

# Line of Balance Analysis of the New WPI Residence Hall



A Major Qualifying Project  
Submitted to the faculty of  
Worcester Polytechnic Institute  
In partial fulfillment of the requirements for the  
Degree of Bachelor of Science

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## **Abstract**

This project proposes a scheduling approach to coordinate the final stage of activities to be conducted in the construction of a new WPI residence hall. Based on the traditional schedule generated by the Critical Path Method, the proposed approach uses the Line of Balance method to coordinate in more detail subcontractors performing repetitive operations within the building. The project also presents a structural design for a section of the building foundation to support lateral loading during construction.

## **Acknowledgments**

We would like to extend a special thanks to Neil Benner as well as the entire Gilbane team including Melissa Hinton, Don Veneris, and Colin Thrift for their continued support and assistance for the project. Additionally, we appreciate all the guidance that Professor Salazar has given us over the course of this project as well as Professors Jayachandran and Tao for their valuable input regarding our capstone design experience.

## **Capstone Design Experience**

The Civil and Environmental Engineering program at WPI requires to have all Major Qualifying Projects (MQPs) include a Capstone Design Experience to meet educational ABET objectives. Through this exercise students demonstrate their engineering design knowledge. In order to meet this requirement, this MQP proposes an alternate design solution for the southeast foundation wall of the new residence hall known as the j-line wall.

Due to conditions required by the scheduling of construction operations the close proximity between the foundation wall of the residence hall and the adjacent parking structure, generated lateral forces that the wall, as originally designed, was not able to withstand. The project engineers developed and implemented a bracing system that appropriately reinforced the section of wall in question. This MQP proposes an alternative solution that does not require external bracing.

In this report, calculations will show that a base key poured below the foundation wall footing would have prevented the need and expense of external reinforcing steel. The additional passive force created would have prevented the sliding failure to which it was susceptible. A base key would have been installed with the footing and would not have caused a delay in the building schedule.

This portion of our Major Qualifying Project is intended to satisfy the ABET requirements as it is a culmination of earlier course work and incorporates engineering standards with realistic constraints in the design. The constraints imposed on this alternative design consider construction economics, environmental factors, sustainability, constructability, and safety factors. We used our knowledge garnered here at WPI to find

the most cost effective design that is also efficient with respect to time and materials.

The wall must be easily constructed with ease to keep the overall cost low but must also be durable to last the lifetime of the building. Finally, safety is of primary concern to this project. Any design generated must comply with all State and National Building Codes to prevent injury that may occur during construction or even prevent damages that could result in structural failure of the residence hall.

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## **1.0 Introduction**

Worcester Polytechnic Institute (WPI) has steadily increased the number of accepted freshman in the last few years. WPI's Master Plan calls for the gradual growth of the institution. As a result, there has become a shortage of on-campus housing, leaving the upper-classmen to either enter a lottery system, or be forced into off-campus apartments. To address this issue, WPI has approved the construction of a new residential building. This new building will have 232 beds consisting mainly of suite formatted rooms for upperclassmen. It will also house Residential Services on the first level, as well as a variety of facilities. It is projected that this dormitory will assist in relieving the demand for on-campus housing. Parking on-campus is very limited. To address this issue, WPI is engaging in another project, a parking garage on the east side of the dormitory, parallel to Dean St.

Gilbane Construction Co. (Gilbane) has been hired as Construction Managers (CM) for the ongoing construction process. This roughly \$30 million construction project was started in March 2007, and is expected to be completed in August 2008, before the 2008-09 academic year begins. Gilbane and WPI are working with Cannon Design, the architectural team, to make this building architecturally and structurally sound, as well as LEED (Leadership in Energy and Environmental Design) certified. This project is being fast-tracked and even had excavation and demolition begin at the same time.

As the last phases of the project are now starting to take place, there is an increased need for the detailed planning and coordination of the activities involving numerous contractors working simultaneously to complete these operations. After

speaking with Gilbane's project manager, Neil Benner, he expressed his concern with the scheduling for the close-out activities of this project. Due to all the necessary move-in activities such as furniture, appliances, etc., a well planned schedule must be created to ensure the project close-out goes well. There is increased pressure with time constraints for this building to be ready to be occupied for the beginning of the 2008 academic school year.

To help relieve some of this pressure, the first objective for this MQP was to analyze all the construction activities that needed to be completed from January to August 2008, and design a finish work schedule that will have the building open in time for the new academic year. Our close-out schedule utilized the Line of Balance (LOB) Method, a method that illustrates the progress of similar tasks for multiple rooms and floors. This method provides a very powerful, yet simple display of the many tasks to be closely coordinated to aid WPI in achieving a timely certificate of occupancy for the building with enough time to be prepared for the arrival of incoming students.

The second main objective for this project incorporates a Capstone Design Experience. Initially, both structures, the residence hall and parking garage, were planned to be built in a sequential fashion but time constraints once again took precedence. Simultaneous construction of both facilities presented a structural issue for a section of the east foundation wall not previously anticipated. At the same time, it allows for early construction of the foundation of the parking garage. To alleviate scheduling problems later on, Gilbane made the decision to pour the foundations of the garage in September 2007.

Due to the residence hall's close proximity to the parking structure, soil was

removed from one side of the residence hall foundation causing an undesired lateral load. The foundation was not designed for these lateral loads. Gilbane remedied this problem by adding bracing to one side of the foundation. This project proposes an alternative solution to the design of the foundation wall that can withstand the lateral forces, as well as the weight of the residence hall, without additional external bracing. The alternative design was analyzed to determine affects it has on both the cost of the project and the schedule.

With all these factors coming into play in our MQP, we believe this provided us with a well-rounded engineering and project management experience. This is a culmination of our 4 years of study as well as leaving a legacy for future WPI students.

## **2.0 Background**

### **2.1 Close-Out Schedule**

The construction and management of any project involves many steps; one of these vital final steps is the project close-out. An actual list of these steps is compiled in *Project Management for Engineering and Construction* by Garold D. Oberlender (Oberlender, 2000).

These steps are:

- System Testing and Start-up
- Final Inspection
- Guarantee and Warranties
- Lien Releases
- Record and As-Built Drawings
- Check List of Duties
- Disposition of Project Files
- Post Project Critique
- Owner Feed- Back

System Testing and Start-up includes the actual testing of machinery to ensure mechanical completion and functional operation. This is done to make sure all components are working to full expectation. The owner's representative works closely with the project manager and the designer to make sure everything is functioning properly. Once the owner's representative and other agencies such as the Fire Department and the Building Inspector signs off, signifying substantial completion, a Certificate of Occupancy is issued and the building is turned over to the owner.

The Check List of Duties is a very important part of the Close-Out process. Within this check list there are some key procedures that must be completed. These procedures are a certificate of substantial completion: Clean-Up, Punch List, and Call backs. The Punch List is one of the most important parts of this process because at this time an owner's representative goes through the building and makes sure that it is in the condition that he or she deems adequate for the move in.

During the final inspection, the project manager goes through the Punch List and makes sure all of the tasks are taken care of. While this process is going on the owner is beginning to move furniture and other appliances. At the same time the Punch List is going on, the contractor is obtaining a Certificate of Occupancy. The Certificate of Occupancy is given out by the state and city and is needed in order for the owner to move in. Once the Punch List is complete, there is a final walk-through inspection that includes the owner, contractor and design professionals who have worked on the project.

In accordance with the provisions of the contract, the contractor is required to guarantee all materials and equipment that have been installed in the project. This guarantee usually lasts for a time period of one year in which the quality of work is under high scrutiny and all defects are properly detected and documented.

A lien is a right to keep possession of property belonging to another person until a debt owed by that person is discharged. This right is given to a subcontractor, material supplier, or anyone else who has worked on the project and has not been properly paid. At this time, they are entitled to file a lien on the project until they are paid. The General Contractor is at fault and must pay off the liens; otherwise a surety company will take control of the project or the contractor could take advantage of the project's bonds. In

response to this, the owner can withhold payments to the contractor to make sure all debts are paid, or pending work is completed. Lien releases is when a contract stating that a certain portion of the agreed upon work is done is signed by the contractor and owner releasing the any liens regarding that work. This withheld money is called retainage. When the General Contractor receives the retainage, it signifies that all work has been satisfactorily completed.

At the end of the project the subcontractors are required to submit As-Built drawings of their work. This is done due to the fact that in construction, the original drawings do not always reflect the resulting placement of the various building components. Throughout the project, there are changes and revisions to the drawings that are caused by unexpected amendments. Because of this, there must be documentation to give the true location of the installed components for future reference.

Disposition of Project Files is a very important part of the close-out process. As the construction project goes on, the contractor maintains two files: a record file and a working file. Record files are all files that have vital importance to the project such as all legal documents and contracts. A working file is a file that is compiled by the project manager that includes all job related documents such as meeting minutes, contractor change logs, and other similar documents.

The Post Project Critique happens at the end of the project. This is when the owner and other major players in the project come together to discuss the positive and negative aspects of the entire project. This step is important because it helps out all parties involved in deciding what worked well or did not work.

After the project is completed and the product is in use, another meeting is set up

in which the owner gives feed-back. This is another critical part of the project because the building has been in use and it is important to know if everything is working the way it is supposed to be.

The close-out process is a lengthy one with many parties involved, including the owner, sub-contractors, construction manager, architect, and accountants. Before the final phases of construction begin, the project manager and the sub-contractors meet to plan and coordinate all finishing activities, otherwise known as the card trick meeting. This meeting consists of organizing all sub-contractors activities to ensure they will all reach critical milestones. This process is a tedious task that can take up a considerable amount of time. (Oberlender, 2000)

## **2.2 Line of Balance**

Gilbane currently uses the Critical Path Method (CPM Method) which outlines all the tasks that must be completed at a specific time to ensure that the project is completed on schedule. There are a lot of repetitive tasks involved in the last stages of the project. The results of the schedule calculation resulting from the use of the CPM method are usually presented in graphic form using a bar chart. This display however, does not provide the level of graphic detail required to easily identify all tasks involved in their spatial interdependence. As such, an alternative method was used by the team to provide more detail for the project scheduler for activities taking place between January and August 2008.

The Line of Balance (LOB) method can be utilized to coordinate multiple repetitive tasks to identify potential delays, or idle times in the construction process. The LOB method was first developed in the 1940's by the Goodyear Company, and then furthered by the U.S. Navy in the 1950's (Arditi & Tokdemir, 2003). Since that early stage of development, there have been many variations of the LOB method, but the principles remain the same. It has become a common practice to use this method in planning high-rise buildings, where many of the components of the construction process are similar, and can be completed in an ordered manner. The main objective of the

To develop an ideal LOB schedule, many factors must be considered. The first is the order of tasks. For example, gypsum board must be installed before painting is begun. To determine the length of the task, an optimum crew size and rate-of-output must be ascertained. This can be done through communicating with knowledgeable individuals, such as a scheduler, the project manager, and especially the actual subcontractor



performing the work. Once this information is received, the number of units to be completed can be plotted against time. The slope of the oblique line will equal the actual rate of output and show the start and finish of each task.

When building a house, there are some tasks that can be started before the previous task is finished. **Figure 1** illustrates how the LOB method can be applied to several units. It shows that the roof construction is started in the first unit before the brickwork is finished in the last unit, but right after the foundations are finished. Additionally, the slopes of the lines are different, signifying the ability to complete a task at varying rates, for different start dates. However, if the Brickwork was started even just one week later, it would interfere with the Roof Construction because it has a slower rate of production, and thus delay the entire project.

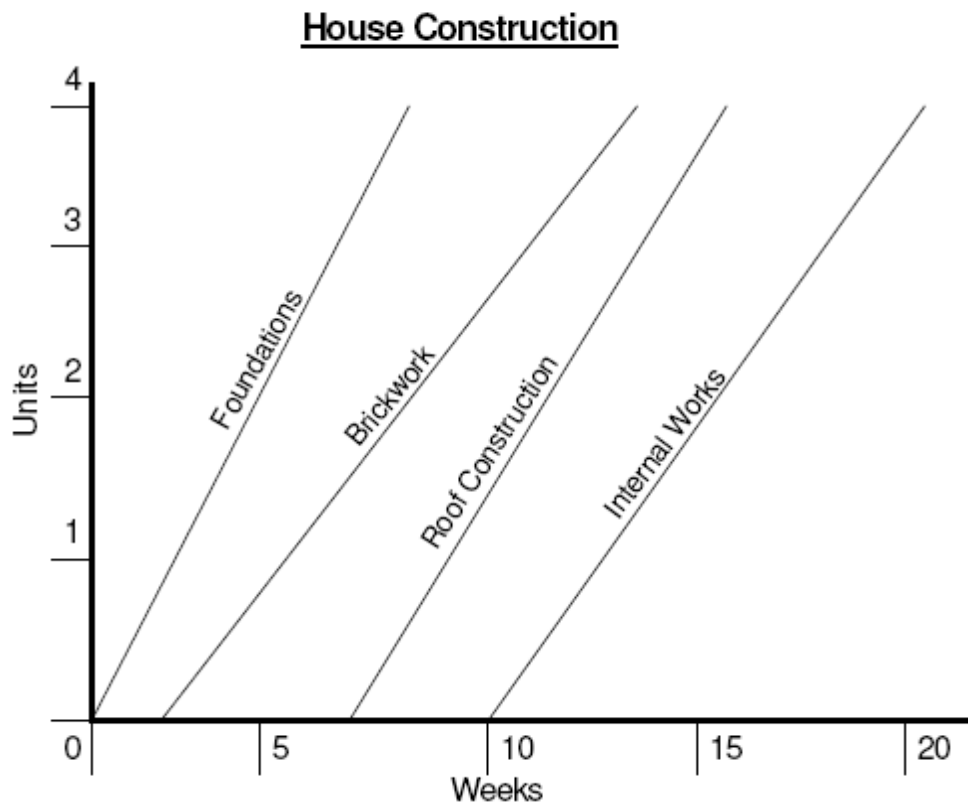
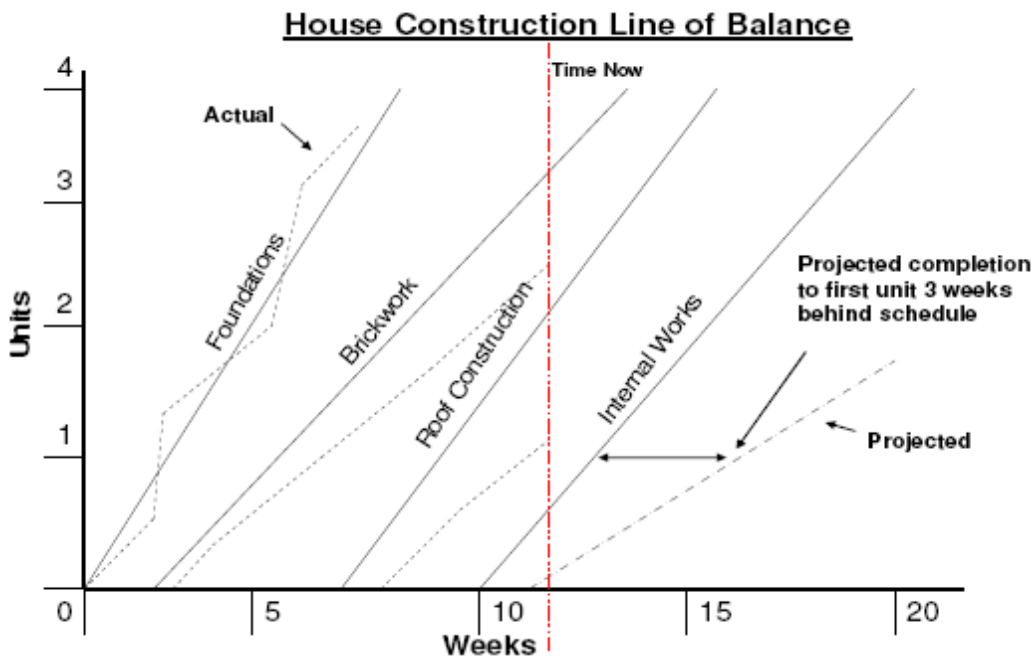


Figure 1: Example of LOB Diagram (Whatley, 2006)

Once construction is started, the progress can be tracked using the LOB diagram. This is extremely useful for the Project Manager, who must ensure that the project is completed on time. By plotting the actual work versus the proposed schedule, one can easily see if a particular task is proceeding as planned, slower than planned, or faster than planned. This can then be used to take corrective measures, whether it is by increasing materials, man-hours, or even by reducing man-hours. This then can prevent longer delays in the future, or issues derived from intersecting tasks. This method of plotting the actual work versus the projected schedule is illustrated in **Figure 2**.



