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MASTER

EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES

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PREFACE

The National Waste Terminal Storage Program was initiated to conduct the research to select a site for the disposal of high level radioactive waste in deep geologic formations. As part of this program, the Savannah River Laboratory at Aiken, South Carolina, is conducting geologic research of generic applicability on the potential subsurface damage to a repository from an earthquake. Part of this study involved the collection of data on subsurface damage due to an earthquake, and another part involved the calculation of displacement fields as a result of an earthquake. Both of these studies were conducted by Terra Tek of Salt Lake City. This report is an abridged and combined version of both studies which was presented at the Rapid Excavation and Tunneling Conference in Atlanta, GA, on June 19, 1979.

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ABSTRACT

The potential seismic risk for an underground facility is considered in the evaluation of its location and design. The possible damage resulting from either large-scale displacements or high accelerations should be considered in evaluating potential sites of underground facilities.

Scattered through the available literature are statements to the effect that below a few hundred meters shaking and damage in mines is less than at the surface; however, data for decreased damage underground have not been completely reported or explained. In order to assess the seismic risk for an underground facility, a data base was established and analyzed to evaluate the potential for seismic disturbance.

Substantial damage to underground facilities is usually the result of displacements primarily along pre-existing faults and fractures, or at the surface entrance to these facilities. Evidence of this comes from both earthquakes and large explosions. Therefore, the displacement due to earthquakes as a function of depth is important in the evaluation of the hazard to underground facilities. To evaluate potential displacements due to seismic effects of block motions along pre-existing or induced fractures, the displacement fields surrounding two types of faults were investigated.

Analytical models were used to determine relative displacements of shafts and near-surface displacement of large rock masses. Numerical methods were used to determine the displacement fields associated with pure strike-slip and vertical normal faults.

Results are presented as displacements for various fault lengths as a function of depth and distance. This provides input to determine potential displacements in terms of depth and distance for underground facilities, important for assessing potential sites and design parameters.

INTRODUCTION

The potential seismic risk for an underground facility must be considered in evaluating the ultimate location. The possible damage resulting from either large-scale displacements or high accelerations should be considered in evaluating a potential site. Statements have been made to the effect that below a few hundred meters shaking and damge in mines are less than at the surface; however, data for decreased damage underground have not been completely reported and explained.

In order to assess the seismic risk for an underground facility, a data base must be established and analyzed to evaluate the potential for seismic disturbance. To develop this data base, pertinent literature was searched to document the damage or non-damage to underground facilities due to earthquakes and to evaluate the significance of these data. A number of reports listed damage from earthquakes to underground structures such as mines and tunnels, but these were primarily of a qualitative nature. Displacements associated with four major earthquakes in several parts of the world were documented in 1959.[1] More recently, the effect of earthquakes on shallow tunnels, primarily in the United States, has been collected and analyzed.[2,3] In addition to these data, a large number of individual reports have indicated both damage and non-damage resulting from earthquakes of magnitudes greater than 5.[4-8]

In addition to these data, other sources of potential information were investigated. These include:

- More complete and recent data from foreign sources in earthquake-prone areas such as Japan.
- Data from mining operations where earthquakes are initiated by the mining process. (These needed to be evaluated in terms of the potential damage from equivalent far-field earthquakes.)
- Results from the nuclear events at the Nevada Test Site and the Alaskan Test Site as well as Plowshare experiments. These tests provide the most quantitative data in the near-field environment. These tests were well-instrumented and may assist in evaluating and establishing damage criteria.

Earth risk maps (Figure 1) have been formulated for the United States based on historical damage to various areas.[9-10] This map is directly correlative with maps showing the location of major earthquakes (intensity 5 or greater). This correlation is due to the fact that the risk map was developed from surface damage associated with historic seismicity; however, how the risk map applied to underground facilities is not yet known.

The resulting velocity, acceleration, and displacement spectra from an earthquake are usually plotted as a function of frequency (period) on a pseudo-velocity diagram. These plots are helpful in evaluating and designing surface structures. Relationships of surface acceleration and velocity have been established as a function of intensity and magnitude with distance.[4,5] The relationships between predominant period and magnitude as a function of distance have also been developed.[11]

Potential hazards of earthquakes to the integrity of an underground facility can be categorized into whether the site is in the near-field or far-field of the earthquake. The near-field is defined by seismologists as the region around an earthquake where seismic waves have not completely decoupled into separate compressional (P) and shear (S) waves and as a result involve complicated motions with high accelerations. The far-field is simply the region beyond the near-field, although the boundary is not sharp and involves a transition zone. Actual distances from the source at which the transition between near and far-field occurs depend on the source (size, type, and geometry) and on the medium properties, but generally is less than several fault lengths. For small events ($M_b < 1.0$) this distance may be less than one kilometer, but for large events ($M_b > 7.0$) the transition may occur at distances tens of kilometers from the source.

We are not concerned with the details of separating near and far field effects as much as delineating the most likely earthquake hazards to underground facilities. From a seismological viewpoint, however, it is important to differentiate between these two regions because effects in the near-field of an earthquake is poorly understood with complicated techniques required to model even the simplest earthquakes.

Unlike surface structures, which can be damaged by large horizontal ground accelerations, the integrity of underground facilities may be susceptible to permanent displacements which might cause damage or change permeabilities, and thus, alter groundwater movements. High accelerations can still cause damage and will also be considered. The inducement of such motion can occur either in the near-field or far-field of an event and is relatively independent of the details of the source. A major factor is the relative alignment of pre-existing fractures to the motion due to the seismic waves. Static displacement fields of earthquakes were computed as a means of analyzing the significance of permanent deformation associated with earthquakes. These displacements are insignificant beyond a few fault lengths from the source. However, within a few fault lengths, the displacements vary greatly depending on the source geometry and depth. These studies represent an initial attempt to quantify the most obvious seismic hazards to underground facilities.

EXISTING DATA BASE ON EARTHQUAKE DAMAGE

Tunnels and Shallow Underground Openings

Data on the seismic stability and behavior of shallow underground openings are very well summarized by Rozen[2] and Dowding.[3] Observations from 71 tunnels responding to earthquake motions were compared. Dynamic behavior was compared with intensity and magnitude as a function of distance. The studies compared calculated accelerations at the ground surface with tunnel damage and showed that the tunnels are less susceptible to damage than surface structures or facilities. Peak acceleration at the surface of less than 0.2 gravity (g) did not damage the tunnels; between 0.2 and 0.5 g, damage was only minor; and damage was significant only above 0.5 g (Figure 2).[2,3] Most of the damage that occurred was located near a portal. Richter magnitude and Modified Mercalli intensity were correlated with acceleration for various cases in Figure 3.[2,3] Large accelerations are correlative with large magnitudes and high intensities. At any one specific site, calculations of surface accelerations were based upon the earthquake magnitude and epicentral distance through attenuation laws developed by McGuire.[12] No reduction was made for attenuation with depth.

Dowding[3] summarized that (1) tunnels are more stable than structures located on the surface; and (2) critical frequencies are lower for large underground chambers than tunnels because of the increase in the size of underground chambers.

The conceptual designs of many underground facilities indicate that configurations will probably be ∿10 m, rather than 100 m in diameter; hence, (1) critical frequencies calculated from Rozen's data for underground openings of this size are ∿150 Hz, and, therefore, threshold damage would not occur unless the facility was relatively close to the epicenter; (2) perhaps most importantly, the primary cause of failure of these underground excavations is relative movement along pre-existing faults, or at the portal of the tunnel which is located at ground surface.

Duke and Leeds[1] reviewed information on tunnel damage as well as some mine damage due to earthquakes and drew the following conclusions:

(1) Severe tunnel damage appears to be inevitable when the tunnel is crossed by a fault or fault fissure which slips during the earthquake.

(2) In tunnels away from fault breaks, severe damage may be done by shaking to linings and portals in the epicentral region of strong earthquakes where construction is of marginal quality.

(3) Well-constructed tunnels outside the epicentral region, but away from fault breaks, can be expected to suffer little or no damage in strong earthquakes.

(4) Within the usual range of destructive earthquake periods, intensity of shaking below ground is less severe than on the surface.

Mines or Other Deep Structures

Reports on earthquake damage to underground mines have generally been qualitative in nature. Quantitative data have been much more difficult to obtain and come primarily from a few sources. Most of the quantitative data are in the form of displacements or accelerations noted in mines in Japan, South Africa, and the United States.

Several Japanese investigators measured earthquake motion simultaneously at the depth and surface. Nasu[13] determined the ratio of displacements due to earthquakes at the surface and in tunnels at depths of up to 160 m. One of the most striking displacements was the 2.3 m transverse horizontal offset 0.6 m beyond a tunnel heading during the 1930 Tanna Earthquake. Surface/depth displacement ratios were 4.2, 1.5, and 1.2 for periods of 0.3, 1.2, and 4 seconds, respectively. The geology consisted of lake deposits at the surface and volcanic andesite and agglomerates at the 160 m depth. Nasu concluded that underground motion may be four times less than at the surface.

