SOME CONSIDERATIONS IN THE DESIGN OF FOUNDATIONS FOR EARTHQUAKES

by William W. Moore and *
Robert D. Darragh

Introduction

The response of structures to earthquake vibrations is the subject of study and research by many specialists. Seismologists record and interpret the amplitudes, accelerations and periods of seismic waves and locate their epicenters on active faults. Structural Engineers analyze the shears and moments induced in structures by seismic forces and design the structural members to resist these forces. As is well known, significant contributions to earthquake engineering have been made by research in these fields. In another specialized field of engineering, seismic design has been making progress. This field is Soil Mechanics and Foundation Engineering. The purpose of this paper is to present some of the factors which should be considered in the design of foundations for seismic loads.

Foundation Design for Vertical and Lateral Loads

Failure of a structure is caused by excessive deflection, not excessive stresses. The same is true of foundation failures. However, the time-rate of deflection is more often of controlling importance in the design against foundation failure than in superstructure design.

Let us consider how the time-rate of deflection of soils affects the design of building foundations. Figure 1 illustrates a typical settlement pattern for a building under static loading conditions. We shall assume that the building is supported on spread footings and that the structural engineer has specified the allowable total and differential settlements which the building can withstand, say one-half inch differential settlement between interior and exterior columns.

Settlement calculations are based upon Terzaghi's Theory of Consolidation (1) by which the compression of the foundation soils under the applied building loads is determined from laboratory consolidation curves. The time-rate of consolidation is dependent upon the rate at which water and air can escape from the voids of the soil subjected to increased pressures from building loads. This rate is relatively fast for sands and slow for saturated clays.

Now, let us consider the effect of seismic loads on the settlement behavior of this typical building. It is assumed that the structural analysis for lateral earthquake loads has resulted in a 50 per cent increase in the vertical loads on the exterior column footings. In considering how the foundations should be designed for the increased vertical loads due to these lateral forces, it might seem obvious that the exterior footings should be made 50 per cent larger to accomodate the combined vertical and seismic loads. However, as the old saying goes, "beware of the obvious."

* Senior Resident Partner and Staff Engineer, Dames & Moore, Soil Mechanics Engineers, 340 Market Street, San Francisco, California.

What will be the effect on the settlement pattern of the building if the size of the exterior footings is increased because of seismic design considerations, while leaving the interior footings at the same size as required for support of dead loads? Obviously, the settlement of the exterior footings under dead loads would be less than previously considered for the smaller footings, and the differential settlements between exterior and interior columns would be increased.

Thus, an apparent conflict exists in the design of foundations for vertical static and lateral seismic loads. To resolve this conflict, it is necessary to consider the difference in loading conditions for the vertical and lateral loads, and the behavior of the foundation soils under these different conditions. First, it should be realized that the time duration of loading is very important in predicting the response of foundation soils to loading. Design wind loads may be imposed frequently or for a sufficient length of time so that they can be considered similar to other live loads to which the structure is subjected. However, short-time wind, seismic or blast loads require a different concept of foundation design than used for conventional live loads.

One approach to the design of foundations for these short time loads is to permit an increase in the allowable bearing pressures. If there were a single magic number that could be used for this increase, whether it be 25 per cent, 33 per cent, 50 per cent or 100 per cent, foundation design would be greatly simplified. However, this easy solution is no more applicable to all different types of soil than a similar generalization would be to the various types of structural materials. Soils will react to short time loads in accordance with their varying physical properties. Generally speaking, sands are quite sensitive to these shock loads; clays are relatively insensitive. To examine this difference between sandy and clayey soils and to evaluate its effect on foundation design, the load deflection characteristics of each soil type will be considered.

Load Settlement Characteristics of Sandy Soils

Figure 2 presents a typical load settlement curve for a spread footing on sandy soils. The solid line represents the deflection of the footing under permanently applied (dead) loads. Because of the relatively fast drainage characteristics of sand, these settlements will occur quite rapidly.

