Using 3D Terrace Modeling to Preserve the Incan Site of Saqsaywaman

A Thesis
Presented to the Faculty and Staff of Engineering and Applied Science
University of Virginia

In Partial Fulfillment
of the requirement for the Degree
Masters of Science (Civil Engineering)

By
Teresa Marie Jarriel
May 2016

APPROVAL SHEET

The thesis

is submitted in partial fulfillment of the requirements

for the degree of

Master of Science

AUTHOR

The thesis has been read and approved by the examining committee:

Richard W. Miksad

Advisor

Brian L. Smith

Sean M. Ferguson

Accepted for the School of Engineering and Applied Science:

Craig H. Benson, Dean, School of Engineering and Applied Science

May

2016

Acknowledgements

Thank you to all of the student members of the 2015 UVA Research Team:

Gina O'Neil, Civil Engineering Graduate student, University of Virginia
Edward Tiernan, Civil Engineering Undergraduate student, University of Virginia
Olivia Daniszewski, Civil Engineering Undergraduate student, University of Virginia
Aaron Banaziewicz, General Science Undergraduate student, Fordham University
Jack Roswell, Undeclared Undergraduate student, Brown University

An additional thank you to our coworkers, sponsors, and supervisors:

Carmen Ortiz, Civil Engineering Graduate, Universidad Nacional de Ingenería
Álvaro Javier, Civil Engineering Graduate, Universidad Nacional de Ingenería
Jorge Soto, Civil Engineering Graduate, Universidad Nacional de Ingenería
Frank Rojas, Civil Engineering Graduate, Universidad Ricardo Palma
Kenneth Wright, Wright Water Engineering, Project Sponsor
Dr. Ing Jorge E. Alva Hurtado, Rector, Universidad Nacional de Ingenería
Dr. Ing Leonard Alcayhuaman, Vice Rector Academico, Universidad Ricardo Palma
Alexei Vranich, UCLA Costen Instute of Archeology
Sr. Fermin Diaz Angulo, Gobierno Regional Cusco, Project Sponsor
Dr. Arminda Gibaja Oviedo, Chief Archeologist, INC at Cusco
Lic. Mario Fernando Caller Salad, Oficina Central de Cultura UNI, Project Coordinator
Ing. Jose Antonio Reynoso Palma, Parque de Saqsaywaman
Ing Edith Quirquihuana Zavala, Parque de Saqsaywaman

A very special thank you to my advisor and mentor Dr. Richard Miksad for his support and guidance in conducting this research.

Abstract

This research presents an analysis of the damage inflicted by uncontrolled runoff upon the three Great Walls of the UNESCO World Heritage site of Saqsaywaman, Peru. The analysis is based upon recreating the original Inca terracing system using AutoCAD Civil3D modeling. The results of the 3D model creation and runoff analysis show that implementation of the Inca terracing scheme will improve upon the current runoff conditions and protect the three Great Walls from further damage.

Table of Contents

List of Figures

I. Introduction

The Incan Empire is well known for its domination of much of the western coast of South America from the years 1425-1532 AD. From their impressive textile manufacturing to their methods of conquering and efficiently ruling various tribes during their time of expansion, the Inca left their mark on the history of South American Andean culture. But one field the Inca truly excelled in was their skills as engineers. With no written language or modern tools such as wheels, they managed to not only construct structures and impressive roadways in the difficult terrain of the Andean mountains, but also implemented impressive water management methods to allow these structures to be maintained in unfavorable water climates. The world heritage site of Machu Picchu is a well-known example of one of these engineering feats, but countless other remarkable sites scattered across the Sacred Valley twenty or so kilometers North of Cusco are just as impressive. One of these sites called Saqsaywaman (Figure 1), roughly translating to "Royal Hawk [1]," stands about 300 meters overlooking the Inca capital of Cusco. Saqsaywaman is currently in a state of disrepair, and it is imperative for cultural, historical, and tourism purposes that it be restored to its original state.

Figure 1: Three Great Walls of Saqsaywaman [15]

This research will explore how implementation of an Inca style terrace system at Saqsaywaman will protect the site from further hydrologic damage.

II. Historical Background

The construction of Saqsaywaman was originally started in 1438 by the Inca Pachakuteq and was completed just prior to the arrival of the conquistadores in the early 1500’s [2]. At any point in time it is believed that 25,000-30,000 people were working on its construction, which is understandable when one considers the vast amounts of energy needed to move, shape, and place each of the stones in the walls. Saqsaywaman has had various uses during its existence. Originally it is believed Saqsaywaman was used as a ceremonial site for Inca rituals, the top sector being reserved for important religious rituals and the open field below for various activities/events that could be viewed from the two adjacent hills [3]. During the Spanish invasion, Saqsaywaman was used as a stronghold because of its advantage of high ground during battles. It is currently used as a major tourism site, drawing in hundreds of tourists each day.

i. Damage: 1532-1600

Almost every aspect of Inca culture was touched when the conquistadores arrived in 1532 and Saqsaywaman was no exception. In fact, the Inca defeat at the hands of the Spaniards marked the beginning of the various stages of degradation of this impressive site. Possibly because of its close proximity to the main city of Cusco, Saqsaywaman experienced more damage throughout the years than other more secluded and overlooked sites such as Tipon and Machu Picchu. During and after the bloody and complex history of the defeat of the Incan Empire by various Spanish conquistadores, Saqsaywaman was systematically damaged in a series of distinct stages.

During the last years of the Incas (1570’s) Spaniards sought to subjugate the Inca people. This meant not only killing their population, but also destroying their way of life. One of the justifications used in the conquering by the Spaniards was the spread of Christianity to the "pagan" Inca people. Saqsaywaman was seen as a reminder of the pagan past of the Inca and had no place in the Christian nation the Spaniards were trying to establish [2]. Lead by the feared Pizzaro brothers, various religious sites were stripped of gold and demolished. The main towers and structures of Saqsaywaman were torn down and many stones that were capable of being moved were transported from the site to the city of Cusco below for construction purposes. Even today many of the stones in the main buildings in historic Cusco can be traced back to Saqsaywaman. While many of the smaller stones from the South side and upper zones of the site were moved, the three monolithic walls avoided the waves of destruction because of the difficulty in moving the largely secured stones.

ii. Damage: 1600-1935

In the centuries after the Spanish conquest of the Inca, Saqsaywaman was largely untended. Any visitor could drive to the site, move soil around, remove stones, and inflict damage intentionally or otherwise. For a small fee an average person could remove truckloads of stones from the site at their discretion [3].

iii. Damage: 1935-present

Since 1935, various excavations have taken place at Saqsaywaman. In some areas excavations were very successful at unearthing the bases foundation of important ruins. The excavation of Muyuqmarka on the top West side of the site is one example of success (Figure 2).

Figure 2: Excavated ruins of Muyuqmarka

In addition to excavations, there have been attempts to digitally reconstruct the site design using archeological clues. A sample of one of these reconstructions created by Ricardo Mar is displayed in Figure 3.

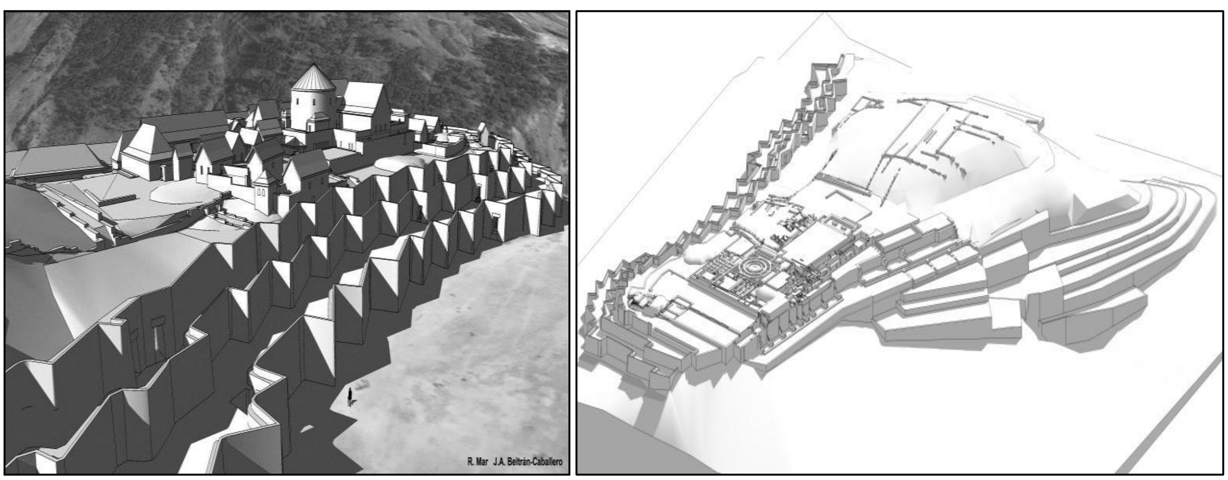


Figure 3: Ricardo Mar hypothetical recreation of Saqsaywaman [4]

Unfortunately, even after these attempts to recognize the importance of the site, protect, and understand it, the compilation of previous errors as well as new unintentional errors in excavations were too much to stop the pattern of degradation. Specifically, some excavation trenches were dug carelessly by unskilled laborers on the site, and these excavations changed the original topography and runoff patterns of the surface. These changes altered the original design and integrity of the hydrology of the site. As much as the damage over the years has affected the site, the most notable dramatic change that spurred UVA's initial involvement in the project was the complete collapse of a large section of the third wall in 2009. The collapse was caused by hydrostatic pressure building behind the third wall created from a 70% increase in runoff as result of topographical changes above the section [5]. This wall was not designed by the Incas to handle the large amounts of runoff that was redirected towards it. Before elaborating more on the collapse, it is necessary to review additional technical details about the site of Saqsaywaman.

III. Background Technical Information on Saqsaywaman

a. Overall layout/sections

Figure 4a shows the entire site of Saqsaywaman with North pointing upwards. A flat grassy plaza about 80 meters across separates Saqsaywaman from a large granite outcropping hill called Rodadero. From atop Rodadero, one can see the most notable feature of Saqsaywaman, the three great monolithic walls spanning over 350 meters across laterally. In addition, the East and West hillsides of the site that will be included in the focus of this study are labeled. Figure 4b shows the three Great Walls labeled and viewed from atop Rodadero.

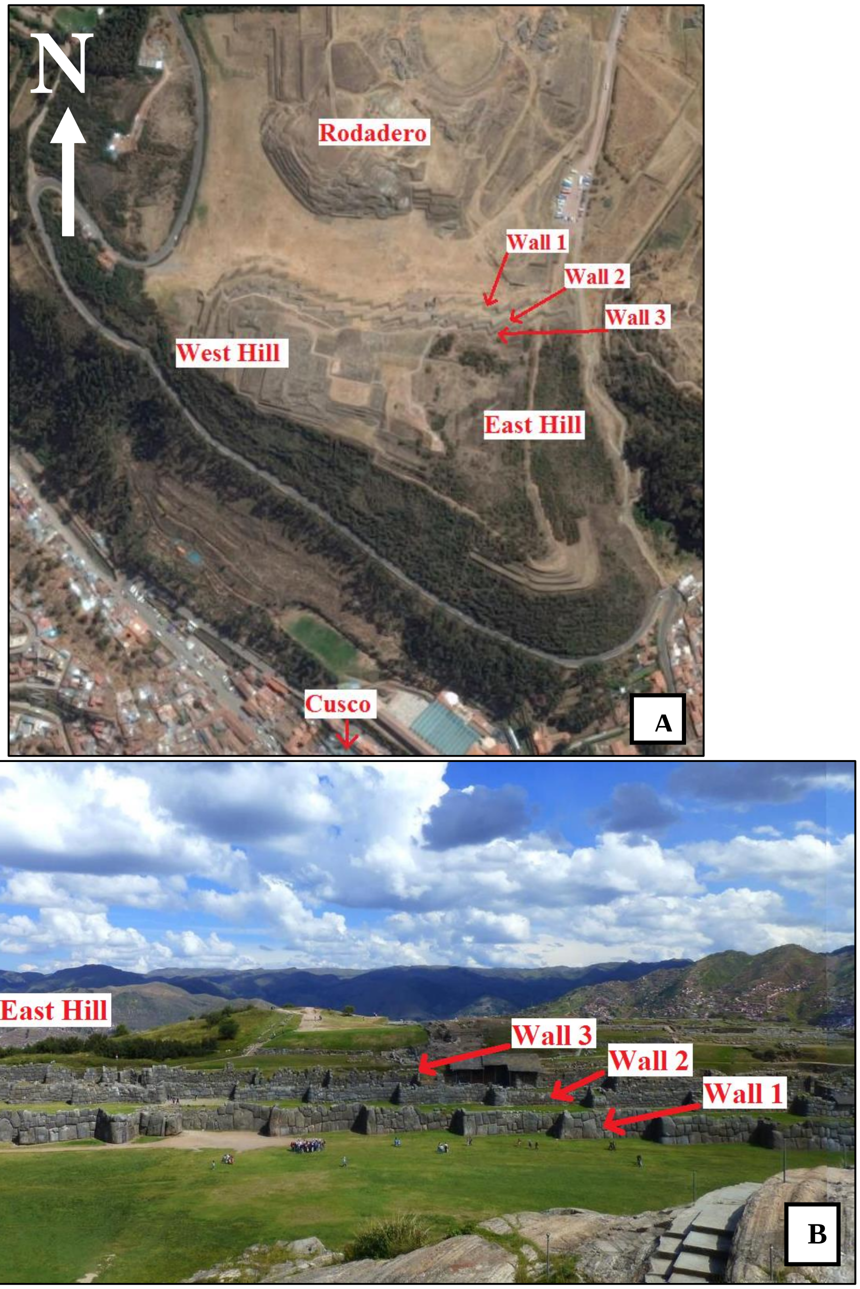


Figure 4: Scope of the entire Saqsaywaman complex (a) plan view (b) from Rodadero

b. Wall composition

The walls are composed of thousands of stones fitted together seamlessly without the use of mortar (Figure 5). The largest of these stones weigh up to 200 tons, and many of the stones were transported from a quarry region 35 kilometers away from the site [6].

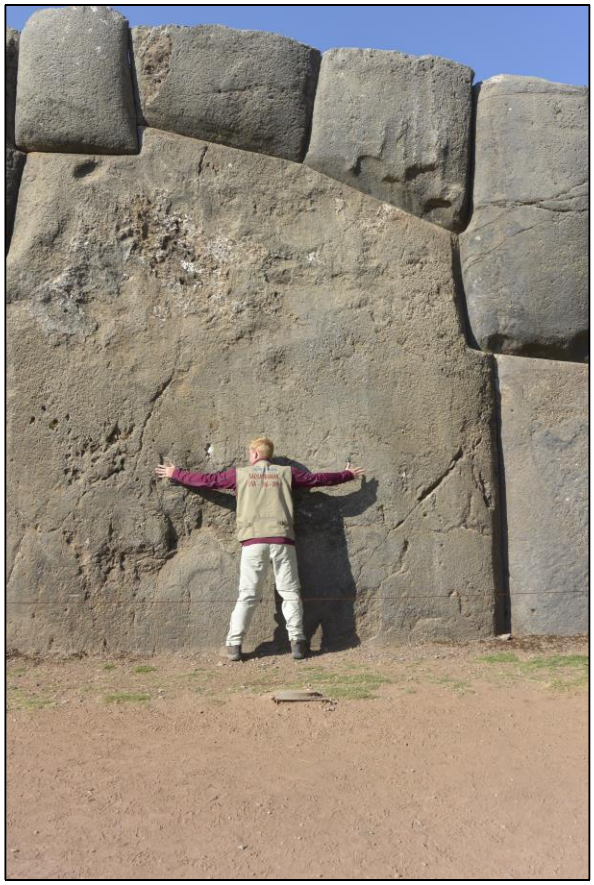


Figure 5: Stones size visual

The three walls have very different properties even though they are relatively similar in outward appearance (Figure 6). The lowest elevation wall, referred to as the *first wall* or *wall 1,* is on average 6 meters tall, is comprised of the largest stones in general, and is made of a double layer of thick stones. A flat region separates this wall from the next, and this region is about 8 meters wide. The middle wall, referred to as the *second wall* or *wall 2,* is similarly a structural two layer wall with smaller stones intersticed between, is slightly shorter in average height, and contains multiple drainage ports that span across the wall's width. A second flat region separates the second wall from the third wall. This region is thinner than the first, and is close to three meters wide. The top-most wall, here on out referred to as the *third wall* or *wall 3,* has a structure very different than the other two walls and is the most important in terms of the scope of this paper. The *central section* of the third wall is a simple terrace wall with no apparent drainage and little structural strength to withstand hydrostatic pressure build. It is made of a single layer of stones with a back fill consisting of soil and larger broken stones that comprise most of the strength of the wall. This backfill is relatively impermeable.

