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Prince of Wales Fort: Structural Wall Analysis

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Abstract The Prince of Wales Fort, in Churchill Manitoba, was constructed in the early 18th century by the Hudson Bay Trading Company (HBC) in an effort to secure the fur trade in northern Canada. The fort is a Vauban style rubble masonry construction, and is the most northerly fortification of this kind. In the 1920's the fort received recognition as a National Historic Site by the Historic Sites and Monuments Board of Canada, at which time monitoring and repairs began under the leadership of Parks Canada.

As a result of the fort's northern latitude it has been subjected to extreme temperatures and freeze thaw cycles causing a gradual break down of the mortar within the escarp walls. Recently, climate change has led to an increase in the average local temperature shifting the thermal gradient within the earth rampart. During spring and summer, high volumes of ground water have drained through the walls washing out much of the degraded mortar. The result is a partially grouted rubble wall, encased with ashlar face stones. These deteriorating core conditions have caused significant lateral deflections in several areas and failure in others. The core wall material will be analyzed by modeling it as an irregular granular material. Using this approach, different levels of cohesion can be used to determine the in-situ mortar conditions and the strength of the structure.

Keywords: Rubble masonry, stone masonry, granular materials, historic structure, mortar washout, degradation, finite element model

Introduction

Over the last 250 years the Prince of Wales Fort has been subjected to extreme weather conditions. Freezing and thawing of water in the walls, intense wind, snow and rain have been the cause of continuing degradation and even collapse. In recent times, ongoing maintenance has been necessary to maintain the fort as a historic monument. However, over the last decade deterioration has become increasingly rapid, specifically on the north wall. Climate change is thought to be the cause of this accelerated deterioration. Rising temperatures have shifted the thermal gradient through the core of the walls, causing more core material to thaw, consequently allowing increased washout and degradation of the mortar within the walls.

In response to the deterioration, a stabilization project commenced in 2003 and remains in progress. The stabilization project began with the installation of shoring at all locations with visible wall deformations. This was done to prevent further deterioration or possible collapse. Ashlar face stones on each deteriorated section are individually removed, and the inner core is stabilized using flat stones and mortar. The size of the face stones, up to 2000 lbs each, makes this process slow and cumbersome. Due to the harsh climate, the work season is limited to the summer months, meaning sections of wall are typically dismantled one summer and rebuilt the next. Based on the current state of degradation this project is expected to take ten years. However, during this stabilization project it was observed that the north facing wall, which was previously undamaged, has recently begun degrading at an alarming rate. One section of the north wall is currently being stabilized, and other sections will soon require attention if the current rate of deterioration continues. The current reactionary maintenance method has subsequently been deemed insufficient as a long term solution. Alternatively, the design and implementation of a process to slow the rate of deterioration would allow the current stabilization work to be completed, and less invasive maintenance to be continued into the future. In order to develop this preventative approach, the failure mechanisms must first be understood. This will be done though computer aided modeling of both the core material and the ashlar face stones.

History

Construction on the Prince of Wales Fort began in 1731 at the mouth of the Churchill River and was completed 40 years later. The fort was constructed by the Hudson Bay Trading Company (HBC) to safeguard this trading post against the French, with whom the English were competing for trade dominance. After 10 years of occupation and trading an attack by the French caused the fort to be abandoned, and it remained this way for 150 years. Although in poor condition, in the 1920's the Prince of Wales Fort was recognized as being of national significance by the Historic Sites and Monuments Board of Canada. This recognition is attributed to the fort's status as the most northerly construction of its kind, and as it commemorates the historic French-English rivalry over the bay and its resources. Parks Canada (formerly The Parks Branch of the Department) took responsibility for the conservation of the fort, and reconstruction took place through the 1930's. Fig. 1 is an aerial view of the Prince of Wales Fort.