If instrumentation were provided to record the load settlement response of the footing to short time loads, a pattern similar to that indicated by the dash lines on Figure 2 would be obtained. The magnitude of the settlement is primarily dependent upon the soil structure. For dense sandy soils, the deflection is relatively small; the deflection increases with the decreasing density of the sand deposit. If the density of a saturated sand is less than a certain critical value, the soil structure could collapse during a seismic disturbance, transferring the load to pore water and causing a flow failure known as liquifaction. Some of the sensational flow sides in Holland and China have been due to this phenomenon. If this behavior is anticipated, either the loose sandy soils should be stabilized or the building should be supported independently of this stratum.

In establishing allowable bearing pressures and in estimating foundation deflections for short term loads, a general knowledge of the behavior of the foundation soils must be relied upon. Since no laboratory procedures are presently in general use to duplicate the effect of seismic loads on soils, experience must guide the Engineer in the design for these loading conditions. Footings founded on loose sands may yield or fail during seismic disturbances, even though their behavior under permanently applied vertical loads may have been satisfactory.

Buildings founded on a dense sand formation may suffer no damage during an earthquake, even though the short time vertical loads may be much higher than those imposed permanently. Thus, some increase in bearing pressures for footings founded on dense sandy soils may be permitted for short time seismic loads without sacrificing an adequate factor of safety against failure; a representative increase in allowable bearing pressure for seismic forces is from 20 to 30 per cent.

Load Settlement Characteristics of Clay Soils

Generally, clays are less desirable foundation materials than sands because of their greater compressibility. However, clays do possess some advantages over sands with respect to their behavior under short time loads.

Figure 3 presents a typical load settlement curve for a spread footing on clayey soils. The settlement curve for permanently applied loads is similar in shape to that for sandy soils, although the magnitude of the deflection and the time-rate of its occurrence may be quite different, and the curve indicates more abrupt yielding at loads above the design range. As illustrated on Figure 3, a footing founded on clay would not exhibit appreciable deflection during a one-second seismic load, because the intergranular structure of the clay cannot adjust to the change of load during this short time. Although high pore pressures may be developed in the clay by the increased loads imposed during earthquakes, the time lag for consolidation of the clay will prevent appreciable deflections from occurring. Thus, footings on clayey soils may be designed for comparatively high, short-time loads without excessive deflection in the foundations. The allowable bearing pressures will be dependent upon the type of structure and upon the general characteristics of the soil. Again, experience and judgment rather than a precise laboratory testing procedure must, at present, be relied upon. For typical clayey soils, the allowable bearing pressures for dead plus live loads may be increased from 25 to 100 per cent for seismic loads.

Structural Response to Seismic Loads

The previous discussion should not be construed as advocating that the short-time vertical loads due to lateral forces can be ignored if the soils do not deflect appreciably under these loads. There is ample evidence that severe overstressing of the structural elements of the foundation can occur, even though the same forces do not cause failure of the foundation soils. The Pacific Fire Rating Bureau has reported several examples of this behavior in elevated water tanks caused by the Arvin-Tehachapi, California earthquake of July 21, 1952 (2).

Figure 4 depicts the damage suffered by the structural elements of the foundation for a 100,000-gallon water tank on a 100-foot high tower located at Maricopa Seed Farms about 15 miles southeast of Taft, California and 10 miles northwest of the epicenter of the July 21, 1952 earthquake. The anchor bolts were stretched and the concrete under the base plate was crushed. However, these high vertical loads did not cause any adverse effect on the foundation soils. The water tank at the Seed Farms was supported on friction piling because adequate support for the permanently applied loads could not be obtained by spread footings founded on the relatively weak sandy and silty subsoils. However, the lack of foundation failure cannot be explained solely by the use of piling, as similar overstressing of the foundation connections has been observed in the case of tanks founded on spread footings. This example simply gives evidence to the fact that high vertical loads can be imposed during earthquakes, but that these loads would not necessarily cause detrimental deflection of the foundations.

Foundation Design for Overturning Forces

So far, this paper has considered only seismic loads which produce concentric pressure distributions on the foundation soils. In the design of foundations for tall stacks and vertical vessels, the assumption of concentric pressure distribution under lateral loads is not valid.

