The Use of Deep Soil Mixing as Channel Slope Stabilization Method – US Army Corps of Engineers Bechara Middle Section Project Case Study.

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Abstract

This project describes and validates the design of a slope stabilization technique for the Bechara Middle Section (BMS) channel which is located in the Bechara Industrial Area, San Juan, Puerto Rico. The BMS project consisted of approximately 720 foot earth open-channel and is a subcomponent of the Rio Puerto Nuevo Flood Control Project constructed by the US Army Corps of Engineers. Pre-construction soil conditions of the site consisted of soft clays and organic material that precluded the excavation of the proposed channel geometry. The soil slope stabilization design option for the BMS was 2 continuous soil treated zones A and B, by means of improving the existing soft soil conditions with the technology of Deep Soil Mixing. The slope stability of the channel was analyzed by modeling the improved soil in GeoStudio-Slope/W and was found to be in compliance with the required design factors of safety.

Introduction

The Bechara Middle Section project is located in the Bechara Industrial Park, near the Puerto Nuevo Complex Port, in San Juan Puerto Rico. The project was constructed between 2012 and 2016 as part of the Rio Puerto Nuevo Flood Control Project by the US Army Corps of Engineers (USACE) to reduce the chances of flooding in the Bechara Sector. The work of this project includes the construction of an approximately 720 foot earth open-channel between the end of an existing concrete box culvert and Kennedy Avenue, using the Deep Soil Mixing (DSM) technology as soil stabilization method to improve subsurface conditions.

Background

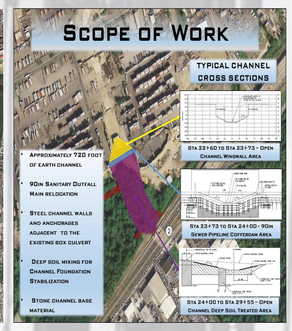
The Bechara Middle Section (BMS) Channel project is a subcomponent of Río Puerto Nuevo (RPN) Flood Control Project of the USACE. The purpose of the authorized RPN Flood Control Project is to protect lives and property from damages attributable to a 1% exceedance probability flood along the River and its tributaries. This level of protection is commonly called "100-year" flood protection [1]. Prior to 1950's the Río Puerto Nuevo originally flowed into San Juan Bay thru the BMS project vicinity and the river's mouth was located at the Puerto Rico Port Authority (PRPA) docks. In the 1950's the river's mouth and lowermost ¾ mile of channel were re-routed to the east, to empty into Martín Peña Channel. In the early 1960's, after the river had been diverted, the PRPA began to build the Puerto Nuevo Port Complex, and USACE dredged the new Puerto Nuevo Navigation Channel in San Juan Harbor to serve these docks [1].

The new port was built over fill deposited into the area north of Kennedy Avenue (formerly all mangrove swamp). This fill effectively "plugged" the lower end of the natural Puerto Nuevo River drainage and did not provide an alternate outlet for drainage north of Margarita Creek.

Problem

The construction of the BMS provides the drainage infrastructure required in the developed Bechara Industrial Park area by connecting the existing industrial channel south of the work area with the existing concrete box culvert located north. These were both built in previous phases of the project. The lack of this connection often caused high water stages and flood on the industrial/commercial area upstream. Based on the poor soil conditions in the site the proposed geometry of the channel couldn't be achieved to the required depth of El -9.0 feet, even during its construction phase. The study validates the design of using Deep Soil Mix as slope stabilization technique.

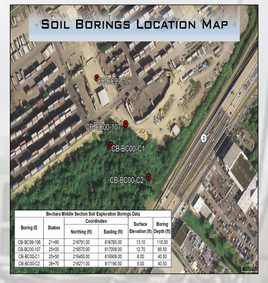
Project Location & Scope



Methodology

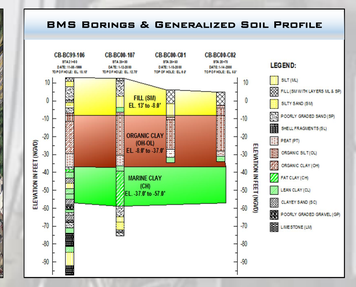
Soil Exploration & Subsurface Conditions

Four (4) disturbed borings were selected from a total of thirteen (13) existing soil borings available along the entire Bechara Industrial Park Channel to obtain design soil parameters for the analysis.



