over to the left and reach a maximum at which point the soil-grain structure collapses. After the collapse there is a sudden increase in pore-pressure and the strength falls rapidly to the steady-state strength.

Another way of describing this is that liquefaction is initiated at the collapse point.

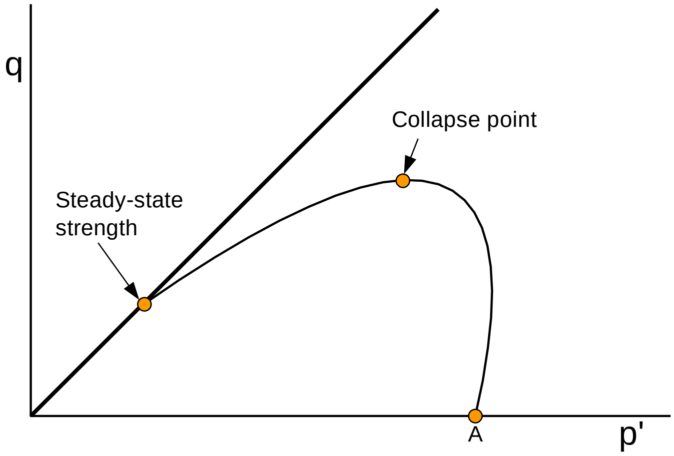

Figure 1-2 Effective stress path for loose sand under monotonic loading

Figure 1-3 presents the picture for a series of tests on triaxial specimens at the same initial void ratio, but consolidated under different confining pressures. A straight line can be drawn from the steady state strength point through the peaks or collapse points. Sladen, D'Hollander and Krahn (1985) called this line a Collapse Surface. Similar work by Hanzawa et al. (1979) and by Vaid and Chern (1983) suggests that the line through the collapse points passes through the plot origin (zero shear stress, zero mean stress) as opposed to the steady-state strength point. They called the line a *Flow Liquefaction Surface*.

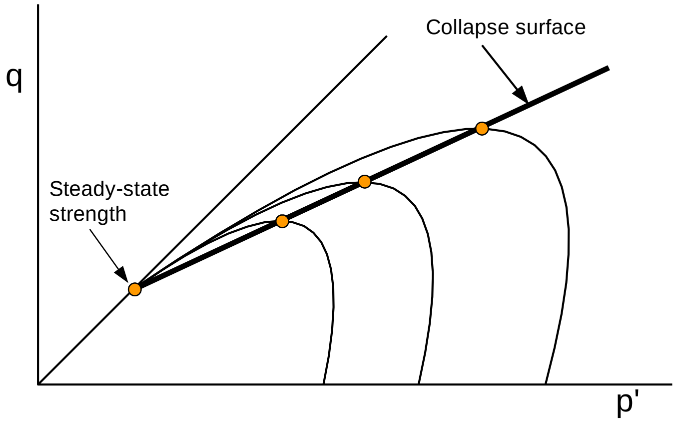

Figure 1-3 Collapse surface illustration

The fact that the sudden loss in strength is related to the collapse of the soil-grain structure has been vividly demonstrated by Skopek et al. (1994) with laboratory tests on dry sand. The highlight of their testing is shown in Figure 1-4 and Figure 1-5. The samples were tested under a constant shear stress. Initially, the void ratio remained relatively constant, but then dramatically decreased when the soil-grain structure collapsed, particularly for the Path 2 test. The point of significance is that this behavior occurred for dry sand; that is, the volumetric compression occurred in the absence of any pore-pressure. The only logical reason then for the compression is that the grain-structure changed.

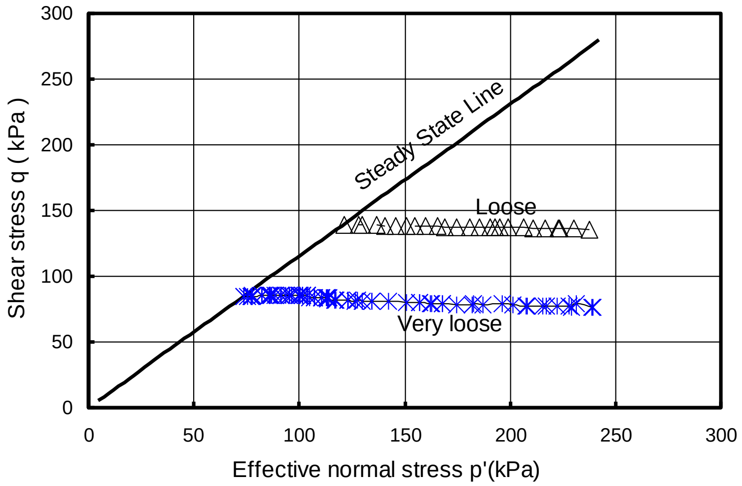

Figure 1-4 Tests on dry sand (after Gu et al. 2002)