The diagram on the left of Figure 5 depicts the theorectical and approximate pressure distributions on sandy soils for a rigid mat foundation supporting concentric vertical loads. As indicated by the theoretical pressure diagram, the highest pressure occurs under the center of the foundation, where the soils are confined by the surcharge effect of the imposed load as well as that of the overburden pressure. If the foundation is designed to impose average limiting pressures indicated by the approximate pressure diagram, the confinement is sufficient to prevent overstressing of the foundation soils.

When the stack is subjected to lateral loads, a redistribution of pressure occurs beneath the foundation as shown by the diagram at the center of Figure 5. Although the area of the trapezoid which approximates the eccentric pressure distribution may be no greater than the area of a rectangle representing the approximate concentric load pressures, failure of the foundation may be produced. The failure is caused by the fact that the concentration of pressure now occurs near the edge of the foundation where the effective confinement is produced only by the adjacent overburden. This confinement may be insufficient to prevent outward plastic flow of the overstressed soils and failure of the foundation may occur at the edges.

The effect of high edge pressures may be most critical under sustained wind loading conditions, but it also can produce foundation failure during seismic loads. As the stack rocks on its foundation during an earthquake, progressive failure of the soil at the edges may occur. To prevent these adverse effects, the maximum edge pressures for overturning loads may be limited to a specified percentage of the design pressures for concentric loads. The theoretical pressure distribution for eccentric loads can be approximated by a trapezoidal diagram for which the maximum edge pressure should be limited to some percentage of pressures for concentric loads; 70 to 80 per cent are typical values for sandy soils. The pressure distribution for the mat foundation under these limiting seismic conditions is indicated on the right diagram on Figure 5.

In clayey soils, the effect of high edge pressures is not as severe as it is on sandy soils, since the strength of clay is mainly a function of its intermolecular attraction, called cohesion, rather than of the internal friction which is dependent upon confining pressures. Generally, similar bearing pressures can be used for eccentric or concentric loading conditions on clayey soils.

Seismic Design of Pile Supported Structures

Industrial buildings in reclaimed marshland areas often present special problems in seismic design. The presence of weak and compressible soils to considerable depths frequently requires pile support of the structural frame and machinery of these buildings in order to avoid adverse settlement behavior. Figure 6A is a schematic drawing of such a pile supported building.

Two approaches to the seismic design of the building are possible. Figure 6B illustrates an assumption which is sometimes made regarding the transfer of an assumed lateral force on the superstructure into the ground by means of bending resistance of the piling.

The alternate approach is to consider that the seismic forces are transmitted to the foundation by the ground motion rather than by the response of the superstructure. Recorded ground motion data seem to indicate that shear waves of large amplitudes and relatively slow velocities are created in extensive deposits of weak bay muds by earthquakes. The behavior of a pile supported building under this concept of ground motion is illustrated on Figure 6C. When one considers that the ground surrounding the pile cap may deflect laterally as much as several inches in relation to the pile tip, it can be seen that the forces induced by ground displacements may be much greater than the forces transferred to the piling by an assumed lateral force applied to the superstructure. Thus, ground motion considerations may govern the foundation design for seismic forces.

In the design of pile foundations to resist the ground motion, it is impractical, if not impossible, to hold the structure in place while the ground moves in relation to the piles. What is important in seismic design is that the structure be well tied together so that it acts as a unit under the vibratory loads. A suitable bond must be developed between the structure and the surrounding soils so that the structure will not slide along the ground surface, but will move with the ground motion. To insure this behavior, the piles should be capable of deflecting with the ground displacements and the inertia forces set up in the building should be transmitted to the subsoils by evaluating the permissible lateral resistance offered by the soils adjacent to the pile caps and grade beams.

