Chapter 1

FOUNDATION DESIGN OF EARTHQUAKE RESISTANT STRUCTURES ON BAY AREA LANDFILL

Rob Tuma

Introduction

Earthquake occurrence in the San Francisco Bay Area has the potential for large-scale environmental, property, and human destruction. Studies have shown that, in addition to many minor shocks, the expected frequency of damaging earthquakes in the Bay Area is about 12 per century, and at least one of these is expected to be a great earthquake, comparable to the San Francisco earthquake of 1906 (Goldman, 1969). That earthquake caused damage to property costing over $400 million dollars and more than 700 people lost their lives (Borcherdt, 1975). The effects of a similar earthquake today could be disastrous. Studies estimate the loss of life to be as high as 100,000 people and property damage in the billions of dollars (Algermissen et al., 1972).

The Bay Area is a high risk zone, in part, because it is intersected by three major active faults: the San Andreas, Hayward, and Calaveras faults. Landfill areas also present a particularly complex challenge in the design of earthquake-resistant buildings due to their relatively high water content and uncompacted soil. In fact, historical observations indicate that by far the greatest earthquake damage to facilities in San Francisco has occurred in the areas of filled ground (Clough and Chameau, 1979). Understanding the forces at work between a building and the soil during an earthquake is essential to the design of safe structures. Unfortunately, there remains a great deal of uncertainty regarding the safest foundation design. It is the intent of this report to summarize the types of foundations presently in use and those that may be used in the future in the design of earthquake-resistant structures in the Bay Area landfills.

Past Studies

Knowledge of the interaction between a building and the land during earthquakes is, of course, limited by the number of occurrences from which to make comparisons. Although an abundant volume of literature exists, information in this category is not well substantiated and many quantitative studies rely to a large extent on models. Only a few key studies concerning Bay Area landfill in relation to earthquakes are mentioned here.

A study of the kinds of soil likely to be used for Bay fill and their ground response during earthquakes has been reported by Seed (1969). Steinbrugge (1969) studied the effects of soil movement on developed structures. Both studies illuminate the potential for substantial settlement of mud and sand deposits in the event of an earthquake, and rate different soils for stability. Because earthquake-resistant design is such a broad subject, many documents have been published providing guidance in design techniques, but most make clear that the information is not all-inclusive. The scope of this report mandates describing only a few of the key works. A thorough discussion of structural response to earthquakes and the corresponding determination of structural form is covered by Dowrick (1977). Various forms of earthquake-resistant substructures are suggested, but Dowrick emphasizes that little comparative work has been done. A helpful guide that attempts to identify where research is needed in earthquake-resistant design of structures is presented by the Committee on Earthquake Engineering Research (1982). The report also evaluates the effectiveness of past earthquake engineering research to form a basis for improved design of future structures.

Bay Area Mud

The stability of a building resting on filled ground ultimately depends upon the stability of the ground underneath the fill. Fill on the margins of the Bay is underlain by a few to several hundred feet of soft mud and sand (Trask and Rolston, 1951). Figure 1 illustrates a typical profile of the layers of filled land and natural soils found along the margins of the Bay. The thick sand bodies that underlie portions of fills are usually dense enough to represent little threat to stability, but thin

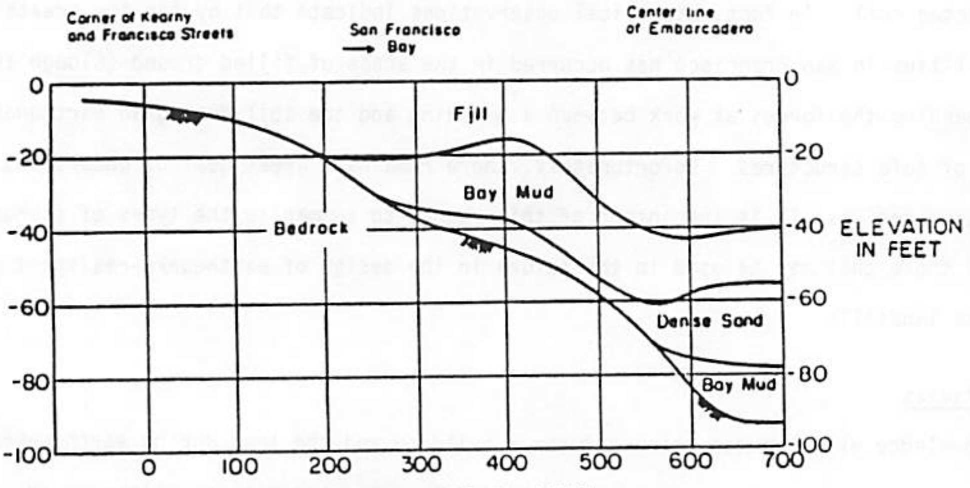

Figure 1. Subsurface profile from the foot of Telegraph Hill, in San Francisco, illustrating the typical composition of soils along the margins of the Bay.

