Levee Monitoring System

Better Management through Better Information

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Abstract: The level of flood protection in the Sacramento-San Joaquin Delta is currently considerably substandard, as the existing system of levees offer one hundred year level protection at best. To improve safety in the region, a system of networked sensors monitoring the health of these levees should be considered. Sensors considered include piezometers, which are the traditional means of monitoring seepage flow, micro electro-mechanical systems obtaining readings of pore water pressures, temperatures and inclinations, and voltmeters connected to electrodes for the detection of self potentials generated by subsurface flows. This would allow officials access to real time information concerning which areas are in need of repair or which areas may need to be evacuated to prevent loss of life.

C E database subject headings:
data collection, failures, floods, levees, networks, probe instruments, safety, technology.

Introduction

The levees in the Sacramento-San Joaquin Delta are a crucial component of California's economy. Not only do they help protect roughly two-thirds of the state's water supply, their geographic location also means that these levees provide flood protection to urban areas such as Sacramento, Stockton and to islands in the delta that are now below sea level due to subsidence. Despite the vast importance of the area, the levee system is in extremely poor condition due to several factors- the weak, compressible native soils, the lack of proper engineering during the construction process and high levels of erosion. As a result, the level of protection is below the 100 year level in much of the Delta, which is actually poorer than the system in place in New Orleans prior to Katrina, which was rated as providing protection at roughly the 250 year level (Florez, 2006).

A monitoring system would help address the crisis on several levels. First, should such a failure be imminent, resources could be mobilized to make emergency repairs to the levee, flood preparations such as sandbagging could take place and in severe situations, evacuations can be ordered to minimize the lives lost. Secondly, a monitoring system would provide better information for the prioritization of repairs. The key advantage of real time information occurs with respect to the physical condition of the levees, inspections yield only information about a specific section at a specific time. While during an inspection a levee may be sound, it may not be the case the next day as levees are part of a dynamic system- that is, the environment changes. A storm could cause water levels to rise for example, and in fact, the once river conditions surpass certain conditions, levees on the Sacramento River go into a "monitor stage" where patrol of the levees becomes mandatory (SAFCA). But failure is not limited to storm conditions. For example, a burrowing animal could compromise the levee materials and thus the stability of the levee itself. A monitoring system would be able to identify these problems as they can develop even during unanticipated periods.

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Background

The Delta

The Sacramento-San Joaquin River Delta constitutes roughly 738,000 acres of land located inland from the San Francisco Bay at the confluence of the Sacramento and San Joaquin Rivers. The Delta was originally a freshwater marshland rich in peat deposits, but by the 1870s the Delta began its transformation into an agriculturally based area. During this time period, some of the first levees were constructed on what is now Sherman Island and Twitchell Island by Chinese laborers (DWR). Today, the Delta is a source of agribusiness worth over half a billion dollars per year (USGS). In addition to its importance to agriculture, the Delta is also a crucial source of freshwater to much of the state of California. More than two-thirds of California's population, or over 20 million people, get at least a part of its freshwater from the Delta. (USGS) Southern California in particular stands to be negatively affected in the event of a significant disaster affecting the supply of water from the Delta.

Today, the Delta consists of some 57 islands, which are protected from flooding by over 1,100 miles of levees. One of the major problems with the Delta is that has been sinking below sea level, primarily due to the overdraft state of the groundwater basin. A yearly rate of subsidence of about one to three inches per year has resulting in many of the Delta's islands lying as much as 10 to 25 feet below sea level (USGS). This puts tremendous importance on the ability of the Delta's levees to withstand the constant stresses created by water pressure, because if any number of them fail the magnitude of the flooding would be disastrous, not just to the immediate vicinity, but to the entire state due to saltwater intrusion. Last year nineteen levees in the Delta were determined by the Army Corps of Engineers to be "at risk of failure." For example, if the Natomas Levee were to fail, as many 70,000 people would be at risk. In addition, the Sacramento International Airport and ARCO Arena, the home of the Sacramento Kings, could be flooded by as much as twenty feet of water (Popular Mechanics, 2010). One significant failure occurred in 2004 when a portion of the

Upper Jones Tract Levee, located about ten miles east of Stockton, collapsed, flooding the entire island with 150,000 acre feet of water. The levee breach took three weeks to repair and the island, located ten feet below sea level, required an additional five months to dewater.

Figure 1: Satellite Image of the Delta (Google Earth, 2010)

Figure 2: Upper Jones Tract Levee Failure (DWR, 2010)

The Levee System

Altogether, more than 47 billion dollars of infrastructure are protected by these levees, although this figure includes the entire Central Valley and not just the Delta area (DWR, 2010). Of the roughly 1100 miles of levees in the Delta, 385 miles consist of what are known as "project levees," which were built by the Army Corps of Engineers and then turned over to local authorities (DWR). The remainder are built and maintained by landowners and reclamation districts (Florez). Unfortunately, these levees are widely considered to be the most vulnerable levee system in the United States- below the one hundred year protection level in many locations, trailing even New Orleans, whose levees are estimated to have been at the 250 year level pre-Katrina. Other comparable metropolitan areas such as Tacoma and St. Louis have flood protection reportedly at the 500 year level (DWR, SAFCA, 2010). Studies indicate that a low end estimate of the damage caused by a catastrophic failure of the levees would amount from 30 to 40 billion dollars in the first five years (Florez, 2006). Further compounding the problem is the fact that flood protection in the Delta is underfunded, a problem that is expected to continue for some time despite the passage of legislation aimed at improving the levee infrastructure due to the economic difficulties currently faced by the state.

