4

UNDERWATER PIT EXCAVATION

Creating a place to put the intake structure at a depth of more than 330 ft [100 m] was considered one of the most challenging aspects of the marine work.

The top of the excavation was at an elevation of 825 ft [251 m] AMSL, 262 ft [80 m] below the water level. The bottom of the excavation was at an elevation of 756 ft [230 m], an 80 ft [24 m] deep pit. At bid time, a pit with a bottom dimension of 41 ft × 61 ft [12 m × 19 m] was envisioned.

However, after careful consideration, it was decided to enlarge the pit in order to have two precast tunnel rings and the entire shield of the TBM inside a homogeneous material, such as tremie concrete, instead of tunnel segments being positioned in the transition between fractured rock and concrete.

This required a significant increase in the dimensions of the bottom of the pit. The revised dimensions were 65 ft × 107 ft [20 m × 33 m].

In addition, it was discovered during excavation that the overburden was not as deep as expected. The final quantity of excavated material was approximately 48,000 yd^3 [43,545 m^3], of which approximately 14,400 yd^3 [13,063 m^3] was overburden and 33,600 yd^3 [30,481 m^3] was rock. The rock excavation was approximately three times the total quantity expected at the beginning of the project.

The material at the bottom of the lake is a mix of alluvial fan gravel, vesicular and non-vesicular basalt, and small amounts of clay.

Several options had been considered during preparation of the proposal, and the selected excavation method included the use of shaped charges and a large airlift system. These methods were extensively reevaluated during the execution and construction phase.

FIGURE 4.1 (PAGE 50) **Functioning like mini-canons, shaped charges are prepared for placement and detonation at the excavation site.**

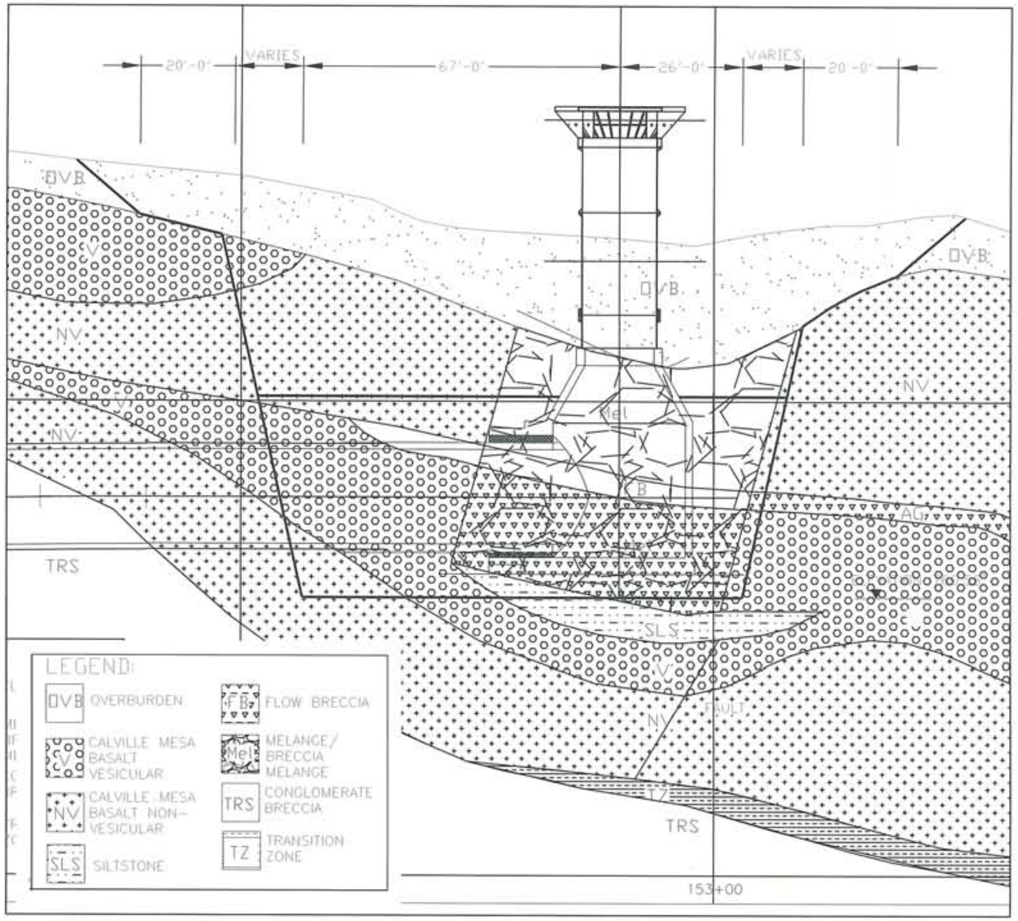


FIGURE 4.2 **Detail from VTC's drawing M-995 showing the geologic conditions based on borehole samples at the excavation site: generally basaltic rock influenced by intense tectonic jointing.**