Figure 1: Aerial view of Prince of Wales Fort looking north (Manitoba Field Unit 2003)

Wall Section

Construction History From 1731 to 1743, the foundations were built within a 9 foot wide trench from large stones bedded in mud or clay mortar. The Vauban style fort was then constructed with a split boulder faced rubble masonry, and the hurried construction was completed by 1747. From 1748 to 1771, the split boulder face stones were systematically replaced with ashlar masonry (Heritage Conservation Program 2000). This method was more labour intensive as it required extensive cutting of the hard face stones, and work was subsequently completed at a slower rate.

Materials The walls are constructed primarily of two local stone types; Churchill quartzite, which is a quartz wacke with a compressive strength of 188 MPa, and dolostone, with a compressive strength of 186 MPa. Mud (or clay) mortar was used primarily within the core material, and due to its low strength acted mainly as filler while a lime mortar was used in setting the face stones (Heritage Conservation Program 2000).

Face Stones The face stones are only regularly shaped in one plane. Due to the high compressive strength of the stones, it was typical that only the front be cut to have regular edges and finish. While bearing areas were cut on the top and bottom of the stones, the back was typically left uncut, and tapers off irregularly. The face and side view of two stones, removed from a section of the north wall, can be seen in Fig. 2. From this figure the high degree of variance in the size and shape of these stones is clearly visible.

(a) *(b)* *(c)* *(d)*

Figure 2: Wide stone, view from top (a), and side (b). Narrow stone, view from front (c), and side (d)

Wall Core The core of the wall is composed of loosely packed stones and mud or clay mortar, and is subsequently a highly variable material. Some stones within the core measure up to 1 m in diameter, and little mortar is present in most locations. A cut boulder, which was removed from the wall during the stabilization project, can be seen in Fig. 3. Probing of the south curtain wall, using a fiberscope, was completed prior to the beginning of the stabilization project, and an example of the typical results can be seen in Fig. 4.

(a) *(b)* *(c)*

Figure 3: Cut boulder, view from left hand side (a), top (b) and right hand side (c)

Dimensions The escarp wall is comprised of a rubble masonry core with ashlar face stones. The total height of the wall sections, including a 1.8 m parapet, is 4.8 m. This height is divided into 10 courses of ashlar masonry of heights ranging between 360 mm and 600 mm. The length of the stones typically ranges between 300 mm and 1000 mm, and their depths between 200 mm to 480 mm. A similar construction, for the foundation, continues 2.1 m underground and is 2.7 m wide. Behind the wall lies an earthen and gravel backfill which reaches a height of 3 m. A general cross sectional view can be seen in Fig. 5.

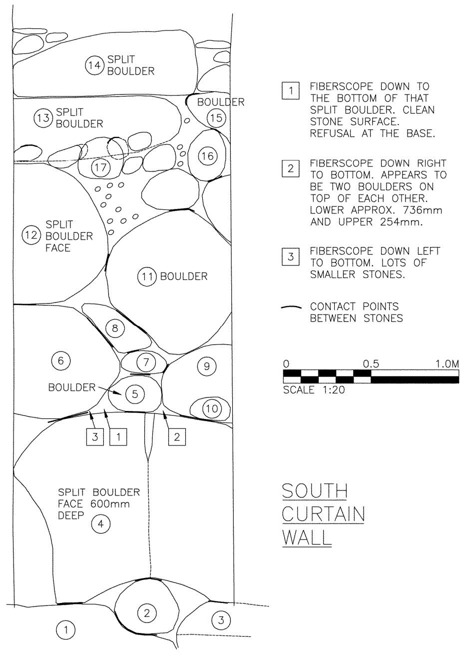

Figure 4: Results of fiberscope probe of South curtain wall (Heritage Conservation Program 2000)

