Erosion Control Using Modified Soils

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Abstract

As a result of Hurricane Katrina, many sections of the flood protection systems in New Orleans were eroded due to plunging water, and sections of flood walls were determinately damaged. Therefore, mitigating this type of erosion and failure is necessary for counteracting similar catastrophic events. This study evaluated the method to mitigate erosion due to plunging water by strengthening the soil with ground modification. The Vetiver plant and Polyhedral Oligomeric Silsesquioxanes (POSS) were the two main ground modifiers used in this test. Test results showed that both POSS and the Vetiver were effective in reducing erosion. POSS showed good erosion resistance with good applicability to field soils, Vetiver showed higher resistance to erosion by plunging water; but required time to achieve well established root/stem system.

Introduction

Erosion caused by plunging water during Hurricane Katrina caused extensive damage to the levee systems in New Orleans, Louisiana. Plunging water in New Orleans is most commonly used when expressing water that is falling over the top of a flood wall (e.g. T-Wall, I-Wall). This plunging water causes impact erosion and is different from typical runoff erosion because the impact erosion is initiated from the flow whose direction is normal to the ground surface while the typical runoff erosion is initiated from flow whose direction is parallel to the ground surface.

New Orleans is located on the Gulf Coast of Louisiana and is surrounded almost entirely by water: the Gulf of Mexico, the Mississippi River, Lake Pontchartrain, and numerous canals. Also, a substantial portion of New Orleans is located approximately seven feet below sea level as shown in Figure 1, and all rainwater must be pumped up to the canals, Mississippi River, or lakes. Due to these conditions, during times of excess rainfall and failure of pumping stations, New Orleans may experience severe flooding; that actually happened during Hurricane Katrina.

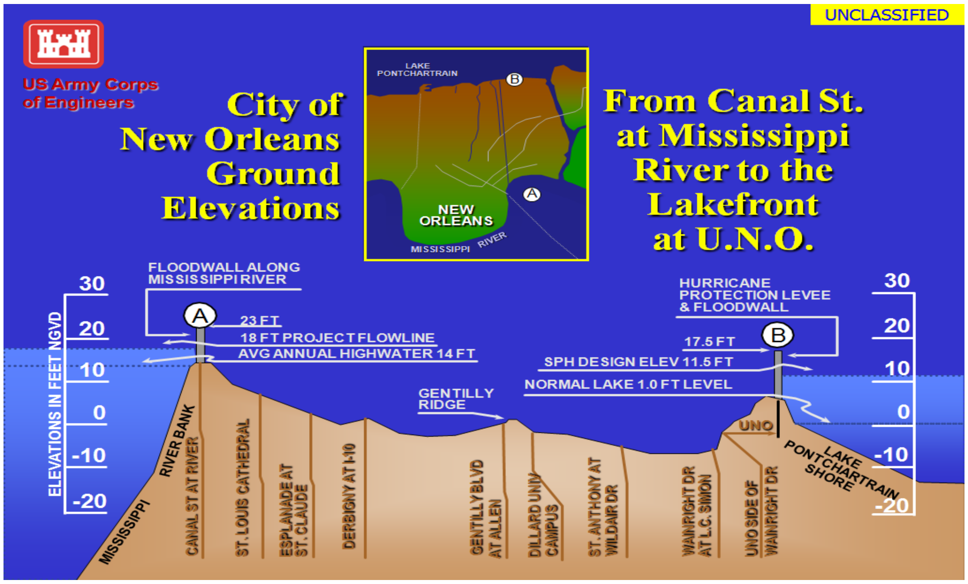

Figure 1: Representative Cross Section of New Orleans (IPET 2007)

Trying to cope with rising flood waters, New Orleans has implemented several techniques to prevent flood damage including elevated levees and flood walls. Particularly, raising the levee level accompanies the widening the levee base, it may interfere with the private land ownership in urban areas. Therefore, most levee systems in urban areas cannot be raised higher than their current height; concrete flood walls are constructed on the top of the levees instead.

Hurricane Katrina made landfall on August 29, 2005 as a category three hurricane with peak wind speeds sustaining 125 mph, causing roughly two billion dollars worth of damage to the infrastructure [IPET 2007]. The storm surge that accompanied Hurricane Katrina was roughly 12-14 feet high. In addition to the storm surge, rainfall was estimated to be at 14 inches over a 24-hour period. However, these are only estimates because most of the instruments used to measure storm surge and rainfall were destroyed [IPET 2007]. Eighty percent of the New Orleans metropolitan area was flooded [IPET 2007].

New Orleans hurricane protection systems were not designed to accommodate for such high water levels. The highest water level in canals exceeded the height of the flood walls by 1 to 2 ft. Approximately 50 major breaches occurred in the hurricane protection system; 46 of these breaches were the result of overtopping water. The overtopping water caused soil erosion, which eventually led to the failure of many floodwalls [IPET 2007].