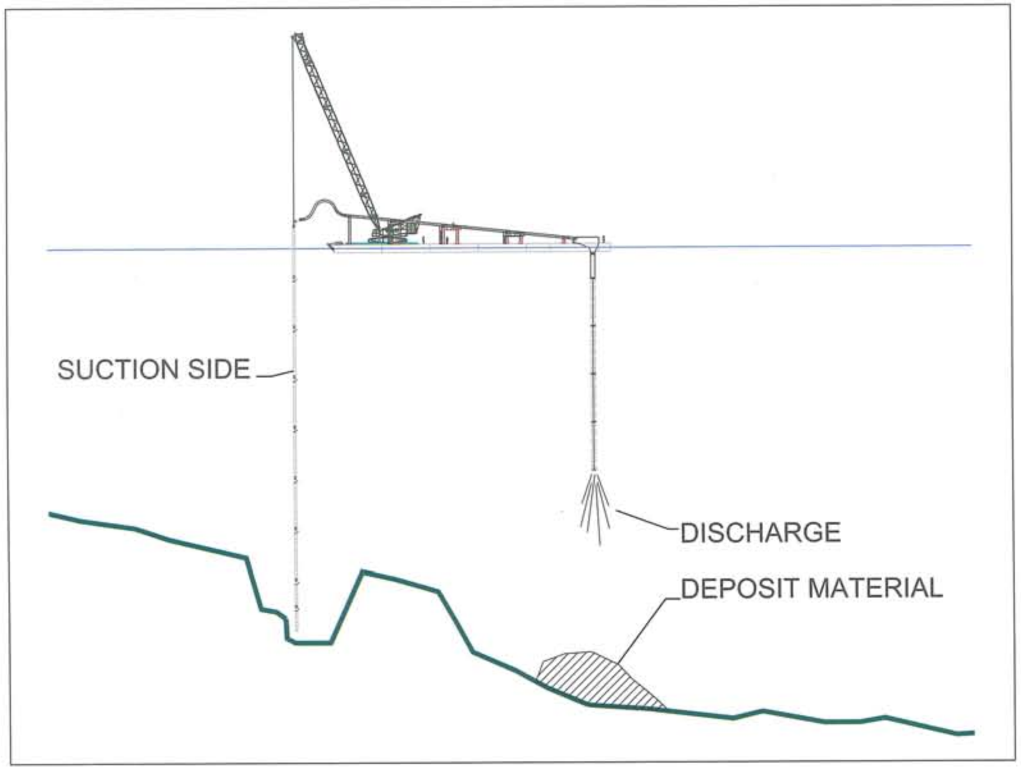


FIGURE 4.3 Excavation of the overburden material was performed chiefly by an airlift system mounted to the crane barge.

4.1 OVERBURDEN EXCAVATION

The overburden was to be excavated with an airlift system, complemented by the use of a crane with a clamshell bucket. The airlift system, successfully used by Impregilo-Healy on another project, was designed by VTC with the assistance of underwater specialist Mr. Rik Pellegrims of Rijmenam, Belgium. Two Atlas Copco air compressors supplied air to a 20 in. [500 mm] diameter pipe to perform the airlift excavation. See Figure 4.4 for photos of the airlift assembly.

The overburden was expected to be mostly silt and sand. However, it proved to be mostly highly weathered desert soil with a mixture of gravel, sand, and occasionally, large pockets of rock. The overburden was removed mostly with the use of the airlift, but rockier, coarser material would clog the airlift pipelines, necessitating use of the crane-and-clamshell method.

4.2 SELECTION OF ROCK EXCAVATION METHOD

The rock excavation was the most challenging marine excavation operation due to the depth of the excavation and the material to be removed.

FIGURE 4.4 (PAGE 53) The crane barge configured for airlifting. ① Being outfitted at the staging area. ② In use. ③ A flexible pipe allowed manipulation of the suction side by crane. ④ Air compressors with airlift line above. ⑤ Hopper used to hold excavated material. ⑥ Airlift pipe and crane.


①


②


⑥


③


⑤


④

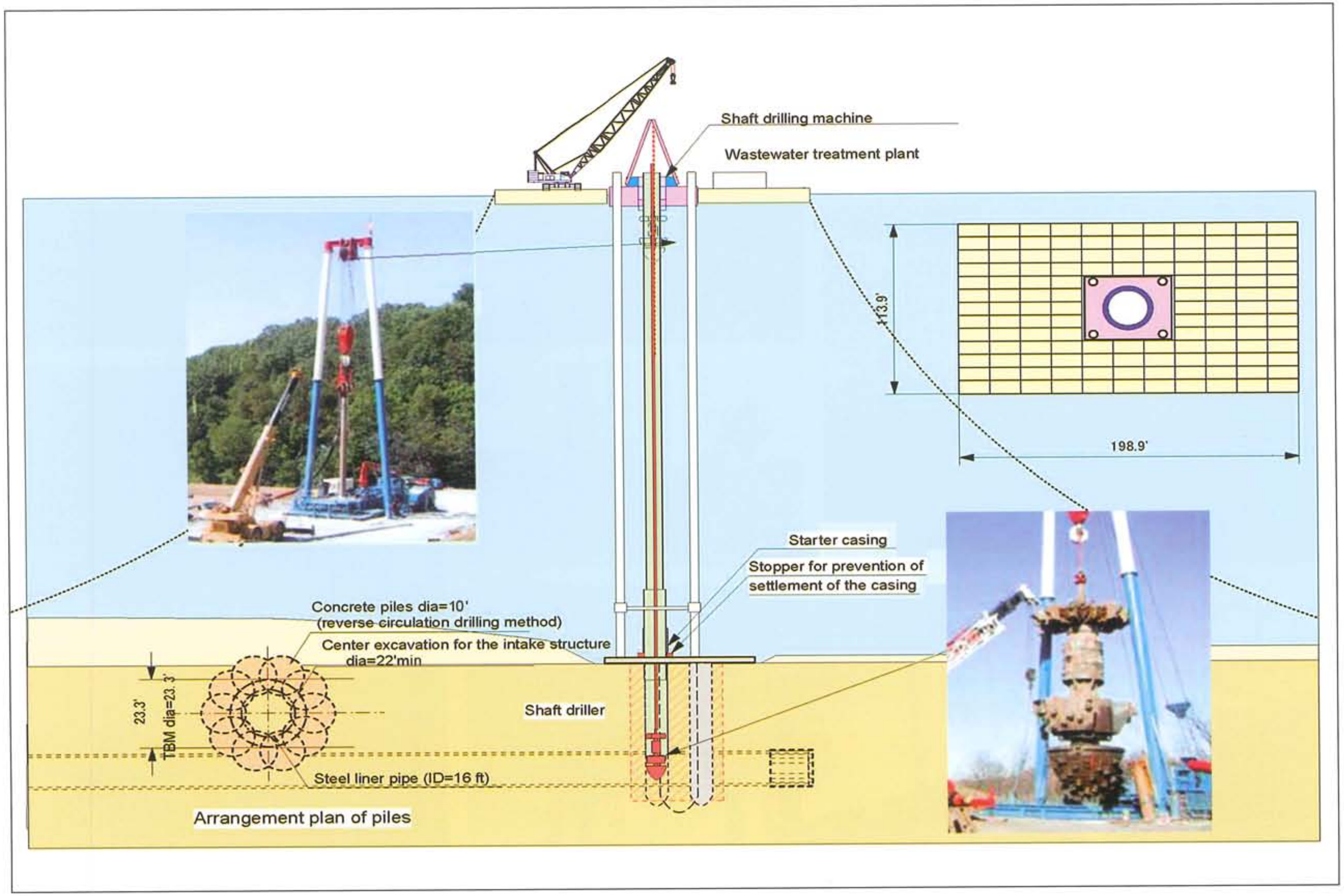


FIGURE 4.5 One excavation option considered by the SNWA involved placing an interlocking circle of secant piles, shown here.