**Figure 2: LOB Actual V. Projected (Whatley, 2006)**

Preparing a visually appealing LOB diagram can be a challenge for the scheduler as well. Arditi, Tokdemir, and Suh addressed this particular issue:

*“If too many activities are plotted, the diagram becomes a jungle of oblique lines that also sometimes cross each other. An alternative is proposed that displays the LOB diagram of each individual path, one path at a time. The use of color-filled*

*lines as well as vertical and horizontal lines showing the movement of the crews can also help.” (Arditi, Tokdemir, & Suh, 2002).*

There are many different ways to display a LOB diagram, and one must consider the complexity, number of tasks, and the time displacement when formatting the diagram.

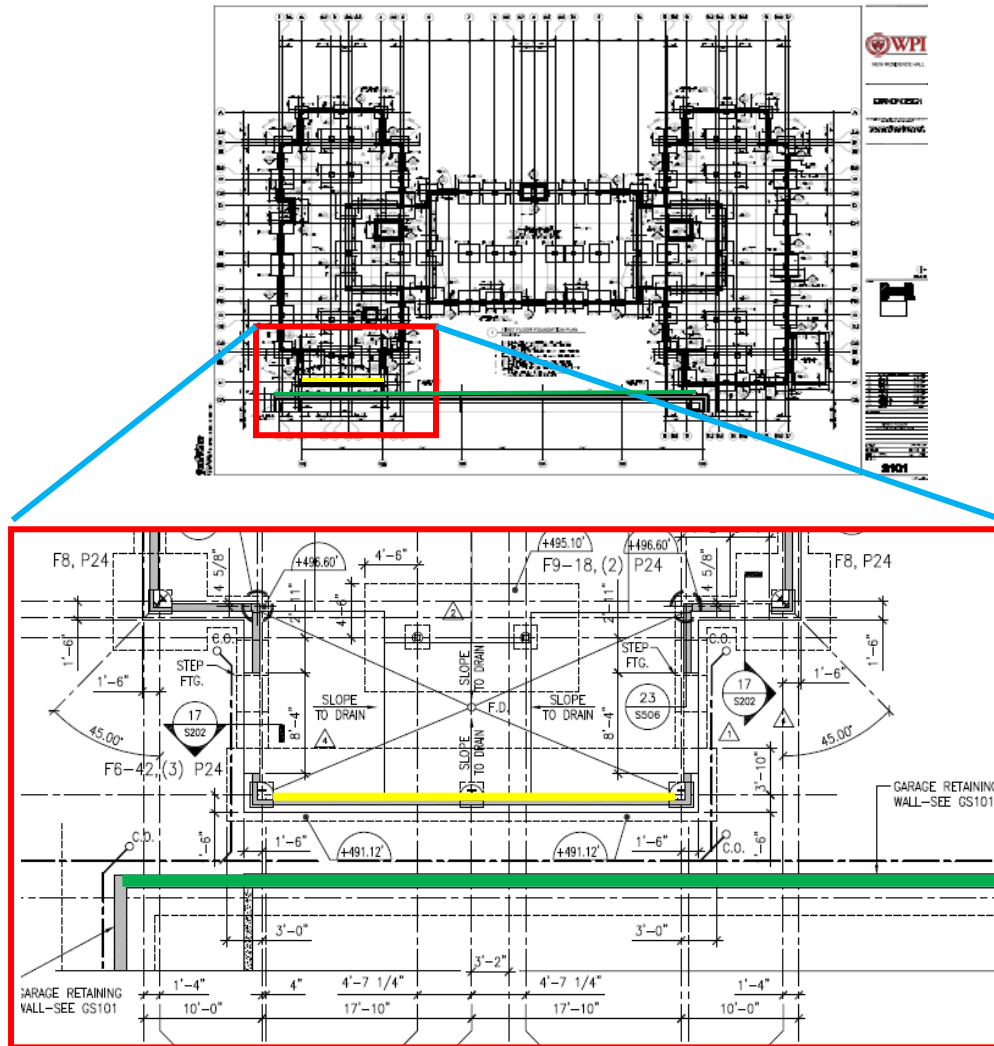
The LOB method is extremely useful for both planning, and monitoring work. It can show rate of progress for several units based upon the slope of the line, while a line chart cannot show rate of progress for the building. A line chart makes it more difficult to show delays for an individual unit, and no one will know the project will be delayed until the task interferes with other tasks. With the LOB diagram, one can quickly see when the actual work slope, and the proposed work slope do not coincide, and remedy the problem before it affects the next task. While bar charts only display the end result date the LOB shows production rates that can be visually displayed, which is where its value comes into play.

Using the LOB method is valuable because it can apply similar tasks and activities to several units. One can quickly see whether the project is being completed on time, or which activity/task is holding it up. The Critical Path Method (CPM) that Gilbane uses only shows the activity as a whole with end dates. This means that one will not know if the project will be completed on time until that particular activity runs over its scheduled timeframe.

### 2.3 J-Line Wall

Due to conditions required by the scheduling of construction operations the close proximity between the foundation wall of the residence hall and the adjacent parking structure, generated lateral forces that the wall, as originally designed, was not able to withstand. Although a field solution was created and implemented, after speaking to the Gilbane team, we saw a need for finding an alternate proposed solution that may have been more cost effective.

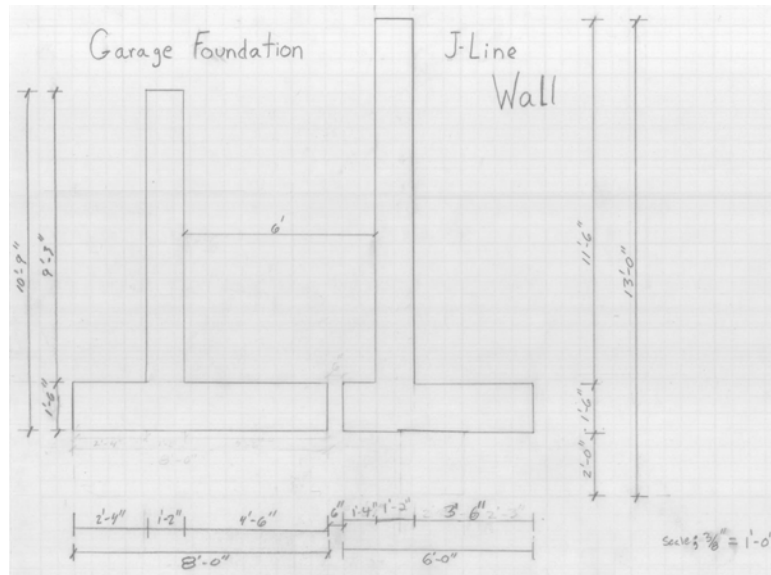
To assist in locating points of interest on structural plans, there is typically an alpha-numeric grid with lettered lines oriented in the latitudinal direction and numbered lines going across in the longitudinal direction. The j-line coincides with the new residence hall's foundation we are analyzing, so it was known during construction as the "j-line" wall. **Figure 3** below shows the j-line wall with respect to the rest of the structural plans.



**Figure 3: Plan View of Residence Hall: Close up of J-line wall (yellow) and parking garage (green) on south east corner**

During the summer there are fewer students around the construction site allowing for material storage in alternate locations. Closing down the adjacent Boynton St. to store materials freed up the previous storage site, the footprint of WPI’s new parking facility, for early construction. Therefore, the residence hall was being constructed simultaneously adjacent to the parking facility. Their foundation walls are spaced only 5 feet apart and their footings are only 6 inches apart at the base. The two foundation walls are in such close proximity to each other that in order to properly pour the foundation of the parking facility, the soil needed to be removed completely from one side of the

residence hall foundation. A cross section of this wall is shown to scale next to the garage foundation wall, in **Figure 4**.



**Figure 4: Scaled Cross Sections of J-line and Garage Foundation Walls**

The removal of soil would not have been a problem if the residence hall construction had been further progressed. Because of the early stages of construction, there was limited normal load acting on the foundation wall which would have caused a stabilizing force. The decreased weight combined with the proximity of the garage structure's foundation caused a potentially hazardous situation.

The wall was initially designed to withstand only the weight of the residence hall transferred vertically down through the columns and was not designed to carry a lateral load. The lateral pressure resulting from the difference in soil height between the two sides of the wall caused a force that it was not originally designed to carry. Fearing possible structural failure that could potentially cause costly delays or harm to the

building or workers, the project engineers worked to develop a solution that could be implemented after reinforcing bar and forms had already been laid.

Even though the concrete had not yet been poured, it would have still been far more expensive to remove the forms and bars to create a structure that could support the extraneous lateral load caused by this temporary construction condition by itself. At this point in a construction project it is more cost effective to develop an on-site solution to most problems fixing what has been completed. As soon as Gilbane Building Co. noticed the conflict of design loads and construction loads during planning construction on June 8, 2007, plans were made to adjust the integrity of the foundation on site and not through major redesign.

The solution decided upon was to brace the wall by welding additional external horizontal steel reinforcements to the wall re-bar already in the form just before the concrete was poured. This anchored the wall to the adjacent walls (“A” bars) and the floor footing (“B” bars) as seen in **Figure 5**, mitigating the effect of the differential soil elevations. The designed bracing solved the problem and there was no structural failure in the element. There were no time delays and the total cost of engineers redesigning the structure, materials, and welding was \$9,000 (Hinton, 2007). After this setback was discovered and solved, our project team was tasked to determine if an alternate solution would have been more cost effective.

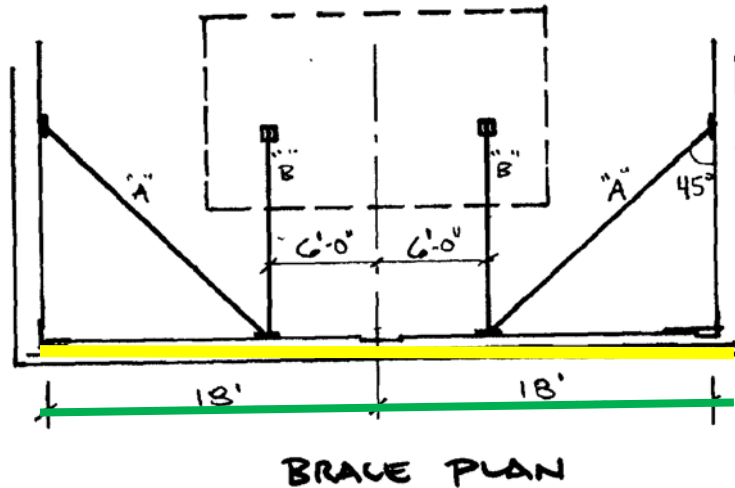


Figure 5: Plan View: Bracing Solution (j-line wall: yellow, garage wall: green)

A designer cannot be expected to consider the loads sustained during the construction process based on how the job was scheduled as well as the loads of the completed building. However, our team set out to determine if a more cost effective design would have been created if the building were designed this way, capable of withstanding the force from the difference in soil elevations, would have been a more cost effective solution than welding on additional external bracing. Our intention was to determine the dimensions of this stronger wall and conduct a cost/scheduling analysis of this design compared to the working solution that is now in place.

The cost involved in building a bigger, stronger wall does not merely stop at the price of extra concrete and steel. In the case of the residence hall, the wall was designed to withstand the weight of the building at the end of the project. Additional engineering costs would have been incurred if the designers wanted the wall to withstand the weight of the residence hall at the time of the garage foundation pouring as well as the force of uneven fill. Many other factors must be taken into consideration when an element of a structure changes. For example, if the wall becomes stronger, it must become larger,



possibly requiring a larger footing, a bigger excavated trench, and a larger form in which to pour the wall. Our team investigated these factors and performed cost/benefit analysis to determine if the alternate design we created would be more cost effective than the existing design with external bracing including the savings in General Conditions cost.

### **3.0 Line of Balance diagram**

#### **3.1 Close-Out Schedule**

When a project is near completion Gilbane sets up a Card-trick meeting where subcontractors come to schedule upcoming activities. This meeting was planned and our intent was to present our LOB diagram to the Project Manager of the project before the Card-trick meeting to assist the scheduling.

We created a schedule from Gilbane's master schedule using the LOB method for all finishing activities that needed to be completed in the last seven months of the project for the second through fifth floors (not the first floor because residential services will be located there). This method is ideally suited due to the similarities and repetitiveness of the activities between all the rooms and activities on each of these floors. We received a task list from Gilbane in PRIMAVERA format, and imported all information into Microsoft EXCEL. We also imported important inspection and completion milestone dates. Once the task list was populated, we sorted the data in a way that graphs could be generated by Microsoft EXCEL to create the LOB diagram. This diagram was reviewed by the project manager prior to the card trick meeting that took place on February 7, 2008 (See section 5.1). The goal of this meeting was to address all scheduling concerns by both the subcontractors and Gilbane. As a result of this meeting, a new schedule reflecting input by all subcontractors responsible to carry the work in the field was generated.

We met with the Neil Benner, the Project Manager, so he could voice his scheduling and logistical concerns. From this meeting, we adjusted our schedule to reflect his concerns. As a project manager, his main concern is finishing the job on time

and within budget. WPI is planning to occupy the residential building for start of the 2008-09 academic year. Therefore, WPI wants to ensure that they have enough time to properly prepare the building for student occupancy which includes moving in furniture as well as testing mechanical and electrical systems. Using the LOB Method, one can quickly ascertain in a visual manner whether this goal is accomplishable or not.

The use of the Critical Path Method (CPM) is a great way to determine activities that may delay construction and push the finish date back. Once the critical path is determined, the PRIMAVERA file can then be used to create a Line of Balance (LOB) graph. This graph visually displays the progress of activities over time, by floor.

The first task to convert a CPM to an LOB is to add the activities into Microsoft EXCEL. Any information for the activities (ie. duration, subcontractor, floor, completion status, etc) should have its own column. This allows for commonalities between floors to be easily sorted and displayed. This is discussed in section 3.3. There should also be a column added to differentiate between common activities and the different floors that activity is to be conducted on. This column should be numerically numbered as this will be the Y-Axis representing the floor number on the LOB graph. As the Project Manager's guiding principle is to schedule the job floor by floor and then to move crews along performing the same task this diagram could become particularly useful.

