GEOPHYSICAL, GEOLOGICAL, GEOTECHNICAL, AND MECHANICAL TESTING OF ROCK

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ABSTRACT

The US Army Corps of Engineers and the Port Authority of New York and New Jersey are deepening 42 kilometers (26 miles) of navigation channels of New York harbor to -15m (-50ft) MLW. The project requires dredging 50 million cubic yards of rock and sediment. At the halfway point, the project was on schedule and on the US$1.6 billion budget.

A major challenge in the project is unrippable rock. The cost of blasting and removing unrippable rock is many times the cost of removing sands and silts. We have mapped the geology and the physical properties of the rocks and sediments throughout the project. All data, maps, and cross-sections are compiled into a single reference frame. All measurements are integrated in the interpretation. The plans and specifications, maps and cross-sections constitute the primary information for managing the construction and engineering of the harbor-deepening project.

We have developed geophysical techniques and operate them daily to determine the top-of-rock and to map and quantify the properties of the rock and rock strata. Our techniques include calibration with core borings. Orthosonography yields aerial-photograph-like maps of the areal extent. Sub-bottom seismic images, which are depth migrated, profile the approximate depth to rock and rock strata. All images are georeferenced. We have obtained several hundred standard penetration test (SPT) core borings.

We interpret the seismic sections through selection of horizons and estimation of physical properties. The seismic properties are correlated with mechanical properties to estimate the response of the rock strata to ripping. The results are calibrated with the results from core borings. We present the results as geological and geotechnical cross-sections with core borings.

Keywords: Dredging, material separation, orthosonograph, seismic analysis.

INTRODUCTION

The US Army Corps of Engineers and the Port Authority of New York and New Jersey are deepening 42 kilometers (26 miles) of navigation channels of New York harbor from -12 m (-40ft) to 15m (-50ft) MLW.

The challenge is removing unrippable rock. Unrippable rock may cost 7-10 times the cost of removing diggable materials when blasting is required. In Murphy, et. al. (2011b) we discuss the general concepts and applications of plans and specifications in the giant New York deepening project.

The fundamental concept is to relate geophysical and geotechnical measurements of intrinsic properties such as elastic moduli and electrical resistivity to effective mechanical properties such as rippability, and diggability. Rippability and diggability are effective engineering properties. Both properties depend on rock's intrinsic properties (e.g., density, modulus, and strength) and fabric (e.g., strike, dip, joints and fractures, foliation, and Rock Quality Designation (RQD). Rippability is the response of rock to steel tines (teeth, claws) penetrating and ripping (pulling) through rock. Rippability is highly dependent on the size of the excavator, bucket, and ripping claw in use and the penetration and ripping process. Productivity is the rate (volume per time) of a process; there is ripping productivity and excavation productivity. Diggability is the quality describing the ease with which rock can be excavated. Diggability depends on rippability and the productivity of ripping and excavation. Diggable rock is both rippable and capable of good productivity. We discuss the uncertainties associated with these relationships. Of particular interest is how the uncertainties may be approached from different positions in the project.

The rippability in Arthur Kill is strongly affected by the layering, strike and dip of the shale. Reflection seismology maps the top of rock. The sediments are readily distinguished by compressional-wave velocity less than 2km/s (6,560ft/s). The rock strikes N36°E and dips to the northwest at 15°. The top-of-rock map shows that the shale is

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exposed on most of the channel bottom. The strata correlate extremely well along strike. We have produced a stratigraphic column for the Passaic Shale that relates erosion resistance to seismic velocity.

ROCK MAPPING

The areal extent of and depth to unrippable rock must be characterized to determine the volume of rock that will require blasting before removal by dredging.

To produce maps of the distribution and depth to rock, we use sidescan orthosonography, multibeam bathymetry, subbottom seismic profiling, calibration cores, and test digs. We calibrate the geophysical measurements using borings and laboratory measurements of ultrasonic velocities and rock strength.

We mapped the geology and the physical properties of the rocks and sediments throughout the Arthur Kill navigation channel, New Jersey and New York. All data, maps, and cross-sections are compiled into a single reference frame. All measurements are integrated in the interpretation. The maps and cross-sections are the primary information for managing the harbor deepening project. We selected 10 areas for test dig based on seismic velocities and boring correlations. We estimated seismic velocity using diffractions in single-offset, high-resolution seismic data. We performed the test dig in these areas and correlated the field results with the estimated results from the seismic experiment.

We obtained over one hundred standard penetration test borings. The geotechnical properties in the boring provide the ground truth for the maps and cross sections. The core testing provided estimates of unconfined compressive strength, tensile strength, and compressional- and shear-wave velocities. The estimates of the composition, bedding, and fracture density establish the geometric configuration at the point of the boring.

The high-definition reflection seismology is an important measurement for two reasons. First, previous investigators and handbooks relate compressional wave velocity to rippability. In the literature, a compressional-wave velocity less than 3km/s is considered rippable (Caterpillar, 2006). The second reason is that seismic imaging resolves bedding thickness, fracture density, and porosity.

One may characterize unrippable hard rock as being intact and having low porosity, high ultrasonic and seismic velocity, high elastic modulus, high strength, high electrical resistivity, low fracture density, and high rock quality designation (RQD). We used a compressional-wave velocity of >2,300m/s (>7,540ft/s) to determine rock. We use a compressional-wave velocity of >3,000m/s (>9,840 ft/s) to determine harder, more intact, less fractured rock. We used a rock quality designation (RQD) cut-off value of 50% to separate poor quality, fractured rock (RQD<50%) from good quality, intact rock (RQD>50%).

Rippability and Productivity

Productivity measures the result of a dynamic process in terms of a flux in volume per unit time, say cubic yards per hour. Productivity in dredging may be equal to (a) the volume of material removed from the source per unit time (hours), or (b) the volume of material placed into the scow per unit time, or (c) the volume of material placed at the placement site per unit time.