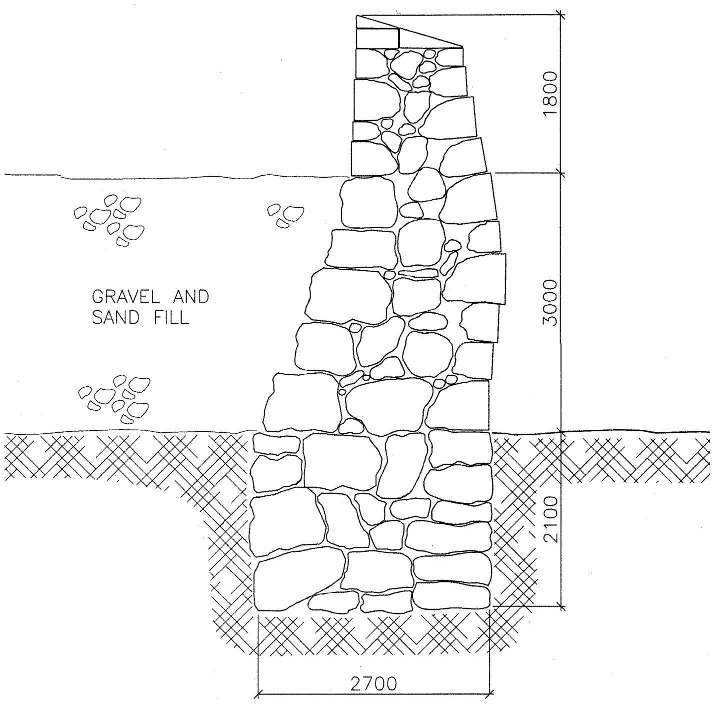

Figure 5: General wall cross section (Heritage Conservation Program 2000)

Deterioration and Deformations

When the transition was made from split boulder to ashlar masonry, the cut boulders were often left in place and used as core material for the wall. Subsequently, the bond between the inner core and outer wythe lacks key stones and is instead connected primarily by the clay mortar that was used in this phase of construction. This has increased the potential for debonding of the outer wythe from the core, and during the stabilization project severe degradation of the mortar behind the face stones has been observed.

The weak mud mortar that was initially placed between the stones, within the core of the wall, was of low strength and acted primarily as a filler material. Under current conditions, little of this mortar is still present within the escarp wall, though some can still be found at the level of the foundation. This has been caused by water in the rampart draining through the more porous escarp wall, and thus breaking down and carrying out the mortar. The harsh climate has also exposed the walls to many freeze thaw cycles, and the expansive pressure of water trapped in the wall has accelerated the degradation greatly. Due to the subsequent loose packing of the core material the load is distributed by stones bearing on each other, rather than mortar holding them together, thus decreasing the stability of the core system.

As the core material in the escarp wall has become more unstable over time, the large stones have begun shifting and applying considerable pressure onto the face stones. At the same time, the connection between the face stones and the core material has been reduced, both due to washout of mortar and the lack of keystones in the initial construction. Subsequently the outer wythe, acting largely independent of the core material, is subjected to lateral pressure causing gradual bulging of the curtain wall at approximately mid height. This problem is often focused in areas between gun embrasures, and thus directly below the parapet which acts as an additional load. As the outer wythe delaminates from the core material the parapet loads the outer wythe eccentrically, thus increasing the lateral deformations.

Plan for Modeling

Developing an understanding of rubble masonry under washout conditions poses several major challenges. Water flowing through the wall tends to follow the path of least resistance leading to high variance in the mortar conditions across any given cross section. This will create areas of localized mortar absence surrounded by mortar of reduced strength, while mortar in other areas is unaffected. Further variance in mortar conditions will occur over the height of the wall according to exposure weathering and ground water runoff. Additionally, the northern latitude of this construction means that a low sun angle will expose only the south facing walls to direct sunlight, causing walls oriented in other directions to experience varied magnitudes and frequencies of freeze thaw cycles, which further compound water related issues.

The core of the wall is subjected to several loads. These loads include the pressure from the earthen rampart, which will have an approximately triangular distribution, as well as the vertical load from the parapet that will be shared between the core material and the outer wythe. Gravity forces due to the weight of the material will be of particular importance, as the large stones tend to roll into available gaps. The core material will be idealized as a granular material for the purpose of the model. Using this model it will be possible to assume varied levels of cohesion and determine the horizontal pressure gradient accordingly.