Kanai[14] measured accelerations at depths up to 600 m in copper mines in Paleozoic rock at Hitachi, but unfortunately recorded data were from small earthquakes. The ratio of surface maximum displacement to that at the 300 m depth was about 6:1.

Iwasaki[15] obtained acceleration records to depths of 150 m below the surface during a 5-year period from borehole accelerometers installed at four locations around Tokyo Bay. Three of the sites were in sands and clays, and one was in a siltstone. During the period of operation, data were obtained from 16 earthquakes ranging in magnitude from 4.8 to 7.2. Iwasaki concluded from the analysis of the accelerations recorded in the boreholes at the different depths, that the distribution of the maximum accelerations varies considerably with the change of soil conditions near the ground surface. Ratios of the surface acceleration to that at the deeper layer (110 to 150 m) are about 1.5 at a rocky ground, 1.5 to 3 at sandy grounds, and 2.5 to 3.5 at a very clayey ground. Although the acceleration values are smaller at deeper layers, frequency characteristics of underground seismic motions are close to those of the surface motions.

Information on earthquake damage from South Africa was obtained during discussions with U.S. Geological Survey personnel. On December 16, 1976, a damaging earthquake of magnitude 5.0 to 5.5 was recorded at Welkom, South Africa. The surface damage was extreme, with large structures failing. Displacements ≤10 cm were noted in the mine at a depth of 2.0 km. The focal depth of the earthquake was ∿6 km.

In both the Rand Gold district and the Orange Free State district, studies were conducted to assess the relationship of acceleration, displacement, and frequency of earthquakes to magnitude during mining operations. These mines are up to 4 km in depth. McGarr[16] noted that shear displacements on the order of 5 to 10 cm were associated with rock bursts of magnitude 2 to 3 due to resulting stress redistribution. These data are very important and, along with the data at Welkom, may give some indications of upper bounds of displacements near earthquake sources in these very hard rocks.

The U.S.G.S.[17] study of the Alaskan earthquake of 1964 reported that no significant damage was reported to underground facilities, such as mines and tunnels, as a result of the earthquake, although some rocks were shaken loose in places. Included in this analysis were reports of no damage in the coal mines of the Matanuska Valley, the railroad tunnels near Whittier, the tunnel and penstocks at the Eklutna hydroelectric project, and the Chugach Electric Association tunnel between Cooper Lake and Kenai Lake. There were also no reports of damage to the oil and gas wells in and along Cook Inlet. The reports of non-damage from the Alaskan earthquake are significant. This earthquake was one of the largest (M = 8.5) to occur in this century, and surface damage was extreme.

During the 1960 Chilean earthquake, one of the strongest earthquakes on record, miners in coal mines heard strange noises but felt no effects of the quake. Later examination of these mines, which extend under the ocean, showed several old faults, but no new movement.[18]

Similar results were reported by Cooke[19] for the Peru earthquake of May 31, 1970. The earthquake of Richter magnitude 7.7 did no damage to 16 railroad tunnels totaling 1740 m under little cover in zones of MM VII to VIII intensity. Also, no damage was reported to the underground works of a hydroelectric plant, and 3 coal and 2 lead zinc mines in the MM VII intensity zone.

Nuclear Events as Earthquake Simulators

The use of nuclear events as equivalent earthquake sources has been discussed.[20,21] The data from nuclear events can be useful in assessing the potential damage from earthquakes to underground facilities. The resulting velocities, accelerations, and displacements from nuclear events have been monitored carefully because of their importance to defense-related issues. In many cases, the data are obtained at conditions that would be near the hypocenter of the earthquake and thus more severe than would be anticipated from any earthquake affecting an underground facility. It should be possible, however, to place certain bounds on the maximum accelerations, velocities, and displacements expected from comparable earthquakes. This would be helpful in establishing damage criteria for potential earthquake damage.

At the outset, it is important to compare nuclear events with earthquakes to determine the scaling relationships between the two. An important point to make is that a comparable magnitude only indicates that P-wave signals from both earthquakes and explosions are of equal strength. However, nuclear explosions tend to produce much weaker surface waves than do earthquakes of comparable body-wave magnitude (Figure 4). As a consequence, the surface wave energy associated with an earthquake of a given body-wave magnitude is on the order of ten times that of an explosion of an equal body-wave magnitude.[20] Therefore, a magnitude 5 explosion does not have the same potential for causing ground motion damage at the surface, as does a magnitude 5 earthquake. An analysis of displacements, accelerations, and velocities at depth and at the surface from nuclear events in rock is given by Pratt[21] and Perret.[22]

Wells

The damage to water and oil wells has been documented in a limited number of reports. Failure of water wells is primarily due to sanding or silting, but, in some instances there has been crushing, bending, or shearing of the casing due to differential movement of the surrounding rock. The latter mode of failure has also affected some oil wells. The damage to wells appears to be more of a near-surface phenomenon than one at depths of >100 m, except where the well crosses a fault.

Some damage to wells occurred during the earthquake on February 9, 1971, in San Fernando, California.[23] Minor damage was reported to a few oil wells in the area, and all seven wells which supplied water to the city of San Fernando suffered damage during the earthquake causing a severe water supply problem. Oil wells in the greater Los Angeles area which cross faults have had the casing ruptured by movement along the faults, but, it is uncertain if the movement is creep of a tectonic origin or settlement due to subsidence. Damage to wells in the San Joaquin Valley due to compaction of sediments which is caused by the withdrawal of groundwater is relatively common, but this damage is due to aseismic causes. A reduction in peak acceleration of a factor of 5, from 0.05 g at the surface to 0.01 g at the depth of 165 m in a borehole, was noted during the Briones earthquake ($M_L = 4.5$).[24] The borehole was located in the Hayward fault in Berkeley, California.

The U.S.G.S. documented the effects of the Alaskan earthquake, March 27, 1964, on wells throughout most of Alaska and the changes in water levels noted in the lower 48. Waller[25] summarized the damage to wells in Alaska as mainly due to sanding or silting of the well or differential movement of casing caused by movement of the surrounding rock. Three city wells were damaged in Anchorage and possibly one private well. Three city wells in Seward were damaged and rendered useless by ground movement and fissuring. In Valdez, one well had the casing sheared at a threaded joint 4.7 m below ground surface. No damage was reported to any of the oil and gas wells in and along Cook Inlet.

In general, the performance of wells during earthquakes is quite good, with the major damage resulting from bending, crushing, or shearing of the casing due to differential movement of the surrounding rock. The major damage appears to be to shallow wells that are in unconsolidated sediments and near the surface. There is very little damage to wells deeper than about 100 m except where the well crosses a fault plan along which movement occurs.

In summary, the damage to underground tunnels, mines, and wells does not have a large data base, especially with respect to measured displacement. However, the relation between velocity (and thus distance for M = 5, 6, and 6.5) and damage level has been summarized by Rozen.[2] Strong tensile and some radial cracking was noted at surface velocities of 152 cm/sec which would occur at distances of about 7 to 8 km during a magnitude 6.5 earthquake. Even at these levels, seismic damage would be negligible in competent rock.

The data for measured displacements as a function of depth are summarized in Table 1 and Figure 5. Surface displacements range from at least 1 to 10 m, depending on geology, magnitude, etc., but decrease markedly with depth. Displacements of ≤25 cm have been measured at 100 m depth in *in situ* rock masses. Displacements of <7 m have been noted along pre-existing faults. The data base below 500 m is almost negligible. The one data point from South Africa needs more detailed study of displacement, rock type, and local tectonic environment.

BLOCK MOTION PHENOMENA

The role of block motion or differential displacement along either pre-existing or induced fractures due to earthquakes or large explosions can enhance our understanding of displacement fields in light of the small data base from earthquakes. The major questions that need to be discussed are:

- Are observed surface faulting phenomenon restricted to the surface?

- How deep and how distant from the event can differential displacements occur?

- How does the source type determine surface and near-surface rupture and deformation phenomenon?
- Can potential block motion be predicted in terms of location and magnitude with respect to various geologic structures, faults, fractures, and joint systems?

The relationship of seismic aftershocks to total stress field changes and the role of *in situ* stress and fluid content on the relative strength properties of the rock masses needs to be determined. Surface waves (Raleigh and Love) related to fault motions and tectonic energy release need to be analyzed. We also need more critical measurements and predictive models from the field tests to relate surface and subsurface effects. The important data include: (1) geologic evidence of surface displacements from earthquakes and large explosive events to evaluate both surface and subsurface displacements; (2) seismological evidence based on spontaneous block motion during earthquakes from far-field ground motion recordings, from observations of surface faulting, from near-field ground motion recordings and studies of aftershock activities; (3) data from high explosives simulation experiments; and (4) a variety of analytical models results to evaluate block motion.

Geological Evidence for Block Motion

Acceleration, velocity, and displacement, as a function of distance and magnitude of earthquake, has been discussed in detail previously.[21] Observed fault displacement at depth from some of the larger earthquakes are summarized in Table 1 and plotted as a function of depth in Figure 5.