Rippability is an effective engineering property of a material. It is not an intrinsic property; it is not observer invariant; it depends on the equipment being used. Rippability in dredging is a measure of material response of the seafloor to penetration by a specific excavator with a specific bucket and teeth. Ripping by an excavator is a form of treatment that breaks up the rock so that the rock could then be produced by conventional means. Conventional means might include production by the excavator itself. Ripping costs must be compared to other methods of loosening material on a cost per cubic yard basis. It is generally thought to be less expensive and safer than blasting.

Tooth penetration is often the key to ripping success. The penetration force is the maximum sustained downward force generated by the lift cylinders at the ripper tip required to lift the dredge stern to a prescribed elevation. The pry-out force is the maximum sustained upward force generated by lift cylinders at the ripper tip. The breakout force is measured with the teeth impacting the top of the rock strata.

A clamshell dredge cannot rip, but it can produce. An excavator can rip and produce. A cutter suction dredge can rip. Ripping is an art rather than a science and depends on operator skill and experience (Caterpillar, 2006). The number of teeth used, the length and penetration of the teeth, direction, and throttle must all be adjusted according to the conditions.

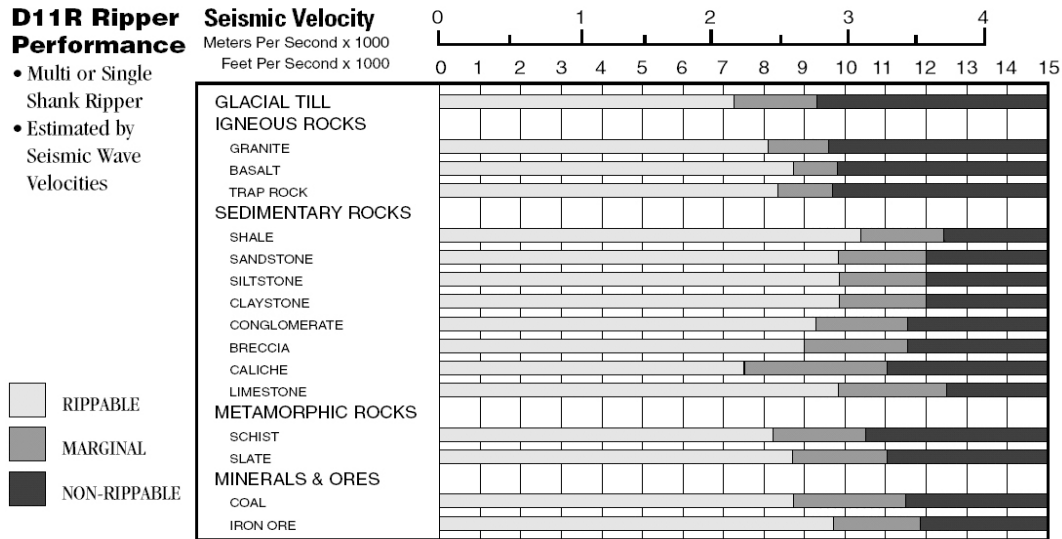Figure 1 graphs the D11R ripping performance of various rocks versus seismic velocity on land.

Figure 1. D-11R ripper performance on land in a variety of rocks and sediment (Caterpillar, 2006).

Figure 2 plots the data that Caterpillar measured for D-10 productivity versus seismic velocity. The productivity vanishes above 3,000m/s (9,840ft/s).

Rock Quality Description (RQD) acquired during SPT core descriptions provides a semi-quantitative measure of the jointing, fractures, and bed separations in cores. RQD relates well to fracture density and rippability. RQD is a simple and effective measurement.
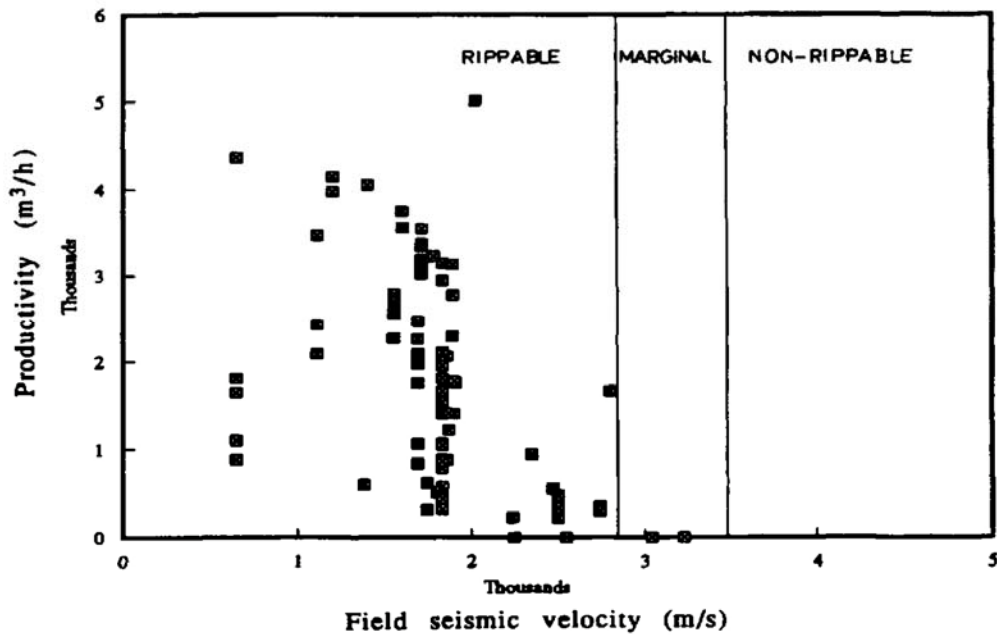

Figure 2. Productivity in m³/hour of a D-10 tractor in sandstones (MacGregor et al., 1994).

Rippability may be qualitative: rippable, marginal, and/or non-rippable. Or it may be semi-quantitative on a scale of rippability ratings from 0-100: 0 being highly rippable and 100 being unrippable. In either description, rippability is dimensionless. We propose an effective engineering rippability with dimensions equivalent to viscosity, Pa s.

