

**University of Alberta**

Advanced Quantitative Techniques to Enhance Heavy and Civil  
Construction Information Modeling

by

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## Abstract

Site development in heavy and civil construction need to consider many rules such as ensuring proper drainage, prevention of flood, safety driving, optimizing earthwork, minimizing fleet travel distances, proper fleet matching and achieving high equipment utilization rates. In recent decades, numeral researchers have presented different solutions to improve this process; however they have been either too complicated to be practical or oversimplify the problem definition by ignoring critical facts. This thesis presents three advanced quantitative techniques to enhance current earthwork construction practices including: a modification of least squares method to optimize the earthwork, an application of transportation simplex method to minimize the fleet travel distance, and an earthwork construction process simulation to ensure the accuracy of earthwork operations analysis. The thesis also includes an actual case study to demonstrate the practicality and effectiveness of the proposed methodology.

## Acknowledgement

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# Chapter 1 Introduction

## *1.1 Motivation*

Earthwork in land development intends to shape the existing ground surface to fit its designed usage such as buildings, roads, irrigations etc. To reduce cost, earthwork demands careful assessment of the three main stages in land development, includes: (1) Cut / fill balance, making the cut / fill earthwork either balanced or minimize the surplus / borrowing material, at the same time, maintaining grading design to prevent erosion and flooding and, provide safe driving environment etc. (2) Design and minimization of onsite time of the earthmoving equipment, to minimize the fleet travel distance, both cut / fill stockpile volume and distance from each cut stockpile to each fill stockpile need to be considered. (3) Equipment utilization and fleet matching to select the most efficient and economical equipment for the project.

Earthwork optimization, base on the utilization of the least squares method, “the least squares method is still considered the most widely used method” (Gebre-Selssie 1991). However, utilizing the least squares method faces many challenges including: (1) the impractical mathematical model (2) complexity of the optimized solution (3) the over simplified mathematical model.

For fleet travel distance minimization, all researchers have focused on road/highway earthwork construction and limited practical solutions for site grading earthwork construction have been formalized yet. Furthermore, since the Monge-Kantorovich solution, the major fleet travel distance minimization solution for road earthwork construction only supports one mass move direction along the axis (chainage). It does not have ability to solve a two directional mass transportation problem in the context of site grading. New solutions need to be formulated to solve this problem.

For earthwork construction simulation, previous simulation models have been

presented too simple and more factors need to be taken into consideration. In addition, the majority of previous earthwork construction simulation models have been setup in Activity Cycle Diagram (ACD) based simulation tools such as CYCLONE (CYCLic Operations NETwork). Fewer simulation models have been presented in Process Interaction (PI) simulation tools such as SDESA (Discrete-Event Simulation Approach). SDEAS is developed to simplify the modeling of resource cycles and resource transit between different locations in a site layout plant (Lu et al., 2007) Since the earthwork activity is relatively simple but resource utilization and relocation is more complex, SDESA is considered more fit for rapid development of simulation models for practical earthwork construction operations.

## ***1.2 Research Objectives***

The research presented in this thesis focuses on optimizing, modeling, and simulating the earthmoving operation during the process of land development. Earthmoving is the first step of construction stage for land development and it is usually the most uncertain part for the scheduling and estimating process. Time and time again the earthwork got cost over burn and schedule overrun. In contrast to earthwork, estimating the rest of project is not that problematical: quantities and costs for steel, concrete, machinery, pipe and cable etc. can be closely estimated because there are few unknowns in these areas. Due to the complexity of the earthwork process and whether dependable, the earthwork commonly has high potential shift from the original estimate and schedule. The research is trying to bring the gap closer and has three distinct objectives:

- 1) Improve the existing earthwork optimization method by modifying the least squares method model.
- 2) Improve the existing earthwork mass transport practice (application of transportation simplex method) and simulation method (though the simulation tool SDESA).
- 3) Develop a framework of a computer-based integration system to seamlessly link various special tools to support land development in heavy and civil.

## ***1.3 Thesis Organization***

Chapter 2 contains a summary of the literature review. There are three areas in

which papers have been reviewed: earthwork optimization, earthwork simulation, spreadsheet applications and CAD/Excel data exchange.

Chapter 3 discusses the methodologies that have been used in this research. It includes data inquiry, prototype and modeling, programming, implementation, and validation.

Chapter 4 presents a new approach to improve the existing earthwork optimization method by use of the least squares method and Excel spreadsheet. To support that optimization, topsoil stripping depth, soil shrink/swell factor, and site grading should be determined up front.

Chapter 5 presents a new way to solve the mass transportation problem (transportation simplex method), which complements the existing earthwork simulation method through SDESA.

Chapter 6 presents a case study to illustrate application of above proposed new methods.

Chapter 7 gives the conclusion and discusses future study.

## **Chapter 2 Literature Review**

### ***2.1 State-of-the-Art literature in Earthwork Optimization***

There are numerous methods to conduct site grading earthwork optimization. These methods include the least squares methods (Givan, 1940; Chugg 1947; Smerdon et al., 1966; Scaloppi and Willardson, 1986; Reddy et al., 1996, Reza, 2004), Fixed Center Method (Raju 1960), Warped-Surface Method (Harris et al., 1966), Residual method (Shih and Kriz 1971a, 1971b, 1973), Theory of probability (Hamad, 1981) and Non-linear programming (Hamad and Ali, 1990, Reddy and Wilardson, 1996). Although numerous researchers have introduced several different methods for earthwork optimization, “the least squares method is still considered the most widely used method” (Gebre-Selssie, 1991).

The least squares method was originally proposed by Givan (1940) to address the problem of grading a rectangular field site. Throughout the years, the least squares method for earthwork optimization has undergone continuous development. Chugg (1947) applied this method to irregularly shaped sites. Sowell et al., (1966) introduced several design alternatives to best fit the grading requirements. Scaloppi and Willardson (1986), using the least squares method, developed a computational procedure to calculate the slopes of a graded plane. Reza (2004) presented another extension method, which is called the Weighted Average Method, derived from the traditional least squares method.

Extensive research has been conducted regarding earthwork optimization for highway projects as well. The most popular and accurate method used is the weighted ground line method. Ammar et al., (2003) noticed this in earthwork construction areas, and provided a mathematical model to determine the volume for earthmoving. Taking this into account, Goktepe (2004) added a new factor to the weighted ground line method. However, the weighted ground line method is not applicable to typical land development projects since it is based on the

earthmoving along a linear grade line in one direction and land development earthmoving in two directions.

## ***2.2 State-of-the-Art literature in Earthwork Simulation***

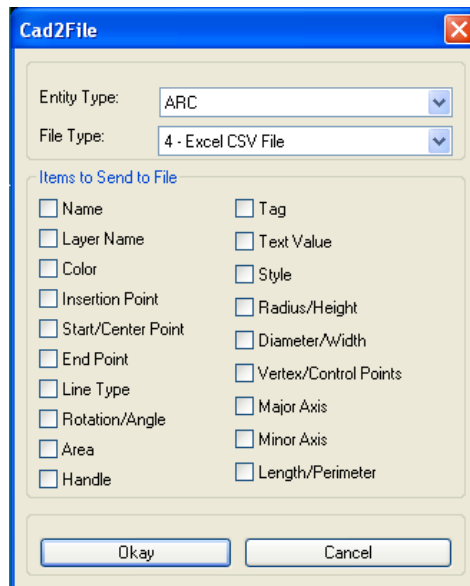
Operation simulation is an effective analysis tool in construction for optimizing the processes and equipment selection in order to minimize time and cost. Halpin (1977) presented the CYCLONE method generically model construction site processes. Based on CYCLONE, Martinez (1996) introduced another tool called STROBOSCOPE to enhance the flexibility and extensibility of simulation modeling. To further improve the Activity Cycle Diagrams (ACD) based simulation methodologies for the construction applications, Lu et al., created an tool called SDESA to streamline resource cycle modeling and resource transit simulation to view, assess, and improve the construction process (Lu 2003; Lu et al., 2007). The SDESA methodology is intended to make application of the simulation method as easy as the critical path method (CPM) while also lending a better support for handling construction practices' random and sporadic characteristics. SDESA has been successfully used to solve numerous construction and operation problems. Chan et al., (2008) applied the SDESA methodology to simulate a precast viaduct construction. Lu et al., (2009) used SDESA to simulate Hong Kong's Kai Tak Airport demolition.

## ***2.3 State-of-the-Art literature in Spreadsheet and Data Exchange***

McGill et al., (2004) pointed out that spreadsheets are the most commonly used tools for end user development of applications. Organizations depend heavily upon them for decision making. The same rule applies in the area of civil design and research. Almost every part of the civil design process requires the use of spreadsheets (e.g. Powell et al., 2006). Edwards et al., (2000) presented general rules to create an end-user development or a DIY spreadsheet system. He also pointed out that these systems can be split into two types, data-oriented and logic-oriented systems, from which the data and logic models are derived. Both systems are widely used in civil design. For example, through the use of spreadsheets,

Holm (1990) developed complex petrogenetic modeling and Dexter et al., (1991) developed water balance modeling.

When extracting data from CAD to Excel, since this function is not available in AutoCAD itself, a numerical third party plug-in has been created to provide this function. Psanders (2008) created a third party plug-in called Cad2File, which is used in the present research for illustrating the concept design of HCCIM. The interface is shown in figure 2-1.



**Figure 2-1 Cad2File interface**

This plug-in function can export a selected feature (e.g. arc, line, circle, ellipse, point, solid, text, etc.) to a file, either in text format or Excel .csv format. The feature selects characters such as name, layer name, color, insertion point, line type, rotation, area, value, style, length, etc. This information can be used in the further calculation or data analysis from the HCCIM calculation part.

For extracting data from Excel to CAD, Hotchkiss (2007) and Manrique (2009) provided a method for inserting blocks using a transformation matrix from an Excel file. The transformation matrix A has the following syntax:

R00	R01	R02	T0
R10	R11	R12	T1
R20	R21	R22	T2
0	0	0	1

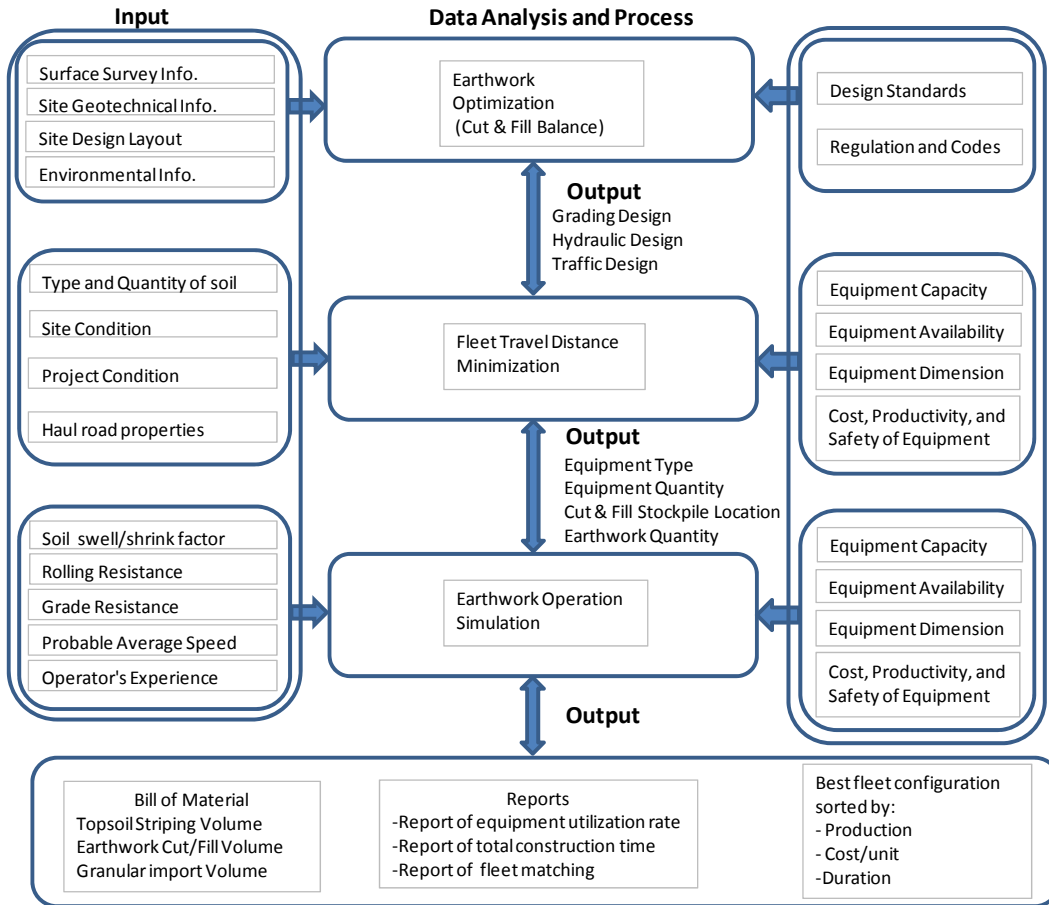
Where:  $R_{ij}$  = Rotation along the  $ij$  vector, with 0 = X, 1 = Y and 2 = Z axis

$T_i$  = Translation on the  $i$  axis, with 0 = X, 1 = Y and 2 = Z axis



## Chapter 3 Proposed Methodology

Figure 3-1 shows the main process of typical civil earthwork construction. There are three major stages for earthwork construction: earthwork optimization, fleet travel distance minimization, and earthwork operation simulation.



**Figure 3-1 Proposed methodology main procedure**

For earthwork optimization, input both project information such as survey, geotechnical report, site layout, environmental data. and the design criteria such as standards, regulations and codes, a model is setup to minimize one particular cell ( $\Sigma$ ) which summarizes all the grid cells' earthwork volume by changing three variables (the highest point elevation, the slope along x axis and the slope along y axis). Certain constraints are defined accordingly, such as the

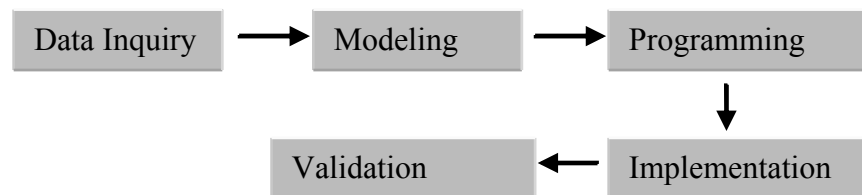
minimum/maximum slope along the x and y axis. After this step, grading/hydraulic/traffic design will be generated.