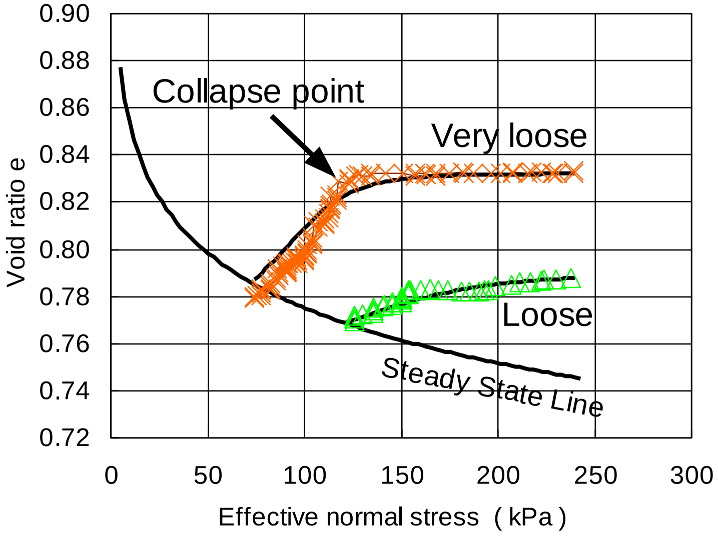

Figure 1-5 Tests on dry sand (after Gu et al. 2002)

An important point is that the sudden loss in strength and the resulting liquefaction can occur under monotonic load – not just cyclic loading.

Cyclic loading can also lead to liquefaction as is illustrated in Figure 1-6. Say a sample is at a stress state represented by Point B and a cyclic load is applied. Pore pressures will continue to increase until the stress cyclic path reaches the collapse surface. The soil will then liquefy and the strength will suddenly fall along the collapse surface to the steady state point.

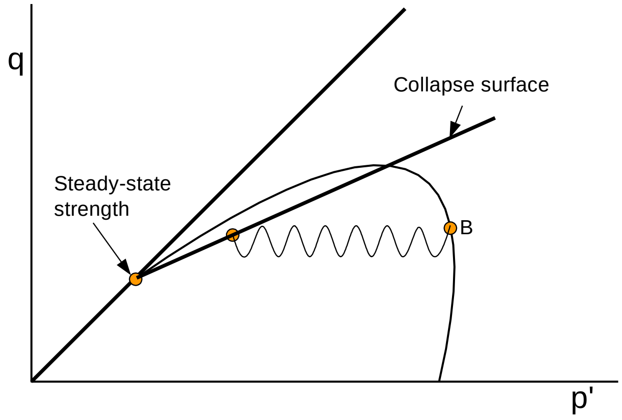

Figure 1-6 Cyclic stress path from B to the collapse surface

Dense dilative soils

The effective stress for dense dilative soils is as shown in Figure 1-7. A stress path starting from Point A rises to meet the steady-state point without going through a peak and with no loss in strength.

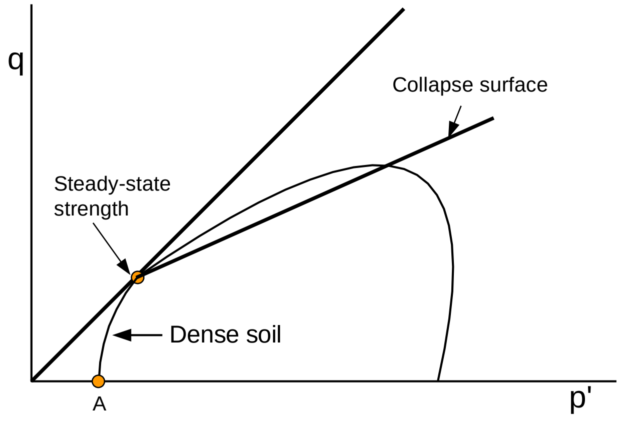

Figure 1-7 Stress path for a dense dilative sand

Excess pore-pressures will also be generated in dilative sand if subject to cyclic loading. Say a soil sample is at a stress state represented by Point B in Figure 1-8. Under cyclic loading, pore-pressures will increase until the effective stress state reaches Point C. Thereafter, Point C will simply move up and down along the stress path between Point A and the steady-state point. If the cyclic loading ends at Point C and then there is further static loading, the soil will dilative and increase in strength until the stress state reaches the steady-state point.

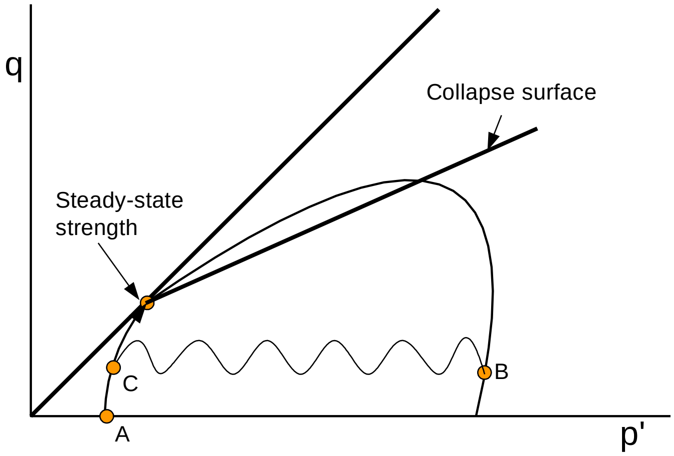

Figure 1-8 Stress path for cyclic loading with starting static stress state below steady-state strength

The strain associated with the cyclic loading from Point B to C in Figure 1-8 is called cyclic mobility.

