APPENDIX E

SUBSIDENCE REPORTS

SUBSIDENCE AND LEVEE INTEGRITY IN THE SACRAMENTO-SAN JOAQUIN DELTA

By
The Subsidence Sub-Team
of the Levees and Channels Technical Team

DRAFT

December 16, 1998

Summary

Island subsidence has played a key role in bringing the Delta islands to where they are today; relatively tall levees (8 to 25 feet above sea level) protecting interiors (up to 22 feet) below sea-level. Island subsidence is an important issue in the Delta. The Subsidence Subteam, however, was tasked with addressing the relation of island subsidence to levee system integrity.

The risk to levee integrity from island subsidence has diminished because of improved levee maintenance practices and land management practices. Island subsidence rates have decreased, and levee construction techniques have improved. In addition, a zone of influence extending from the levee crest to some distance inland has been identified, beyond which interior island subsidence will not affect levee integrity. The levees lose ground elevation on their own due to the addition of levee material, but this is a very different process than island subsidence. This report addresses subsidence as it affects levee integrity within the zone of influence adjacent to levees.

Goal

The goals of the Subsidence element of the Levee Program are to reduce or eliminate the risk to levee integrity from subsidence, and assist in the coordination of subsidence-related linkages with the other CALFED programs.

Scope

The Long Term Levee Protection Plan focuses on subsidence that affects the levee system. This report describes Delta conditions, causes of subsidence, subsidence as it affects levee integrity, mitigation options related to levee integrity, and target areas for subsidence control based on the best available information. Subsidence issues, concerns, and solutions will also be addressed in the Ecosystem Restoration and Water Quality Programs.

Conditions In The Delta

Surface and subsurface materials. (References 5 through 12)

The present-day Delta deposits began to form during the end of the last glacial period, 7,000 to 11,000 years ago as sea level began to rise (Ref 4). As the Delta evolved, tributaries formed a series of channels, natural levees, berms, islands and sloughs. The major rivers and channels periodically incised, then were backfilled as the climate changed. Tules, reeds, and other fibrous aquatic plants growing at water level were preserved as peat beds when post glacial sea levels rose slowly and inundated the

Delta. Under natural conditions, the islands received fine- and coarse-grained sediments during river floods. As a result, the subsurface sedimentary profile generally contains inter-bedded layers of sand, silt, clay and peat of varying thickness. The complexity of subsurface conditions is reflected in the wide variety of surface soil types found throughout the delta. The surficial materials encountered in the Delta include mineral soils, mineral organic complexes, organic soils, and peat.

Ground surface elevations. (Reference 11, Delta Atlas)

Ground surface elevation varies throughout the Delta from the high ground along the levee crests to the low ground in the island interiors. Levee crest elevations generally range from about 8 to 25 feet above sea level. A significant portion of Delta land surface is below sea level. Lowest surface elevations are on the order of 22 feet below sea level. Refer to Figure 1 (based upon a 1974 survey) for an indication of the extent of land surface elevation below sea level. Updated ground surface elevation data is needed.

Island Subsidence and Levee Subsidence

Definition

Subsidence is a downward movement of the ground surface over time. For the purposes of this report, "Island subsidence" refers to the loss of interior Delta island ground surface elevation. The downward movement of the levee itself, generally due to an application of a load, is referred to as "levee subsidence." The causes and impacts of levee subsidence are much different than the causes and impacts of island subsidence, but the primary causes of both will be discussed here together because there is an overlap of contributing causes.

Causes of Island Subsidence and Levee Subsidence (References 1 through 12)

Island subsidence and levee subsidence in the Delta are mainly caused by near-surface processes including consolidation/settlement, shrinkage, and aerobic decomposition. Other near-surface causes of island and levee subsidence include anaerobic decomposition, wind erosion, and burning. Deep seated causes of subsidence include the withdrawal of oil, natural gas, and water, and tectonic activity. These causes were assumed to contribute little to present-day subsidence.

a) Consolidation/settlement: Consolidation/settlement occurs in response to an increase in load, such as when ground water is removed or when materials are deposited in an area by humans or nature. Consolidation due to levee building (increasing loads on foundation materials) is the primary cause of levee subsidence. Consolidation also occurs due to increased effective stress on underlying peat and decreased buoyant forces supporting peat as a result of

incremental dewatering (Ref. 1).