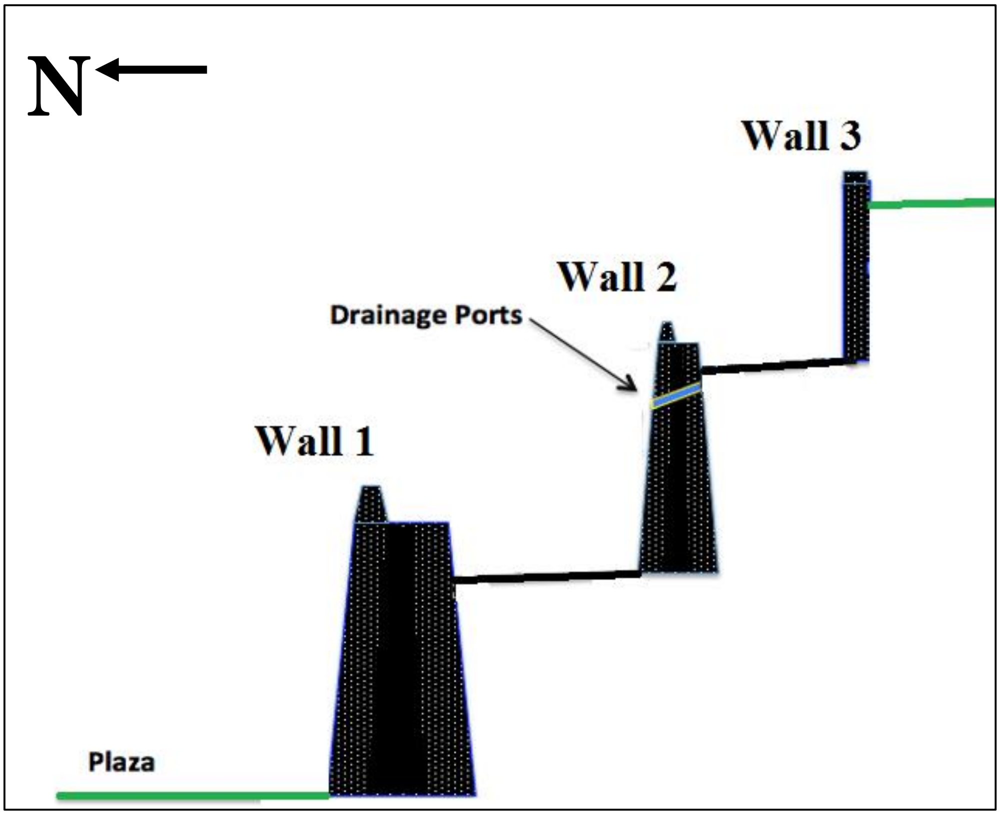


Figure 6: Sketch of three walls general composition

c. Subsurface composition

In terms of the deeper subsurface geology of the site, an INC report showed that the ground beneath much of the site including beneath the first and second walls is mainly composed of a strong base. Contrastingly, beneath the middle section of the third wall the subsurface is composed of *brecha,* a fragmented stone composition weaker in terms of foundation strength (Figure 7). The stronger foundation can support the larger stones in the structural walls whereas the brecha beneath sections of the third wall does not have the strength to support such a wall. This geological subsurface information may explain why the first two walls are structural and the third wall has a section that is a simple terrace wall.

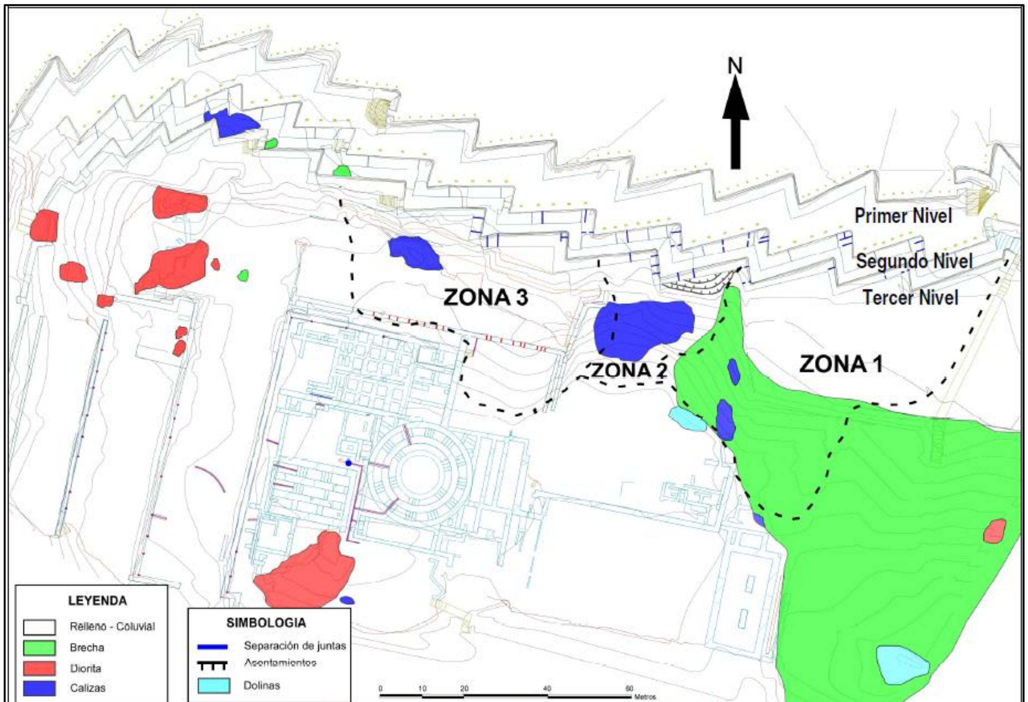


Fig. 5 Mapa Geológico y geodinámico de los Baluartes

Figure 7: Subsurface geologic map [7]

d. Implications

Important additional information can be assumed from the composition of the walls and terraces. Here we will briefly touch on some of the key points that support the hypothesis that the third wall was not intended to handle significant runoff and that a different mechanism would have had to be present to handle it. First, the presence of drainage ports in the second wall and lack of drainage ports in the third wall implies that the third wall was not intended to handle runoff like the second wall was. Drainage ports would be used to transport water falling on the second terrace through the wall down to the next layer in a controlled manner. Lack of drainage ports on the third wall implies that the third wall was not supposed to have significant amounts of water running across it. Secondly, the fact that the first two walls have a permeable backfill and the third wall's backfill is not as permeable is also evidence that the third wall was not intended to cope with significant runoff. Permeable soil allows water to infiltrate in a dispersed controlled manner, while impermeable backfill behind the third wall concentrates the flow of water to directly at the interface of stone and backfill (see Figure 10). This concentration adds horizontal stress on the wall that the simple terrace wall would not be able to handle. One can therefore again assume that the impermeable backfill indicates that the third wall was not intended to handle runoff. Lastly, the different structural components of the walls give clues to their purposes. The first and second walls are fully structural walls that are physically capable of withstanding horizontal force because of the size and strength of their stones. However, as previously mentioned, the third wall has sections that are not structural and instead are simple terrace configurations. These thinner weaker sections could not support large amounts of water flowing horizontally, and as such, we hypothesize that the Incas never intended the third terrace wall to receive vast amounts of runoff water.

Even while the rest of the site was being harmed, for hundreds of years the three monolithic walls stood relatively unyielding to nature's conditions. It is therefore reasonable to assume that modern day actions upon the site have caused the more dramatic degradation, and that these actions must have changed the intended runoff patterns.

IV. UVA Project

Often it takes a dramatic event to spur long needed change. Such was the case with Saqsaywaman. During the winter rainy season of 2009, a large section of the middle wall collapsed suddenly. As one can see in Figure 8, the collapse involved the movement of huge stones that had remained relatively stationary for centuries.

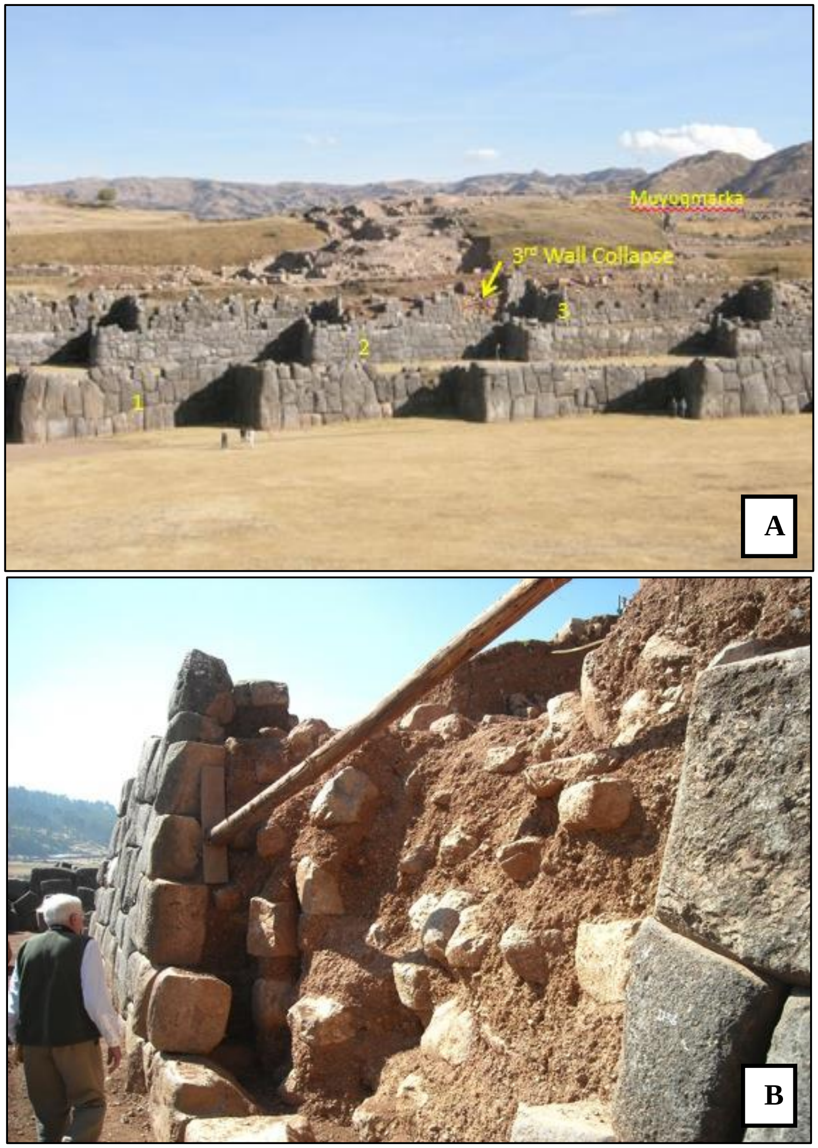


Figure 8: Collapsed section of the third wall (a) relative location (b) collapse [16]

A team of UVA students led by Dr. Richard Miksad was recruited to investigate the causes of the collapse. It was discovered that a buildup of hydrostatic pressure behind the central portion of the third wall caused the collapse. An archeological dig was conducted in the ground above the third wall in the months before the collapse. This dig uncovered important original Inca stonework, and to protect the stonework from damage due to the elements, an impervious clay was laid over top of the surface as shown below in Figure 9.

Figure 9: Impervious clay surface above third wall collapse [16]

This impervious surface had the unintended consequence of altering the natural infiltration and runoff patterns of the top section of the site, and caused a water slide of sorts to be directed perpendicular to the third wall. As previously mentioned, the construction of the third wall involved a single stone layer with a relatively impervious soil rock mixture backfill for strength and lacked drainage ports [6]. As this increase in water cannot effectively move through the impermeable backfill, instead it wedged itself between the backfill and the single layer of stones creating a hydrostatic pressure force gradient directed directly out into the wall (Figure 10). This force ultimately was the cause of the collapse of 2009.

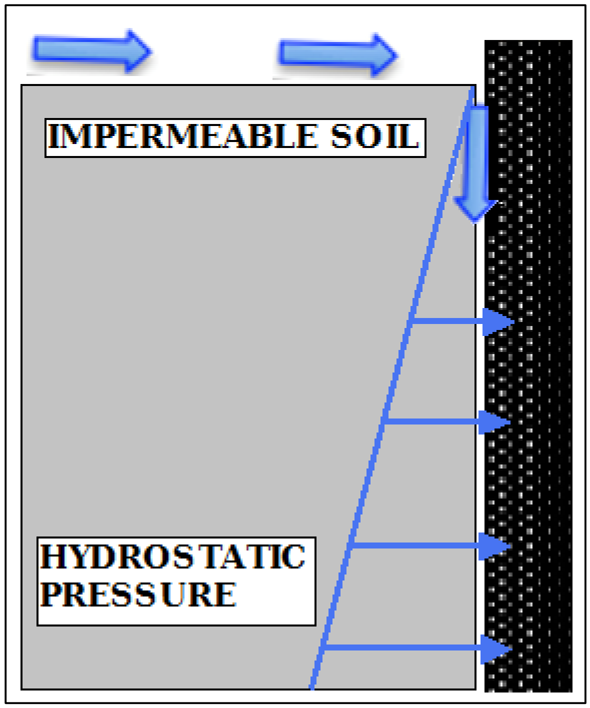


Figure 10: Hydrostatic pressure build

Although this singular event could be pinpointed to one mistake on the part of the people doing the excavation, it spurned a larger investigation into the runoff infiltration patterns on the site. The center section of the third wall displays the effects of hydrologic damage most dramatically because of its impermeable backfill and lack of strength of its smaller terrace wall stones, but the rest of the site is experiencing similar damage albeit in a less dramatic fashion. Walls 1 and 2 have more permeable backfill to disperse the effects of the hydrostatic pressure build across the entire span of infiltration zone, and their larger stones are better able to withstand that pressure, but they are still showing signs of damage. The first and second walls have not collapsed yet, but in various sections, severe bulging can be observed that was not seen ten years ago. In addition to the bulging there are various other visible examples of damage. The batter (vertical slope of the wall face) of the original walls has historically been around 10% tilted backwards to provide resistance to horizontal pressure forces exerted on the back of the wall. In July 2010 a survey was conducted that the batter in some areas was as little as 2% [6] (Figure 11a). Bulges in the wall can also be observed at various locations along the length and supporting rods have been placed against these locations to temporarily restrain the damage (Figure 11b). Previously impeccably aligned stones now can be seen to be separating from one another (Figure 11c) and experiencing shear damage (Figure 11d). In addition, the walls are being eroded and have begun to fracture in numerous locations (Figure 11e).

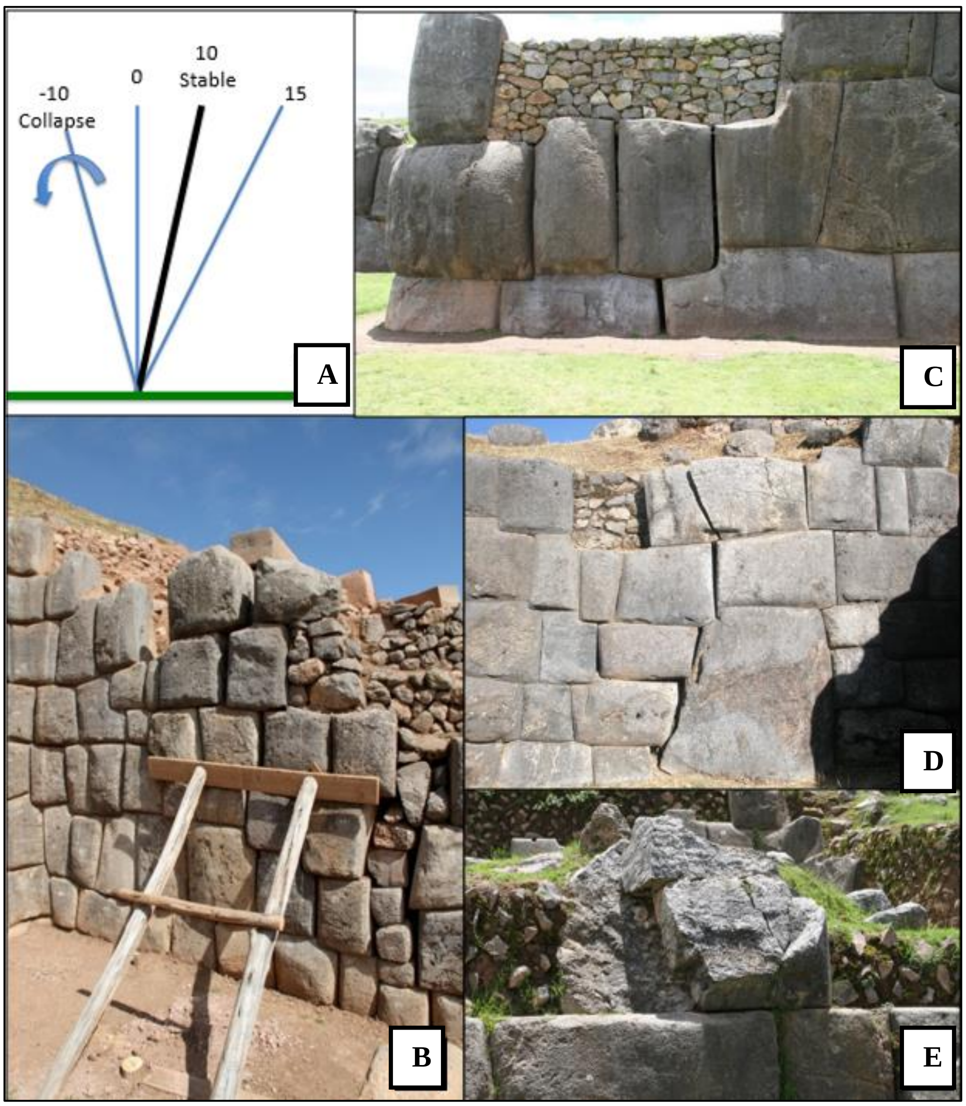


Figure 11: Physical evidence of damage to walls: (a) batter diagram (b) bulging and support structures (c) wall separation (d) vertical shearing (e) fractured stone [16]

Many of these problems in all three walls of the site can be traced back to incorrect water movement patterns. The movement of the stones seen in the decreased batter, wall separation, and bulging can be attributed largely to hydrostatic pressure and the physical damage in the form of fractured stones can be partially attributed to erosion as water flows over areas of the wall it did not flow over beforehand. All three walls are vulnerable to increasing amounts of damage if the underlying hydrologic problems aren't resolved.

