Chapter 3

LAND STABILITY ALONG THE EAST BAY SHORELINE

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The East Bay shoreline area under study is not the original bay shoreline; rather it is composed of landfill which has been placed since the 1920's. In order to be thorough in the planning process for the area, one must consider the type of land on which future developments of any kind may occur. When structures are built on the filled areas covering the perimeter of the bay, it is important to know what the foundation soils under the fill are, what is used for fill material, and the physical properties of these two components under various conditions.

Foundation Soils

Foundation soils are the substrate upon which fills are placed. The success or failure of a fill is often due to the type of foundation soil on which it is placed. Three types of substrate occur on the bay bottom (excluding the underlying bedrock): older bay mud, sand deposits, and younger bay mud.

Older bay mud is a silty clay, with varying amounts of sand and gravel, and is of less than 40% weight water. It blankets and fills channels in the bedrock. It is in an overconsolidated state, which means that it is denser than would be expected just from the weight of the sediments which overlie it. It is overlain by either sand or younger bay mud (Goldman, 1969). It would be a good foundation for fill: however, it is generally overlain by weaker foundation soils.

Sand deposits are found in a number of lenses which occur between the older and younger bay mud units. There are some areas where sand lenses occur within the younger bay mud as thin layers, or as fingers which interdigitate with the bay mud. The sand is a preferable foundation soil to younger bay mud, although under certain seismic conditions it can become liquified and lose its ability to bear a load.

Younger bay mud (bay mud for brevity) is the foundation soil on which most fill material is placed. The bay mud is of estuarine origin and is a soft, plastic silty clay with particles ranging from clay size (less than 2 microns) to very fine sand (less than 100 microns). It is much more moist than older bay mud with more than 50% of its weight in water. Included in the mud are various organic substances such as shells, vegetable matter, and peat. There are also lenses and stringers of sand and gravel. The buildup of the bay mud occurred over a long period of time. When the oceans rose as glaciers melted, the previously exposed valleys and ravines of the bay were inundated, and the bay mud was deposited. Because the topography of the underlying bay bottom is irregular, the thickness of the bay mud varies greatly (Lee and Praszker, 1969).

The bay mud is in an unconsolidated, semi-fluid, jelly-like state. There are water- or air-filled voids in the bay mud which take up about twice the volume of the solid particles. Bay mud is highly impermeable, that is, it is very difficult to squeeze the water out of the voids. Because of this, bay mud is weak and incapable of supporting appreciable loads. In order to decrease the volume in the voids and hence consolidate the mud, it is necessary to force the water and air out of them. An applied external pressure will help the process and accelerate it.

Fill Materials

Fill generally relates to material which can be placed on firm or semi-liquid ground with a resulting increase in the surface elevation. Various materials are used for fill. Sand is an important source of hydraulic fill in the bay. Other sources of fill material include dredged bay mud, garbage mixed with sand, and imported and compacted fill from excavations and grading of land in the hills. Commercial quarries produce stone for use as rip-rap, but this material cannot be used as fill on bay mud as it simply sinks into the mud without appreciably raising the ground level (Goldman, 1969).

Reaction of the Bay Mud to Imposed Loads

Bay mud is a semi-viscous "jelly" which can easily change in geometrical configuration. When fill is placed on bay mud, the mud will behave more like a plastic than a solid, and will try to move rather than compact under the load. The capacity of the bay mud to support an external load such as fill material is not measured so much by the force of the load as by the deformation that the load may cause in the mud (Lee and Praszker, 1969).

Bay mud will tend to flow laterally when fill is placed on it. If it were possible to confine the mud laterally, then the only effect of placing the load on the mud would be to compact the mud and force the water and air out of the voids. In that case the mud could support an almost infinite load. In reality the mud isn't confined and can therefore move laterally if an appreciable load is placed on it. When fill material is placed on mud, the force it exerts on the mud must be kept low (no more than 300 lbs/ft^2) to keep the lateral deformation to a minimum. It would be ideal if the load could cover the entire fill area at once, so as to spread the load out equally over a large area and thereby decrease the load which each individual unit of bay mud would have to support. In actual practice the fill material is placed by end-dumping on a limited area. The material is spread stage-by-stage. Areas toward the edge of the fill which haven't yet been loaded are free to react plastically due to the load on the adjacent areas (Lee and Praszker, 1969).