For fleet travel distance minimization, input both project information such as soil type, site condition, project condition, haul road properties etc. and design criteria such as equipment capacity, availability, dimension, cost etc. First a distance matrix, which shows each cut cell to each fill cell's distance, is setup. Then a mass matrix is setup, which gives each cut and fill cell's import/export volume. Finally a combined matrix is setup to minimize one particular cell ( $\Sigma$ ), which represents the sum of all the fleet distances by changing variables denoting the quantity of earth to be moved from one cut cell to the other fill cell. After this step, equipment type and quantity, cut and fill stockpile location and earthwork quantity takeoffs will be generated.

Input data for defining earthwork operation simulation, include- project site information (such as soil swell/shrink factor, rolling resistance, grade resistance, vehicle average speed, operator's experience etc.) and outputs from fleet travel distance minimization (such as equipment type and quantity, cut and fill stockpile location, earthwork quantity etc.) Though SDESA, a resource-based deterministic simulation model is setup. To run the simulation model, an accurate operation schedule can be generated to reflect a real site situation. At the same time, equipment utilization rates and best balanced fleet are generated as well.

These three new techniques, modification of the least square method for cut and fill balancing, the transportation simplex method applied for earthwork fleet travel distance minimization and the resource-base simulation modeling for earthwork operation analysis and fleet matching optimization, will be integrated in a system called HCCIM (Heavy and Civil Construction Information Modeling). The prototype of HCCIM holds potential to augment existing civil design software with newly developed research tools featuring both analysis and collaboration functions.

The following methodology forms the basis of this research. The first step of the research is data inquiry into a number of past earthmoving projects. Second, a model is built to support the framework of the research. Third is modeling and programming to achieve those functions which have been described in the framework. Fourth is application of new techniques to a case study. Finally is validating the functions to gauge if the goals have been achieved.



**Figure 3-2 Research process**

### ***3.1 Data Inquiry***

The data inquiry covers a wide range of sites, including: non-metal mine, metal mine, power plant, pump station, and refinery. For non-metal mines, both coal and oil sands mines have been chosen. Two kinds of data are collected, project input data and design criteria data. Project data include: project location and conditions, surface survey information, geotechnical information, design layout, environmental information, soil swell/shrink factor, rolling resistance, grade resistance etc. Criteria data include: design standards, regulation and codes, construction equipment information etc. Figure 3-2 shows the data inquiry process. Once data collection is completed, it is identified whether that data is useful and validated for the research or not, whether that data is only applicable to one particular project or can be used for other projects.

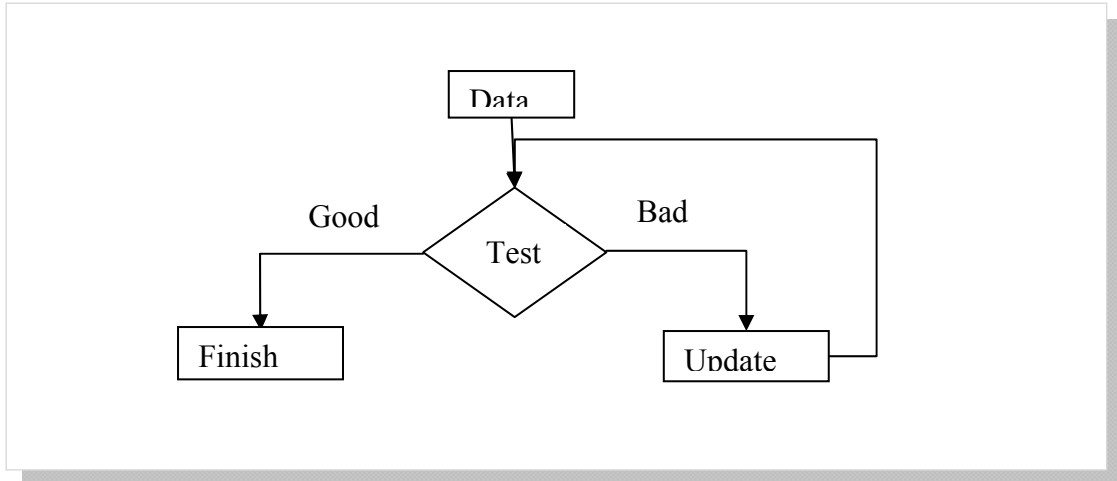
### ***3.2 Modeling***

The 3D existing surface and designed finished surface modeled by Bentley InRoads. Then those models information transfer to earthwork optimization model which is in Excel Solver. The optimization results transfer to Fleet distance Minimization model which is in Excel Solver as well. The minimization result becomes the input of earthwork simulation model in SDESA.

### ***3.3 Implementation***

For compatibility and easy maintenance, Auto LISP and Visual Basic (VB) are used for the CAD plug-in portion. VB is used for data exchange and processing and VB for Application is used for the Excel plug-in part. Once each routine is finished, the test has been completed. To better use existing resources, instead of building a standalone system, the system is built as an add-on attachment to the present system.

Once the model has been built, several different scenarios are used for implementation. Each part is tested, once valid test results are obtained, in other words, cut and fill is balanced or borrow/surplus material is minimized, travel distance is minimized and equipment utilization rate and total construction time are optimized. If that module still needs improvement, updates and modifications will take place for better fitting. For example, if the earthwork operation simulation shows the equipment utilization is too low, then, fleet matching and distance minimization will be re-conducted. The test results are also compared against the traditional design and manual calculation. For example, the least squares method will be calculated though using the Solver or Gauss-Jordan elimination, and the transportation simplex method will be calculated using Solver and Vogle's/Russell's method.



**Figure 3-4 Implementation model**

### ***3.4 Validation strategy***

Since a variety of sites are investigated in this research, with different conditions, processing requirements, and construction and operation methods, the validity of a method needs to be checked. By conducting sensitivity analysis in the validation process. If this process needs further improvement, it must be subjected to further study. For example, one of the earthwork optimization models uses the same site information as previous researchers. The result shows fewer earthworks from different elevation and slopes than the previous model. One of the simulation model compare the previous CYCLONE earthwork operation model and the new SDESA earthwork model. The result shows different equipment utilization rate which is more realistic.

## **Chapter 4 Earthwork Optimization**

### ***4.1 Defining the Input***

There are many inputs before setup the earthwork optimization model as Figure 3-3 shows. Input such as survey information, geotechnical report, design layout etc. are straight forward to use. The following information provides input to the optimization modeling and addressed as follows.

#### **4.1.1 Topsoil stripping depth**

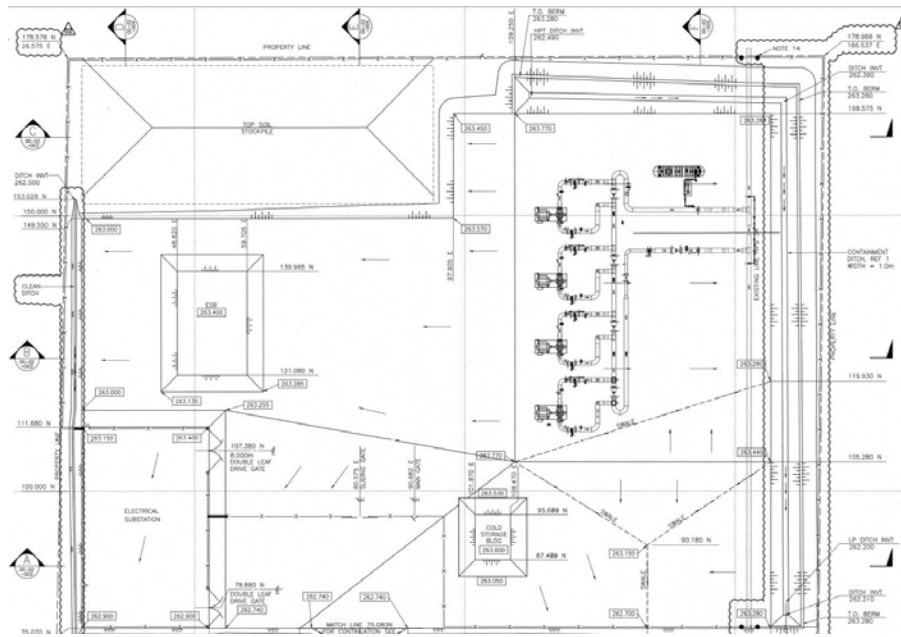
Topsoil is a fertile, loamy, organic material that usually forms the top layer of the earth's surface and is essential for vegetative growth. Since topsoil formation is slow, and takes 300-1000 years of growth per inch, it is usually considered a nonrenewable material. Furthermore, topsoil's bearing capacity usually is very poor and cannot be used for earthwork construction. That demands particular attention in the design of earthwork.

Due to environmental protection concerns and poor bearing capacity, the topsoil should be stripped before site grading work. The topsoil can either be stockpiled on the site or taken away from the site. During geotechnical investigation, though the borehole drilling, several locations' topsoil depth information will be ascertained through borehole logs. However, these boreholes usually have different topsoil depths. In current practice, a value higher than the average topsoil depth is used, and then multiplied by the area to get the topsoil stripping volume. This method is not accurate and can cause problems especially for the situation that topsoil is stockpiled on site. Since the stockpile size is determined during the design stage, when the topsoil volume is larger than expected, it is difficult to change the stockpile size or location. For the tender process, topsoil stripping work usually has a separate unit price instead of a lump sum bid, and the quantity will be measured during the construction.

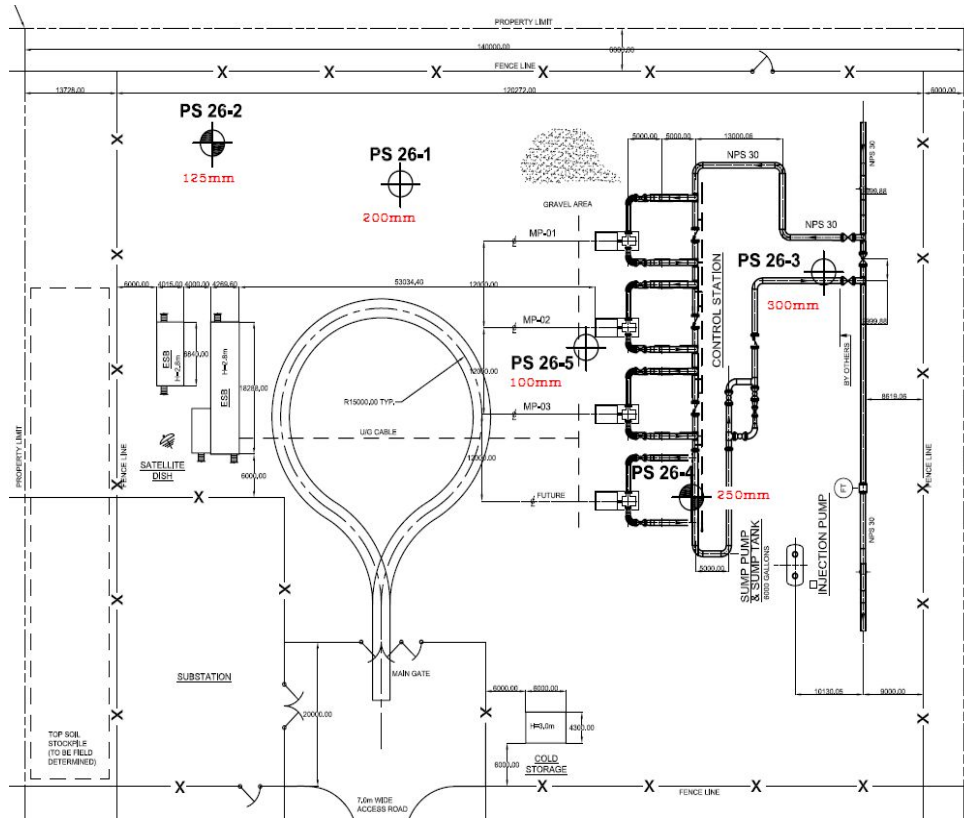
Figure 4-1 shows a typical pump station layout and Figure 4-1 shows there are

five boreholes were drilled on this site and the recode shows the topsoil depth are varies from 100mm to 300mm.

Based on the description above, a better method needs to be developed to determine the topsoil stripping volume. The current results are based on limited information but with better analysis though Weka (Remco et al., 2010), the average topsoil stripping depth can be found in a more accurate way. Weka is a machine learning created by the University of Waikato. After input all the previous topsoil information data (include 39 different sites) in Weka, it will run to find the best fit formula to determine the topsoil depth. Ideally this tool can fit the purpose of determine the average topsoil depth, the trial run shows the determined topsoil depth has about 35% accuracy. To improve the accuracy, more research can be done in the further.



**Figure 4-1 Sample of small site layout**



**Figure 4-2 Sample of topsoil depth**

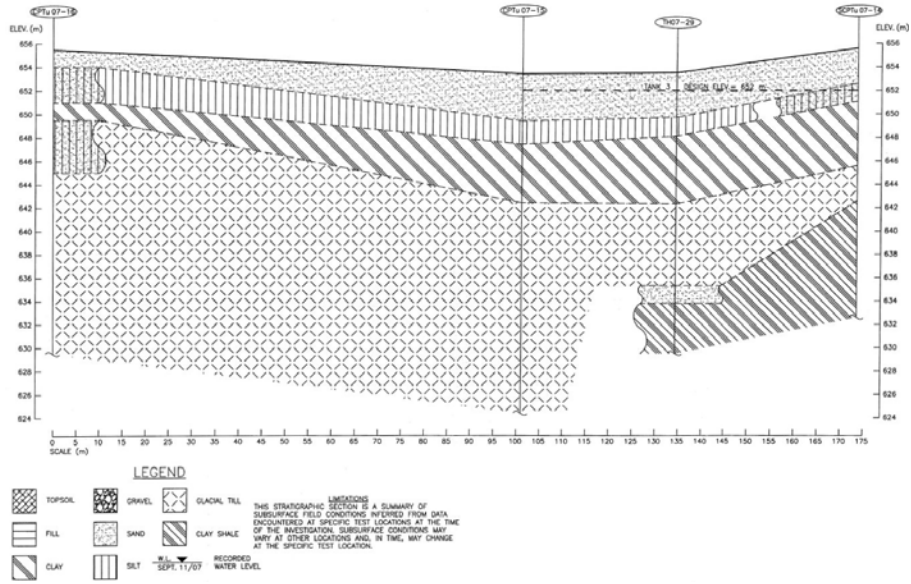
For large site developments, a construction stripping plan is needed for efficient topsoil stripping work. This kind of large site cannot be reduced to one single average topsoil depth. In the engineering stage, the total topsoil volume will be calculated by each deferent depth and areas. In the construction stage, the equipment movement plan will consider the topsoil depth pattern to achieve a better civil grading construction plan.