Caterpillar Tractor Company has long related seismic velocity to production and rippability (Caterpillar, 2000, 2010). Caterpillar relates rippability and production in the following way. The productivity is measured by recording the time spent ripping, then remove and weigh the ripped material. The total weight divided by the time spent is equal to the hourly production. If measured by volume in scow, then the density is used, and the estimate is only as good as the density assumed. Our estimates are based on volume removed from the ground as measured by pre-dredge and post-dredge surveys.

Unrippable hard rock is characterized by being intact and having low porosity, high ultrasonic and seismic velocity, high elastic modulus, high strength, high electrical resistivity, low fracture density, and high rock quality designation (RQD). We used a compressional-wave velocity of >2,300m/s (>7,540ft/s) to determine rock and >3,000m/s (>9,840 ft/s) to determine harder, more intact, less fractured rock. We used a rock quality designation (RQD) cut-off value of 50% to separate poor quality, fractured rock (RQD<50%) from good quality, intact rock (RQD>50%).

ARTHUR-KILL EXAMPLE

S-AK-2/3 begins at the western end of S-AK-1 in Arthur Kill just north of Shooter's Island and continues west to the AK Railroad Bridge just north of the Goethels Bridge (Figure 1). The channel connects Howland Hook container terminal with the Kill Van Kull, New York Harbor, and the Atlantic Ocean. It also connects the Arthur Kill petroleum port with the Kill Van Kull, New York Harbor, and the Atlantic Ocean. S-AK-2/3 is 9,750ft long and 700ft wide. The channel has a 40° turn, northwest of Port Ivory and just east of Howland Hook. Most of the material to be removed by dredging to achieve the required grade of -52ftMLW will be Passaic Shale.

The rock that underlies the channel in S-AK-2/3 is the stratigraphically lowest strata, of the thick Triassic-to-Jurassic Passaic Shale in the Newark Basin (Earthworks, 2003, 2009). The Lower Passaic Shale is highly stratified with alternating layers of hard sandstone (UCS<8,000psi) and softer shale (UCS<5,000psi). The strike of the beds is N36°E, and the dip is 15° to the northwest. The strike and dip are uniform throughout S-AK-2/3. In the earlier 42ft project, the rock in S-AK-2/3 was dug without blasting. The rock from -11.2m (-37ft) to -13.1m (-43ft) MLW was compliant, weathered, and fractured. Ripping was a successful substitute for blasting. Seismic investigations indicate that some of the rock in the 12.8-15.8ft (42-52ft) prism will be stiffer than during the 42ft project. Figure 3 shows the general description of the geology in the area of investigation. The geological cross-sections shows the Passaic Shale underlies the Pleistocene sediments, most of which was removed in previous dredging projects.

Figure 4 shows an example from the one of the several down-dip seismic cross sections through S-AK-2/3. This shows an example of the sections that segment the stratigraphic package to estimate diggability. The dip is 15° to the northwest. The cross sections have been processed to quantify the seismic velocity of the rock and sediments from seismic diffractions. The color of the strata indicates the seismic velocity measured two feet below the top of rock. The stratigraphically higher layers in the west have a higher compressional wave velocity than the lower layers in the east.

Figure 5(A) is the top of rock map based on an integrated interpretation of borings and reflection seismology. Note the strike is N36°E. The stratigraphic thickness (the thickness perpendicular to the strata) is almost 1,830m (6,000ft) along the 2,970m (9,750ft) of the channel. There are several regions that have sediment troughs through to -16.6m (-54.5ft) MLW. Figure 5(B) and (C) plots maps for the top of fast rock horizon. The map in (B) shows the top of fast rock horizon based on the 3.0km/s (9,840ft/s) criteria. The map in (C) shows an alternative rock horizon based on the 2.9km/s (9,150ft/s) criteria.