Seismological Evidence for Block Motion

The seismological evidence for block motion from both earthquakes and large explosions include, for the large explosions, far-field ground motion recordings, the observation of surface faulting, and near-field ground motion recordings.[26,27] There is also evidence of possible block motion activity from earthquake or nuclear events. Earthquakes occur when the local tectonics stress field increases beyond the failure strength of the rock mass. The stress release, which may cause block motion displacements is probably caused either by a prestressed medium or by the asymmetry of the source of the earthquake.[26]

Simulation Experiments

Evidence of block motion exists from near-surface, high explosive tests.[28] These include tests in sedimentary and igneous rock. The differential displacement, particle velocity, and potential displacements at actual and scaled ranges were measured for these high explosive events. Block motion displacements observed in these events include joint block displacement, thrust block displacement, and fracture and bedding plane movements. Surface displacements up to several feet have been measured.

Models

Various analytical models have been formulated to estimate potential displacements during loading due to explosions. Dai and Lipner[29] have developed models to assess various regions of interest for block motion displacements. This would include the free-surface region where thrust block model and surface block-dynamic response models are applicable, and at depth where kinematic and incipient fault motion models are applicable. These models may be modified for an earthquake source, both in terms of geometry from the deep source and in terms of the nuclear/earthquake source energy ratios. The relative influence for a particular joint fracture or fault system will be important. Whether a shear failure occurs depends on the distance of the fault or discontinuity from the source, the orientation of the discontinuity, and the local *in situ* stress conditions. These considerations are the obvious ones and must be addressed in order to make quantitative predictions concerning failure. However, in most practical instances analytical solutions can be prohibitively complicated because of material inhomogeneity and nonlinear effects near the source in the presence of free surface.

One idealization of this problem that has been solved analytically is one of incipient fault motion due to a spherical elastic wave in an infinite homogeneous isotropic medium.[30] Using reasonable frictional failure criteria, the failure surface of an arbitrary plane was calculated as a function of orientation and distance from an explosive source. Results from the analytical solution indicated orientations closer to $\theta = 60°$ are clearly most susceptible to failure. They also indicate that the timing of the pulse arrival and the pulse shape affects joint failure. For very sharp pulses and angles less than 35°, failure will not occur no matter how close the joint or fault is to the source radius. These results should be transferable to earthquake sources.

STATIC DISPLACEMENT FIELDS OF EARTHQUAKES

Surface Displacements

The use of permanent surface deformation to infer something about the faulting parameters followed the development of dislocation theory. A dislocation surface is a plane within an elastic medium across which there is a discontinuity in the displacement vector (i.e., a fault). Steketee[31] used the theory of dislocations in a semi-infinite, isotropic, elastic medium as a mathematical model of faulting. Chinnery[32] used some of Steketee's results to study the surface deformation around rectangular, vertical, strike slip faults.

Accompanying the development of the theory was the accumulation of geodetic data on observed surface deformation associated with large earthquakes. One of the earliest earthquakes with well-documented surface displacements is the San Francisco earthquake of 1906. Horizontal displacements greater than 4 m were documented near Tomales Bay (Figure 6). Vertical displacements associated with the 1964 Alaskan earthquake were documented over an area of about 200,000 km^2 with maximum uplift averaging 3 m over a broad area. Table 2 summarizes surface deformation data from a number of large earthquakes.

Most of the data on static deformation associated with earthquakes is confined to surface observations for obvious reasons. Thus, in the studies mentioned earlier, the equations of the deformation field were often simplified by eliminating the depth dependent term. Yet, that is exactly what is required for this study. Therefore, a computer program was developed which provides the static deformation field around a fault as a function depth.

Theory and Computations

Steketec[31] derived the general solution for the static displacement field in a semi-infinite medium using a Green's function approach. Assuming the discontinuity Δu_i is a rigid body displacement (i.e., a constant displacement fault segment), the solution is given as:

$$U_k = \frac{1}{8\pi\mu} \iint_{\Sigma} \Delta U_i \; Wij^k \; V_j \; d\Sigma$$

where U_k is the displacement, μ is the rigidity modulus, Σ is the dislocation surface, ΔU_i are the displacements on Σ, and v_j are the direction cosines of the normal to the surface element $d\ \Sigma$. The $W_{ij}K$ terms are the Green's functions representing the displacement fields in a semi-infinite medium due to a set of elementary force systems.

Consider the rectangular coordinate system depicted in Figure 7(a). Chinnery[28] integrated the above expression over a rectangle in the X_1-X_3 plane. He further restricted the problem to the case of a constant displacement $\Delta u_i = \Omega$ in the X_1 direction. With these assumptions, an analytic solution is possible. The solution, even in indefinite integral form is very long and cumbersome and will not be reproduced here. Chinnery simplified his expression by setting the depth parameter X_3 equal to zero and assuming that Lame's parameter λ is equal to μ. The latter assumption is adopted; however, the depth dependence is retained. The resulting equations were programmed for rapid calculations of the static displacement fields as a function of depth for various vertical strike-slip fault sizes. Corresponding equations and programs were developed for the vertical dip-slip fault.

An example of the output of the programs is given in Figure 8. Here displacements are plotted and contoured as a function of distance along or away from the fault. To generalize the results as much as possible, the fault parameters are normalized by the half-length (L) of the fault. Thus, the length of the fault (2 L), the depth to the top of the fault (D1), depth to the bottom of the fault (D2), and the width of the fault (D2 - D1) must be multiplied by the half-length in order to convert the numbers to true distance units. The displacements in the medium are normalized by the constant slip (Ω) on the fault and are in units of millimeters of displacement per meter of slip on the fault. The output of the program for any input of fault parameters, L, D1, and D2 has the following format: at each specified depth the U_1, U_2, U_3, and U_4 components of the displacements are tabulated in one quadrant of $(X_1 - X_2)$ space. The U_1, U_2 components are, respectively, the components of horizontal displacement in the X_1, X_2 directions; the U_3 component is the vertical displacement (positive down); and the U_4 component is the total displacement (i.e., the vector sum of U_1, U_2, and U_3). Only one quadrant is necessary due to symmetry.

For the actual computations we chose to look at three different geometries for each of the strike-slip fault and dip-slip fault cases. Case I modeled long, shallow faults by setting D1 = 0.0 and D2 = 0.1; Case II modeled square, shallow faults by setting D1 = 0.0 and D2 = 2.0; and Case III modeled square, deep faults by setting D1 = 2.0 and D2 = 4.0. In each case, displacements were calculated at depth values of 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, and 4.0 (recall that these numbers are normalized by the fault half-length). Because the amount of output for even the few cases considered was enormous, the results were tabulated and plotted in the following manner: for a specific surface location (X_1, X_2) the total displacement as a function of depth was plotted for each of the three cases for both strike-slip and dip-slip faults producing a total of six curves for each plot. We chose the seven locations shown in Figure 7(b) as representative of the displacement field. In this manner a large amount of information is presented in a small number of figures.

Displacements as a Function of Depth

Details of the displacement pattern around faults vary greatly depending on the particular component of displacement and the type of fault (strike-slip or dip-slip). For the purpose of this report only the total magnitude of displacement will be considered in detail. Because the total magnitude in effect averages all three components, the variations of displacement as a function of azimuth from the center of the fault are smoothed out. Therefore, the variations in displacement that occur away from the fault at an angle of 45° is representative of the azimuth range 0° to 90°. Figure 9 illustrates the total displacement as a function of distance from the fault at the surface and a depth of 1.0. All three cases for both dip-slip and strike-slip faults are plotted on each graph. For most cases, the displacement drops off rapidly away from the fault. In fact, for the shallow square fault, vertical dip-slip case, the displacements just beneath the fault can exceed the actual slip on the fault. This must be due to some sort of free-surface amplification effect. There are several cases for which the maximum displacement occurs away from the fault. At the surface, the square, deep strike-slip fault reaches a maximum at a distance slightly greater than half a fault length away; the square, deep dip-slip fault reaches a maximum near a quarter of a fault length away. At a depth of half a fault length, the displacement curve for the long, shallow strike-slip fault changes drastically from the surface curve.

The displacements as a function of depth are presented graphically in Figures 10 and 11. At a point close to the fault (Figure 8) all the curves, except one, have a maximum value of about 400 mm/m at a depth where the fault is located. For these cases, the displacements become very small within half a fault length away from the depth at which the maximum occurs. The one exception to these generalizations is the shallow, square fault which was mentioned earlier. At a full fault length away the displacements are diminishing, but are still near the maximum value of the other cases.

At the point (I, 1), the displacement curves tend to vary less drastically with depth (Figure 11). With two exceptions, the curves remain near a value of 100 mm/m. The exceptions are the long, shallow faults. The strike-slip fault has displacements which increase rapidly from a minimum value at the surface to a maximum near a depth of 1.0. The dip-slip fault has displacements which decrease from a maximum at the surface to nearly zero at a depth of 4.0.