As previously mentioned, the Inca were master engineers, not only for their time, but even by today's standards. If you look at other sites in the sacred valley that were more untouched, you would be hard pressed to find another site that allowed detrimental water flow patterns to harm the integrity of structures. By comparing notable features of other sites and clues at Saqsaywaman, we formed the following hypothesis about the root cause of the changes to the intended Inca runoff patterns: before changes were made to the site by various parties, *terraces* and base channel culverts along these terraces were used to run water in a controlled fashion parallel to the walls.

V. Justification of Theory of Terraces

a. Technical Soundness

Before exploring archeologic evidence of the existence of terraces at Saqsaywaman, it is important to elaborate on how terraces themselves could resolve the runoff issues at the site. Terraces can reduce the velocity and volume of surface runoff perpendicular to a surface down a slope by reducing the slope itself. To explain this phenomenon a bit more, consider the following hypothetical sloped surface divided into three sections A, B, and C (Figure 12).

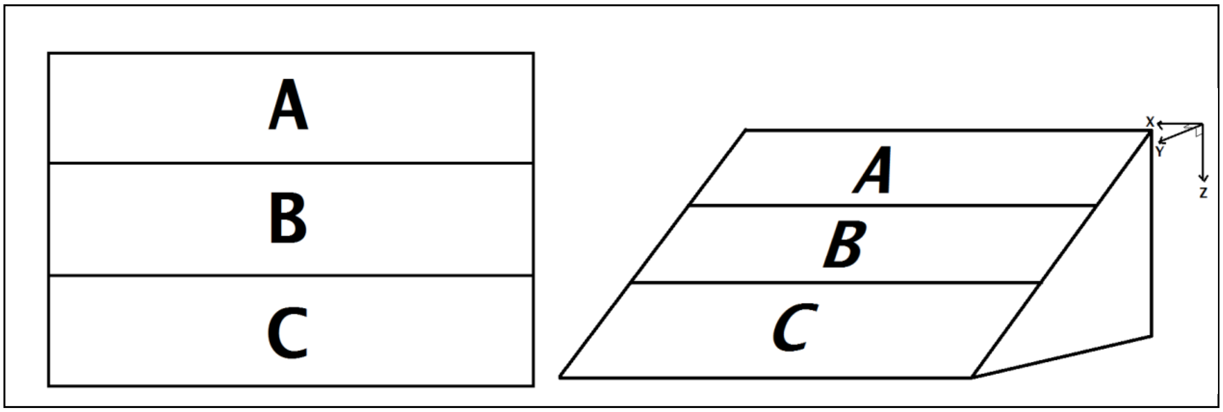


Figure 12: Hypothetical sloped surface

First, *without* terraces, the surface has the steepest downward slope in the "zy" direction. It also has a slight grade in the "x" direction. If one was to simulate rainfall with a volume V on the surface and watch the path it took down the slope, the water would develop an increasing flow vector as it moved down the slope due to gravity. The majority of the velocity would be in a direction perpendicular down the surface because of the large slope in that direction, and the "x" component of the slope would slightly deflect the velocity to the left. The total volume V of water from section A would largely be transmitted to sections B and C sequentially down the surface creating increasingly damaging flow conditions (Figure 13). This is the situation occurring in the current configuration without terraces.

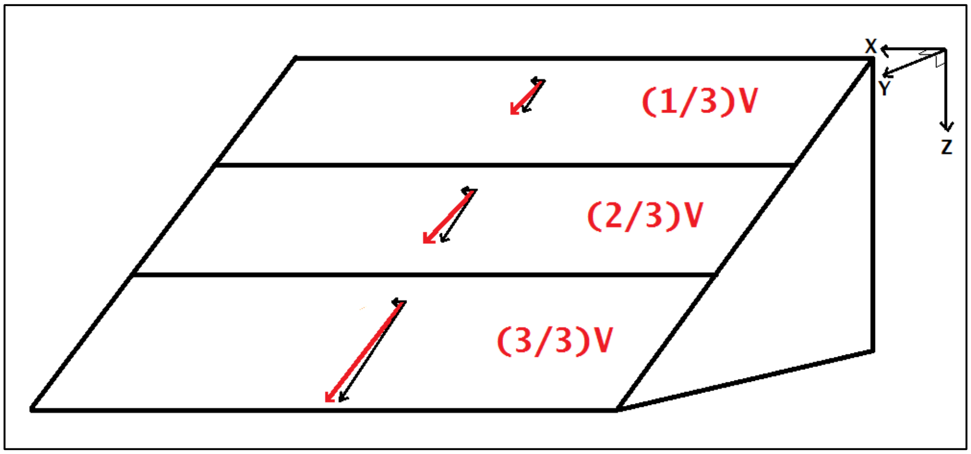


Figure 13: Runoff without terraces sketch

Contrastingly, consider the same surface *with* terraces. This surface has the same slight grade in the “x” direction, but now has no slope in the “zy” direction like before. Now if one was to simulate rainfall with volume V on the surface and watch the path it took, the water path would only be influenced by the “x” direction slope and would flow laterally parallel to the surface. Without this “yz” flow, water would not be transmitted across the section boundaries and sections A, B, and C would only need to deal with $\frac{1}{3}V$ each respectively (Figure 14). This is a depiction how the flow could behave if terraces were implemented. This configuration is preferable because not only is the water now moving in the correct direction, but also the velocity of the water is decreased as the slope is decreased. This decreased velocity lessens erosion control issues.

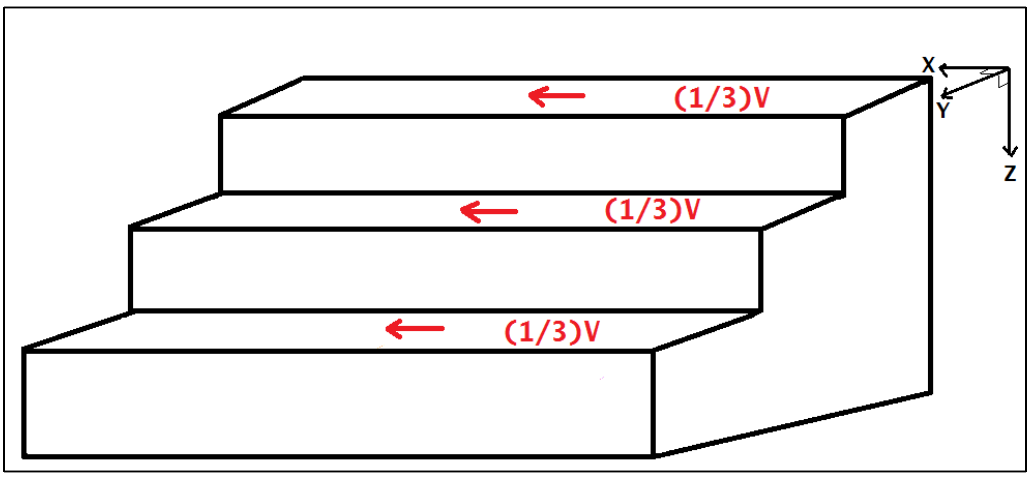


Figure 14: Runoff with terraces sketch

A simple conceptual analysis of these effects on our site can be seen by looking at the following general flow direction graphic created by former M.S. student Kenny Lohr. These hypothetical terraces were drawn in based off of a sketch by Gasparirni and Margolies displayed in Figure15. Figure 16a shows the general surface runoff patterns without terraces. Water collects on top of the third wall and runs mainly perpendicular to the walls as predicted in Figure

13. The compounding effects of water moving from terrace to terrace can also be observed via the increasing size of flow arrows as you move down the slope. Figure 16b shows the general surface runoff patterns if terraces were implemented. As one can see, with the terrace configurations, assuming water flows along terraces in culverts, and assuming water flows from one terrace to the next in a series of controlled drops, water now flows parallel along the walls as predicted by Figure 14.

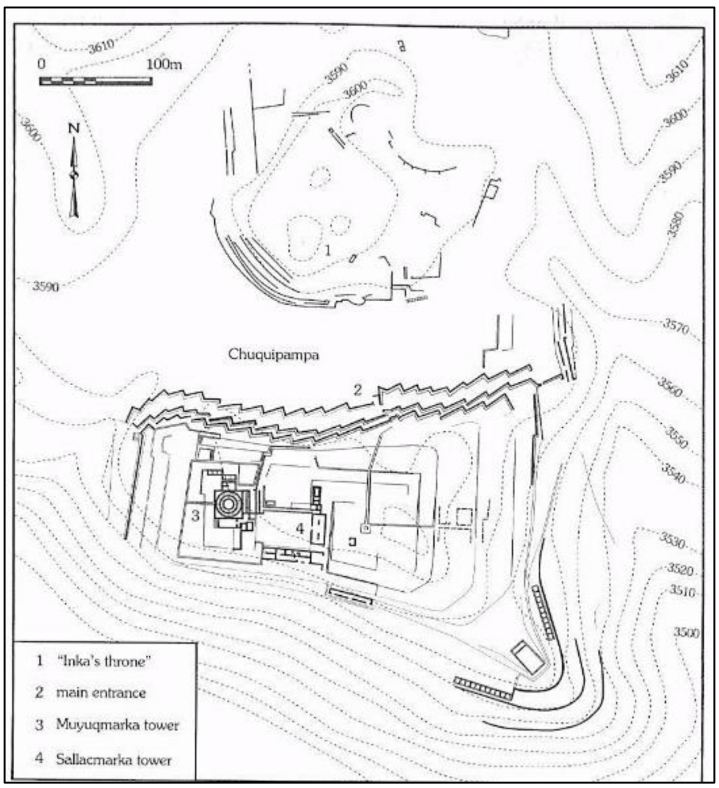


Figure 15: Gasparirni and Margolies sketch of terrace locations [8]

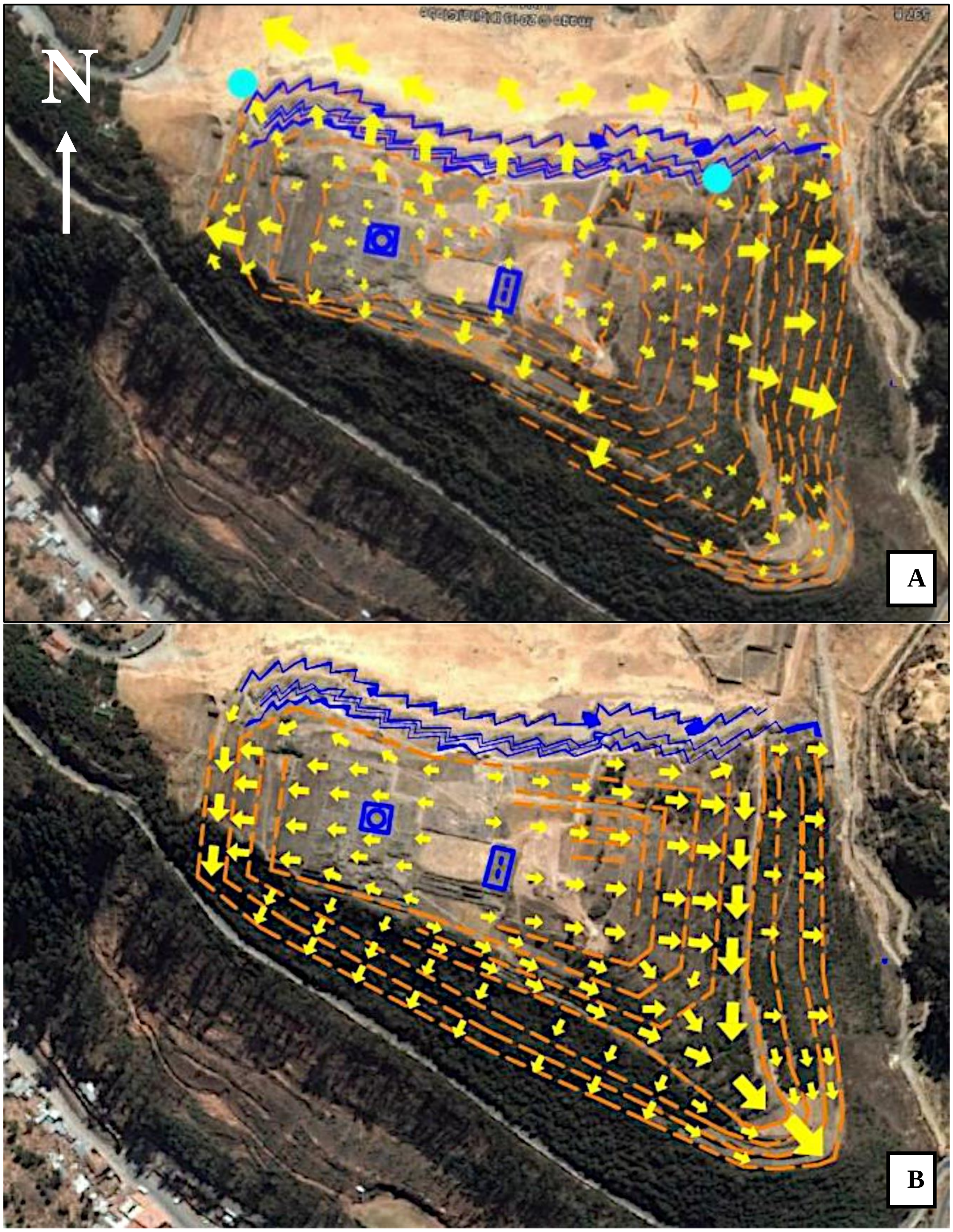


Figure 16: Conceptual flow directions (a) without terraces (b) with terraces [6]

One may be curious why these drawings focus on the East hill of the site when the North side is where the walls we want to protect are located. The Inca were masterful in their water management practices. Because of this we assume they would not have simply diverted water away from the three walls and let it run uncontrolled off the East and West sides of the site. They would instead have created a comprehensive terracing system that wrapped around the entire site and would move the water in a controlled fashion through drains and drops to a collection point on the back South side of the site where it would not be in danger of affecting the three Great Walls. Because of this, the terrace analysis conducted for this research will largely focus on the East hill of Saqsaywaman.

b. Examples of terraces at other Sacred Valley sites

Aside from the hydraulic soundness of the theory, the second piece of evidence that led to this hypothesis was the effective use of terraces at various other Inca sites in the Sacred Valley. The first example of correct management of water can be seen at the site of Ollantaytambo about 40 kilometers northwest of Saqsaywaman. As you can see in Figure 17a below, terraces were implemented on the side of this site to control the flow of water directly down the hillside. On the staircase, one can observe a thin channel that allows water to cross the system of terraces in a controlled manner and be redistributed to other areas for use (Figure 17b).

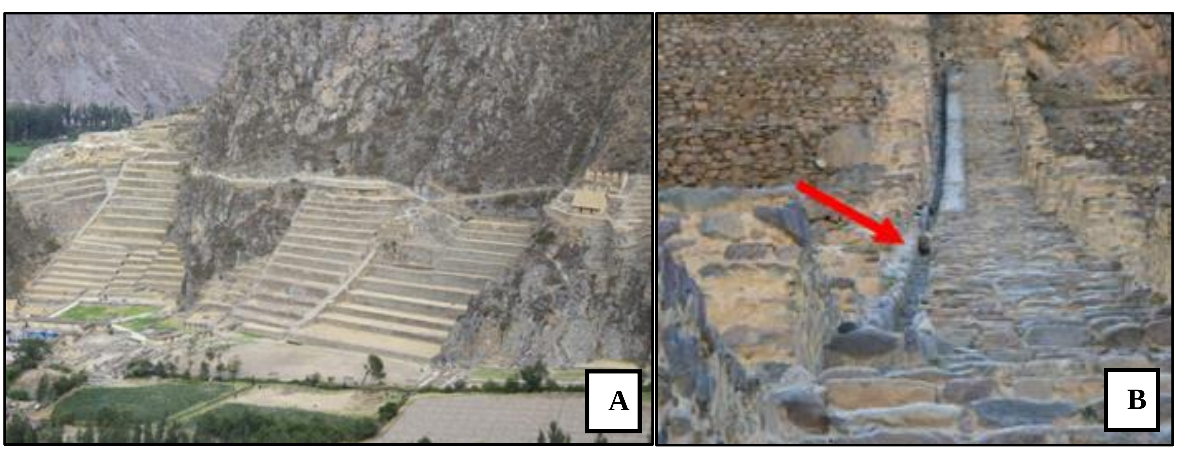


Figure 17: Ollantaytambo (a) Terraces (b) evidence of drainage along stairs on side [16]

In this case, the water flows to the lowest terrace and then into a series of religious fountains at the base of Ollantaytambo. Another site by the name of Tipon that implements similar water control methods is pictured in Figure 18. Again, one can see that terraces are used to prevent the flow of water directly perpendicular to the slope and instead water is gathered by a series of terraces and culverts until it can be re-distributed in the form of an artful fountain. Tipon is a great example of the previously mentioned base channel culverts along terraces that we expect to see at Saqsaywaman. In addition, the well-known site of Machu Picchu has various terrace culvert designs that can be seen as you walk through the ruins that control and manipulate water in similar ways (Figure 19).