Figure 6 shows the stratigraphic column of the Passaic Shale and two examples of rock cores in the channel. The stratigraphic column is interpreted and obtained from the seismic images, and mapped with the results of the diffraction velocity analysis, the color is the velocity at an elevation of -16.3m (-53.5ft). The expected behavior of the rock is greatly simplified by understanding the stratigraphic erodibility within the Passaic Shale.
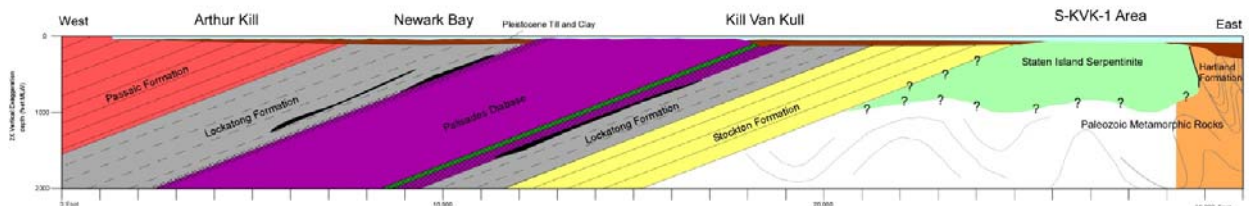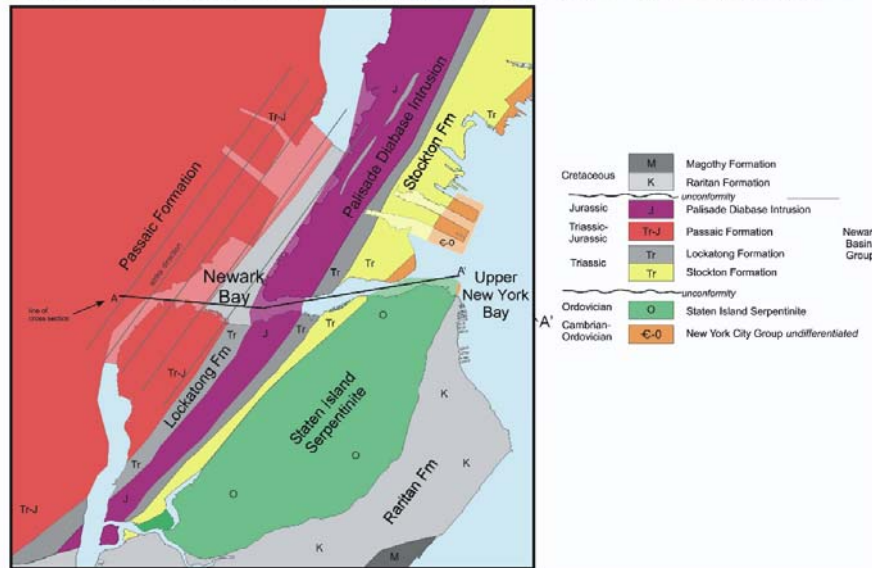
Figure 3. Geology of Arthur Kill. Top is the location map for the area of investigation. Middle is a general