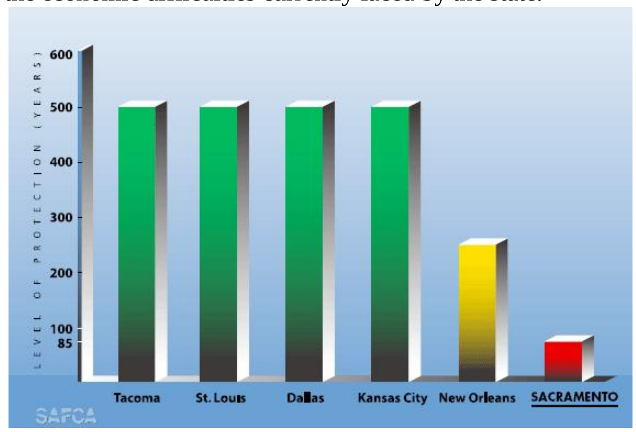

Figure 3: Flood Protection Levels By City (SAFCA, 2010)

Mechanisms of Levee Failure

In earthen levees, failures tend to fall under three broad categories- failure due to structural causes, hydraulic causes and failure due to surface erosion. Regardless of the initial mode of deterioration, most situations will eventually evolve into some form of slope instability- a structural failure. Since levees are "series" systems, a compromise at one location results in the compromise of the entire system. Piping, a hydraulic failure related to seepage, is the most common mechanism that leads to failure (Seed et al, 2005).

Structural Causes

As discussed earlier, slope instability is a structural levee failure that could be caused by other failure mechanism. Instabilities are a class of failure that can be further subdivided into three categories: bearing capacity failures, during which the foundation soils are unable to support the weight of the levee (which tends to occur during construction, as the soil has not had the opportunity to consolidate), lateral translational stability failures, which occur when the levee begins to slide as the result of elevated water levels, and thus pressure, on the water side, and rotational stability failures, which are caused by a combination of high pressure on the water side and undercutting on the same side, thereby allowing hydraulic forces out of equilibrium. Other forms of structural failures are impacts, for example, caused by debris pushed against the levee during a storm surge, and failures of elements such as sheet piles, walls and gates. Structural failure of levee elements often occurs in conjunction with other modes, such as foundation failures or overtopping (Seed et al, 2005).

Hydraulic Causes

Hydraulic failures, the result of seepage in various forms, are the most common reasons levees fail. The first category is what is known as underseepage. This occurs when the foundation materials underlying a levee are excessively permeable, allowing a relatively higher rate of seepage flow through the soils (USACE, 2000). Underseepage increases the pore water pressures and creates a reduction in shear strength, which over time will lead to slope instability (Seed et al, 2005).

A variation on underseepage is what is known as bottom heave, or alternatively, blowout. This is a failure at the toe of the levee, occurring when the water pressure in the levee foundation increases beyond the overburden pressure exerted by the levee materials at the toe, allowing soil to be displaced. The movement of soil particles creates additional voids through which even more flow concentrates, exacerbating the problem by transporting more material off the embankment, until the levee fails. The third type of hydraulic failure consists of those caused by erosion and piping, of which there are three subcategories. Exit seepage erosion and piping is the most common worldwide, and develops when the underseepage flow begins to increase the exit gradient. This eliminates the resistance to erosion, allowing a hole to form, through which additional flow will converge. This "pipe" further increases the gradient and erosion, and eats its way backward into the levee until a rupture occurs (Coduto, 1999).

Internal seepage erosion is the result of a similar process that begins with the displacement of soil grains from the center of the levee, usually indicative of insufficiency, or even the lack of, a filter section whose function is to trap fine grained particles from being advected by the flow of water. As the soil is transported out of the levee, the voids allow for flow to concentrate, leading to even more soil being pulled out of position, eventually causing the levee to wash out. Finally, the piping process can be initiated by burrowing animals and roots (Seed et al, 2005).

Surficial Erosion

These types of failures occur when water flows over an exposed surface. For example, if a levee overtops, the land side acts as a spillway, which scours materials on the land side, weakening the levee. Very few levees guard against this type of failure. Surficial erosion can also caused by scour on the water side of the levee and by impacts of waves, especially if the levee is not armored with rip-rap (Seed et al, 2005).

Sensors

A common theme in the many potential failures that could occur in a levee is the threat posed by seepage and changes in pore water pressure that occur as a result of seepage flow. To predict failure in a levee therefore, it will be critical to examine how to detect and measure these parameters. Three types of sensors are considered: piezometers, which have traditionally been used to instrument leaky embankments, micro electromechanical systems, and voltmeters, to take advantage of naturally occurring self potential phenomena.