Figure 18: Tipon terraces and drainage channels [17] [16]

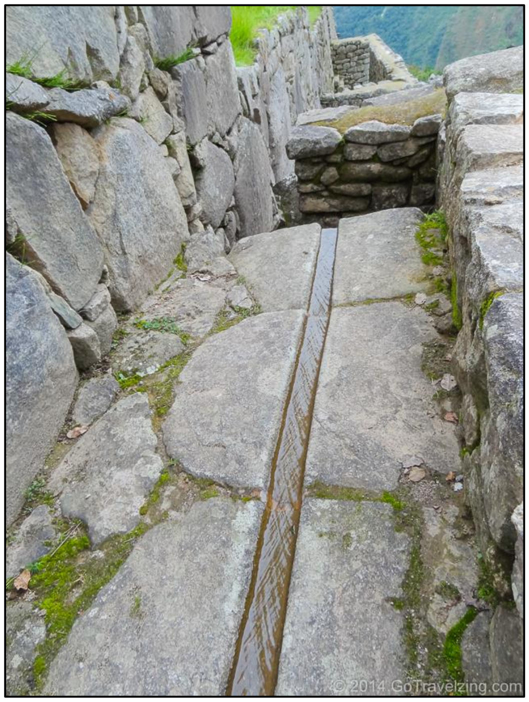


Figure 19: Machu Picchu culvert [18]

All of these examples serve as evidence that the Incans took careful consideration in the design of their structures to ensure that water did not flow uncontrolled over sites. These sites were all made during the same century, so it is reasonable to assume water management techniques implemented could have also been used at Saqsaywaman. Not only were terraces used at other sites, but even in Saqsaywaman itself you can observe techniques that controlled the flow of water. As previously mentioned, walls 1 and 2 have permeable backfills and the wall 2 has drainage ports spanning its cross-sections, both signs these walls were intended to allow proper drainage and prevention of hydrostatic pressure builds that could damage the walls. The collapse of a section of the center of the third wall revealed a backfilled with impervious soil rock mixture, so based off their previous demonstration of mastery of water runoff control, one can reasonably assume that they must have never intended for water to reach this third wall.

They must have had a mechanism to divert water away before it hit wall 3, and the hypothesis of terraces fits this assumption.

c. Visual evidence at Saqsaywaman

The next piece of evidence to substantiate the formation of the terrace hypothesis came from aerial imagery showing the existence of at least one section of a terrace wall that has since then been covered by soil deliberately for unknown reasons (Figure 20). In addition to this previously visible terrace wall, there is evidence of terraces along the stair case on the East upper side of the site. As you can see in Figure 21b, there are distinct levels that could indicate terraces used to exist in these locations. Lastly, the grades of the East side of the site are sloped in such a way that one can almost see evidence of where terraces used to be simply by walking along and observing. This piece of evidence is the least strong because the back side of the site has been regraded during various excavation when soil was moved in an unregulated manner, but is evidence nonetheless. This slope is shown in Figure 21a.

Figure 20: Old picture of Saqsaywaman showing terrace that has since been buried [16]

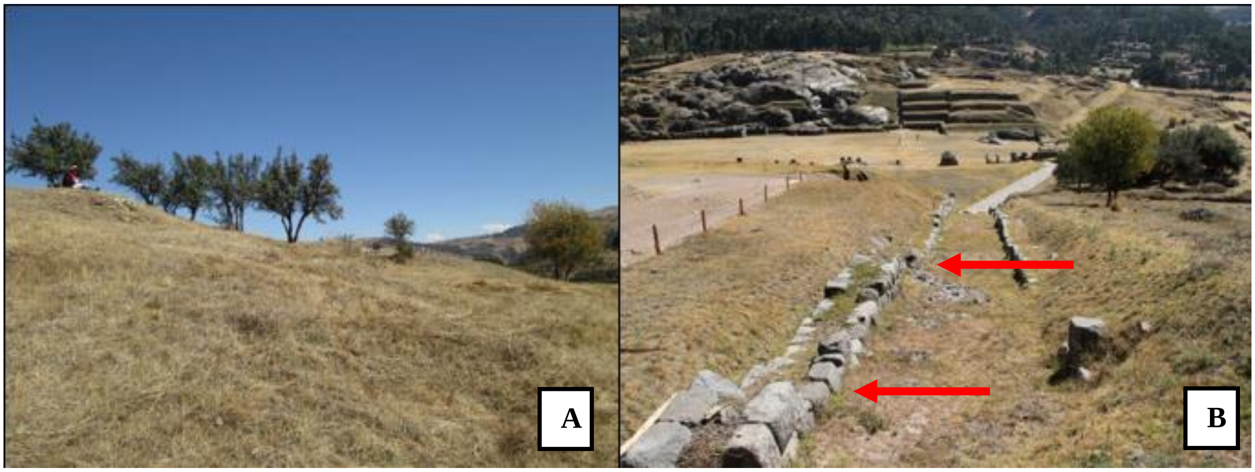


Figure 21: Evidence of old terrace grading (a) along stairs (b) on back East side of site [16]

These visual clues were not enough to prove the terrace hypothesis. In order to adequately substantiate this hypothesis, two main goals were set that guide the remainder of this paper:

1) Locate Inca terraces on site using subsurface profiling and visual evidence
2) Show using 3D hydrologic models that implementing terraces will improve the hydrologic patterns of the site

The first of these two goals was the focus of the Summer 2015 research trip to Peru, and the second of these two goals is the focus of my MS thesis technical report section following.

VI. Goal 1: Locating Inca Terraces on Site

The first of these goals was the focus of the summer 2015 trip to Cusco. Led by Dr. Miksad, a team including myself and fellow UVA students, Edward Tiernan and Gina O'Neil, sought to obtain evidence of terraces on the back side of Saqsaywaman. In addition to UVA students and faculty, we collaborated with two Peruvian universities, Universidad Nacional de Ingenieros (UNI) and Universidad de Ricardo Palma (RP). Three non-invasive techniques were used to locate the terraces: seismic refraction, ground penetrating radar, and total station point location of visual evidence.

a. Seismic Refraction

For the summer 2015 project, students from UNI and RP collaborated using a *SmartSeis ST Geometrics* model seismic refractor. A series of 24 geophones operating at 14 Hz frequency were lain across cross-sections of interest [9]. In order to initiate the data collection, the end of the device was hit with a heavy hammer (Figure 22). This impact creates P-waves and the arrival time of these P-waves at various geophone nodes along the length of the ladder can be measured. When an object inhibits the P-waves motion, it shows up as a disturbance on the machine. An example of a reading of the seismic refraction machine can be seen below in Figure 23, where points of interest are marked with arrows.

Figure 22: Team conducting seismic refraction test

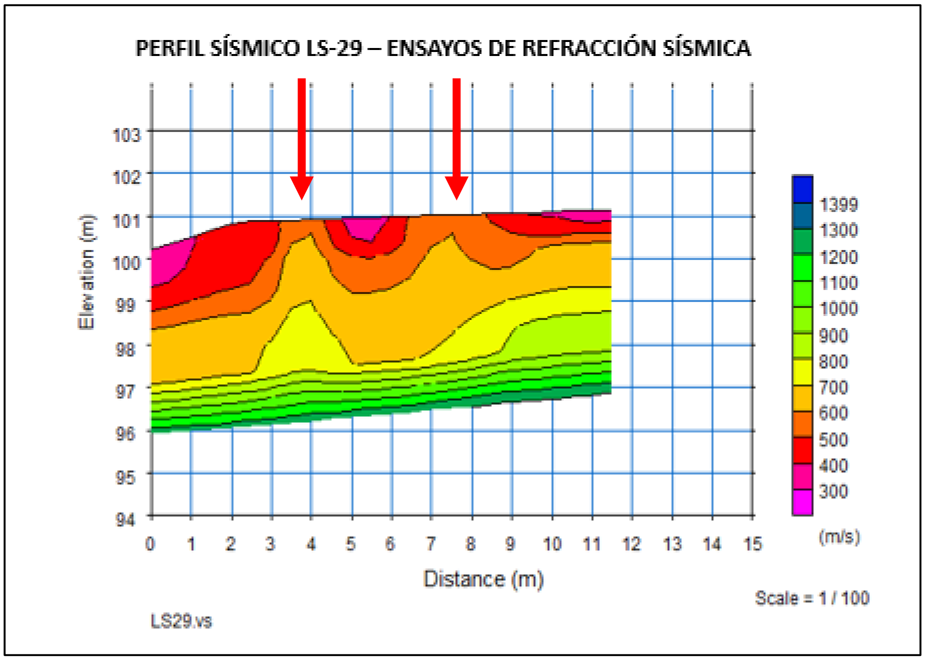


Figure 23: Example reading of seismic refraction machine [9]

Seismic refraction is a good tool for subsurface characterization because the output graph can be read relatively easily and it gives accurate information for composition of the material based on travel time of the P-wave.

b. Ground penetrating radar

The second technique used to corroborate the results of the seismic refraction was Ground Penetrating Radar (GPR). UVA students used a *Quantum Imager Ground Penetrating Radar* model at 200 MHz frequency (Figure 24a). GPR transmits a radio signal into the ground, objects beneath the surface reflect the signal back to the machine, and the time it takes for the signal to be returned at various depths is recorded in picture format [10]. An example of the output of one of the GPR runs is shown below in Figure 24b.

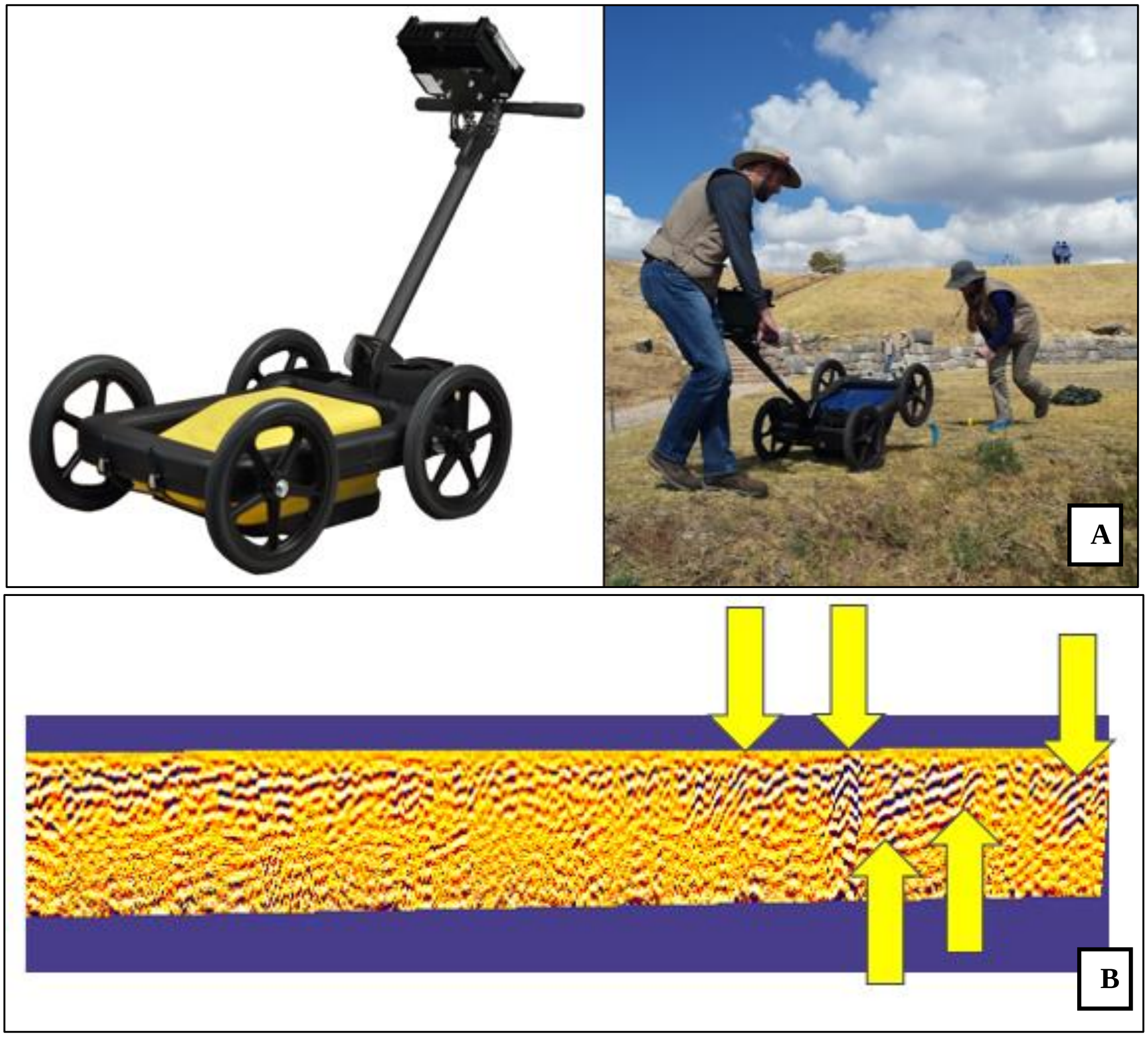


Figure 24: GPR (a) machine and use (b) sample reading [19]

GPR is a good tool for subsurface characterization because it is similarly non-invasive and returns valuable data. On the tablet the starting and ending GPS locations of the run are recorded, and the user can click on points along the run screen output at their discretion to identify points of interest. While in some cases this user flexibility is helpful, a limitation of the GPR is that it is more difficult to visually see the disturbances on the screen. Figure 24b is a good example of how complex a reading from the GPR can be. In addition to this limitation, GPR has resolution issues. Linear runs do not necessarily accurately depict the dimensions of 3D objects under the surface, and if you make the runs too dispersed, you can miss important information.

To simultaneously reduce the error in each of the two machines and validate the results, the GPR was run over the same tracks that the seismic ladder was placed, and the results were compared side by side. Figure 25 shows the tracks that were run over the site with rough sketch field approximation green lines connecting common points of disturbance. Figure 26 below is one example of this side by side comparison of results, and as you can see, at points 1 and 2 there are disturbances on both of the machines that could very well represent buried terraces. In order to validate the reliability of both of techniques, both the seismic and GPR were run over the hillside with the re-buried terrace shown in Figure 20. Because we knew there should be a disturbance shown on any subsurface profile, it was a good way to validate the method's accuracy. When this test was conducted, both the GPR and seismic refractor were in fact able to detect accurately the existence of the known buried terrace at this location.

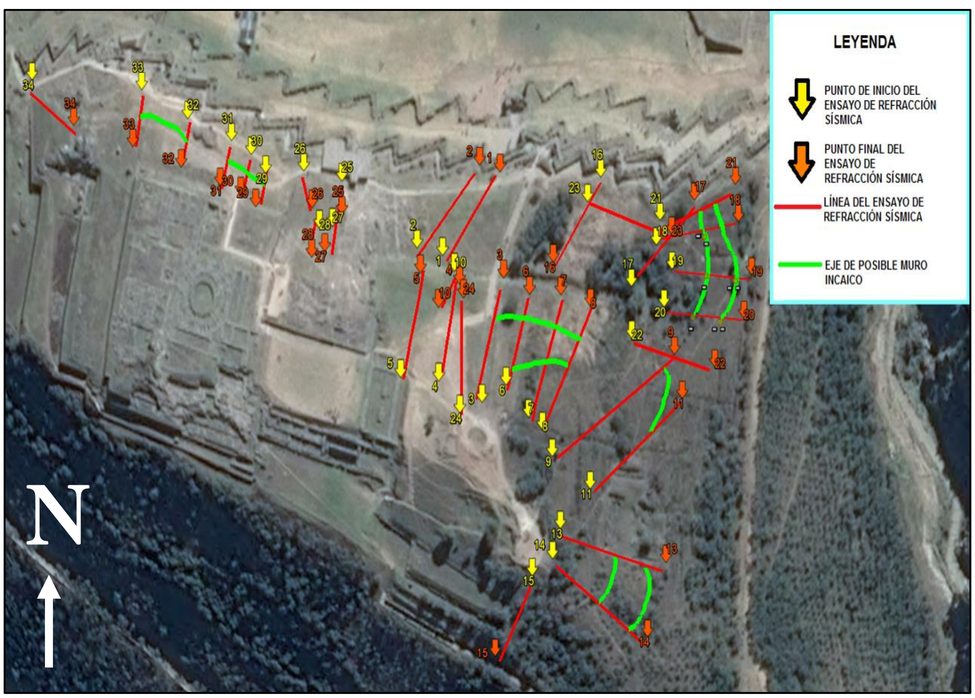


Figure 25: Aerial display of all the GPR and seismic refraction runs with green lines connecting common disturbances [9]

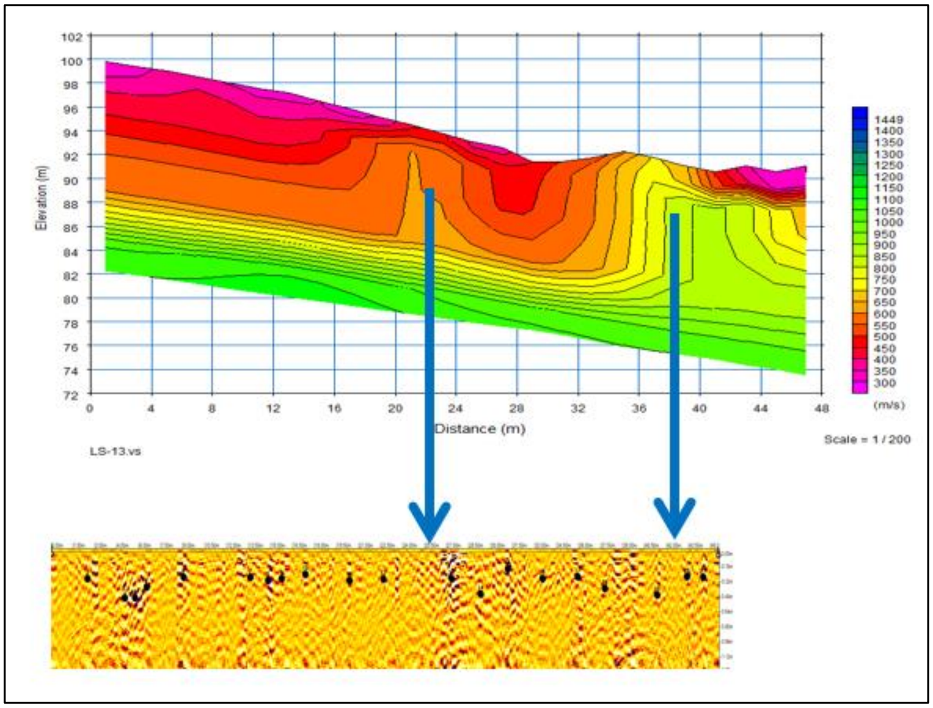


Figure 26: Corresponding disturbances in the GPR and Seismic Refraction readings

c. Total station point measurements of visual evidence

The final piece of data used to corroborate the location and existence of buried terraces on the back side of Saqsaywaman was visual evidence. Using a *Topcon GTS-240 HW Series electronic Total Station* model (Figure 27), a small group of UVA students including myself walked around the site looking for segments of terrace that remained above ground. One area showing three clear terraces can be seen in Figure 28.