#### **4.1.2 Soil shrink / swell factor**

In practice, the design engineer either eliminates the shrink/swell factor or treats the soil as a uniform layer, and then applies a shrink/swell factor. But in reality, the subsurface is usually divided into several different layers, with each different soil layer having its own shrink/swell factors. Figure 4-3 shows a sample of subsurface terrain layer information. Furthermore, certain unsuitable soil like glacial till cannot be used as fill. Such unsuitable materials should be taken out



from cut/fill balance. Without taking the soil type into account or even simply treating it as one single type of soil, the earthwork will be inaccurate. The new proposed method uses the geotechnical software to create separate terrain layer information from geotechnical borehole logs and other sources of information, then combined with the surface model to get an accurate result.



**Figure 4-3 Typical cross section of the underground terrain**

For heavy industry site development, electricity conductivity usually has been tested for electrical grounding purposes. So far, the Wenner array method is the most commonly used method to test electricity conductivity. The array tests a section of earth by putting electrodes into the earth at 1~2 meter intervals. A current is injected through the outer electrodes and the potential is measured between the inner electrodes. The test is usually performed in the upper 7-8 meters of the soil, which covers the grading depth needed for most projects. Since different soils have different levels of electrical conductivity, the conductivity information can be used to improve subsurface terrain profiling as well. Table 1 shows electrical resistivity for different soils.

Table 1 Resistivity of soil resistance of single rods

Soil Description	Group	Average	Resistance of 5/8
------------------	-------	---------	-------------------

	Symbol*	Resistivity ( $\Omega$ .cm)	in (16 mm) $\times$ 10ft (3m) Rod ( $\Omega$ )
Well graded gravel, gravel-sand mixtures, little or no fines	GW	60000-100000	180-300
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	100000- 250000	300-750
Clayey gravel, poorly graded gravel, sand-clay mixtures	GC	20000-40000	60-120
Silty sands, poorly graded sand-clay mixtures	SM	10000-50000	30-150
Clayey sands, poorly graded with slight plasticity	SC	5000-20000	15-60
Silty or clayey fine sands with slight plasticity	ML	3000-80000	9-24
Fine sandy or salty soils, elastic silts	MH	8000-30000	24-90
Gravelly clays, sandy clays, salty clays, lean clays	CL	2500-6000**	17-18**
Inorganic clay of high plasticity	CH	1000-5500**	3-16**

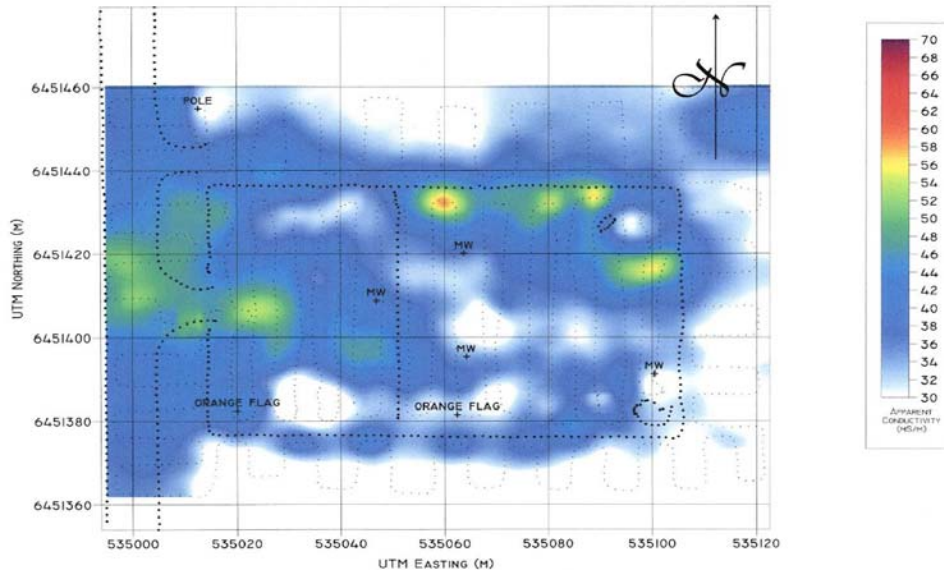
\*The terminology used in these descriptions is from the Unified Soil Classification and is a standard method of describing soils in a geotechnical or geophysical report.

\*\*These soil classification resistivity results are highly influenced by the presence of moistures.

ANSI/IEEE Std 81-1983 IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System. Clause 4.1.4.

A sample of an electrical conductivity map shows below in figures 4-6 and 4-7.

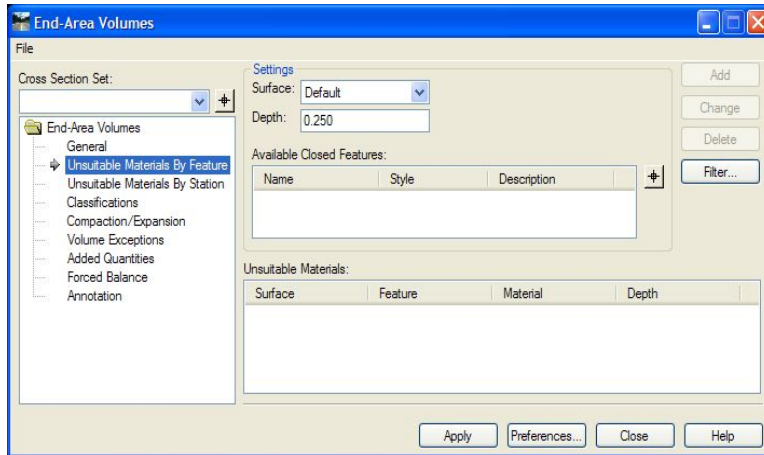




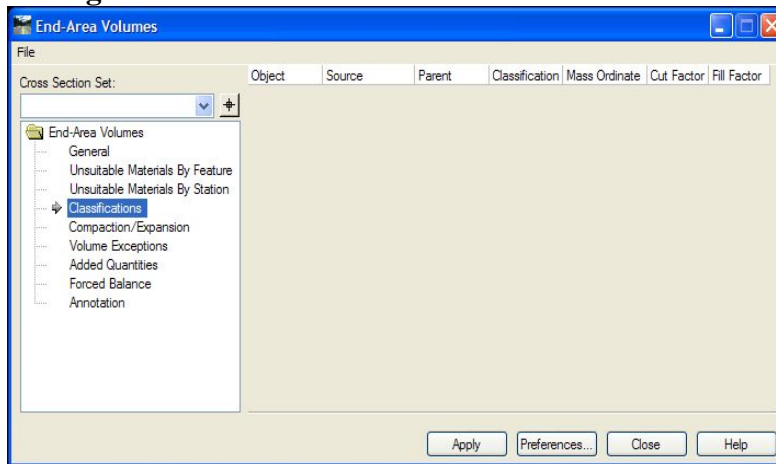
**Figure 4-6 Sample of a lateral conductivity map**

After the subsurface information obtained through the borehole drilling, electrical conductivity tests and other geotechnical exploration are performed. The resulting information can be transferred to earthwork software with different features attached to layer names. The software imports different terrain surfaces, and applies a different shrink/swell factor to each.

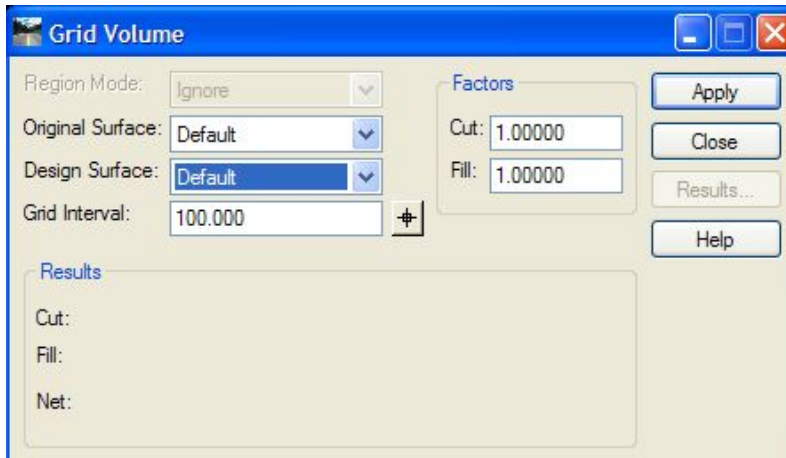
Then each soil's shrink/swell factor is considered in the earthwork calculation. A more accurate earthwork volume can be calculated this way. The best method to calculate the earthwork volume is the end area (cross-section) method because easily identifies different layers. Figure 4-7, 4-8 and 4-9 show the detail setting of end area method.



**Figure 4-7 Screen shot of end-section calculation1**



**Figure 4-8 End-section earthwork calculation2**

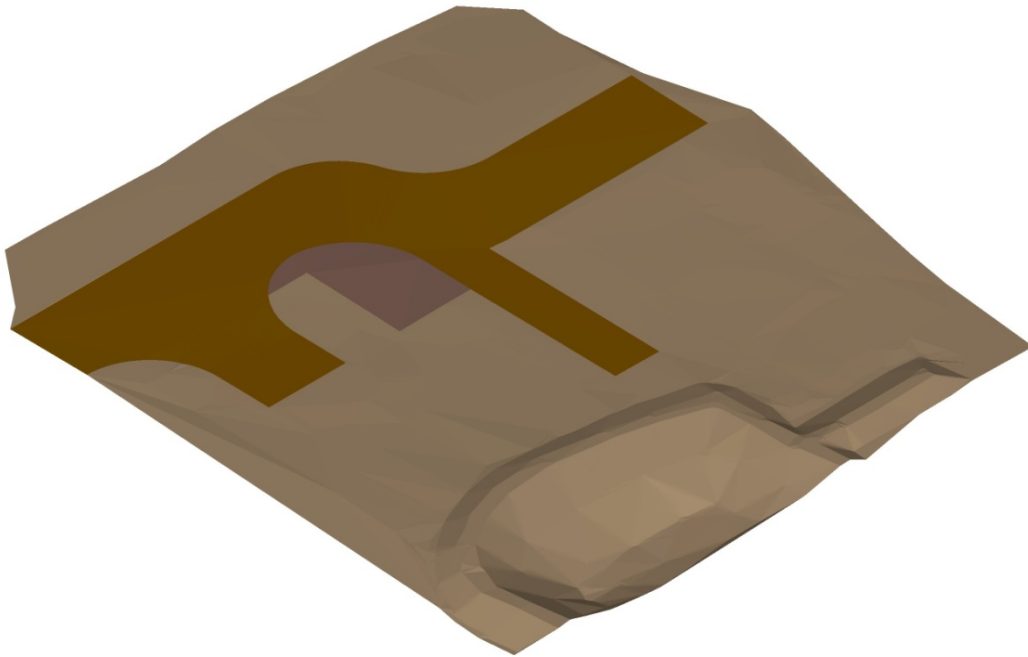


**Figure 4-9 End-section earthwork calculation3**

### 4.1.3 Site type

#### 4.1.3.1 The highest point of the site on one corner

This type of site usually needs one of the corners to be the lowest spot to drain to the low spot.



**Figure 4-10 the highest point at the site corner**

As the figure shows, the highest point for this site is on the upper corner, the site slope runs down from the upper corner to bottom corner. In this site design, all stormwater will be drained to the bottom corner pond.

#### 4.1.3.2 The highest point of the site in the center

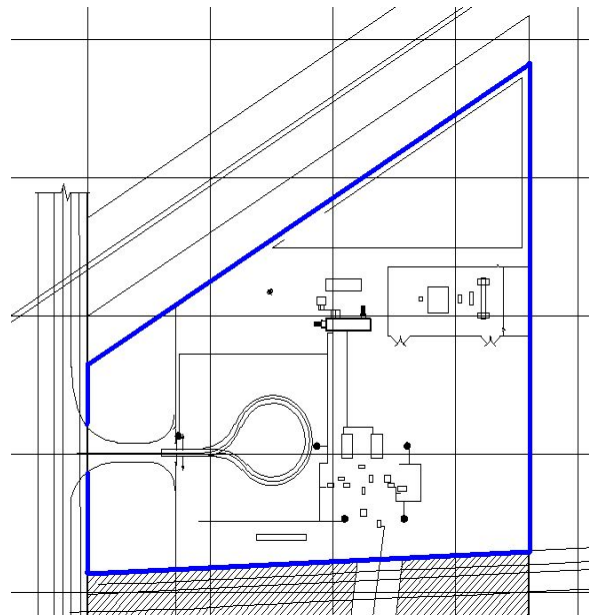
This type of site usually has a building/structure/equipment in the center, and from this center, the grading slope runs down towards the four corners.



rather than having four different slopes used for draining storm water outside of the site. At the bottom of one of the slopes, a containment ditch is built to collect the water. That containment ditch or water detention pond is usually designed to contain 24 hours 1-30 year rain. After the rain, the operator will inspect the water for contamination and open the valve and release the water. Since this kind of design needs four different slopes, the traditional single / double slope earthwork optimization is not fully applicable. As such, a modification of traditional least squares method must be developed to solve this kind of site grading problem.

