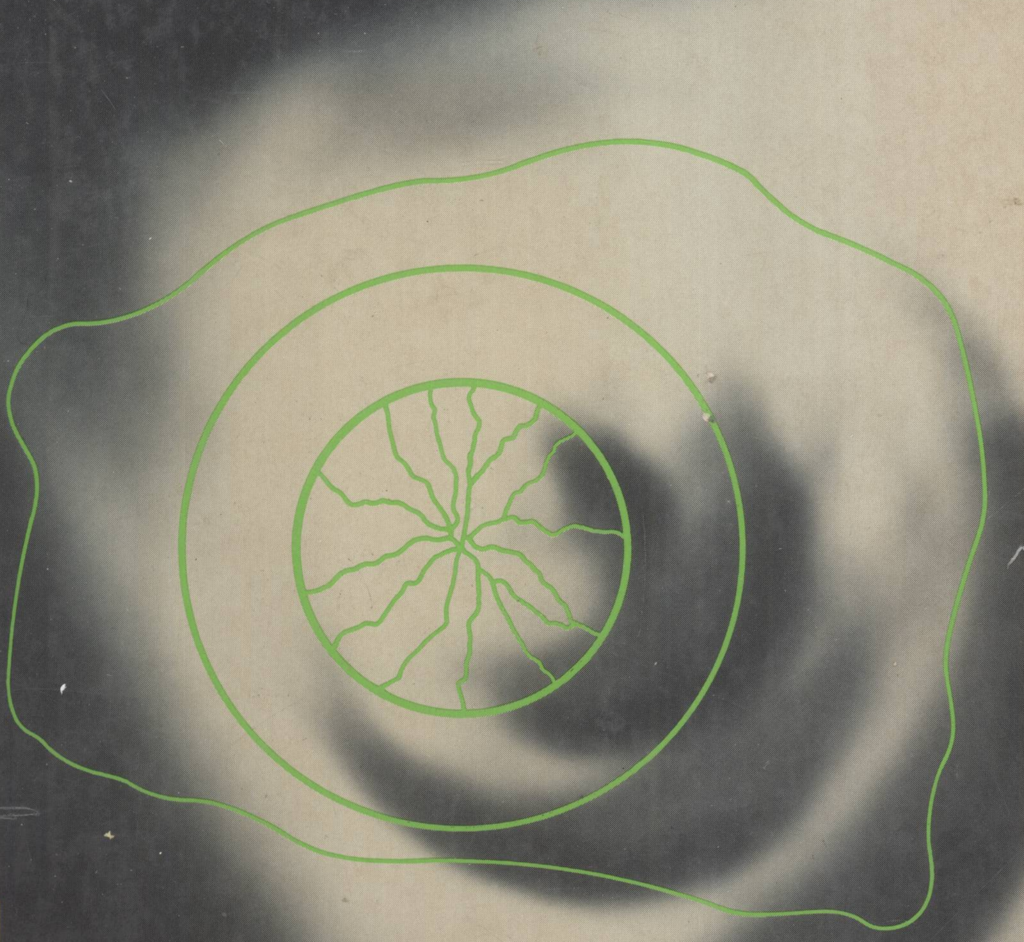
EARTHQUAKE ENGINEERING

Damage Assessment and Structural Design

S. F. Borg



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Damage Assessment and Structural Design

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Earthquake Engineering

WILEY SERIES IN

METHODS AND APPLICATIONS IN CIVIL ENGINEERING

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EARTHQUAKE ENGINEERING
S. F. Borg

This book is dedicated to the women in my life.

First and foremost,
Audrey, my dearest wife

Then, my daughter, Jill

And my daughters-in-law, Lise and Susan

And my grand-daughters, Kristina and Laura and Margo

And my mother, Pauline

Preface

A new approximate approach to various aspects of earthquake engineering is presented in this book. The theory developed will be applicable to earthquakes of, roughly, magnitudes greater than five.

The fundamental quantity — the key to all of the procedures and methods derived — is energy. Starting with the initiation of the earthquake (a mechanism) and proceeding through timewise and spacewise analyses of energy on the surface of the earth, one is led to a procedure, based upon simple energy principles, for an approximate analysis of structures within the effective earthquake field. Two major observables — two fundamental sets of field or experimental data — are utilized in the theoretical developments. These two sets of data are: 1. The accelerograph record which gives timewise information, at a point, about the earthquake; and 2. The isoseismal contour chart which gives spacewise information over the region affected by the earthquake.