Several considerations were taken into account when selecting the most suitable excavation method:

- Uncertainty of the rock topography.
- Steepness of the slopes in order to maintain the bottom of the excavation clean.
- Utilize methods that minimize the use of divers.
- Difficulties associated with operation and control of hydraulic equipment at a depth of 330 ft [100 m].
- Impacts on the natural ecosystem, especially methods to mitigate fish mortality.

VTC worked with several specialists and specialized companies, analyzing ideas and methods to implement a successful excavation. However, with such complex work to be performed, none of the subcontractors or suppliers were willing to guarantee successful performance.

The various investigated excavation options were:

- Drilled Shaft Option (Figures 4.5 and 4.6): Excavation of medium-to-large diameter (3 ft [0.9 m] to 10 ft [3 m]) secant piles using a down-the-hole hammer in a rectangular pattern, then breaking the rock between the shafts using chisels or explosives. A template frame was planned to maintain the pattern of drilling activity.

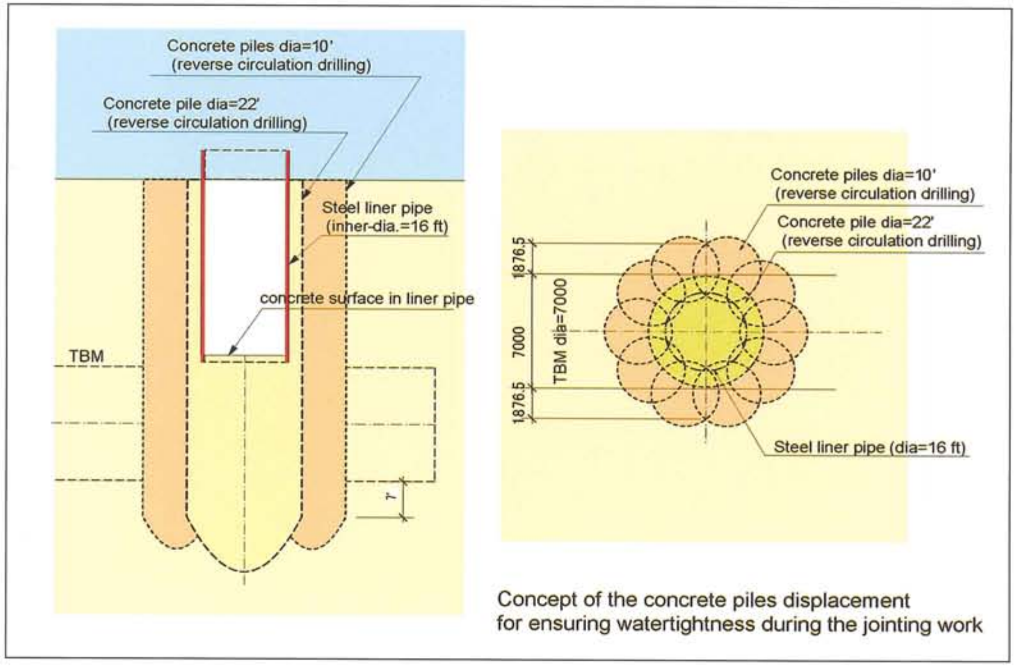


FIGURE 4.6 **Once the secant piles were set, a shaft was to be excavated and lined with steel to allow intake riser placement.**

- Remote Operated Equipment Option (Figures 4.7 and 4.8): Excavate using a prototype heavy hydraulic excavator equipped with a crusher head.
- Drill and Blast Option (Figure 4.9): Holes, drilled from a barge using a hole template, loaded with explosives. Resulting debris removed by crane and clamshell bucket.
- Shaped Charges Option: Rock excavation using shaped charges.

4.3 SELECTION OF SHAPED CHARGES

A large matrix of the pros and cons of each solution was prepared to evaluate risks related to the environment, required equipment, reliability, technical feasibility, duration, and cost. Eventually, VTC chose to excavate using shaped charges, as proposed by Nitrex of Lonato de Garda, Italy.

Shaped charges operate like a directed projectile: An explosive substance is positioned above an aluminum shell that is attached to a spacer, providing an adequate distance from the rock surface. The space between the rock surface and charge is designed to allow development of a slug created by rapid melting of the aluminum plate when the charge is detonated. The slug impacts the rock at high velocity, creating a crater or fracturing the rock (Folchi 2010). In many ways, this was a primitive approach to rock breaking, but since using explosives is a common tool in rock excavation, only a

FIGURE 4.7 **Another excavation method considered used virtual reality techniques to control a first-of-its-kind excavator equipped with a crusher head and airlift system to transport excavated material.**