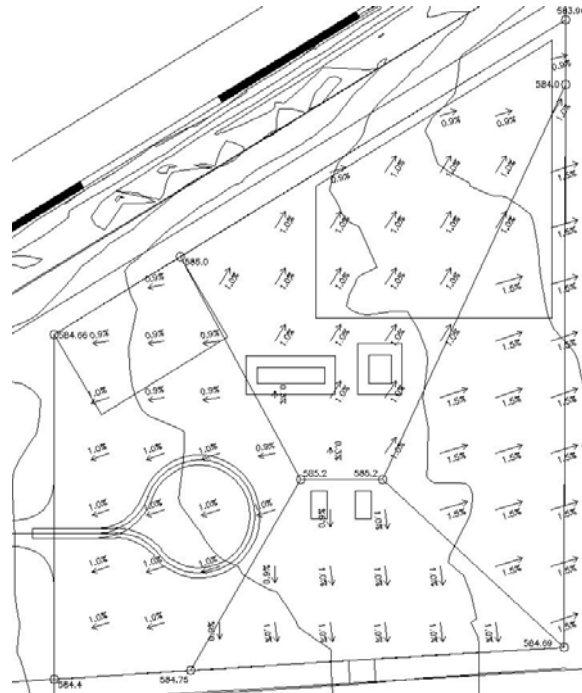
#### **4.1.3.3 The highest ridge line at the site center**

This kind of site grading usually has a few building/structure/equipment lined up in the center. The slope runs from that highest ridge to four corners of the site.



**Figure 4-13 the highest ridge in the center**





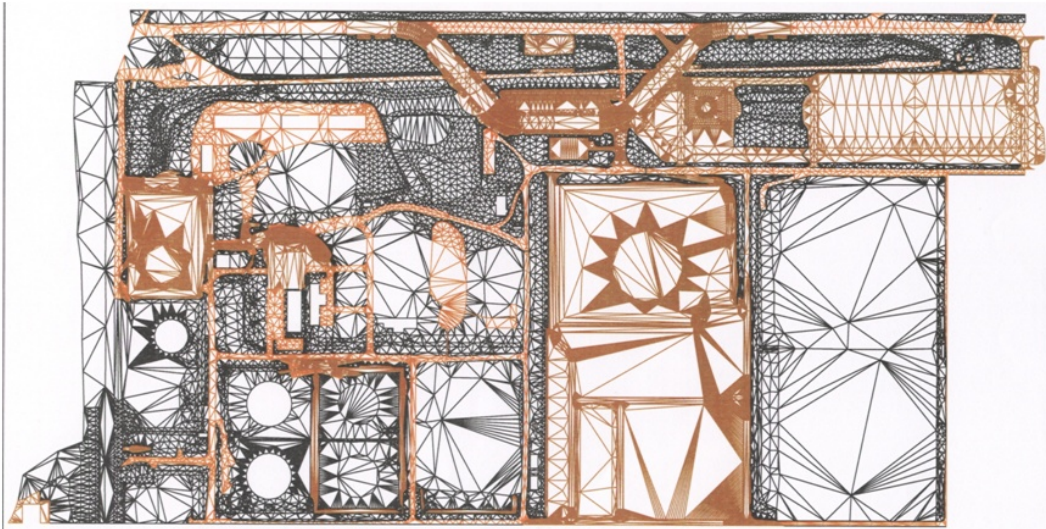
**Figure 4-14 the highest ridge in the center**

Since this kind of design needs four different slopes, the traditional single direction slope earthwork optimization is not fully applicable. As such, a modification of the traditional least squares method must be developed to solve this kind of site grading.

#### **4.1.3.4 The Variable cell size**

This kind of site usually located on large site grading projects such as a refinery plant. The traditional least squares method is not suitable for this kind of site since the site is divided into several different units and each unit has a different area. However, it can be done though introducing an “area weight factor” quadratic optimization. For quadratic optimization, the first run focuses on the whole site and each cell as one unit. Since the units have different areas, an additional variable, the area weight is introduced to deal with this issue. The second run optimizes each single cell. If each cell has its own  $i$  and  $j$ , there would be too many  $i$ 's and  $j$ 's in the model. However, it also not feasible to set up a single  $i$  and  $j$  for the whole site. An area weight factor,  $a$ , is introduced to account for the

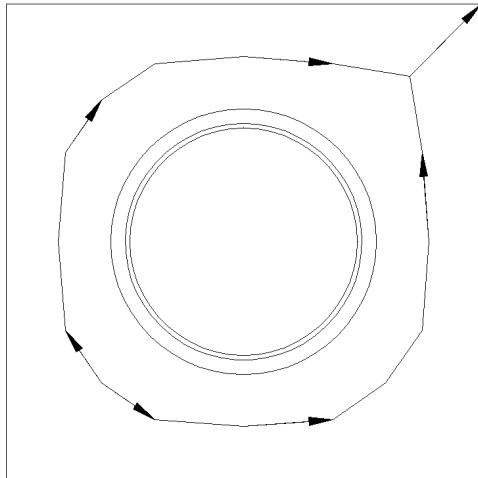
area's difference. The refinery's plot plan design is based on the industrial process, which best meets the operation requirements, should be used for implement the grading. Since the refinery plant is divided into different units of different areas, each single unit has its own slope and drainage direction, but the whole site's drainage should flow in one or two lowest point(s), final the water will be drain out from these low points.



**Figure 4-15 the cell's size is varies**

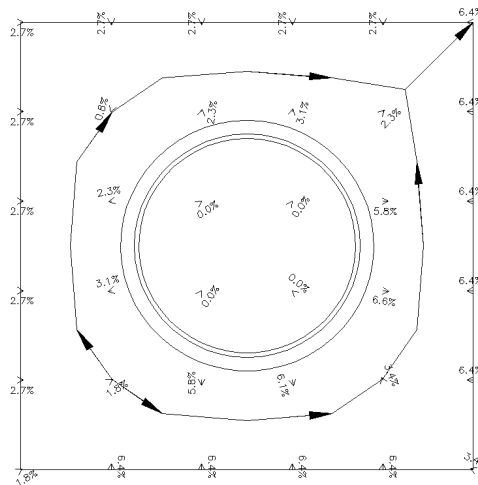
#### **4.1.3.5 Grading along a sloped line**

Unlike other site grading, the tank lot grading requires a second containment to ensure no oil will release to the environment when a leak happens. Usually a soil berm or concrete / steel wall is installed around the containment area to prevent the oil from escaping. A liner is laid underneath the containment area to prevent the containment water from entering the soil. Also, the tank farm area's grading is isolated from other areas. Then, tank farm grading usually has a swale around the tank, and water from the tank is directed to the swale. The same procedure applies to the outside of the swale.



**Figure 4-16 Sample of a tank farm layout**

As Figure 4-14 shows, the whole tank lot grading is based on the drainage ditch around the tank. The outlet of the tank lot will be the lowest point for the entire tank lot. If a line is set up to fit both proper drainage and balance the earthwork, then the grading is optimized.



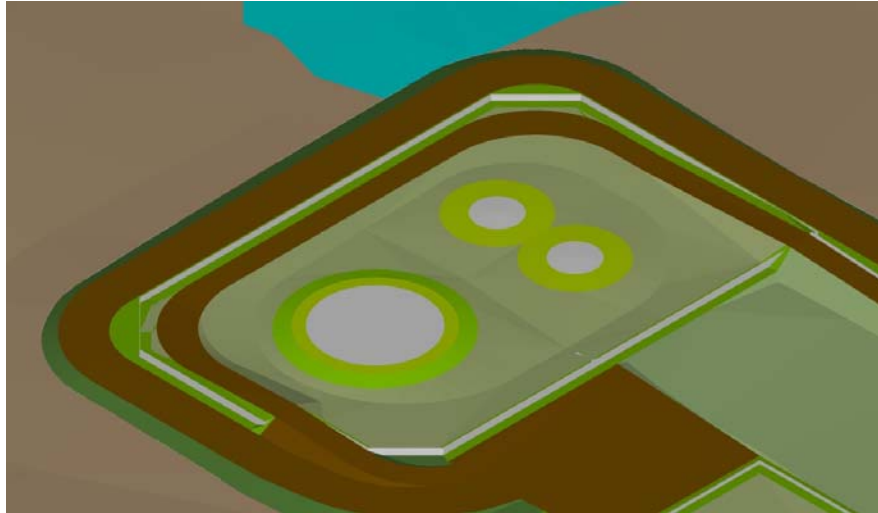
**Figure 4-17 Sample of a tank lot grading design**

At the end of the swale, there is a corner of the containment where a dump well or catch basin is located. Here, the water is collected and drained out of the tank lot. As Figure 4-17 shows, the storm water will be drained to the collection ditch that is in the middle of the tank lot and then to the outlet corner. The tank lot grading will follow this ditch as a backbone line.



**Figure 4-18 Picture of a tanklot outlet**

For this kind of application, the traditional least squares method will not be sufficient since it is based on a grid method, in which the slope has various directions. For infrastructure projects, numerous researchers have created a method called the weigh grade line method to minimize the linear project's earthwork. Since the tank lot grading follows the swale, this kind of site can be treated as a linear project. The vertical profile of the swale is a continuous piecewise linear line, smoothed by vertical curves allocated where the grade changes. The point dividing two consecutive grade lines of different elevations is called a vertical point of intersection (VPI) point. Centered on each VPI point is a parabolic vertical curve that helps avoid abrupt changes in grades.



**Figure 4-19 Sample of a tank lot grading design**

#### **4.1.4 Traditional Site Grading Design**

For a typical traditional site grading design, once the design engineer receive all relative input information such as the existing ground surface survey, the geotechnical report etc., the grading design can start. Based on the existing surface, one or two of the lowest points are chosen where the site's water is drained. These points' design elevations have to be higher than the existing surface, otherwise the whole site's drainage will backup to the site. This will ensure that the rain water from the site will be released into the surrounding environment properly. Once the lowest point's elevation is determined, a slope between 0.5% and 3% will be chosen to get the highest points of the site. This kind of grading design should maintain a grade line which is parallel to the major building / structure / equipment. From there, the design engineer can develop several scenarios with each solution's drainage pattern being different, and with the containment ditch/pond on a different side of the site. As such, various scenarios may arise. Experienced engineers can eliminate certain scenarios to reduce the earthwork. Usually 2 or 3 scenarios will be compared, and the best solution with the minimum earthwork will be chosen. This is a preliminary stage of the grading design, which needs further details, such as putting in ditches and buildings, will come later. Typical a 2% slope within 3 metres of the building

perimeter is required, this is called localization grading. The ditch and pond information also needs to be entered and some buildings/structures/equipments such as the electrical substation need do the localization grading as well. In certain, sites such as compression station sites, the potential containment area will be around the compressor, where the elevation is highest and no water will drain into the compressor area. Sometimes site design elevations have to be lower than the surrounding area, and so a ditch should be created between the site and the neighborhood to prevent neighborhood's water entering the site. In the design elevation, the elevation of the entrance road should be considered. Usually the public road/highway is higher than the existing surface, and the access road that connects the site to the public road should have a maximum slope. If the slope is too steep, then site design elevation modification should be considered.

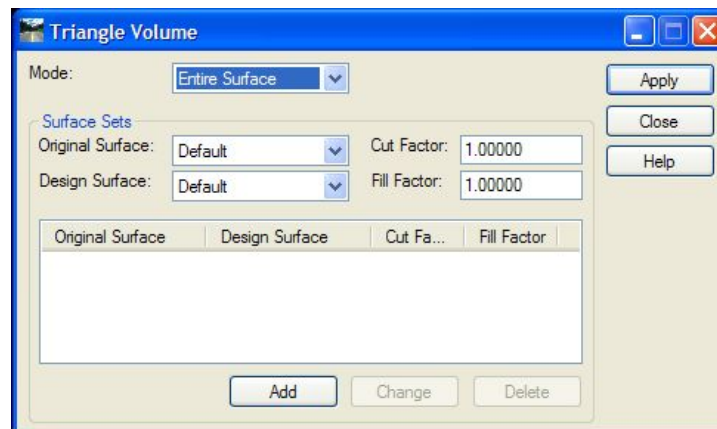
A number of factors must be taken into account when designing the vertical profile of a swale. The two most important factors are cost and hydraulic efficiency. Earthwork related costs make up the majority of all costs related to vertical profile design. Imbalanced earthwork requires moving earth mass from the construction site to a certain external land fill or from an external borrow pit to the construction site. In either case, the transportation of these large amounts of earth is not only costly but can pose a threat to the environment. Therefore, it is common practice for engineers to balance the cut and fill within the site whenever possible. Slope protection work is also required at most cut and fill locations.

Once the grading design is done, earthwork calculation usually is done through cross-section, contour, or grid cell methods. The cross-section method is most commonly used for roads, ditches, trenching and other projects, where the length is greater than the width. For these kinds of projects, the cross-section is the same or of several different types. The cross-section can be plotted for a certain distance, and then compared to decide the area difference between the existing surface line and the design surface line. Then the difference is multiplied with the length to derive that portion's earthwork volume. The total volume of the

earthwork will be the summary of those small portions. Nowadays, the cross-section method is also used on site grading earthwork. Through the use of computer programs, the area difference can easily be calculated.

The contour method requires a contour grading plan. The amount of cut or fill is determined by averaging the change in areas due to grading on two successive horizontal planes.

The grid method for calculating earthwork quantities averages cut or fill depths over a unit area. The product of the averaged depths with the unit area is the net incremental volume of the cut or fill. The sum of all incremental fill volumes gives the total for the site. Recent computer programs provide another new method called the triangle method to calculate the earthwork. This is the most accurate method.



**Figure 4-20 Triangle volume calculation**

Currently, for a cut and fill balance, alternative plans are compared but no optimization takes place. Thus, it largely relies on the engineer's own experience and skills. Furthermore, the calculation is usually separate from CAD, which has no function to support it. The present research will develop present an integrated system that unifies cut / fill quantity calculation and geomatics design. It is able to use Excel files for optimization and calculation and then exports the result to CAD. Similarly, CAD information can also be exported to Excel for optimization

and calculation.