geological description of New York and New Jersey Harbors. Bottom is a cross-section along the general area.
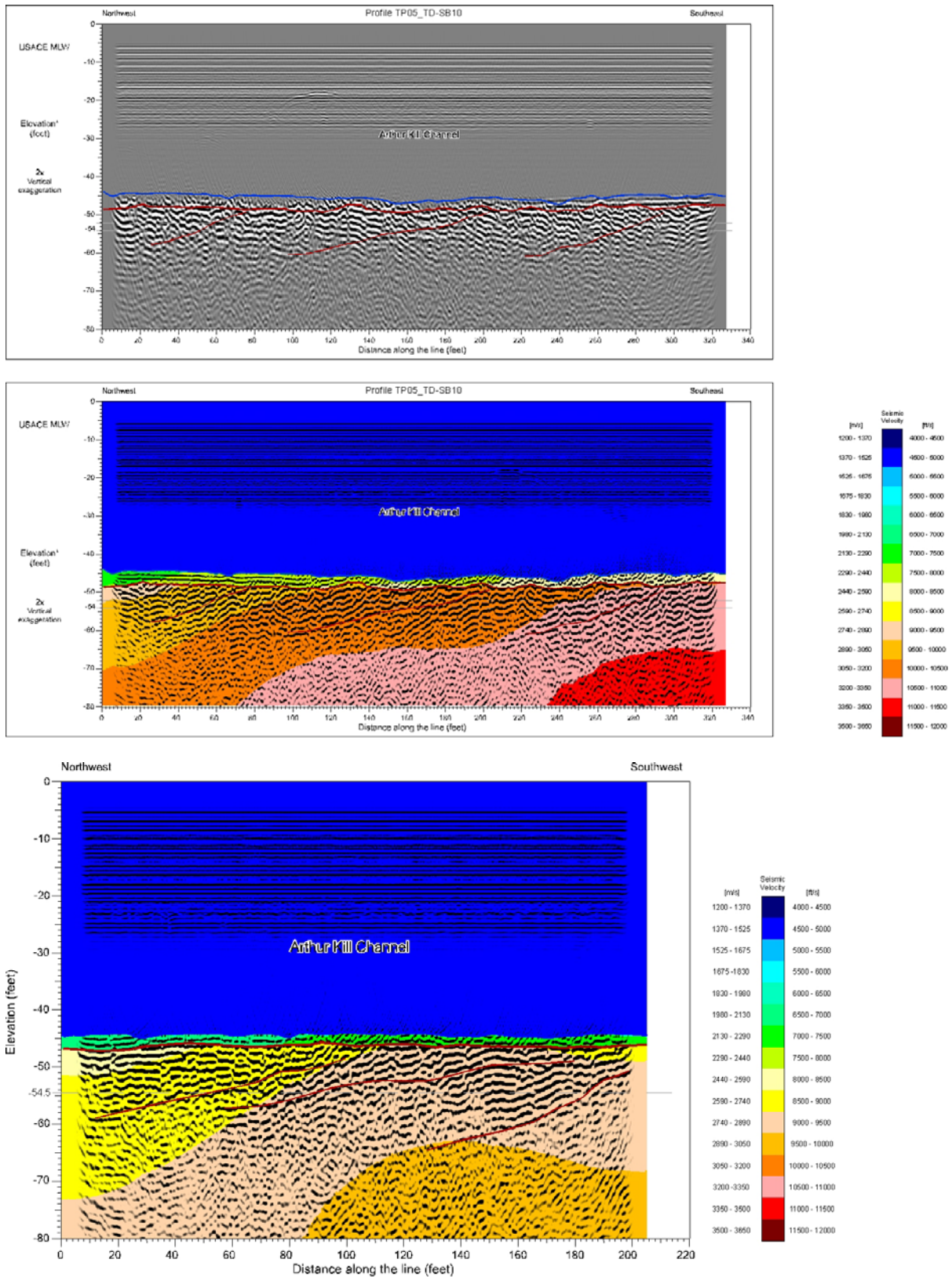
Figure 4. Seismic image and result of diffraction velocity analysis. Note that the global inversion result of diffraction analysis produces a velocity model consistent with the geology of the area.
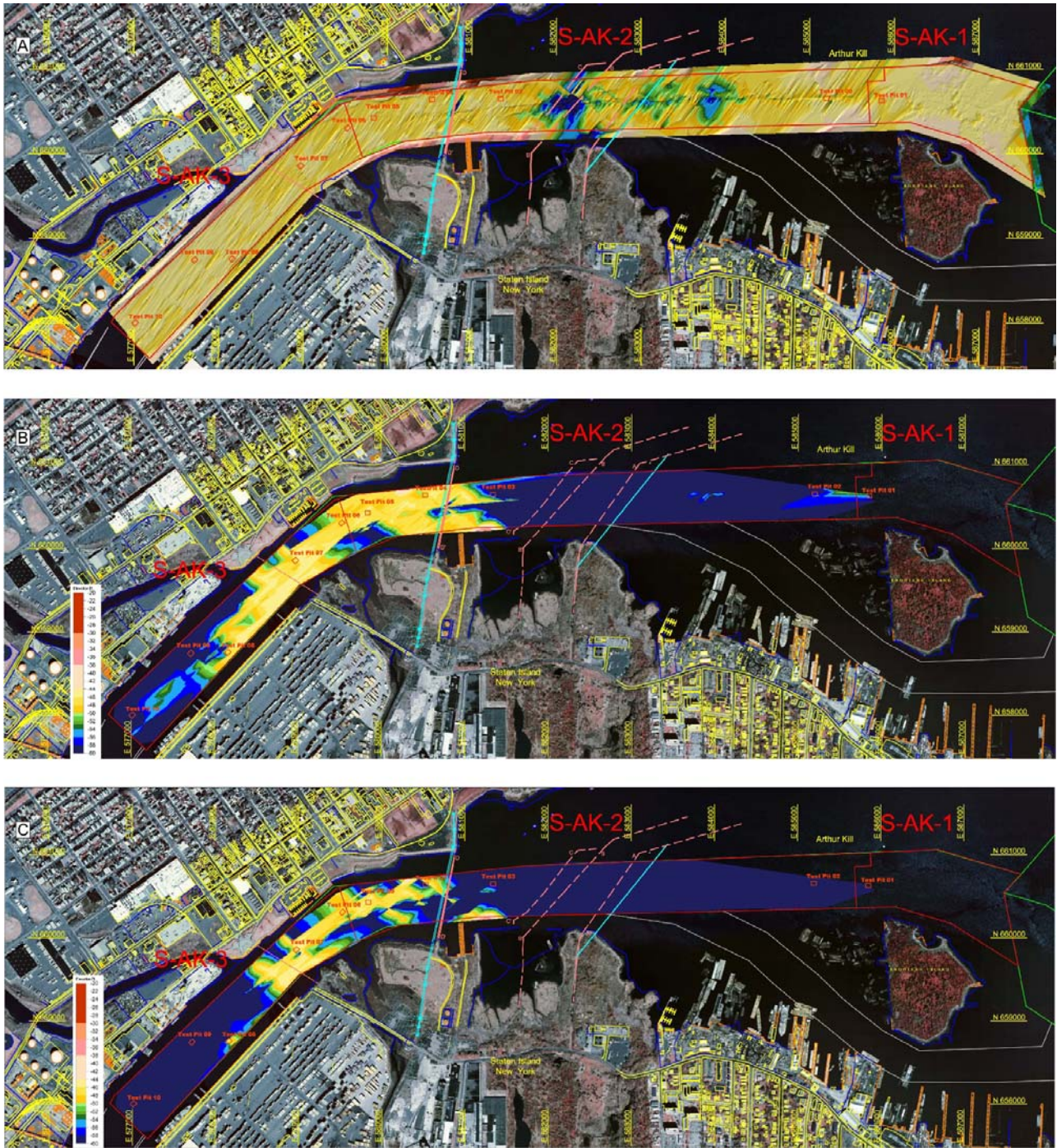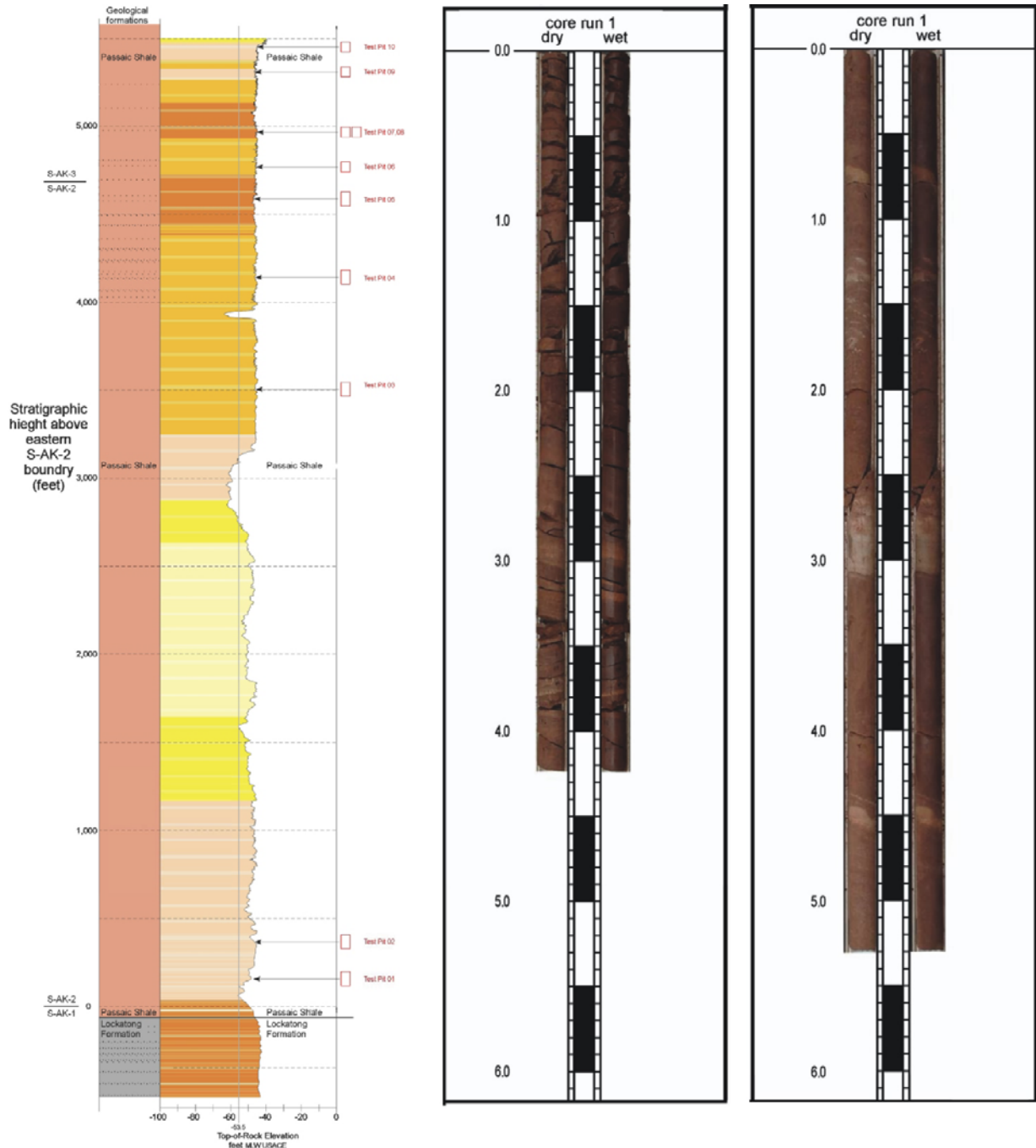
Figure 5. (A) Top of rock horizon map from seismic single-offset cross sections and boring. (B) Top of rock horizon based on 2.9 km/s (9,150ft/s). (C) Top of fast rock horizon based on 3.0 km/s (9,840ft/s).