This work is being completed to show each activity and how it directly affects the activities following it. Once all the activities have been added to Microsoft EXCEL, and the Activity Descriptions are the same for the same activity occurring on each floor, the data is ready to be sorted. The data can be sorted in a variety of ways, allowing for the display of data arranged according to time, alphabetically, by duration length, or a variety

of other options. To sort the data click on Data > Sort. From the drop down box, select Activity Description in the first box, in the Then by, box, select start date. Click OK. This will sort the data alphabetically by Activity Description, then within each activity, by the start date.

### 3.2 Converting Critical Path Method to Line of Balance Method

Now the data can be graphed so one can visually determine when an activity conflicts with another. Select Insert > Chart > Chart Type = XY Scatter. For a sub-type select the connected dots option. Click Next. The data will be arranged using Series. Select the Series tab and add a new series. The “Name:” is the Activity Description, the “X-Values:” is the Early Start column (make sure you only select the dates that pertain to that particular activity, and the Y-Values is the Floor column. See **Figure 6** for clarification.

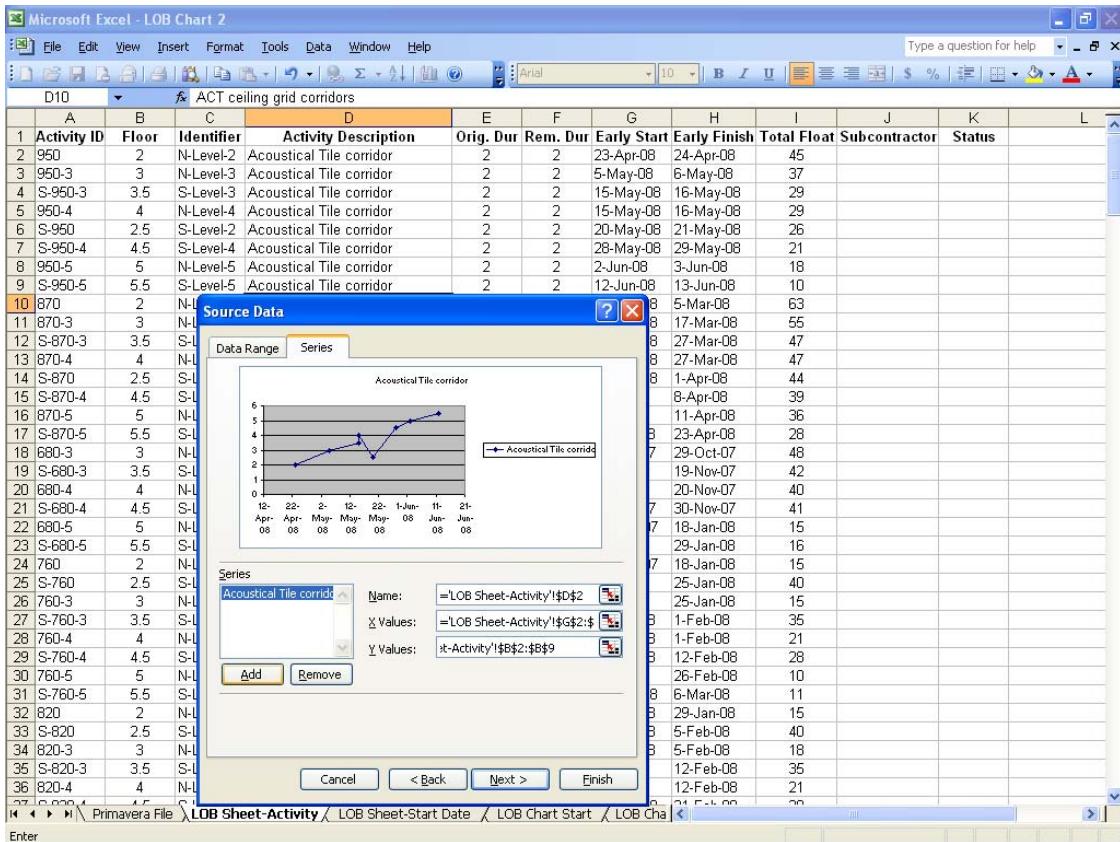
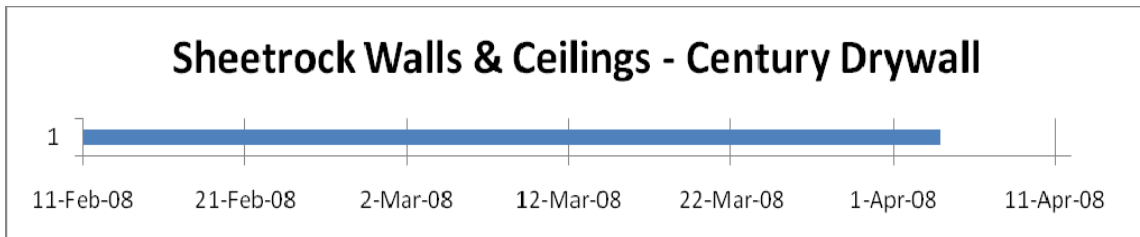


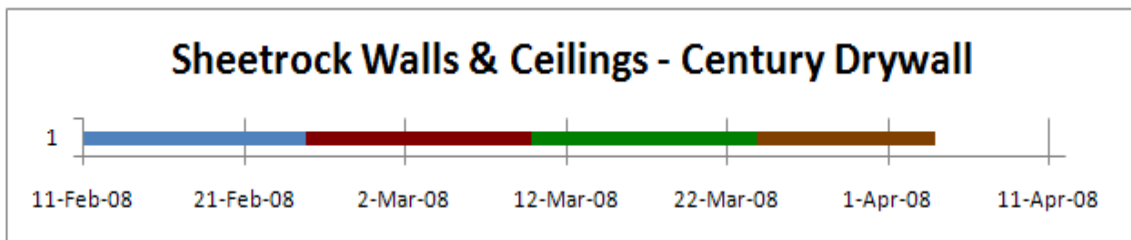
Figure 6: LOB Graph-Series Description

Figures 7 through 10 show how this process was applied to a single activity (Sheetrock Walls & Ceilings) performed by subcontractor Century Drywall over a given

period of time. The CPM diagrams are compared to the LOB diagrams to contrast the differences on the visual displays generated by both methods. **Figure 7** illustrates the CPM block diagram in which the entire activity is shown over a period of time. **Figure 8** takes **Figure 7** and divides the activity by floor (Blue = 2<sup>nd</sup> floor, Red = 3<sup>rd</sup> floor, Green = 4<sup>th</sup> floor, Brown = 5<sup>th</sup> floor). **Figures 9 and 10** display the LOB graphs based upon start or end dates. It should be noted that the end date of one activity does not always coincide with the start date of the following. The first two figures do not clearly illustrate any interferences with other activities, while the LOB figures show that when a slope increases or decreases (thus the task progresses more quickly or slowly), the activity may interfere with other activities (see **Figure 13** for a multiple task LOB diagram).



**Figure 7: Critical Path Method Diagram**



**Figure 8: Critical Path Method Diagram (by floor)**  
 (Blue = 2<sup>nd</sup> floor, Red = 3<sup>rd</sup> floor, Green = 4<sup>th</sup> floor, Brown = 5<sup>th</sup> floor)

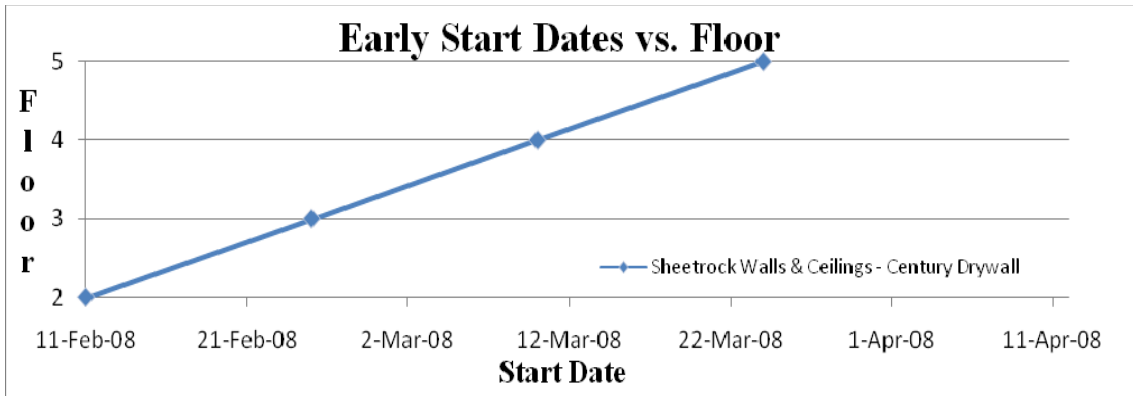


Figure 9: Line of Balance Diagram (start dates)

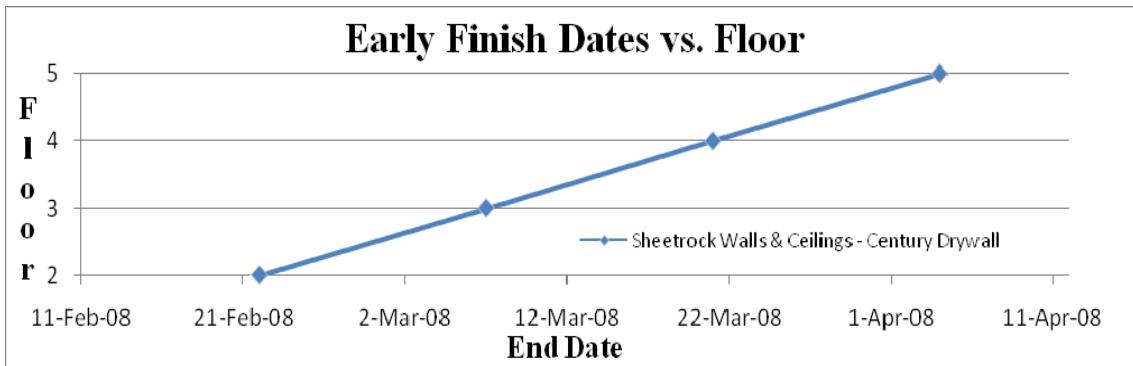


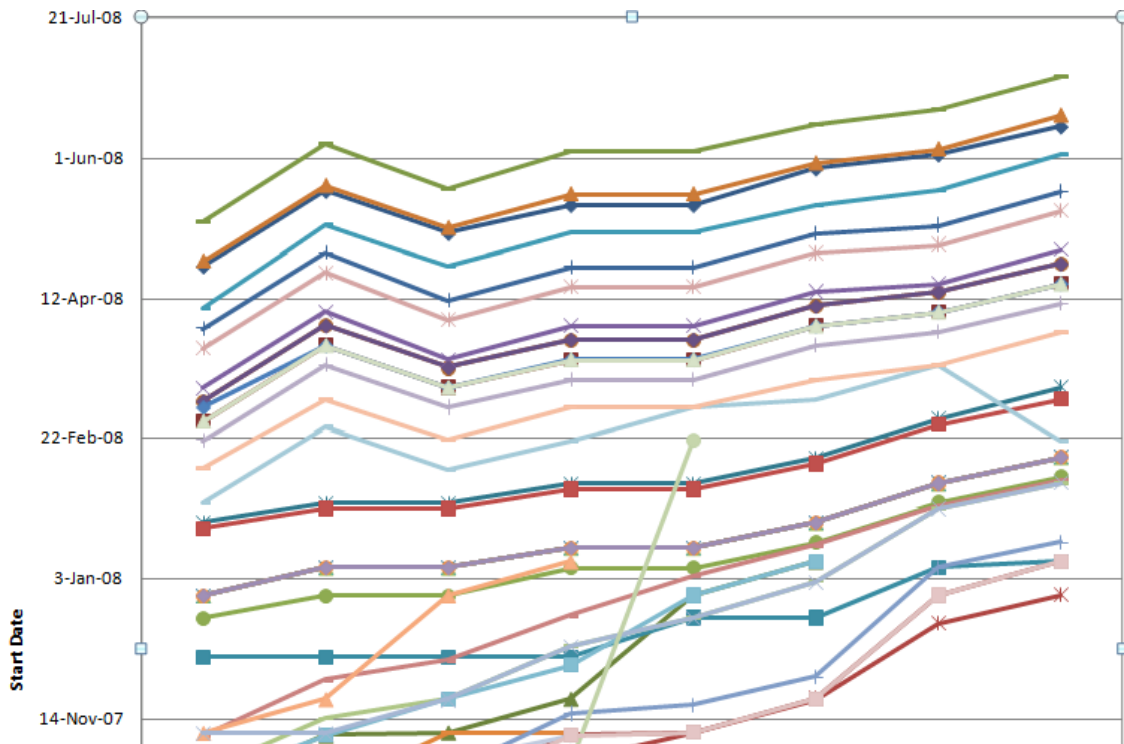
Figure 10: Line of Balance (end dates)

### 3.2 Creating the Line of Balance Schedule

Generating a set system or method for converting a CPM to LOB was challenging at times. There were issues with using a PRIMAVERA task list and being able to graphically display the data to illustrate a LOB graph. This issue was overcome by importing the data into a Microsoft EXCEL spreadsheet. Unfortunately, all the data could only be copied into a single column, and thus there was a large amount of time spent organizing the data into the proper columns and creating similar numerical identifiers to allow the data to be graphed.

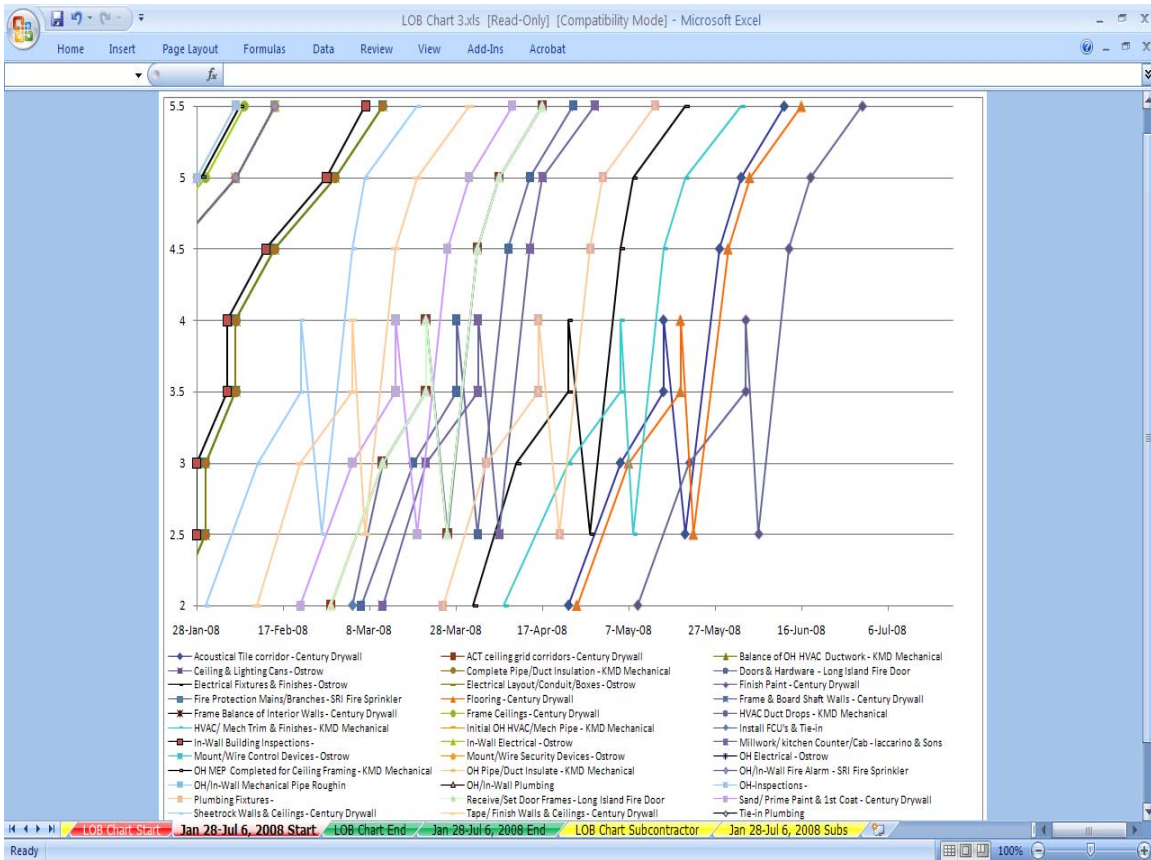
Once all the data was arranged, the next problem that was attacked was how to graph it. Microsoft EXCEL has a variety of graphing options available. Once it was discovered that graphing the data by using series instead of defining the axis was easier, the work went smoother. The first graph had the data arranged by floor, and the lines ended up going backward in time to go the next level under construction. For example, for a particular activity, Floor 2 starts on 1 April, Floor 3 starts on 5 April, and Floor 4 starts on 3 April. The line would go chronologically by floor, instead of by date. Thus the line would go from 5 April, backwards to 3 April. See **Figure 11** for further clarification. The issue was that Microsoft EXCEL was graphing the data exactly how it is listed in the spreadsheet. Because the activities were arranged according to floor, the data was being graphed as such. By using an XY Scatterplot, and presorting the data first by activity description, then by start date, the data was graphed according to the start date (see **Figure 12**).