Source: Clough and Chameau, 1979

layers of sand or sand "lenses" present in some Bay muds may undergo liquefaction in the event of a strong earthquake. Liquefaction is a process by which an unconsolidated water-saturated sediment, commonly fine sediment with sand lenses, experiences a sudden loss of strength during an earthquake and behaves like a liquid when shaken. The liquefied soil loses its ability to remain in place and support a structure (Committee on Earthquake Engineering Research, 1982).

Bay muds are typically soft, organic clays subject to significant compaction over a long time under heavy loads (Clough and Chameau, 1979). Investigations also show that Bay muds have a generally high likelihood of liquefaction (Youd et al., 1975). Of soil samples taken around the margins of the Bay, 94 percent indicate a high to moderate probability for liquefaction (Youd et al., 1975). Compounding the problem are thick deposits of Bay mud which display large amplifications in horizontal ground shaking during a seismic event in comparison to other soil deposits (Borcherdt, 1975). Quantitative measurements of ground motions near the Bay from nuclear explosions in Nevada clearly illustrate the magnitude of this difference (Figure 2). The amplitudes of ground shaking in areas of Bay mud are five to eight times larger than those of nearby bedrock sites (Borcherdt, 1975). This must be taken into account, especially in areas that will also incorporate landfill.

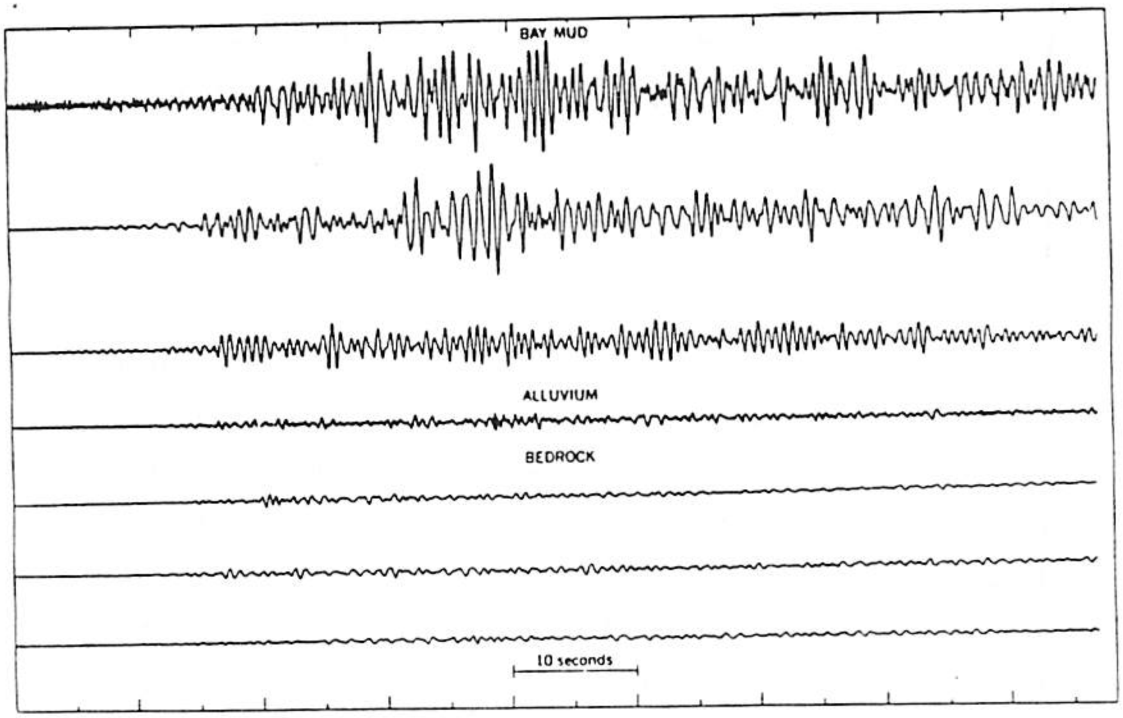

Figure 2. Recordings of horizontal ground motion at several sites in San Francisco, generated by a nuclear explosion in Nevada.

