Soil Retention System Design and Analysis

Executive Summary

The National Museum of the Marine Corps has a unique design element that portrays an image that the building is built underground. In order to achieve this appearance, the areas surrounding the building are backfilled. The backfill is approximately 38 feet in depth. As a result, the walls have been designed to withstand the large lateral loads imposed by the backfilled soil.

The National Museum of the Marine Corps is a project that has been funded by generous donations from numerous parties. Therefore, the project has been designed to be built in phases as funding becomes available. A later phase of the project includes the addition of an IMAX theater and more exhibit gallery space for the museum. This expansion is to be located in one area of the backfilled locations.

In an attempt to reduce the cost and constructability of the future expansion of the building, an analysis was conducted to design a soil retention system around the exterior wall of the building. The goal of the soil retention system is to significantly reduce the lateral loads imposed on the exterior wall of the building, thus reducing the size and complexity of the wall. A reduction in size and complexity of the wall will reduce the costs associated with the future expansion through the walls.

Another reason for the design of a soil retention system is due to the unique design of exterior buried ductwork servicing the Central Gallery spaces of the museum. The original design calls for backfill (up to and around) the exterior ductwork. This design will result in potential construction issues and damage to the in-place work when backfill begins.

The result of this analysis was the design of a sheet pile retention system. The sheet pile system has been design to be 6’ from the exterior wall. The majority of the soil loading has been taken off the wall and the wall was reduced to one-half the original design size with a significant reduction in reinforcing steel required. The initial cost of this system increases the overall project cost; however, future construction costs will be significantly less as a result of this design. Therefore, the overall cost associated with this system will result in a cost savings for the owner of this facility.
Overview

The unique design of the National Museum of the Marine Corps creates the illusion that the building is buried underground. To achieve this appearance, the designers have sloped the ground increasing towards the base of the massive skylight system. The images below clearly illustrate this design.

![Architectural Renderings of National Museum of the Marine Corps](image)

Figure 2.1 – Architectural Renderings of National Museum of the Marine Corps

The museum has been designed in a way that has allowed for a phased construction of the building. This was an important design feature for the owner in order to begin construction of the facility without all of the funding up front. The project has been funded mainly by generous donations from numerous individuals and organizations. As a result, in order to accelerate the construction of the new museum facility, the project has been divided into phases. When funding becomes available the next phase of construction will be awarded. One of the larger phases of the building will be the expansion of the building to include additional exhibit gallery space along with an IMAX theater. The figure below illustrates the initial construction phase and the final building layout.
Phased construction is advantageous to an owner who may not have all of the funding for the entire project up front prior to construction. This method of delivery allows the owner to begin construction of the initial phase of a project and continue to accumulate funding to finance the remaining phases of construction. Although phasing is an attractive approach for owners, it can become a potential hindrance to the contractors. When a project is using phased construction, a designer must design the components of a building to withstand any temporary design conditions that may result from the phased construction.

In the case of the Marine Corps project, the owner has chosen to expand the museum in the area of the exhibit gallery and IMAX Theater at a later date. Thus, in place of this portion of the building, the designer (in an effort to maintain the architectural experience of the building) must backfill the area against the exterior wall of the building. In turn, this results in a more complex design of the exterior wall of the building. The loads imposed by the backfill require a much stronger wall than if the project was being built all at one time without any phases. Therefore, the costs associated with the phasing have potential cost increases for an owner.

**Existing Design Conditions**

The original design conditions for the C1 wall around the Central Gallery have been shown in Figures 2.4 and 2.5 below. Figure 2.4 represents an architectural section of the wall illustrating the main components of the system. Figure 2.5 represents a
structural detail of the same wall with an emphasis on the structural components of the system.

The design of this portion of the museum calls for a 38 feet earth backfill against a concrete wall. Essentially, a retaining wall scenario has been created and the wall must
be designed using the same method as a retaining wall. The backfill creates lateral earth pressure that must be accounted for.