Figure 6. Passaic Shale stratigraphic column and rock cores. The profile on the left is the top of rock elevation. This is related to the natural weathering profile. The rock in the Lockatong Formation and above 975m (3200ft) has been previously dredged. The rock core on the center has an RQD=9. The rock core on the right has an RQD=100.

Test Pits

We selected 10 areas for test digs based on seismic velocities and boring correlations. The test-pit program was to evaluate (1) diggability and (2) productivity using an excavator and (3) the effects of traffic on productivity.

Eight (8) of ten (10) test pits were dug in the 6 days (approx. 132 hours) allotted for the project. Four (4) of the eight (8) pits achieved refusal above -16.3m (-53.5ft); four (4) were dug to -16.3m (-53.5ft). After slow progress on the second day, e4 decided to dig trenches in as many pits as possible to maximize the useful information. Test pits 05, 06, 07, and 08 did not achieve refusal above -16.3m (-53.5ft) MLW. Test pits 01, 02, 03, and 04 achieved refusal at -15.7m (-51.6ft), -15.2m (50.0ft), -14.7m (-48.1ft), and -15.1m (-49.7ft) MLW, respectively. The total volume produced was 1,274m^3 (1,666.6yds^3). Test pit 05 produced the most rock, 321.3m^3 (420.2yd^3) in 24.6hrs of digging there. Test pit 03 produced the least rock, 31.8m^3 (41.7yd^3), in 9.25hrs of digging. Test pit 03 achieved refusal at -14.7m (-48.1ft) MLW. We show example results for Test pit 05.

We report productivity in two forms to evaluate how stoppage time (ship traffic & maintenance) affects productivity. Unloaded productivity removes the stoppage time. Loaded productivity includes stoppage time.

The unloaded productivity (removing traffic and maintenance hours) varied from 27.44m^3/h (35.9yd^3/hr) in test pit 07 to 3.44m^3/hr (4.5yd^3/hr) in test pit 03. Test pit 05 had unloaded productivity of 13.1m^3/hr (17.1yd^3/hr). The average unloaded productivity was 15.6m^3/h (20.4yd^3/hr). The loaded productivity (adding traffic and maintenance hours) varied from 14.6m^3/hr (19.1yd^3/hr) in test pit 06 to 1.99m^3/hr (2.6yd^3/hr) in test pit 03. Test pit 05 had loaded productivity of 9.4m^3/hr (12.3yd^3/hr). The average loaded productivity was 9.9m^3/hr (12.9yd^3/hr). The total number of buckets in the 85.25 hours of production was 1,744. Test pit 05 had 541 buckets in the 24.48 hours operation time, for an averaged time per bucket of 2.71 minutes. The production per trip was roughly 0.76 m^3/bucket (1yd^3/bucket).

Test-Pit 05: Example

Figure 7 shows the pre-dredge multibeam survey for test pit 05 measured prior the digging operations. Figure 8 shows the post-dredge multibeam survey for test pit 05 measured right after digging operations. Figure 9 plots the difference on elevation between the pre-dredge and post-dredge surveys for test pit 05. Figure 10 plots the angular displacement of the dredge during the test dig on the 24.48 hours operations. Refusal was not achieved.