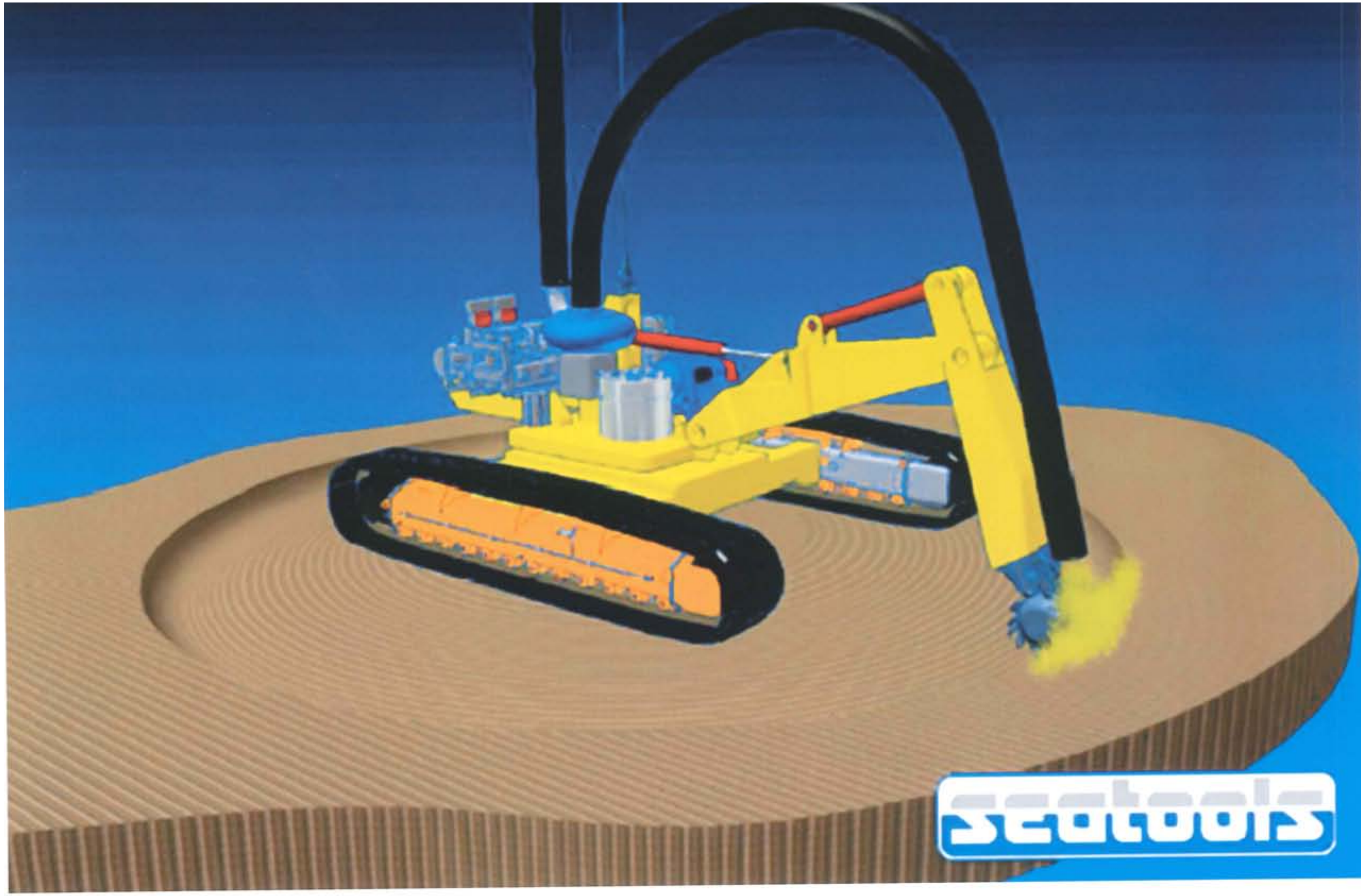


FIGURE 4.8 **Detail of the proposed underwater excavator.**

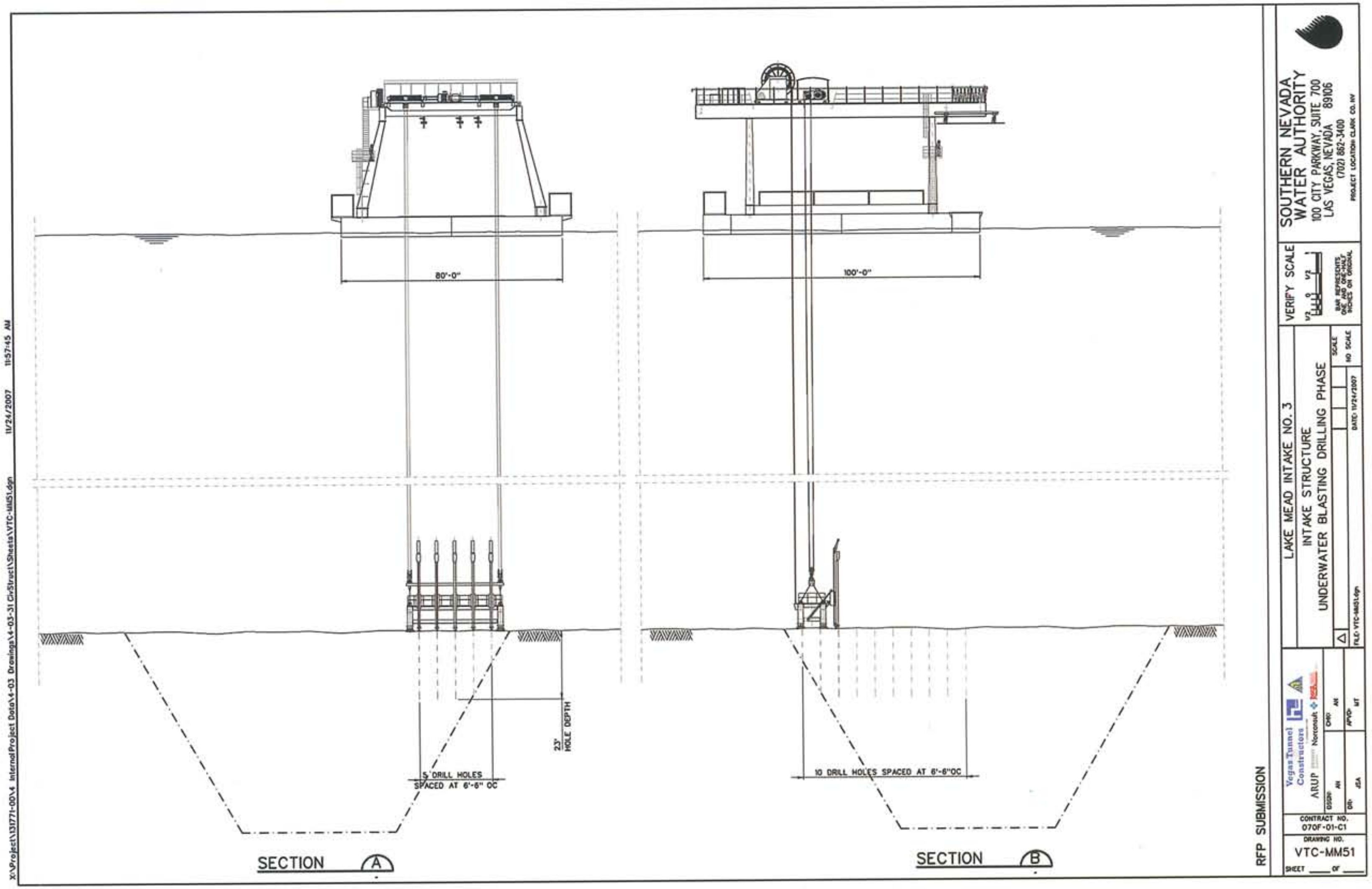


FIGURE 4.9 The drill and blast excavation, as outlined in the proposal documents, was considered but not selected because shaped charges were deemed more reliable on the expected steep, varied topography.

few items had to be engineered. These were the size of explosive charge, the optimal distance from the explosive to the rock surface in which to create the slug, the spacing of the charges and a way to maintain that spacing while keeping the charges perpendicular to the rock surface, and a reliable system to consistently detonate the charges at such a depth.

