Geotechnical aspects on design and construction of stabilization ponds

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Abstract

A geotechnical methodology is presented in this paper which should be followed in order to prevent and avoid water leakage, geological faults, slope failures and uncontrolled settlements in stabilization pond systems. Identification of special problem soils (expansive, collapsible, dispersive and highly compressible) is also described, together with some solutions to handle the stabilization or improvement of such soils. This paper is based on the experience obtained by analyzing the behavior of several case studies that were carried out for different soil conditions in Mexico. Several geotechnical recommendations are given for the design and construction of stabilization ponds. The criteria and recommendations of this work will become important and practical tools for designers and constructors to improve the life of this kind of facility.

Keywords: stabilization ponds, geotechnics, problem soils, soil permeability, wastewater treatment.

1 Introduction

Wastewater treatment in Mexico is quite behind the potable water supply and sewer systems services given by municipalities and governments. It is estimated that 170 m$^3$/s of municipal wastewater is generated and according to the last census (1999), 54% of the existing wastewater treatment facilities are stabilization ponds systems. The flow to be treated by this system is estimated to be around 17.5 m$^3$/s.

From the environmental, economical, political and social points of view, wastewater treatment represents a very important issue in Mexico. Nevertheless, the efficiency of these plants is not good enough to accomplish the pre-established goals. Dealing with pond systems, many facilities have several
Some of them are related to the design and construction of the pond embankments and excavations, the impermeability of the bottom and wet slopes of the embankments, control of settlements, among others.

This paper presents the geotechnical methodology that should be carried out in order to prevent and avoid water leakage, geological faults, slope failures during excavation and embankment construction, as well as uncontrolled settlements of stabilization pond systems. Identification of special problematic soils (expansive, collapsible, dispersive and highly compressible soils) is also presented, together with some solutions to handle the stabilization or improvement of such soils. This paper is based on the experience obtained by analyzing the behavior of several case studies that were studied for different soil conditions in Mexico.

2 Main geotechnical aspects

Following results obtained during geotechnical inspection and analysis of performance records of several stabilization ponds constructed in Mexico and taking into account design and construction experiences gained in other types of embankment, the main geotechnical deficiencies or failure mechanisms in pond systems can be summarized in three categories: flow-induced deficiency or failure, instability and deformation ([1-3,7]).

Flow-induced deficiency or failure
- Overtopping. The water flows over embankment crest causing washout or total destruction of the structure.
- Piping. This is a form of concentrated seepage through a section of soil which is either permeable than its surroundings or is subject to a particularly high hydraulic gradient. Concentration of flow may lead to transport and loss of soil particles by progressive erosion.
- Particle migration. Transport of materials within soil mass, generally occurring along the wet side revetment. Suffusion also takes place by which finer particles are transported by water percolation from between a soil skeleton formed by coarser material. If there is not control of this kind of leakage, a piping failure might take place and the consequences will be very serious (fig 1).
- Leaks. Water leaks may occur through the pond bottom and embankment. They cause escape of water and diffusion of contaminants into surface water and groundwater.
- Scour. Removal of soil particles from the soil-water interface by current or wave induced shear forces. It may be in combination with hydraulic gradient forces or by rainfall run-off above the water line.
- Erosion. Local concentrated erosion may be present on the dry side of embankment by precipitation. Wave erosion will damage the wet side face of the embankment (fig 2).
Figure 1: Flownet through an embankment of a stabilization pond.

Figure 2: (a) Erosion and scour at the wet side of an embankment; (b) Detail of the embankment’s erosion.

**Instability**

- **Geological fault.** When pond is constructed over an active geological fault that is not discovered during design, embankment and liner system may be disrupted due to fault opening (fig 3).

- **Slides.** Slip circles and deep sliding are frequent failure modes. Local shear failure parallel to the slope is possible either within the soil mass or at the soil-revetment interface. Local bearing failure may also be present. Many factors can cause slides and local failures: rapid drawdown, pre-existing slip planes within soil foundation, lenses and bands of weaker material, overloading on the embankment crest, inadequate slope design, etc.

- **Liquefaction.** Complete loss of grain-to-grain contact by an increase in pore water pressure or by shock loading of a loosely compacted granular soil. Consequent loss of effective stress results in a nearly zero shear strength and the soil behaving as a liquid.
Deformation

- Settlement. Deformation due to reduction in volume of soil. Settlement may be caused by consolidation, compression and shrinkage.
- Heave. Deformation due to increase in volume of soil. Heave may be caused by frost leave and swelling soils. Heave might occur particularly during the excavation stage.
- Cracking. Cracks may be transverse (perpendicular to the embankment axis) or longitudinal (parallel to the embankment axis), external or internal, shallow or deep. They appear due to differential settlement and soil shrinkage.

Many of these defect mechanisms and failure modes are interrelated and should be anticipated and analyzed during site investigation and geotechnical study. Piping and overtopping are of particular concern because are responsible for the major percentage of serious incidents and failures reported in the literature.