As another solution to the seismic design of pile supported structures, batter piles are sometimes considered. Although batter piles may be effective in resisting lateral loads applied above the ground surface, they are usually no more useful than vertical piles in resisting the lateral forces of ground motion. Also, in marshland areas, batter piles must resist the bending forces produced by subsiding fills, whereas only axial downdrag forces are produced on the vertical piles. The forces exerted on the piling under static conditions are illustrated on Figure 5D. Thus, batter piles may be more a disadvantage rather than an advantage in foundations designed for both static and seismic loads under some soil conditions.

Conclusions

The principles of soil behavior to be considered in the seismic design of foundations are simple in concept but often become somewhat involved for specific practical conditions. Since most soils are neither ideal sands nor clays, special consideration must be given to the seismic behavior of the multiplicity of soils found in nature. Despite the limitations in our present knowledge, the probable behavior of foundations under seismic loads can usually be anticipated, at least approximately. This behavior cannot be ignored without the danger of adverse foundation deflection and perhaps failure.

To date, experience and judgment are the main sources of criteria available to the Engineer for the design of foundations for seismic loads. Some progress has already been made in the more scientific approach of the seismic design of foundations. A number of investigators are pursuing studies in the dynamic behavior of soils. The A.S.T.M. is rendering valuable aid by assembling information and discussions of unsolved problems in Soil Dynamics (3). Geophysical data, such as the measured velocities of compressional waves in various types of soils will very probably permit the calculation of dynamic soil properties. These data may, in the future, be used in estimating the deflection characteristics of foundations under seismic loads. Shear tests in which loads are applied and released in rapid cycles may give some indication of the response of the soils to dynamic loads, but the time lag in response of the usual present day mechanical equipment prevents the shear data from truly approximating seismic loading conditions. However, additional laboratory procedures and increased knowledge of the behavior of soils under short-time loading conditions are being developed in research studies. These procedures will no doubt become sufficiently simple and practical so that foundations can be designed for seismic conditions considering the actual soil properties at a specific site.

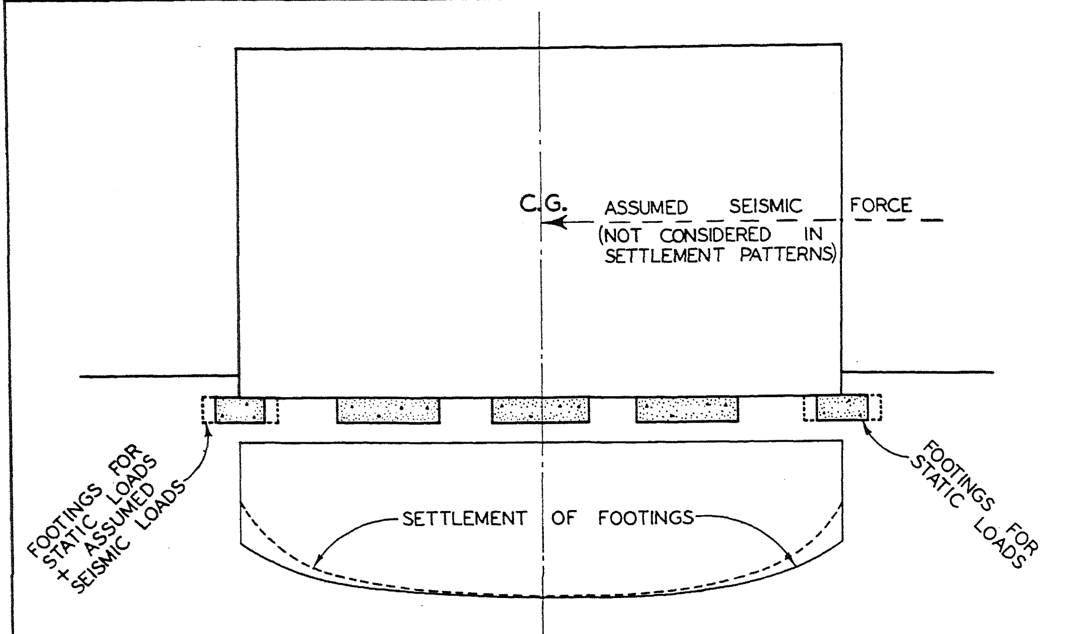
Bibliography

(1) Terzaghi, Karl, "Theoretical Soil Mechanics", John Wiley and Sons, 1943.