This option was selected because it was judged to be the most flexible and least risky. All other methods could prove to be infeasible during execution and jeopardize the project due to the time it would take to develop and implement an alternate system. In the case of the drilled shafts, there were no foolproof ways to gauge the spacing of the drilled shafts, deal with varying topography, or be sure that the rock between holes would not cave in. Drilling a blast pattern, then loading it with conventional explosives, tying them together, and consistently detonating the charges would require extensive testing and new products. The underwater hydraulic excavator would be a totally new and unproven production machine. On the other hand, the shaped charges were known to work; it was only a question of the number of charges needed. Time and cost could vary according to the effectiveness of the method, but the completion of the excavation would not be put at risk by the use of the shaped charges.

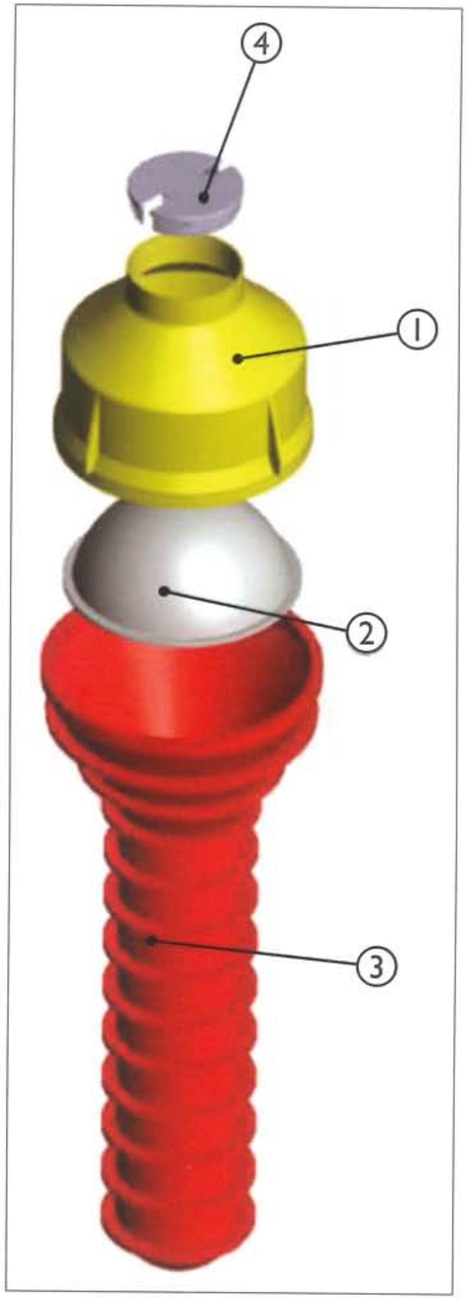


FIGURE 4.10 **Designed specifically for the Lake Mead Intake No 3 project, the shaped charges are composed of: ① upper shell, ② liner, ③ bottom shell, and ④ plug.**

4.4 EXCAVATION BY SHAPED CHARGES

The big advantages offered by the charges were the options to vary the pattern, place them on slopes of varying degree, and even the possibility to demolish entire outcrops using few charges and precise positioning with the use of an ROV. Another advantage of using shaped charges was that all excavation operations could be executed without using divers, removing the safety hazard of underwater diving. The other marine work operations were to be done without divers as well, and this theme was kept consistent during marine excavation.

The design of the charges was done with continuous support from Nitrex and the added consultation of various international experts. During the course of the project, the shaped charges were modified to improve their efficiency and their water tightness. The size of the bottom shell was enlarged to better address the shot, and the design of the gasket was improved to decrease the chance of water entry.

Nitrex supplied the shaped-charge housings, including the upper shells, bottom shells, plug, and all plastic material. Nitrex also supplied the aluminum liners for the charges from which the slug developed during detonation. The top part of the canister (items 1, 2, and 4 shown in Figure 4.10) was shipped directly to Austin Powder Company of Cleveland, Ohio. Austin filled each charge with about 20 lb [9 kg] of composition B explosive, which was placed directly

FIGURE 4.11 **Shaped charges. ① Composition B explosive. ② Concrete ballast. ③ Charges arranged on a test frame. ④ Part of a slug following detonation. ⑤ Shaped charge shells.**

atop the aluminum dome. Austin shipped the shaped charges to VTC, where they were stored in a dedicated explosive magazine and used when needed. The bottom shells of the charges were sent directly to VTC, where they were fitted with a concrete ballast to offset the buoyancy caused by the air in the canister.

During development of the excavation program, VTC made a presentation to officials of the LMNRA. Due to concerns about plastic from the shaped charge canisters housings ending up in the lake, Nitrex altered the plastic formula to make the housings biodegradable.

4.5 BLASTING OPERATION

It took some time to develop a method that could be executed efficiently and accurately in the field. At the beginning of the operation, a method statement was formulated by VTC in conjunction with Nitrex. Testing of the shaped charges was carried out for more than two months to ensure a feasible method of execution. Some aspects of the work were not practical in the field, and the method statement and details were modified to improve overall efficiency. As the blasting work was performed, productivity increased over a couple of months until the operation was streamlined.

As many as 49 charges were set off at one time. Blasts larger than 36 charges were more effective for excavation but caused a lot of damage to the equipment on the air mirror barge located directly above the blast. The typical shot pattern was a grid of 6 × 6 charges,

FIGURE 4.12 **Shaped charges being prepared on the blasting barge.**

FIGURE 4.13 **Testing the flexibility of the PVC-pipe grid, which kept the charges at proper spacing.**

resulting in 36 total charges spaced at 3 ft [0.9 m] covering one square field of 16 ft × 16 ft [5 m × 5 m] to 20 ft × 20 ft [6 m × 6 m].