#### ***4.2 Earthwork Optimization/Simulation Model***

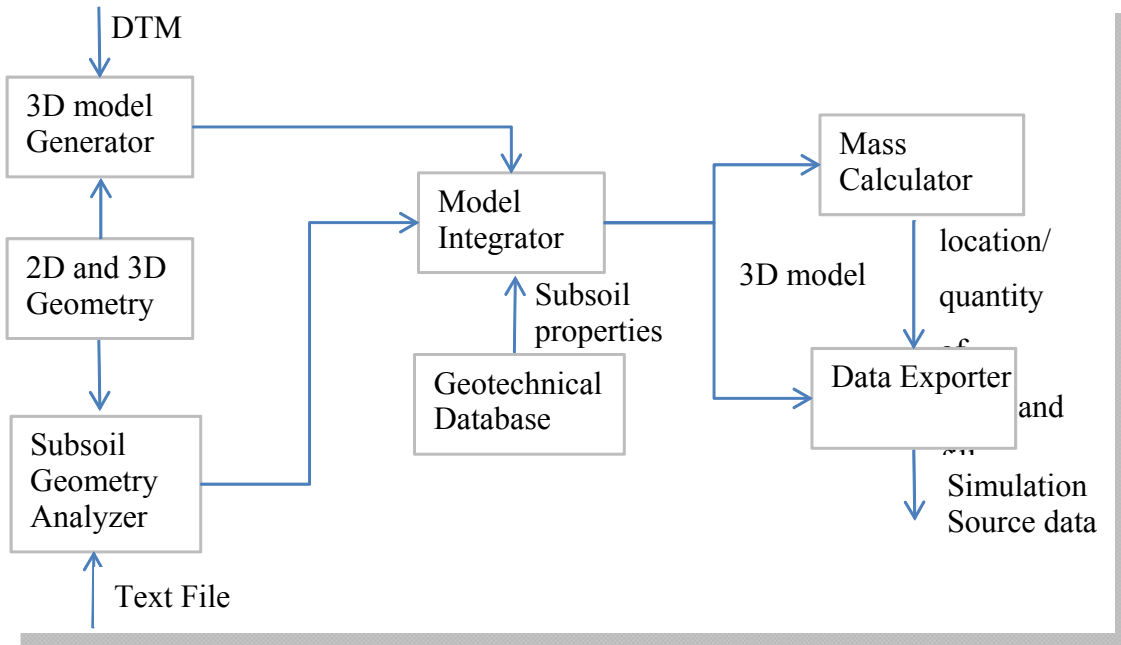
In the current practice, many earthwork decisions, such as equipment selection and utilization, are made on the basis of experience. However, this often leads to over or underestimation, which results in delays in the schedule or increased costs. The major objective of this research is to apply optimization and simulation techniques to minimize the earthwork quantity and maximize the efficiency of the resources to obtain the best possible tradeoff between time and cost. Low efficient activities can be identified during the simulation process so improvements can be made accordingly.

Grading and drainage are two components that are interdependent during the design stage. Technically, grading design and hydraulic calculations must always be treated as two different stages, through a trial and error approach. If the second stage does not work, then the first stage must be redesigned. If the algorithm can combine the grading and hydraulic stages in a single programming problem, this will ensure global optimization. There are also certain aspects particular to heavy construction practice, such as preventing containment, handling oily water, handling special fire protection systems, and special elevation requirements for the equipment. These aspects need to be considered when designing a site development strategy.

The research presents a practical way to planning and analyzing of the earthwork construction by integrating optimization and simulation techniques. In contrast to present practices, the new approach is able to do the earthwork optimization by retrieving all the information from a design 3D model (including 3D surface model and 3D sub-surface model). The most important information needed to simulate earthwork processes is the locations and quantity takeoff of cut and fill, which are considered in the simulation process. To generate this data, the site needs to be separated into small cells with a certain length and width. The



material quantity for each needs to be defined. This mass haul data is much more fine-grained than that used in traditional approaches and forms an excellent basis for performing a detailed earthwork process simulation. The SDSEA is used to describe resource entities and their respective cycles such as loaders and trucks, along with their behavior and cycle time required. This allows the user to identify bottlenecks and slack periods and reconfigure the resources accordingly. The simulation result can also feed back to the earthwork design, if the simulation model shows the earthwork design can be improved in certain way, the earthwork design can be adjusted to produce better cost and schedule-performance measures. The following figure shows the frame work of the new optimization/simulation integrated system.



**Figure 4-21 Optimization / Simulation integrated system**

### ***4.3 Earthwork Optimization***

#### **4.3.1 Traditional least squares method for earthwork optimization**

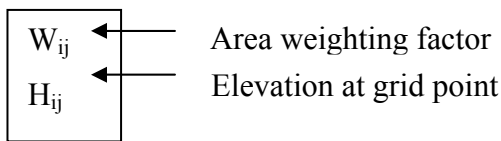
Traditionally, designs of site grading are done manually by experienced civil engineers though the cell grid method, or end section method. With the manual process, usually several solutions will be created and the best one will be chosen. Because the design work and earthwork calculations are quite extensive, the work

is both time and resource consuming, and it relies heavily on human expertise. In the past few decades, researchers have tried to find a mathematical model to find the best design plane for grading design. Those methods include least squares methods (Givan 1940, Chugg 1947, Scaloppi and Willardson 1986, Reddy et. Al 1996), Fixed Center Method (Raju 1960), Warped-Surface Method (Harris et al., 1966), Residual method (Shih and Kriz 1971, 1973), Linear programming (Semerdon et al., 1966), Non-linear programming (Hamad et. al., 1990, Reddy et. al., 1996) and Weighted Average Method (Reza 2004). Although numerous researchers introduced different methods for earthwork optimization, ‘the least squares method is still considered the most accurate and widely used method (Gebre-Selssie 1991).

Scaloppi and Willardson (1986) presented a hand calculation solution to use the least squares method to find the minimum cut and fill plane. Their solution is shown from Eq. 4-1 to Eq. 4-17 as below. The samples data from Chugg (1947) are used to illustrate the procedure for finding the plane surface of best fit for an irregularly shaped field and to illustrate the use of the least squares plane in land grading design. The relative elevations of the field surface are given in the Figure 4-22, which also shows the rectangular grid system used in the computations and the area weighing factors needed for the computation of cut and fill volumes.

O	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>	X <sub>6</sub>	X <sub>7</sub>
Y <sub>1</sub>	0.65	1.00	1.00	0.55	0.0	0.0	0.0
	6.6	6.1	6.7	6.7			
Y <sub>2</sub>	0.80	1.00	1.00	0.80	0.0	0.0	0.0
	5.7	5.4	5.9	6.0			
Y <sub>3</sub>	0.85	1.00	1.00	1.40	0.0	0.0	0.0
	4.7	4.4	5.0	5.4			
Y <sub>4</sub>	1.20	1.00	1.00	1.00	1.00	1.30	0.75
	4.0	3.8	4.2	4.4	4.2	3.9	3.8
Y <sub>5</sub>	1.20	1.00	1.00	1.00	1.00	1.00	1.10
	3.4	3.1	3.5	3.4	3.6	3.2	2.9
Y <sub>6</sub>	0.80	1.00	1.00	1.00	1.00	1.00	1.30
	2.7	2.2	3.2	2.6	2.4	2.3	2.2
Y <sub>7</sub>	0.0	1.35	1.00	1.00	1.00	1.00	1.00
		1.5	2.0	1.6	1.8	1.7	1.5
Y <sub>8</sub>	0.0	0.80	1.20	1.25	1.25	1.12	0.55
		0.7	1.2	0.7	1.0	1.0	0.9

Area assigned to a grid point



**Figure 4-22 Optimization sample**

The computation is performed considering unit distance and unit areas according to the proposed procedure. At the end of the computation, the appropriate actual field dimensions can be used to compute the volumes of cuts and fills. The field and office procedure followed is outlined as follows.

1. Stake the field in a regular grid pattern. Measure the distance from the last grid point in each line to the edge of the field in both directions in order to define the field boundaries.

2. Determine the elevation of each grid point and the elevation of the soil surface at the end of each grid line projected to the edge of the field. This latter information is not used in the computations but is needed to mark cuts and fills at the edges of the field for the benefit of the machine operators when the actual grading is done.
3. Draw a plan map of the field and sketch the field boundaries.
4. At each grid point, write the elevation.
5. Write a weighting number for each grid point above the elevation of the grid point to indicate the area weighting factor for that grid point. Interior regular grid points have a weighting factor of 1.00. Grid points on the boundary will have area weighting factors greater or less than 1.00 depending on the amount of surface area represented by the grid point. For area outside regular grid dimensions that could be represented by more than one grid point, add the extra area to the grid point in the direction of least slope.
6. Assign zero elevations for grid points that fall outside the field boundaries.
7. Using the least squares method, compute the equation of the least squares plane, and the coordinates and elevation of the centroid. Any grid point with a zero elevation is not included in the calculation.

The equation shown below for simplified computation.

$$A_1 = \sum_{x=1}^7 \sum_{y=1}^8 \delta_{xy} = 45 = N = \text{actual number of grid points in the field}$$

if  $\delta_{xy}$  is empty, then  $\delta_{xy}=0$  otherwise  $\delta_{xy}=1$  Eq.4-1

$$A_2 = B_1 = \sum_{x=1}^7 x_i \times \sum_{y=1}^8 \delta_j = (1 \times 6) + (2 \times 8) + (3 \times 8) + (4 \times 8) + (5 \times 5) + (6 \times 5) + (7 \times 5) = 168$$

Eq.4-2

if  $\delta_j$  is empty, then  $\delta_j=0$  otherwise  $\delta_j=1$

$$A_2 = (a \times b) + (c \times d) + \dots + (e \times f) = 168$$

$a = x_1$   $b =$  number of y values at  $x_1$   $c = x_2$

$d =$  number of y values at  $x_2$   $e = x_7$   $f =$  number of y values at  $x_7$

$$A_3 = C_1 = \sum_{y=1}^8 y_j \times \sum_{x=1}^7 \delta_i = (1 \times 4) + (2 \times 4) + (3 \times 4) + (4 \times 7) + (5 \times 7) + (6 \times 7) + (7 \times 6) + (8 \times 6) = 219$$

Eq.4-3

if  $\delta_i$  is empty, then  $\delta_i=0$  otherwise  $\delta_i=1$

$$A_3 = (a \times b) + \dots + (c \times d) = 219$$

$a = y_1$   $b =$  number of x values at  $y_1$   $c = y_8$   $d =$  number of x values at  $y_8$

$$B_2 = \sum_{x=1}^7 x_i^2 \times \sum_{y=1}^8 \delta_j = (1^2 \times 6) + (2^2 \times 8) + (3^2 \times 8) + (4^2 \times 8) + (5^2 \times 5) + (6^2 \times 5) + (7^2 \times 5) = 788$$

Eq.4-4

$$B_2 = (a \times b) + \dots + (c \times d) = 788$$

$$a = x_1^2 \quad b = \text{number of } y \text{ values at } x_1 \quad c = x_7^2 \quad d = \text{number of } y \text{ values at } x_7$$

$$C_3 = \sum_{y=1}^8 y_j^2 \times \sum_{x=1}^7 \delta_i = (1^2 \times 4) + (2^2 \times 4) + (3^2 \times 4) + (4^2 \times 7) + (5^2 \times 7) + (6^2 \times 7) + (7^2 \times 6) + (8^2 \times 6) = 1273 \quad \text{Eq.4-5}$$

$$C_3 = (a \times b) + \dots + (c \times d) = 1273$$

$$a = y_1^2 \quad b = \text{number of } x \text{ values at } y_1 \quad c = y_8^2 \quad d = \text{number of } x \text{ values at } y_8$$

$$B_3 = C_2 = \sum_{x=1}^7 x_i \delta_i \times \sum_{y=1}^8 y_j \delta_j = (1 \times 1) + (1 \times 2) + (1 \times 3) + (1 \times 4) + (1 \times 5) + (1 \times 6) + (2 \times 1) + (2 \times 2) + (2 \times 3) + (2 \times 4) + (2 \times 5) + (2 \times 6) + (2 \times 7) + (2 \times 8) + (3 \times 1) + (3 \times 2) + (3 \times 3) + (3 \times 4) + (3 \times 5) + (3 \times 6) + (3 \times 7) + (3 \times 8) + (4 \times 1) + (4 \times 2) + (4 \times 3) + (4 \times 4) + (4 \times 5) + (4 \times 6) + (4 \times 7) + (4 \times 8) + (5 \times 4) + (5 \times 5) + (5 \times 6) + (5 \times 7) + (5 \times 8) + (6 \times 4) + (6 \times 5) + (6 \times 6) + (6 \times 7) + (6 \times 8) + (7 \times 4) + (7 \times 5) + (7 \times 6) + (7 \times 7) + (7 \times 8) = 885 \quad \text{Eq.4-6}$$

$$B_3 = (a \times b) + \dots + (c \times d) = 885$$

$$a = x_1 \quad b = y_1 \quad c = x_7 \quad d = y_8$$

$$F_1 = \sum_{x=1}^7 \sum_{y=1}^8 h(x_i y_j) = 6.6 + 5.7 + 4.7 + 4.0 + 3.4 + 2.7 + 6.1 + 5.4 + 4.4 + 3.8 + 3.1 + 2.2 + 1.5 + 0.7 + 6.7 + 5.9 + 5.0 + 4.2 + 3.5 + 3.2 + 2.0 + 1.2 + 6.7 + 6.0 + 5.4 + 4.4 + 3.4 + 2.6 + 1.6 + 0.7 + 4.2 + 3.6 + 2.4 + 1.8 + 1.0 + 3.9 + 3.2 + 2.3 + 1.7 + 1.0 + 3.8 + 2.9 + 2.2 + 1.5 + 0.9 = 153.2$$

$$\text{Eq.4-7}$$

$$F_1 = (a) + (b) + \dots + (c) = 153.2$$

$$a = h(x_1, y_1) \quad b = h(x_1, y_2) \quad c = h(x_7, y_8)$$

$$F_2 = \sum_{x=1}^7 \sum_{y=1}^8 [(x)h(x_i y_j)] = (1 \times 6.6) + (1 \times 5.7) + (1 \times 4.7) + (1 \times 4.0) + (1 \times 3.4) + (1 \times 2.7) + (2 \times 6.1) + (2 \times 5.4) + (2 \times 4.4) + (2 \times 3.8) + (2 \times 3.1) + (2 \times 2.2) + (2 \times 1.5) + (2 \times 0.7) + (3 \times 6.7) + (3 \times 5.9) + (3 \times 5.0) + (3 \times 4.2) + (3 \times 3.5) + (3 \times 3.2) + (3 \times 2.0) + (3 \times 1.2) + (4 \times 6.7) + (4 \times 6.0) + (4 \times 5.4) + (4 \times 4.4) + (4 \times 3.4) + (4 \times 2.6) + (4 \times 1.6) + (4 \times 0.7) + (5 \times 4.2) + (5 \times 3.6) + (5 \times 2.4) + (5 \times 1.8) + (5 \times 1.0) + (6 \times 3.9) + (6 \times 3.2) + (6 \times 2.3) + (6 \times 1.7) + (6 \times 1.0) + (7 \times 3.8) + (7 \times 2.9) + (7 \times 2.2) + (7 \times 1.5) + (7 \times 0.9) = 516.5$$