(2) Moran, Donald F. and Steinbrugge, Karl V., "Earthquake Responce of Elevated Water Tanks and Refinery Structures", Paper presented in San Francisco, California, November 1, 1955, before the Structural Engineers Association of Northern California; not yet published.

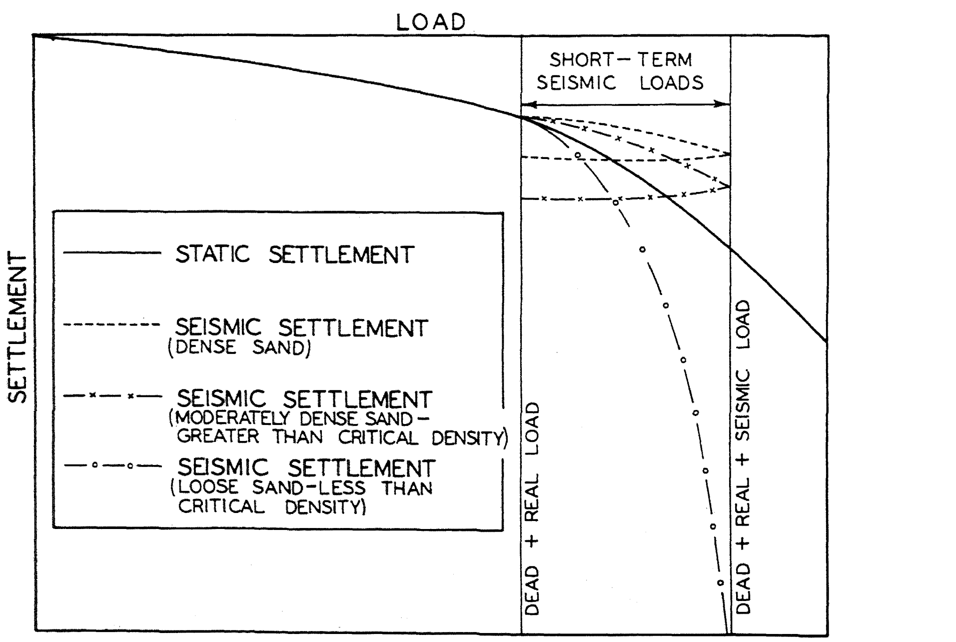
(3) American Society for Testing Materials, "Symposium on Dynamic Testing of Soils", A.S.T.M. Special Technical Publication No. 156, 1953.

Figures



SETTLEMENT PATTERNS FOR BUILDING UNDER STATIC LOADS

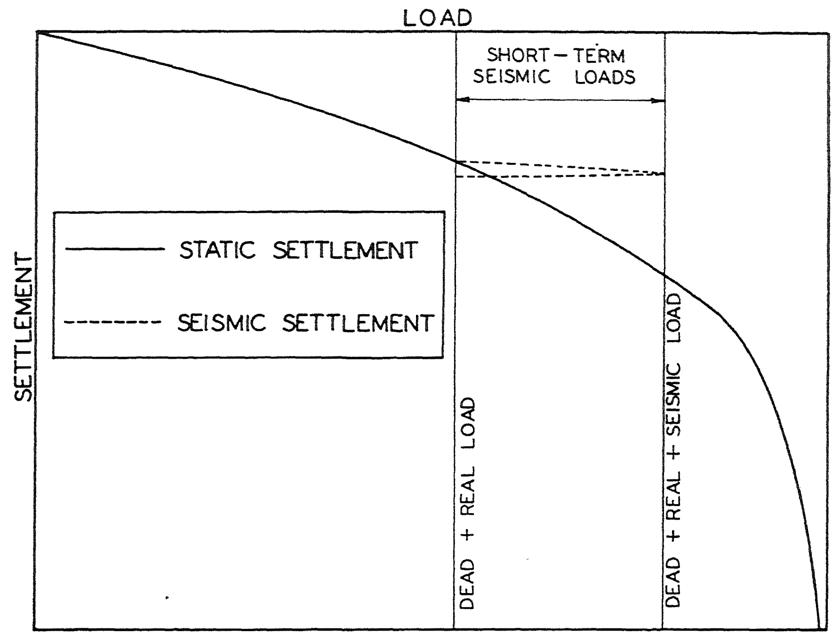
(FIGURE 1)