If fill material is placed incorrectly, these areas bulge or produce mud waves, while the filled areas tend to sink. When mud waves form, the mud is said to be in a state of "plastic flow." Mud waves should be avoided in a fill as they will cause unequal, or differential, settlement of the fill over time. To prevent the occurrence of mud waves, the ideal method of placing fill material is by means of a hydraulic dredge, whereby the dredger pours fluid and fill material such as sand or mud over large areas and the sediment builds up slowly and evenly (Lee and Praszker, 1969).

Fill which is placed in this manner acts as a "blanket." A large fill blanket normally constitutes an area of infinite dimensions, so that each elemental area of the mud under the center of the blanket is protected by confining pressures from its neighboring mud units. Conditions change rapidly when approaching the edge of the fill blanket. At the center of the fill area, the mud is confined and so can only move downward due to the imposed load of the fill material. At the edges of the fill, however, the mud is no longer confined by neighboring units or an imposed load, and is free to move upwardly and laterally. The maintenance of flat slopes at the boundaries of the fill may help control the tendency of the mud to flow plastically away from the imposed load.

Plastic flow of mud at the edge of a fill is one type of boundary condition. Fill may also be placed on mud which rests on an inclined plane. In this case, gravity will pull the loaded fill and mud slowly down the incline. Two typical boundary conditions may occur; the boundary closest to shore may show cracks of the fill and the offshore boundary may show heaving of the mud beyond the fill.

Placing the fill hydraulically at a slow rate may prevent problems such as mud waves and lateral movement of the mud. The rate of filling shouldn't exceed 3 ft/yr. The height of the final fill should also be limited.

Settlement of Fill

Once fill material has been placed on the mud, it and the underlying mud will settle for various reasons including: time, settlement of the fill material itself, plastic flow of the mud under the fill load, lateral movement of the mud resting upon an inclined surface, and seismic activity (Lee and Praszker, 1969).

Fill material will settle to a certain degree over time, regardless of the quality and degree of compaction of the fill material (FIGURE 1). The amount of settlement over time is a function of the compressibility of the mud, its depth (thickness), and the density and height of the overlying fill material. In ideal situations the fill will settle uniformly over time, but in practice the mud thickness, fill thickness, and fill density are not uniform throughout the fill area so that differential settlement occurs.

Uniform settlement of newer fills shouldn't be expected on bay mud. Even on older filled areas, some differential settlement will occur when a load is imposed on it. The amount of differential settlement on older fills can be determined by field observations, and design features should be incorporated into structures which are to be placed on the older fills.

The final settlement of 10 feet of fill over 40 feet of bay mud is 4 feet (FIGURE 1), and 48% of this settlement will take place in the first five years (FIGURE 2). Thus, from FIGURE 2 it can be seen that the most critical settlement of fills on bay mud less than 40 feet thick takes place in the first five years. On these older fills (i.e., over five years old, as in the area being studied), it can be assumed that future settlement will follow the observed settlement, will be slow and not in excess of six inches. The differential settlement will probably be only about 3 inches in 20 years (Lee and Praszker, 1969).

A process known as surcharging is sometimes used to alleviate some of the problems of settlement. A larger amount of fill than is ultimately intended is placed on the site. After enough time has passed for the mud to compress, the excess fill is removed. Further settlement of the mud is largely reduced or eliminated.

Seismic Hazards

There are several serious problems to contend with in the event of an earthquake. Earthquakes are displacements of the earth along faults. Neither horizontal rupture nor vertical faulting should be a problem in the area of study, as no known faults underlie the area.