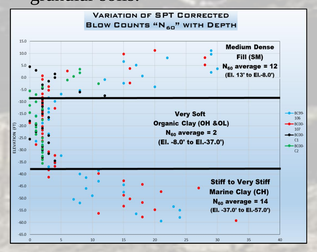
Bechara Middle Section Soil Exploration Boring Data

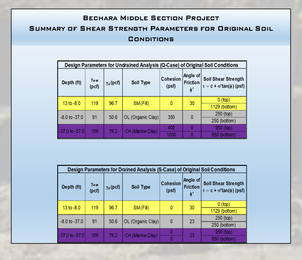
Boring ID	Station	Coordinates Northing (ft)	Easting (ft)	Surface Elevation (ft)	Boring Depth (ft)
CB-BC99-106	21+80	218791.00	816765.00	13.10	110.00
CB-BC06-107	24+00	218370.00	817008.00	12.70	85.50
CB-BC06-C1	25+50	218400.00	816900.00	6.00	40.50
CB-BC06-C2	28+70	218271.00	817140.00	9.00	45.50



Soil Parameter Selection

Design soil parameters for the stability analysis were selected using the data collected from the four (4) soil borings. For the shear strength, the SPT blow count number (N) was used in conjunction with correlation to estimate the cohesion of clayey material and the angle of friction of granular soils.





Design Parameters for Undrained Analysis (U-Case) of Original Soil Conditions

Depth (ft)	γ_{wet} (pcf)	γ_d(pcf)	Soil Type	Cohesion (psf)	Angle of Friction, ϕ	Soil Shear Strength $\tau = c + \sigma * \tan(\phi)$ (psf)
13 to -8.0	119	96.7	SM-FB	0	30	0 (top) 1129 (bottom)
-8.0 to -37.0	91	50.6	OL (Organic Clay)	200	0	250 (top) 250 (bottom)
-37.0 to -57.0	109	76.2	CH (Marine Clay)	400 - 500	0	400 (top) 500 (bottom)

Design Parameters for Drained Analysis (S-Case) of Original Soil Conditions

Depth (ft)	γ_{wet} (pcf)	γ_d(pcf)	Soil Type	Cohesion (psf)	Angle of Friction, ϕ	Soil Shear Strength $\tau = c + \sigma * \tan(\phi)$ (psf)
13 to -8.0	119	96.7	SM-FB	0	30	0 (top) 1129 (bottom)
-8.0 to -37.0	91	50.6	OL (Organic Clay)	0	23	250 (top) 250 (bottom)
-37.0 to -57.0	109	76.2	CH (Marine Clay)	0 - 0	23	900 (top) 900 (bottom)

Geotechnical Design Criteria

The geotechnical design criteria used for this study is shown is Table 3. The factor of safety (FoS) requirements shown in the table were the minimum slope stability requirements of reference [7] using circular slip surfaces. Reference [8] was used for the criteria of stability analysis during earthquake events. Analyses were performed in GeoStudio-Slope/W 2018-R2 Student Version software using circular slip failure methods of Ordinary Method of Slices (OMS), Spencer, Morgenstern-Price, Bishop and Janbu. Failure mechanisms are based on force-moment equilibrium considering normal and shear forces between slices.

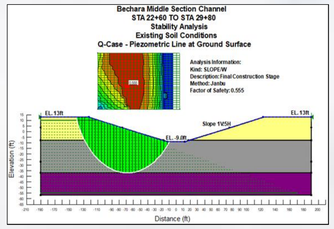
Slope Stability Analysis Results

Existing Conditions Analysis

Based on the available survey and soil data of the site, the analyses on current conditions showed that if the BMS channel was constructed in such soil conditions, the slopes were going to be unstable

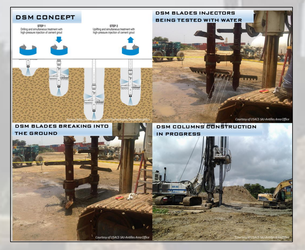
SUMMARY OF FACTOR OF SAFETY FOR SOIL ORIGINAL CONDITIONS

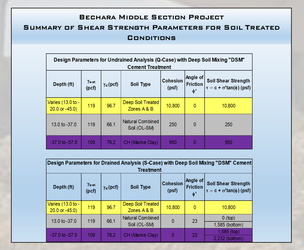
Slope Stability Analysis Cases	Minimum Factor of Safety Required	OMS	Spencer	Morgen-stern-Price	Bishop	Janbu
Final Construction Stage with Excavation Open at El -9.0' (U-Case) West Bank	1.5	0.624	0.625	0.631	0.636	0.555
Final Construction Stage with Excavation Open at El -9.0' (S-Case) West Bank	1.3	0.821	0.924	0.925	0.869	0.786
Operational Stage with Channel Water at El 1.0' (U-Case) West Bank	1.5	0.764	0.777	0.784	0.769	0.692
Operational Stage-Drawdown with Channel Water at El -2.0' (S-Case) West Bank	1.3	1.016	1.090	1.090	1.103	0.984



Design Solution - Deep Soil Mixing

Given the poor soil conditions of the site, the option of deep soil mixing (DSM) method was proposed as slope stabilization. The DSM procedure employs stabilizer admixtures such as cement, slag and other pozzolanic materials to improve soil conditions and provide ground stabilization. These stabilizers agents are blended with the natural soil by mixing equipment that delivers the agents in dry powder form (dry method) or slurry form (wet method). The equipment usually consist of multiple-axis or track vehicle with vertical rotating shafts that have overlapping mixing paddles to create walls of overlapping soil mix columns. The DSM design for channel stabilization consisted of continuous soil treatment areas divided in two (2) Zones, A and B, between STA 24+00 to STA 29+55. Table 5 presents the DSM parameters used in soil treatment operations, where 10,800 psf was the minimum compressive strength required for DSM design after soil was treated [2].