As a result of the massive lateral loads imposed on the wall by the backfill, the wall is 2 feet thick and approximately 45 feet in height. To further accommodate the lateral loads, there is an immense amount of reinforcing steel in place. The vertical reinforcement consists of #11 bars @ 6 inches on center on the outside face of the wall and #11 bars @ 12 inches on center on the inside face of the wall. The horizontal reinforcement consists of #6 bars @ 12 inches on center on both faces of the wall.

As previously mentioned, the long term plans for the Marine Corps museum include expansion in the area of the proposed backfill. The new expansion will result in the removal of this wall for passage into the new portion of the museum. Therefore, it can be said that this area of wall is only temporary until the final phase of the project begins. It has been assumed the columns along this wall adequately carry the loads from the skylight above and that the wall does not carry any of the skylight loads. Based on the vast amount of reinforcing steel in this wall and the overall size of the wall, it can be assumed that the addition of this portion of the museum could be presumably difficult.

Typically, when a wall is designed for a “non-permanent” condition, the use of knock-out panels is typical. A knock-out panel is a section of the wall that does not contain the typical reinforcing steel (of the rest of the wall) in order to reduce the difficulty of cutting this portion of wall out. In the case of the Marine Corps museum, the use of knock-out panels was not an option given the loading imposed on the wall. If the knock-out panels were installed along the C1 wall, the wall would likely fail due to the lateral loads from the backfill.

As a result of the loading conditions, the C1 wall had to be designed as if it were a permanent structure that would be exposed to the lateral loads of the backfill for a long period of time.

Another design feature that is a direct result of the lateral loads of the backfill is the shear key element of the foundation system. The structural detail of the wall (Figure 2.5) shows the shear key below the footing. A shear key is a structural element that is designed to counteract the potential sliding of the wall based on the load conditions.
Essentially the wall is an oversized retaining wall and the load calculations resulted in a large potential for sliding. The best way to counteract sliding is the use of a shear key, albeit an expensive solution, but in most cases the only option available.

A unique element of this building system is the use of exterior buried ductwork by the designer. In order to supply air to the Central Gallery spaces, ductwork must run to the entire area of the room. With no other alternative, the designer was forced to use an exterior ductwork system. Figure 2.4 shows the ductwork locations and the backfill up to the wall and around the ductwork culverts.

**Alternate Soil Retention System Selection**

In an effort to reduce the overall cost of the museum project for the owner and to reduce the complexity of the expansion of the museum by reducing the overall size of the C1 wall, an analysis to determine an alternative soil retention system was conducted.

In order to determine the best solution for this scenario, multiple options were considered. Based on research of numerous soil retention methods, three alternatives were investigated further: a geogrid synthetic soil reinforcing, a slurry wall system, and a sheet pile wall system.

**Geogrid Synthetic Soil Reinforcing**

The first alternative investigated was the use of a geogrid synthetic soil reinforcing system. Essentially, layers of geosynthetic grids are placed in the soil during the backfill operations. The system acts as a gravity system in which the vertical loads of the soil create a tensile force in the geosynthetic members that counteract the lateral loads of the soil mass. The figure below illustrates a variety of schematic applications of the geogrid soil reinforcing.
As a result of this information, the use of the geogrid system initially appeared to be an appealing method for the Marine Corps museum case. However, the design calculations resulted in a system of geogrid layers placed 6 inches apart for the majority of the height of the wall with an embedment length of approximately 28 feet. At this stage, this option was eliminated because it would be extremely costly and time consuming for this alternative. The overall duration of the backfill process would be extremely long due to the amount and size of the geogrid members and would not be advantageous to the project as a whole; therefore, a cost analysis was not conducted for this alternative.