3 Geotechnical site investigation

Site investigation involves the determination of the nature and behavior of all aspects of a construction site and its environment that could significantly influence or be influenced by a project. Some of the most important aspects to be considered are:

- Groundwater effects: seepage, pumping, infiltration and percolation.
- Environmental considerations: leachate contamination, health and safety issues on surrounding properties and inhabitants.
- Excavation: short and long term stability, drawdown of water level and possible damage to top clay layer.
- Ground improvement: barrier system and compaction.
- Placement of fill: slope stability, settlements or heave.

The soil stratigraphy should be determined precisely including soil composition, layer thickness, soil inhomogeneity in horizontal extension, and location of water table. It is also important to discover sand lenses, weak layers and other relevant minor geological features. The investigation is not limited to the construction area; it should also cover widespread geological risks such like landslide, regional subsidence and mining activity, among others. Many regions including Mexico are seismically active. Earthquakes may cause severe damages to embankments, barrier systems and other facilities of pond systems. It is important to anticipate seismicity on the construction site and take it into account in design.

Reconnaissance investigation is the first phase of site characterizations. Borehole drilling and sampling are necessary for more detailed subsurface investigations. Soil samples should be tested in laboratory to determine their physical, hydraulic and mechanical properties. Several compatibility tests should be carried out to analyze the effect that some contaminants, salts or temperature changes have on the mechanical or index properties of the soil that form the ponds systems. It has been observed, for instance, severe changes in the permeability and the Atterbeg limits in compacted clays under KCl solutions (Silva, [5])

In situ tests of subsurface soils often provide better information at lower cost than taking and testing samples. Among several types of in situ tests, the field permeability test and standard penetration test are the most frequently used. By using the first of these tests, the permeability of pervious layers below the water table can be found measuring the drawdown in piezometers located at certain distances from a pumped well. Various types of borehole permeability tests made by pumping water either into or out of the boring are also used. Coefficient of permeability of soils can be determined form these tests. On the other hand, when using the standard penetration test, the number of blows can be correlated to shear strength and other parameters of soils.

4 Soils that require special investigations

There are many so-called problem soils because they cause mayor damages to structures and embankments and they cannot be identified easily using routine soil testing procedures. In Mexico, expansive, collapsible and highly compressible soils are frequently found and dispersive clays are occasionally present.

Expansive soils are widely distributed in Mexico. These soils are frequently found in non-saturated residual soil deposits of fine material that contain clay minerals of the montmorillonite or illite type. These soils are very sensitive to changes in humidity. Because of water adsorption in the active clay minerals
they expand when decompressed and in contact with water; they also strongly
shrink when are exposed to drying. If the embankment is constructed of or
founded on expansive soils, evaporation, rainfall, temporal humidity variation
and change in water level of a pond may cause swelling and shrinkage of soils,
and consequently differential settlements and fissures of the embankment might
occur. Shear strength of expansive soils also changes with humidity variation
and stability problem may arise in embankments. Expansive soils can be
identified by visual inspection and determination of their physical and
mechanical properties. Volume change under flooding can be determined in
odometer testing.

Collapsible soils are fine sediments transported and deposited by winds. They
range from sand dunes to loess deposits whose particles are predominantly of silt
size with certain amount of fine sand and aggregated clay particles. Although of
low density, the naturally collapsible soils have a fairly high strength because of
the clay binder that is frequently calcium carbonate. However, they are easily
eroded when flooded with water or rained on. Collapse of soil structure cause
large settlements. These soils can be identified in odometer testing.

Highly compressible clays are frequently found in Mexico and one of most
notable example is the Mexico City clay which has a water content as high as
350 to 400%. These clays of volcanic origin and other organic soils are highly
compressible that may cause serious damage to barrier systems and
embankments in pond systems.

In some parts of Mexico dispersive clays have been found. These soils are
usually high in adsorbed sodium and disperse or deflocculate easily and rapidly
in water of low salt content. The higher the percentage of sodium cation, the
higher the susceptibility to dispersion. Such clays generally have high shrink-
swell potential, low resistance to erosion, and have low permeability in an intact
state. Dispersive clay soils are identified by running the pinhole test, the crum
test and the SCS dispersion test. Chemical tests are also frequently used to
determine exchangeable sodium percentage, sodium adsorption ratio, percent
sodium and total dissolved salts. Dispersive soils are troublesome for
embankment stability, by causing piping and rainfall erosion on slopes and
channels.

A simple way to improve a problem soil site is to remove the problem soils
and replace them with higher quality materials. This treatment is most common
for organic deposits and highly compressible soils, but it has also been used for
collapsible and expansive soils. It is often to mix soils of high swelling potential
(collapsibility) with those of low swelling potential (collapsibility). The use of
chemical additives is other effective technique to improve problem soils.
Chemical stabilization can involve mixing and compaction of near-surface soils
and those located at depth if special equipment is used. Chemical substances
such as lime and Portland cement can be used alone or in combination to reduce
the swelling and dispersion potentials of soils. Collapsible soils might be
improved by pre-saturation and pre-loading procedures. Various other soil
improvement techniques are also available and can be used if its cost is
justifiable.
There are several geotechnical publications in which all these problematic soils are described with details, together with the methods to identify them and to treat them in order to improve their mechanical behavior; see for instance Vain Impe [6] and Schaefer [4].