Piezometers

Piezometers are very common devices that measure pore water pressures, and using this information, patterns of subsurface fluid flow can be determined (USACE, 1995). There are many different types of piezometers, ranging from open standpipe piezometers, which are similar to observation wells, to vibrating wire piezometers, which were selected for this project due to the ease with which they are connected to datalogging equipment and the fact that they respond only to changes in pore water pressure and are isolated to stresses acting on the housing (USACE, 1995). Piezometers for this monitoring system are estimated to cost 100-200 dollars per node, and they will have to be placed fairly close together as pore pressures can dissipate rapidly. For more information on the placement of piezometers, please refer to the sensor design portion of this paper.

Micro Electro-Mechanical Systems (MEMS)

MEMS are extremely small systems, generally on the order of micrometers in size, consisting of a processing unit and sensors that can interact with their environment. The development of MEMS is the result of advances in nanotechnology (Glaser, 2010). The Dutch company Alert Solutions has developed a proprietary system specifically geared toward levee monitoring called GeoBeads based on MEMS, capable of measuring the parameters of pore water pressure, temperature, and inclinations/deformations (Koelewijn, 2009). Costs, including overhead such as datalogging and power, are estimated (factoring in an economy of scale) to be 1000 dollars for a single unit, 750 dollars for projects over 30 units, 500 dollars for projects over 100 units, and 350 dollars for projects over 1000 units (Peters, 2010). Since the primary parameter measured remains pore pressure, the MEMS will have to sited together in a similar configuration to the piezometers, although the availability of several parameters will generate much higher quality information. Furthermore, although GeoBeads presents the highest initial equipment cost, there could be a cost savings in testing and implementation, as extensive testing of the system for flood protection applications has already occurred. Based on this preliminary research, it is estimated that GeoBeads are capable to providing up to 48 hours of warning prior to a failure.

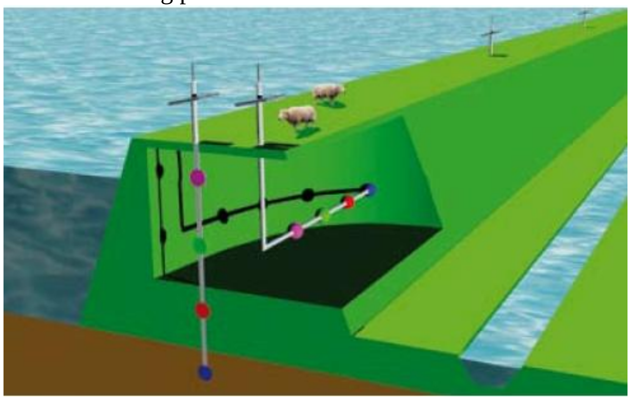

Figure 4: GeoBeads (Alert Solutions, 2010)

Measurements of Self Potential Using Voltmeters

The final method considered was the use of voltmeters to measure self potentials. This intriguing phenomenon, which is also known as streaming potential, is the result of an electric double layer effect (Moore, 2007). As a fluid such as water enters to pore spaces of a media such as soil, ions present in the water are attracted to oppositely charged ions present in the soil. When the fluid is advected by a process such as seepage, some of the aqueous ions are sheared away from the ions present in the porous media, which generates small currents that can be measured by embedding electrodes connected to voltmeters into the levee (Moore, 2007). As a result, flow patterns can be delineated and the magnitude of flow can be approximated (Sharma, 1997). The self potential method is primarily used as a surveying method for geophysical exploration, although it has been applied to the evaluation of embankment dams and levees for the purposes of charting flow. However, long-term monitoring use of this method is not well documented. The primary advantage of self potential measurements is the low cost of roughly 50 dollars per unit. It is important to note that these measurements could potentially be skewed by buried metal.

Figure 5: Self-Potential Electrodes (Tinker & Rasor, 2010)

Sensor Placement Design

Sensors Measuring Pore Water Pressure/Hydraulic Head (Piezometers & MEMS)

In order for the proposed piezometers and MEMS to function properly, they need to be placed close enough together so that deviation from the steady state condition can be detected before they dissipate. The two parameters can be related to one another by the function:

$$u = \gamma_w h \quad (1)$$

where u is the pore water pressure, γ_w is the unit weight of water and h is the head (Coduto, 1999). To understand how these parameters change with respect to position within the levee, the relationship known as Darcy's Law is introduced:

$$Q = kiA \quad (2)$$

where Q is the flow rate, k is the hydraulic conductivity, A is the area perpendicular to the flow direction, and i, the hydraulic gradient, is defined as follows:

$$i = \frac{\Delta h}{L} \quad (3)$$

where Δh is the change in head over a distance L (Coduto, 1999).Taking the differential form of Darcy's Law results in the following equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_S\frac{\partial h}{\partial t} \quad (4)$$

where K_i is the hydraulic conductivity in the x, y and z directions respectively (Schwartz and Zhang, 2003). This equation can be simplified by assuming steady state flow conditions, resulting in the equation:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=0 \quad (5)$$

which can be simplified even further by assuming that the porous medium is isotropic and homogeneous ($K_x = K_y = K_z$ = constant), resulting in the Laplace equation:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \quad (6)$$

where one last assumption can be applied, which is that there is no vertical flow, resulting in the equation