Figure 27: Total station model and use

There are a few areas of the site east slope where there are clear terraces such as in Figure 28; however, there are multiple places on the site where soil and rock have been moved in unregulated manners, and excavations have been started and abandoned leaving piles of rubble and mounds of soil. These factors make it difficult to say what is a collapsed terrace, what is a moved stone, and what is simply the ruins of a different kind of structure. The clear terraces shown in Figure 28 and the results of the GPR and seismic refraction are more heavily considered as evidence in the terrace location determination steps following.

Figure 28: Example of some of the visual terraces on the East side of the site that remain above ground level [16]

d. Combination: analysis and mapping

The final result of the summer's work were three CSV point files that each showed the location of points of interest that could represent disturbances caused by buried terraces. These point files were used in a series of steps that resulted in lines representing a hypothetical terrace configuration.

First, the three point files were imported into an ArcMap 10.3 program. Each file's data had to be manipulated in a specific way to get it into a common coordinate system and format. For this project, Universal Transverse Mercator (UTM) Zone 19 South was chosen for the projection because of its location accuracy relative to Cusco. Figure 29 shows the mapped points of interest on the site.

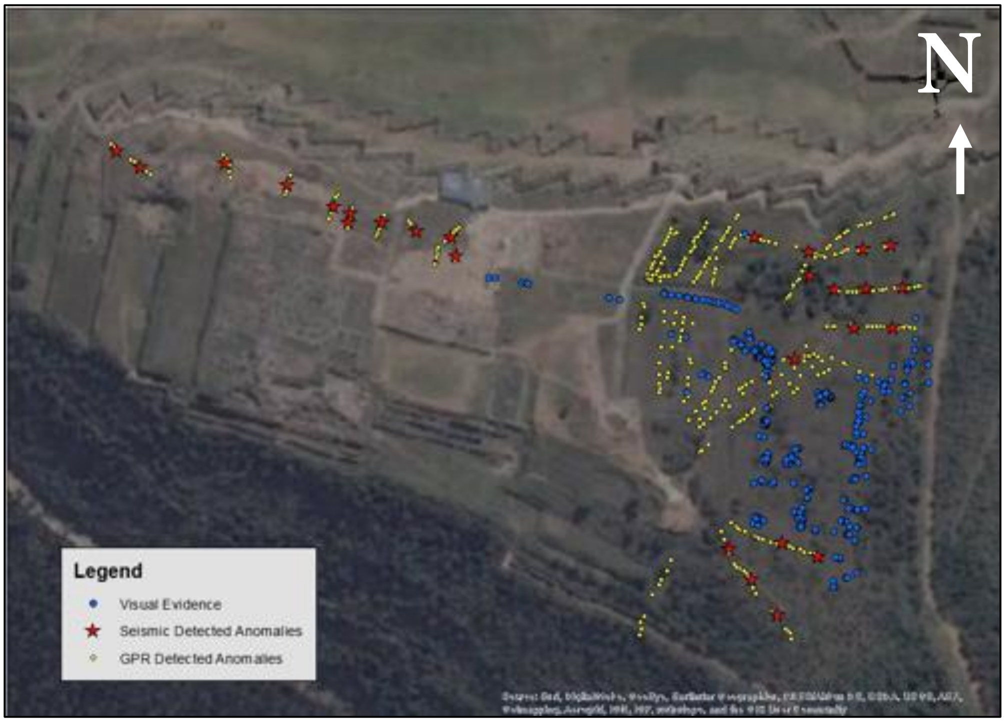


Figure 29: All points of interest collected summer 2015 [11]

In addition to the points of interest collected in summer 2015 from the three methods previously elaborated on, it is important to note the necessity to connect hypothetical terraces lines to actual existing terraces. On the West side of the site, there are six terraces that can be seen in Figure 30. On the East side of the site there are three terraces that can be seen in Figure 28. Figure 31 shows these existing terraces on the west side of the site in a map format along with the east side terrace location (shown in purple dots). It is reasonable to assume based on other Inca site terrace systems that the terrace system for Saqsaywaman wraps around the site in a relatively continuous manner. This holistic terrace design hypothesis is one assumption that was used when drawing in the hypothetical terrace lines in the ArcMAP file.

Figure 30: Existing terraces on East side of site

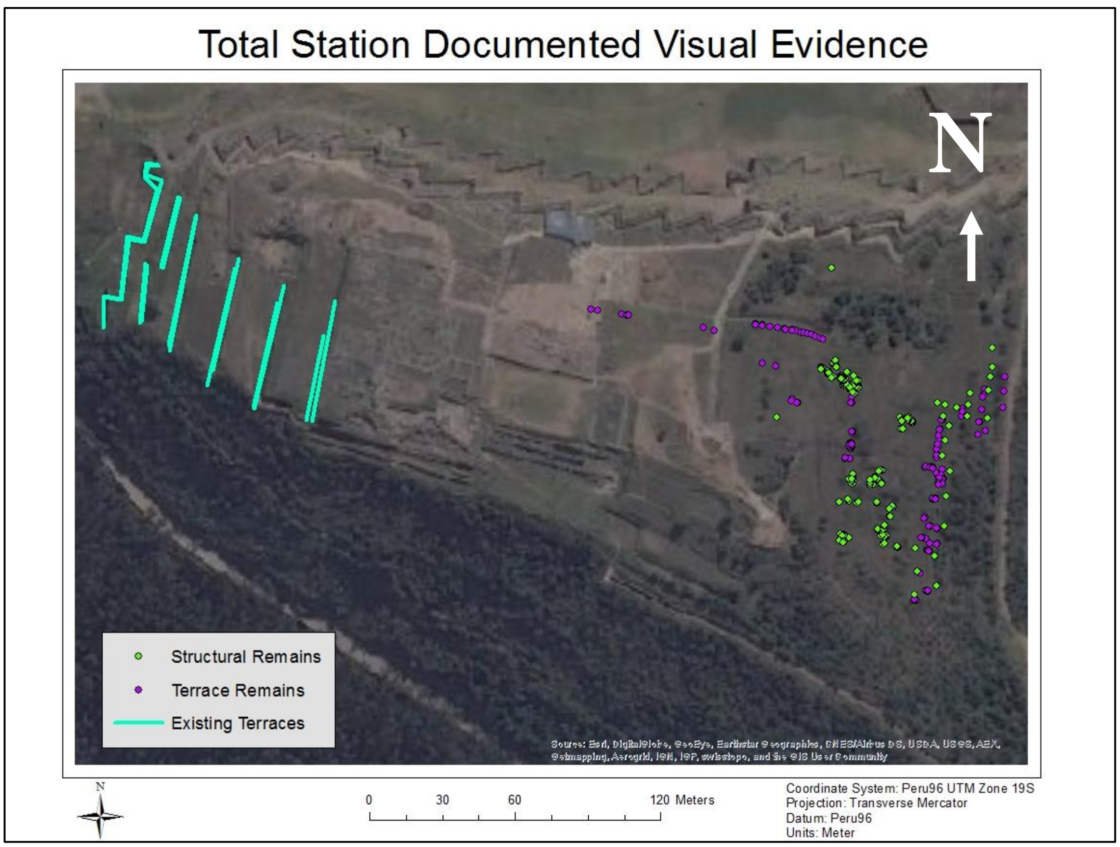


Figure 31: Compiled visual evidence map [11]

Next, once the data was all compiled into one map, lines of hypothetical terraces were drawn based on points of agreement between the existing terraces, seismic disturbances, and GPR disturbances. These hypothetical terrace lines can be seen in Figure 32. Three of the terraces on the lower west side do not curve around like the rest, and this is because of evidence that these terraces merged with drainage channels at the corner sections of the three monolithic walls.

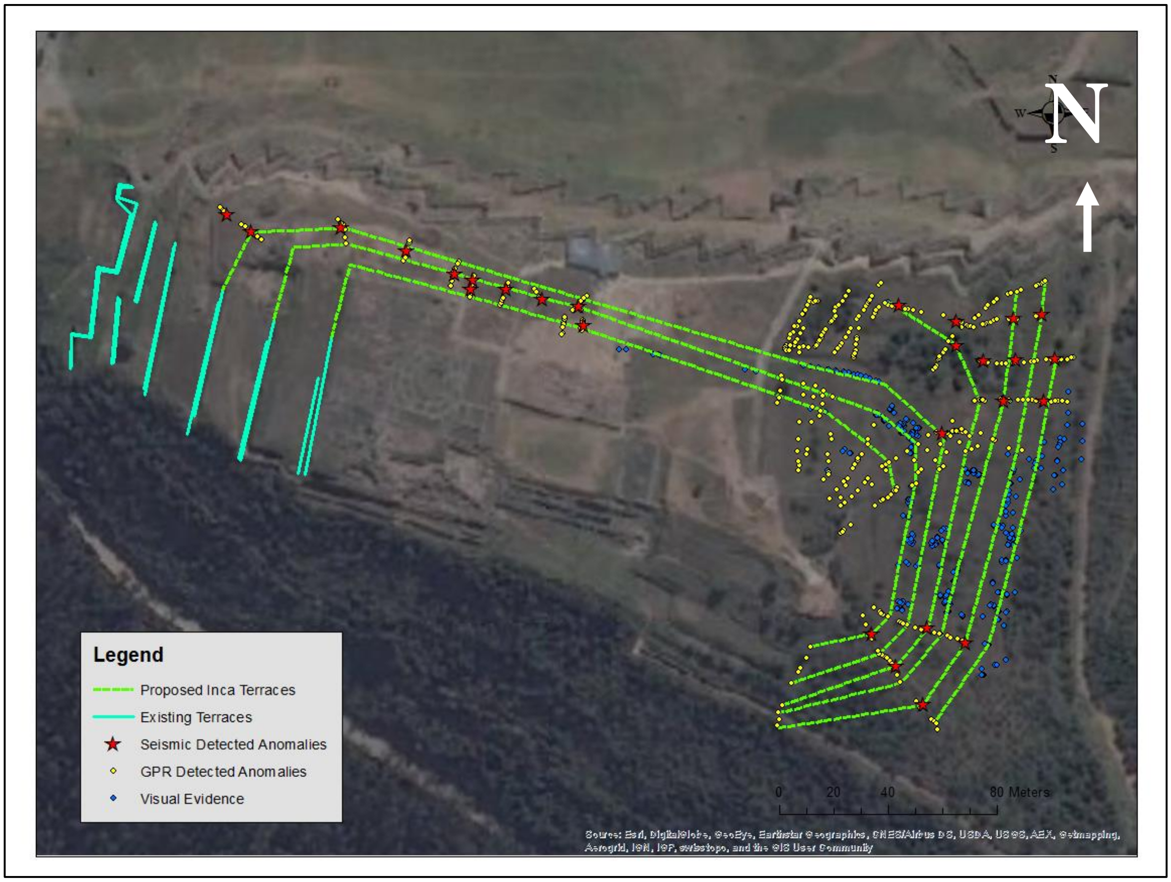


Figure 32: Proposed terrace lines [11]

These terrace lines shown in green in Figure 32 were the base for the next stage in validating the terrace hypothesis: using 3D modeling tools to demonstrate improvements terraces could have on site.

VII. Goal 2: Surface Model Creation and Comparison Analysis

As previously outlined, the second goal to fully validate the theory that implantation of original Inca terraces would remediate the detrimental runoff patterns of Saqsaywaman involves the use of a model to show physically how the flow directions and magnitudes would change. In order to do this, AutoCAD Civil3D was used in conjunction with the ArcMap terrace data created. The remainder of this paper documents my new contributions to the research project analysis work.

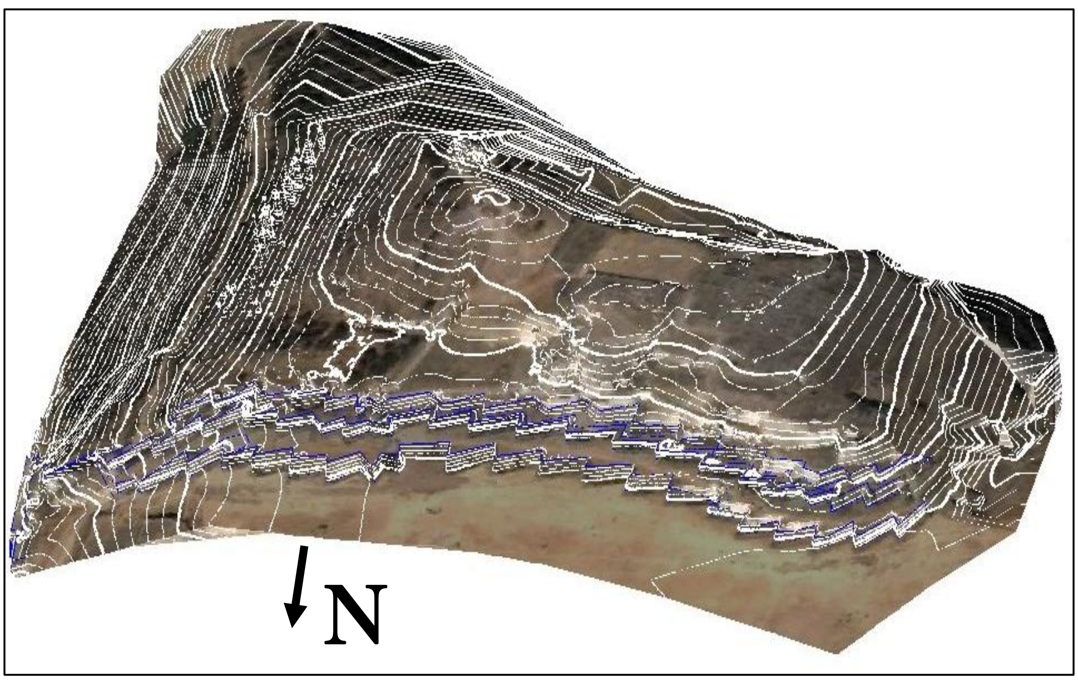
a. Surface Creation Methods

To begin, appropriate compatible DWG files had to be created from the data in the ArcMap map package. This was done by selecting the layers in the ArcMap drawing needed, and using the “Export to CAD” command. This process was repeated for the polyline group titled “Inca_terraces1” as well as for the polyline group titled “existing_Wterraces.” The end result of this step is a set of two DWG files with the polylines representing the terraces that can now be imported into AutoCAD.

The next step was to start a new AutoCAD Imperial 2015 drawing we will call the “terrace drawing.” The datum for the drawing was set to “UTM-WGS 1984 datum, Zone 19 South, Meter, Cent. Meridian 69d W” to match the datum used in the ArcMap file.

Next, the previously created DGW files for existing terraces and proposed terraces were opened in the terrace drawing. Although these objects had elevations assigned to them as part of their attribute data in the ArcMap file, upon conversion to the DWG format, their elevation data was lost. To solve this problem, and to allow for easier manipulation of the lines, each of the lines was converted into a feature line. The feature lines could now have their elevations altered manually or by referencing a surface.

For accuracy and time's sake, I chose to set elevations by referencing the feature lines to a surface. To do this, it was necessary to import a current 3D surface model of Saqsaywaman. For the five years preceding the summer trip of 2015, UVA students have used total station measurements to get over 5000 data points that together make up a comprehensive representation of the topography of the site. Student Ann Menefee created a current TIN (Triangular Irregular Network) surface model of the site as part of her undergrad thesis 2015 (source). A TIN surface takes points as input and uses a method to interpolate elevation data between known points. These points are then connected into triangles [12]. Figure 33 shows this surface created from a few angles with contours and imagery placed below for reference.