b) Shrinkage: Shallow de-watering is considered a cause of island and levee subsidence because it leads directly to shrinkage and drying of soils above the water table, consolidation of soils just above the water table, and leads to aerobic decomposition of organic soils above the water table. The relative effect of each of these factors depends on the amount of organic matter in the soil, the depth of de-watering, and climate. With each incremental lowering of the water table, the contribution to island subsidence from shrinkage, consolidation, and oxidation are all high. With time, long-term island subsidence is sustained by oxidation. Shrinkage is governed by the initial moisture content and the organic matter content. Fine grained organic soils and peat can shrink 50% or more in volume.

c) Aerobic decomposition (microbial oxidation): Long-term island subsidence is sustained primarily by the microbial oxidation of soil organic carbon. The peat soils contain a complex mass of carbon. Microorganisms such as bacteria and fungi use it as an energy source resulting in peat decomposition and the release of carbon dioxide (CO2) under drained, oxygen-rich conditions. Studies by the Department of Water Resources and the US Geological Survey (Deverel and Rojstaczer, 1996) demonstrate that the amount of oxidation is proportional to the soil temperature and moisture content.

Oxidation rates increase with temperature, higher pH, and higher organic matter content of the soil. There is an optimum moisture content for oxidation; oxidation decreases at very high and very low moisture contents. Drainage and tillage promote aerobic decomposition, but island subsidence is not substantially affected by crop type. Island subsidence due to oxidation will decrease with time as the organic matter content in the upper soil decreases and the relative percentage of mineral constituents increases. There does not appear to be a correlation between peat thickness and subsidence rates. There is a direct correlation between depth to the water table and the amount of subsidence due to microbial oxidation. The higher the water table, the less the island subsidence.

Levee Subsidence (Reference 4,12,13)

Most levee subsidence is caused by the weight of the levee fills compressing the foundation materials. The foundation materials underlying the levees vary throughout the Delta from various thicknesses of peat soils to mineral soils. Rate of levee building and foundation conditions govern levee subsidence rates and the total amount of subsidence. Geotechnical engineering fundamentals must be applied to safely and economically build new levees and rehabilitate existing levees founded on weak, compressible materials.

Regardless of load application to the levees, the levees settle with time. In the 1960's, a set of curves

was developed for estimating crest settlement with respect to variables of peat thickness, height of levee, and age of levee. These curves were updated to incorporate recent data, and are included as Figures 8 and 9. These curves of predicted movement were compared with actual crest elevation measurements on selected islands, and results indicated that measured settlements were generally comparable to calculated values and ranged from 2 to 7 inches per year (Ref 5).

There is a great deal of information on the causes and effects of interior island subsidence, but interior island subsidence has never been directly linked in publications to levee subsidence. A recent Corps of Engineers geotechnical report stated that, "Independent of the island subsidence, the levees settle with time. This settlement is caused primarily as a result of consolidation and plastic flows of the underlying organic soils. Since island subsidence is independent of levee settlement, numerous levee geometries are produced (Ref. 5)." Although "independent," the Corps document recognizes that island subsidence may influence levee integrity. This document also presents the concept of a "zone of influence(ZOI)," beyond which interior island subsidence does not affect levee integrity.

The Corps developed curves for estimating settlement of fills placed on organic material (figures 6 and 7). Considerable judgement should be exercised in using these curves. As examples, settlements were calculated using these curves for a 4.5-foot-thick stabilizing berm and a 2-foot-thick subsidence control cap. Assuming a 45-foot-thick unconsolidated peat layer, the 4.5-foot thick fill causes approximately 13.8 feet of total settlement at an initial time-averaged rate of about 6 inches per year, and the 2.5-foot-thick soil cap causes approximately 6.0 feet of total settlement at an initial time-averaged rate of about 2 inches per year. Based on experience, the calculated settlements are too high and the initial settlement rates are too low. It is common in the Delta for new fill to settle rapidly and total settlement to be roughly equal to the applied fill layer thickness. When compared to interior island subsidence, levee subsidence (settlement) can be significantly greater than island subsidence and is probably the primary reason for performing a high level of levee maintenance.

Near-levee subsidence will effect levee stability. This subsidence is the result of de-watering and the associated consolidation, shrinkage and decomposition of high organic content materials near the levee. Engineering analysis indicates there is a discrete distance away from a levee, a zone of influence, beyond which subsidence no longer adversely affects levee integrity.