Source: Borcherdt, 1975

Bay Area Fill

Portions of the Bay waterfront as it is known today were created primarily by massive filling operations over the past century. In downtown San Francisco, for example, the portion of shoreline bounded by Sansome and Folsom Streets, originally known as Yerba Buena Cove, illustrates the size of this endeavor. It is estimated that over 20,000,000 cubic yards of fill were placed in Yerba Buena Cove alone (Clough and Chameau, 1979). In order to determine the best choice of foundation for structures on the margins of San Francisco Bay, it is necessary to acquire a knowledge of the characteristics of fill.

The term "fill" generally means a granular substance that can be placed over relatively solid ground in order to raise the surface elevation (Goldman, 1969). The standard fill materials used in the Bay Area are broadly divided into three classes: uncompacted fills of various soils mixed together, hydraulic sand fills, and well-compacted fills of select materials (Seed, 1969). Uncompacted fills are relatively loose and, under earthquake conditions, are vulnerable to differential soil settlement and liquefaction from substantial water absorption. With time they may condense enough to support small buildings safely, but they are considered to form the poorest foundations for most structures. Hydraulic sand fills, which have been used extensively in the Bay Area, consist of moderately dense material that potentially is subject to some degree of settlement during an earthquake. However, small differences in the degree of shaking can produce significantly different results in the amount of soil settlement. Thus, some locations may prove adequate if they are determined to be relatively dense. Finally, well-compacted fills or "engineered fills," have been used most extensively during the last thirty years. These fills are constructed and deposited under the supervision of engineers using firm, dense materials in order to ensure the best compaction possible. Fills made in this manner are unlikely to settle or liquefy and can actually be more stable than many natural deposits (Seed, 1969).

Earthquake Forces on Fill

Choosing a site for building foundations near the Bay shoreline to resist earthquakes requires evaluating several geological hazards, including landslides, consolidation, and liquefaction (Degenkolb, 1977). Landslides are likely to occur when the ground vibrates, causing the shearing (or moving) force to increase and the friction force to decrease. If the surface slope is great enough, large-scale movement of the soil may occur, damaging the foundation's structure. However, the shoreline around most of the Bay is relatively level, and landslides due to earthquakes are likely to be negligible (Seed, 1969).

Consolidation occurs when, due to excess shaking, the ground compacts from a larger volume to one that is smaller. Loose particulate soils surrounding the Bay, for example, may consolidate during an earthquake, causing a significant change in the water level and damage to the foundation. Ground settlements can also lead to differential settlement of soils beneath structures. As a result, the unequal distribution of the building's weight on the ground can cause the structure to topple (Seed, 1969).

Liquefaction, as defined above, is a process by which a highly water-saturated soil turns to liquid under severe shaking and is unable to support a structure (Committee on Earthquake Engineering Research, 1982). Liquefaction poses a real threat in the Bay Area, especially during the rainy season. Many areas contain saturated sand and cohesionless soils either at the surface or at depths less than 50 feet (Bishop et al., 1973). In what is known as a flow slide, large deposits of liquefied soil may actually flow some distance laterally. For example, a road near Lake Merced in San Francisco, built on saturated landfill, slid into the lake during a small earthquake in 1957 (Seed, 1969).

Earthquake Forces on Foundation

In designing building foundations to resist earthquake forces, one must not only provide certain minimum strengths for normal loads, but one must also consider the performance at great overloads and deformations (Degenkolb et al., 1977). Because of this the whole concept of structural design changes. Earthquake forces are the result of vibrations in the ground acting on a structure. The ground vibrates both vertically and horizontally, causing the structure to move or vibrate several times more than it would under stable conditions. The forces causing the vibrations can sometimes be greater than ten times the forces during stable conditions (Degenkolb, 1977).