**Slurry Wall System**

A slurry wall system was investigated as another potential option for the Marine Corps museum. A slurry wall is a soil retention method composed of soil and bentonite that ranges in size from 2 to 5 feet thick. A slurry wall is installed using a trench excavation technique – a trench is excavated, a reinforcing steel cage is inserted into the trench and the slurry material is placed in the trench. A slurry wall is similar to that of a concrete with a slurry mixture in place of concrete. As a result, the cost of a slurry wall can be significantly higher. Typical applications of a slurry wall are for deep excavations in order to retain groundwater from the excavated area.
Based on the installation methods, cost, and design of the slurry wall, this method was not a feasible option for this project. Using a slurry wall in this scenario would essentially be reducing the size of the concrete wall and the building of a slurry wall of equal or greater size would increase the cost adjacent to it.

Sheet Pile Earth Retention System

Final investigation into soil retention systems was the use of a sheet pile earth retention system. A sheet pile wall system is composed of interconnected sheets composed of wood, concrete, or steel. Sheet pile systems are typically temporary structures and are relatively cost effective. Sheet piles can be driven into the ground and then backfilled on the side, or the sheet pile can be driven and then the material on one side may be excavated. The image below is an example of a sheet pile system.

Following an in-depth investigation of the sheet pile retention method, it was determined that this could be a feasible solution to the design conditions of the Marine Corps museum. On the surface, the sheet pile system appeared to be a relatively cost effective method, minimal constructability concern, and adequate to withstand the loads imposed on it. Therefore, the sheet pile earth retention system was chosen as the alternative for the soil retention around the C1 wall.

Design of Alternate System

(Note: A detailed calculation log can be found in the appendix of this document.)
Based on the initial investigation, the optimal alternative soil retention method for the National Museum of the Marine Corps project was determined to be the use of a sheet pile wall system. Following the initial investigation, further research was conducted on the conceptual and technical applications of a sheet pile system.

Sheet pile wall systems can be classified into two distinct classifications: a backfilled structure and a dredged structure. In the case of the backfilled structure, the sheet piles are driven into the ground and backfilled on one side. The dredged method consists of the sheet piles being driving into the ground and then material from one side of the sheet pile wall is excavated. The soil retention aspect of the Marine Corps museum will be a backfilled method. The diagram below depicts the construction sequence of this form of sheet pile wall.

Sheet pile wall systems can be designed and constructed with wood, steel, or concrete. For this case, steel has been chosen as the best alternative because of its high strength, ease of installation, and cost. The use of steel sheet piles as a backfilled system provides two design alternatives; a cantilever wall, or an anchored system.
Figure 2.9 - Two types of Sheet Pile Walls: Cantilever and Anchored

The diagrams above illustrate the two design alternatives for the sheet pile system. Design calculations were conducted for both alternatives. However, based on the results of the calculations, the anchored system was chosen as the best system for this application. The cantilever alternative required the length of the sheet piles to be approximately 1.5 times greater than that of the anchored system.

The first step in the sheet pile design was to determine the loads acting on the wall from the backfill material. Following a design procedure from Braja Das’s, *Principles of Foundation Engineering*, the critical stresses and loads were determined. (Note: A detailed calculation log can be found in the appendix of this document.) The following figure 2.10 is a stress diagram for proposed sheet pile wall system including the loads and stresses at the critical points on the retention wall system.
Based on the results of the load calculations, the total length of the anchored sheet pile wall is 46.5 feet. The maximum moment was then calculated at the zero stress location on the wall (Approximately 9.05 feet from the top). The maximum moment was 4312.65 ft-lbs / ft. of wall. Using the maximum moment, the required section modulus was determined to be 1.725 in$^3$/ft. A required sheet was chosen based on the section modulus, a PZ22 member with a section modulus of 18.1 in$^3$/ft. Figure 2.11 represents a detail of this member.
Once the sheet pile was designed, the anchor and tieback system needed to be designed. For this anchored sheet pile wall design, a system of concrete deadman anchors, steel tieback rods, and soldier beams have been designed for the anchor support, located 4 feet below the top of the wall.