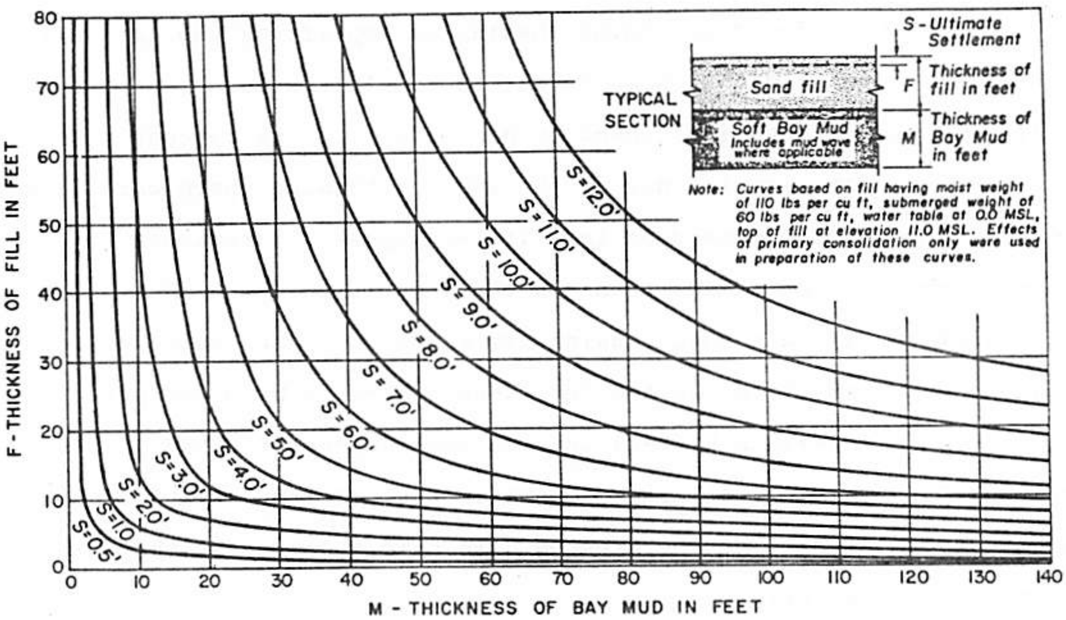

FIGURE 1. Settlement of Fills as a Function of Thickness of the Fill and Thickness of the Underlying Bay Mud.

Source: Lee and Praszker

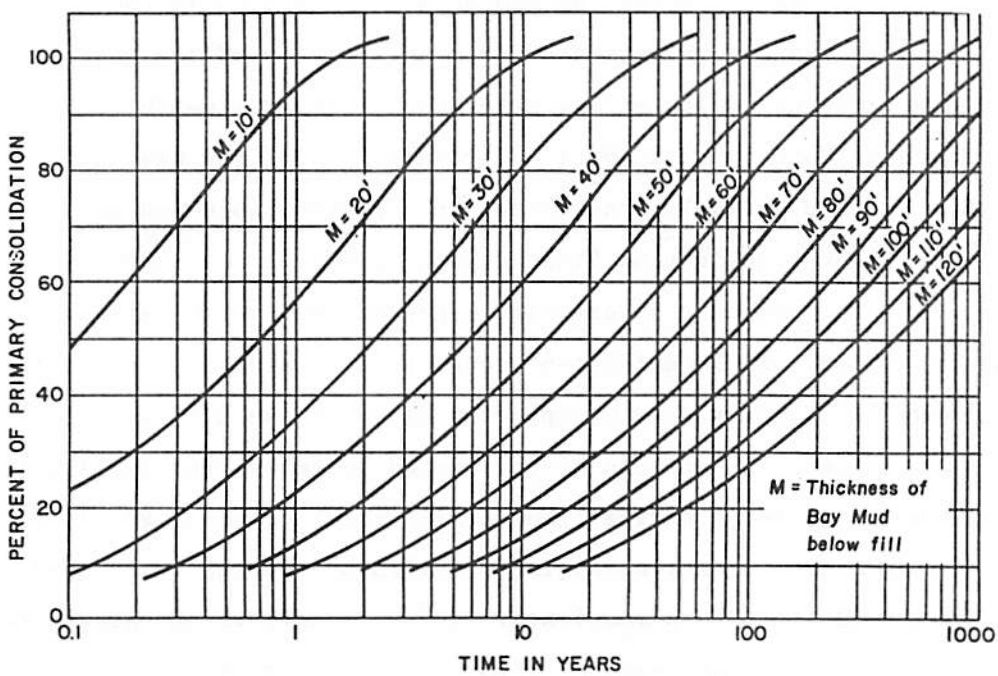

FIGURE 2. Percent Settlement of Fills over Time as Function of the Thickness of the Bay Mud