At the point (2, 2), the displacement curves have even less character. Almost all the curves are nearly linear with depth, lying between values of 30 mm/m and 100 mm/m. The lone exception is the long, shallow strike-slip which again decreases monotonically to zero at a depth of 4.0.

Earthquake Source Parameter Relationships

In the preceding section, the fault model parameters were normalized by the half-length of the fault. Although the normalization generalizes the results, it makes the interpretation of the results in terms of actual earthquakes more difficult. To use the results of the preceding section, for example, we need to know for a given magnitude earthquake the corresponding approximate fault length. Data are required to provide the necessary relationships among the appropriate earthquake parameters to make the results of the previous section more meaningful.

The most commonly used measure of the size of an earthquake is the magnitude; either local (M_l), body wave (M_b), or surface wave (M_s) measurements. These magnitude measurements only sample a narrow frequency range of the seismic wave spectrum. A better measure of the size of an earthquake would sample a broader range of the spectrum. Such a measure is the seismic moment, M_o, which is proportional to the long period level of the seismic source spectrum. In terms of physical parameters,

$$M_o = \mu \Omega S$$

where μ is the rigidity of the medium around the source, Ω is the average slip on the fault, and S is the area of the fault. Although the calculation of M_o of an earthquake is more involved than any of the other magnitude measurements, more moment calculations are becoming available, especially for the larger earthquakes.

Magnitude needs to be related to two other fault parameters; namely, fault length (L) and average fault displacement (Ω). At the present time empirical relationships are probably the best. These are usually confined to the larger magnitude earthquakes, but because the larger earthquakes are of primary interest, the deficiency of data on smaller earthquakes is not critical. In Figure 12 from Chinnery[32] some of the earlier data on magnitude displacement are plotted. Since that time, much data has been accumulated, but the more recent data uses seismic moment instead of magnitude as the independent parameter.

For example, the surface horizontal displacements noted for the 1906 San Francisco earthquakes (Figure 6 and Table 2) agree with those calculated for a shallow, long, vertical strike-slip fault. The calculated displacements also agree with the magnitude-displacement curve (Figure 12). The magnitude-fault length curve also agrees with the observed field data.

CONCLUSIONS

The potential seismic risk for an underground facility will be one of the considerations in evaluating the possible locations. A literature search and evaluation was performed to document the damage or non-damage to underground facilities due to earthquakes. Damage was delineated in terms of displacement and acceleration. The sources of data include both U.S. and foreign experiences of earthquake damage to tunnels, mines, wells, and other underground facilities.

The major conclusions developed from an assessment of the information obtained in this study are summarized as follows:

(1) There are very few data on earthquake damage in the subsurface. This fact itself attests to the lessened effect of earthquakes in the subsurface because mines exist in areas where strong earthquakes have done extensive surface damage.

(2) More damage is reported in shallow, near-surface tunnels than in deep mines. Specifically, data are very sparse below 500 m.

(3) In mines and tunnels, large displacements occur primarily along pre-existing faults and fractures or at the surface entrance to these facilities.

(4) Data indicate vertical structures such as wells and shaft are also not as susceptible to damage as are surface facilities. Even in the Alaskan earthquake of 1964 (M = 8.5) few wells were damaged.

(5) Not enough data were found to assess the exact influence of rock type, but the effects are less in consolidated materials than unconsolidated materials, such as alluvium. Geologic structures, such as faults, seem to be a dominant factor in underground damage.

(6) Frequencies most likely to cause damage to subsurface facilities are significantly higher (50-100 Hz) than the frequencies (2-10 Hz) that cause damage to surface facilities.

(7) Acceleration and displacement data from nuclear explosions may give close-in upperbound limits for large earthquakes.

(8) More analysis is required before a seismic criteria can be formulated for the siting of an underground facility.

Analysis of observed "relative motion" data and calculations of displacement fields for various fault types and geometries indicate:

(1) Most block motion displacements have been recorded at the surface or at free surface of tunnels.

(2) Relative block motion can occur at depth, but displacement decreases markedly with distance and a decrease in energy source.

(3) Analytical models have been developed to predict displacement as a function of distance and energy and to predict fault motion as a function of distance and orientation from a given source.

(4) Calculated displacement fields from vertical strike-slip and vertical dip-slip faults indicate that:

    (a) Displacements drop off rapidly from the fault in most cases studied.

    (b) At a depth of one-half a fault length, the displacement curve for a shallow strike-slip fault (e.g., San Andreas) changes drastically from the surface displacement curve.

    (c) Of the models calculated, shallow square vertical strike-slip and dip-slip faults give the maximum displacement as a function of depth.

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TABLE 1

DISPLACEMENTS AT DEPTH FOR MAJOR EARTHQUAKES

LOCATION (Years)	DEPTH (m)	DISPLACEMENT (cm)	TYPE	M
San Francisco (1906)	214	137	Shear Existing Fault	8.3
South Africa (1976)	2,000	10		5.1
Japan (1930)	140	750	Horizontal	7.0
Japan (1930)	160	239	Horizontal	
Japan (1930)	160	51	Vertical	7.0
San Fernando (1971)	Surface	190	Vertical	6.5
Japan (1923)	76	25		8.16
Japan (1923)	50	<1		8.16
Kern County (1952)	50	<20		7.6
Kern County (1952)	73	<20		7.6

TABLE 2

SOURCE DIMENSIONS FOR SOME STRIKE SLIP FAULT MOVEMENTS[21]

Fault Movement	Magnitude M	Fault Length L (km)	Fault Displacement D (m)	Focal Depth (km)
San Francisco, USA	8.3	435-450	5.0-6.4	5-10
Mongolia	8.3	280	4.7-10.0	20
Tango, Japan	7.5	18-20	2.7-3.4	15-20
Turkey	7.5	50-60	4.3	15
Imperial Valley, USA	7.1	60	1.7	10
Dixie Valley, USA	7.1	62	3.7	15
North Izu, Japan	7.0	24-30	2.7-3.8	20-25
San Miguel	6.8	19	0.85	5
Parkfield USA (June 28)	5.5--6.4	38	0.05-0.5	3-12
Parkfield USA (June 29)	4.9	33	0.005	12
Parkfield USA (Aug. 12)	4.2	16	0.002	3.4
Parkfield USA (Oct. 27)	4.0	8	0.01	1.3
Parkfield USA (July 24)	3.8	10	0.002	1.7
Parkfield USA (Aug. 3)	3.7	3.5	0.01	2.0
Imperial Valley, USA	3.6	10	0.012	1.1
Parkfield USA (July 2)	3.6	8.5	0.01	0.6
Parkfield USA (Aug. 19)	3.4	3.3	0.007	1.0
Turkey	8.0	340	3.7	
Alaska, USA	8.0	200	6.55	
Kern County, USA	7.7	65	3.1	
Turkey	7.6	180	3.5	
Tottori, Japan	7.4	8	1.5	
Cedar Mountain	7.3	61	0.85	
Turkey	7.3	60	1.0	
Fukui, Japan	7.3	25	1.0	
Taiwan	7.1	13	2.4	
Turkey	6.8	16	1.0	