Zone of Influence

The zone of influence is an area from the crest of the levee to some distance inland where island subsidence may impact levee integrity. Beyond this zone of influence, island subsidence will not affect levee integrity. Although the ZOI for a reach of levee can only be determined using site-specific data, geotechnical engineering analysis and judgement can be applied to characterize its extent. The Subteam estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest, depending on site-specific conditions. Since the ZOI is a site-specific characteristic, it could change with time as site conditions

change. The following engineering analyses could contribute to the determination of the ZOI on a site-specific basis.

a) Static stability: geotechnical engineers use stability analysis to determine factors of safety and critical failure modes for earthen structures (Refer to Figure 2). Numerous Delta levee stability analyses indicate that there is a definable distance from the levee beyond which soil properties and changes do not affect levee stability. The limiting distance often turns out to be approximately 3- to 4-times the thickness of the peat layer beneath the levee. For example, the thickness of the deepest peat layer in the Delta is approximately 60 feet (Refer to Figure 3) . Therefore, any island subsidence beyond 180-to 240 feet from the levee would probably not affect static levee stability. If the peat layer was less thick, which it is for most of the Delta, then the distance would be smaller for static stability.

b) Seepage: Subsidence of the land side ground surface adjacent to a levee may cause through-levee and foundation seepage changes. Changes in hydraulic gradients, seepage volume, water levels, and exit gradients may all result from subsidence. Site specific analysis will determine whether these changes impact levee integrity, however, we can use generalized flow net analysis to make some observations.

Flow net analyses indicate that critical exit gradients are most likely to be exceeded at or in close proximity to the levees. Critical gradients are less likely to be exceeded as the distance from the levee increases. In addition, flow net analyses indicate that drainage ditches located near the levees can have a detrimental effect on levee seepage (Refer to Figure 4). Interior island subsidence adjacent to levees could affect seepage by decreasing the seepage path. A shorter seepage path leads to increased seepage. Increased seepage may lead to piping and levee integrity problems.

Seepage analyses also indicate that there is a definable distance from a levee beyond which soil properties and changes in ground surface elevations do not affect seepage and levee integrity. Similar to the stability analyses, determining a precise zone of influence with respect to seepage is difficult, because seepage is dependent upon complex local subsurface conditions and levee and foundation geometry. What the seepage modeling and "flow nets" show, however, is that there are limits beyond which changes and affects are negligible. Thus we can deduce that there are boundaries beyond which changes will not affect seepage and levee integrity. This boundary can be determined through site-specific analysis, but from a practical standpoint, wherever an open seepage collection trench can be constructed without jeopardizing levee integrity, then interior island subsidence beyond that point is unlikely to be a levee concern.

c) Deformation: Deformation is the spreading movement of soft soils in a reaction to load. Deformation can also be the result of loss of support at the levee toe, i.e, subsidence, and excavation of a drainage ditch. The Sherman Island deformation analysis report (ref 13)

provided analysis for an island that might be considered worst-case due to the thickness of the peat layer beneath the levee and the size (load) of the levee. Although the Sherman Island analysis did not consider the impact of future island subsidence on deformation, the information indicates that there is a distance beyond which deformations do not occur. For the computer deformation modeling, a boundary condition was set at approximately 300 feet from the crest of the levee, a distance beyond which deformation did not occur. Extreme future island subsidence may impact a levee, however, it is important to note that island subsidence occurs slowly, and that levees usually adjust to island subsidence as it occurs without detrimental effects on stability.

Clearly, the zone of influence will vary with site specific levee and foundation conditions and levee geometry. For example, the greater the height of the levee embankment above the island floor and the greater the thickness of weak and compressible layers, such as peat, the wider is the zone of influence. Monitoring and research will later define this zone.

Hydrostatic Pressure.

It has been commonly reported that subsidence of island interiors leads to increased hydrostatic pressure and levee instability. The implication that levees are now required to withstand a greater hydrostatic head of water than they were originally constructed is inaccurate in that the exterior water elevations remain the same. However, a decrease in the land mass resisting such hydraulic pressures may occur. Also, seepage forces and quantity will change due to increased hydraulic gradient. The decrease of island surface elevations is a contributing cause to the need for ongoing work to maintain the height and desired safety factor of the levees. Periodic levee improvements replace some of the land mass that was lost to subsidence.