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \quad (7)$$

Next, consider the equation for steady state, ground-water flow in a homogeneous, unconfined aquifer

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)=0 \quad (8)$$

With the boundary conditions

$$h|_{x=0} = h_0 \quad (9)$$

And

$$h|_{x=l} = h_L \quad (10)$$

which, assuming Dupuit's assumption that groundwater moves horizontally in an unconfined aquifer is valid, gives a solution of

$$h = \sqrt{{h_0}^2 + \left({h_l}^2 - {h_0}^2\right)\frac{x}{L}} \quad (11)$$

Then considering equation 7 and equation 11 with boundary conditions of the water level on the water side of the levee at 15-20 feet above that of the ground surface, the head at the toe being 2 to 5 feet below the ground surface and that when the head enters a transient stage, for example due to piping, that due to the constant boundary conditions on the water and land side, the head at some distance y>>L remains constant, gives a required spacing of around 10 feet, allowing for detection of changes in hydraulic head and pore water pressure. Since seepage failures such as piping can begin both at the exit face near the toe and internally, two offset rows will be installed. The offset will create a classic three-point problem that allows the for ease of contouring the heads and pore pressures using methods such as inverse-distance weighting to determine the direction of seepage flow and identify concentrations that could indicate piping.

Self Potential Sensor Placement

The use of self potential as a long term monitoring system has not been well documented, making the selection of proper spacing much more variable. According to Jeffrey Moore, a researcher who has made heavy use of this method, the maximum spacing for this application would be roughly 100 feet apart and the limit of better information yield occurs at a spacing of roughly 6 feet. Moore suggests a spacing of 30 feet in most places, with spacing as close to the minimum of 6 feet as is economically feasible in the most critical sections of levee. The reason for the high level of variability in the spacing is the approximate nature of the information given by this method, which provides accurate mapping of flow, but only rough estimates of the magnitude (Moore, 2007).

Sensor Selection: Weighted Analysis

In order to make an objective decision regarding the sensor type to implement, a weighted analysis was completed.

Selection of Weighting Categories

The categories used for the weighted analysis are: the total cost of the proposed system, the quality of the information yielded, the accuracy, durability/resilience and documentation/precedent. The total cost was considered because it is an important component of any decision making process- policymakers need to know how much something will cost and compare that to the benefits offered by the system. A cost benefit analysis will be undertaken as part of the project once sensor selection is completed. The quality of the information yielded is a crucial consideration, as the data must be relevant to the potential levee failures, and accuracy is important because a monitoring system that gives poor information regarding levee performance serves no purpose. For this project, accuracy and information quality are to be differentiated as follows: information quality refers to the relevance of the data to predicting failure, and accuracy refers to how close the reported values are to the true value. The durability and resilience of the system must be considered since the monitoring function is to be performed over long periods of time. Finally, the documentation and precedent for each method is needed to determine the extent of the next steps to be taken for the project.

Selection of Weighting Factors

Of all the categories considered, the most important were deemed to be the accuracy of the sensors and the quality of information. So as to reflect this, it was decided that these two categories would account for the majority of the weight. Accuracy was given 30 percent weight, slightly more than the information quality because accuracy issues have the potential to compound over the lifespan of the project, whereas informational shortcomings can be addressed during system design. Total cost was also given a heavy weighting since California has historically underfunded flood protection, and given the current budget crisis, it may not be wise to assume that this situation will change despite increasing public awareness of the poor condition of Delta levees. Likewise, durability and resilience of the system should be considered- in order to avoid a weak link system, there needs to be excess capacity in the system, so the ability of the system to compensate for the loss of a node and the likelihood of this node to malfunction should be weighted heavily. The final category, documentation and precedent, was weighted at 10 percent because its impact occurs primarily during the design phase. If there is little information and past practice with a sensor methodology, more testing needs to be done and a more conservative design should be considered due to the lack of information concerning real world performance. These factors are elaborated upon in Table 1 for each sensor.

Table 1: Weighting Score Explanations (on a point scale from 1 – 10, 10 being best)