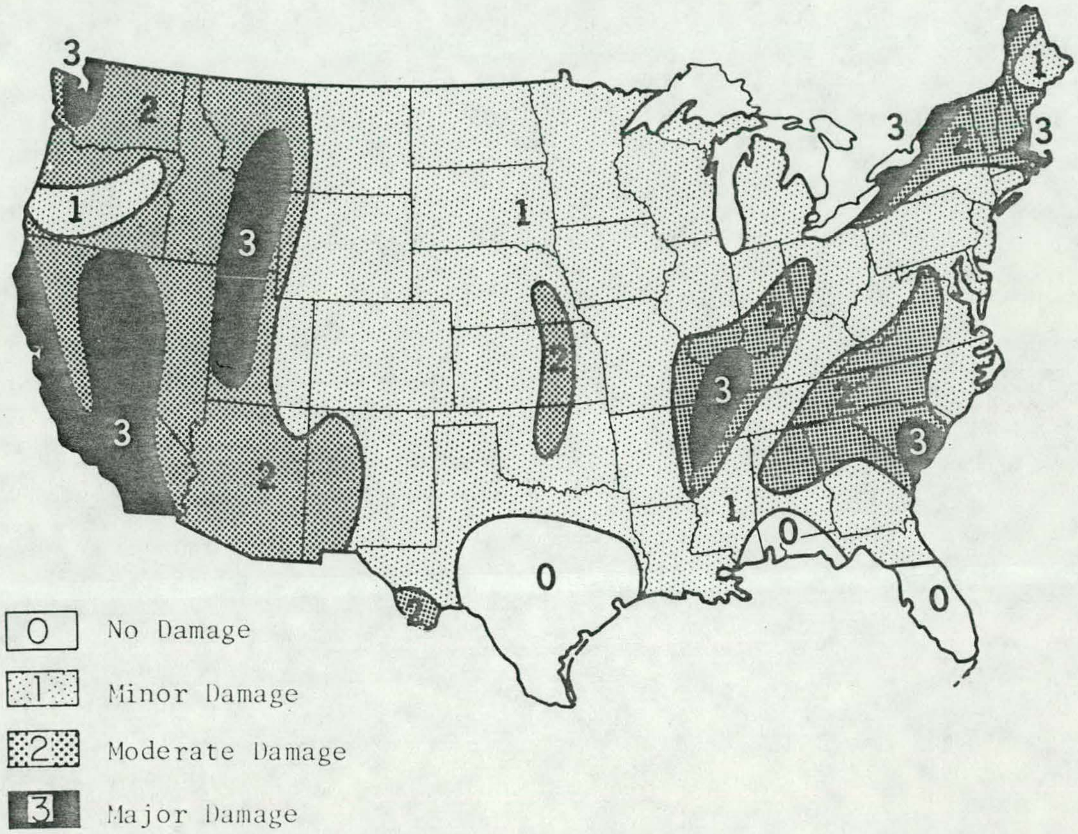


FIGURE 1. Risk of Damage from Earthquakes in the United States

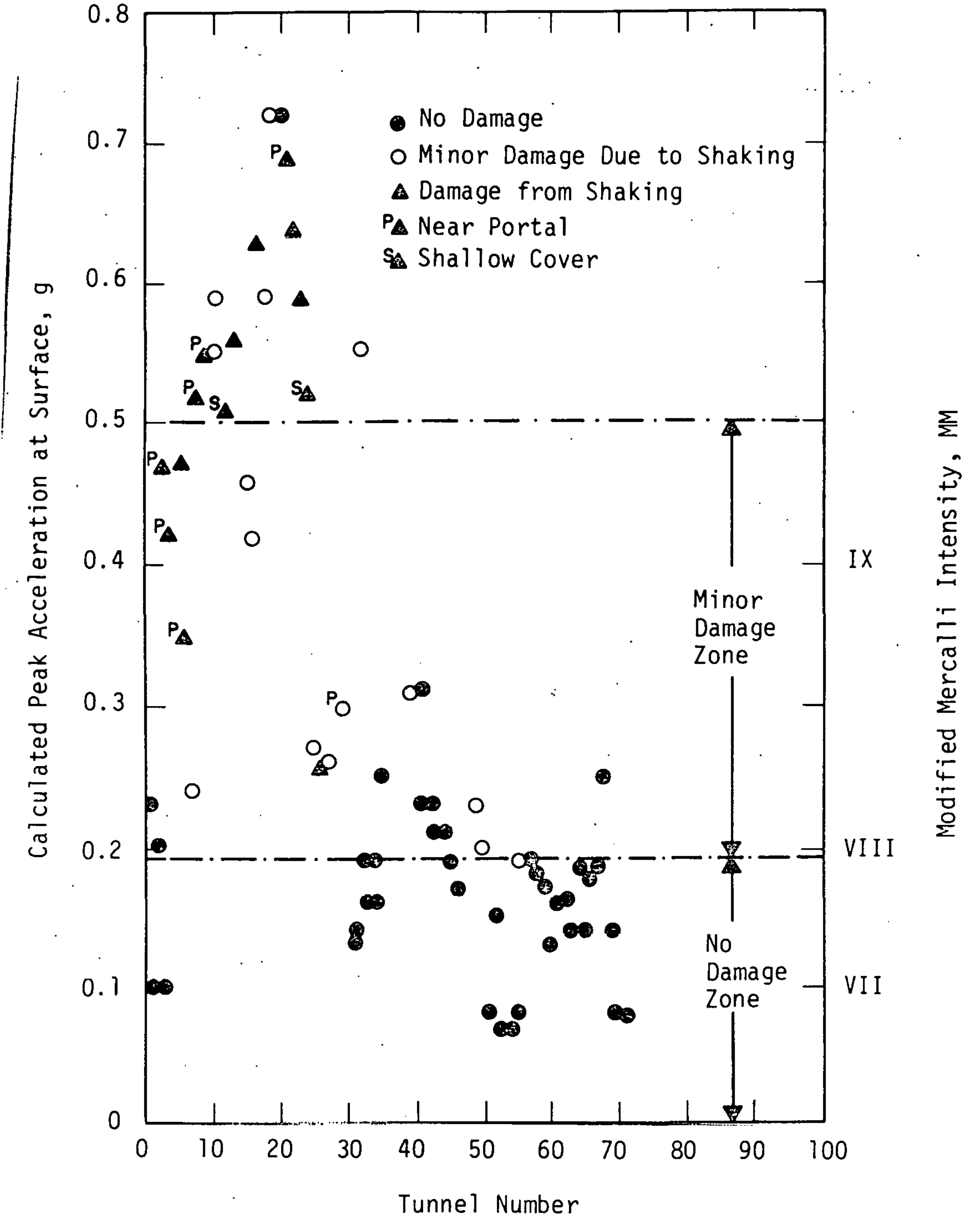


FIGURE 2. Calculated Peak Acceleration at the Surface and Associated Tunnel Damage

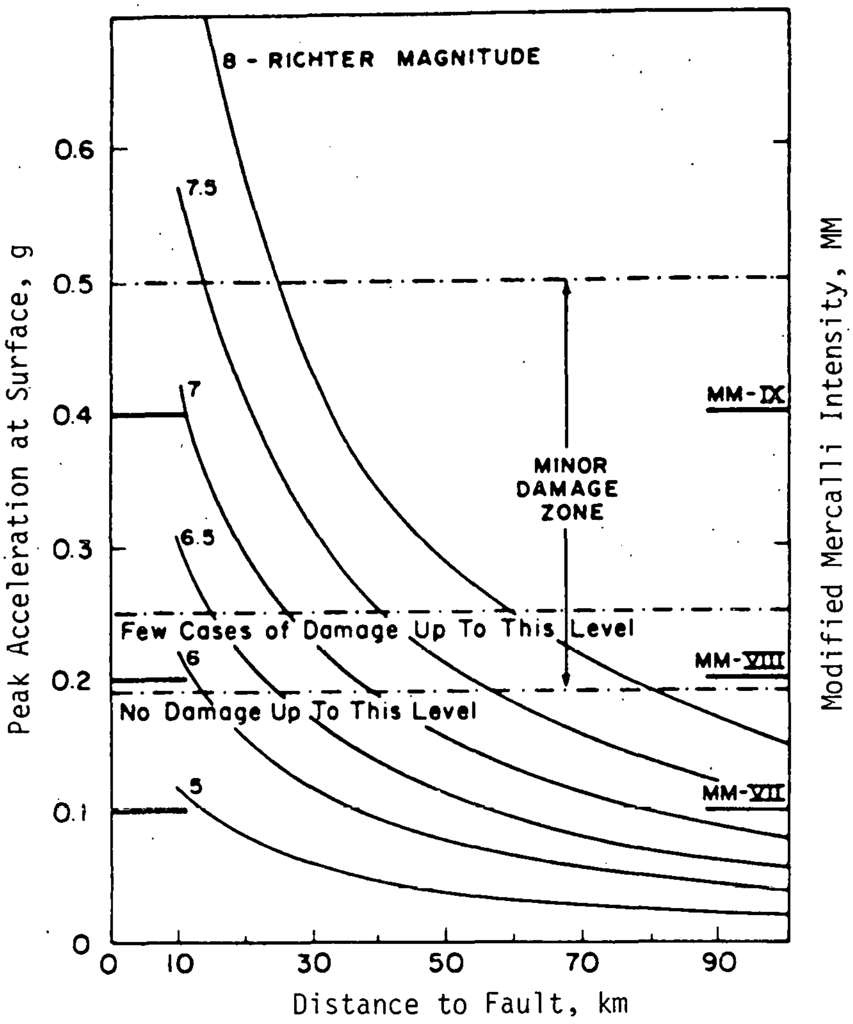


FIGURE 3. Accelerations, Modified Mercalli Intensity, and Associated Tunnel Damage

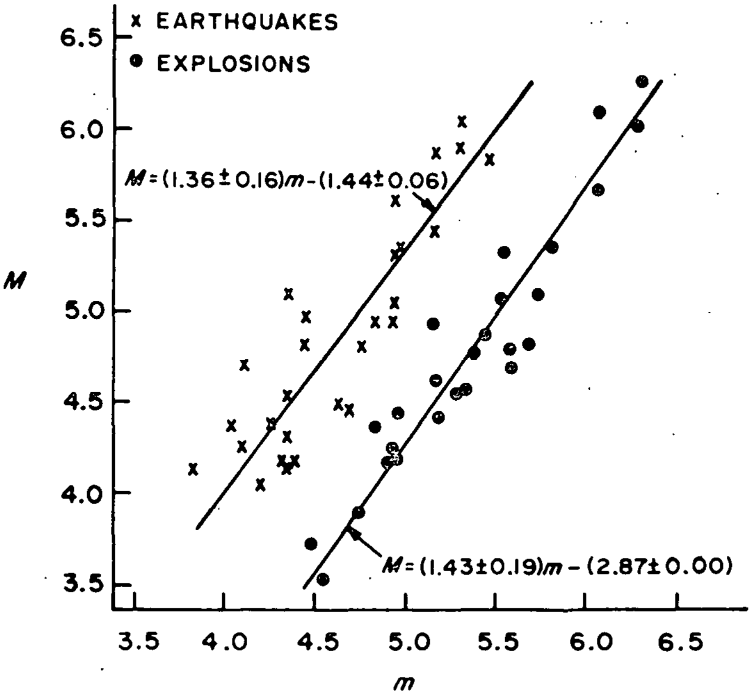


FIGURE 4. Mean Surface-Wave Magnitude (M) Versus Body-Wave Magnitude (m) for 28 Earthquakes and 26 Nuclear Explosions in Southwestern North America, as determined by Canadian Measurements