Figure 11 shows a cross-section along the transverse for test pit 05. The digging operations sampled alternating layers of hard sandstone and softer shale. Figure 11 bottom shows a photograph of the excavated rock in test pit 05.
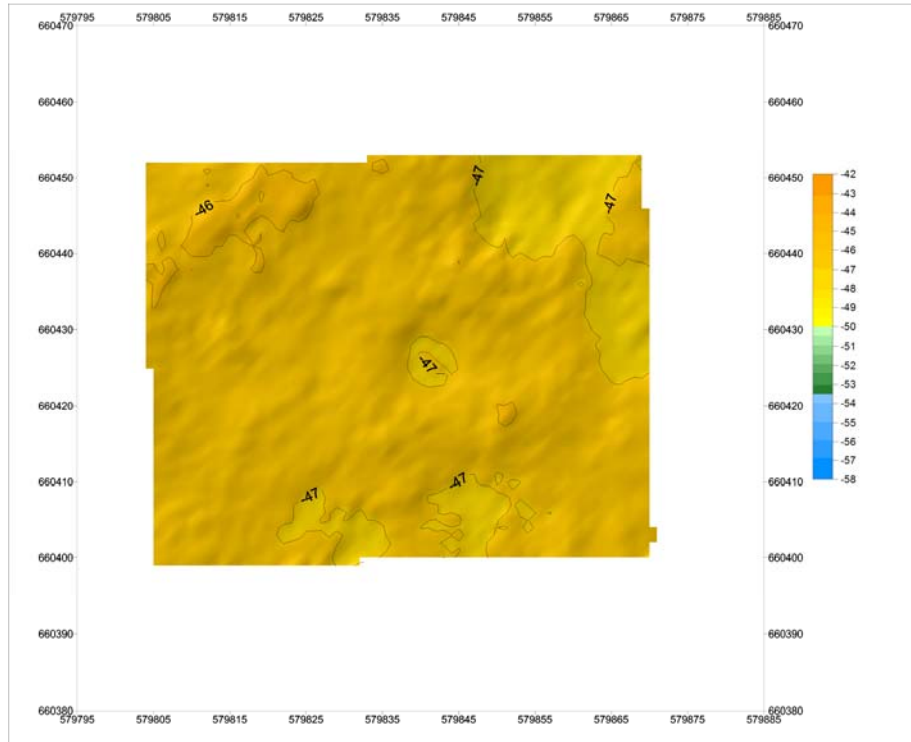
Figure 7. Test pit 05: pre-dredge bathymetry. The contour interval is 1ft.
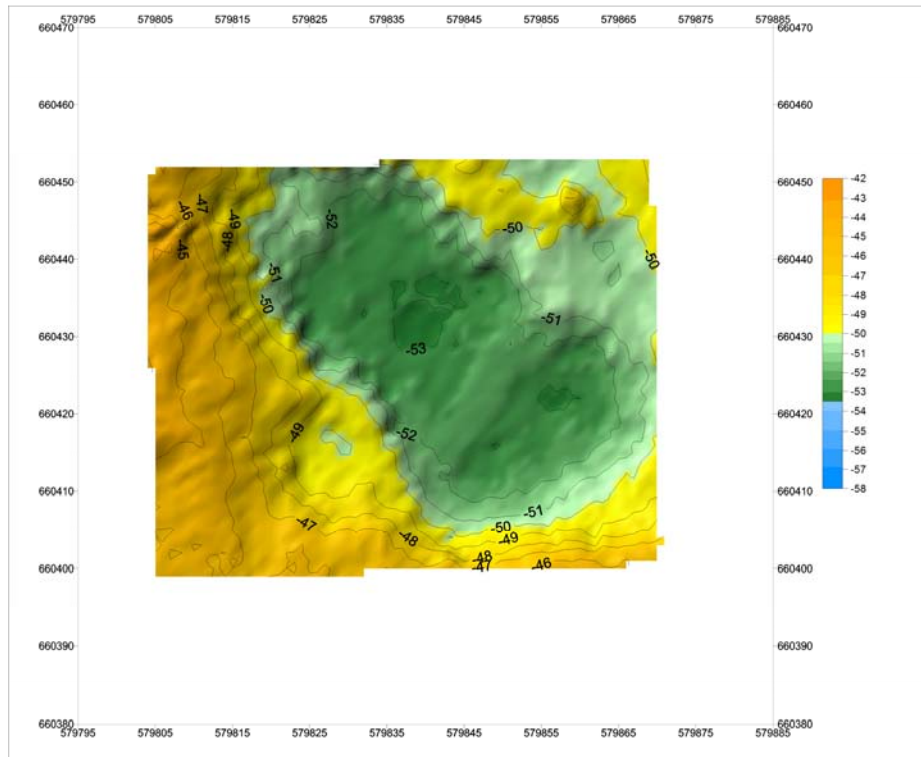

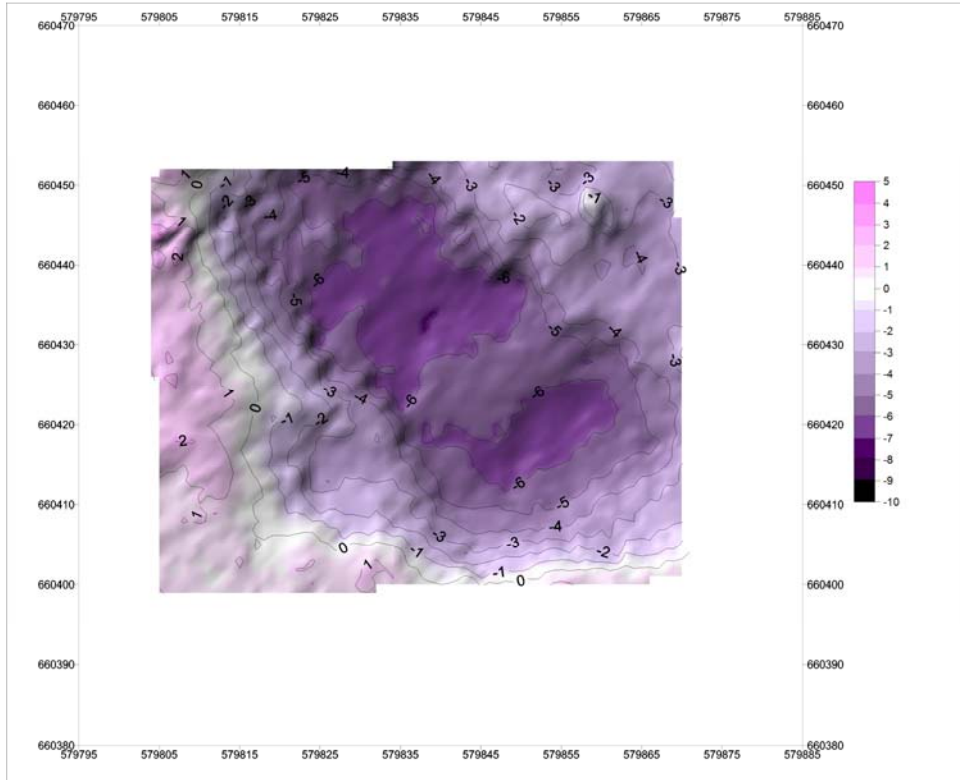**Figure 8. Test pit 05: post-dredge bathymetry. The contour interval is 1ft.**