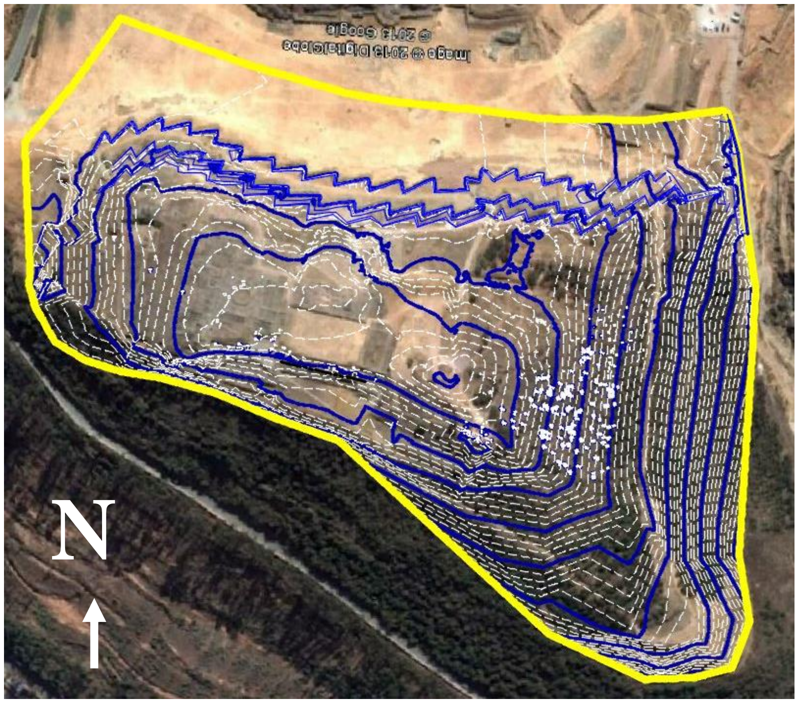


Figure 33: current surface model [13]

Because of the enormity of the size of this current surface DWG file, instead of importing the entire surface file, a data reference was created. A data reference allows a user to only import in the surface itself, not the original point files that were used as a template to create said surface. Data references maintain the original resolution of the surface data. Unlike an XREF that simply lets the user see a surface shadow in the background, a data reference allows the referenced information to be adjusted and interacted with, while still maintaining its improved workable file size. This data reference was created in a separate drawing of the current surface file. Now this main surface subset of the entire current surface DWG file was made available for reference in the terraces drawing. The main surface was added to the terrace drawing using the “promote” command in the data shortcuts section of the prospector tab.

The surface is added in at the actual elevation (3500-3600 meter range), whereas the feature lines representing the terraces are at an elevation of 0 meters. This can be corrected by selecting one of the feature lines and assigning its elevation values using the “Elevations from surface” tool in the feature line tool box. You can see in Figure 34, now the feature lines have elevation values that match them directly to the main surface. This is a better method than manually entering in elevations from the ArcMap file every few feet because it automatically gets tens to hundreds of points elevations along the line directly from the surface. The increased number of elevation points improves the accuracy of the terrace location model.

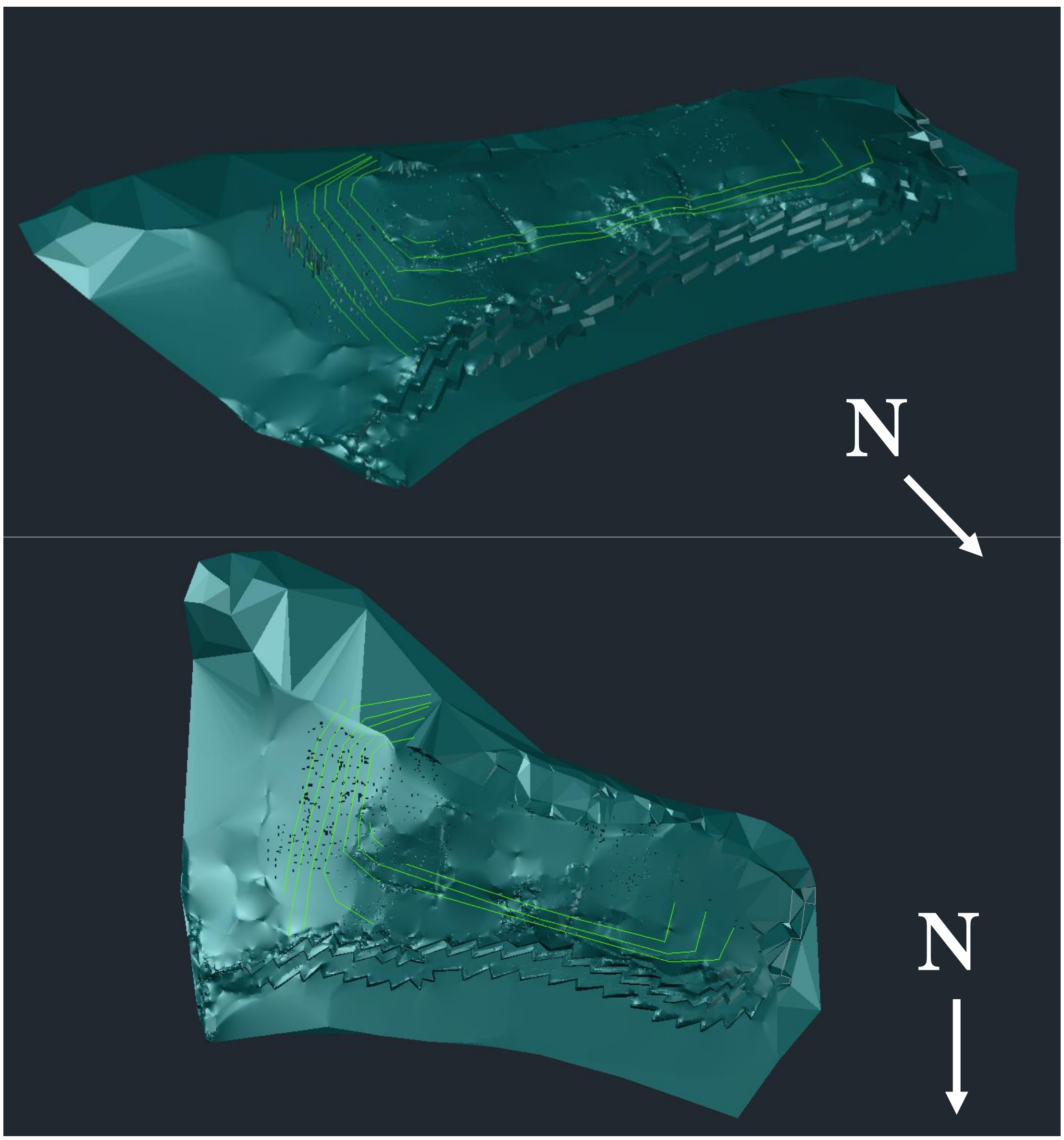
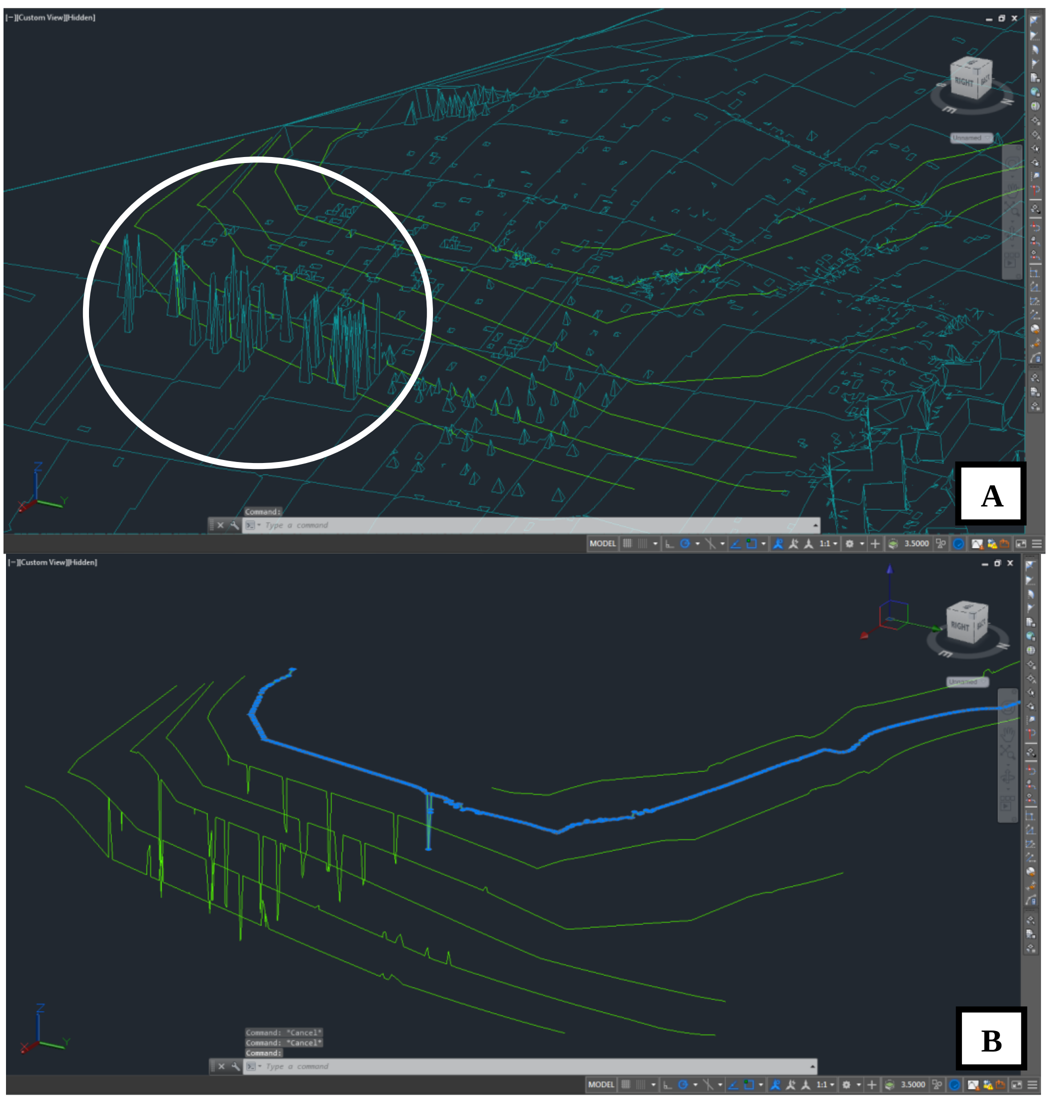


Figure 34: Draped surface lines over current model

One issue with this "elevations from surface" tool is that our current surface model has multiple erroneous points (points 1-5 meters above or below the actual surface, shown in figure 35a). When the "elevations from surface" tool was implemented, a few of the spikes in elevation were projected onto the feature line (Figure 35b). Based on ground truth field observations I made while actually present on the site in Peru, I deemed these points to be erroneous and not representative of the actual surface. As such, I deleted these corrupted data points from the surface and recreated the feature lines from this corrected surface. The smoothed and corrected final terrace lines are displayed in Figure 35c.



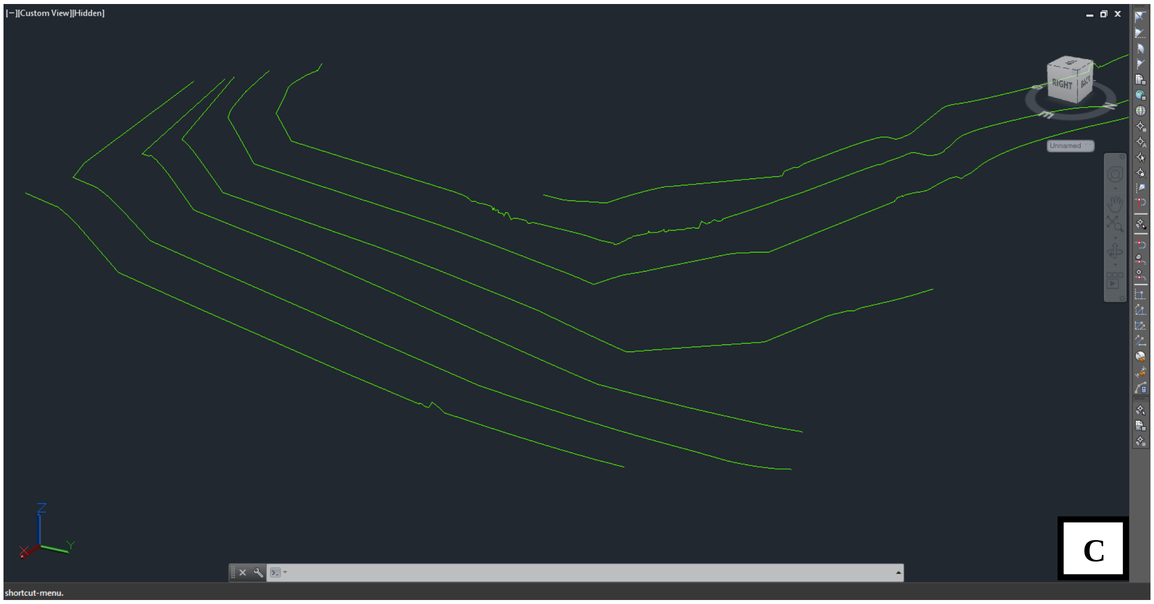


Figure 35: Error corrections for feature lines

A second set of feature lines needs to be created to use as breaklines for the surface. At this stage we have a surface with corrected feature lines draped on top (Figure 34) but what we need are lines embedded in the surface to set as breaklines so that we can cut into the current surface and create terraces beneath. To explain this concept further, the following section will reference Figure 36. Figure 36a is a simplified conceptual depiction of the surface current surface with terrace lines 1-4 draped over. Figure 36b represents a side view of the same surface. Figure 36c is a simplified depiction of the terraced surface we wish to construct based off of lines 1-4. Figure 36d is a side view of the same terraced surface.

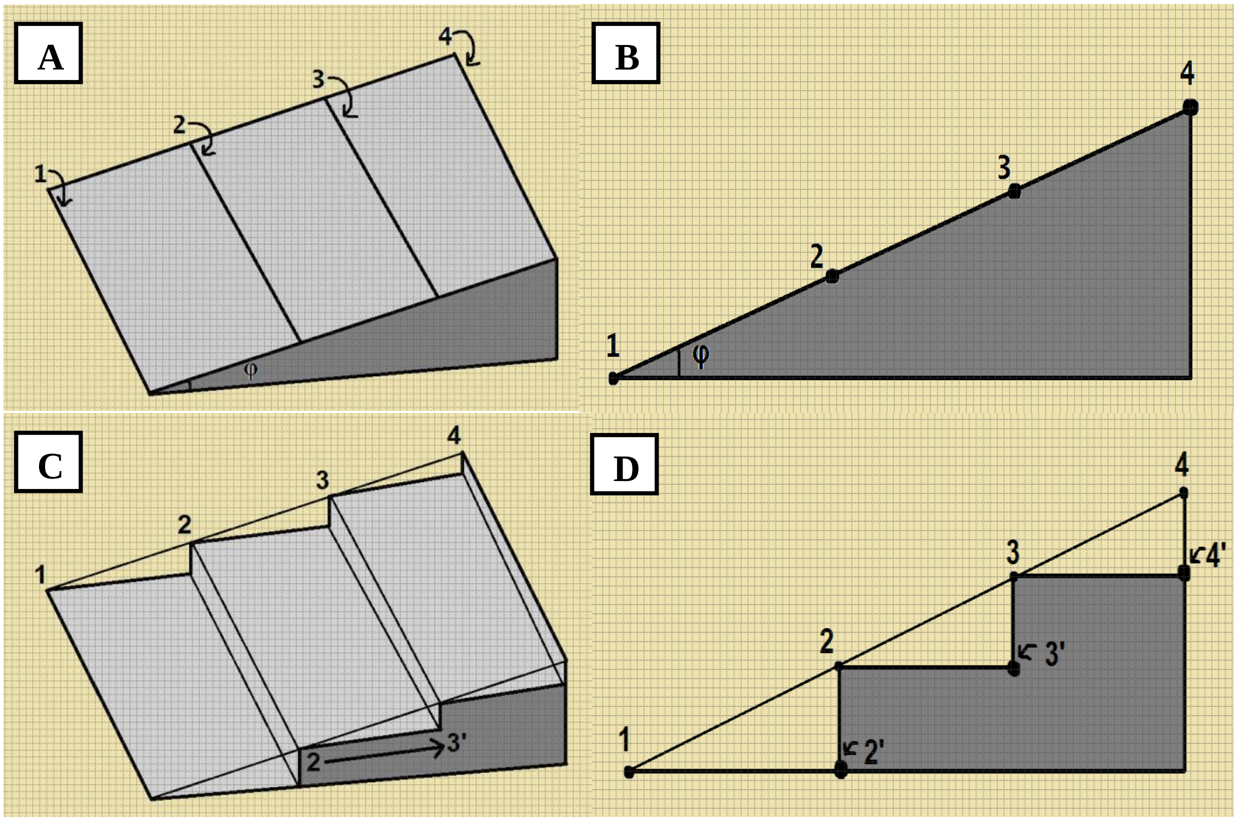


Figure 36: Breakline analysis example

In order to create this new surface in 36c, lines 1'-4' must be drawn in directly below lines 1-4. To draw one of these lines, line 3' for example, one would have to make a copy of line 3, and change its elevation to be equal to its current elevation minus the average difference between lines 3 and 2. In equation form:

$$elevation\ 3' = elevation\ 3 - [average\ elevation(line\ \ 3 - line\ 2)] \qquad \text{(Equation 1)}$$

Ideally this equation would set the elevation of a point of the 3' line equal to the elevation of line 2 at the location directly across from it, but each of the terrace lines in the drawing have a different number of elevation points comprising them, so this coordination is not possible. Instead, we can simply subtract a set average value from every point on line 3 to create the 3' line.

In AutoCAD, to accomplish this task, the "create feature line from stepped offset" tool was used. This allows the user to select a feature line to offset, enter the offset distance, and enter the new elevation of the offset feature line. The elevation of each replicated feature line was adjusted by the elevation as specified in the above Equation 1. The resulting network of feature lines representing the terraces with both feature lines draped over the surface and the corresponding feature lines beneath to be made into breaklines is displayed in Figure 37.