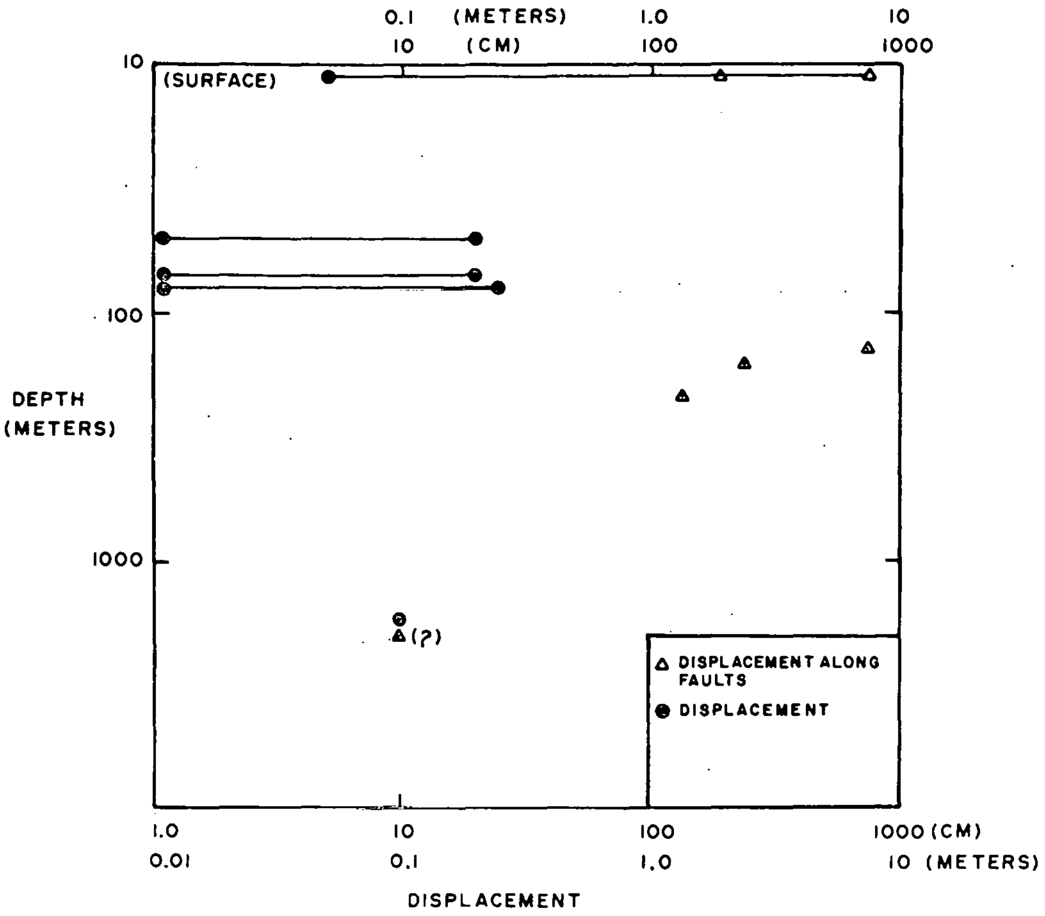


FIGURE 5. Measured Range of Displacements as a Function of Depth

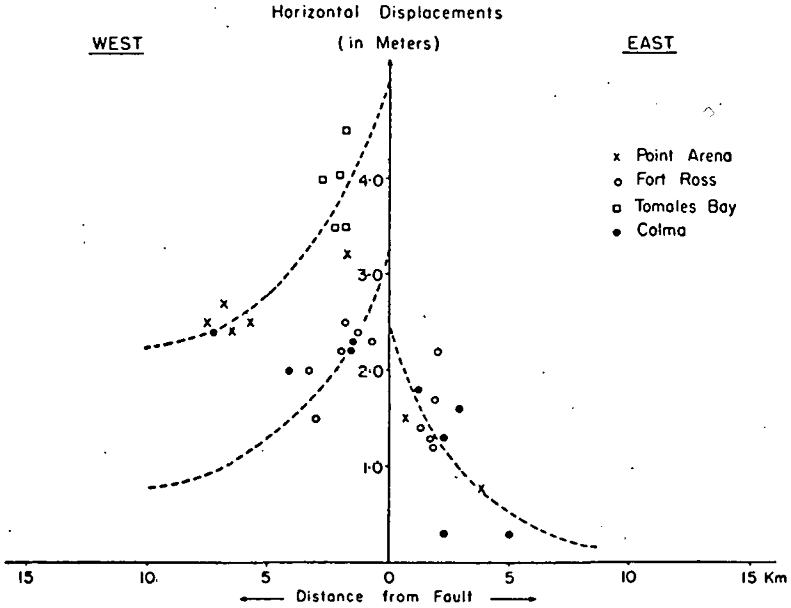


FIGURE 6. Fall Off of Horizontal Displacements with Distance from San Andreas Fault for 1906 Earthquake in California

$$U_k = \frac{1}{8\pi\mu}\iint_\Sigma \Delta u_i \, \omega_{ij}^{k} \, \nu_j \, d\Sigma$$