**Figure 11: First LOB Graph - Data sorted by floor**

Initially, the schedule that Gilbane was using had the building divided into pods (North and South). Each floor had two pods, North and South, thus creating a total of 10 pods, or 8 in our particular area of focus (floors 2 to 5). The graph based upon start date (**Figure 12**) had each pod displayed on the Y-axis, and the Start Date displayed along the X-axis. The pods are numbered as follows, 2.0 = Second Floor North Pod, and 2.5 = Second Floor South Pod. This numbering allowed for the information to be sorted and visually displayed in a chronological order. One will notice however, that the tasks went from pod 3.5 back down to 2.5. This could have potentially been an issue due to having to move equipment between floors a number of times, instead of working chronologically North Pod to South Pod, then moving up the next floor and repeating the same pattern. Additionally, pod 3.5 and 4.0 were scheduled to start all activities on the same day. This meant that there would have to be two crews working simultaneously to keep on schedule.



**Figure 12: LOB: Start Date vs. Pod**

Gilbane’s scheduler, Colin Thrift, decided in January to schedule the project according to floor, instead of by pod. This quickly eliminated any confusion about which pods would be worked on in which order, as well as ensuring that each task progressed in a linear fashion, from the second floor all the way up to the fifth floor. **Figure 13** illustrates these changes. It clearly shows the LOB method because each task progresses linearly by floor, in a constant manner. There are a few irregularities, such as the task “Install FCU’s & Tie-In – KMD Mechanical” (green line with triangular markers). It slows significantly for the fifth floor. While this means it crosses other lines, those lines involve sanding and painting the walls and these tasks may not affect each other. The solid red lines are critical completion dates and inspections. This final graph quickly

shows the viewer which tasks are critical for completion by those solid red lines, and whether the schedule should be adjusted accordingly.

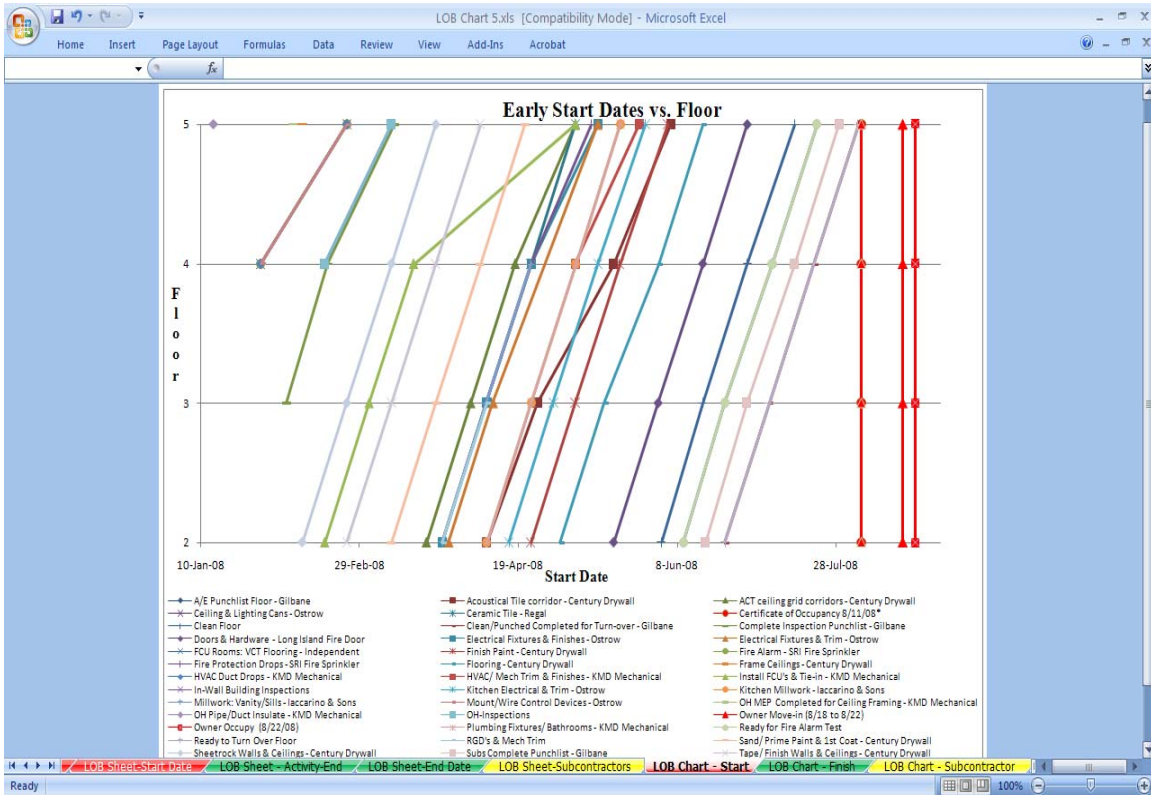


Figure 13: LOB: Early Start Dates vs. Floor

A different issue that was easily resolved involved incorporating the subcontractor names directly on the chart. By having their names in the legend, each subcontractor would know exactly what they were responsible for and where the problems were, without having to switch between several spreadsheets looking for their name. This was resolved by attaching the subcontractor name to the activity description. By adding their name into the Activity Description column, their name instantly became part of the title for that particular series. There is still a separate column for subcontractors, which allows the user to sort the data according to subcontractor and easily identify which tasks

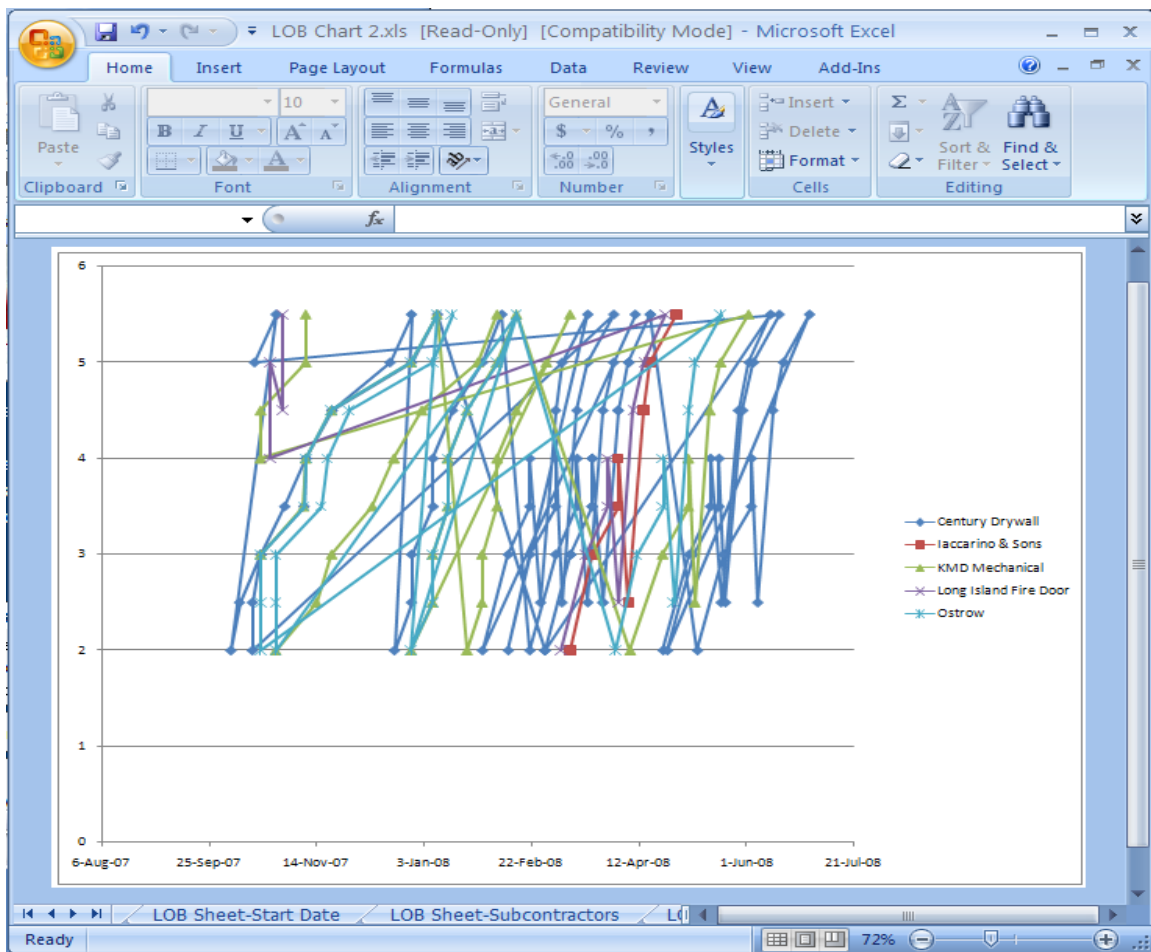
are attributed to which subcontractor.

The Headings were as follows:

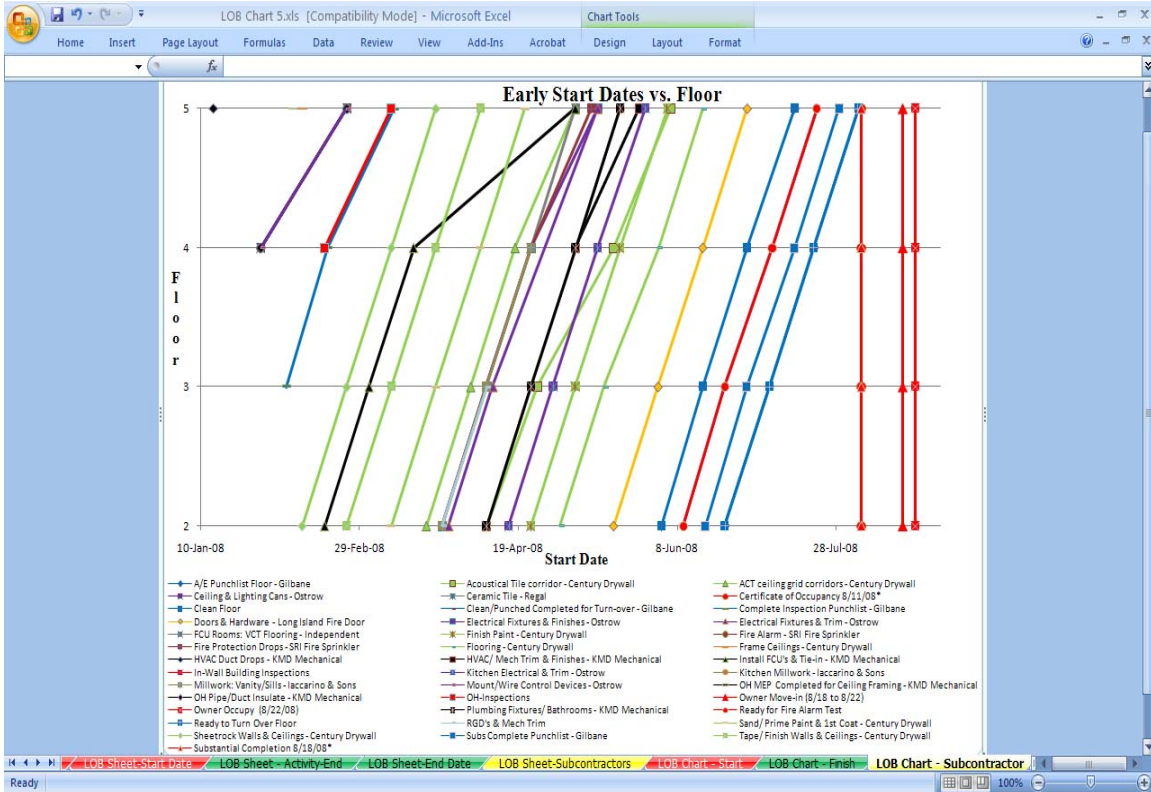
- Activity ID
- Activity Description
- Original Duration
- Remaining Duration
- Early Start
- Early Finish
- Total Float
- Variance Target 1 (Early Start)
- Variance Target 1 (Early Finish)
- Actual Start
- Actual Finish
- Level
- Location
- Sequence
- Bid Package
- Sub Bid Package
- Variance Target 2 (Early Start)
- Variance Target 2 (Early Finish)

The first attempt at creating the LOB diagram in which lines identify the subcontractor resulted in a chart that was extremely confusing, due to the lines having

had no clear distinction between time and floor (see **Figure 14**). This was adjusted by using the Task Start Dates in conjunction with the column that had both the Subcontractor and Activity Description within it. Then, within the graph, the marker and line color was changed according to each individual subcontractor. This was done by right clicking on the individual legend entries, selecting “Format Data Series” and adjusted the various colors. The end product, **Figure 15**, was very clear as to who was responsible for which activities. Additionally, all Completion and Inspection Dates were included in the graph as solid red lines so that it would be easy to determine which task would quickly become the critical ones.



**Figure 14: Subcontractor LOB Graph - Data Sorted by Subcontractor**



**Figure 15: LOB: Early Start Dates vs. Floor (Subcontractor)**

Once all the series have been defined you need to name the axes and graph. Click Finish once the proper area is selected and the graph will be formulated. The objective of the chart is to not have any overlapping, or crossing lines. If this occurs, then the dates should be adjusted so there is not a conflict between subcontractors attempting to complete conflicting activities on the same floor. **Figure 15** illustrates a good LOB, with very few irregularities.

This work may be considered “dirty work” but it is the foundation of our project and is necessary to set-up for the LOB diagram.

### **3.3 Initial Review of LOB diagram by Project Manager**

The team met with Melissa Hinton (Project Engineer) to go over some questions concerning missing drawings on October 16<sup>th</sup>, 2007. The drawings were needed to locate room numbers and we also needed sectional views of the J-Line Foundation Wall. She provided us with the Architectural and Structural Drawings.