The characteristic response of a building to earthquake forces is often defined by its fundamental period of vibration, the amount of time it takes for the building to complete one cycle of motion. It is analogous to the time which elapses between successive high points of the swing of a pendulum. If the frequency of the ground motions and the building are the same, forces on the building are amplified and damage is increased. If the frequency of vibrations between the building and the ground are very different, then relatively smaller forces are induced in the building. Bay muds and fill have relatively low frequencies of vibration (Seed, 1969); therefore the key is to construct buildings with high frequency characteristics.

Types of Foundations

In order to create as much differentiation as possible between the frequency of a building and the ground, current design practice for foundations on Bay fill tries to incorporate both the vertical and horizontal stresses caused by an earthquake (Dowrick, 1977). Unfortunately, there remains a considerable amount of uncertainty about the effects of the forces induced by ground shaking. The main problem of earthquake foundation design occurs in transferring the energy of the base area to the ground without destroying the structure. In other words, during an earthquake, the ground applies a force to the substructure. The substructure must apply an equal and opposite force to the ground, otherwise the excess energy from the ground is spent in the destruction of the building.

In areas prone to landslides during earthquakes, the foundation usually incorporates an externally attached device to combat the effects of ground motions (Degenkolb, 1977). The simplest form utilizes a retaining wall placed in the flow path to stop soil movement (Figure 3a). For increased strength,

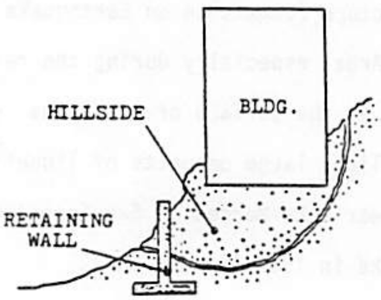

Figure 3a.

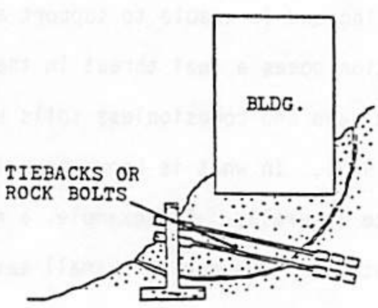

Figure 3b.

Figures 3a, 3b, 3c. Externally attached devices as solutions to landslide under seismic conditions.

Source: Degenkolb, 1977

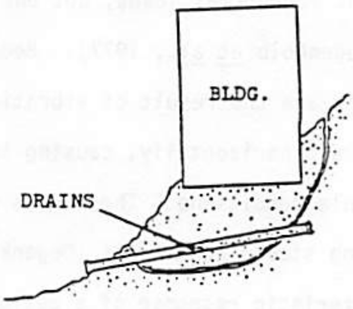

Figure 3c.

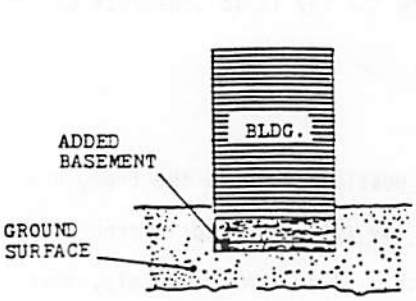

Figure 4. Basement as solution to ground surface consolidation under seismic conditions.

Source Degenkolb, 1977

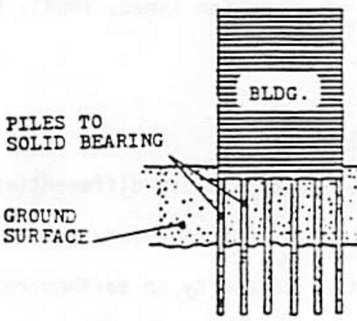

Figure 5. Piles extended to solid substrate as solution to surface soil liquefaction under seismic conditions.

Source: Degenkolb, 1977

long metal rods termed "tie-backs" or "rock bolts" can be attached to the retaining wall and are implanted deep into a stable part of the substrate (Figure 3b). Drains placed under the substructure to remove water in order to increase friction between the building and ground may also be installed (Figure 3c).

If the possibility of consolidation in the soil exists, basements often provide a way of reducing the net pressure on the supporting soil (Figure 4) (Degenkolb, 1977). Other solutions include dividing the substructure into several sections called rafts or pads. Should the ground under one of the pads condense, the pads are designed to allow a large portion of the weight of the building to be concentrated on the pads that remain intact.