LOAD-SETTLEMENT PATTERNS

(SPREAD FOOTINGS ON SANDY SOILS)

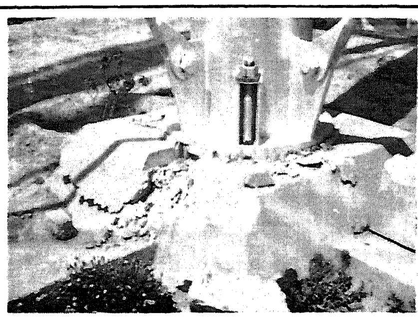
(FIGURE 2)



LOAD-SETTLEMENT PATTERNS
(SPREAD FOOTINGS ON CLAYEY SOILS)
(FIGURE 3)

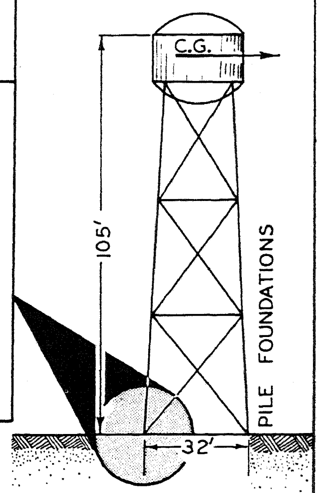
BENT PLATES ON ANCHOR BOLT DETAIL. DARK PLATE ON TOP IS NEW. BOLTS STRETCHED. NOTE WELDED CONSTRUCTION.

NOTE THE TAKE-UP IN LOWER PANEL RODS. OVERALL TAKE-UP ABOUT 1 1/2 INCHES. PROGRESSIVELY LESS TAKE-UP IN UPPER PANELS.



(PACIFIC FIRE RATING BUREAU PHOTOGRAPHS)