On Dec. 13, 2007, our team met with the Project Manager, Neil Benner, for the Residence Hall project. We had a lot of pending questions and wanted some much needed input from him on our project. Our most important question was determining when the Card-Trick meeting will take place. This is vital information because we need to know when we need our finished product needs to be completed by. At this point it is still unclear whether or not our Line of Balance diagram will be used in the meeting, or if it will be a supplementary tool used by Neil, prior to the meeting. At the time of this meeting he did not have an exact meeting date, but said that it would take place sometime in late January. We said that we would stay in contact to find the actual date as we approach late January.

When we were going over our spreadsheets and Line of Balance with Neil we pointed out a couple potential problems. We narrowed it down to an Activity ID number, (940-4), that was scheduled as the same time as another activity. More specifically, South Level 3 and North Level 4 were planned to be started and completed simultaneously. Once we brought this point up to Neil, he was impressed with our findings as we reminded him of a decision he had made many months prior. He and Gilbane's scheduler (Colin Thrift) had planned on two crews, one on each section. Neil had since forgotten his plans so with our LOB diagram we gave Neil something to jot down on his notebook

to relay the message to the Sub-contractor to double the crew size for the activity start date and duration.

Neil thought our project was worth-while as well as helpful. He made a couple of valuable suggestions after we presented our work to him. Since the Project Schedule has been updated as of November 30<sup>th</sup> he wanted us to update actual progress vs. projected progress. At this point, on our LOB diagram we had many activity dates, floors, completion dates and appeared a bit messy. He suggested to us that we create a LOB diagram illustrating Milestone dates to simplify the graph. He also suggested that we meet with Colin the scheduler to take his thoughts into consideration.

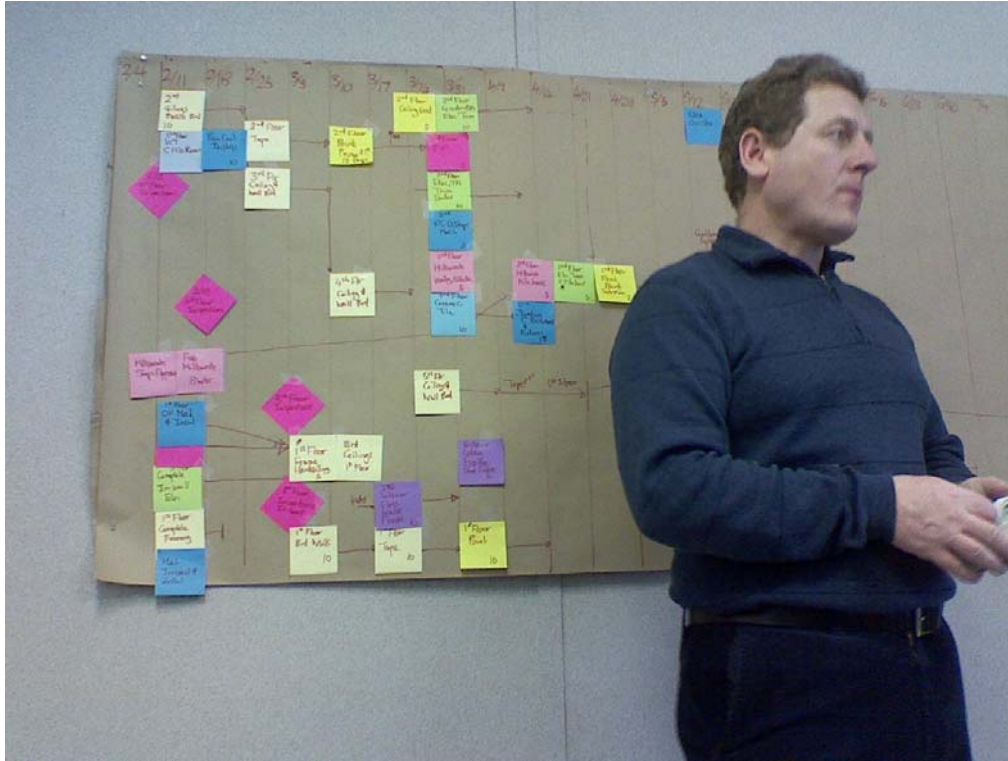
In conclusion, Neil told us that Gilbane would use our project as a supplementary tool in addition to Gilbane's standard scheduling methods.



### **3.4 Card-Trick Meeting**

The crucial sub-contractors for the end of the project assembled together on Feb. 7, 2008 to attend Gilbane's Card-Trick Meeting. The lead scheduler Colin Thrift ran the meeting at the front of room. On the wall there was a generalized schedule with vertical lines indicating the first Monday of each week. He had various color post-it notes which were to be placed in the appropriate locations with the task and duration of the activities. Each color indicated the different tasks that each sub-contractor was held responsible for. Colin connected each post-it or card by a line showing the path to follow in order to reach critical dates.

He had pre-established milestones that he needed to confirm dates with the project managers from each of the sub-contracting companies. Colin systematically went around the room beginning with Century Drywall and inquired task durations as well as start dates. As he jumped from one sub-contractor to the next, many coordination issues were addressed. Issues like procurement lead times to organizing the sub-contractors in a way so that they weren't running into each other were a couple of the main topics.



**Figure 16: Card-Trick Meeting Wallboard**

The goal for completion is August 4, 2008. As this was the final Card-Trick meeting of the project all dates were critical to reach the completion date.

From this Card-Trick meeting an updated schedule was generated taken directly from the cards on the scheduling board. After being reviewed this was the last and final schedule to carry out the successful completion of this project.

Directly following the meeting our MQP team met with Colin. We presented him with our LOB diagrams and explained to him how we extrapolated the schedule provided to us by Gilbane to the LOB diagrams. His initial observation was that the steeper the lines the more crucial that task would be. More crews would be needed to sustain the pace of the activity. If there was any delay it would significantly change the slope of the line resulting in a crossing of lines, which is a warning for potential scheduling problems. He was impressed with our material and thought it was a good early detection tool to

bring to light potential issues. He went on to say that PRIMAVERA is a good scheduling tool to present the critical path however with the LOB diagram it shows in greater detail the relationships between each task and each different sub-contractor.

There was one change that needs to be noted. When the project first started they categorized the schedule for activities such as concrete placement and erecting structural steel by North and South pod. However, these finishing activities are only categorized by floor. This not only simplifies Gilbane's scheduling techniques but also lets our LOB diagram flow much better.

## **4.0 Foundation Design Review**

### **4.1 Research**

As stated previously, this portion of the project was intended to redesign the j-line foundation wall of WPI's new residence hall to withstand unspecified lateral loading caused by fill removal. Cannon Design's drawings were studied along with the actual foundation wall in the field to obtain a better understanding of what needed to be done. It is important that the process by which this solution was developed be determined to understand the mindset of the involved parties at the time. We garnered all the information that played a part in this decision including, but not limited to, the schematics, plans, and the loads that the wall would experience if the external fill were removed without bracing.

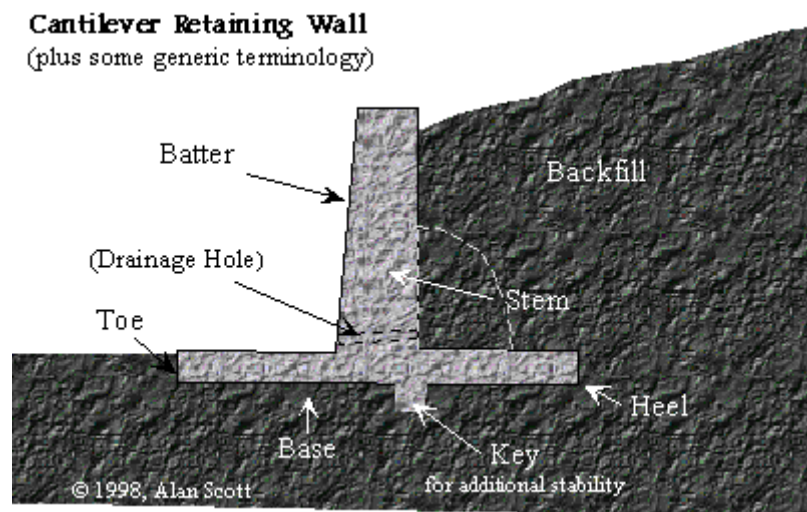
We studied specifically what solution was developed, how it was developed, and what materials were used in the construction. To do this, we acquired the Request for Information (RFI) documents, field sketches (SKS), and other documents pertaining to this solution seen in appendix A. These documents aided us in creating a cost/scheduling analysis to determine the best alternative.

## **4.2 Field Solution**

Melissa Hinton, Gilbane's Project Engineer, was interviewed to gain an understanding of the situation that occurred in the field and provided information on time and expense that went into the external bracing solution. The total cost was \$9,000 including design work, approval, and the one day of a welder on site to attach the bracing however there were no time delays as the work was done simultaneously with the rest of the project (Hinton, 2007). In order to determine if an alternative would be more cost effective we compared the cost of the existing wall including the additional \$9,000 in bracing fees against the expense of our alternative design that does not include the General Conditions cost. The expense must include not only the cost of more materials but also the specialized design and any on-site considerations that may occur.

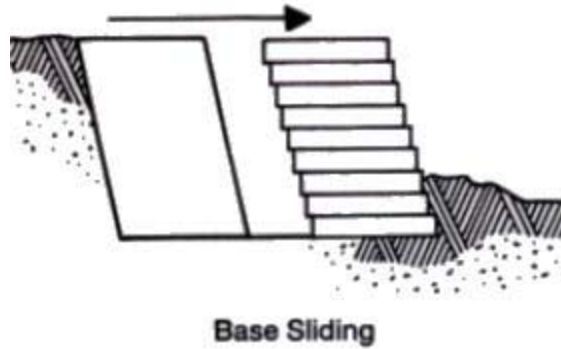
### 4.3 Modes of Failure

Under the conditions created by the construction schedule, the foundation wall was essentially acting as a cantilevered retaining wall as can be seen in **Figure 16**. This type of wall can fail in one of three ways: sliding, overturning, and bearing capacity failure. The force required to cause these failures can be calculated using  $\gamma$ , the unit weight of the soil and  $\Phi$ , the effective friction angle of the soil.



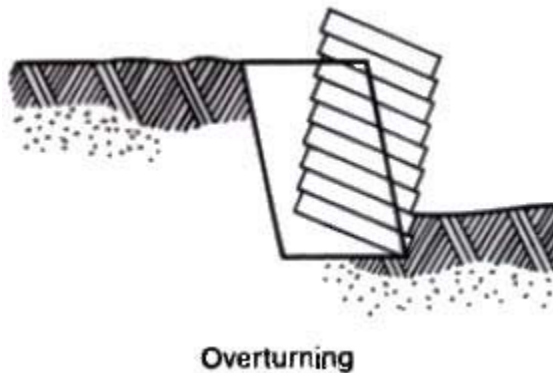
**Figure 17: Cantilever Retaining Wall**  
(Dr. Scott, 2006)

**Figure 17** below illustrates sliding failure, which occurs when the lateral earth pressure exceeds the resistance provided by the wall. This resistance is caused by the frictional force of the base against the soil. This type of failure may be averted by adding a key or lengthening the heel to provide additional frictional force against sliding.



**Base Sliding**  
**Figure 18: Example of Base Sliding Failure**  
(TerraCell, 2006)

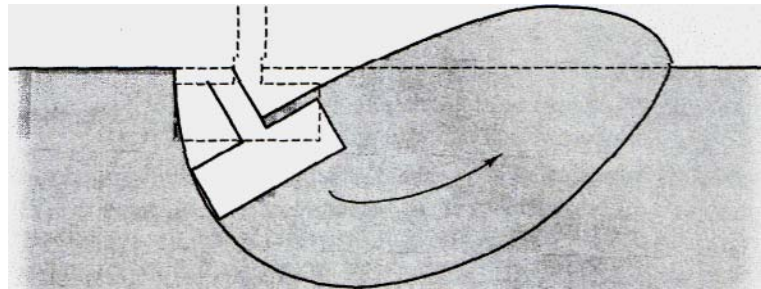
**Figure 18** demonstrates an overturning force on the wall as it rotates about the toe. Overturning is caused by the sum of the destabilizing forces multiplied by their moment arm. The righting moment is the product of the weight of the wall and its moment arm. If the overturning moment exceeds the righting moment, the wall will fail by rotating about around the toe of the structure. To increase stability in the wall, the toe and heel can be elongated to lengthen the magnitude of the righting arm.



**Overturning**  
**Figure 19: Example of Overturning Failure**  
(TerraCell, 2006)

Bearing capacity failure, shown in **Figure 19**, occurs when the loading pressure in the footing from the superstructure exceeds the bearing capacity of the soil. Failures of this type are catastrophic and must be avoided at all cost. Increasing the size of the footing,

and therefore reducing the force per unit area on the soil is one way to avert such disasters. This type of failure will not be considered in the paper because this type of failure would have been considered in the initial designs. Removal of soil from one side will not change the bearing capacity of the soil underneath the wall.

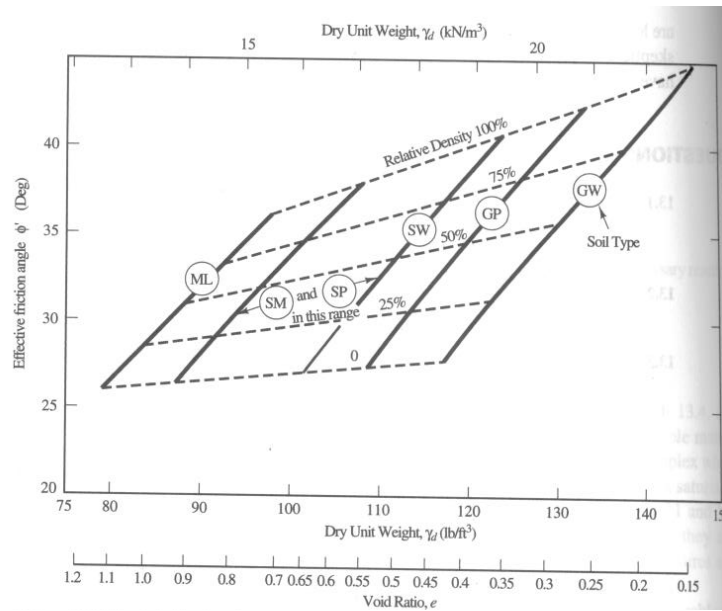


**Figure 20: Example of Bearing Capacity Failure**  
(Coduto, 1999)



#### 4.4 Design Procedure

The soil was classified in the Briggs soil report as sandy gravelly compacted to 95% of maximum dry density from standard Proctor. Based on the information shown on **Figure 20**, it was determined that this type of soil (SW, sandy, well graded) has a unit weight ( $\gamma$ ) of 115 pcf and an effective friction angle ( $\Phi$ ), the angle at which failure is most likely to occur, of 35 degrees (Coduto, 1999). There is an equation to find the lateral soil pressure induced by a vertical load for each of three conditions: at rest  $K_0$ , active  $K_a$  and passive  $K_p$ . The  $K$  values are multiplied by the vertical effective stress ( $\sigma_z$ ) to find how much horizontal force will be applied to the wall due to the vertical loading applied.