Total Cost	
Self Potential Method	Each node is estimated to cost around 50-75 dollars. The spacing for the SP sensors can be significantly larger than that of the other sensors. Score: 9
Vibrating Wire Piezometers	There is high variability in piezometer cost. Estimates of cost range from 100-200 dollars per node, and this is complicated by the need for closer spacing for accurate measurement of pore water pressures. Score: 5
MEMS	The cost for a MEMS system similar to the GeoBeads system designed by Alert Solutions is approximately 350 dollars for each node. The spacing for the MEMS will be similar to the VW-piezometers since the primary parameter to be measured, pore water pressure, is the same. Score: 4
Information Quality/Yield	
Self Potential Method	The self potential method provides high quality information regarding the pattern of flow, but can only give rough estimates quantifying the amount of flow. Thus, deriving other parameters such as hydraulic head will be subject to high error. Score: 4
Vibrating Wire Piezometers	Piezometers yield information directly related to seepage causes, such as bottom heave/blowout. The primary obstacle to high quality information here is that these fluctuations only take place very close to where the failure is occurring. Score: 5
MEMS	MEMS are subject to the same challenges as VW-Piezometers; however, since MEMS measure other parameters, such as temperature anomalies and inclinations/deformations, the system is not as reliant on detection of changes in pore pressures. Each one of these parameters can independently indicate potential failure. Thus, there is high redundancy even within an individual location. Score: 9
Accuracy	
Self Potential Method	As indicated earlier, SP measurements give only rough estimates of flow and a means to compare flow relative to other locations. Score: 5
Vibrating Wire Piezometers	Pore water pressure sensors typically have an accuracy of 0.025% FS. That means there is very little error. Score: 8
MEMS	MEMS get an addition point over VW-piezometers due to the availability of

	additional data to assist in the calibration process.
Durability & Resilience	
Self Potential Method	The SP method relies upon electrodes embedded in the levee. To quote Professor Steven Glaser, the electrodes will essentially last forever. While the quality of information does not compare to the other methods considered, loss of a node does not highly impact the quality further. Based on information from Dr. Jeff Moore, ideal spacing for the levee configuration is around 10 m, but as much as 30 m would not create too high of a negative effect. This means that two adjacent sensors can fail. Score: 9
Vibrating Wire Piezometers	As stated earlier, pore pressure fluctuations dissipate rapidly, necessitating the need for very close spacing. If one node fails, this could result in a seepage failure going unnoticed for a significant period of time. Score: 5
MEMS	The beauty of MEMS is that each node gathers multiple parameters, so the failure of one collection agent does not correlate to the failure of the entire node. MEMS also have a long lifespan, especially considering that they will be embedded in the levee and therefore protected from many outside forces.
Documentation & Precedent	
Self Potential Method	SP is primarily a surveying method. There is little documentation on its application as a monitoring system and so far, research has indicated that the SP method has not been deployed for use as a long term solution to identifying seepage. Significant testing will likely need to take place.
Vibrating Wire Piezometers	Piezometers have been used previously to monitor seepage in embankment dams, etc. The US Army Corps of Engineers has a manual (EM 1110-2-1908) detailing the use of these sensors for monitoring purposes.
MEMS	MEMS are a relatively new technology but there has been significant testing with respect to the application of MEMS to the monitoring of levees in the Netherlands (Flood Control 2015, Deltares, Alert Solutions, et al.)

Weighted Analysis Results

The results, summarized in Table 2, indicate that MEMS are the best choice for this application. However, discussion with Rick Carter, the Superintendent of Twitchell Island, indicates that the cost barriers are still potentially too high. Carter recommends a two-tier system of MEMS in critical areas and self potential sensors in areas of lesser concern.

Table 2: Weighted Analysis Results

	SP	Piez	MEMS
Total Cost (.20)	9	5	4
Information Quality & Yield (.20)	4	5	9
Accuracy (.30)	5	8	9
Durability & Resilience (.20)	9	5	8
Documentation & Precedent (.10)	4	8	7
Total	6.3	6.2	7.6

Computer Data Reduction

Once the sensors are in place, the challenge then becomes that of data collection and analysis (Glaser). To properly monitor the entire system, there will be thousands of nodes propagated over all 1100 miles of levees in the Delta. Suppose that each of these nodes reports information at the rate of one reading each minute. The sheer volume of data that would be generated by such a system would not only make human processing impossible due to financial constraints, in all likelihood, this information overload would paralyze the system simply by the fact that the amount of people involved in analyzing the information would effectively prevent any one person to make sense out of specific data points. Therefore, the data should first be reduced to comprehensible levels by computer analysis that generates concise alerts at specified time intervals and when certain thresholds are crossed. For example, a script could be written to identify when there is a change in the trending pattern of the information, when specific nodes are reading values that are disproportionate to surrounding nodes or when nodes are giving values that are inconsistent with expected conditions. If a node is indicating significantly higher water flow relative to other locations for example, the script would identify this, and generate an alert indicating the data at the node and a certain amount of nodes in the vicinity. An engineer could then examine this information and conclude that there is potentially piping occurring at or near the node location and based on the extent of the flow and the rate at which the flow is changing, make a decision to mobilize repair resources or recommend an evacuation to the relevant authorities. A final advantage of computer automation is that it would help keep operating costs low, as labor is a very expensive resource.

Benefits of a Sensor Network

Due to the haphazard construction and the age of the levee system, as well as the dynamic nature of flood control, failures can occur without warning, as exemplified by the incident involving the Upper Jones Tract. While the Sacramento Regional Flood Control Agency requires patrolling of the levees once certain water levels are reached, in such storm conditions, affected areas are likely to already be at maximum preparedness levels (SAFCA). During normal conditions, yearly inspections can only provide so much information, especially since data valid one day may no longer hold the next given that the levees must interact with the environment, which exposes them to outside factors that cannot be controlled for and are difficult if not impossible, to anticipate (such as burrowing animals, physical impacts). Thus, real time monitoring of the levee system provides a real advantage for officials as they seek to properly manage repairs and safeguard the lives and infrastructure dependent on levee protection.