Island Subsidence

Island Subsidence will be generally discussed here, because the focus of this report is subsidence as it impacts levee integrity. Island subsidence impacts levee integrity only when it occurs in proximity to a levee. Subsidence within the ZOI may decrease stability, increase seepage, increase the potential for piping, or increase the potential for levee deformation. At many locations, however, island subsidence is occurring too slowly or too far from the levee to be a threat to levee integrity. As long as the ZOI is protected from subsidence, levee integrity with respect to island subsidence should be assured. Although island subsidence outside of the ZOI does not impact levee integrity, it does impact the interior of Delta islands and their associated land uses.

Historically, time-averaged Delta-wide island subsidence rates have ranged from about 0.5 to 5.0 in/yr. Recent research indicates that island subsidence varied from about 0.2 in/yr to 1.2 in/yr for soils with organic contents varying between 20% and 50% (Reference 4, Rojstaczer and Deverel (1995).

Subsidence rates are slowing . Present day subsidence rates were measured continuously from 1990 to 1992 by Deverel and Rojstaczer (1996) on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24, and 0.32 inch per year on Sherman, Jersey, and Orwood, respectively.

Island subsidence rates are site specific. No single island subsidence rate, such as the commonly used 2.5 to 3 inches per year, is valid for an entire island. Total island subsidence rates vary greatly and average island subsidence rates at specific sites appear to be diminishing with time. Rates may be greater in areas subjected to new or deeper de-watering.

Remedial Action and Prevention

The approach to control of levee subsidence will be fundamentally different than the means and methods employed to control island subsidence because of the differences in the primary causes of subsidence.

Levees (References 4 through 13)

Potential levee subsidence mitigation actions that should be considered are:

1)Thorough application of geotechnical engineering principles and practices in conjunction with proven construction methods. Levee subsidence will continue as long as levee building and repair continue to add loads onto weak compressible foundations.

2)Seepage control, de-watering efforts, excavations, and land management activities in proximity to levees must be modified to minimize adverse impacts to levee integrity.

3)Stability and drainage berms can be strategically located and sequentially constructed to minimize or prevent levee deformation.

4)Land leveling and other ground surface modifications (e.g. ditching) should be restricted within the zone of influence. High ground water levels and vegetative growth could be tolerated in some areas to accommodate measures aimed at reducing island subsidence due to oxidation.

Island Interiors, Including the ZOI (References 1 through 10)

Currently the best approaches to managing island subsidence, include a) minimizing or preventing the lowering of the groundwater level, b) capping or covering susceptible surface deposits with mineral soil,

and c) permanent shallow flooding. and d)reverse wetland flooding.

Delineation of Target Areas for Subsidence

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence control and prevention program. It appears from this initial prioritization effort that only some islands and in some cases only parts of islands are affected. Refer to Figures 5-1 through 5-8, Subsidence Target Areas, for examples of islands and levee reaches most likely to be affected by subsidence (Deverel 1997, References 1&2). The number of levee miles potentially affected by subsidence was calculated using Figure 5. About 60% of the levees in the central and western Delta, but less than 30% of all the levees in the legal Delta, are targeted for subsidence control.

The objective of the maps in Figures 5-1 through 5-8 is to target areas for subsidence monitoring and control in the Delta. The general approach was to enter recent available data for the Delta for island subsidence rates, depth of peat soils and soil characteristics into a geographic information system (GIS). The estimates for rates of island subsidence and peat thickness are an improvement relative to the previous efforts by the Department of Water Resources because 1) the error in the estimated island subsidence rate is lower, quantifiable and the result of uniform elevation change measurements, and 2) the estimates for peat thickness are based on more recent and comprehensive data.. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of target areas in greater areal detail than entire islands such as is presented in Department of Water Resources (1980).

The areal distribution of island subsidence rates and peat thickness is used to delineate target areas for additional data gathering and monitoring. The maps in Figures 5-1 through 5-8 used the estimated ZOI boundary of 500 feet around the islands. Within this boundary, the target areas are those where the island subsidence rates are high and there is substantial peat remaining. The target areas have time-averaged island subsidence rates greater than 1.5 inches per year (island subsidence rates ranged from about 0.4 inches per year to 5 inches per year) and peat thickness greater than 10 feet within the 500 foot boundary.