This study primarily focuses on preventing or reducing erosion from overtopping water through ground modification. In order to do this, the bare (untreated) soil samples were used as a reference soil. As a reference soil, we tested bare soils that have no chemicals added or additional enhancements that may increase erosion resistance of the soil. All the soil samples that have been tested are a mixture of fine and course soils. The fine and course soil was taken from a quarry site in New Orleans and mixed in the lab based on material specification of levees [Vroman 2008].

Test Samples

The fine grained soil was classified as CH or CL with the percentage passing the # 200 sieve about 80%, and the course grained soil was classified as SM with the percentage passing the # 200 sieve was 4.5%. For detailed sample mixing and preparation procedures please refer to Song et al. (2010). There are four different mixtures of fine and course soil that have been conducted in testing: 50/50, 57/43, 65/35, and 73/27 (with % of fines being the first number and course materials following respectively). Also, there are four different degrees of compaction at which samples are tested: 95%, 91%, 87%, and 83%. With four mixtures and four degrees of compaction, this gives a total of sixteen different combinations of soil samples as shown in Table 1.

Table 1: Basic Soil Properties of Soil Samples (Song et al)

Soil Identification	Degree of Compaction (%)	Total Unit Weight $\left(\frac{\mathrm{kN}}{\mathrm{m}^3}\right)$	Dry Unit Weight $\left(\frac{\mathrm{kN}}{\mathrm{m}^3}\right)$	Void Ratio	Degree of Saturation (%)
F50S50	83	16.5	14.1	.96	48
Clay 15%	87	17.1	14.6	.88	52
Silt 35 %	92	18.3	15.7	.86	54
Sand 50 %	99	19.5	16.7	.74	62
F57S43	85	16.8	14.2	.9	54
Clay 18%	88	17.4	14.7	.83	58
Silt 40 %	92	18.1	15.4	.76	64
Sand 42 %	97	19.1	16.2	.67	73
F65S35	84	17.9	14.5	.9	57
Clay 20%	87	17.8	14.9	.84	61
Silt 45 %	91	19.1	16.2	.78	65
Sand 35 %	97	20.2	17	.62	82
F73S47	83	16	12.8	1.15	58
Clay 23 %	87	16.6	13.3	1.05	63
Silt 50 %	90	17.4	14	.96	69
Sand 27 %	95	18.2	14.6	.89	74

For a chemical ground modifier, Polyhedral Oligomeric Silsesquioxanes (POSS) is used. POSS is a liquid chemical poured onto soil samples to reduce erosion. There are two different POSS consolidates used in the erosion testing: SO1455 (3% TriSilonolIsooctyl POSS, $C_{56}H_{122}O_{12}Si_7$) and SO1458 (3% TriSilanolPhenyl POSS, $C_{42}H_{38}O_{12}Si_7$) [www.hybridplastics.com]. After completion, the samples treated with POSS were cured and dried at room temperature for two weeks. This process allows the POSS ample time to penetrate into the soil samples and interact with the soil.

For a biological ground modifier, the Vetiver plant (*Chrysopogon zizanioides)*, commonly referred to as Vetiver, and originates in Southern India, is used. It is a very tall and dense grass that provides good stability and is sterile and non-invasive to other plants and animals. Vetiver has been used in Southern India for many years for erosion control and slope stability enhancement because Vetiver is a very deep rooted grass (Hengchaovanich, 1996), as shown in Figure 2. The roots of Vetiver are thought to be able to penetrate into soils as deep as 2-3 meters depending on the ground conditions (Hengchaovanich, 1996). In addition, the reinforcing effect of this root system provides additional resistance to the shearing force of plunging water (Hengchaovanich, 1996).

Figure 2. Root system of Vetiver (www.vetiver.org)

POSS and Vetiver are the primary ground modifiers used in this research. The test results will be discussed further in this paper.

Test Set Up and Procedure

The University of Mississippi Erosion Test Bed (UMETB) is a combination of two tanks, five pumps, and pipes that were designed to mimic plunging water in New Orleans. The UMETB circulates water to/from an inner tank that circulates water to/from an outer tank. In doing so, the water passes through a planar nozzle that is .003 mm thick that simulates water plunging over a flood wall. The velocity of this plunging water was controlled to be 6 m/s; this is about the same velocity of plunging water from the top of 1.8 m (6ft.) high flood walls.

Figure 3: Depiction of UMETB

Soil samples are prepared accordingly as discussed the Test Samples chapter. Before any soil samples are made, the maximum dry density and optimum water content are measured for each mixture by the Standard Proctor Test (ASTM D698).   The basic soil properties of each mixed and tested soil samples are shown in table 1.