The curtain wall is much longer than it is tall, (32 m long, 4.8 m tall), and is comprised of a repeating pattern of gun embrasures and parapet walls. It is possible to model a section of wall that spans between the centrelines of two gun embrasures, thus isolating the critical section, below the mid portion of the parapet. This section would be modeled using plate elements, allowing rotation about the horizontal in-plane axis at their junction, thus representing the rotation at mortar joints. The face of the plate elements will be seeded with gap elements, which represent the bed joints in the masonry, and would open at a critical stress level. The boundary conditions on the two sides of the plates would be taken as restrained vertically, and in both horizontal directions, as it is considered to be at a sufficient distance from the critical section; rotation would, however, be permitted in the three directions. In order to represent the boundary condition at the base of the wall accurately, the plate would be modeled to the bottom of the foundation, at which point it would be restrained from movement in both horizontal directions, as well as vertically. The front face of the plate would be restrained from moving forward, up to the level of the ground.

Modeling of the core material as a granular material should produce a horizontal pressure distribution that increases with increasing depth. This pressure distribution would subsequently be applied to the back of the ashlar face stones. Under these conditions, if the outer wythe were modeled as a plate element, yield line failure should be evident. The observed deformations do not seem to be consistent with a yield line pattern, and this may be attributed to the eccentricity of the parapet, the irregular application of the pressure as point loads, and the varying depth and contact area of the face stones. A further complication in this unique case is caused by the irregularity of the core material. Due to the washout of the mortar, the pressure from the core material is not applied uniformly; instead, it acts as point loads at the random points of contact. This randomness must be accounted for in the model. It may be possible to do this by applying a grid of random areas to the stress distribution, subsequently finding net forces at several points. These forces will then be applied to the inner side of the ashlar face stones. Coupling these forces with the eccentrically applied load from the parapet and the self weight of the ashlar face stones, it will be possible to model the outer wythe and determine the total lateral displacements. Finally, it will be possible to calibrate the model to represent the in situ conditions by iteratively applying varied levels of cohesion to the granular core, and comparing the calculated deflections to the actual deflections.

Conclusion

In order to understand the behaviour of the rubble core of the escarp walls of the Prince of Wales Fort, the walls will be divided into two parts and modeled separately. First the core material will be modeled as a granular material, in order to mimic the irregular rubble masonry under washout conditions. The pressures determined from this model will then be reduced to a random grid of point loads by determining the reactions over surface areas that vary from the minimum stone size to the maximum. A model of the ashlar face stones will be constructed, considering the face stones as a free standing structure subjected to their self weight, the weight of the eccentric parapet, and the random distribution of point loads. Plate elements will be used to model the face stones and the boundaries will be considered fully fixed on both sides, while the base will be fixed in the horizontal and vertical direction. Gap elements will be seeded in the plate to represent the joints between the stones, and these elements will be formulated to open under the tensile force that is equivalent the load required to rotate open the bed joints in the wall. This model will be calibrated using iterative calculations under different levels of cohesion, in order to determine the core conditions of the already dismantled section of wall

Once calibrated, the model will be a useful tool to determine the core conditions of sections of wall showing low to moderate deformation levels. Subsequently, the effectiveness of different remediation techniques, such as grout injection or anchorage can be determined by applying the restraints they provide to the model.

References

[1] Heritage Conservation Program, Real Property Services for Parks Canada (2000) "*Prince of Wales Fort 1999-2000 Structural Condition Assessment and Recommendations DRAFT*," Public Works and Government Services Canada, HCP Project 410278.

[2] Manitoba Field Unit Unit (2003) "*Prince of Wales Fort National Historic Site of Canada, Safegurading for Future Generations - a Ten Year Plan DRAFT*," Parks Canada.