The effects of liquefaction may be reduced by using piles extended to a solid substrate (Figure 5) (Degenkolb, 1977). Present evidence suggests that the use of piles in areas subject to earthquakes can prevent major damage to the structure (Steinbrugge, 1969). Integral action of different foundation designs is often used in structures founded on two types of soil (Figure 6) (Dowrick, 1977). For example, piles may be extended from the area of the substructure that lies on soil subject to liquefaction to a firmer soil below the surface, while large pads are used to support that portion of the building resting on ground more susceptible to consolidation. Integral action is designed to provide adequate strength to deal with differential ground movements, but extensive planning is necessary to ensure that the substructure operates as one unit. Details regarding the actual implementation of such a substructure are too complex for this report, but further explanation is provided in Dowrick (1977).

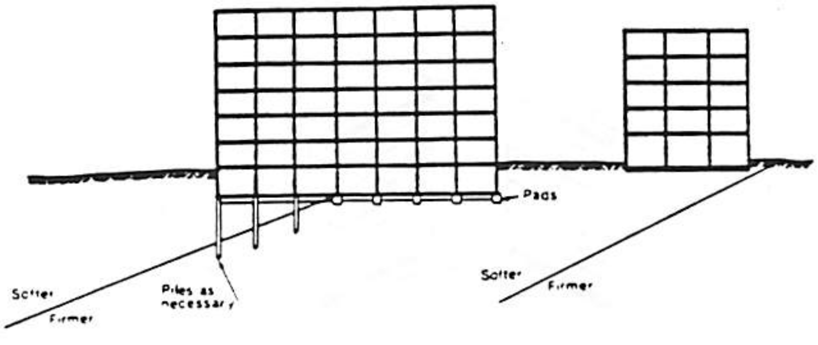

Figure 6. Integral foundation design used for structures built over two types of soil subject to differential seismic movements.

Source: Dowrick, 1977

Although pile foundations are vital in some applications, there are several disadvantages. Liquefaction of a sufficient amount of soil near the surface may allow the piles to move laterally, causing buckling of the piles. Pile foundations, though helpful to maintaining structural integrity, are unlikely to protect a building from the ground shaking. And if the soil settles, the piles will be subjected to an additional downward force from the surrounding soil (Seed, 1969).

New Technology

Recently an important development in earthquake-resistant design, called Base Isolation, has been implemented (Dynamic Isolation Systems, Inc., 1985). The normal approach to providing seismic resistance from the ground shaking has been to attach the structure firmly to the ground and then to design a structure strong enough to survive the forces caused by ground motions. Just as an automobile uses shock absorbers to reduce vibrations, base isolation introduces a "shock absorber" at the *base of a building*, allowing the structure to survive an earthquake.

The heart of the base isolation system is the lead-rubber bearing (Figure 7), which acts as the shock absorber between the building and the ground. A lead-rubber bearing is a laminated bearing of alternating

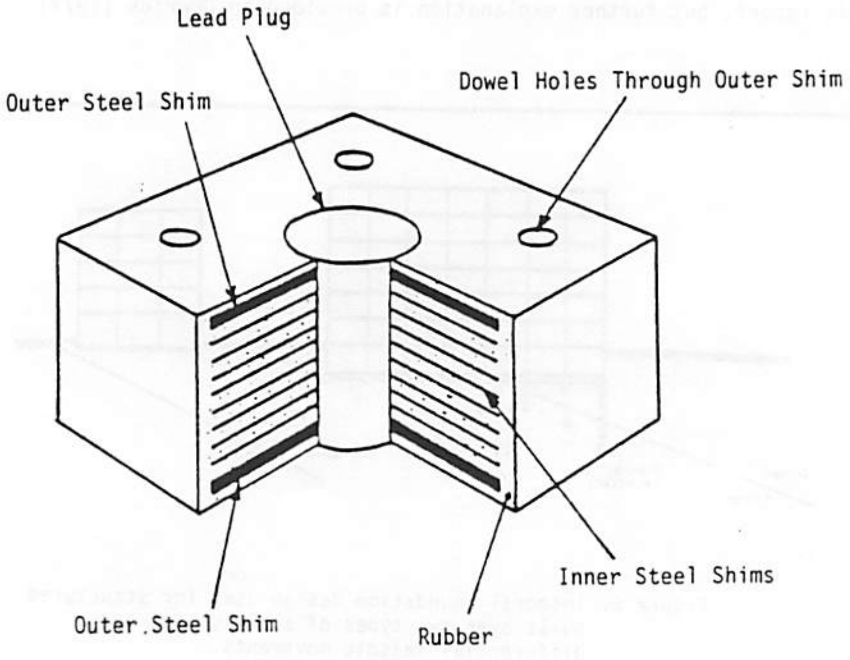

Figure 7. Lead-Rubber Bearing.