Invariants are looked for and obtained. That is, approximate relations or equations or curves are developed that hold for all accelerograms and for all isoseismal charts, within an accuracy consistent with the manner in which these data are obtained and also consistent with the engineering applications for which these are used.

New fundamental parameters are introduced — terms that are strongly related to the earthquake event and only to the earthquake event. Indeed, it was the author's conviction that this must be so which led him to the various parameter–invariant relations. These, in turn, by a series of logical rational steps assume a form which is of engineering use. This is done by extending the form of the invariant quantities and transforming them into relations that determine temporal and spacewise variations of surface energy.

This surface energy is related to damage and finally is utilized as the basis for the structural analysis process.

Engineering simplicity is looked for but not at the expense of accuracy suitable for ordinary engineering purposes. A major aim was to develop an approximate comprehensive rational earthquake engineering theory that could be used by everyday engineering design offices using elementary computer programs. The book will succeed or fail as it is or is not so used.

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1. The National Science Foundation for their seed grant PFR 7822846 which enabled the author to develop the initial ideas discussed in the text.
2. The Trustees of Stevens Institute of Technology for granting the author a

sabbatical leave during which time the book could be written.
and finally (but not the least),
3. Professor Dr. John H. Argyris, Director of the Institute of Statics and Dynamics of Aero-Space Structures at the University of Stuttgart for inviting the author to be a Guest Professor at his Institute during the sabbatical year and for there providing the facilities and atmosphere so necessary and helpful in the preparation of the manuscript.

Introduction

In 1976, the National Science Foundation-Department of Interior (USGS) issued a detailed plan with options for augmenting the earthquake related research programs of various government agencies.* The plan lists a number of critical areas of required research.

For example, in *Sec. 5 Engineering, Objectives and Activities*, it describes several desirable (and perhaps necessary) areas of research that require clarification before engineers can really hope to develop rational damage assessment and structural analysis–design procedures.

Among those mentioned which relate to the material in this text-book are the following:

Subelement a:	Characterization of ground motion for structural analysis and design
Objective:	Develop methods to characterize the nature of the input motions and corresponding response of simple systems for use in engineering analysis, planning and design.
Activities:	1. Develop analytic models to estimate the special characteristics of ground motion and the acceleration, velocity and displacement time-histories of this motion for use as input motion in structural analysis and design. 2. Develop techniques for measuring the severity of earthquake effects based on parameters significant in engineering analysis and design.
Subelement d:	Investigation of structural response
Objective:	Develop analytical procedures for characterizing the earthquake response of structures and structural elements based on both analytical and experimental studies
Subelement f:	Post-earthquake investigations
Objective:	Obtain information for engineering analysis and design from observations of damage (or lack of damage) following earth-

* *Earthquake Prediction and Hazard Mitigation Options for USGS and NSF Programs*, Sept. 15, 1976. A more recent study, *Earthquake Engineering Research—1982*, prepared by Committee in Earthquake Engineering Research, Commission on Engineering and Technical Systems, National Research Council, published by National Academy Press, Washington, DC 1982, generally repeats the recommendations of the earlier report.

quakes that support the development of improved U.S. engineering practices and construction techniques.

This text presents rational approaches that bear directly on the important topics described above.

There are three basic principles upon which the theories are founded:

1. Earthquake engineering is a unique discipline in applied mechanics and as such has its own particular invariants, parameters, variables, and similar quantities.
2. The source for all the quantities mentioned in 1. are the two major observation banks (or experimental data or field data) of earthquake engineering, these being:
   (a) The accelerogram which, physically, must be related to the variation with *time* of ground energy at a *point* in the earthquake field.
   (b) The isoseismal contour map which, physically, must be related to the variation with *distance* of the ground energy over the *entire area* affected by the earthquake.

Therefore:

3. *Energy* is the key element in the earthquake event, starting from its initiation (the mechanism) and proceeding timewise and spacewise until its completion.