An erosion mold is a wooden container designed to hold soil samples for testing [Jang et al. 2010]. Erosion molds are built of lumber and a clear acrylic plate. The clear acrylic plate is used to view the erosion progress during testing by a video camera. The acrylic plate has a network of measured marks (1 cm x 1 cm) in order to accurately quantify erosion behavior on the video camera. After being built, the erosion molds are measured in order to obtain the volume: $\text{Length } (.253\text{ m}) \times \text{Width } (.20\text{ m}) \times \text{Height } (.20\text{ m}) = \text{Volume } (.010537323\text{ m}^3)$. The soil samples are compacted at a specific degree of compaction in the erosion molds. Compaction is carried out in eight separate layers in order to obtain uniform compaction. Also, in order to mimic field compaction techniques, a gasoline powered tamper (Dynapac, LF45) was used for compaction. A coat of bentonite and water paste are applied to the inside of the erosion mold to decrease the amount of friction between the soil and the erosion mold during compaction (For further details on this technique, please see Jang et al. 2010).

During times of excess rainfall, flooding, and hurricanes the soils surrounding the area may be soaked. To reproduce this condition, soil samples are completely submerged in water for 48 hours before testing, this can be seen in figure 3. The water level was kept .05m above the sample in order not to apply to much water pressure to the samples. The dimensions of soil samples are measured before and after submersion in order to calculate changes in soil parameters such as void ratio and the degree of saturation.

Figure 3: Soil Sample after being submerged

Testing Procedure

The following test procedure is followed in this study.

1) Mount the erosion mold under the nozzle.

2) Set the video camera in front of the graduated acrylic plate to record the erosion profile with time.

3) Focus the video camera on the grid of the acrylic plate.

4) Turn on the five sump pumps (three of 1/3 HP for out-flow, two of 1/2 HP for in-flow) to circulate water from inner tank to outer tank via the nozzle so that it initiates the erosion on the soil sample surface.

5) Record the erosion process with the video camera.

6) Analyze the recorded video images with PMB (Picture Motion Browser) software and obtain erosion depth and lap time data.

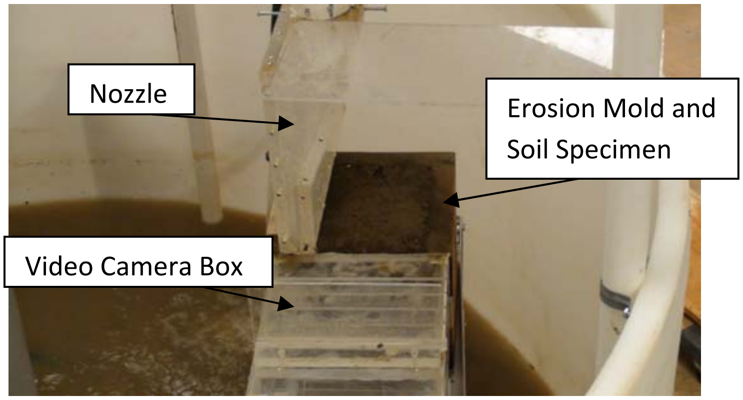

Figure 4: Erosion testing procedure

Analytical Equations for Erosion

The excess shear stress concept (Hanson et al.2002 modified from Stein et al. 1993), postulates that erosion of soil takes place if the effective shear stress from the moving fluid is higher than the critical (resisting) shear stress as shown in eqn (1). In addition, it is noted that the erosion depth depends on three factors: erosion rate coefficient (k_d value), the difference between the effective shear stress and the critical shear stress, and the erosion time. This study computed k_d so that erosion resistance of different soils may be compared quantitatively. This study, however, computed k_d at each time step rather that computing a single average k_d throughout the test. $\frac{dD}{dt}$ at a certain time is obtained from the test, τ_o and τ_c are obtained from tests and hydrodynamics. The calculation procedure of k_d at time intervals is shown as follows.

$$\frac{dD}{dt}=k_d(\tau_o-\tau_c)^a \qquad (1)$$

Where:

D=erosion depth

t=time

k_d= erosion rate coefficient

τ_o= shear stress caused by flowing water

τ_c= critical shear stress

a= constant

Eqn (1) is solved using dimensionless parameters as follows

When $D^*\leq D_P^*$

$$T^*=D^*\left(\frac{D_p^*}{1-D_P^*}\right)^a \qquad (2)$$

When $D^*\geq D_P^*$

$$T^*-T_p^*-\left[-D^*-\ln\left(1-D^*\right)\right]_{D_P^*}^{D^*}=0 \qquad (3)$$

Where:

$$D^{*}=\text{normalized erosion depth}=\frac{D}{D_e} \quad (4)$$

D=erosion depth at a given time

D_e=equilibrium erosion depth

$$D_p^{*}=\text{normalized depth of potential core}=\frac{D_p}{D_e} \quad (5)$$

$$D_p=\text{depth of potential core}= C_d^2 y_0 \quad (6)$$

$$C_d=\text{diffusion constant}=\sqrt{5.5(1+\cos\theta)} \quad (7)$$

θ= impinging angle

y_o=thickness of plunging water

$$T^{*}=\text{normalized time}=\frac{t}{T_r} \quad (8)$$

$$T_r=\text{reference time}= \frac{D_e}{k_d\tau_c} \quad (9)$$

$$T_p^{*}=\frac{\tau_c}{\tau_e}\left(\frac{\tau_c}{\tau_e-\tau_c}\right)^{a} \text{ Stein et al 1993 (a=1)} \quad (10)$$

$$\tau_c=\text{critical shear stress}=\frac{D_p}{D_e}\tau_e \quad (11)$$

$$\tau_o=\text{effective shear stress}= C_d^2 C_f\ \rho\ u_0^2\frac{y_o}{D} \quad (12)$$

$$C_f=\text{coefficient of friction}=\frac{0.0474}{2}R_0^{-\frac{1}{5}} \quad (13)$$

$$R_0=\text{Reynolds Number}=\frac{2y_0u_0}{\nu} \quad (14)$$

u_o= flow velocity of impinging water

This research focuses on the research conducted by Stein et al (1993, 1997) and Hanson et al (2002, 2003). Their research proposed finding a constant k_d value, which is a detachment coefficient. However, the Stein et al and Hanson et al. approach was modified by Jang (2010) by using non constant k_d incorporating the change of erosion coefficient due to the changes in soils strength, confining pressure, density and so on. This study adapted concepts by Jang, and the details of this approach can be found in Jang.

All of the values are known for the equations (3) through (14), except for k_d, D_e, and τ_c. However, the final erosion depth (D_e) can be found by plotting erosion depth vs. time and finding the ultimate value; then, the value for τ_c can be computed. After these two parameters are found, it is not difficult to use a spreadsheet to find the detachment coefficient k_d.

Sample calculation at $time = 200\, seconds$ for POSS treated (SO1458) soil sample (F50S50 at 83% Degree of Compaction) is conducted here. The correlating erosion depth for this time was found to be 5.5 cm; this can be seen in figure 5.

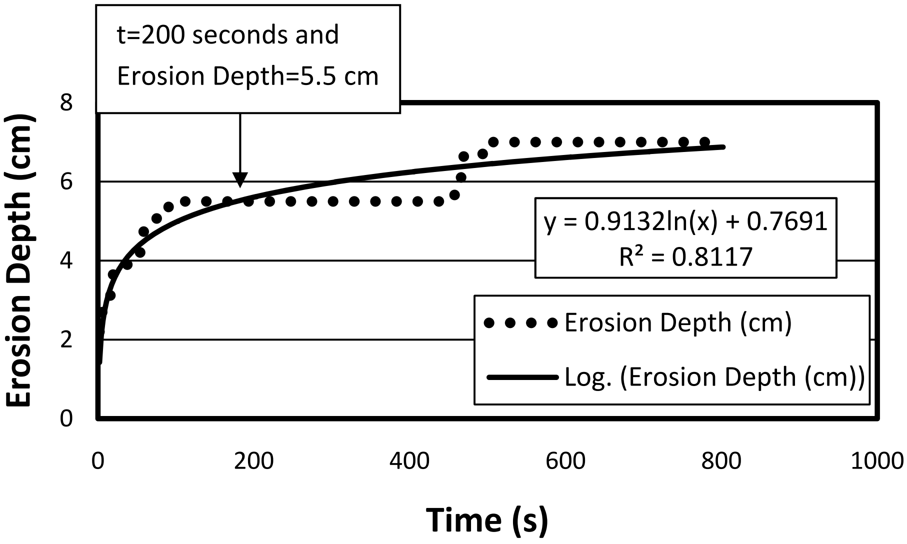

Figure 5: Sample graph in order to show k_d calculation

In order to perform these calculations it is assumed that the time to reach equilibrium depth (D_e) is one hundred days; the depths in figure 5 were found using logarithmic curve fitting. Therefore from figure 5 it is found that $De = .1535\ m$.