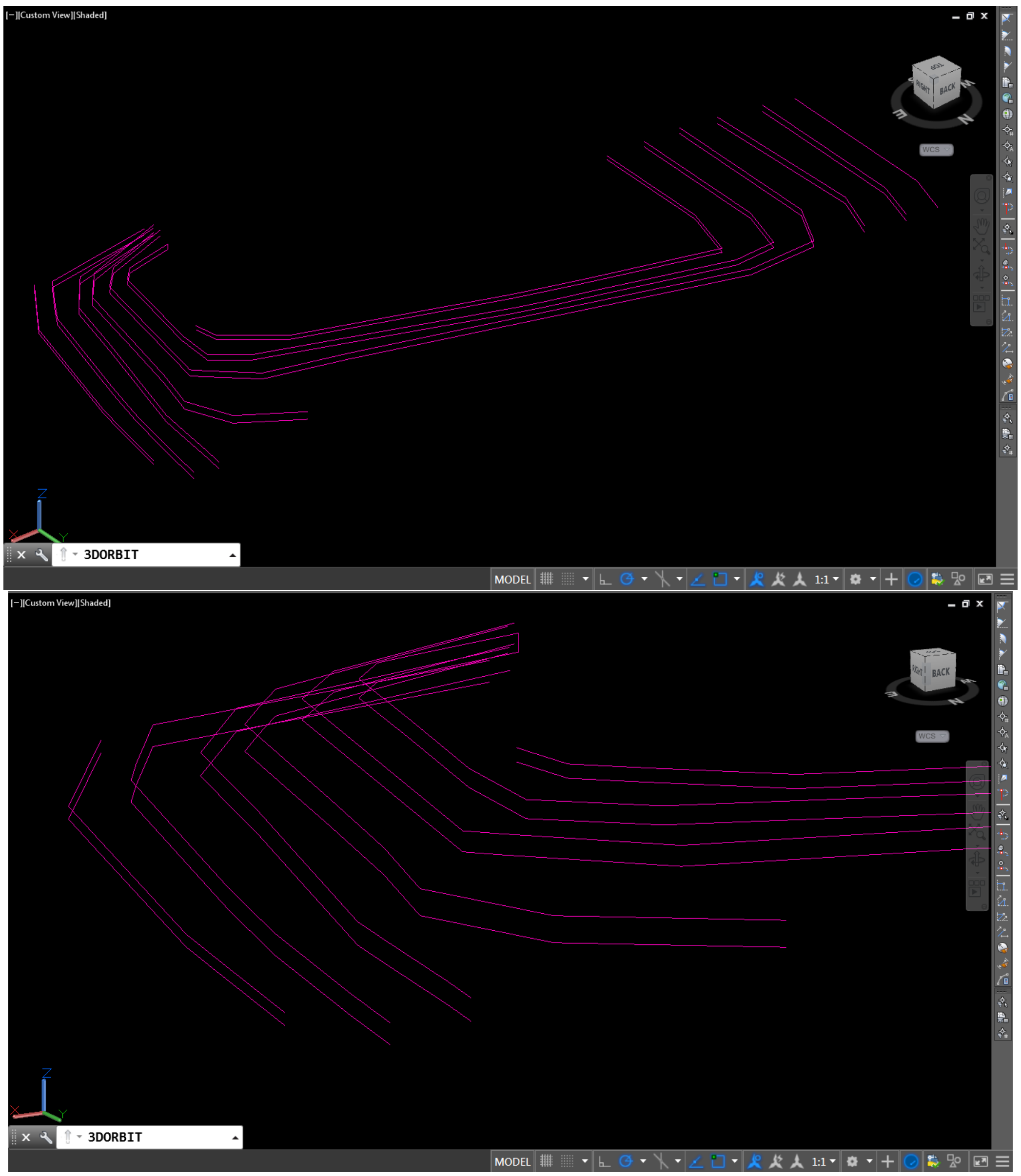


Figure 37: Network of terrace feature lines

The next step was to create breaklines from these copied feature lines. A breakline is a line in a surface that define features that slope triangles of the TIN surface cannot cross [12]. This was accomplished by selecting all of the feature lines in Figure 37 and using the “add to surface as breakline” command. Figure 38a displays the raw effect of simply adding these lines to the surface. As one can see, even though the terrace lines are present, the points that used to define the existing surface are also still present pulling the surface back up to the pre-terrace elevation. These points represent the ground that we wish to cut out of the surface. In order to get the clean terrace lines we are trying to implement on the site, the old surface points between terrace lines (shown as red dots in the accompanying graphic on Figure 38b) must be erased.

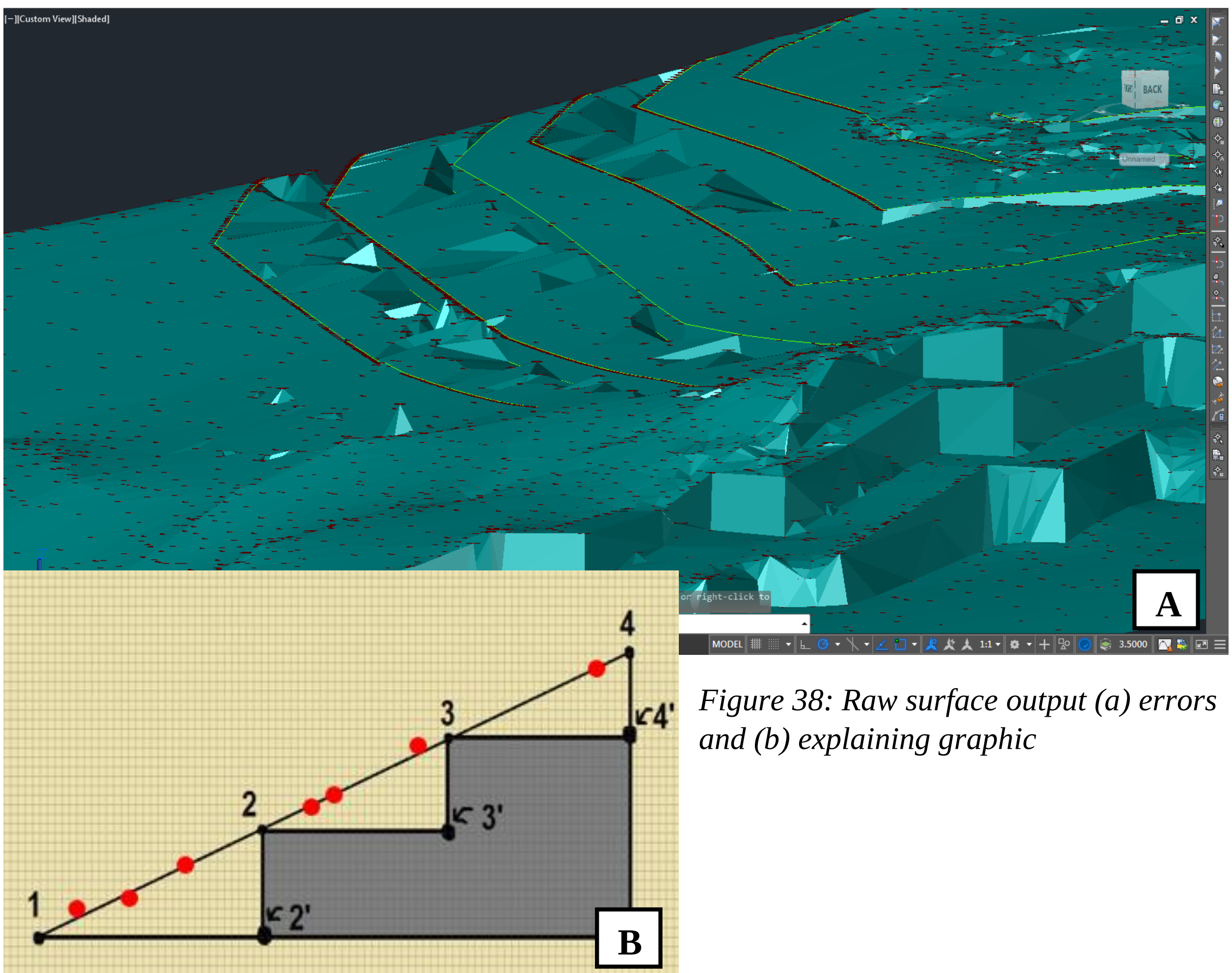


Figure 38: Raw surface output (a) errors and (b) explaining graphic

These points were erased using the surface point editor menu. Figure 39a and 39b show the old surface points file before and after editing out the previous surface elevation points.

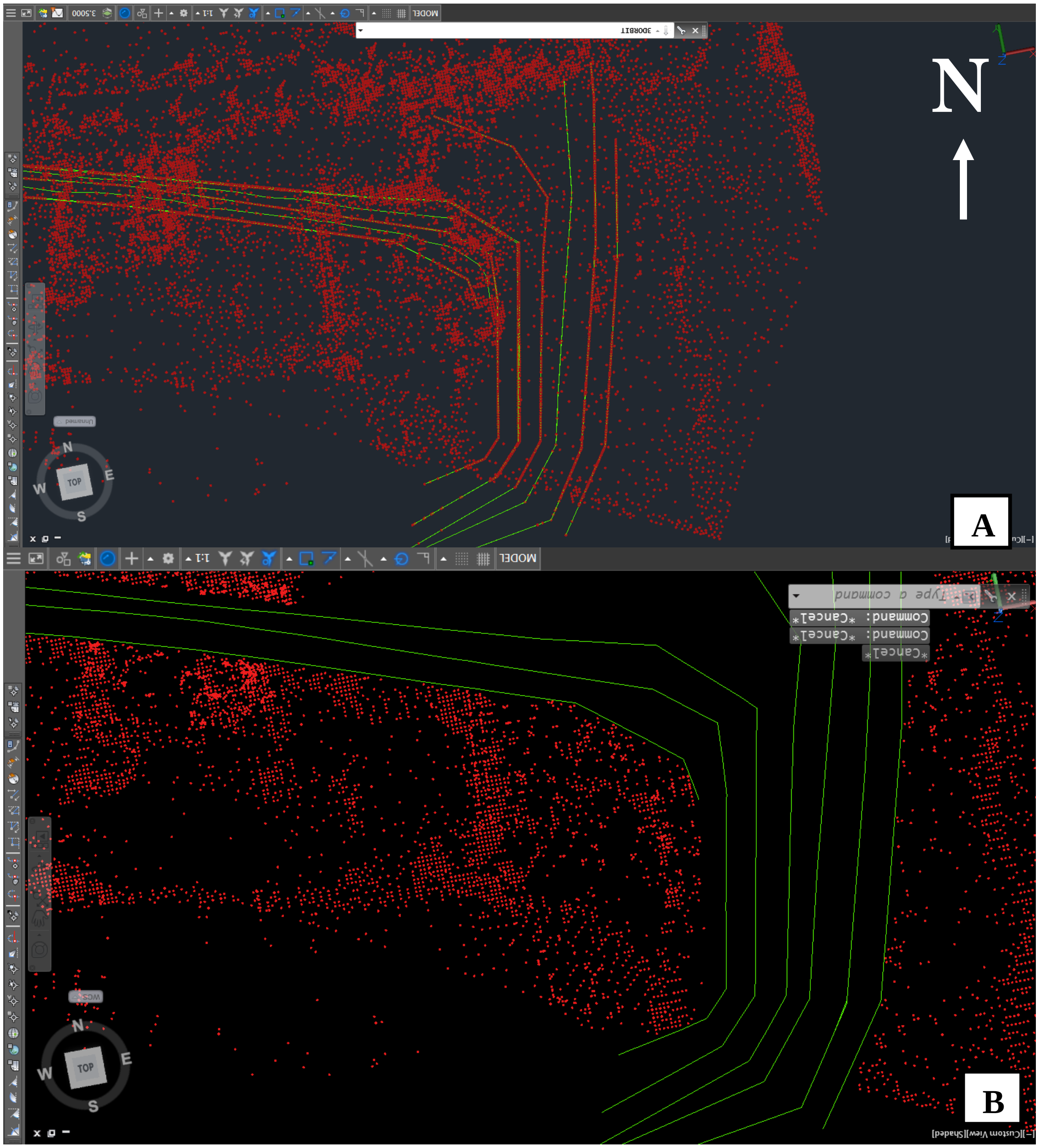


Figure 39: Surface point editing (a) before point removal (b) after point removal

Figure 40 displays the new corrected terraced surface that will be used as the basis for the analysis in the following section.

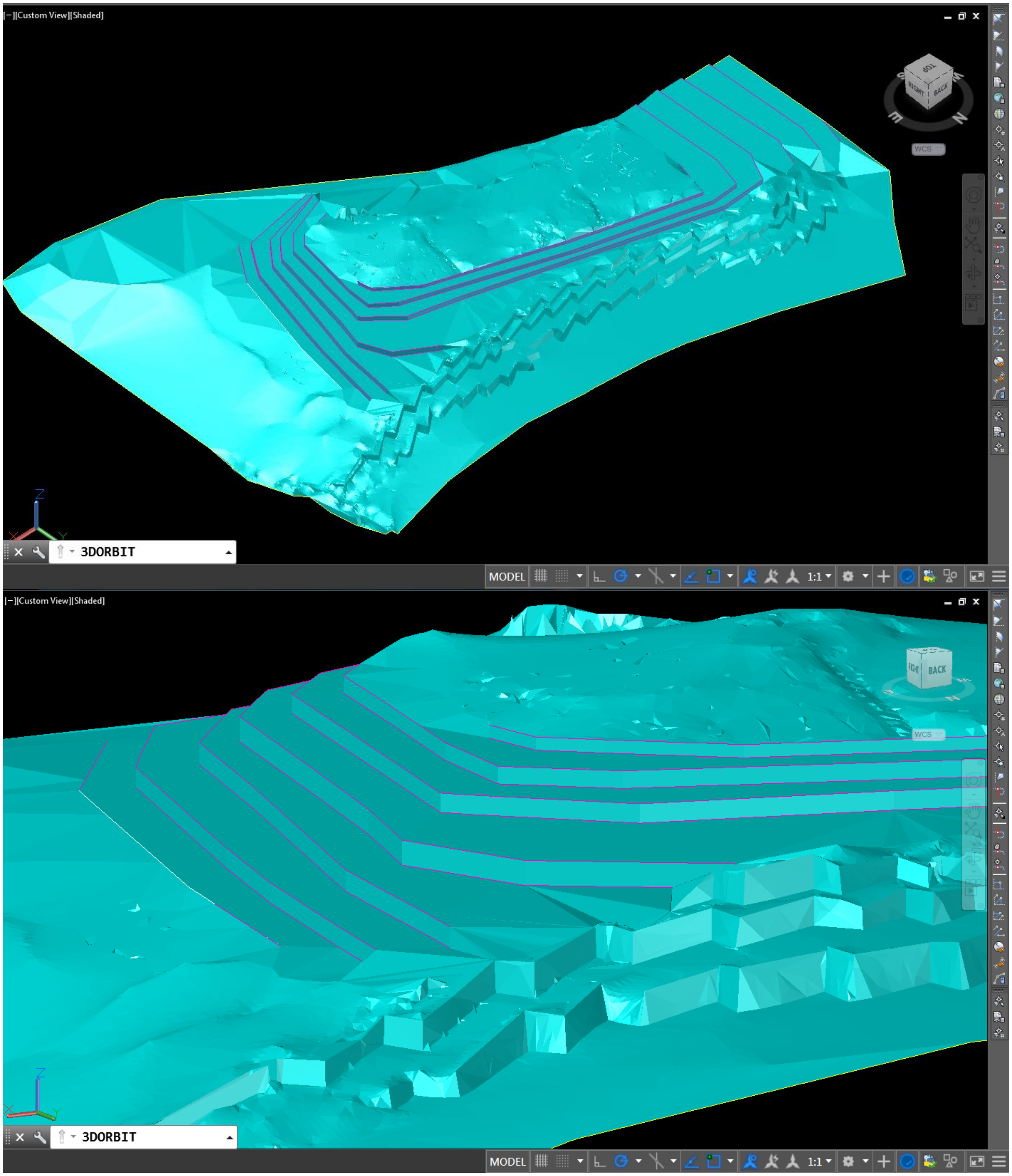
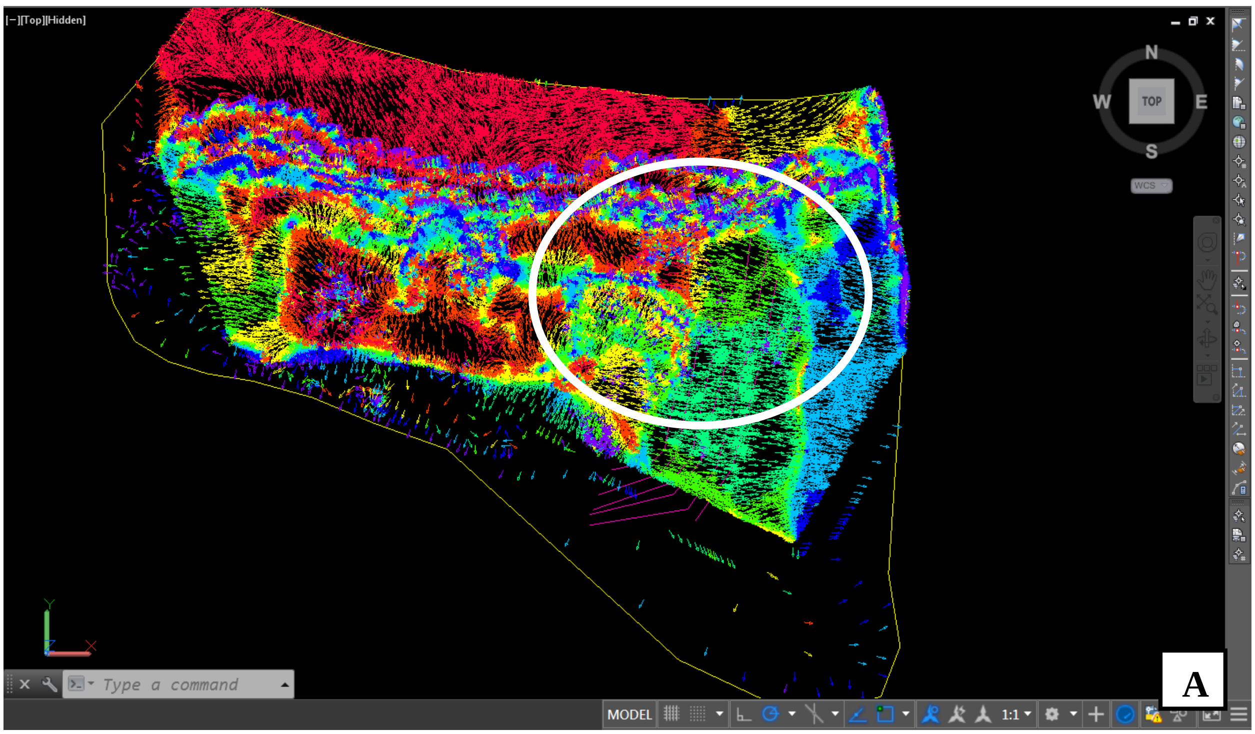


Figure 40: New surface with terraces

b. Comparison: Flow Direction

There are multiple ways to analyze how water flows along and off of the newly created terraced surface in Figure 40. One way is to use slope direction arrows. By looking at patterns of slope direction on the site, you can see the general direction of the flow water would take on the surface. In addition, this is a useful tool because the arrow's color indicates the grade of the slope. Slopes go from low grade (red) to high grade (purple) in a rainbow fashion. Figure 41a shows the flow direction arrows for the surface without terraces. If you zoom in on the circled region (Figure 41b) you can see that there are marked problem regions of the site where there are steep high grade blue and green arrows flowing perpendicular to the walls and down the hillside. This kind of steep uncontrolled flow is not desirable and has been causing the damage to the site.