Source: Lee and Praszker

The most familiar aspect of earthquakes is ground shaking. There is a general decrease in the intensity of ground vibrations with distance from the epicenter of a quake. However, there are local variations in intensity due to soil conditions. Bay muds can magnify the effects of ground shaking by amplifying the intensity of shaking at certain frequencies. In some cases, the amplification of ground shaking is greater than the attenuation caused by distance from the epicenter (Borcherdt et al., 1975). For example, during the 1906 earthquake there were wide variations in the amount of damage done in different areas. Structures built on filled areas suffered greater damage than did those built on bedrock.

The effects of amplified ground shaking are expected to be least for those sites underlain by bedrock, intermediate for those underlain by older bay mud, and greatest for those underlain by fill and bay mud (Borcherdt et al., 1975). It is interesting to note that the areas for which the effects of amplified ground shaking are expected to be the greatest are also those areas that are the most susceptible to liquefaction.

Liquefaction is the transformation of a granular material from a solid state into a liquefied state. If saturated cohesionless soils are subjected to earthquake vibrations, the tendency to compact may be accompanied by an increase in the water pressure in the voids in the soil, which results in an upward flow of the water to the surface. The water emerges as mud spouts or sand boils (Seed, 1969). The potential of soil to liquefy is estimated from an analysis of the severity and duration of ground motion, the depth of the water table, and the depth of clay-free granular sediments (Youd et al., 1975). Virtually all of the bay mud and deposits underlying bay mud lie below the normal groundwater table and present a persistent potential for liquefaction (Youd et al., 1975).

There occur clay-free granular layers within the bay mud which have a high potential for liquefaction. If liquefaction occurs in a sloping soil mass, the entire mass will move laterally to the unsupported side. These flow slides can occur on ground with a low slope and can be instigated by relatively small earthquakes. The most common failures during liquefaction which occur on gentle to nearly horizontal slopes are lateral-spreading landslides. During these landslides, the soil will liquefy and flow, then resolidify, and reliquefy if the ground keeps shaking. The margins of lateral-spreading failures usually crack and settle differentially (Youd et al., 1975). Lateral spreading landslides would probably be the most pervasive type of ground failure associated with liquefaction on the edges of the bay. Much of the bay mud experienced lateral-spreading during the

1906 earthquake (Youd _et_ _al_., 1975).

Soil which liquefies on level ground is known as "quick" soil. Quick soil often loses its bearing capacity with the result that structures, embankments or other loads sink into the liquefied ground. Buried tanks or other buoyant vessels may rise to the surface. Since most of the ground on the East Bay shoreline is gently sloped, lateral-spreading landslides will be a greater problem than quick soil, should the area liquefy during an earthquake. It is known that liquefaction occurs in clay-free granular layers; however, the actual locations of these layers isn't known sufficiently well to be able to plot them (Youd _et_ _al_., 1975).

Many instances of bulkhead failure have occurred during earthquakes due to liquefaction of the backfill. The bulkheads are sheet pile or concrete walls which are placed in the water and backfilled to create a dock or pier. The backfill is sand or sand and gravel. Since it is difficult to compact the backfill below the water level, the backfill is often a loose, saturated sandy material which is vulnerable to liquefaction. The bulkheads can withstand the normal pressure of the fill, but if the backfill liquefies, the increase in lateral pressure can push the bulkhead outwards, often causing it to break.

Permits

Much of the East Bay shoreline is filled land. The chronology of the filling of land is covered in the accompanying report by Allison Turner.

After 1968, the Army Corps of Engineers required permits for any use in the area of its jurisdiction, which extends up to the mean high tide water line. Much of its jurisdiction overlaps with that of the San Francisco Bay Conservation and Development Commission (BCDC).