5 Particular geotechnical provisions

Apart from site investigations and geotechnical analysis (water flow, chemical diffusion, stability and settlement studies), a number of provisions should be considered in order to avoid or minimize deleterious effects from different environment actions.

Excavation. Soil top layer is generally not proper for pond construction because is frequently clayey, organic, weathered or fractured. The removal of the clay top layer may not be excessive in order to make use of the barrier capacity of the lower part of the layer. The remaining thickness of the clay layer after excavation depends upon local geological conditions, grade and materials balance considerations, the heave potential and the thickness required to provide adequate contaminant attenuation. The excavation depth should be determined based on all these factors.

Liner. The pond is a container of contaminated water over long periods of time, so a barrier system should be designed to avoid the filtration. Its purpose is not only to limit the physical escape of the liquid to either surface water or groundwater, but also to avoid the chemical migration by the process of diffusion whereby the contaminants migrate from a point of high concentration to points of lower concentration. Clay liner and geomembrane are two of the most used barrier systems. Soils classified as CL (clay of low plasticity), CH (clay of high plasticity) or SC (sandy clay) in the unified classification system are commonly used to construct clay liners which are expected to have a hydraulic conductivity less than 1x10^{-9} m/s. Although the low hydraulic conductivity is the main design criteria for clay liners, other factors such like cracking, strength, compatibility, diffusion and temperature cannot be underrated. Geomembranes may be used alone or in combination with low permeability soils.

Revetment. The wet side face of the embankment should be protected from wind and wave action by riprapping the face with rock blocks. Riprap should extend at least one meter below the low anticipated water level. Reinforced grass surface prevents gullying on the dry side of embankment.

Freeboad. The pond overtopping should be avoided because it endangers the security of the embankment, contaminates land and property outside of the pond, requires excessively expensive repairs and might cause serious public alarms for the safety and good performance of the pond system. In order to prevent overtopping, a freeboard must be provided between the maximum water level and the minimum crest elevation. The freeboard is determined considering the
wind effect and long-term embankment and foundation settlement. The freeboard allowance for wind-induced wave action is the height of run-up of the significant wave as computed from adopted wind criteria. The freeboard allowance for settlement should be estimated from settlement analysis and seismic consideration for the embankment.

Compaction. Compaction procedures should be designed for materials that will be used for construction of clay liners and embankments. Generally accepted compaction criteria, in which maximum dry density and optimum water content define the required compaction energy, are adequate for embankment constructions. However, if expansive soils are used in the embankment construction, strongly compacted soils will have high heave potential. It is preferred to construct the surface layer of the embankment placing expansive soils compacted with low compaction energy. For clay liner, the compaction procedures should be very well controlled to obtain a low permeability. It is generally believed that higher water contents than the optimum are helpful to achieve a lower permeability and adequate shear strength.

Earthquake defensive measure. If the pond is constructed in seismic zones, additional defensive measure should be taken. These might be: providing more gentle slopes, allowance of ample freeboard for settlement and slumping, design of crest details for preventing erosion in the event of overtopping, allowance of wide crest to mitigate propagation of transverse cracks that may be generated during shocks, etc. These measures are mentioned assuming that the embankment has a homogeneous clay section. Construction of filter and drainage systems is very helpful to reduce even more effectively earthquake damages.

6 Conclusions

Geotechnical considerations are important to assure the success of stabilization pond systems. The overtopping and other geotechnics related damages may cause excessive repair costs and serious public alarms for the security and good performance of the pond systems. In general, it is justifiable to spend money on geotechnical investigation, testing and engineering analysis; by doing so it will be cost-effective for the project. The geotechnical recommendations made in the present work are based on experiences gained in Mexico and expected to be helpful to current design practice of stabilization ponds.

Since the most important parameter for the correct function of these water treatment systems is the permeability of the liners and the one of the in situ soils, special supervision has to be done when measuring this parameter during both the design and the construction stages. There are some special permeability tests that should be carried out while investigating this parameter.

Finally it is recommended to carry out geotechnical investigation, analysis and design from the beginning of project planning during site selection period. This process should continue until construction and first operation stages are completed. Geotechnical engineer’s inspection is important during excavation in
order to discover new geological features and verify the accuracy of design assumptions. Quality control during embankment compaction has to be carried out and design specification should be fulfilled. The period of the first impoundment is one of the most critical conditions in which piping might occur. Frequent inspection is necessary during operational period but more detailed inspections are required after extreme events such like strong rainfall, rapid drawdown and earthquake.

References