$$\Delta u_i = U$$

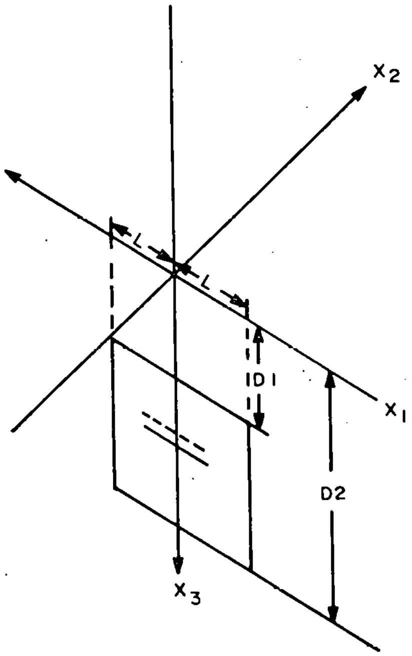


FIGURE 7(a). Coordinate System for Calculation of Displacement Fields

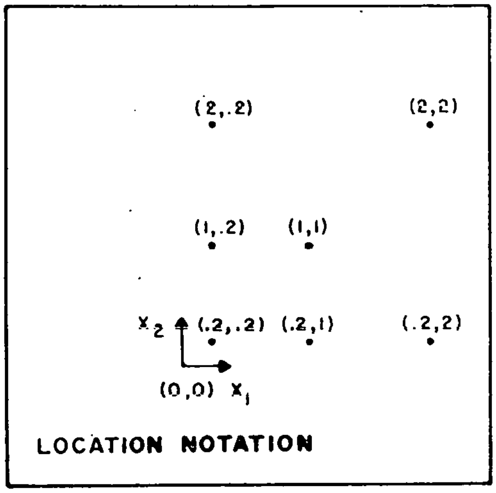
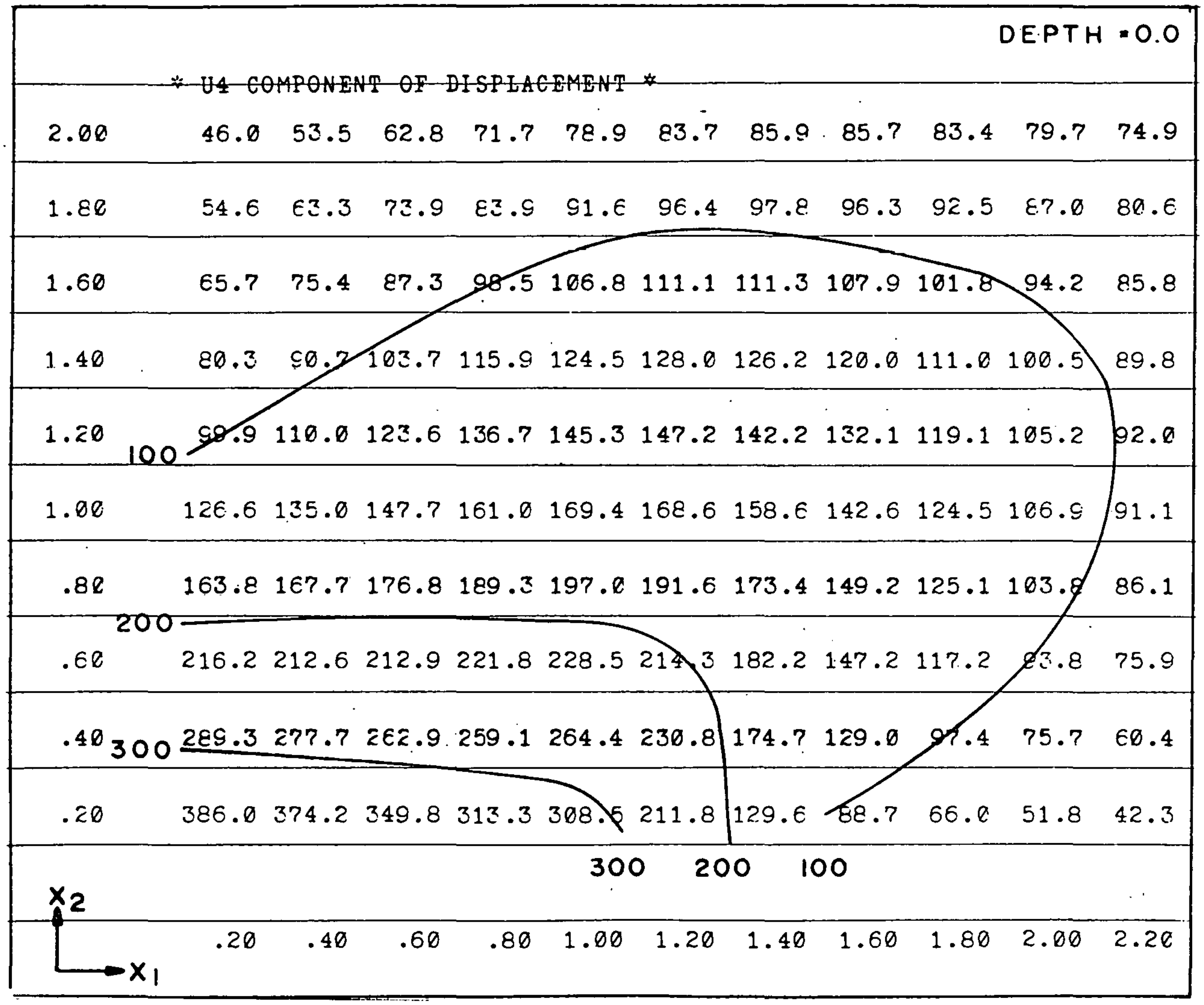


FIGURE 7(b). Location Notation for the Calculated Displacement Fields



DEPTH =0.0

~~* U4 COMPONENT OF DISPLACEMENT *~~

2.00	46.0	53.5	62.8	71.7	78.9	83.7	85.9	85.7	83.4	79.7	74.9
1.80	54.6	63.3	73.9	83.9	91.6	96.4	97.8	96.3	92.5	87.0	80.6
1.60	65.7	75.4	87.3	98.5	106.8	111.1	111.3	107.9	101.8	94.2	85.8
1.40	80.3	90.7	103.7	115.9	124.5	128.0	126.2	120.0	111.0	100.5	89.8
1.20	99.9	110.0	123.6	136.7	145.3	147.2	142.2	132.1	119.1	105.2	92.0
1.00	126.6	135.0	147.7	161.0	169.4	168.6	158.6	142.6	124.5	106.9	91.1
.80	163.8	167.7	176.8	189.3	197.0	191.6	173.4	149.2	125.1	103.8	86.1
.60	216.2	212.6	212.9	221.8	228.5	214.3	182.2	147.2	117.2	83.8	75.9
.40	289.3	277.7	262.9	259.1	264.4	230.8	174.7	129.0	97.4	75.7	60.4
.20	386.0	374.2	349.8	313.3	308.5	211.8	129.6	88.7	66.0	51.8	42.3
	.20	.40	.60	.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20

FIGURE 8. Displacement Contours (mm displacement/meter slip on fault) for Vertical Strike Slip Fault, Fault Semi-length = 1.0, Depth to Top of Fault = 0.0, Depth to Bottom of Fault = 2.0

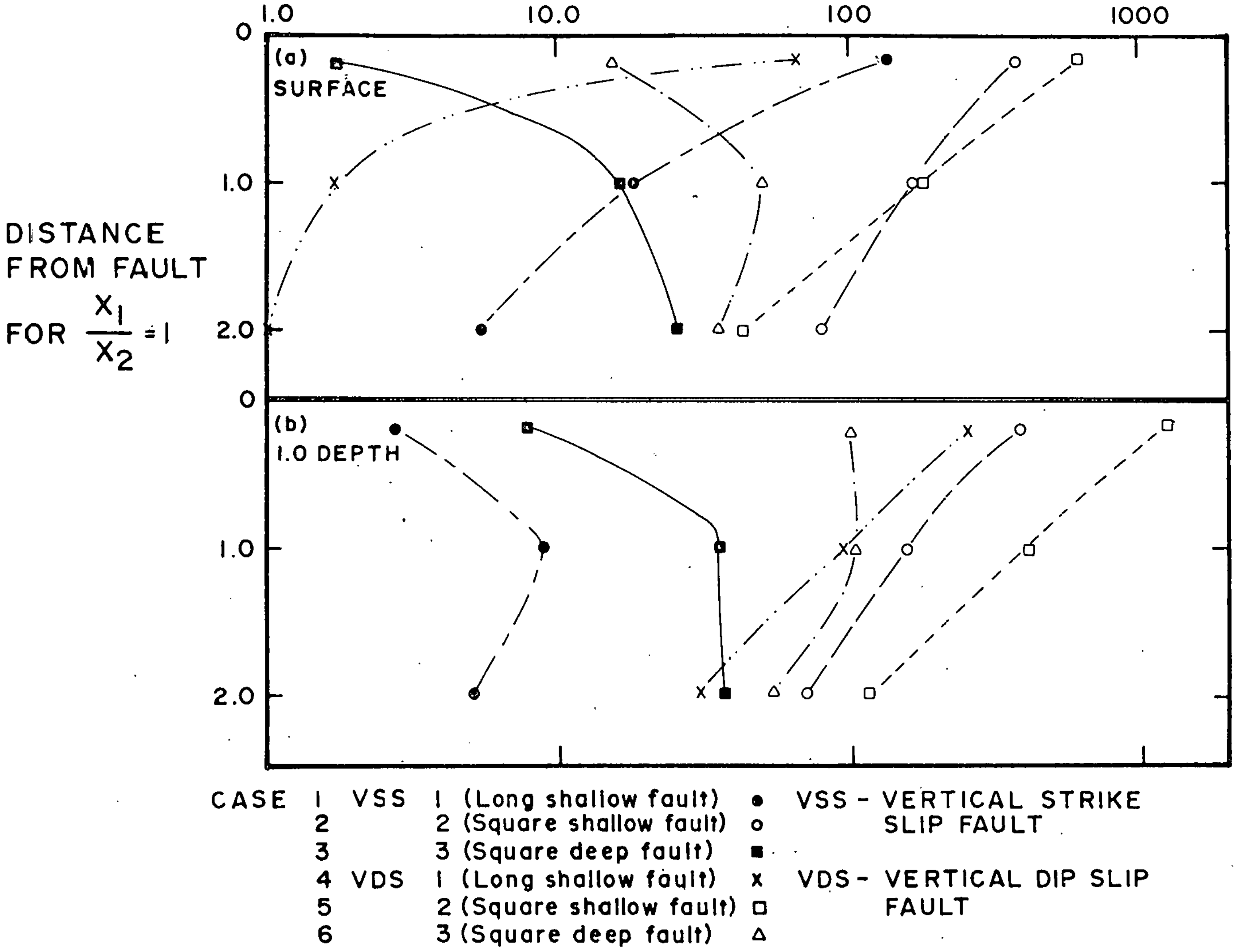


FIGURE 9. Displacement as a Function of Distance from Fault at the Surface and at a Depth of 1 Fault Length