To begin the anchor system design, the required tie rod size was found to be a 1 inch diameter. Based on the total length of the wall (approximately 192 ft.), the tie rod spacing was chosen to be 8 feet apart. With this information, the size of the soldier beams was calculated to be W6x16’s at 24 feet in length. The concrete deadman anchors were then found to be 3’x3’x3’, providing a force of 4050 lbs which is much greater than the required 1929.5 lbs. as determined by the design calculations. The diagram below is a schematic illustration of the tieback and anchor system for this wall including the designed dimensions.
Figure 2.12 - Schematic of Tieback and Anchor System with Dimensions

The subsequent figure (Figure 2.13) is section cut of the designed sheet pile wall system. Note the location of the sheet pile wall to be 6 feet from the outside face of the C1 wall to allow for the concrete curbing for the metal panel façade at the top of the wall. The concrete deadman anchors have been located 15 feet from the sheet pile wall and 4 feet below the final grade. Also, in order to provide stability for the base of the sheet pile wall to prevent the wall from any lateral movements, 13 feet of backfill has been placed between the concrete wall and the sheet pile wall.
Figure 2.13 - Section of Designed Sheet Pile Wall System
Figure 2.14 provides a plan view of the sheet pile wall in retrospect to the rest of the museum building. The sheet pile wall system consists of a sheeting system 46.5 feet tall and approximately 192 feet in total combined length. There are 9 soldier beams and 32 tiebacks and deadman anchors.

Project Impacts

Upon completion of a successful design for the sheet pile wall system, an analysis was done to determine the impact of this new element to the overall project. Four main potential impact areas have been analyzed: design impacts, cost impacts, schedule impacts, and constructability impacts.
Design Impacts

One of the main goals for the alternative design of the earth retention system around the C1 wall was to remove and/or reduce the lateral loading on the wall. This, in turn would potentially decrease the overall size and complexity of the wall. Following the design of the sheet pile wall system, an analysis of the new load conditions on the C1 wall was conducted.

The results of this analysis determined that the original design of the wall was much greater than required with the new system in place. As a result, a redesign of the concrete wall was completed. (Note: All design calculations can be found in the appendix of this document.) The design calculations for the new loading conditions reduced the thickness of the wall by one-half its original thickness (i.e. from 2’ to 1’) and significantly reduced the amount of reinforcing in the wall. The table below (Figure 2.15) and the details (Figure 2.16) compare the original wall to the newly designed wall.

<table>
<thead>
<tr>
<th>Original Wall Design</th>
<th>New Wall Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Strength</td>
<td>5000 psi</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>2 ft.</td>
</tr>
<tr>
<td>Vertical Reinforcing</td>
<td>#11@6” VOF, #11@12” VIF</td>
</tr>
<tr>
<td>Horizontal Reinforcing</td>
<td>#6@12” HEF</td>
</tr>
<tr>
<td>Shear Key</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>5000 psi</td>
</tr>
<tr>
<td></td>
<td>1 ft.</td>
</tr>
<tr>
<td></td>
<td>#7@12” VEF</td>
</tr>
<tr>
<td></td>
<td>#5@12” HEF</td>
</tr>
<tr>
<td></td>
<td>NO</td>
</tr>
</tbody>
</table>

Figure 2.15 - Comparison Table of Original Wall to New Wall Design

Figure 2.16 - Original Wall Detail and New Wall Detail
Another result of the implementation of the sheet pile retaining system was the elimination of the shear key portion of the footing. The spread footing design was not altered as it is assumed to be adequately designed to distribute loads from other portions of the building. However, the shear key was designed to counteract the lateral loading on the wall from the backfill to reduce sliding. By removing the huge lateral earth loads, the shear key has been eliminated.

Although the sheet pile is a significant design alteration in some regards, the design carefully maintained the architects original design concept for the building. Figure 2.4 clearly illustrates the architects exterior design features at this location and it can clearly be seen in Figure 2.10 that the newly designed retaining system does not impede on these design features. The sheet pile system also creates a cavity in which the ductwork can be installed and remain accessible for future maintenance; an added feature that was not feasible with the original design.