Source: Dynamic Isolation Systems, Inc., 1985 rubber and steel layers with a lead plug inserted into a hole in the middle of the unit. Installation of the bearings beneath a building has two major effects on the building under seismic loads. The behavior of the bearing allows the building significantly to dissipate energy transferred from the moving ground, and considerably lengthen the fundamental period of vibration at which the structure responds to the earthquake compared to a non-isolated structure (Dynamic Isolation Systems, Inc., 1985). The lateral flexibility of base isolation systems is designed to ensure that the period of the structure is well above that of the range of the predominant earthquake input, thus significantly reducing the forces transmitted to the structure (Dynamic Isolation Systems, Inc., 1985). The seismic energy is absorbed in the bearings instead of structural components, relieving support columns from energy dissipation roles and any subsequent damage.

The energy-dissipating bearings can be placed anywhere between the main support columns of a building from below the basement to the first floor. The usual location is in a sub-basement directly on the foundation or at the bottom of the first story colums if no basement is present (Figure 8). Installation involves "wedging" the bearing between the building above and a solid base below and attaching the three elements together with metal dowels (Figure 9).

So far only one structure, a freeway overpass near Candlestick Park, south of San Francisco, has been outfitted with the bearings (Buckle, 1986, pers. comm.), but base isolation systems appear suitable for many filled areas along the margins of the Bay. Base isolation system structures respond best when the subsoil is moderately stiff, the structure is between two and ten stories tall, the structure is relatively

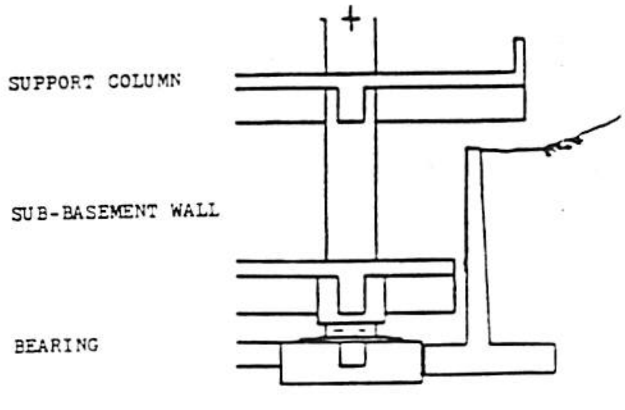

Figure 8. Location of bearings in a sub-basement.

Source: Dynamic Isolation Systems, Inc., 1985

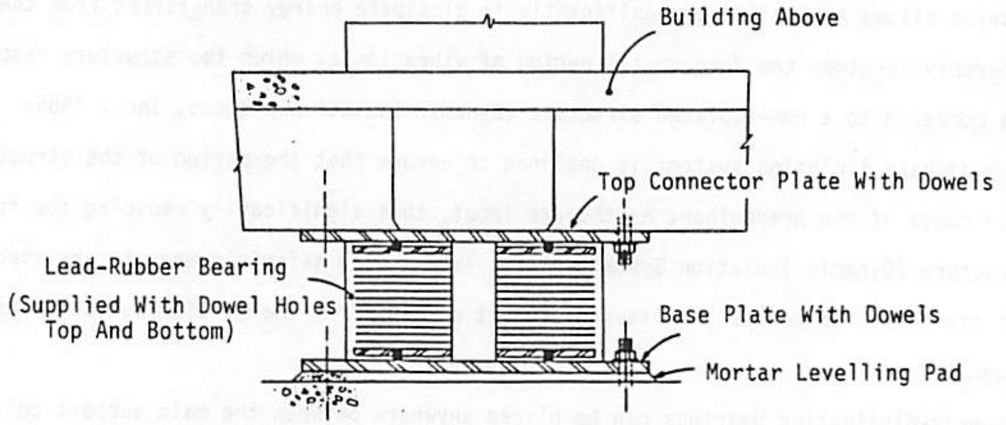

Figure 9. Installation of bearing using dowels.
Source: Dynamic Isolation Systems, Inc., 1985

squat, and the site permits horizontal displacement of the base of the structure of approximately six inches (Dynamic Isolation Systems, Inc., 1985). The kinds of buildings and soil conditions required on filled areas of the Bay are often compatible with these characteristics.