Figure 9. Test pit 05: difference map. The contour interval is 1ft.
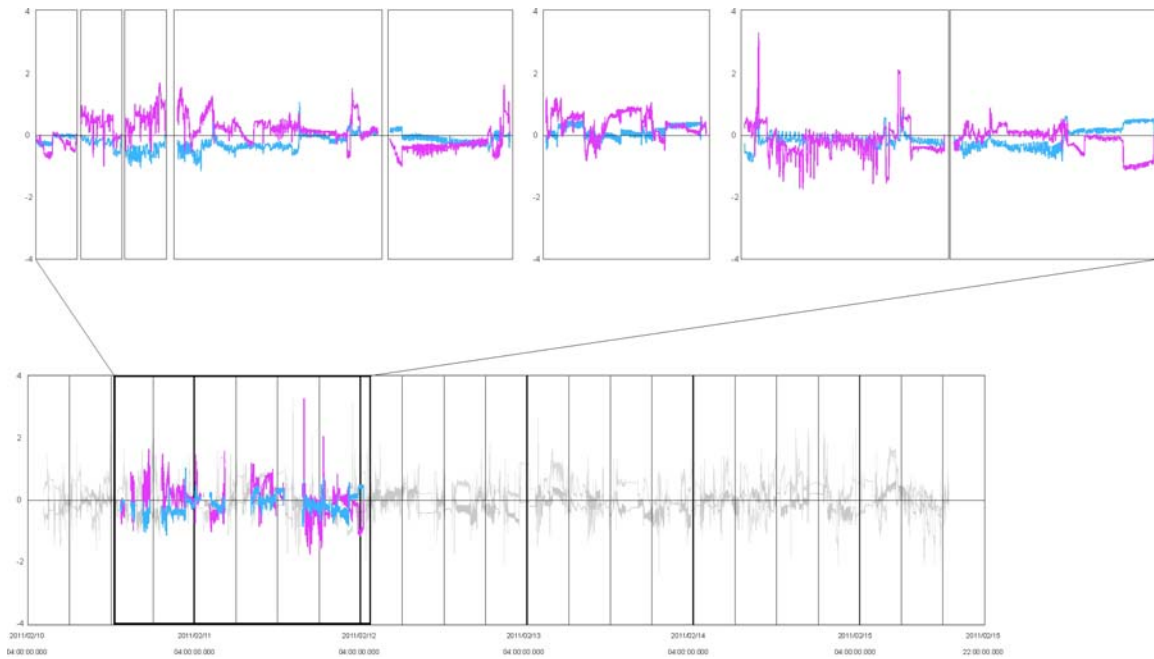

Figure 10. Test pit 05: monitoring. (Above) the time interval of dredge pitch and roll for the test pit 05. (Below) the interval within the entire duration of the test digs.
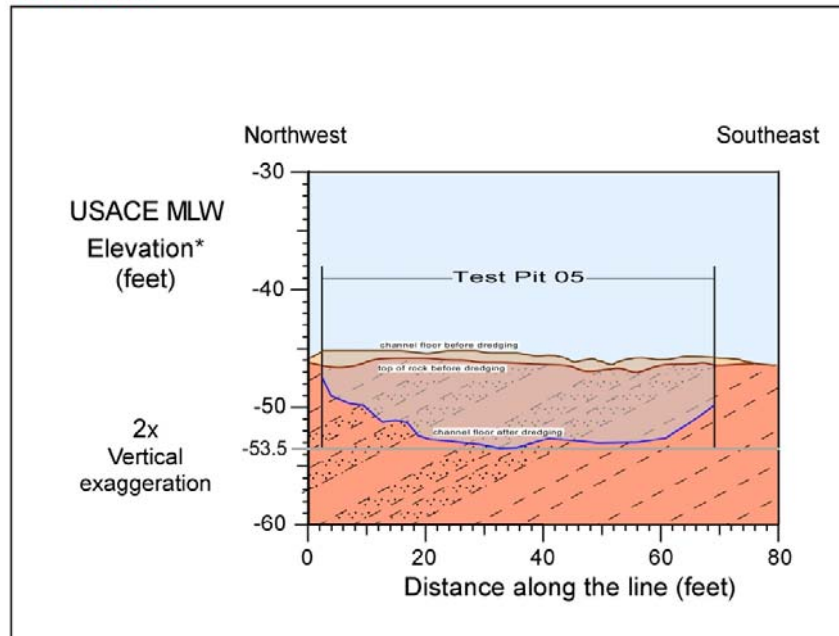
Figure 11. Test pit 05: (Above) cross section after dredging. (Below) material from test pit.

CONCLUSIONS

1. We mapped the rock surface along the Arthur Kill channel using a suite of geophysical and geological measurements and selected ten test-dig sites.

2. The objectives of the test digs were (1) estimate the rippability of the rock with the smallest excavator, (2) determine the productivity of the smallest excavator, and (3) evaluate the effect of traffic on productivity.

3. The rock in S-AK-2/3 is the lower strata of the Passaic Shale. The Lower Passaic Shale is highly stratified with alternating layers of hard sandstone (UCS<8,000psi – Vp: 2,743m/s (9,000ft/s)) and softer shale (UCS<5,000psi – Vp: 1,828m/s (6,000ft/s)), as measured in laboratory with samples taking from the test pits.

4. The strike of the beds is N36°E, and the dip is 15° to the northwest. The strike and dip are uniform throughout S-AK-2/3.

5. Productivity was measured as equal to the volume of material removed from the source per unit time (hours). The unloaded productivity (removing traffic and maintenance hours) varied from 27.4m^3/hr (35.9yd^3/hr) in test pit 07 to 34.0m^3/hr (44.5yd^3/hr) in test pit 04. The average unloaded productivity was 15.6m^3/hr (20.4yd^3/hr).

REFERENCES

Caterpillar (2000), Handbook of Ripping, 8th Edition, Caterpillar, Peoria, IL.
Caterpillar Performance Handbook (2006), Edition 36, Caterpillar, Peoria, IL.
Caterpillar Performance Handbook (2010), Edition 36, Caterpillar, Peoria, IL.
e4sciences | Earthworks, (2009), "*Geophysical investigation in S-NB-2 and S-AK-2/3, NYNJHDP. Arthur Kill S-AK-2/3 Navigation Channels*", USACE-NYD, W912DS-09-D-0001, Task Order #0002.
Earthworks, (2003), "*Surface geophysical exploration: Newark Bay and Arthur Kill Channels, Arthur Kill rock evaluation",* USACE-NYD, USACE-NYD DACW51-02-D-0005, IDC 180, Delivery Order 0003

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