Data known from UMETB:

θ=angle that water strikes soil=90^0

y_o=plunging water width=.003 m

u_o=velocity of water=6 $\frac{m}{s}$

ν=viscosity of water=$1.004\times10^{-6}\ \frac{m^2}{s}$

ρ=density of water=1000 $\frac{kg}{m^3}$

Solution:

equation (4) ; $D^*=\frac{D}{D_e}=\frac{5.5}{15.0919}=.3644$

equation (7); $C_d=\sqrt{5.5(1+\cos\theta)}=\sqrt{5.5(1+\cos 90\text{ degree})}=2.345$

equation (6); $D_p=C_d^2 y_0=2.345^2*.003=.0165$

equation (5); $D_p^*=\frac{D_p}{D_e}=\frac{.0165}{.1535}=.10749$

$D^* \geq D_p^* \rightarrow .3644 \geq .10749$

Therefore equation (3) will be used for the calculation of k_d

equation (3); $T^*-T_p^*-\left[-D^*-\ln\left(1-D^*\right)\right]_{D_p^*}^{D^*}=0$

equation (7); $R_0=\frac{2y_0u_0}{\nu}=\frac{2(.003)6}{1.004\times10^{-6}}=35856.57$

equation (14); $\frac{0.0474}{2}R_0^{-\frac{1}{5}}=\frac{0.0474}{2}35856.57^{-\frac{1}{5}}=.0029$

equation (12); $\tau_o=C_d^2C_f\rho\, u_0^2\frac{y_o}{D}=2.345^2(.0029)(1000)\left(6^2\right)\frac{.003}{.055}=31.31\text{ p}$

equation (11); $\tau_c=\frac{D_p}{D_e}\tau_e=\frac{.0165}{.1509}*31.31=3.42\text{ p}$

equation (9); $T_r=\frac{D_e}{k_d\tau_c}=\frac{.1535}{k_d(3.4235)}=\frac{.044837}{k_d}$

equation (8); $T^*=\frac{t}{T_r}=\frac{200}{\frac{.044837}{k_d}}=4460.586*k_d$

equation (10); $T_p^*=\frac{\tau_c}{\tau_e}\left(\frac{\tau_c}{\tau_e-\tau_c}\right)^a=\frac{3.4235}{31.31}\left(\frac{3.4235}{31.31-3.4235}\right)^1=.0134\text{ p}$

All values are known, and can now be substituted into equation (3)

$4460.56*k_d-.01343-[-.3644-\ln(1-.3644)]-[-.10749-\ln(1-.10749)]=0$

$4460.56*k_d=.108443405$

$$k_d = .000024311 \frac{m^3}{N*sec}$$

Since most soil parameters such as density, shear strength, and water content vary with depth; the detachment coefficient k_d should also vary with depth. This was accomplished by analyzing the erosion behavior at time intervals of 2 seconds, and calculating a k_d value for each time interval, in doing so it allows for the calculation of a non-constant k_d value.

Results

Bare Soil: The representative sample that was chosen for comparison was F50S50, which has 60% fines and 40% sand, and a degree of compaction at 83%. The primary reason for this is that this sample shows quite low resistance to erosion in previous studies [Jang, 2010]. This is illustrated in Figure 6. In principle, if a chemical or a plant can control erosion for this sample, it should be able to decrease erosion in other samples with higher clay percentages and degrees of compaction. The computed final erosion depth, or equilibrium depth (D_e), was found to be .494 m when time is equal to 100 days; this is illustrated in Figure 7. The actual equilibrium depth would be slightly higher when time is equal to infinity, however for analytical calculations the time was assumed to be 100 days for calculation simplicity.