The term "peat" has been defined in many different ways. For the maps in Figure 5, "peat" will refer to peat or peaty mud of tidal wetlands comprised of the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 to 11,000 years. The peat thickness shown on the maps was calculated as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps(1976-1978). Atwater's delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soils surveys. The maps reflect borehole data collected as of 1980.

Monitoring

Subsidence monitoring should be tied to constructed base level projects because these areas provide the most economical opportunities for gathering more data in conjunction with construction explorations and monitoring. Subsidence monitoring should start with an evaluation of existing soils and their distribution and a determination of land surface elevation within Target Areas in the Delta. Efforts should be directed to areas on and adjacent to the levees, within the ZOI. From a new, continually updated database, a target list of levees and islands being impacted by subsidence can be maintained. Monitoring will allow subsidence control to be adaptively managed as levee rehabilitation goes forward. This monitoring efforts will be coordinated through CALFED's Comprehensive Monitoring, Assessment, and Research Program (CMARP).

Conclusions

Although subsidence has caused problems in the past, and will continue to be a problem for island interiors, the potential impact of island subsidence on levee integrity has diminished. Land management and levee maintenance practices have improved and island subsidence rates have decreased. As long as island subsidence is adequately managed within the ZOI, levee integrity should be unaffected. Although the ZOI for a reach of levee can only be determined using site-specific data, the Subteam has estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest depending on site-specific conditions. The ZOI could change with time as site-specific conditions change.

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence monitoring, control, and prevention program.

The levees identified as being target areas for subsidence remedial action and prevention will require screening and integration with other issues affecting levees such as seismic stability requirements, ecosystem restoration, and Delta water operations. This integration will allow a better prioritization of future subsidence remediation of the Delta levees.

References: Subsidence in the Sacramento-San Joaquin Delta

1. Deverel, Steven J., et al.,(1998); Subsidence Mitigation in the Sacramento-San Joaquin Delta.

2. Deverel, Steven J., (1997) ; Priority Areas For Subsidence Mitigation In The Sacramento-San Joaquin Delta. Draft.

3. Deverel, Steven J. and Stuart Rojstaczer, (1996); Subsidence of Agricultural Lands in the Sacramento-San Joaquin Delta, California: Role of Aqueous and Gaseous Carbon Fluxes; Water Resources Research, Vol.32, No.8, August 1996.

4. Rojstaczer, Stuart and Steven J. Deverel , (1995); Land Subsidence in Drained Histosols and Highly Organic Mineral Soils of California; Soil Science Society of America Journal Volume 59, No. 4 July-August 1995.

5. U.S. Department of Defense, Corps of Engineers, Sacramento District, South Pacific Division and State of California, Department of Water Resources and The Reclamation Board, 1993; Sacramento-San Joaquin Delta, California Special Study, Documentation Report.

6. U.S. Department of Agriculture-Soil Conservation Service (1989); Land Subsidence in the Sacrament-San Joaquin Delta Literature Review Summary.

7. U.S. Department of Agriculture-Soil Conservation Service (1989); Land Subsidence in the Sacrament-San Joaquin Delta Literature Review.

8. California, State of (1986); Delta Subsidence Investigation, Progress Report; The Resources Agency, Department of Water Resources, Central District.

9. Burke, Helen K. (1980); Report on Causes of Subsidence In The Sacramento-San Joaquin Delta and A Strategy For Controlling Its Rate.

10.California, State of (1980) ; Subsidence of Organic Soils In The Sacramento-San Joaquin Delta; The Resources Agency, Department of Water Resources

11. Weir, Walter W. (1949) ; Subsidence of Peat Lands of the Sacramento-San Joaquin Delta; Summary by Agricultural Extension Service, San Joaquin County.

12. California, State of (1995); Sacramento San Joaquin Delta Atlas, California Department of Water Resources Reprinted 7/95.

13.U.S. Department of Defense, Corps of Engineers, Sacramento District, Geotechnical Branch, Soil Design Section (1998) ; Office Report titled "Sherman Island Levee Test Section, Geotechnical Basis

of Design.."

14. Foott, Sisson, and Bell (1992) ; Threatened Levees on Sherman Island. A reprint from Stability and Performance of Slopes and Embankments II Proceedings, GT Div/ASCE, Berkeley, CA, June 29-July 1, 1992.