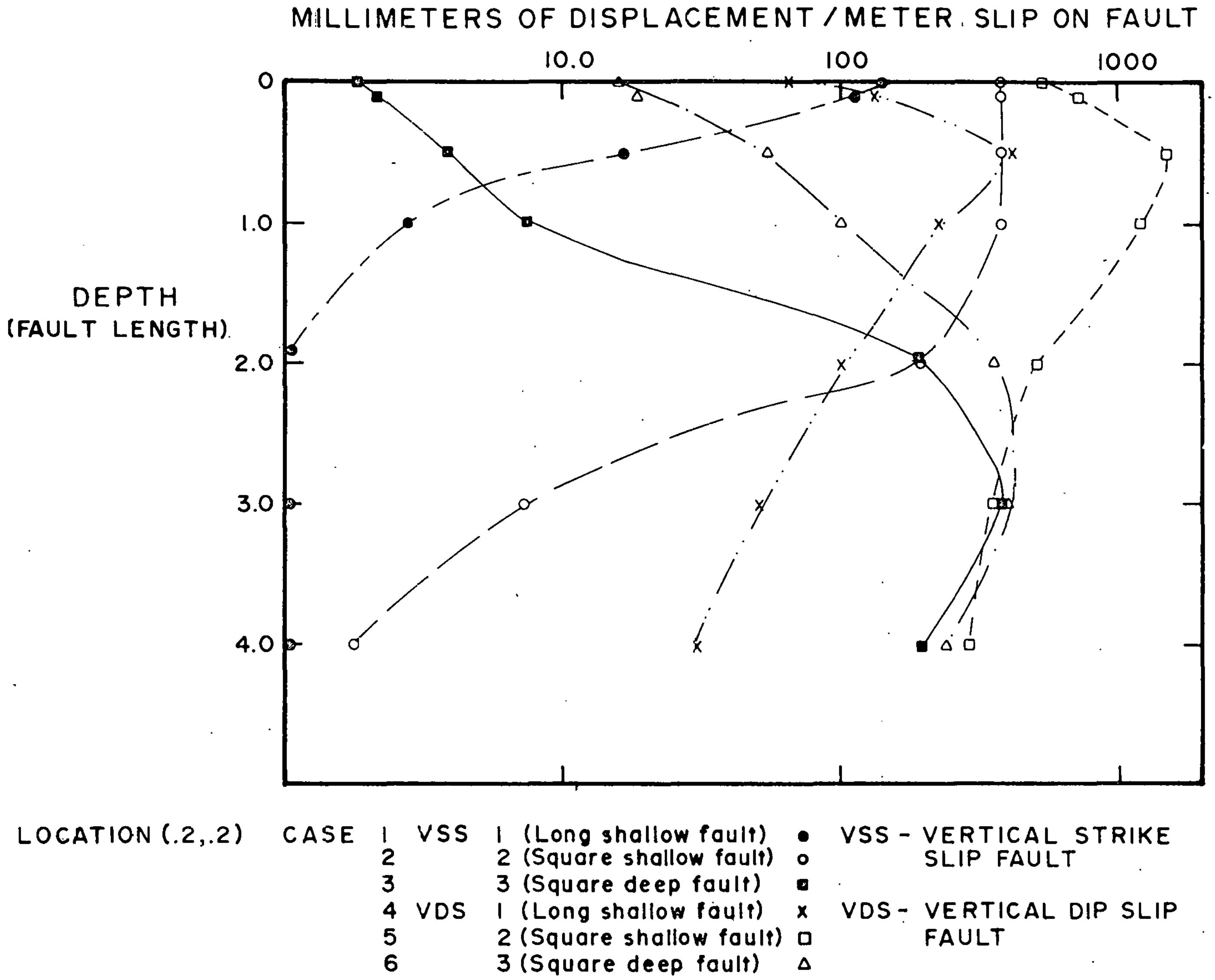


FIGURE 10. Displacement as a Function of Depth in Terms of Fault Length

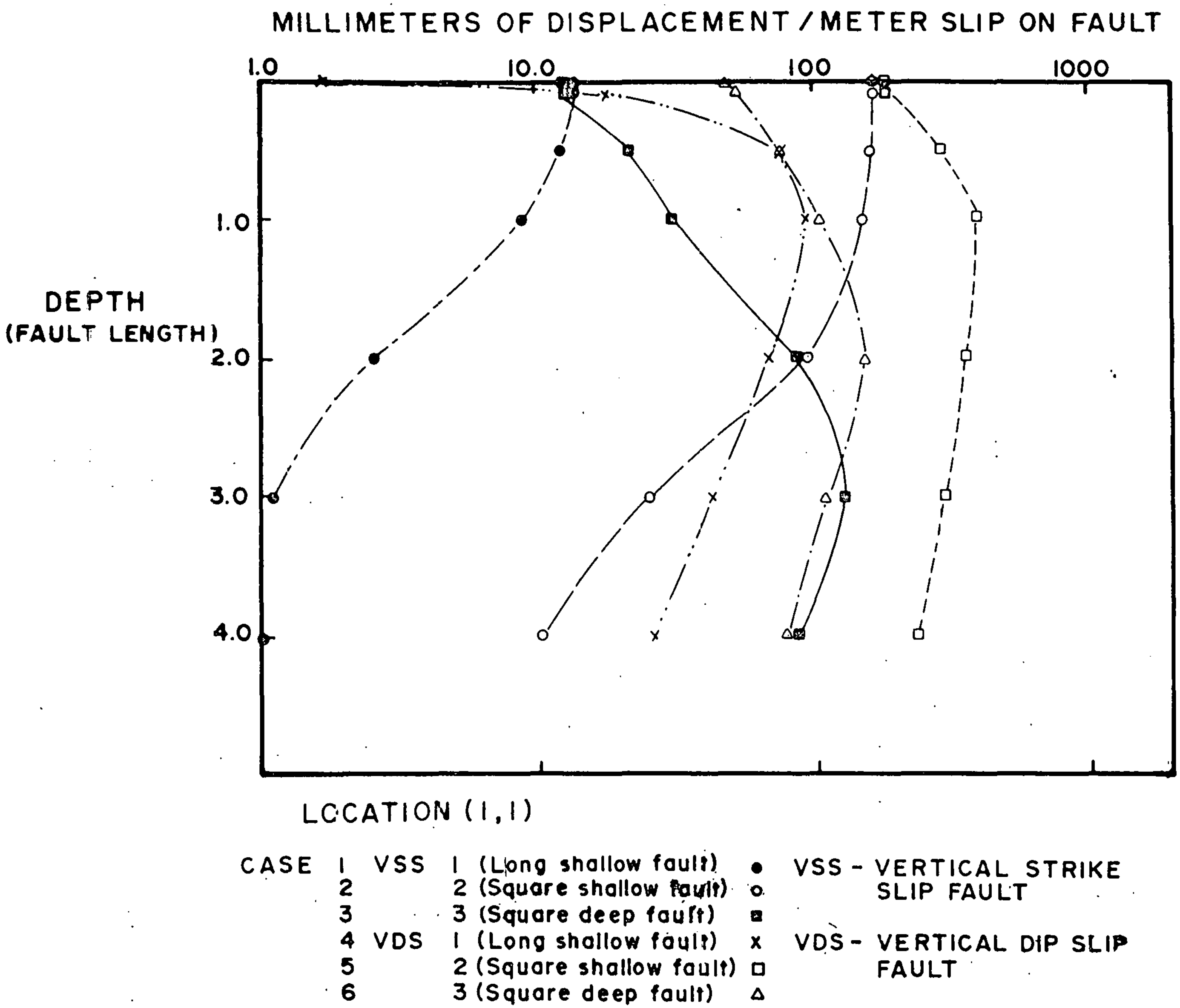


FIGURE 11. Displacement as a Function of Depth in Terms of Fault Length

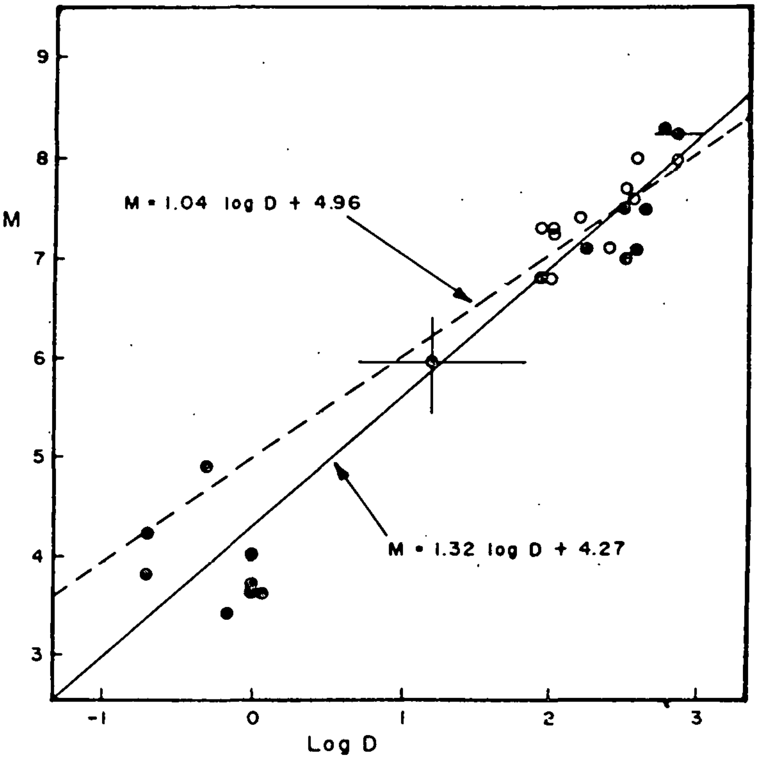


FIGURE 12. Magnitude M Plotted Against the Logarithm of the Displacement D. The Solid Line is a Least Squares Fit to All of the Points. The Dashed Line is a Least Squares at the Points with M > 6.5