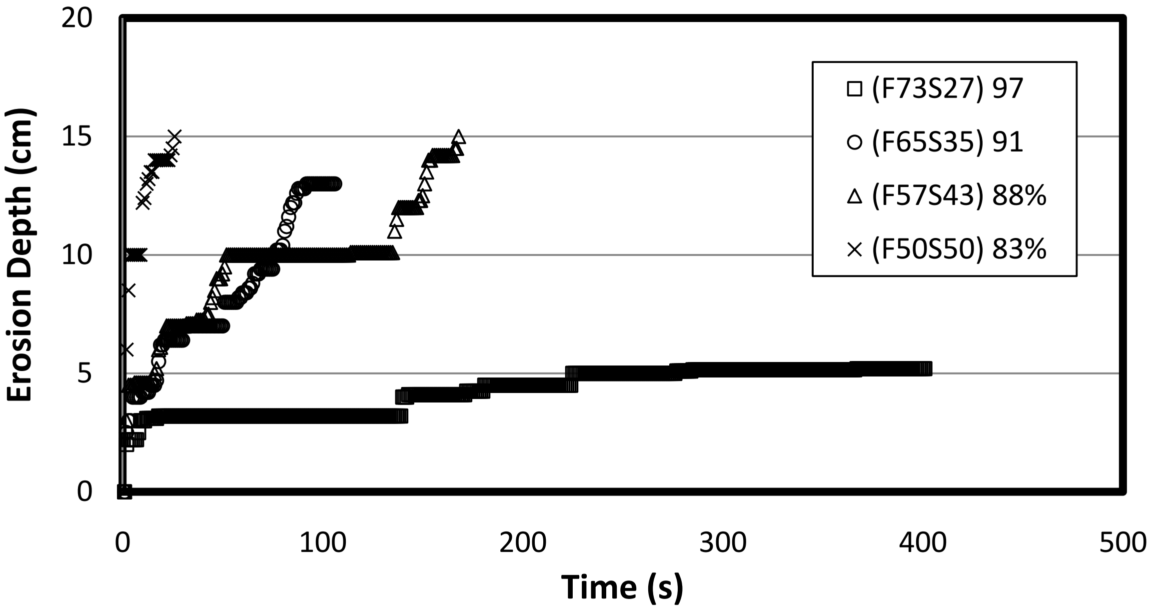

Figure 6: Erosion Depth vs Time relationship for bare soils

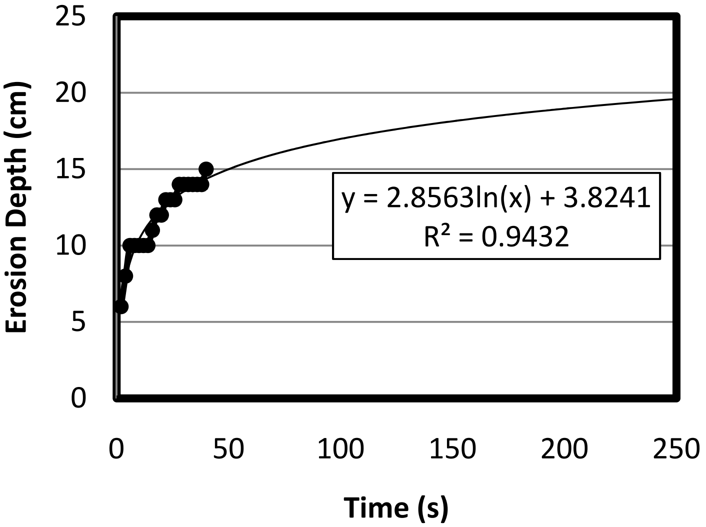

Figure 7: Equilibrium Depth Equation

POSS Treated Samples: There were three tests conducted for POSS samples because there were two different types of POSS chemicals (SO1455 and SO1458), and the results along with bare soil can be found in Figure 8. These treated specimens showed a substantially higher resistance to erosion than the bare soil. The same clay content and degree of compaction was used for the POSS samples (F50S50 and DOC 83%) and bare soil samples. However, SO1458 was found to be the most effective at preventing erosion. To compare the erosion resistance of samples in a more quantitative manner, the erosion rate coefficient was computed and compared in Figure 9. Figure 9 shows that POSS treated samples show more than 20 times erosion resistance than bare soils at shallower depths.