The overall impact on the design was a very positive impact. The wall was reduced in size, the shear key was removed, and new access space was created without altering the original design intent of the architect.

Cost Impacts

Value engineering is often a term used to describe an effort to reduce project costs in some way without limiting the quality of a building. In most instances, contractors generally perform a vast amount of value engineering on a given project to reduce the project costs. And the result of this analysis and redesign of an earth retention system is no different.

Whenever a potential change, or modification, to the original design of a building is well-established, cost is always a driving factor. Once a project has begun construction, the owner has a well-established estimate as to the total cost of the project. Therefore, any potential significant change to the project will be difficult to persuade the owner on if the cost is not equal to or less than the estimated cost of the original design. As a result, cost of implementing the sheet pile wall system was carefully tracked to measure the overall feasibility.
In order to most accurately estimate the financial impact of the sheet pile wall system, three major components were required:

1. Cost estimate of the original wall design
2. Cost estimate of the sheet pile wall system and the new wall design
3. Estimate of future demolition/expansion through both wall designs

The following table (Figure 2.17) provides the estimated values of these three components. The estimate was performed with the use of CostWorks 2004 software and the detailed estimates can be found in the appendix of this document.

<table>
<thead>
<tr>
<th>Construction Costs</th>
<th>Demolition Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original Design Conditions Cost</strong></td>
<td><strong>Demolition Original Design Conditions</strong></td>
</tr>
<tr>
<td>Original 2’ Thick Wall</td>
<td>Original 2’ Thick Wall</td>
</tr>
<tr>
<td>$192,645.39</td>
<td>$239,760.00</td>
</tr>
<tr>
<td>Shear Key</td>
<td>$222,719.49</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>Total</strong></td>
</tr>
<tr>
<td><strong>$222,719.49</strong></td>
<td><strong>$222,719.49</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>New Design Conditions Cost</strong></th>
<th><strong>Demolition New Design Conditions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>New 1’ Thick Wall</td>
<td>1’ Thick Wall</td>
</tr>
<tr>
<td>$128,645.79</td>
<td>$191,808.00</td>
</tr>
<tr>
<td>Sheet Pile System</td>
<td>$252,093.41</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>Total</strong></td>
</tr>
<tr>
<td><strong>$252,093.41</strong></td>
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<table>
<thead>
<tr>
<th><strong>Construction Cost Difference:</strong></th>
<th><strong>Demolition Cost Difference:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>-$29,373.92</strong></td>
<td><strong>$47,952.00</strong></td>
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<table>
<thead>
<tr>
<th><strong>Total Cost Savings:</strong></th>
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<tbody>
<tr>
<td><strong>$18,500</strong></td>
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Figure 2.17 - Cost Comparison Estimates of Original and New Design Conditions

The construction cost information listed in the table above is considered to be the installation costs of these systems at this stage in the project. Notice the original design condition was estimated in two parts: the concrete and the shear key while the new design condition was estimated for the concrete wall and the sheet pile system. Since there was no change in the spread footing, the cost would not change. As mentioned previously, the redesign did eliminate the shear key. Although the reduction of the wall size and the elimination of the shear key reduced the cost of the wall, the new cost of the sheet pile system ultimately created a project cost increase of $29,374.

Following a comparison of the construction costs of the two system designs, a forecast for future expansion cost comparison of the two systems was compiled. The original wall design was twice as thick as the new design with more than double the
amount of reinforcing steel. Therefore, as the costs in the table indicate, the expansion through the original design wall is greater than that of the new wall. The cost savings associated with the new design conditions were close to $48,000.

As a result of these estimates the final cost impact to the overall project would be a cost savings of approximately $18,500. Although this is not a significant amount of money in context with the overall project costs, it will make this new design element much more feasible because it does not cost more money to implement in the long run. The initial costs are higher and without determining the costs of the future expansion it would appear to have been an unfeasible design solution. However, the analysis of the future expansion costs determine the sheet pile wall system was a positive impact on the overall project and will ultimately save the owner a few dollars in the end.