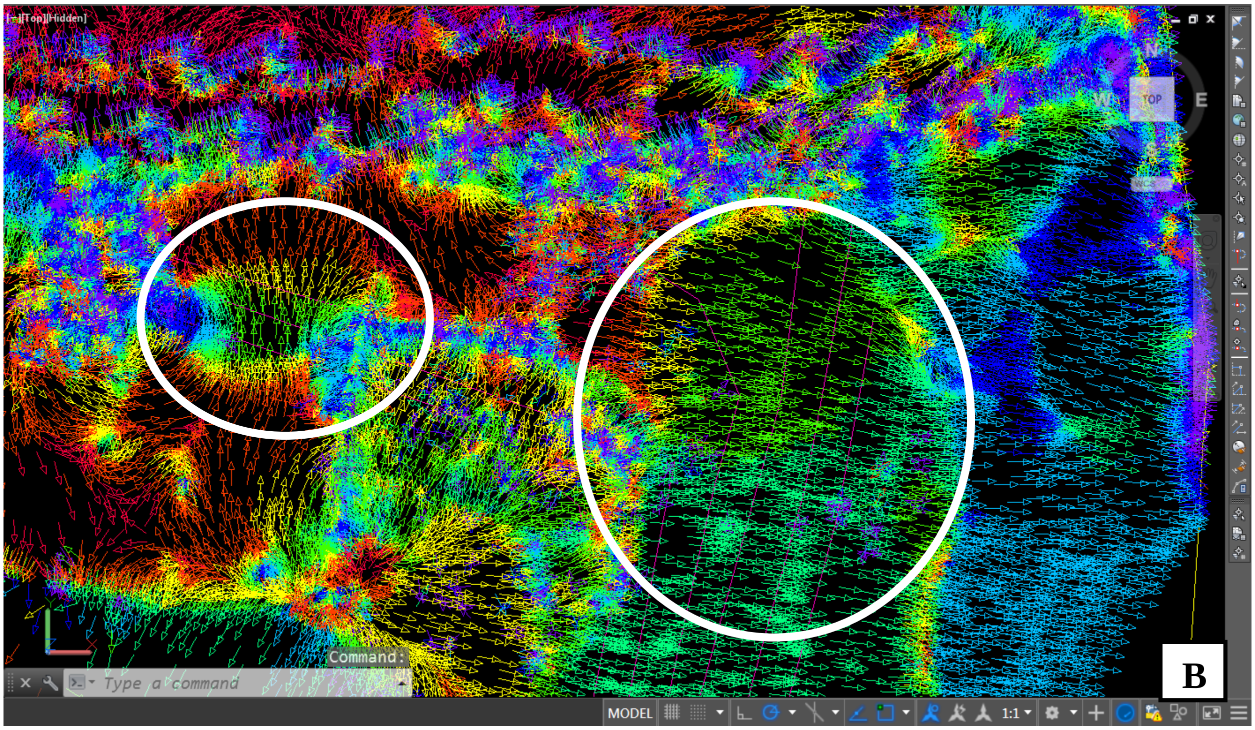


Figure 41: Slope direction arrows without terraces (a) zoomed out (b) zoomed in region

Figure 42a below depicts the slope direction arrows for the surface with terraces incorporated. If you zoom in on the same region as Figure 41b, you can see that the same regions that used to have steep green arrows perpendicular to the walls and down the hillside now have red low grade arrows pointing parallel to the walls and along the terraces. In some places on the East hillside you can observe the red arrows pointing backwards slightly towards the base of the terrace lines. This is consistent with our hypothesis that water would be directed parallel to the walls in base channels along the base of terraces.

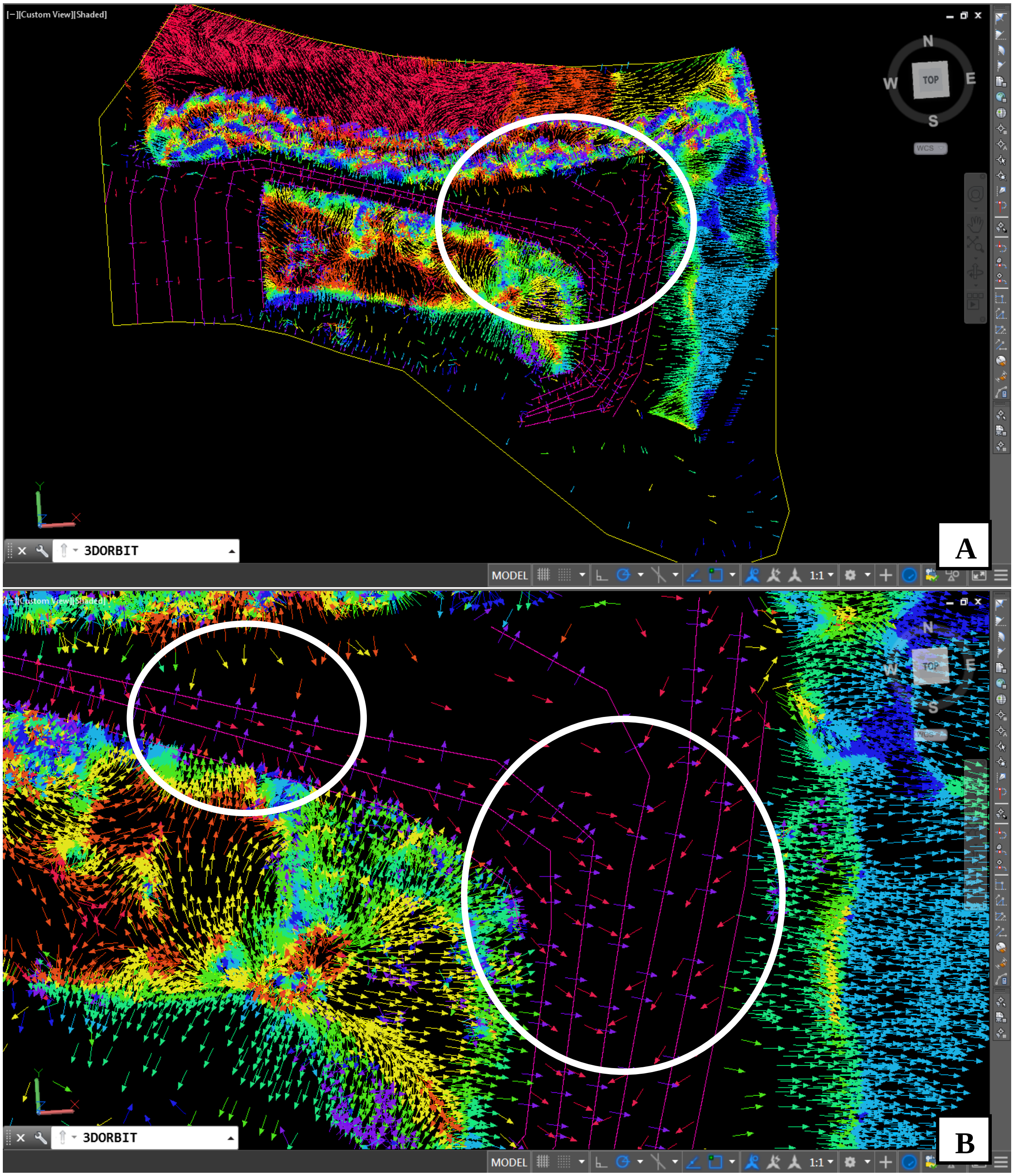


Figure 42: Slope direction arrows with terraces (a) zoomed out (b) zoomed in region

The results of this analysis indicate that without terraces, a large section of water would flow directly into the three Great Walls from the top of the site. When terraces are added into the surface, the direction of flow is now largely parallel to the walls as we expected it to be. This validates the theory that terraces would improve the direction of surface runoff on the site.

c. Comparison: Slopes

Aside from the direction of surface runoff, another problem that causes damage to the site is the magnitude of the runoff. According to Manning's Equation for open channel flow, the velocity (V) of water flowing along a surface will be proportional to the square root of the slope (S) (Equation 2):

$$V = \frac{1.49(R^{2/3}S^{1/2})}{n} \qquad \textit{(Equation 2)}$$

Therefore, a smaller slope would decrease the runoff velocity, decrease erosion, and overall allow for more controlled runoff patterns. Water will move in the direction of the largest slope. Without terraces, water will move down the face of the East hill (Figure 43a). When terraces are added to the surface, the slope perpendicular to the walls with a terracing system is nearly zero, so the dominating slope that will determine the flow velocity of water is the slope along the terraces (Figure 43b).

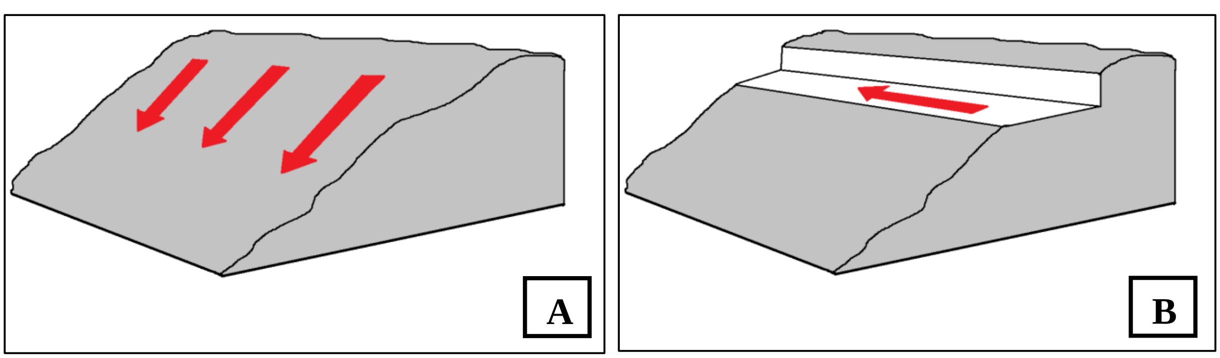


Figure 43: Flow in maximum slope direction diagram

The average slope along the west terraces was found using a surface slope calculation tool to be 1.5% in a direction parallel to the terraces. Before implementation of the terrace, the average slope of the East hill down the hill was 19.5%. Because runoff velocity would be proportional to the grade, this decrease in grade of the East side of the site demonstrates how terraces would prevent further degradation via erosion.

VIII. Conclusions, Future Work, and Recommendations

Several key conclusions can be gained from this study. First, the results of the subsurface profiling section of this study indicate that buried Inca terraces exist on the site of Saqsaywaman at or near the locations indicated in the model. Second, we can conclude that modeling shows incorporating these original Inca terraces into the surface of the site improves the runoff patterns by directing water away from the three Great Walls and by decreasing the average slope of the site in the direction of runoff flow.

This model could be improved in multiple ways. First, the terraces are very angular. This is because of simplifications made in connecting points of disturbance on the seismic and GPR lines. This could be corrected by conducting additional field tests to get a higher resolution set of subsurface profile runs. In addition, the terraces have a grade of 1.5%, but according to a study conducted on the Incamisana at Ollantaytambo, a typical channel slope was closer to 3% [13]. Further field measurements of Sacred Valley terraced sites and Saqsaywaman itself should be conducted to get an idea for the actual average slope along terraces and this new slope value should be incorporated into the terraced model. Lastly, depth-of-disturbance data from the subsurface profiling tools could be incorporated into the model. In the created terrace model for this study, terrace top lines were draped across the surface, but according to the GPR readings, in some regions disturbances are present from 0.5-2 feet into the surface.

It is imperative to maintain the historical integrity of Saqsaywaman because of its cultural importance. Invasive construction on the archeological site is to be avoided as much as possible. Because of this, it is recommended that more data be collected before implementing this terracing plan to validate the existence of the terraces. A full system of archeological test excavations should be conducted at points along the expected terrace locations before any construction begins.

This model can not only show visually and numerically the improvements that can be made to Saqsaywaman's topography, but because of the compatibility with AutoCAD extension packages and other modeling programs, it can be used as a basis for further study. For example, detailed field measurements could be taken documenting soil type and the rational method could be applied to the model to see a more detailed analysis of how runoff occurs given a specific precipitation event. These additional analyses in conjunction with a cut-fill plan for the actual implementation of the terrace design could be used as part of a proposal for additional funding for the preservation of Saqsaywaman.

There are many challenges associated with this project. In addition to the technical difficulties associated with data collection in rough terrain, balancing cultural awareness, archeological considerations, and engineering requirements is also difficult. Regardless of these challenges, changes should be made to ensure the preservation of the impressive Inca site of Saqsaywaman for generations to come.

IX. References

[1] Wright, R. (1986). Cut Stones and Crossroads: A Journey in the Two Worlds of Peru (pp. 66) Penguin Books.

[2] Dean, C. (2011). Inka Ruins and the Discourse of Mystery. *Third Text*, 25, pp. 6.

[3] Miksad, R (2015). The Role of Inca Terraces in Preserving the Walls at Saqsaywaman. Presentation given at the University of Virginia.

[4] Mar, R. (2013). El conjunto arqueológico de Saqsaywaman (Cusco): una aproximación a su arquitectura. Universitat Rovira i Virgili, pp 29-32.

[5] Wildfire, L., Miksad, R.W., Perez, A., Culotti, A., Beckman, E., Vranich, A., & Wright, K.L.(2011). A paleo-hydrologic analysis of rainfall-runoff and drainage of the incan ruins of Saqsaywaman, Cusco, Peru.

[6] Lohr, K (2014). Restoring and Preserving the Incan Cultural Wonder of Saqsaywaman. (Masters of Science, University of Virginia).

[7] Cardenas, J. et al (2009). Estudio Geológico y Geodinámico de los Baluartes en el sitio Arqueológico de Saqsaywaman- Cusco. República del Perú, Sector Energía y Minas. INC.

[8] Gasparini, G,. Margolies, L., Inca architecture (P. J. Trans) Bloomington, IN. Indiana University Press.

[9] Javier, A., Ortiz, C., Rojas, F. & Cruz, J. (2015) Informe Preliminar de ensayos geofísicos en el parque arqueológico de Saqsaywaman.

[10] Takahashi, K. et al (2012). Basics and Application of Ground-Penetrating Radar as a Tool for Monitoring Irrigation Process. *Problems, Perspectives and Challenges of Agricultural Water Management*, pp. 155-160.

[11] O'Neil, G. (2016). Locating Inca Terraces at Saqsaywaman to Restore the Original Drainage System and Protect the Great Walls (Masters of Science, University of Virginia).

[12] AutoCAD Civil 3D User's Guide (2013).

[13] Menefee, A. (2014). Restoring Incan-Era Drainage Systems to Saqsaywaman, Peru: A Topographic Study for Historic Preservation.

[14] Wright, K. R. et al (2016). Incamisana: Engineering an Inca Water Temple. *ASCE Press*, pp. 53.

[15] Choquequirao and Machu Picchu, Peru. Lakedistrictwalks.com. Retrieved March 11, 2016.

[16] Miksad, R. (Photographer) (2015). [Digital].

[17] Tipon. Tripadvisor.com. Retrieved March 11, 2016.

[18] Machu Picchu Drainage Channel, gotravelzing.com. Retrieved March 11, 2016.

[19] Quantum quarterview. US Radar Inc. Subsurface Imaging Systems. Retrieved March 11, 2016.