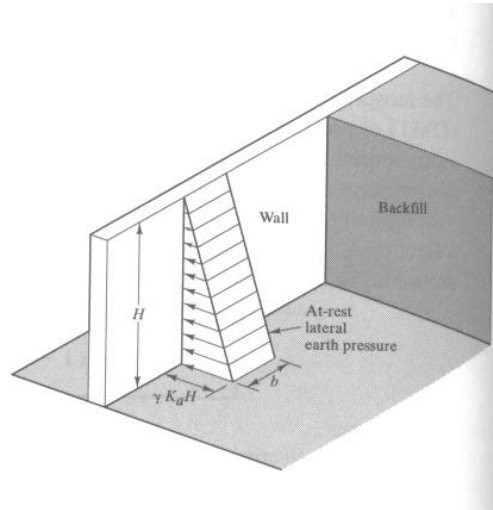


**Figure 21: Typical  $\Phi$  Values for Cohesionless Soils without Clay or Cementing Agents (Coduto, 1999)**

The first option is when the wall is in the at rest position; for this, we assume the wall is unyielding and will not move at all under the force the soil exerts. If a vertical pressure is applied from soil or additional surface loads, a force will be felt in the

horizontal direction that compounds linearly with the depth the effects of this force can be seen in **Figure 21**. A value for the force felt is calculated using the equation:

$$K_0 = (1 - \sin\Phi) \\ = 0.43$$



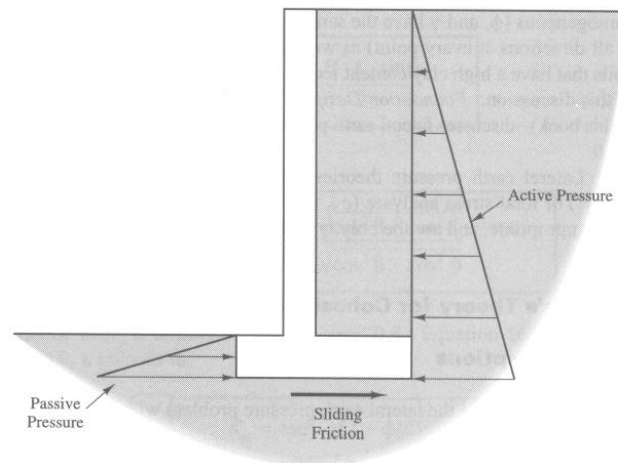
**Figure 22: At Rest Pressure Acting on a Retaining Wall**  
(Coduto, 1999)

The second method is the active condition  $K_a$ . The previous condition assumes that the wall is perfect and does not move, although this seems like a strict requirement for a wall, the top of almost every wall moves outward when loaded by cantilever deflection or by rotation of the entire structure about the toe, even if it is just a fraction of an inch (Wang & Salmon, 1979). Even these minuscule movements alter the lateral earth pressure. The active condition assumes that the wall moved away from the retained material when loaded and is described with the equation:

$$K_a = \tan^2 (45^\circ - \Phi/2) \\ = 0.27$$

The final condition, the passive condition  $K_p$ , is the opposite of the active condition and occurs when the wall moves into the retained material when loaded. Typically this occurs at the toe of the wall (Coduto, 1999). The combination of the active condition along the stem and the passive condition along the toe of the wall determines the total horizontal force acting on the wall. See **Figure 22** to see how the forces will act. The passive condition equation yields:

$$K_p = \tan^2(45^\circ + \Phi/2) = 3.68$$



**Figure 23: Active and Passive Pressure Acting on a Cantilever Retaining Wall (Coduto, 1999)**

If above the groundwater table in a homogeneous soil, which happens to be this case, the  $K$  values are constants multiplied by  $\sigma_z$  which varies linearly with depth, therefore the resulting horizontal stress ( $\sigma$ ) also varies linearly with depth and the force applied is the area of the triangle (Coduto, 1999). The resultant force will act 1/3 of the

way up from the base of the triangle. The following equations describe the unit force per unit length acting on the wall from the active and passive condition contributions:

Active

$$P_o/b = \gamma H^2 K_a / 2 \\ = 2616 \text{ lb/ft}$$

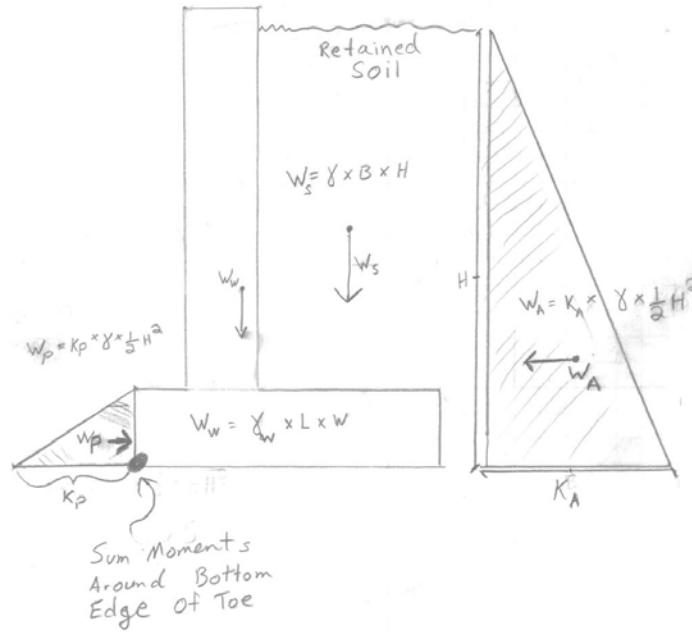
Passive:

$$P_o/b = \gamma H^2 K_p / 2 \\ = 476.1 \text{ lb/ft}$$

Where:

$$P_o/b = \text{force per unit of length} \\ \gamma = \text{unit weight of soil} \\ H = \text{depth of the soil}$$

For the existing wall before the bracing was added, these calculations describe two forces, one acting to upset the wall while the passive force resists this motion. To determine the total resultant rotational force acting on the wall, the overturning moments must be compared to the magnitude of the resisting soil force, the weight of the wall, and the passive force, each multiplied by its righting arm. The resulting moments will be summed around the bottom edge of the toe as seen in **Figure 23**. Shown in **Table 1** are the contributing moments, the forces and the moment arms by which they are multiplied. For the purpose of this moment equation, the driving moments are counter-clockwise and the resisting moments are clockwise based on which way they act to overturn the wall. As can be seen, the force generated by the active condition is clockwise and therefore, the only driving force.



**Figure 24: Illustration of Overturning Forces Summed Around the Toe**

**Table 1: Forces and Moments on Wall**

Force Contribution	Force Magnitude	Distance From Toe	Moment
Active	2616 lb	4.33 ft	11317 ft-lb (ccw)
Passive	476.1 lb	0.50 ft	238 ft-lb (cw)
Soil	5016.8 lb	4.10 ft	20569 ft-lb (cw)
Wall	3416.4 lb	1.75 ft	5979 ft-lb (cw)

To find the factor of safety of this structure the resisting moments must be divided by the driving moment. The larger the factor of safety, the more stable the wall will be, but also more expensive. There must be a balance between economics and safety. An appropriate value for the factor of safety against overturning is usually considered adequate when it is 2.0 or greater; it is recognized as stable without being excessive with respect to materials and resources. (Wang & Salmon, 1979).

$$FS = \frac{\text{soil} \times \text{distance} + \text{passive} \times \text{distance} + \text{wall} \times \text{distance}}{\text{active} \times \text{distance}} = 2.36$$

This factor of safety is greater than 2.0 and is more than enough to keep the wall from overturning when the soil on one side is removed. The weight of the soil on the large base contributes the most to the stabilizing moments. Next, the wall will be analyzed for its resistance to sliding failure

**Sliding failure:**

Sliding occurs when the driving forces that push the wall away are larger than interface frictional force between the footing and soil Sliding will be evaluated by comparing horizontal driving force vs. horizontal resisting forces, largely from friction force between the footing base and the underlying soil and the passive earth force. One may think that the friction of the soil against the wall will be the determining factor, but in reality the soil will first fail internally and not between the soil and concrete. The resisting forces are the passive force added to the product of the normal force of the wall and soil by the tangent of the interfacial effective friction angle. The interfacial frictional angle is between different materials: soil and wall footing for this case; this angle can be approximated from effective friction angle and the interface condition)

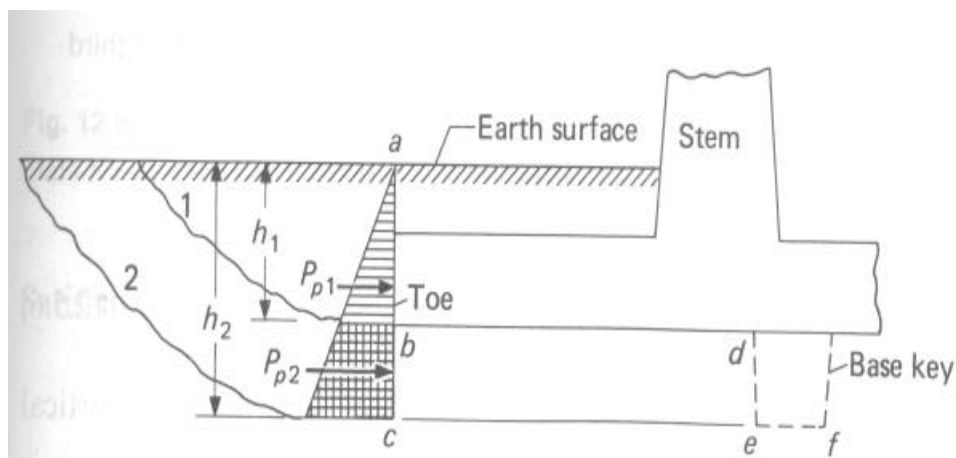
$$\begin{aligned} \text{RF} &= \text{passive} + (\text{wall} + \text{soil}) * \text{TAN}(0.5\Phi) \\ &= 3133 \text{ lb} \end{aligned}$$

Next, find the driving forces, the forces that aid in pushing the wall away from the soil. The only force behaving in this manner is the active load with a magnitude of 2616 lb. The resisting forces are a little more than 500 lb greater than the driving forces. This,

however, does not mean the wall is in a safe condition. Again the factor of safety must be calculated by dividing the resisting forces by the driving forces. An acceptable value for the sliding factor of safety if not accounting for the resisting passive force is 1.5. In this case 2.0 will be required because the passive force will be considered (Wang & Salmon, 1979).

$$\begin{aligned} \text{FS} &= \text{RF/DF} \\ &= 1.19 \end{aligned}$$

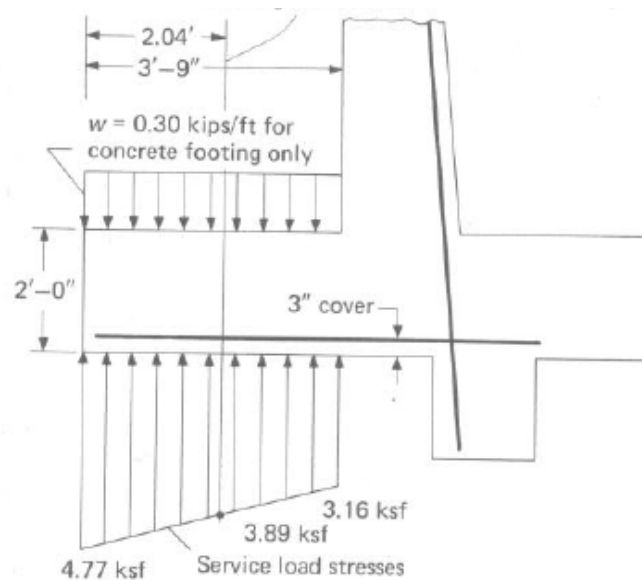
Although this value is greater than 1.0 and therefore is not in immediate danger of sliding, the factor of safety is not met and the wall is not considered stable or acceptable from the design perspective. There are several methods to increase this margin of safety when still in the design phase of the wall. One of the most common methods when lateral space is at a premium is to insert a base key. This is a structure placed below the base to provide for additional passive force by increasing effective depth from  $h_1$  to  $h_2$ , refer to **Figure 24**, to resist the sideways movement of the wall.



**Figure 25: Additional Passive Resistance from Base Key**

(Wang & Salmon, 1979)

Typically the ideal location for the base key is to have its front face 5 in. before the back face of the stem of the wall. This placement allows the reinforcing steel from the stem of the wall to be extended into the key as seen in **Figure 25**. With the exception of this, additional reinforcement is not needed (Wang & Salmon, 1979).



**Figure 26: Example of Reinforcement Extending into Base Key**  
(Wang & Salmon, 1979)

To find the required depth of the key, the deficit of the resisting forces that must be overcome to induce the desired factor of safety must first be calculated then overcome. The resisting forces, without the passive force total 2660 lb/ft. The active force that acts to push the wall away has a magnitude of 2616 lb/ft. The resisting forces must be twice as strong as the driving force. This means another 2575 lb/ft are required to be exerted by the passive force generated by both the toe of the wall and the depth of the key.



The force required will be used to find the depth of the key needed. Essentially, this requires using the passive force equation in reverse to find H from the known passive force. After performing the calculations it is found that the key size must be 2 feet in depth to cause enough passive resistance to prevent the wall from sliding.

$$(P_o/b^2)/(\gamma * K_p) = H^2$$

H= 3.5 ft subtracting the footing depth, H<sub>key</sub> =2.0 ft

Where:

$$P_o/b^2 = 2575 \text{ lb}$$

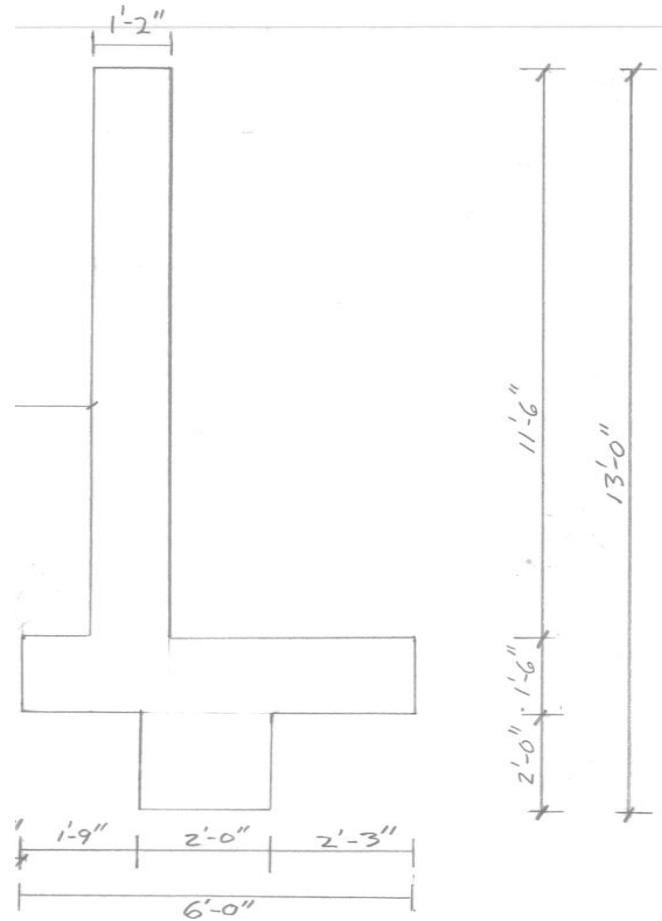
$$\gamma = 115 \text{ pcf}$$

$$K_p = 3.68$$

H = Depth required to produce sufficient passive force

Generally the key is made square resulting in a 2 ft x 2 ft dimension for the base key. This, if poured for the entire length of the 39 ft long J-line wall would result in an additional 5.8 cubic yards of concrete used at a cost of \$70 per yard (On The House media, 2008) is a little over \$404. There is no extra cost for delivery or placing as the placement will occur at the same time as the erection of the rest of the footing and no extra work is necessary. The existing reinforcing bar is #8 placed at 18 in. oc. The reinforcing bar will extend 21 in. into the key. The additional steel needed to accomplish this is 46 ft. at a cost of \$174.72 total (Speedy metals, 2008). The steel is not separate from the original steel and no additional bending is needed as it protrudes straight into the key. This results in no additional cost to place the reinforcing steel. To excavate the required 2x2x2 ft trench would not have resulted in a loss of time as it is done at the same time as the trench for the footing. The proposed dimensions of a foundation wall capable of withstanding the induced load of having 12 feet of soil removed from one side is

shown in the **Figure 26** below. The combined cost of concrete and reinforcing steel is \$578.72. The estimated cost of labor and placing concrete, steel, and framing materials for adding a base key is about 2-2.5 times the cost of the concrete and steel yielding, \$1200-\$1800. Therefore the estimated cost of the proposed alternate solution is \$1800-\$2400.