Gu et al. (2002) present a plastic constitutive model based on the framework of soil critical state boundary theory (Roscoe, et al., 1958). This model can be used to completely describe the complex behavior of sand, which includes contraction, dilation, phase change and ultimate failure at the steady state. This is very brief overview of the behavior of fine sands susceptible to liquefaction in response to static and dynamic loading. The purpose here is to only introduce the subject. Kramer (1996, pp. 348 to 368)) presents a more detailed overview of topic and should be studied by those involved in dynamic analyses of earth structures.

Pore-pressure estimation methods based on cyclic stresses involves making corrections for the initial static shear stress level and the static overburden stress (discussed in the chapter on Material Properties). The above discussion clearly shows why the initial static stress state is so important and why early researchers recognized the need for introducing corrections in the cyclic stress approach.

1.4 Permanent deformation

When there is a zone of soil in a soil structure that has experienced a sudden strength loss, there will be some stress adjustment and re-distribution. Zones that have lost their strength will share their excess load with regions that have not undergone the strength loss. The stress re-distribution will continue until the structure has once again reached a point of equilibrium. If the strength loss is so great that the earth structure cannot re-establish equilibrium, the entire structure will collapse, often with catastrophic consequences. If, however, the structure can find a new point of equilibrium, the stress re-distribution will be accompanied by permanent deformations. The chief engineering issue then becomes to determine how the permanent deformation affects the serviceability of the structure. The question is whether the structure is still functional or can it be repaired to again be functional or is the deformation so severe that the structure can no longer be used for its intended purpose?

There is considerable field evidence as summarized by Gu et al. (1993) that much of the stress re-distribution and the accompanying permanent deformation takes place after the earthquake shaking has stopped. If there is a failure, the failure is delayed by minutes or even hours and for this reason the associated deformation is referred to as post-earthquake deformation.

An extremely important implication of the delayed movement and failure is that the deformations are actually driven by static forces – not dynamic forces. The dynamic forces cause the generation of the excess pore-pressures, but the damaging deformations are driven by static gravitational forces. This has important numerical modeling implications. This being the case, a QUAKE/W dynamic analysis can be used to estimate the generation of excess pore-pressures, but a QUAKE/W analysis is not required to estimate the permanent deformation. The permanent deformation can be modeled with a static software product like SIGMA/W.

Modeling the stress re-distribution should ideally include a strain-softening constitutive relationship to simulate the strength loss. These types of numerical algorithms have been developed and used to study the post-earthquake re-distribution. Gu (1992), for example, developed a strain-softening model as part of his Ph.D. dissertation for analyzing the post-earthquake stress re-distribution and was successful in obtaining good agreement between the model predictions and the observed field behavior at two sites. One was the post-earthquake deformation analysis of the Wildlife Site in California (Gu et al. 1994) and the other was the analysis of the progressive failure that occurred at the Lower San Fernando Dam in California (Gu et al. 1993).

SIGMA/W has a stress re-distribution algorithm which can be used in conjunction with QUAKE/W results. The SIGMA/W method uses an elastic-plastic constitutive model and simply re-distributes the excess stress where the stress state exceeds the soil strength. The procedure can be quite effective even though it does not follow a prescribed strain-softening path. The premise is that somehow there was a strength loss and consequently there is a need to re-distribute the stresses. Stated another way, the SIGMA/W procedure gives the correct end point but not necessarily the correct path to the end point.

The analyses of the San Fernando Dams described in the QUAKE/W detailed examples demonstrate that the SIGMA/W approach together with the QUAKE/W results can be effective in investigating the post-earthquake deformation that may be associated with liquefaction even though it is not a completely rigorous approach.

In version 7.1, SIGMA/W also has a “dynamic deformation” analysis that will consider incremental stresses between saved QUAKE/W time steps as a driving force for permanent deformation if the chosen constitutive model allows for some plastic deformation based on stress-redistribution.

1.5 Concluding remarks

Conceptually, the issues as they relate to dynamic analyses, liquefaction, cyclic mobility and permanent deformation are now fairly well understood. GeoStudio now has all the components to examine all these aspects. Good illustrations of this are available in the QUAKE/W detailed examples. The San Fernando Dam Case Histories, for example, involve seepage analyses with SEEP/W, stability analyses with SLOPE/W, dynamic analyses with QUAKE/W and post-earthquake deformation analyses with SIGMA/W.