Design Parameters for Undrained Analysis (Q-Case) with Deep Soil Mixing "DSM" Cement Treatment

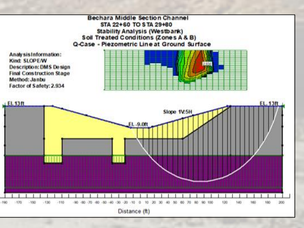
Depth (ft)	γ_{wet} (pcf)	γ_d(pcf)	Soil Type	Cohesion (psf)	Angle of Friction, ϕ	Soil Shear Strength $\tau = c + \sigma * \tan(\phi)$ (psf)
Varies (13.0 to -20.0 or -45.0)	119	96.7	Deep Soil Treated Zones A & B	10,800	0	10,800
13.0 to -37.0	119	66.1	Natural Combined Soil (OL-SM)	250	0	250
-37.0 to -57.0	109	76.2	CH (Marine Clay)	900	0	900

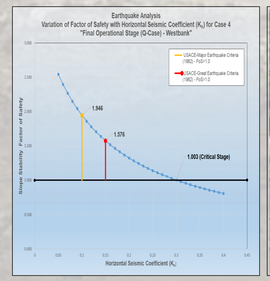
Design Parameters for Drained Analysis (S-Case) with Deep Soil Mixing "DSM" Cement Treatment

Depth (ft)	γ_{wet} (pcf)	γ_d(pcf)	Soil Type	Cohesion (psf)	Angle of Friction, ϕ	Soil Shear Strength $\tau = c + \sigma * \tan(\phi)$ (psf)
Varies (13.0 to -20.0 or -45.0)	119	96.7	Deep Soil Treated Zones A & B	10,800	0	10,800
13.0 to -37.0	119	66.1	Natural Combined Soil (OL-SM)	0	23	0 (top) 1,585 (bottom)
-37.0 to -57.0	109	76.2	CH (Marine Clay)	0	23	1,585 (top) 2,220 (bottom)

SUMMARY OF FACTOR OF SAFETY FOR SOIL TREATED CONDITIONS

Slope Stability Analysis Cases	Minimum Factor of Safety Required	OMS	Spencer	Morgen-stern-Price	Bishop	Janbu
Final Construction Stage with Excavation Open at El -9.0' (U-Case) West Bank	1.5	2.954	2.986	2.986	2.986	2.934
Final Construction Stage with Excavation Open at El -9.0' (S-Case) West Bank	1.3	3.233	3.699	3.707	3.707	3.524
Operational Stage with Channel Water at El 1.0' (Q-Case) West Bank	1.5	3.674	3.704	3.704	3.704	3.627
Operational Stage-Drawdown with Channel Water at El -2.0' (S-Case) West Bank	1.3	4.028	4.753	4.760	4.761	4.509
Final Construction Stage with Excavation Open at El -9.0' (U-Case) East Bank	1.5	2.960	3.028	3.028	3.028	2.999
Final Construction Stage with Excavation Open at El -9.0' (S-Case) East Bank	1.3	3.244	3.753	3.762	3.760	3.564
Operational Stage with Channel Water at El 1.0' (Q-Case) East Bank	1.5	3.681	3.778	3.778	3.741	3.693
Operational Stage-Drawdown with Channel Water at El -2.0' (S-Case) East Bank	1.3	4.034	4.806	4.813	4.813	4.552





Conclusions

- The original subsurface conditions of the BMS channel did not have the required soil shear strength capacity to meet safe USACE slope stability requirements for the flood control project. The results of the slope stability analyses using original soil conditions proved that the proposed geometry of the channel couldn't be achieved to the required depth of El -9.0 feet, even during its construction phase.
- The design parameter presented used for the deep soil mixing technique were validated thru the actual slope stability analysis of the channel. These soil treated conditions were modeled using shear strength parameters that were 40% lower than the actual values obtained from field test program and results were above the minimum factor of safety criteria.
- For the seismic conditions, the pseudo-static analysis results suggests that the DSM option can meet the required criteria during major earthquake and great earthquake events.

Future Work

The following are recommendations for future work of the Deep Soil Mix as Stabilization technique on this project:

- Conduct settlement evaluation of the deep soil treated mass to determine its behavior and long term effects on the flood control channel operation and maintenance.
- The use of other slope stability software such as UTEXAS and USACE-Stability with Uplift to analyze block mode failures and compare them with results of circular mode failures.
- The use of other slope stability software such as PLAXIS 3D to perform seismic analysis.
- Conduct a study of using Deep Soil Mix columns as temporary retaining structure technique and determine its feasibility.

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