Eq.4-8

$$F_1 = (a) + (b) + \dots + (c) = 516.5$$

$$a = x_1 \quad b = h(x_1, y_1) \quad c = x_1 \quad d = h(x_1, y_2) \quad e = x_7 \quad f = h(x_7, y_8)$$

$$F_3 = \sum_{y=1}^8 \sum_{x=1}^7 [(y)h(x_i y_j)] = (1 \times 6.6) + (1 \times 6.1) + (1 \times 6.7) + (1 \times 6.7) + (2 \times 5.7) + (2 \times 5.4) + (2 \times 5.9) + (2 \times 6.0) + (3 \times 4.7) + (3 \times 4.4) + (3 \times 5.0) + (3 \times 5.4) + (4 \times 4.0) + (4 \times 3.8) + (4 \times 4.2) + (4 \times 4.4) + (4 \times 4.2) + (4 \times 3.9) + (4 \times 3.8) + (5 \times 3.4) + (5 \times 3.1) + (5 \times 3.5) + (5 \times 3.4) + (5 \times 3.6) + (5 \times 3.2) + (5 \times 2.9) + (6 \times 2.7) + (6 \times 2.2) + (6 \times 3.)^2 + (6 \times 2.6) + (6 \times 2.4) + (6 \times 2.3) + (6 \times 2.2) + (7 \times 1.5) + (7 \times 2.0) + (7 \times 1.6) + (7 \times 1.8) + (7 \times 1.7) + (7 \times 1.5) + (8 \times 0.7) + (8 \times 1.2) + (8 \times 0.7) + (8 \times 1.0) + (8 \times 1.0) + (8 \times 0.9) = 579.6$$

Eq.4-9

$$F_1 = (a) + (b) + \dots + (c) = 579.6$$

$$a = y_1 \quad b = h(x_1, y_1) \quad c = y_1$$

$$d = h(x_2, y_1) \quad e = y_8 \quad f = h(x_7, y_8)$$

This simplified computations for the least squares plane equation using Cramer's Rule is

$$D = A_1 B_2 C_3 + A_3 B_1 C_2 + A_2 B_3 C_1 - A_3 B_2 C_1 - A_2 B_1 C_3 - A_1 B_3 C_2 \quad \text{Eq.4-10}$$

$$D_1 = F_1 B_2 C_3 + F_3 B_1 C_2 + F_2 B_3 C_1 - F_3 B_2 C_1 - F_2 B_1 C_3 - F_1 B_3 C_2 \quad \text{Eq.4-11}$$

$$D_2 = A_1 F_2 C_3 + A_3 F_1 C_2 + A_2 F_3 C_1 - A_3 F_2 C_1 - A_2 F_1 C_3 - A_1 F_3 C_2 \quad \text{Eq.4-12}$$

$$D_3 = A_1 B_2 F_3 + A_3 B_1 F_2 + A_2 B_3 F_1 - A_3 B_2 F_1 - A_2 B_1 F_3 - A_1 B_3 F_2 \quad \text{Eq.4-13}$$

$$a = \frac{D_1}{D} = 7.3254 \quad b = \frac{D_2}{D} = 0.01049 \quad c = \frac{D_3}{D} = 0.7976 \quad \text{Eq.4-14}$$

Which is gives the following equation:

$$H(x,y) = 7.3254 - 0.01049 x - 0.79762 y \quad \text{Eq.4-15}$$

The centroid location in the field is easily determined by

$$X_c = \frac{(\sum_{x=1}^m \sum_{y=1}^n x_i)}{N} = \frac{A_2}{N} = \frac{168}{45} = 3.773$$

Eq.4-16

$$Y_c = \frac{(\sum_{x=1}^m \sum_{y=1}^n y_j)}{N} = \frac{A_3}{N} = \frac{219}{45} = 4.867 \quad \text{Eq.4-17}$$

The  $x$  and  $y$  distances computed are the number of unit grid spaces. The values computed above are exactly the same as those obtained by Chugg (1947).

For each grid point, compute the elevation of the least squares plane using the equation of the plane. Subtract the plane elevation at the grid point from the field elevation at the grid point and multiply the difference by the area weighing factor for that grid point. Positive differences are accumulated as volumes of cut. Negative differences are accumulated as volumes of fill. The volume of the cuts should be an average of about 15% greater than the volume of the fills to account for shrinkage that occurs during earth moving. The percent difference between cut and fill volumes varies with soils. Change the value of  $a$ , down to increase the volume of cuts, or up to increase the volume of fills to get the required proportional balance between cuts and fills. When the computations are complete, use the equation of the final plane with the appropriate  $x$  and  $y$  coordinates to check critical elevations at the edges of the field to make sure that the plane is not too high or too low and to mark the cuts and fills at the boundaries of the field.

To remove any cross-slope in the field, it is necessary to make  $b$  equal to zero and to force the plane to be horizontal in the  $x$  direction or make  $c$  equal to zero to force the plane to be horizontal in the  $y$  direction. Solve for new values of  $a$  and  $c$ , or  $a$  and  $b$  as appropriate, using the coordinates and elevation of the centroid and two appropriate elevations and grid point locations of the plane at the upper edge of the field. Any plane that goes through the centroid will give the least volume cuts and fills for any specified position of the plane but will not give the minimum earth moving volume, which only occurs for the least squares plane. Change variable “ $a$ ” to balance the cuts and fills. Check critical elevations at the edges.

Since three points determine a plane, the three points used to make a plane horizontal in either direction can be put into Eq.1 and the solution found using Cramer’s Rule. Including the centroid coordinates and elevation of the least squares plane as one of the points guarantees the minimum amount of earthwork

for earthwork for the chosen plane. The system of simultaneous equations for a plane passing through any three points is given in Eq. 4-18 to 4-24:

$$1.0a + x_1b + y_1c = h_1 \quad \text{Eq.4-18}$$

$$1.0a + x_2b + y_2c = h_2 \quad \text{Eq.4-19}$$

$$1.0a + x_3b + y_3c = h_3 \quad \text{Eq.4-20}$$

And the Cramer's Rule solution is

$$d = x_2y_3 + x_1y_2 + x_3y_1 - x_2y_1 - x_3y_2 - x_1y_3 \quad \text{Eq.4-21}$$

$$d_1 = h_1x_2y_3 + h_3x_1y_2 + h_2x_3y_1 - h_3x_2y_1 - h_1x_3y_2 - h_2x_1y_3 \quad \text{Eq.4-22}$$

$$d_2 = h_2y_3 + h_1y_2 + h_3y_1 - h_2y_1 - h_3y_2 - h_1y_3 \quad \text{Eq.4-23}$$

$$d_3 = h_3x_2 + h_2x_1 + h_1x_3 - h_1x_2 - h_2x_3 - h_1h_3 \quad \text{Eq.4-24}$$

$$a = d_1 / d \quad b = d_2 / d \quad c = d_3 / d$$

To level a control point, use the centroid position and elevation plus the elevation and location of the control point and one other point to determine the values of a, b, and c using Eq. 18 to 24 and 1. Change a to balance cuts and fills. Check the final plane elevations at points on the edge of the field to determine whether the final plane position is satisfactory.

To level a control edge, use the centroid position and elevation plus the position and elevation of two points on the control edge to determine a, b and c using Eq. 18 to 24 and 1. If cuts and fills do not balance, recalculate a, b, and c by raising or lowering the elevation of the plane at the centroid location until the cuts and fills are balanced. Check the edge elevations with the final equations.

The procedures outlined above are amenable to calculation by hand calculator, programmable calculator or computer. Each data point has the following dimensions : (1)  $h_{ij}$  = the original ground elevation of a point in the field; (2)  $x_i$  = the coordinate of the point in the x direction; (3)  $y_j$  = the coordinate of the point in the y direction; and (4)  $W_{ij}$  = the relative area weighting factor for the area represented by each grid point. By assigning a zero elevation to grid points



outside the area to be graded, the zero elevation can be used to logically reject points that should not be included in the computations.

The final volume of earthwork is obtained by multiplying the values obtained in Step 8 above for cuts (positive accumulation) and for fills (negative accumulation) by the area represented by a normal grid point. If the elevations are in feet and the grid points are 100ft apart, the area represented by each grid point would be 10,000 sq ft and the computed volumes of cut and fill will be in cubic feet. Since the computations use nondimensional or relative values, any appropriate units can be used.

For dead-level land grading, the centroid elevation can be used as a starting elevation for properly balancing cut and fill volumes. The procedures of items 8 and 12 apply following determination of the centroid elevation.

Ebne-Jalal (2004) further compared results from the same sample for each different methods shown on Table 2. The result shows the optimized x axis slope and y axis slope are quite similar.

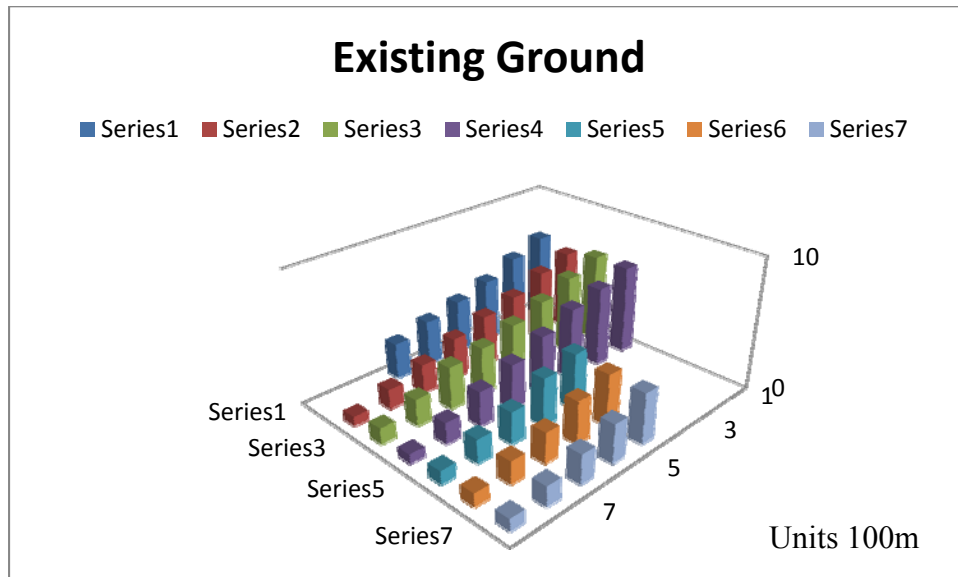
Table 2 Comparison of the results of different methods

Method	b	c	Difference with least-square method	
			b	c
Least Squares	-0.798	-0.011	-	-
Fixed volume center	-0.781	-0.017	0.017	0.006
Symmetrical	-0.788	-0.001	0.010	0.010
Weighted average	-0.783	-0.011	0.015	0.000

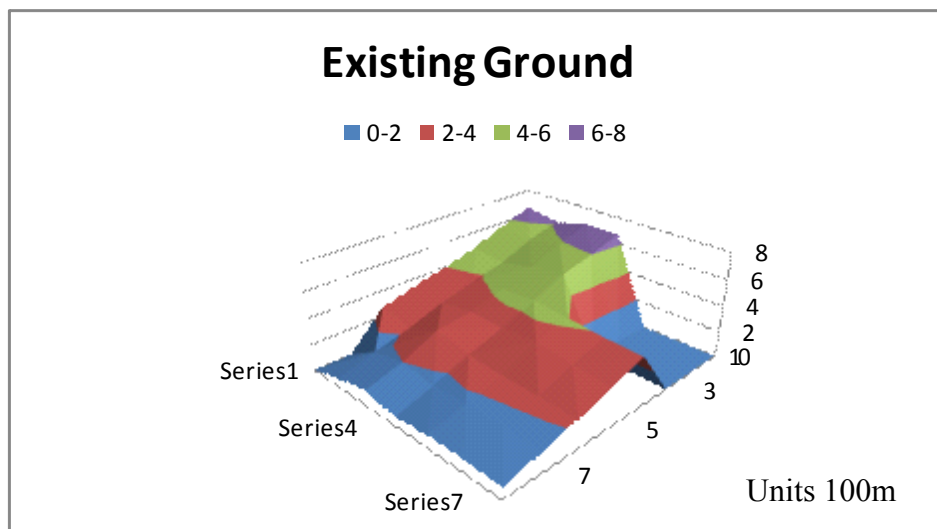
Although the traditional least square method has a long history and researchers who have used it have done extensive work, there are still some room for improvement.

1. The mathematical result, however, does not reflect real situations. Typically, the site grading slope should be between 0.5% and 3%. If the slope is smaller, water may accumulate on the site; if the slope is larger, erosion can occur. In other words, the previous optimization result giving the slope along the x axis does not reflect a real site grading design. Earthwork configures the surface of the land by removing or adding earthen material to shape the land and best suit the project. With a slope as steep as 79%, the site cannot be used. The model should be able to control the site slope within certain ranges.
2. Since heavy hand calculations are involved in the solution, it will be very beneficial to calculate those data by computer. The program also needs to predefine several different site types to reflect different site grading requirements. The proposed way, which is to generate a data matrix and solve it though Excel Solver will meet that requirement. The least square method can be done more accurately by handling the data as a matrix and solving it by Solver.
3. The previous method considers the center of each cell elevation is the average of that cell's elevation. When the cell is relatively big, the average elevation is not very accurate. The best approach is to get the four corners of each cell's elevation then get the average elevation. See the following figure 4-22 and 4-24 as below. The traditional model treats the surface as separate columns and the new proposed model smoothens the surface continuously. To achieve that, the other weight factor needs to apply to make it work. The previous research creates a weight for area factor in order to control the site boundary shorter or larger than the predefined cell. The new weight factor is based on the cell's location. Corner point is only used once, then its weight factor should be 0.25, the edge point elevation used twice then its weight factor should be 0.5. The point in the centre is used 4 times each, then, its weight factor is 1. The new weight factor to represent the cell's average elevation will make the calculation more accurate.
4. Although the traditional least squares method is based on grid cell earthwork calculation methods, this method cannot meet the requirement for certain sites. For example, this method is based on the premise that each small cell has the same area, but sometimes for heavy industry, a cell has to be divided into different areas and those cells usually need to be considered as one piece and the other example is that can only allow two single slopes in each direction for the design surface. For a site as section

4.1.3.2 and section 4.1.3.3 has four slope directions, the traditional model fails.