**Figure 27: Cross-Section of Final Design**

The field solution proposed by the project engineers cost a total of \$9,000. This fee includes the time of the engineers to design the field solution to show that it would solve the instability, materials, and finally the labor of the welder to spend the day attaching the structural reinforcement to the re-bar that would soon be imbedded in the

foundation of the j-line wall. It is difficult to discover, while designing a building for final loads, what extraneous loads would be induced during construction after an unforeseen schedule change. Given the time at which the instability was recognized, the project engineers found a relatively inexpensive solution that worked well.

However, had the instability been noticed far before it was, when the wall was still being designed the first time, the resulting cost of adding a key to the wall would have been concrete, reinforcing steel, labor and forming. The resulting cost difference if the designers had known previously of the interference between the garage and the j-line wall would have been over \$6,000. Though this is quite substantial, it is minimal considering the cost of the entire project how infrequently these situations happen. Though moving up the start date of the garage caused the instability additional cost, the time saved by the change more than makes up for the expense external bracing.

## **5.0 Observations of Gilbane's Project Management Practices**

Throughout the construction process Gilbane held weekly meetings including all parties involved in the project. These members included WPI's representatives, Gilbane's project management team with superintendents, project managers, schedulers as well as safety and quality managers. There were also members of the Cannon Design team which coordinated with both WPI and Gilbane. They discussed problems that were occurring, and often times made group decisions on issues which kept everyone on the same page.

Our MQP team attended these weekly meetings regularly for the first three terms of 07-08 school year. Held every Wednesday, there was a Construction Meeting in the morning and an Owners Meeting following in the afternoon. The morning meeting involved more of a superintendent's perspective on the project and dealt heavily with issues including scheduling, procurement of materials, crews, and safety issues. The Owners meeting, although often times including many of the same members, discussed more issues related to budget, overall schedule, and making decisions regarding both.

One instance that stands out early in the process was the decision for an air conditioning unit. It was suggested to go with a product known as the Smart Chiller. This product was somewhat new, and although it was initially more expensive it was much more efficient long-term and would more than pay for itself within 5 years. Being that this product was new, there was a concern that this product had not proven itself. After investigation and interviewing companies that have made the choice to go with the Smart Chiller, the project team got confirmation of the Smart Chiller as all positive responses were received. This is a good example of how Gilbane made decisions. They collect all information available and re-convene to decide collectively.

These weekly meetings really gave all parties involved the sense of a team striving toward one common goal which is to bring this project to successful completion on-time and within budget while maintain quality and safety.

## **6.0 Conclusion**

To help ensure WPI attempts to solve the housing issue, our team decided to take a closer look of the potential scheduling and cost saving problems that could arise during the project and presented Gilbane with tools to find the solution for each. The LOB diagram clearly depicts potential scheduling problems and warns the Project Management team of potential problems that could arise in a visual manner. It was brought to our attention that a crucial foundation wall had been improperly designed and we wanted to find the best viable solution. In addition to attending weekly Owners and Construction meetings hosted by Gilbane we also attended the final Card Trick meeting. In this meeting all subcontractors gave durations and completion dates for their critical paths and the final schedule will be updated accordingly by the Gilbane team.

## **6.1 Line of Balance Results**

There are many different ways to visually display a construction schedule. By using the Line of Balance (LOB) method to display repetitive tasks such as painting several dorm rooms, one can easily view whether the task is being completed on time, or, if it is progressing faster or slower than projected, what other tasks it will interfere with. The power of this visual representation is the ability to quickly identify trouble areas and remedy them with the responsible parties.

The typical Critical Path Method (CPM) diagram is a simple bar graph displaying the early start and end dates of the task for the entire project. By taking that information from the bar graph and creating a LOB diagram that shows each floor, and the start and end dates for said task on each floor, one can determine whether a second crew will be needed, or if there will be interference on a given floor due to another task being completed. This information is not obtainable from a bar graph due to its very nature that it only has the ability to display one set of data. The LOB diagram, when all the various tasks are input into it, illustrates start and end dates, potential interferences with other subcontractors, the criticality of a particular task, and the rate of completion for each floor.

## **6.2 J-line Wall Results**

Due to the close proximity of the residence hall to the garage, a problem arose when analyzing the structures before placement. If the problem was found and fixed before the placement of structure, money could have been saved. In our review of the structure we found that by adding a key beneath the wall, it would have stabilized the foundation wall from sliding. This fix would have resulted in a total cost between \$1800 and \$2400 with no time lost during construction. This problem was a result of a scheduling change that was not likely to have been foreseen at the time of design. However, if the designers had known the implications of additional space while students were home for the summer would allow the construction of the garage to be moved up, they most likely would have noticed that the proximity of the two structures would have interfered with the design of each. Had this been the case over 6,000 dollars could have been saved.



### **6.3 Future of Project (3D Visualization Drawings) Models**

On December 13, 2007 Tocci Building Corporation came to WPI to do a presentation. This presentation was about their revolutionary new way to start a construction project. Tocci makes use of Autodesk REVIT an Object Oriented 3D computer program to actually build the building within the computer before construction starts. They go through all the various stages of construction. With this program they are able to come up with a 3-D model of building with respect to time and schedule. They are able to digitally configure all Mechanical, Electrical, and Plumbing systems (MEP) in 3D throughout the building and see where there might be some interference problems before construction even begins.

Our MQP group believes that this new method will indeed revolutionize the construction industry. This new method is very helpful due to the fact that instead of looking at 2-D drawings, one can view the building in 3-D and have the ability to virtually walk through the building. This new method assists the sub-contractors by diffusing some of their questions because they are able to visualize what and where the final product will be.

This type of program also assists the scheduler, because they can determine which tasks are important for the project to move onto the next phase of construction. By incorporating the LOB diagrams into this electronic database, it will aid in viewing the various task completion dates, by floor. As the building is being built virtually, one can follow the LOB diagram and determine which subcontractors are needed at each stage of the project. Additionally, the program can be altered to reflect all the change orders that

occur during construction. This allows the scheduler to change the schedule accordingly, and modify the schedule to reflect further complications.

This method of virtually displaying the building before construction begins will work only if all the drawings are 100% completed before starting the project. This could pose a problem for fast track projects. It would be difficult to be able to do this type of work due to the fact that in order to create the 3-D drawings it takes a great amount of time and the drawings must be near complete. Another negative point of doing this would be the cost of having the drawings put on the computer. We believe that in the future this will be a great tool to use, but right now these issues make the 3-D format at times impractical. This technology will allow a project to be designed in the 3-D format and then create 2-D drawings that are used in today's projects. Tocci sees evidence that there is a desire to move everything to electronic format, which will allow for many new methods to be discovered that may simplify the planning and management processes.

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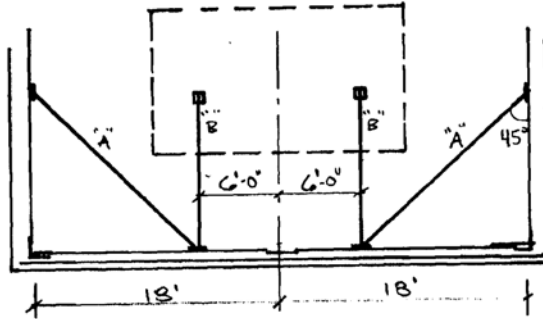
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# Appendix A – Field Sketches of J-Line Wall



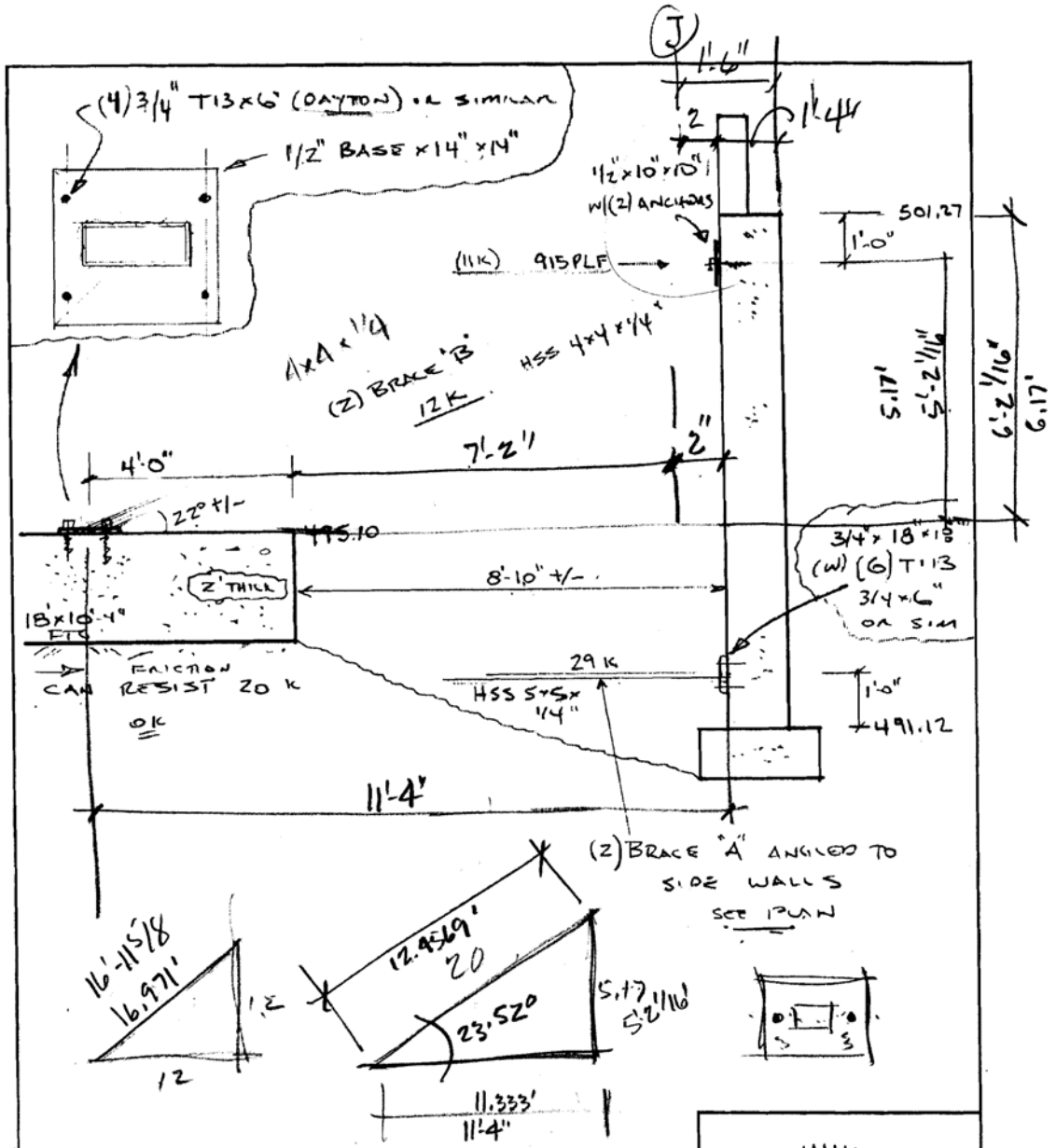
BRACE PLAN

BRACE "A" L=17' P=29K USE HSS 5x5x1/4" → W 8x30  
 CHECK AISC 13TH ED. Pg. 4-57  $P_{ALLOW} = 55.9 K < 29$   
OK

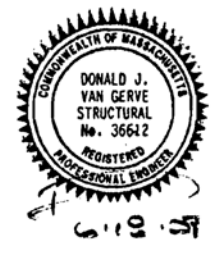
BRACE "B" L=14' P=11K USE HSS 4x4x1/4" W 8x30  
 Pg. 4-59  $P_{ALLOW} = 40.9 K < 11 K$   
OK

ITEM: BRACING W/P			
FOR: FRANCIS HARVEY - TIM HARVEY			
DATE: 6-18-07	DWG #: 61805 BRACE	SHEET 1	OF 6
DONALD VAN GERVE, PE 137 WEST RD CANTON CT 06019			
dvgpe@comcast.net		Cell: 978-943-6869	860-693-1738 FAX 1739





ITEM: BRACING WPI			
FOR: FRANCIS HARVEY			
DATE: 6-13-07	DWG #: 61307 BRACING	SHEET 2	OF 6
DONALD VAN GERVE, PE 137 WEST RD CANTON CT 06019			
dvgpe@comcast.net		Cell: 978-943-6869	860-693-1738 FAX 1739

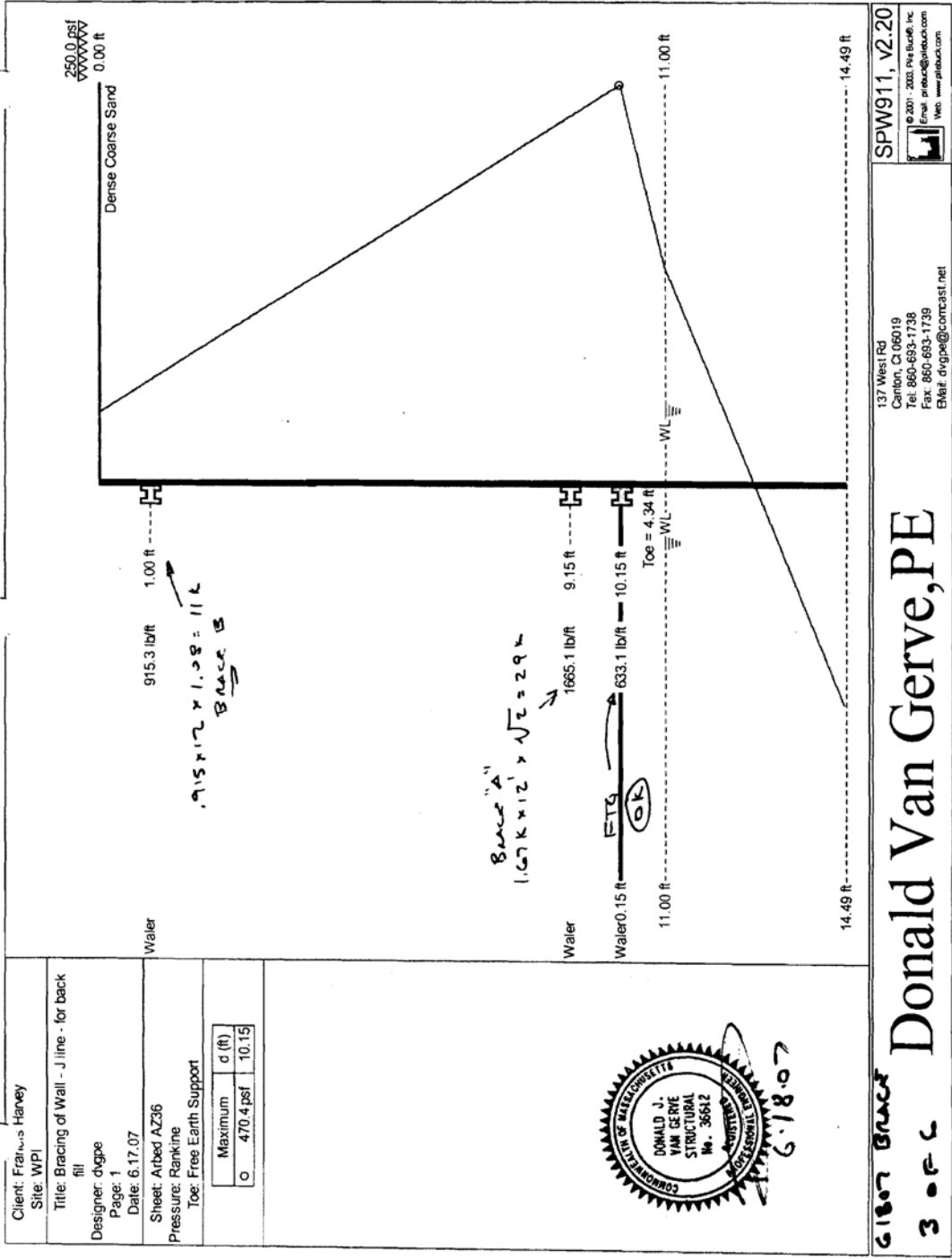


398

$$11.3332 = 128.437$$

$$5.172 = 26.729$$

$$\sqrt{155.166} = 12.457'$$



Client: Francis Harvey  
 Site: WPI  
 Title: Bracing of Wall - J line - for back fill  
 Designer: dvgspe  
 Page: 1  
 Date: 6.17.07  
 Sheet: Arbed A236  
 Pressure: Rankine  
 Toe: Free Earth Support