Conclusions

The advent of base isolation systems and other designs undoubtedly will have a powerful impact on the future of earthquake-resistant design. The development of computer software and the skills of engineers in studying the interactions between structure and ground have transformed these complex models from theory to practical reality. However, even with what is now known through research, earthquake-resistant design always involves an unknown condition of how much the specified forces will be exceeded. In order to reduce the danger inherent in this unknown quantity, progress will demand quantifying the relationships between the geologic conditions, the foundation, and the structure into measurable parameters.

REFERENCES CITED

Algermissen, S.T., W.A. Rinehart, and J. Dewey, 1972. A study of earthquake losses in the San Francisco Bay area; National Oceanic Atmospheric Administration, U.S. Department of Commerce, report prepared for the Office of Emergency Preparedness, 220pp.

Bishop, C.C., R.H. Chapman, G.B. Chase, R.D. Knox, and D.A. Rodgers, 1973. Geological and geophysical investigations for Tri-Cities seismic safety and Environmental Resources Board; California Division of Mines and Geology, Report No. 19, 43pp.

Borcherdt, R.D., 1975. Studies for Seismic Zonation of the San Francisco Bay Region; U.S. Geological Survey Professional Paper 941-A, Washington, D.C., 102pp.

Buckle, I.G., engineer, Dynamic Isolation Systems, Inc. Personal communication, 1986.

Clough, G.W., and J.L. Chameau, 1979. A study of the behavior of the San Francisco waterfront fills under seismic loading; Report No. 35, by The John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, for U.S. Geological Survey, Department of the Interior, Office of Earthquake Studies; Stanford University, Stanford, California, 121pp.

Committee on Earthquake Engineering Research, 1982. Earthquake Engineering Research - 1982; Washington, D.C., National Academy Press, 266pp.

Degenkolb, H.J., 1977. Structural Concepts; seminar presented at Seismic Institute for Architectural faculty, Stanford University, Stanford, California, August 10, 1977; American Institute of Architects Research Corp., Washington, D.C., 69pp. (Available at Earthquake Engineering Research Library, Richmond, California.)

Degenkolb, H.J., T.D. Wosser, and L.A. Wyllie, 1979. Practical earthquake resistant design of building structures; unpublished report, 25pp. (Available available at Earthquake Engineering Research Library, Richmond, California.)

Dowrick, D.J., 1977. Earthquake Resistant Designs; Great Britain, John Wiley and Sons, 374pp.

Dynamic Isolation Systems, Inc. (DIS), 1985. Base Isolation of Buildings; Berkeley, California, 200pp.

Goldman, H.B., 1969. Geology of San Francisco Bay. Pp. 9-29 in Geologic and engineering aspects of San Francisco Bay fill, H.B. Goldman, ed., California Division of Mines and Geology, Special Report 97, 130pp.

Seed, H.B., 1969. Seismic problems in the use of fills in San Francisco Bay. Pp. 87-99 in Geologic and Engineering Aspects of San Francisco Bay Fill, H.B. Goldman, ed., California Division of Mines and Geology, Special Report 97, 130pp.

Steinbrugge, K.V., 1969. Seismic risk to buildings and structures on filled lands in San Francisco Bay. Pp. 101-15 in Geologic and Engineering Aspects of San Francisco Bay Fill, H.B. Goldman, ed., California Division of Mines and Geology, Special Report 97, 130pp.

Trask, P.D., and J.W. Rolston, 1951. Engineering geology of San Francisco Bay, California; Geological Society of America Bulletin, V. 62, pp. 1079-110.

Youd, T.L., D.R. Nichols, E.J. Helley, and K.R. Lajoie, 1975. Liquefaction potential. Pp. A68-A74 in Studies for Seismic Zonation of the San Francisco Bay Region; U.S. Geological Survey Professional Paper 941-A, 102pp.