**Figure 4-23 Existing surface 3D column graphic**

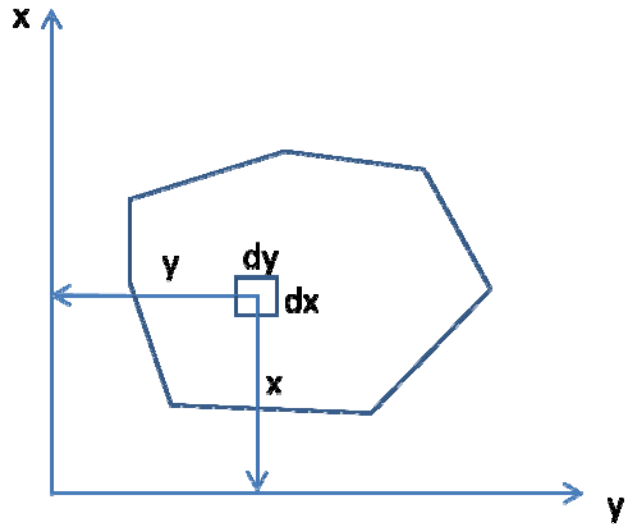


**Figure 4-24 Existing surface 3D surface graphic**

### 4.3.2 Modification of least squares method for earthwork optimization

To use computer to apply the least square method for earthwork, the Cramer's Rule, which is the foundation of previous least square solutions needs to be avoided since it's hard to program. As such, the basic theory of least squares

method needs to be reviewed in order to find a new way to model and solve the problem by computer. The least square method can be illustrated with the following figure.



**Figure 4-25 Least squares method illustration**

$dv$	the earthwork volume at $dx dy$
$H$	the highest design point's elevation
$i_x$	grading slope along x axis
$i_y$	grading slope along y axis
$x, y$	the distance from $dx dy$ to x axis and y axis
$z$	the existing elevation at $dx dy$

Base on the least squares method; find the minimum earthwork volume, satisfying the objective:

$$\text{Min} \sum_{i=1}^n dV^2 = \text{Min} \sum_{i=1}^n (H + ixX + iyY - z)^2 dx dy \quad \text{Eq.4-25}$$

The result is also need fit for a set of constrains as:

$$0.01 \leq ix \leq 0.03$$

$$0.01 \leq iy \leq 0.03$$

Taking the partial differentiation along H, ix and iy directions, and let it equal to 0, giving the following equations

$$\sum_{i=1}^n (H + ixX + iyY - z) dx dy = 0 \quad \text{Eq.4-26}$$

$$\sum_{i=1}^n X(H + ixX + iyY - z) dx dy = 0 \quad \text{Eq.4-27}$$

$$\sum_{i=1}^n Y(H + ixX + iyY - z) dx dy = 0 \quad \text{Eq.4-28}$$

To describe it with double integral, then it will be

$$\int^x \int^y (H + ixX + iyY) dx dy \quad \text{Eq.4-29}$$

$$\int^x \int^y X(H + ixX + iyY) dx dy \quad \text{Eq.4-30}$$

$$\int^x \int^y Y(H + ixX + iyY) dx dy \quad \text{Eq.4-31}$$

If use Gauss function ( [x], x is integer) instead of double integral, then get a group of criterion formulas as

$$n[H] + [x]ix + [y]iy - [z] = 0 \quad \text{Eq.4-32}$$

$$[x]H + [xx]ix + [xy]iy - [xz] = 0 \quad \text{Eq.4-33}$$

$$[y]H + [yx]ix + [yy]iy - [yz] = 0 \quad \text{Eq.4-34}$$

Then put the weight in consideration, the group of formulas will change to

$$[p]H + [px]ix + [py]iy - [pz] = 0 \quad \text{Eq.4-35}$$

$$[px]H + [pxx]ix + [pxy]iy - [pxz] = 0 \quad \text{Eq.4-36}$$

$$[py]H + [pyx]ix + [pyy]iy - [pyz] = 0 \quad \text{Eq.4-37}$$

Then

$$[ph] = 0; \quad \text{Eq.4-38}$$

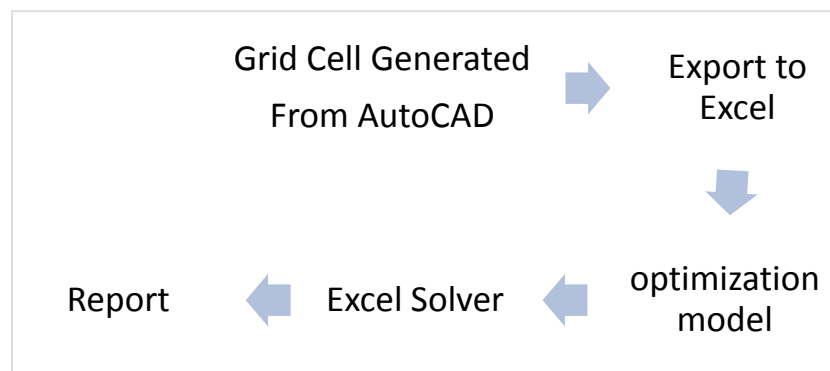
$$h = H + ixX + iyY - Z \quad \text{Eq.4-39}$$

h is the design elevation.

According to observed limitations and suggested solutions as described above, the research develops a new model trying to bridge those gaps. The proposed algorithm is aimed to balance or minimize the cut and fill volume, and at the same

time, it also makes the drainage pattern workable. To do this, an algorithm is introduced in this research for specific contexts. First a ground grid system is generated to fit as much as possible to the site from CAD system. The grid's distance cannot be too large, otherwise the calculation will not be accurate. The grid's distance cannot be too small as well, because too trivial cut/fill cubes will be generated from those grids. If the grid cell is too small, it will be very hard to transfer those location and quantity information to the simulation model. Then, CAD export function can be used to export the geometric information to Excel. Based on the site grading requirement, a site type is chosen to create the model. Then use the least squares method though Excel's 'Solver' function to get the optimum grading elevation and slope. The proposed heuristic solution has been developed, generated and promising results for all the cases tested. The proposed heuristic framework is shown as the following Figure 4-26.

Numerous research papers have successfully demonstrated how to develop a standard spreadsheet system. The excel spreadsheet in HCCIM handles the most common civil analyses and calculations. It is color coded: yellow signifies input needed, green signifies the calculation result, which is used for further calculations, and blue signifies the final result. An algorithm that seamlessly works within the spreadsheet and CAD (Computer Aided Design) packages has also been developed to aid the designer and increase efficiency.



**Figure 4-26 Optimization/Simulation structure**

Excel Solver was created in 1991 by Microsoft. Since then, “it has become the most widely distributed and almost surely the most widely used general-purpose optimization modeling system”. (Fylstra., 1998). Although Solver has a graphical user interface (GUI) and an algebraic modeling language, it is seamlessly embedded in the Excel spreadsheet. The optimization model fit for the specific site can be easily used and changed. For the non-linear model, Solver uses GRG2 (Generalized Reduced Gradient) solution which was created by Leon Lasdon (University of Texas Austin) and Allan Waren (Cleveland State University). For the linear and integer model, Solver uses Bound Constraints Simplex Method and Branch and Bound Method which was created by John Watson and Dan Fylstra (Frontline Systems)

The data matrix can be created using the following steps shown as below

1. Create the first column as cell's name.
2. Since cell X4Y5 is the center of the site, create the second and the third column to show the x and y distance from X4Y5 to that cell.
3. Create the fourth column as cell's z (elevation).
4. Create the fifth column as cell's p (weighing).
5. Create the sixth, seventh and eighth column to show the result of  $p \times x$ ,  $p \times y$  and  $p \times z$ .
6. Create the ninth, tenth, eleventh, twentieth, thirteenth column to show the result of  $p \times x \times x$ ,  $p \times y \times y$ ,  $p \times x \times y$ ,  $p \times x \times z$ ,  $p \times y \times z$ .
7. Create the fourteenth column for the cut or fill of that cell.
8. Create the fifteenth column to show the result of  $p \times h$
9. Get the  $\sum$  from column five to column fourteen.
10. Initialize a number for H, ix and iy.
11. Setup a cell using equation  $[p]H + [px]ix + [py]iy - [pz]$
12. Setup a cell using equation  $[px]H + [pxx]ix + [pxy]iy - [pxz]$
13. Setup a cell using equation  $[py]H + [pyx]ix + [pyy]iy - [pyz]$
14. Setup a cell the volume which should be summation of volumes for step 12, 13 and 14
15. Use Solver as try to find the minimum number of cells in setup 14 by changing the volumes from step 11, 12 and 13's cell.

Table 3 Original optimization result

Cell	x	y	z	p	px	py	pz	pxx	pyy	pxy	pxz	pyz	h	ph
X <sub>1</sub> Y <sub>1</sub>	0	0	6.6	0.65	0	0	4.29	0	0	0	0	0	0.007254	0.004715
X <sub>1</sub> Y <sub>2</sub>	0	100	5.7	0.80	0	80	4.56	0	8000	0	0	456	-0.78135	-0.62508
X <sub>1</sub> Y <sub>3</sub>	0	200	4.7	0.85	0	170	3.995	0	34000	0	0	799	-1.56895	-1.3336
X <sub>1</sub> Y <sub>4</sub>	0	300	4.0	1.20	0	360	4.8	0	108000	0	0	1440	-2.35955	-2.83146
X <sub>1</sub> Y <sub>5</sub>	0	400	3.4	1.20	0	480	4.08	0	192000	0	0	1632	-3.15115	-3.78138
X <sub>1</sub> Y <sub>6</sub>	0	500	2.7	0.80	0	400	2.16	0	200000	0	0	1080	-3.94175	-3.1534
X <sub>2</sub> Y <sub>1</sub>	100	0	6.1	1.00	100	0	6.1	10000	0	0	610	0	0.001764	0.001764
X <sub>2</sub> Y <sub>2</sub>	100	100	5.4	1.00	100	100	5.4	10000	10000	10000	540	540	-0.78884	-0.78884
X <sub>2</sub> Y <sub>3</sub>	100	200	4.4	1.00	100	200	4.4	10000	40000	20000	440	880	-1.57644	-1.57644
X <sub>2</sub> Y <sub>4</sub>	100	300	3.8	1.00	100	300	3.8	10000	90000	30000	380	1140	-2.36804	-2.36804
X <sub>2</sub> Y <sub>5</sub>	100	400	3.1	1.00	100	400	3.1	10000	160000	40000	310	1240	-3.15864	-3.15864
X <sub>2</sub> Y <sub>6</sub>	100	500	2.2	1.00	100	500	2.2	10000	250000	50000	220	1100	-3.94724	-3.94724
X <sub>2</sub> Y <sub>7</sub>	100	600	1.5	1.35	135	810	2.025	13500	486000	81000	202.5	1215	-4.73784	-6.39608
X <sub>2</sub> Y <sub>8</sub>	100	700	0.7	0.80	80	560	0.56	8000	392000	56000	56	392	-5.52744	-4.42195
X <sub>3</sub> Y <sub>1</sub>	200	0	6.7	1.00	200	0	6.7	40000	0	0	1340	0	-0.01473	-0.01473
X <sub>3</sub> Y <sub>2</sub>	200	100	5.9	1.00	200	100	5.9	40000	10000	20000	1180	590	-0.80433	-0.80433
X <sub>3</sub> Y <sub>3</sub>	200	200	5.0	1.00	200	200	5	40000	40000	40000	1000	1000	-1.59293	-1.59293
X <sub>3</sub> Y <sub>4</sub>	200	300	4.2	1.00	200	300	4.2	40000	90000	60000	840	1260	-2.38253	-2.38253
X <sub>3</sub> Y <sub>5</sub>	200	400	3.5	1.00	200	400	3.5	40000	160000	80000	700	1400	-3.17313	-3.17313
X <sub>3</sub> Y <sub>6</sub>	200	500	3.2	1.00	200	500	3.2	40000	250000	100000	640	1600	-3.96773	-3.96773
X <sub>3</sub> Y <sub>7</sub>	200	600	2.0	1.00	200	600	2	40000	360000	120000	400	1200	-4.75333	-4.75333
X <sub>3</sub> Y <sub>8</sub>	200	700	1.2	1.20	240	840	1.44	48000	588000	168000	288	1008	-5.54293	-6.65151
X <sub>4</sub> Y <sub>1</sub>	300	0	6.7	0.55	165	0	3.685	49500	0	0	1105.5	0	-0.02522	-0.01387
X <sub>4</sub> Y <sub>2</sub>	300	100	6.0	0.80	240	80	4.8	72000	8000	24000	1440	480	-0.81582	-0.65265
X <sub>4</sub> Y <sub>3</sub>	300	200	5.4	1.40	420	280	7.56	126000	56000	84000	2268	1512	-1.60742	-2.25038
X <sub>4</sub> Y <sub>4</sub>	300	300	4.4	1.00	300	300	4.4	90000	90000	90000	1320	1320	-2.39502	-2.39502
X <sub>4</sub> Y <sub>5</sub>	300	400	3.4	1.00	300	400	3.4	90000	160000	120000	1020	1360	-3.18262	-3.18262
X <sub>4</sub> Y <sub>6</sub>	300	500	2.6	1.00	300	500	2.6	90000	250000	150000	780	1300	-3.97222	-3.97222
X <sub>4</sub> Y <sub>7</sub>	300	600	1.6	1.00	300	600	1.6	90000	360000	180000	480	960	-4.75982	-4.75982
X <sub>4</sub> Y <sub>8</sub>	300	700	0.7	1.25	375	875	0.875	112500	612500	262500	262.5	612.5	-5.54842	-6.93552
X <sub>5</sub> Y <sub>4</sub>	400	300	4.2	1.00	400	300	4.2	160000	90000	120000	1680	1260	-2.40351	-2.40351
X <sub>5</sub> Y <sub>5</sub>	400	400	3.6	1.00	400	400	3.6	160000	160000	160000	1440	1440	-3.19511	-3.19511
X <sub>5</sub> Y <sub>6</sub>	400	500	2.4	1.00	400	500	2.4	160000	250000	200000	960	1200	-3.98071	-3.98071
X <sub>5</sub> Y <sub>7</sub>	400	600	1.8	1.00	400	600	1.8	160000	360000	240000	720	1080	-4.77231	-4.77231
X <sub>5</sub> Y <sub>8</sub>	400	700	1.0	1.25	500	875	1.25	200000	612500	350000	500	875	-5.56191	-6.95238
X <sub>6</sub> Y <sub>4</sub>	500	300	3.9	1.30	650	390	5.07	325000	117000	195000	2535	1521	-2.411	-3.13429
X <sub>6</sub> Y <sub>5</sub>	500	400	3.2	1.00	500	400	3.2	250000	160000	200000	1600	1280	-3.2016	-3.2016
X <sub>6</sub> Y <sub>6</sub>	500	500	2.3	1.00	500	500	2.3	250000	250000	250000	1150	1150	-3.9902	-3.9902
X <sub>6</sub> Y <sub>7</sub>	500	600	1.7	1.00	500	600	1.7	250000	360000	300000	850	1020	-4.7818	-4.7818
X <sub>6</sub> Y <sub>8</sub>	500	700	1.0	1.12	560	784	1.12	280000	548800	392000	560	784	-5.5724	-6.24108
X <sub>7</sub> Y <sub>4</sub>	600	300	3.8	0.75	450	225	2.85	270000	67500	135000	1710	855	-2.42049	-1.81536
X <sub>7</sub> Y <sub>5</sub>	600	400	2.9	1.10	660	440	3.19	396000	176000	264000	1914	1276	-3.20909	-3.52999
X <sub>7</sub> Y <sub>6</sub>	600	500	2.2	1.30	780	650	2.86	468000	325000	390000	1716	1430	-3.99969	-5.19959
X <sub>7</sub> Y <sub>7</sub>	600	600	1.5	1.00	600	600	1.5	360000	360000	360000	900	900	-4.79029	-4.79029
X <sub>7</sub> Y <sub>8</sub>	600	700	0.9	0.55	330	385	0.495	198000	269500	231000	297	346.5	-5.58189	-3.07004
			153.2	45.22	12485	17984	149.865	5016500	9110800	5572500	36354.5	43934	-138.308	-142.936
H														7.3254
ix														0.01049
iy														0.7976
a	[p] H + [p x] i x + [p y] i y - [p z] =0													14656.4
b	[p x] H + [p x x] i x + [p x y] i y - [p x z] =0													4552352
c	[p y] H + [p y x] i x + [p y y] i y - [p y z] =0													7413036
d														11980044