Sensor Life Cycle

When considering the life cycle of any major project, the entire life cycle, from concept to design, to construction, to operations, maintenance, and decommissioning, must be considered.

Concept

The concept of this project is to institute a levee monitoring system in the Sacramento Delta that gives real time data on the state of the levees with respect to such parameters as ground temperature, pore water pressure, and slope stability, and aims to give warning about possible levee failures. Tests in the Netherlands show that levee failure can be predicted as far as 48 hours in advance.

Design

In order to produce a well designed system, the components that will comprise the network must be well defined. This system is a levee monitoring network that will implement a specific number of sensors placed along the more than 1,100 miles of Delta levees that will give current data on values such as water pressure and levee strength. The data will be collected with a frequency of approximately one hertz- one reading each second. This data will then be collected by data loggers connected at half capacity to allow for future expansion. Computers will run through the data and numerically, as well as graphically, represent the trends of the data along with their time rate of change.

As with any system, implementation of a Delta monitoring system faces many constraints. Economically, it is difficult to say how much governmental, public, and private institutions are willingly to spend on a sensor system although its installation in the Delta would be beneficial to everyone. With the poor economy nationwide and California's personal budget problems it is hard to find organizations willing to push money toward flood control projects. With respect to politics, there are numerous different personal interest groups vying for the benefits (i.e. fresh water) that the Delta has to offer. Farmers want the water for agricultural land in the Delta region while the population of southern California needs the water for everyday uses such as for drinking water. Different interest groups will undoubtedly lobby for different things depending how the outcome will compare to their desired outcomes. A further political constraint deals with the fact that varying levels of government hold areas of land in the Delta, and thus are in charge of different levees. Some levees are also under the ownership of private organizations, be they individuals or companies. Since jurisdiction falls under different levels of government, permits to install a Delta-wide system would be difficult.

Engineering constraints would also be ingrained into the technology of the system itself. Each sensor system would have drawbacks with regards to what parameters they can monitor. For instance, implementing the self-potential method does not detect pore water pressure as do piezometers of MEMS- making it difficult to directly predict failure modes such as blowout. There are also uncertainties with regard to the magnitudes of the readings themselves- use of voltmeters for the self potential method gives only approximate values of flow, and while pore water pressure sensors are highly accurate (up to 0.025% FS), the excess values dissipate very rapidly.

Construction

The organization best suited to being in charge of the sensor network is the California Department of Water Resources (DWR) because they own many of the levees in the Delta and have the most qualifications in dealing with flood control. Therefore the DWR is the organization that will be installing the sensor system. Permits for construction will be a difficult aspect of the construction phase since varying levels of government have different requirements and because some of the levees are considered private land.
Installation of the sensors will depend on the type chosen. Each sensor will have to be inserted into the levee through the use of an auger.

Operations

A staff is needed that understands how to deal with the technology that is chosen to monitor the levee. The data can be collected by data loggers and run through the necessary program by computers but man-power is needed to analyze the data if and when a warning is issued by the program. Tiered thresholds will be implemented, with each level represented a different safety condition. If for instance a level one warning is given in the sensor system this means that the situation would need to be addressed by a human. A level two warning would require an inspection. A level three warning could mean that some type of levee failure is eminent and that appropriate actions definitely need to be carried out. The number of levels and the exact procedures with respect to each is unimportant at this time. More importantly it should be realized that different levels of thresholds are necessary since a warning could mean many different things once detected. A staff would also be needed to deal with the interface between the system and organizations involved such as the government, private industries and the public. If an alert is raised concerning a particular levee, then a rapid assessment should be undertaken in order to with make repairs, minimize the damage, or potentially order evacuations. This interface is already in place in publicly owned areas. Mobilization can be initiated in the time it takes to dial the numbers of those in charge of emergency relief.

Maintenance

Inspecting thousands of sensors over any stretch of time is not feasible so an alternate solution must be devised. One possible method is to choose any n^{th} sensor and to inspect it. Another method is to rely on the data to give accurate results. If the sensor is giving inconsistent readings then it can be inspected to see if the node requires repair. Obviously if a particular node stops providing data then this means a "dead" node and maintenance needs to take care of the problem.

A combination of the two is best. Having a random inspection of the nodes in any local levee sensor network in addition to paying close attention to the data readings of the nodes will keep the sensors under close scrutiny.

Sensors will not be repaired, but replaced. In some cases, the system will be upgraded after if previously sound levees are discovered to be at higher risk than initially assessed. The system is designed with excess data logging capacity to allow for ease of expansion. In the case of the voltmeters, needs for replacement are quite low since they are a durable sensor choice. MEMS have a higher priority when it comes to repair needs. Their durability is not as high and their lifespan is shorter.