The average thickness of material demolished at each layer was 3 ft [0.9 m]. Because the top surface of the excavation measured roughly 120 ft × 170 ft [37 m × 52 m], and the bottom surface of the excavation was smaller (65 ft × 107 ft [20 m × 33 m]), the top layer required about 50 fields of charges, and the bottom layer required about 24 fields of charges.

All blasting data – the number of shots and the number of charges for each shot, the position, and the observation data – were included on a daily report issued by the surveyor on the crane barge. At the end of a week of blasting, the marine work superintendent, the blasting foreman, and the surveyor met to make a plan of blasting and excavation for the following week.

The charges magazine, handling operation, and blasting operation were the responsibility of a VTC licensed blasting foreman who led a blasting team of six people. Usually, the blasting operations were scheduled on the first three days of the week (one shift each morning), leaving the remainder of the week (about eight shifts) for the crane barge to remove the debris and perform the survey operation.

The charges were transported from shore to the crane barge using the blasting barge, which was 40 ft × 40 ft [12 m × 12 m]. On this barge, the charges were positioned in a selected pattern. The bottoms of the charge canisters were connected to one another using ½ in. [13 mm] diameter, thin-wall PVC pipe, which formed

FIGURE 4.14 **Lowering a field of shaped charges to the excavation site.**

a grid. This pipe grid maintained the effective area offset intended for the charges and allowed the charges to follow the profile of the bottom of the excavation (Figure 4.13).

Each shaped charge was hung from the steel frame using a ½ in. [13 mm] nylon rope about 49 ft [15 m] connected to a tippet of thin nylon rope tied directly to the shaped charge. After each blast, the destroyed tippet was replaced, and the ½ in. [13 mm] nylon rope was reused for setting the next round of charges (Figure 4.15). The booster and the detonating cord were connected to each charge, and another long piece of detonating cord was connected to a shock tube detonator. The shock tube reached the crane barge and was set off from the deck of the barge.

FIGURE 4.15 **Each charge was suspended with two ropes: The lower was destroyed in the blast, while the upper could be reused.**

The frame with the entire grid of charges was then lifted with the crane and transfered to the main winch on the air mirror barge.

An air-bubble curtain was used to reduce the effects of the pressure wave created by the detonation. The curtain was made from 2 in. [50 mm] tubing laid on the bottom of the lake in an 80 ft × 80 ft [24 m × 24 m] square with ⅛ in. [3 mm] holes drilled every 18 in. [460 mm].

The air mirror barge was equipped with two winches to maneuver four anchors and one 30-ton [27 t] winch used to lower the frame with the charges attached. The air mirror barge also carried two 1200 ft^3/min at 450 psi [35 m^3/min at 31 bar] Atlas Copco air compressors. Because this barge had to remain above the blasting field, its bottom was protected with a wooden blasting mattress covered with tires (Figure 3.15).

Before any blast operation, the surveyor positioned the air mirror barge in the required position with the help of a global positioning system. The frame and charges were constantly monitored by the ROV during the descent into the excavation. The ROV helped address the position requested. At times, the charges were not set in a stable position on a slope or placed on a ridge and had to be readjusted. After the charges were positioned, the air compressors opened, and a huge quantity of compressed air was discharged about 98 ft [30 m] from the top of the charges. The air expanded during its ascent and created a barrier that helped dissipate the shock wave created by the blast.

Once the charges were laid on the bottom, the crane barge moved approximately 650 ft [200 m] away from the blasting area. The safety boats started circling the perimeter of the blasting area to keep watercraft away until the blast was done. After the blast, the crane barge was moved to a position near the air mirror barge, and the operation was repeated. Typically, three blasts were done per day, three days per week.

4.6 SUMMARY OF BLASTING OPERATIONS

Below is a summary of the rock excavation by shaped charges and crane and clamshell bucket:

- The trial blasting operation started June 4, 2010.
- Excavation using shaped charges started in August 2010.
- The last blast was executed on December 13, 2011.
- 23,725 charges were detonated in 547 blasts.
- On average, 43.4 charges were detonated per field.
- The average efficiency was about 1.2 yd^3 [0.9 m^3] of rock per charge. Efficiency was 1.8 yd^3 [1.4 m^3] of rock per charge while excavating nearer the original lake bottom, decreasing to 1.0 yd^3 [0.8 m^3] of rock per charge as the lower limit of the excavation was reached.

When blasting was completed, there were still about 500 charge canisters remaining unfilled in surplus.

FIGURE 4.16 **ROV screenshot of shaped charges resting on the surface of the excavation site.**

FIGURE 4.17 **Double-crested cormorants (*Phalacrocorax auritus*) on a floating containment near the staging area.**

4.7 ENVIRONMENTAL CONCERNS

A substantial effort was carried out to minimize the environmental impact in and around the work area. These efforts focused on reducing or eliminating fish mortality.

In particular, care had to be taken to avoid any impacts on or deaths of an endangered species, the razorback sucker (*Xyrauchen texanus*). An environmental engineering consultant studied the impacts of deep underwater blasting on aquatic life and proposed mitigating methods. Several methods were attempted, including detonating "scare charges." These were counterproductive, as they caused the death of small fishes, which attracted more fish to the area. The use of acoustic scaring was explored without success, as it was proven completely ineffective for the type of fish present in the area. In the end, we had no choice but to execute the blasting operation and keep the blasting overpressure wave within the parameter included in the work permit: 50 psi [3.4 bar] measured 100 ft [30 m] from the explosion area. The wave was measured during each shot with calibrated instruments. At 100 ft [30 m] from the explosion area, the overpressure averaged 44 psi [3.0 bar].

Considering the duration and the dimensions of the operations, impact was kept at a minimum. The operations did not affect any protected species living in Lake Mead but did produce some floating waste, primarily occurring in the explosion area and the surrounding beaches. The waste was recovered by a dedicated cleaning boat on an as-needed and weekly basis.

4.8 DISPLACEMENT OF OVERBURDEN AND ROCK FRACTURED BY SHAPED CHARGES

The removal of overburden and rock after blasting was executed using mechanical clamshell buckets and the airlift.