**Schedule Impacts**

When considering a design alternative for a building, it is crucial that a study be conducted to determine the impact of the construction schedule. For this system, there are two scenarios in which the sheet pile wall system could impact the schedule. Since the wall has been designed as a backfill system, it is not required that the sheet pile wall be installed prior to any onsite excavation (as is typical in deep excavation conditions). Therefore, one alternative for the installation of the sheet pile system is to install it once the building has been relatively closed in and the majority of the work is being done on the interior of the building. The critical path for beginning of this project is as follows:

![Critical Path Diagram for Marine Corps Museum](image)

**Figure 2.18 - Critical Path Diagram for Marine Corps Museum**

Based on the critical path in the beginning of the project, the installation of the sheet pile system could be done following structural steel erection without impacting the activities taking place in and around the sheet pile wall system. However, the installation of a sheet pile wall consists of driving a sheet pile system into the ground which can cause a great deal of vibration to adjacent structures. Considering the design conditions
of this system and the relative location of the concrete footing and wall adjacent to the sheet pile wall the system could potentially damage the integrity of the structure.

As a result, the installation of the sheet pile wall system is best suited to take place during the bulk excavation of the site. The original grade of the site required a large area of earth to be cut in the area where the sheet pile wall system is to be located. Therefore, by installing the sheet pile system at this time, during bulk excavation, there could also be a potential cost savings in the amount of excavation required because the sheet pile system will retain the soil that was originally to be excavated. (This information was not used during the cost estimate analysis and therefore a potential increase in savings could result.)

The construction alternative to install the sheet pile wall system during the bulk excavation phase of the project appears to be the optimal solution and has been introduced to the original construction schedule. (The construction schedules can be found in the appendix of this document.)

Since the sheet pile system is to be installed in an area originally designed as a cut area, the duration of the excavation has been reduced. The sheet pile installation has been scheduled to begin concurrently with the excavation phase of the project and thus not impacting the critical path of the project.

Constructability Impacts

Constructability issues of the original design of this system with the exterior ductwork originally spawned the notion to investigate design alternatives for this situation. One of the biggest constructability concerns with the original design was how to properly backfill the area around the ductwork without damaging the culvert and the waterproofing of the duct. Another concern was how to properly waterproof the exterior ductwork system and what type of maintenance accessibility was available to the system once the project was complete.

The result of the design of the sheet pile system addressed the main constructability concerns as well as some constructability issues not addressed initially. The sheet pile system creates a cavity around the exterior wall of the building providing
adequate space to install the ductwork system and eliminates the risk of being damaged during the backfill process. Furthermore, the cavity also creates an accessible space for future maintenance on the ductwork system.

As mentioned previously, the Marine Corps project has been designed to be constructed in phases. Therefore, one of the constructability issues that developed during this analysis was the future expansion through this area. The original wall design was 2 feet thick and contained an enormous amount of reinforcement. As a result, the future removal of this wall could be extremely difficult and time consuming and could have a significant impact on the expansion of the facility. Therefore, the design of a smaller and less complex wall system will allow for future expansion to have minimal constructability issues and will have much less of an impact on the expansion.

**Conclusions**

The National Museum of the Marine Corps was designed to be constructed in phases. As a result of this design, the C1 concrete wall had to be designed in order to carry temporary loads imposed by the backfill. The lateral loading on the wall resulted in a design of a significantly large concrete wall with a vast amount of reinforcing throughout, thus making the future expansion through this wall potentially difficult.

Therefore, an analysis was done to determine an alternative earth retention method to minimize the lateral load on the C1 wall and resulted in a redesign of the wall. A sheet pile wall system was designed to meet the load criteria resulting in a smaller and less complex C1 wall. The result of this design alternative was an overall project cost savings of approximately $18,500, a potential reduction in schedule, and improved constructability and accessibility.