Decommission

Possible reasons for decommission of the sensor network would be out of date technology and overall disrepair of the system. With the ever-increasing ability of technology, the future may bring a sensor that far outstrips any of the three sensors that comprise our possible choices. For this reason, decommission of the sensor system would include little more than removal of the data loggers and computers that store and analyze the data provided by the sensors. Removal of the sensors would be mostly unnecessary because the cost to do so what be greater than the need.

Another reason for decommissioning of the system would be in a situation where a levee is rebuilt, or at least repaired. In this situation removal of the sensors could be necessary and replacement of the sensor system might not be done.

The lifespan of the voltmeters is indefinite. According to Professor Glaser they "will last forever." Piezometers and MEMS on the other hand a life span of fifteen years.

Implementation- TDS

One way to assess the viability of a system is by using examining the proposed technology delivery system. The technology delivery system, or TDS for short, takes into account how the system will affect, both positively and negatively, three primary components- the public, government, and industry, with an additional component, the environment. The public sector of any system includes the safety and enjoyment of public sectors: "the pursuit of life, liberty, and happiness." The governmental component of the TDS includes all three levels (local, state, and federal), whose aims are and should be the well-being of the first component, the public. Industry includes public and private companies whose main goal is to earn a profit. Finally, the environment plays a role in any system because of the huge impact that pollution and other wastes have on the environment. The environmental component will play an ever larger role in the future as things such as global warming and sea level rise increase in their rate and importance.

Public

The levees in the Sacramento-San Joaquin Delta influence the lives of California's population in many ways. First, the Sacramento Delta is home to approximately half a million people and it is estimated by the Public Policy Institute of California that this number will double by 2050. The lives of these people are directly affected by the possibility of a future large scale levee system failure. If a levee fails, then people will potentially die, be injured, or know someone who has been killed or injured. Likewise over 20 million of the approximately 30 million people living in California use Delta water as their main source of freshwater. This means that over 2/3 of California's population depends on the Delta for a multitude of activities that include drinking, bathing, household chores, and many others. Therefore public interest in flood protection is understandable. What occurred in New Orleans in 2005 after Hurricane Katrina should not happen again, least of all to a public where the majority is at least partially ignorant, even still, to the major impact that levees have on the lives of thousands. Still, the public has recognized the need for better flood protection and so in 2006 they voted in Proposition 84, which includes funds for many water related topics including flood control and safe drinking water.

A levee failure in the Delta would entail a flood that not only would take the lives of some and injures others, but would also destroy the homes, property and personal possessions of thousands of people. Homes filled with peoples' life possessions and garages filled with expensive cars will be destroyed with the next big levee failure if nothing is done to improve the Delta's level of flood control.

Government

The political component of the Sacramento Delta is a complex one. For starters, three levels of government have jurisdiction in different areas of the Delta. Some areas are under federal jurisdiction, some are under state power, and other areas are in control of county hands. Not all of the

Delta land is under governmental jurisdiction meaning that some is in private control. This has significant importance because, since the Delta is not under jurisdiction of one entity but under the jurisdiction of a multitude of different groups, it means that the difficulty of increasing flood control is also increased. A uniform system wide flood control network in the Delta would be complicated due to the fact that the levees on one island may be privately owned, the levees on an adjacent island may be publicly owned, and the levees on a third nearby island are owned partially by public and private entities.

Some of the federal agencies involved in the Delta are the Federal Central Valley Project and the United States Army Corps of Engineers. Under the state level of government, agencies with Delta jurisdiction are the State Water Project, CALFED, and the California Department of Water Resources (DWR). The DWR is the leading candidate to be in charge of a Delta monitoring system because their involvement in the Delta's levees is more substantial than any other governmental agency. On the local level, some six counties make up parts of the Sacramento Delta: Alameda, Contra Costa, Sacramento, San Joaquin, Solano, and Yolo counties. These agencies, along with many others, make up the list of political stakeholders involved in the Delta. For this reason the governmental component of the technology delivery system with respect to the Delta is quite complex with the lines of responsibility and jurisdiction often blurred.

It is still the purpose of government to maintain the well-being of the public. In this case the increase in flood protection is mandatory. Lives depend on whether or not the Delta's levees can reliably control the public from flooding. With Proposition 84, as mentioned before, billions of dollars are to be allocated toward state funded flood control projects. Words from the bill itself say, "The state has also provided financial assistance to local agencies for local flood control projects in the Sacramento-San Joaquin River Delta." Therefore state and local governments are working in accordance with each other with the specific goal of increasing Delta levee flood protection. Unfortunately the current economic condition of the state has left these projects far from completion. The legislation to provide for the allocation has passed, but the actual funds are not to be found. Once the state of California finds itself in a better economic situation it is the hope that systems to increase Delta flood protection will be implemented.