Equations are obtained for the time–energy and space–energy variations, based upon reasonable physical–technical hypotheses and a study of canonical accelerograms and isoseismal maps. Geological and frequency effects are included in an approximate manner, as are the soil–foundation interactions. All are given in terms of the newly introduced parameters, the 'acceleration index' and the 'isoseismal index' and a first approximation of design charts is given. These relate — in a form suitable for engineering office use — all of the elements that must appear in an engineering design analysis, namely magnitude of the earthquake, efficiency of the earthquake, geology, acceleration index, isoseismal index, soil–foundation interaction, and location–geometry–construction of the structure.

The rational assessment of damage is directly related to the new parameters and invariants. The structural design procedure also utilizes these quantities as well as symmetry — anti-symmetry considerations combined with a free–free beam type vibrational analysis. As part of the overall study, an analysis of model-prototype requirements and how these relate to current testing procedures is developed and critically examined.

In a very general way, the material included in the text covers the entire earthquake event, starting from its initiation (the 'mechanism') up to and including the effect of this earthquake on a structure.

Furthermore, the entire event is treated by a theory which is consistent with the ground rules stated above. In other words — we begin with a theoretical mechanism, for deep focus earthquakes. Following this, the accelerogram and isoseismal invariants are derived, their properties analyzed and their connections with energy developed.

This theoretical basis is then utilized in connection with the two main problems considered in this book, as noted above and as indicated in the text sub-title.

Overall, the treatment presented represents an approximate, rational, comprehensive, theoretical–applied approach to the problems. The basic experimental data — the accelerogram and isoseismal chart — are woven into a single unified theoretical framework which permits the ordinary engineering design office to determine the damage likelihood and also the structural response (shear, moment, deflection) of a particular structure at a particular location when subjected to a particular earthquake.

And all of the above is given in terms of elementary mathematical, physical and engineering concepts and lends itself to computer formulation.

Contents

1

A Deep Focus Earthquake Mechanism

INTRODUCTION

A mathematical–physical model of a deep-focus earthquake will be derived. The model, which is a 'mechanism', is a mathematical formulation that may apply to earthquakes that originate within the mantle of the earth, say 50–800 km below the surface of the earth.

This derived mechanism will have the following properties:

1. It will be a complete, closed form solution to the field equations and boundary conditions assumed for the event.
2. It will be based upon a reasonable, realistic, possible physical explanation for the development of the earthquake.
3. The instability, or trigger, for the initiation of the earthquake is included as a fundamental element in the solution.
4. It will account for the enormous amount of energy which, it is estimated, is released in a major earthquake. This energy shall be calculable using approximate relations.
5. It will account for the production of P and S waves that are generated in earthquakes.
6. It will predict a number of phenomena that may be subject to checks by geologists, rock scientists, and others working in this field.

The proposed mechanism requires the generation of very high stresses by ground surface standards. Although there may be doubt as to whether these could be generated on the surface of the earth, it is a fact that within the mantle the rock is subjected to enormous pressures and these affect the properties of the material in some, as yet unknown, ways. Thus, the required stresses and other properties (including the initiation of the triggering fracture, possibly by some phase change) may conceivably occur as required for the solution presented. Only a check of actual phenomena in the field can prove or disprove this point.

It is certainly a fact that enormous amounts of energy are released in earthquakes. Since these are probably generated by the release of 'locked-in' strain energy, it is conceivable that very high stresses acting on large volumes of material are involved. Both the high stresses and large volumes are part of the mechanism being discussed.

It seems clear that different tectonic earthquakes are caused by more than one mechanism. There is little doubt that fault slippage, such as occurs in typical California quakes, is a common accompaniment of many quakes. However, as noted by Newmark and Rosenblueth,[1] some seismologists hold that earthquakes originate in phase changes of rocks, rather than by fault slippage. Those who favour the phase change (volume change) theory argue that there is little likelihood that geological faults exist below depths of a few hundred kilometres because of the high temperatures and confining pressures, and yet data have been interpreted to indicate that earthquakes have originated at depths exceeding 600 km and up to 800 km.