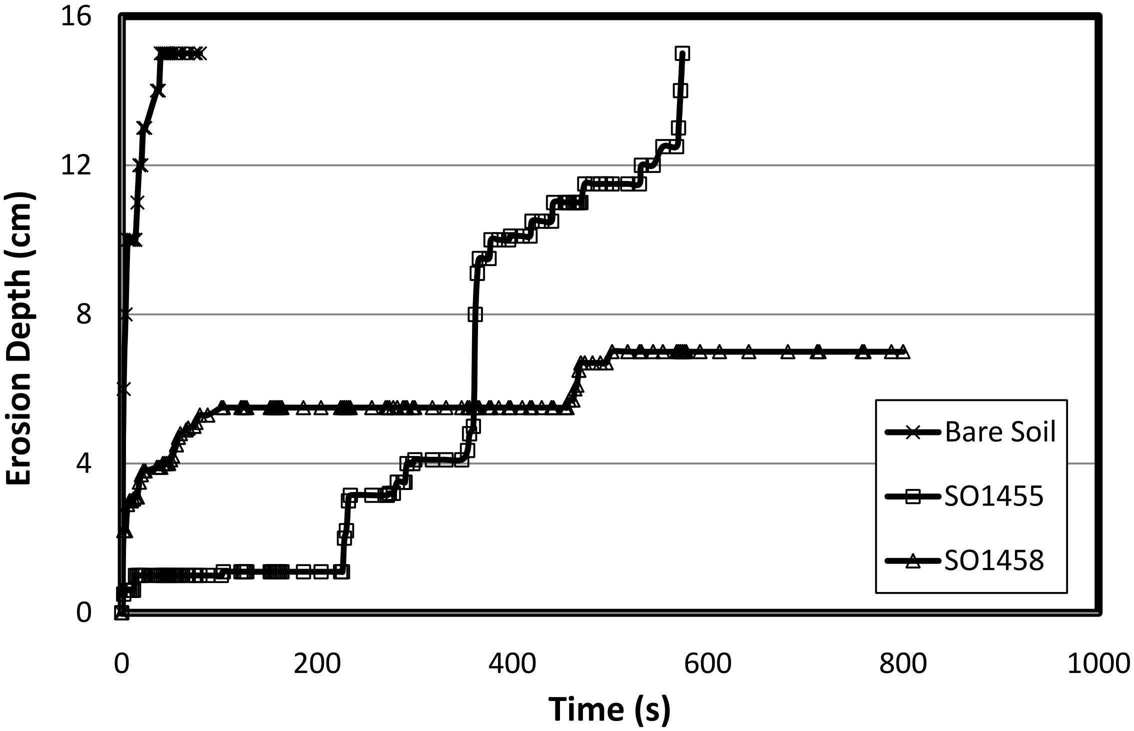

Figure 8: Graphical Comparisons of POSS

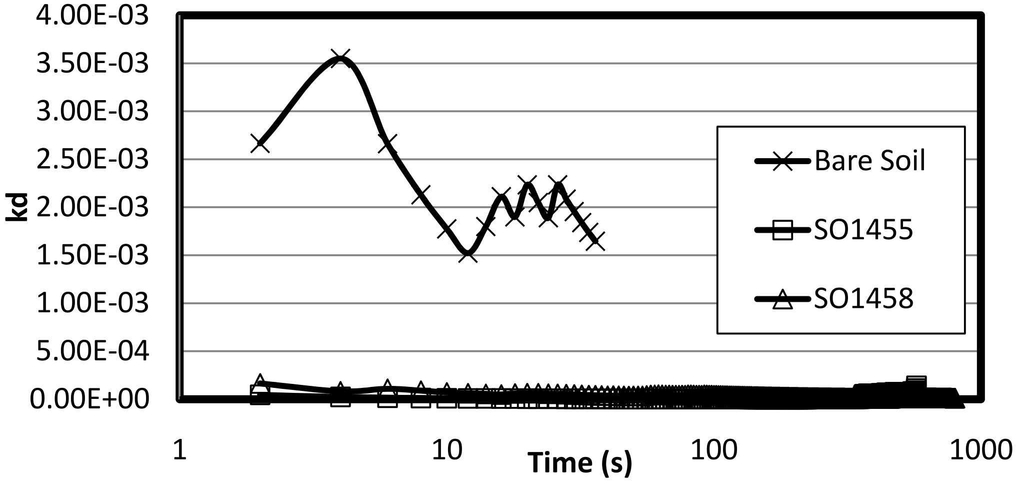

Figure 9: Comparison of k_d values for all POSS samples

It was also observed that after submersion, the POSS samples appeared to be less saturated compared to the bare soils. To confirm this finding, water content of the samples were measured. Figure 10 shows that POSS treated samples decreased the water content an average of 25%. POSS samples show substantially low water contents except at deeper depths, but about the same or higher water content at the bottom. This indicates that POSS might not penetrate to deeper depths and erosion resistance might not be improved.

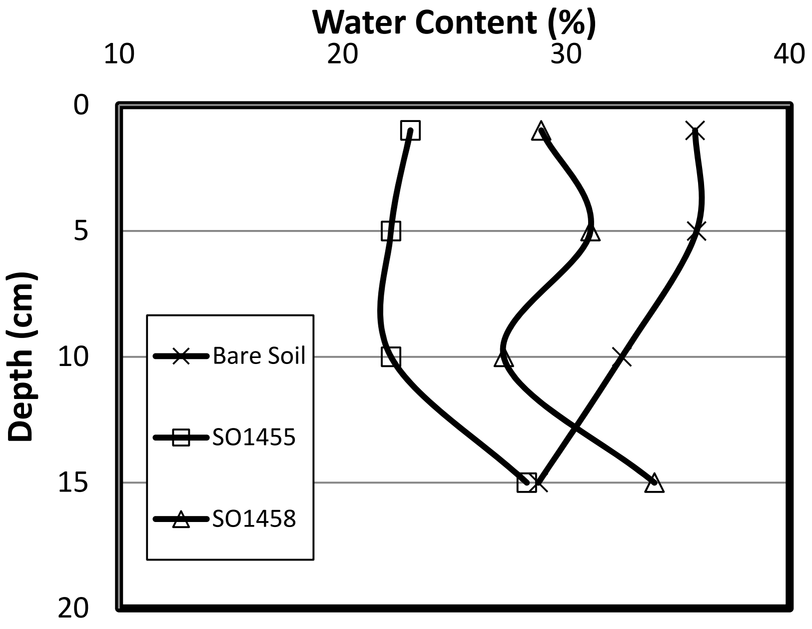

Figure 10: Water Content Comparisons for POSS

The shear strength of the POSS samples was measured by the miniature vane shear test apparatus. The results seen in Figure 11 show the shear strength of POSS samples. Without POSS, the shear strength at the surface to 2 cm depth is very close to zero; however POSS increases the shear strength at the surface substantially, which is also the point of impact for plunging water. After that, the shear strength was reduced to approximately the same level as that of the bare soil at deeper depths. This may explain why POSS treated samples shows (particularly SO1455) quite high erosion rate coefficient at prolonged time. From Figure 11, it seems that the reduction in initial erosion rate is mainly due to the increased strength of samples while the reduction after initial erosion rate is mainly due to the decreased water content of samples.