Two clamshell buckets made by Anvil weighing 5 short tons [4.5 t] and 7 short tons [6.4 t], respectively, with 3.5 yd^3 [3 m^3] capacities were used (Figure 4.19). The airlift system utilized a 20 in. [500 mm] pipe that was supplied air produced by two 1200 ft^3/min at 450 psi [35 m^3/min at 31 bar] Atlas Copco air compressors. The airlift system was mainly used for the excavation of the overburden and the final removal of mud from the bottom of the excavation, which the bucket was not capable of removing. All equipment was installed on the 230 ft × 70 ft [70 m × 21 m] crane barge equipped with the 300-ton [272 t] Manitowoc 2250 crawler crane.

Usually, material was excavated without raising the clamshell bucket above water level to keep cycle time to a minimum. Each excavation cycle took approximately five minutes to execute. Material removed by the airlift was discharged from the tail of the barge at a depth of 131 ft [40 m] by a discharge pipe to avoid turbidity in the lake.

The removal of the overburden and excavation of the rock lasted 22 months. The excavation of the 14,400 yd^3 [13,063 m^3] of overburden material started in January 2010 and finished in July 2010. The testing and excavation using shaped charges started in July 2010 and was completed on December 13, 2011.

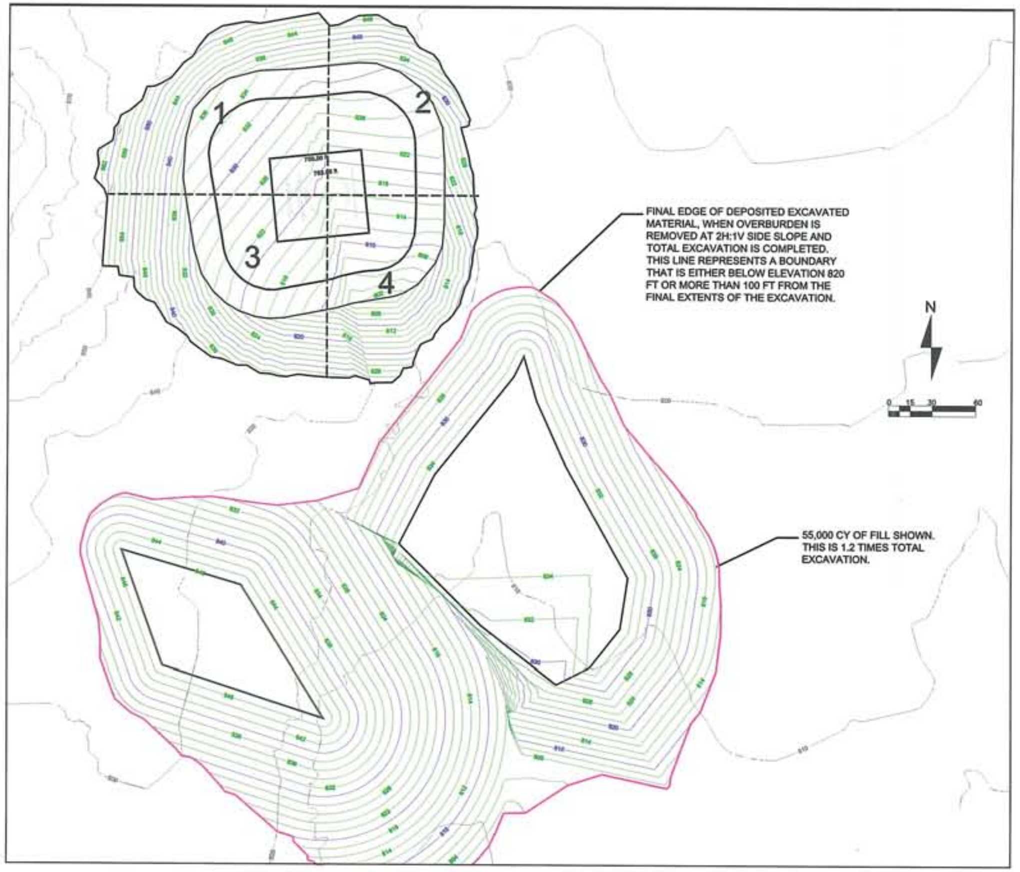


FIGURE 4.18 Detail from VTC's drawing M-708 showing the final bathymetry of the excavation site and the deposited fill.

FIGURE 4.19 Nearly all of the debris created by the shaped charges, more than 33,000 yd³ [25,230 m³], was removed by crane and clamshell bucket operations.

The 33,600 yd³ [30,481 m³] rock excavation lasted 16 months and removed 480 yd³ [367 m³] of material per week on average.

For the most part, the work was performed during a single shift, five days per week, but a second shift was later introduced to speed up the operation. Blasting was generally performed three days a week, and airlifting took place two to three days per week.

Few references of productivity for works of this type are available for comparison, but we did gain some valuable experience:

- The airlift proved successful when operating in certain overburden areas, but in areas with an abundance of rock, the airlift pipe was prone to plugging. The removal of the rock obstructions from within the pipe was excessively time consuming. Most of the excavation was removed by crane and bucket, which was a slower operation.
- Working at a water depth of about 330 ft [100 m], the crane operator loses the ability to "feel" the load being lifted and is not aware of moving a full bucket or an empty one. Additionally, the load cell, when working with a long section of cable, becomes very inaccurate. It becomes difficult to verify the contents of the bucket, which reduces the efficiency of the excavation operations.
- Typically, before starting to excavate, the excavation area was surveyed with GPS and by using the ROV,

but visibility was completely lost after starting the excavation. Ensuring that the crane and clamshell work was being executed in the correct location was difficult due to the pendulum movement of the bucket caused by such a long main line.

- The airlifted material needed to be handled twice because the size of the excavation was too large for the barge to discharge the excavated material outside of the excavation area in one step.

4.9 SURVEYING AND PROGRESS MONITORING OF THE MARINE EXCAVATION

As the excavation progressed, it was necessary to check the amount of material actually been being removed. This was done with the use of a multibeam sonar system manufactured by Kongsberg of Norway. This equipment was operated by Nitrex and AUS. The multibeam sonar system was mounted to a dedicated vessel and used approximately once or twice a week depending on progress. It provided points in X, Y, and Z format, which allowed cut and fill volumes to be calculated based on the difference between the pre-project survey and the most recent survey. The sections from VTC's drawing M-988 show the progress of the excavation (Figure 4.20).