An article in *Science*[2] reports on a meeting of geologists, seismologists, and engineers held in Knoxville, Tennessee in September, 1981. Among other activities, various speculations concerning possible mechanisms were presented. Quoting from the reference: 'John Armbruster and Leonardo Seeber of Lamont–Doherty Geological Observatory, in particular, in discussing the major 19th-century earthquake in Charleston, South Carolina, favoured a nearly horizontal fault separating an upper thin sheet of rock from the crust beneath the fault. They argue that the most violent effects of the 1886 Charleston earthquake covered too large an area to have resulted from a break on a nearly vertical fault. A break on a horizontal fault, on the other hand, could have directed its seismic energy over a much larger area of surface. A horizontal break could be caused by a tendency of the thrust sheet to backslide off the continent...'

The mechanism developed in this chapter is generally consistent with the Armbruster–Seeber view, although it is not a unique representation or solution for the assumed phenomena. It will, however, represent a broad, particular explanation of an earthquake which, by extension and generalization, may give some insight and knowledge of the actual details behind the build-up to and occurrence of a deep-focus earthquake. In this way, some important leads and hints may emerge relating to the two most important problems in earthquake engineering, still unsolved:

1. How to predict when an earthquake will occur.
2. How to 'defuse' an earthquake that is about to occur.

NOMENCLATURE FOR THIS CHAPTER

C = velocity of small disturbance in the solid (velocity of sound)
p = pressure of superplastic material
P = pressure on ruptured area material
r = radial distance coordinate
t = time
u = particle velocity
U_I = initial strain energy of element
U_F = final strain energy remaining in element following rupture
ξ = similarity coordinate
θ = angular variation

ρ = density
σ = stress, positive when tension
ν = Poisson's ratio
μ = viscosity
o = subscript, outer
i = subscript, inner

PHYSICAL ASSUMPTIONS

Deep within the mantle, where the earthquake is assumed to originate, we have a condition of hydrostatic stress, which is shown below on a membrane or strip of thickness t. We assume this is a zero, initial condition, just as such a strip on the surface of the earth is subjected to a hydrostatic atmospheric pressure. Due to tectonic plate movement of the crust of the earth mantle, a tensile stress σ_o is added to the above strip of mantle (see Figures 1.1 and 1.2). This stress is assumed

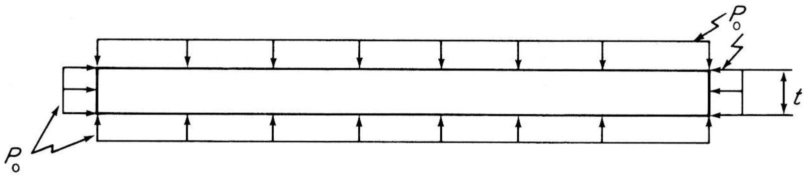

Figure 1.1

to be uniform along the edge of an enclosed area of indefinite extent and we consider the effect of σ_o alone. Thus the layer, initially subjected to the enormous hydrostatic pressures, now has the stresses σ_o applied to it uniformly around the boundary and these stresses introduce a strain energy in the layer caused by stretching (see Figure 1.2). The stress, σ_o, gradually increases and builds up as the tectonic plate or other movement action proceeds. Finally, a value of σ_o is reached that, in conjunction with the initial state of the layer and a possible phase change, leads to a 'rupture' or 'fracture' initiated at a single point. A (see Figure 1.3). (It is interesting to note that Benioff[3] has suggested, on the basis of observed wave forms from three earthquakes, that a class of deep earthquakes may arise when a