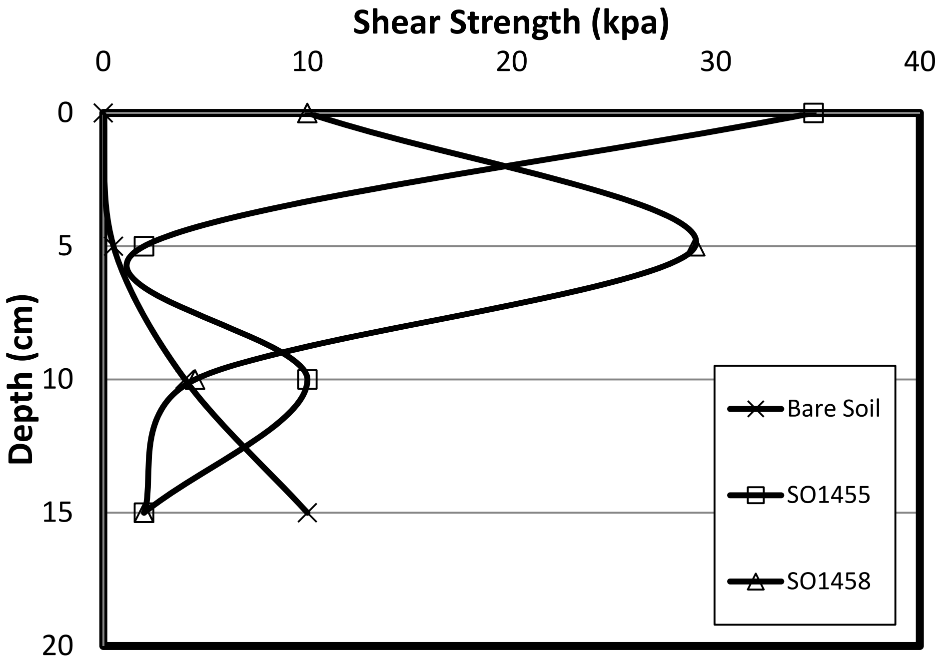

Figure 11: Shear Strength of POSS samples

Vetiver Plant: The Vetiver proved to be very effective in reducing the erosion of soil. So effective that currently no graphs, tables, or data can be obtained for the Vetiver because no erosion occurred. Two separate tests were conducted. The first test was conducted with four inches of the stems and the root system, and no erosion was recorded, the test results can be seen in Figure 12. The second test being the root system of the grass (stems were completely removed). There was also no visible erosion, test results can be seen in Figure 13. From the figures, it can be seen that no measurable erosion occurred to the Vetiver samples, for both the root system and also the stems. The plunging water seemed to never have reached further than the root system of the Vetiver. The structure of the plant (root system and grass stems) also held up well after being exposed to plunging water. Since the water never reached past the Vetiver stems to the actual soil, no data collection could be made. Therefore, the Vetiver proved effective to enhance erosion resistance.

Figure 12: Vetiver stems after erosion testing

Figure 13: Vetiver roots after erosion testing

Conclusion

Erosion caused by plunging water caused extensive damage, in the New Orleans area during Hurricane Katrina. This research focused on reducing erosion through ground modification: erosion mitigation performance of POSS and Vetiver were assessed. Applying the previously developed excess shear stress concept and laboratory tests; all soil samples were evaluated by how effective each sample was at reducing erosion. From the results the following conclusions could be made:

1. POSS reduced erosion depth; as much as 20 times. Shear strength was increased and water content was decreased due to POSS filling the voids in the soil samples.
2. POSS seemed to be effective only to a depth of about 9-12 cm; after erosion reached this depth, samples exhibited the similar erosion characteristics to bare soils. It is thought that this condition is due to POSS only penetrating the soil samples to this depth. However, it is noted that POSS can easily by applied to field soils by simply spraying the liquid.
3. The Vetiver proved to be the quite effective. Erosion was prevented as there was no erosion recorded. Due to the dense vegetation and root system, water was unable to penetrate into soil samples.
4. The Vetiver would be cost effective and relatively easy to apply to soil along earthen levee systems. However it is noted that it may take substantial time to establish and grow Vetiver.

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