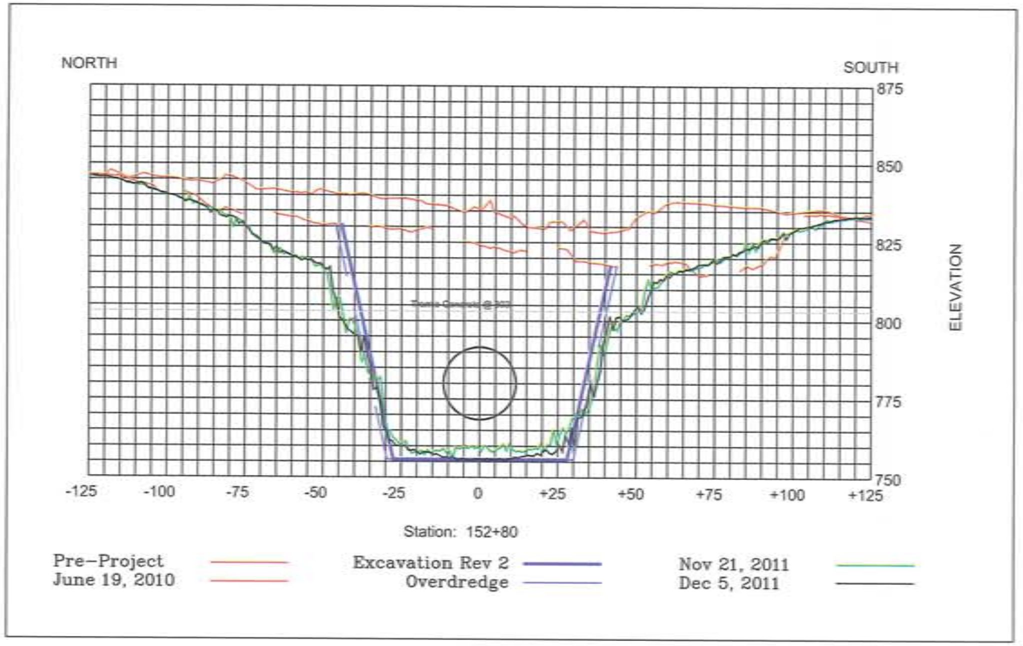
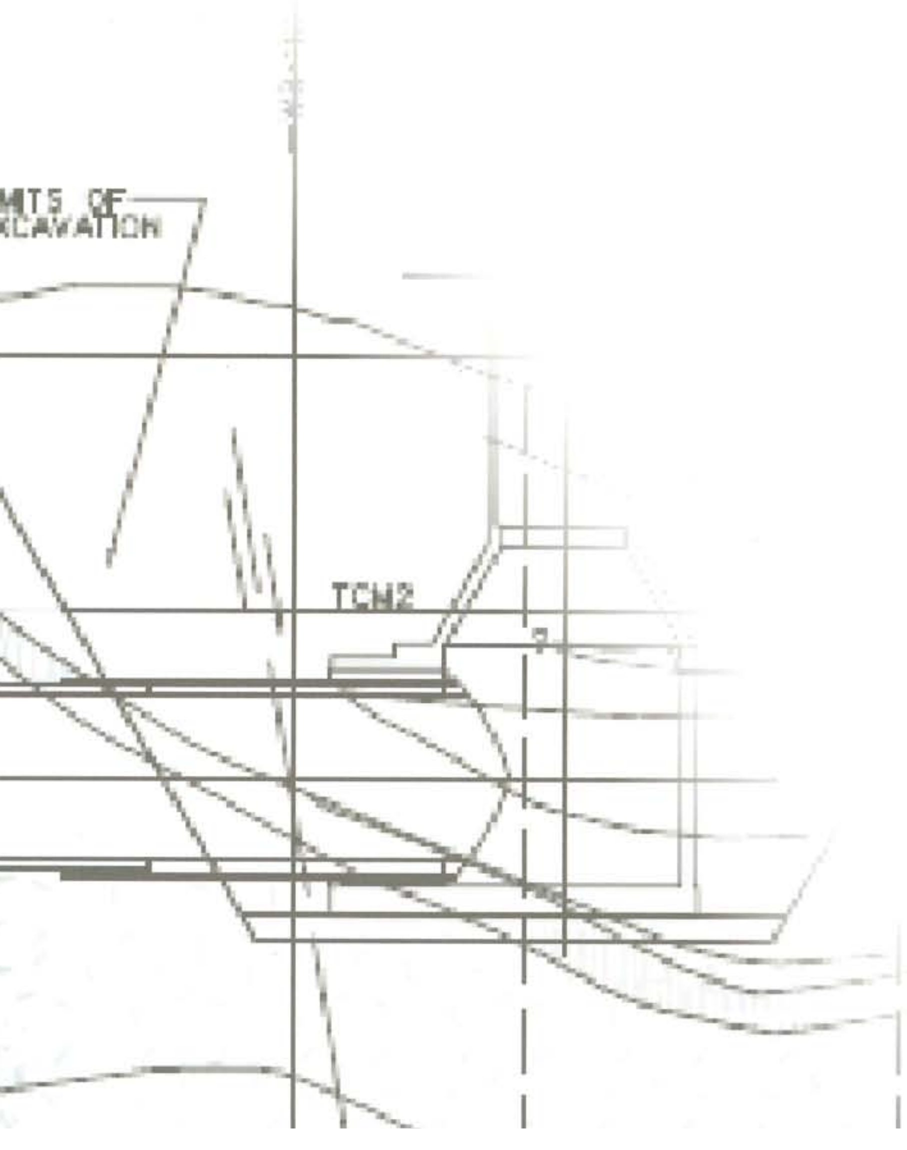


FIGURE 4.20 **Detail from VTC's drawing M-988, "Excavation Cross Sections With Structure and Tunnel." The surveyed bathymetry (green and black lines) were generated periodically to monitor progress.**

LAKE MEAD INTAKE № 3

VOLUME I: DESIGN AND CONSTRUCTION OF THE UNDERWATER INTAKE STRUCTURE



Vegas Tunnel Constructors

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IMPREGILO

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