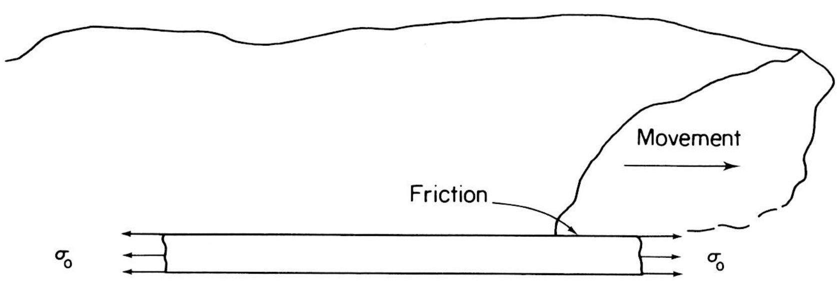

Figure 1.2

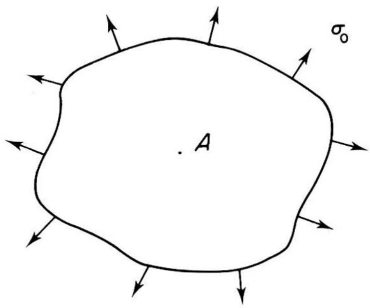

Figure 1.3

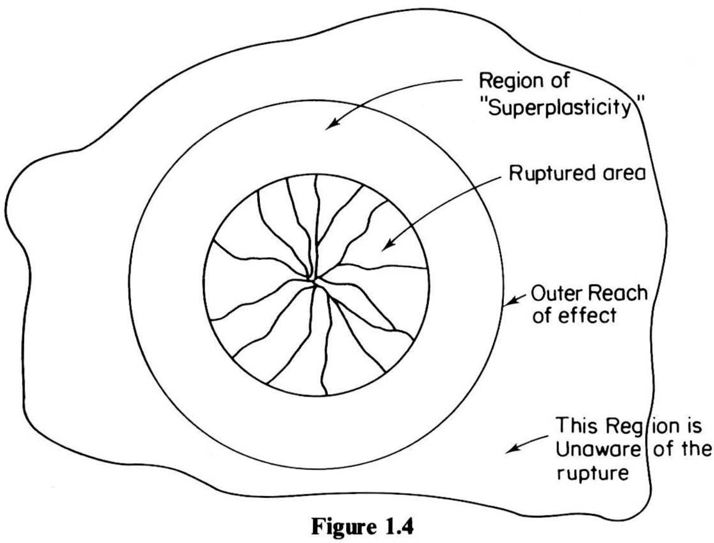

Figure 1.4

phase transition occurs through a region of rock, causing a sudden change in volume.) This failure at point A spreads radially throughout the layer, so that at a time t after initiation of the rupture conditions are as shown in Figure 1.4.

The mathematical development governing the event follows.[4]

MATHEMATICAL ANALYSIS

For the dynamic phenomenon being investigated in this chapter, the material may be assumed to have the properties of a border region fluid–solid, a so-called 'superplastic' material. Therefore the analysis will be based upon the conservation equations of continuum fluid mechanics instead of the somewhat uncertain relations of combined dynamic elasticity–plasticity action, as is usually done in analysing fracture phenomena. Thus the rupturing strip must satisfy the following equations (given in the two-dimensional symmetrical polar coordinate form).

Mass conservation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial r}+\frac{\rho u}{r}=0 \tag{1}$$

Momentum conservation (Navier–Stokes equation):

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+4/3\mu\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u}{r^2}\right) \tag{2}$$

Also, an equation for the velocity of small disturbances (since the effect of the point rupture spreads radially and reaches a finite distance from the centre of rupture),

$$C=C(p,\rho) \tag{3}$$

In the foregoing equations, p is the negative mean value of the principal diagonal elements of the stress tensor, i.e.,

$$p=-1/3(\sigma_r+\sigma_\theta+\sigma_z) \tag{4}$$

so that for the uniform strip stress field we have ($\sigma_r=\sigma_\theta$, $\sigma_z=0$),

$$p=-\frac{2\sigma_r}{3} \tag{5}$$

Physically, the phenomenon may be described in the following manner (this explanation will justify the assumed boundary conditions for the foregoing mathematical formulation of the field equations): (A) For $t<0$, the entire strip is in a uniform tensile stress state, σ_o; (B) At $t=0$, a small puncture is introduced at some interior station. We may think of this as the sudden introduction, along the arc of a small circle (the puncture point) of an equal and opposite, i.e. compressive, stress, $-\sigma_o$. Hence at this inner circle we have

$$\begin{aligned}\sigma_\theta&=\sigma_{\theta F}\\ \sigma_r&=0\\ \sigma_z&=0\\ p&=\frac{-\sigma_{\theta F}}{3}\end{aligned} \tag{6}$$

$\sigma_{\theta F}$ is the 'fracture' or 'tearing' stress for the material, i.e. the tensile stress that will just cause the strip to fracture; and (C) For $t>0$, conditions are as shown in Figure 1.5.