Maximum	d (ft)
0	470.4 psf 10.15

61807 BRACE  
 3 of 6

**Donald Van Gerve, PE**

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 Web: www.prebuck.com

Client: Frank Harvey  
 Site: WPI  
 Title: Bracing of Wall - J line - for back fill  
 Designer: dvgpe  
 Page: 2  
 Date: 6.17.07  
 Sheet: Atbed AZ36  
 Pressure: Rankine  
 Toe: Free Earth Support

Depth Of Excavation = 10.15 ft  
 Surcharge = 250.0 psf  
 Depth Of Active Water = 11.00 ft  
 Depth Of Passive Water = 11.00 ft  
 Water Density = 62.43 pcf  
 Minimum Fluid Density = 31.82 pcf

Soil Profile

Depth (ft)	Soil Name	$\gamma$ (pcf)	$\gamma'$ (pcf)	C (ksf)	$C_u$ (ksf)	$\phi$ (°)	$\delta$ (°)	$K_a$	$K_{ac}$	$K_p$	$K_{pc}$
0.00	Dense Coarse Sand	115.82	88.73	0.0	0.0	30.0	0.0	0.33	0.00	3.00	(2.50)

( ) indicates factored value used in calculations. Factor(s):  $K_p+1.2$

Sheet

Sheet Name	I (in <sup>4</sup> /ft)	E (ksi)	Z (in <sup>3</sup> /ft)	f (ksi)	Maximum Bending Moment (ftlb/ft)	Upland (ft)	Toe (ft)	Pile Length (ft)
Atbed AZ36	606.30	3.04E+07	67.00	25000.0	139417.1	0.00	4.34	14.49

Load Model: Area Distribution

Depth (ft)	Type	Linear Load (lb/ft)
1.00	Waler	915.3
9.15	Waler	1665.1
10.15	Waler	633.1

Supports

Pressure	Maximum	Depth
	470.4 psf	10.15 ft



4 of 6

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Client: Fra... Harvey		Title: Bracing of Wall - J-line - for back fill		Designer: dxgpe		Date: 6/17/07		Sheet: Aired AZ36		Pressure: Rankine		Toe: Free Earth Support		
depth (ft)	P (psf)	M (ft-lb/ft)	D (in)	F (ft-lb/ft)	depth (ft)	P (psf)	M (ft-lb/ft)	D (in)	F (ft-lb/ft)	depth (ft)	P (psf)	M (ft-lb/ft)	D (in)	F (ft-lb/ft)
0.00	83.0	0.0	0.0	2.0	4.67	268.9	-1825.0	0.0	-56.2	9.74	455.3	826.5	0.0	45.9
0.13	87.6	1.0	0.0	12.3	5.00	274.0	-1829.8	0.0	-20.1	9.87	459.9	835.7	0.0	101.2
0.26	92.7	3.5	0.0	24.3	5.13	278.6	-1830.1	0.0	13.2	10.00	465.0	853.6	0.0	162.7
0.38	97.3	7.1	0.0	35.8	5.26	283.7	-1825.6	0.0	50.6	10.13	469.6	876.9	0.0	219.1
0.51	102.3	12.9	0.0	49.1	5.38	288.8	-1816.1	0.0	88.6	10.26	442.4	814.2	0.0	-353.2
0.64	107.4	20.4	0.0	63.0	5.51	293.4	-1803.1	0.0	123.8	10.38	409.0	741.2	0.0	-296.9
0.77	112.0	28.9	0.0	76.3	5.64	298.4	-1783.8	0.0	163.1	10.51	378.7	681.1	0.0	-249.5
0.90	117.1	40.1	0.0	91.6	5.77	303.1	-1761.7	0.0	199.5	10.64	345.3	621.3	0.0	-201.7
1.03	121.7	50.0	0.0	109.3	5.90	308.1	-1732.3	0.0	240.1	10.77	311.9	567.6	0.0	-158.2
1.15	126.8	61.3	0.0	128.7	6.03	313.2	-1697.4	0.0	281.4	10.90	281.6	523.4	0.0	-122.6
1.28	131.9	74.4	0.0	149.2	6.15	317.8	-1660.9	0.0	319.5	11.03	251.7	479.5	0.0	-87.5
1.41	136.5	89.5	0.0	171.5	6.28	322.9	-1615.4	0.0	362.1	11.15	233.7	443.5	0.0	-58.3
1.54	141.6	106.4	0.0	196.8	6.41	327.5	-1569.1	0.0	401.4	11.28	213.9	407.7	0.0	-28.7
1.67	146.6	125.1	0.0	224.7	6.54	332.6	-1512.6	0.0	445.2	11.41	194.1	375.7	0.0	-1.8
1.79	151.3	145.6	0.0	255.0	6.67	337.7	-1450.3	0.0	489.7	11.54	176.1	349.6	0.0	20.5
1.92	156.3	167.3	0.0	288.2	6.79	342.3	-1388.5	0.0	530.8	11.67	156.3	323.7	0.0	42.4
2.05	160.9	191.5	0.0	323.5	6.92	347.4	-1324.7	0.0	576.6	11.79	138.3	302.6	0.0	60.1
2.18	166.0	218.1	0.0	360.8	7.05	352.4	-1254.7	0.0	623.1	11.92	118.5	281.6	0.0	77.0
2.31	171.1	248.1	0.0	399.8	7.18	357.0	-1186.7	0.0	666.0	12.05	98.7	262.7	0.0	91.3
2.44	175.7	280.3	0.0	441.1	7.31	362.1	-1114.8	0.0	713.8	12.18	80.7	247.1	0.0	102.0
2.56	180.8	314.6	0.0	485.2	7.44	366.7	-1034.8	0.0	757.8	12.31	60.9	231.1	0.0	111.3
2.69	185.9	351.1	0.0	531.3	7.56	371.8	-950.8	0.0	806.9	12.44	41.0	216.2	0.0	117.9
2.82	190.5	389.5	0.0	579.4	7.69	376.9	-860.8	0.0	856.6	12.56	23.0	203.3	0.0	121.7
2.95	195.5	429.6	0.0	629.5	7.82	381.5	-760.8	0.0	902.4	12.69	3.2	189.4	0.0	123.3
3.08	200.2	471.1	0.0	681.6	7.95	386.6	-650.8	0.0	953.4	12.82	-14.8	176.8	0.0	122.5
3.21	205.2	514.1	0.0	735.7	8.08	391.7	-530.8	0.0	1005.1	12.95	-34.6	162.7	0.0	119.1
3.33	210.3	558.6	0.0	791.8	8.20	396.3	-400.4	0.0	1052.7	13.08	-54.4	147.9	0.0	113.1
3.46	214.9	604.7	0.0	850.9	8.33	401.3	-275.9	0.0	1105.7	13.20	-72.4	133.7	0.0	105.3
3.59	220.0	653.3	0.0	912.0	8.46	406.0	4.4	0.0	1154.5	13.33	-92.2	116.7	0.0	94.3
3.72	224.6	703.3	0.0	976.1	8.59	411.0	161.7	0.0	1208.7	13.46	-112.0	98.1	0.0	80.6
3.85	229.7	754.0	0.0	1043.2	8.72	416.1	326.1	0.0	1263.7	13.59	-130.0	79.4	0.0	65.9
3.97	234.8	805.3	0.0	1114.3	8.85	420.7	482.0	0.0	1314.2	13.72	-149.8	56.7	0.0	47.2
4.10	239.4	857.3	0.0	1189.4	8.97	425.8	650.6	0.0	1370.5	13.85	-167.8	33.7	0.0	27.9
4.23	244.5	910.3	0.0	1268.5	9.10	430.4	829.5	0.0	1422.2	13.97	-187.6	5.5	0.0	4.2
4.36	249.5	964.3	0.0	1351.6	9.23	435.5	861.7	0.0	1485.4	14.10	-207.4	0.0	0.0	0.0
4.49	254.1	1019.1	0.0	1439.7	9.36	440.6	841.3	0.0	1552.2	14.23	-225.4	0.0	0.0	0.0
4.62	259.2	1084.6	0.0	1533.0	9.49	445.2	829.5	0.0	1624.7	14.36	-245.2	0.0	0.0	0.0
4.74	263.8	1151.4	0.0	1632.1	9.62	450.3	824.0	0.0	1702.2	14.49	-261.4	0.0	0.0	0.0



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## Appendix B – Detailed Calculations

At Rest Condition

$\Phi=35$  degrees

$$K_0 = (1 - \sin\Phi)$$

$$K_0 = (1 - \sin(35))$$

$$K_0 = (1 - 0.67)$$

Active Condition

$\Phi=35$  degrees

$$K_a = \tan^2(45^\circ - \Phi/2)$$

$$K_a = \tan^2(45 - 35/2)$$

$$K_a = \tan^2(45 - 35/2)$$

$$K_a = \tan^2(27.5)$$

$$K_a = 0.27$$

Passive condition

$\Phi=35$  degrees

$$K_p = \tan^2(45^\circ + \Phi/2)$$

$$K_p = \tan^2(45 + 35/2)$$

$$K_p = \tan^2(62.5)$$

$$K_p = 3.68$$

Active Lateral Earth Pressure

$$P_o/b = \gamma H^2 K_a / 2$$

$$P_o/b = (115 \text{ pcf})(12.98 \text{ ft})^2 (0.27) / 2$$

$$P_o/b = 5231.3 / 2$$

$$P_o/b = 2615.68 \text{ lb/ft}$$

$P_o/b$

$\gamma$  (115 pcf)=

$H$  (12.98 ft)=

$K_a$  (0.27)=

force per unit of length

unit weight of soil

depth of the soil

coefficient of lateral earth

pressure in the active condition

Passive Lateral Earth Pressure

$$P_o/b = \gamma H^2 K_p / 2$$

$$P_o/b = (115 \text{ pcf})(1.5)^2 (3.68) / 2$$

$$P_o/b = 952.2 / 2$$

$$P_o/b = 476.1 \text{ lb/ft}$$

$P_o/b$

$\gamma$  (115 pcf)=

$H$  (1.5 ft)=

$K_p$  (3.68)=

force per unit of length

unit weight of soil

depth of the soil

coefficient of lateral earth

pressure in the active condition

Overturning Factor of Safety

$$FS = (\text{soil} \times \text{distance} + \text{passive} \times \text{distance} + \text{wall} \times \text{distance}) / (\text{active} \times \text{distance})$$

$$FS = (5017 \text{ lb} \times 4.10 \text{ ft}) + (476 \text{ lb} \times 0.5 \text{ ft}) + (3416 \text{ lb} \times 1.75 \text{ ft}) / (2616 \text{ lb} \times 4.33 \text{ ft})$$

$$FS = (26785.7 \text{ ft-lb}) / (11327.28 \text{ ft-lb})$$

$$FS = 2.36$$

Table 1: Forces and Moments on Wall			
Force Contribution	Force Magnitude	Distance From Toe	Moment
Active	2616 lb	4.33 ft	11317 ft-lb (ccw)
Passive	476.1 lb	0.50 ft	238 ft-lb (cw)
Soil	5016.8 lb	4.10 ft	20569 ft-lb (cw)
Wall	3416.4 lb	1.75 ft	5979 ft-lb (cw)

Resisting Forces

$$RF = \text{passive} + (\text{wall} + \text{soil}) * \text{TAN}(0.5\Phi)$$

$\Phi = 35$  degrees

$$RF = 476.7\text{lb} + (3416\text{lb} * 1.75\text{ft}) * \text{TAN}(0.5 * 35)$$

$$RF = 476.7\text{lb} + (8433\text{lb}) * \text{TAN}(17.5)$$

$$RF = 476.7\text{lb} + (8433) * (0.31512)$$

$$RF = 476\text{lb} + 2657.48$$

3133.5

$$Rf = 3133.4\text{lb}$$

Sliding Factor of Safety

$$FS = RF/DF$$

$$FS = 3133\text{lb}/\text{Soil}$$

$$FS = 3133\text{lb}/2616$$

$$FS = 1.19$$

Finding required passive force to stabilize wall

$$FS \text{ needed} = 2$$

$$Fs \text{ attained } 1.19$$

Resisting force required to produce needed factor of safety

$$FS = RF/DF$$

$$RF = FS * DF$$

$$RF = 2.0 * 2616$$

$$RF = 5232$$

Resisting force is a combination of normal weight X friction

factor and the passive force acting on the base

$$RF = \text{passive} + (\text{wall} + \text{soil}) * \text{TAN}(0.5\Phi)$$

$$RF = \text{passive} + (3416\text{lb} * 1.75\text{ft}) * \text{TAN}(0.5 * 35)$$

$$RF = \text{passive} + (8433\text{lb}) * \text{TAN}(17.5)$$

$$RF = \text{passive} + (8433) * (0.31512)$$

$$RF = \text{passive} + 2657.48$$

$$5232 = \text{passive} + 2657.48$$

$$\text{Passive} = 5232 - 2657$$

$$\text{Passive} = 2575\text{lb}$$

the passive force required to produce enough resisting force is 2575lb

to find the depth of the key needed to produce this force					
we will use the passive lateral earth pressure equation from above					
$P_o/b = \gamma H^2 K_p / 2$					
$H = \sqrt{2(P_o/b) / (\gamma * K_p)}$		$P_o/b (2575) =$	force per unit of length		
$1.5 + \text{key} = \sqrt{2 * 2575 / (115 * 3.68)}$		$\gamma (115 \text{ pcf}) =$	unit weight of soil		
Key depth = $\sqrt{5150 / 423.2} - 1.5 \text{ft}$		$H (1.5 + \text{key ft}) =$	depth of the soil for sufficient force		
Key depth = $\sqrt{5150 / 423.2} - 1.5 \text{ft}$		$K_p (3.68) =$	coefficient of lateral earth		
key depth = $\sqrt{12.169} - 1.5 \text{ft}$			pressure in the active condition		
key depth = 3.488ft - 1.5ft			423.2		
key depth = 1.988ft			12.16918715		
			3.488436203		