The BCDC shares its jurisdiction over land use decisions with the cities and counties, which retain their normal land use and building permit controls. A permit from BCDC is required for all projects within its jurisdiction, which extends up to 100 feet from water's edge. It issues permits only if they conform to guidelines stated in _The San Francisco Bay Plan_ (BCDC, 1969).

The Bay Plan recommends approval to fill if one of four conditions is met:

1. The filling is in accord with the Bay Plan policies as to the bay related uses for which filling may be needed, such as ports, water-related industry, and recreation, and is shown on the Bay Plan map as likely to be needed;

2. The filling is in accord with policies as to purposes for which some fill may be needed if there is no other alternative, such as airports, roads, and utility routes;

3. The filling is in accord with policies as to minor fills for improving shoreline appearance or public access, and;

4. The filling would provide for new public access to the Bay on privately owned property and for improvement of shoreline appearance in addition to what would be provided by the other Bay Plan policies, and the filling would be for bay-oriented commercial recreation and/or public assembly purposes.

The question of the safety of the fill must also be addressed before the BCDC can issue a permit. The BCDC makes the following findings:

> "Virtually all fills in the San Francisco Bay are placed on top of Bay mud which presents many engineering problems. The construction of a sound fill depends in part on the stability of the base upon which it is placed. Safety of a fill also depends on the manner in which the filling is done, and the materials used for the fill. Similarly, safety of a structure on fill depends on the manner in which it is built and the materials used in its construction. Construction of a fill or building that will be safe enough for the intended use requires (1) recognition and investigation of all potential hazards--including (a) settling of a fill or a building over a long period of time, and (b) ground failure caused by the manner of constructing the fill or by shaking during a major earthquake; and (2) construction of the fill or building in a manner specifically designed to minimize these hazards. While the construction of buildings on fills overlying Bay deposits involves a greater number of potential hazards than construction on rock or on dense hard soil deposits, adequate design measures can be taken to reduce the hazards to acceptable levels."

Potential Uses

The quality of a fill and its underlying foundation soil will determine its ability to support structures for different uses. There are four uses which may occur in the East Bay shoreline area: recreation, industry or commerce, residential, and no further development as in the case of preserving mudflats for wildlife.

Recreational areas are less sensitive to being placed on filled lands composed of a poor selection of fill materials. The added weight of recreational facilities is miniscule and shouldn't cause further consolidation on older filled areas. If the areas are to be newly filled, the most economical type of fill which can be used to support recreational facilities is garbage mixed with sand. The sand is necessary to fill the large voids in the garbage which would otherwise allow the garbage to compress and decompose internally. If part of the area to be filled is submerged, it should be raised above mean sea level with dredged mud and then covered with the garbage and sand.

Fills to be used for industrial and commercial purposes have to be "selected" and fairly incompressible. "Select" fill is well-graded with no large voids which might allow the bay mud to squeeze upward into the fill material. Building loads, roads and utilities are necessary components of industrial and commercial uses, and the mud should not be deformed, if at all possible, to prevent differential settlement. The fill material should be incompressible so that future settlement due to the consolidation of the bay mud can be as predictable as possible. If new fills are to be placed, the surface should be brought above mean sea level by slow hydraulic dredging. Heavy fill materials such as rock are not advisable, because of the difficulty of placing them evenly. Sand is the most suitable type of fill for these purposes (Lee and Praszker, 1969).

Residential uses may be put on fill similar to the type of fill described above for industrial and commercial uses. The difference is that the avoidance of differential settlement is extremely important, because of the need for streets, utilities, and building foundations to remain in the same relative positions to one another. In new fills, the fill quality and method of placing should be strictly controlled to allow for uniform settlement over the entire area. Future settlement of new and older fills due to the imposed load of the development should be considered, so that when the streets, utilities, and house are placed, they are supported in a way which allows them to settle together at the same rate. If new fills are placed for the intended use of residential development, at least five years should elapse before any construction occurs (Lee and Praszker, 1969).