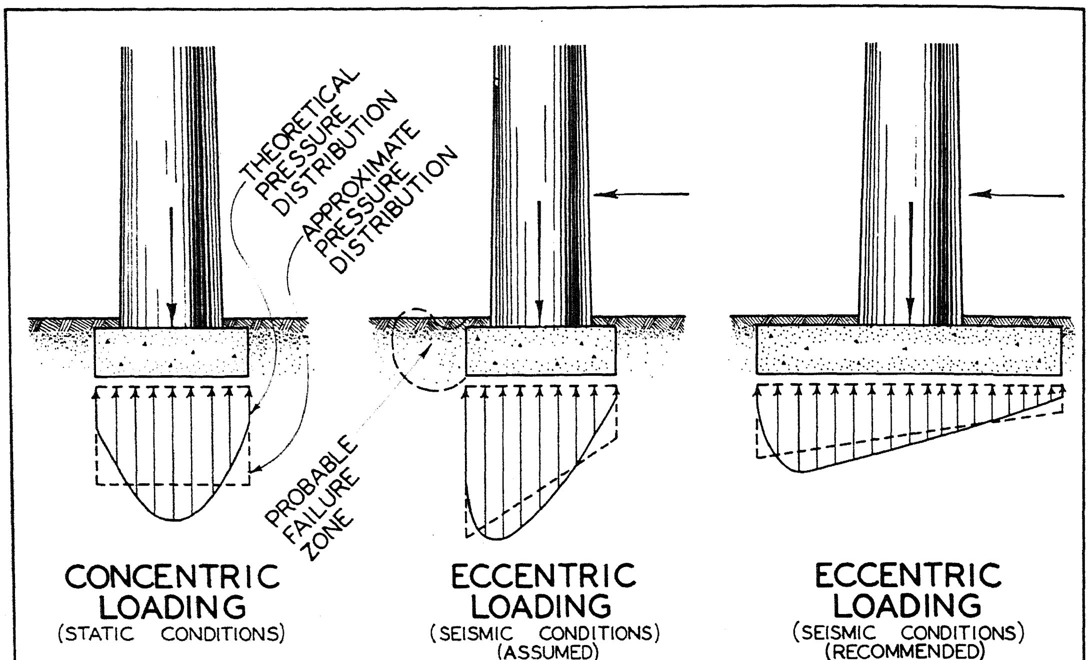
WEIGHT OF TANK & CONTENTS = 926 KIPS



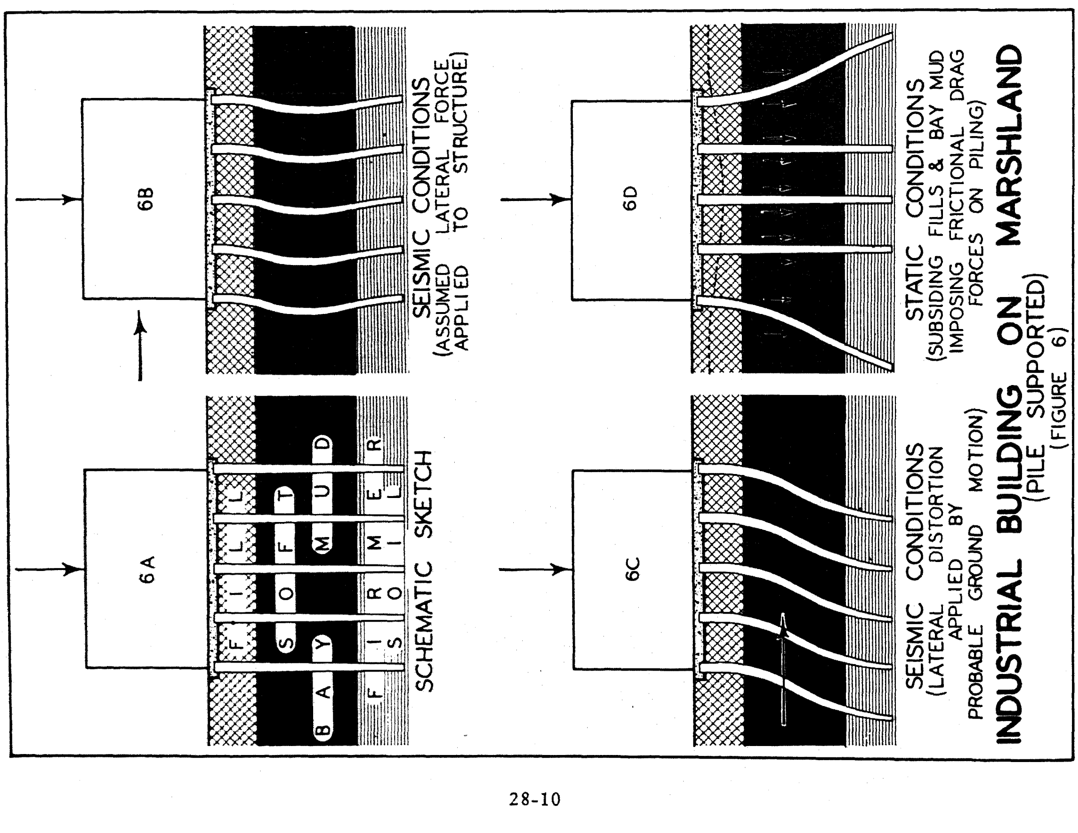
SCHEMATIC ELEVATION OF TANK & TOWER

TANK FOUNDATION AT MARICOPA SEED FARMS AFTER TEHACHAPI EARTHQUAKE, JULY 21, 1952

(FIGURE 4)



PRESSURE DISTRIBUTIONS
(RIGID FOUNDATION ON SANDY SOILS)
(FIGURE 5)



INDUSTRIAL BUILDING ON MARSHLAND
(PILE SUPPORTED)
(FIGURE 6)