Industry

The Delta region has a significant impact on the state's industry, both public and private industry. Privately, one of the biggest industries that is dependent on the Delta levees is agriculture. Delta agriculture is a billion dollar a year business. The PPIC calculates that in 2000 California farmers used 34.3 million acre-feet of water. When one acre-foot of water equals 325,851 gallons of water this means that over 11 trillion gallons of water were used in 2000 for agricultural purposes, which is approximately four times that used for residential, commercial, and other industrial purposes in the same year. The magnitude of havoc that would occur if the Delta's supply of fresh water were taken away due to a massive wide scale levee failure can be seen just by its potential effect on the agricultural industry. Delta water is also important to other vital industries such as fisheries. The Delta smelt is one possible casualty of a Delta levee failure since it is already in danger of extinction. Fisheries in the Delta rely on its supply of fresh water for the purpose of breeding and growing their fish.

In addition to these private industry examples public industries, those owned and operated by the government, are also important. Public industries such as water, electricity, and transportation services are needs that California's population has come to expect and take for granted. For example, $400 billion of California's economy is directly supported by water exports, with most of this water naming the Sacramento Delta as its source. This means that the Delta is an enormous source of revenue for the state. A levee failure where land is inundated with water would mean that the land is ruined for agricultural purposes and that the water is lost for exportation purposes.

Environment

The environmental impact of any project or system is as important as any other aspect and the Delta is no exception. Much of this land was originally marshland and the habitat for many species of animals. It is still sensitive area due to the fact that as mentioned before; so much depends on the Delta's water for agricultural purposes and for animals such as the Delta smelt. However with all of the development of the region and industry's effect on the area, the environment has been negatively impacted. Much of the Delta's 57 islands have subsided anywhere from zero to twenty feet, and many animals such as the Delta smelt are in danger of going extinct. Levee failures that result in the inundation of land surfaces also could have a negative impact on the environment, especially if the breach leads to saltwater intrusion. A Delta levee monitoring system would help lower the likelihood of these consequences.

Cost Benefit Analysis

Another method to examine the viability of a project is to undertake a cost benefit analysis, where all costs associated with the system and all benefits associated with a system are converted to a present value for the purposes of comparison. For this project, a cost benefit analysis for the implementation of this system on Twitchell Island was completed. Rick Carter, the island superintendent proposes a two-tier installation on Three Mile Slough, one of the more critical levee sections protecting the island, as the levee is only partially armored with rip-rap. Carter requests a 1500' section of MEMS and an addition 1500' section of self potential sensors for a slightly better protected area. The costs include the initial equipment costs and the cost to make repairs as deemed necessary by the sensor network. A notable omission is the cost of staffing, as operation could be added to the workload of existing employees. For a full breakdown of the costs, please see the appendix. Similarly, benefits include the cost savings of having to repair a levee breach, the value of land and assets on Twitchell Island, and of course, the value of the lives saved. Please refer to the appendix for the full analysis. The final calculated ratio of benefits to costs was 33.68, an extremely positive value, indicating that the system is economically sound. However, since this design does not instrument the entirety of the island, it is possible that a failure may occur at an unmonitored location, making it unclear to what extent the calculated benefits can be applied. A cost benefit analysis of instrumenting the entire island with MEMS was also completed, yielding a ratio of roughly 13.

Conclusion

Given the dependence of the state on the Delta and its levees and the current precarious condition of the aforementioned levees, the status quo is not acceptable. While a sensor network will offer no tangible physical protection, it will assist agencies in determining how to best utilize the few resources available to them as they will be able to identify areas in the greatest need of attention. Also, such a system will benefit the general public as successful installation would allow for more time to prepare for an impending failure.

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Appendix A: Cost Benefit Analysis (Requested Design)

Item	Price	Quantity	Total Cost
Self Potential sensor (initial cost)	$75/sensor	100 sensors	$7500
MEMS (initial cost)	$500/sensor	300 sensors	$150,000
Auger (initial cost)	$12,500	1	$12,500
Computers (initial cost)	$500	2	$1,000
Uninterruptible Power Supply (initial cost)	$200	2	$400
Data loggers for Self Potential sensors (initial cost)	$4,340	3	$13,020
Electricity (annual cost)	$0.0947/kWh	166 W; 1,454.16 kWh	$137.71/yr
Repairs (total cost)	$10/cut yard	172,222 yd^3; 241,111 cut yards	$2,411,110

Item	Value	Quantity	Total Value
Lives	$1,540,000	15	$23,100,000
Land Value (Lund et al 2007)		3702.2 acres	$9,023,367
Asset Value (J.R. Benjamin and Associates, 2007)			$14,493,000
Single Breach Repair/Damage Costs			$41,162,960

Benefits/Cost = 33.68

Source: Public Policy Institute of California

Appendix B: Cost Benefit Analysis (Team Recommendation)

Costs			
Item	**Price**	**Quantity**	**Total Cost**
MEMS*	350	11616	4065600
Auger	12500	1	12500
Repairs (annual)	10	241111	2411110
		Total	6380806.494
Benefits (Accrued Annually)			
Item	**Value**	**Quantity**	**Total Value**
Lives	1540000	15	23100000
Land Value	varies based on use	3702.2	9023367
Asset Value			14493000
Single Breach Repair			41162960
		Total Annual Value	7022346.16
		Total Benefits	83832768.46
		Benefits/Cost	13.13827155

Source: Public Policy Institute of California