Major buildings as well as some small structures are supported on piles. The study of piles is complex. There are both pros and cons to using piles as foundations. Pile foundations can extend a certain distance into the mud (friction piles), or they can be bored through to the underlying firmer foundation soils. Friction piles are fairly strong, as the mud offers considerable resistance to impact loads. During earthquakes, the piles embedded in the mud will tend to vibrate with the mud. When the motion of the mud is opposite to that of the piles, the mud will flow around the piles, and it is unlikely that the piles will fail so long as the tips are free to rotate. When piles are driven into the underlying rock, earthquakes could cause critical problems. The mud and rock vibrate at different frequencies, which could cause the pile to break at the rock/bay mud interface. Piles have had a good record as far as withstanding earthquakes is concerned. During the 1906 quake, buildings supported by piles survived the earthquake; however, none of the piles were imbedded in the underlying bedrock.

The general practice for smaller one- or two-story structures is to place a blanket of carefully selected and compacted soil which is several feet thick over the bay mud. The fill blanket acts as a mat, and light structures with conventional footings which rest on this mat should not settle differentially (Steinbrugge, 1969).

Smaller structures are more suitable to being placed on existing fills. During earthquakes, the frequency of the ground vibrations is low in bay mud. The taller a building is, the lower is its "natural" frequency of vibration. If the ground is vibrating at the same frequency as a building's "natural" frequency during an earthquake, the effect is to cause the building to vibrate even more violently. This can cause greater damage than would have been caused by the earthquake alone. A single-story building has a fundamental frequency of roughly 20 cycles/second, a ten-story building may have a frequency of 1 cycle/second, and a forty-story building may have a frequency of 0.25 cycles/second. To minimize the effects of ground shakings on buildings there should be a great difference between the fundamental frequency of the building and the frequency with which the ground shakes during an earthquake. Therefore the smaller structures with higher natural frequencies of vibrations would be the safest structures on fill covering bay mud. Tall buildings such as the buildings on the peninsula in Emeryville have to be designed to withstand the extra shaking they would experience during an earthquake.

Concluding Remarks

This report summarizes the hazards which may occur when developing on bay mud. The hazards include settlement over time, which is generally not uniform over a given area, and seismic hazards. Since the Bay Area has a past history of being seismically active, it is prudent to consider seismic hazards when doing any type of project on the filled lands of the East Bay shoreline. Before any construction or development is undertaken, several things must be considered:

1. A thorough test boring and soils engineering analysis of the soil characteristics must be taken;
2. Possibility of further settlement of older fill due to imposed loads;
3. Consideration of the effects of seismic activity on bay mud and therefore on structures which overlie it;
4. Foundations necessary to insure stability of a structure under settlement and seismic conditions;
5. Density of people using a structure who may be injured during an earthquake;
6. Possibility of liquefaction of foundation soils, lenses of liquefiable material such as sand in the bay mud, or of the fill material;

7. Necessity of the structure to be placed on the filled areas rather than on the natural lands further inland; and

8. Other considerations which soils engineers, building designers, City Planners, and other involved individuals feel are necessary to make developments of any sort as safe as possible.

Large earthquakes are expected to occur in the Bay Area once every 60 to 100 years. This is frequent enough to require that all structures and bay fills be designed to resist the forces of earthquakes. The historical record of earthquakes in the Bay Area has shown a greater seismic risk on bay fills overlying bay mud than on firmer soils, or on rock.

Newer fills, especially those constructed since the permit requirements of BCDC and the Army Corps of Engineers were implemented are quite different from the older fills. Experience with the performance of these newer fills under seismic conditions is very small, however. The experience from non-Bay Area fills under seismic conditions shows that newer well-compacted engineered fills perform much better than do uncontrolled fills, from which most of our knowledge of the performance of fills under seismic conditions comes.

Most of the proposed plans for the East Bay shoreline are for development of parks, refuges, and recreational facilities. These types of uses are fine for the area as it is, as most of the fills are older and have already undergone most of their critical settlement. Since these types of uses don't impose much of a load on the area, further settlement is unlikely, and the density of people using the area will be relatively low. In the case of a serious earthquake, injury will be minimal.

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