Table 4 New optimization result

Cell	x	y	z	p	px	py	pz	pxx	pyy	pxy	pxz	pyz	h	ph
X <sub>1</sub> Y <sub>1</sub>	0	0	6.6	0.65	0	0	4.29	0	0	0	0	0	-0.006	-0.003902
X <sub>1</sub> Y <sub>2</sub>	0	100	5.7	0.80	0	80	4.56	0	8000	0	0	456	0.020821	0.0166568
X <sub>1</sub> Y <sub>3</sub>	0	200	4.7	0.85	0	170	3.995	0	34000	0	0	799	0.048644	0.0413477
X <sub>1</sub> Y <sub>4</sub>	0	300	4.0	1.20	0	360	4.8	0	108000	0	0	1440	0.073468	0.0881613
X <sub>1</sub> Y <sub>5</sub>	0	400	3.4	1.20	0	480	4.08	0	192000	0	0	1632	0.097291	0.1167494
X <sub>1</sub> Y <sub>6</sub>	0	500	2.7	0.80	0	400	2.16	0	200000	0	0	1080	0.122115	0.0976916
X <sub>2</sub> Y <sub>1</sub>	100	0	6.1	1.00	100	0	6.1	10000	0	0	610	0	-0.01604	-0.016037
X <sub>2</sub> Y <sub>2</sub>	100	100	5.4	1.00	100	100	5.4	10000	10000	10000	540	540	0.008787	0.0087865
X <sub>2</sub> Y <sub>3</sub>	100	200	4.4	1.00	100	200	4.4	10000	40000	20000	440	880	0.03661	0.0366099
X <sub>2</sub> Y <sub>4</sub>	100	300	3.8	1.00	100	300	3.8	10000	90000	30000	380	1140	0.060433	0.0604333
X <sub>2</sub> Y <sub>5</sub>	100	400	3.1	1.00	100	400	3.1	10000	160000	40000	310	1240	0.085257	0.0852567
X <sub>2</sub> Y <sub>6</sub>	100	500	2.2	1.00	100	500	2.2	10000	250000	50000	220	1100	0.11208	0.1120801
X <sub>2</sub> Y <sub>7</sub>	100	600	1.5	1.35	135	810	2.025	13500	486000	81000	202.5	1215	0.136903	0.1848197
X <sub>2</sub> Y <sub>8</sub>	100	700	0.7	0.80	80	560	0.56	8000	392000	56000	56	392	0.162727	0.1301815
X <sub>3</sub> Y <sub>1</sub>	200	0	6.7	1.00	200	0	6.7	40000	0	0	1340	0	-0.03707	-0.037071
X <sub>3</sub> Y <sub>2</sub>	200	100	5.9	1.00	200	100	5.9	40000	10000	20000	1180	590	-0.01125	-0.011248
X <sub>3</sub> Y <sub>3</sub>	200	200	5.0	1.00	200	200	5	40000	40000	40000	1000	1000	0.015575	0.0155755
X <sub>3</sub> Y <sub>4</sub>	200	300	4.2	1.00	200	300	4.2	40000	90000	60000	840	1260	0.041399	0.0413989
X <sub>3</sub> Y <sub>5</sub>	200	400	3.5	1.00	200	400	3.5	40000	160000	80000	700	1400	0.066222	0.0662223
X <sub>3</sub> Y <sub>6</sub>	200	500	3.2	1.00	200	500	3.2	40000	250000	100000	640	1600	0.087046	0.0870457
X <sub>3</sub> Y <sub>7</sub>	200	600	2.0	1.00	200	600	2	40000	360000	120000	400	1200	0.116869	0.1168691
X <sub>3</sub> Y <sub>8</sub>	200	700	1.2	1.20	240	840	1.44	48000	588000	168000	288	1008	0.142692	0.1712309
X <sub>4</sub> Y <sub>1</sub>	300	0	6.7	0.55	165	0	3.685	49500	0	0	1105.5	0	-0.05211	-0.028658
X <sub>4</sub> Y <sub>2</sub>	300	100	6.0	0.80	240	80	4.8	72000	8000	24000	1440	480	-0.02728	-0.021826
X <sub>4</sub> Y <sub>3</sub>	300	200	5.4	1.40	420	280	7.56	126000	56000	84000	2268	1512	-0.00346	-0.004843
X <sub>4</sub> Y <sub>4</sub>	300	300	4.4	1.00	300	300	4.4	90000	90000	90000	1320	1320	0.024364	0.0243644
X <sub>4</sub> Y <sub>5</sub>	300	400	3.4	1.00	300	400	3.4	90000	160000	120000	1020	1360	0.052188	0.0521878
X <sub>4</sub> Y <sub>6</sub>	300	500	2.6	1.00	300	500	2.6	90000	250000	150000	780	1300	0.078011	0.0780112
X <sub>4</sub> Y <sub>7</sub>	300	600	1.6	1.00	300	600	1.6	90000	360000	180000	480	960	0.105835	0.1058346
X <sub>4</sub> Y <sub>8</sub>	300	700	0.7	1.25	375	875	0.875	112500	612500	262500	262.5	612.5	0.132658	0.1658225
X <sub>5</sub> Y <sub>4</sub>	400	300	4.2	1.00	400	300	4.2	160000	90000	120000	1680	1260	0.01133	0.01133
X <sub>5</sub> Y <sub>5</sub>	400	400	3.6	1.00	400	400	3.6	160000	160000	160000	1440	1440	0.035153	0.0351534
X <sub>5</sub> Y <sub>6</sub>	400	500	2.4	1.00	400	500	2.4	160000	250000	200000	960	1200	0.064977	0.0649768
X <sub>5</sub> Y <sub>7</sub>	400	600	1.8	1.00	400	600	1.8	160000	360000	240000	720	1080	0.0888	0.0888002
X <sub>5</sub> Y <sub>8</sub>	400	700	1.0	1.25	500	875	1.25	200000	612500	350000	500	875	0.114624	0.1432795
X <sub>6</sub> Y <sub>4</sub>	500	300	3.9	1.30	650	390	5.07	325000	117000	195000	2535	1521	-0.0007	-0.000916
X <sub>6</sub> Y <sub>5</sub>	500	400	3.2	1.00	500	400	3.2	250000	160000	200000	1600	1280	0.024119	0.024119
X <sub>6</sub> Y <sub>6</sub>	500	500	2.3	1.00	500	500	2.3	250000	250000	250000	1150	1150	0.050942	0.0509424
X <sub>6</sub> Y <sub>7</sub>	500	600	1.7	1.00	500	600	1.7	250000	360000	300000	850	1020	0.074766	0.0747658
X <sub>6</sub> Y <sub>8</sub>	500	700	1.0	1.12	560	784	1.12	280000	548800	392000	560	784	0.099589	0.1115399
X <sub>7</sub> Y <sub>4</sub>	600	300	3.8	0.75	450	225	2.85	270000	67500	135000	1710	855	-0.01474	-0.011054
X <sub>7</sub> Y <sub>5</sub>	600	400	2.9	1.10	660	440	3.19	396000	176000	264000	1914	1276	0.012085	0.013293
X <sub>7</sub> Y <sub>6</sub>	600	500	2.2	1.30	780	650	2.86	468000	325000	390000	1716	1430	0.036908	0.0479803
X <sub>7</sub> Y <sub>7</sub>	600	600	1.5	1.00	600	600	1.5	360000	360000	360000	900	900	0.061731	0.0617313
X <sub>7</sub> Y <sub>8</sub>	600	700	0.9	0.55	330	385	0.495	198000	269500	231000	297	346.5	0.085555	0.0470551
			153.2	45.22	12485	17984	149.865	5016500	9110800	5572500	36354.5	43934	2.419926	2.54275
H														5.9997554
ix														0.0150344
iy														-0.017823
a	[p] H + [p x] i x + [p y] i y - [p z] = 0													-11.38712
b	[p x] H + [p x x] i x + [p x y] i y - [p x z] = 0													14651.803
c	[p y] H + [p y x] i x + [p y y] i y - [p y z] = 0													-14640.42
d														-0.000001

The traditional least squares method for earthwork optimization can be solved by determinants and Cramer’s Rule. These methods involve manual calculation, which is time consuming and also difficult to program. The method presented in this paper uses an alternative way to solve the linear equations. First, based on the

traditional Grid Cell Methods, the grid cells are created in certain intervals, e.g. every 20m. Then the average existing surface elevation in each cell is extracted from the 3D model. The information is then transferred to an Excel file. Next, the standard linear programming model is created from Excel, and the total number of columns based on the amount of variables is inputted into the model. The variables  $i$  and  $j$  account for  $2n$  columns and the variable  $h$  accounts for 4 columns. The total number of rows is based on how many small cells are in the site layout. Ideally, the cut and fill design should consider more conditions such as quality requirements, and topological, geological, site, and weather conditions. Lastly, the cut and fill volume can be calculated by elevation comparison between the existing surface and the design surface. After these steps, the highest point and the average grade slope line are determined. In this case, as Table 4 shows, the result is that the highest elevation will be on the left-bottom corner with elevation 5.99m and the x axis's slope is 1.5% and y axis's slope is 1.7%. The new method brings a more user-friendly, comprehensive and integrated earthwork design process. To move the highest point coordinate, there are almost an infinite number of feasible grades the designer can choose from, all of which satisfy the geometric specifications of the site.

The optimization objective for this new method is to create an easy way to obtain the site grading design with minimum earthwork. As the results in Table 3 and Table 4 show, the objective function  $\sum$  is much improved from the original least squares model to the new least squares model.

The new approach can also be solved manually. Instead of using Cramer's Rule, the following sample shows how to do a manual calculation by using the Gauss-Jordan Elimination Method to solve the group of linear equations.

36	37	38	39	40	41	42	
	2.76	2.22	2.10	2.09	1.45	1.10	0.92
29	30	31	32	33	34	35	
	3.78	3.38	2.99	2.99	2.42	1.86	1.96
22	23	24	25	26	27	28	
	4.57	4.51	4.25	3.68	3.02	2.62	2.42
15	16	17	18	19	20	21	
	5.37	5.57	5.20	4.86	3.93	3.39	2.95
8	9	10	11	12	13	14	
	6.28	6.36	5.78	4.87	4.16	3.41	3.14
1	2	3	4	5	6	7	
	6.87	6.60	6.09	5.42	4.45	3.89	3.17

**Figure 4-27 Optimization model using least squares method**

This site has total 42 grid cells. The elevation on each corner has been identified. The average elevation for each cell will be calculated from the average of four corners' elevation. The existing ground basically slope from lower left corner to upper right corner. To minimize the earthwork, the design finished grade set the lower left corner as highest elevation as well. The design finished grading is also sloped from lower left corner to upper right corner.

No.	X	Y	Z	P	PX	PY	PZ	PXX	PYY	PXY	PXZ	PYZ	h	Ph
1	0	0	6.87	0.25	0	0	1.72	0	0	0	0	0	0.17	0.0425
2	0	40	6.60	0.5	0	20	3.30	0	800	0	0	132	-0.0359	-0.0179
3	0	80	6.09	0.5	0	40	3.05	0	3200	0	0	243.6	-0.0018	-0.0009
4	0	120	5.42	0.5	0	60	2.71	0	7200	0	0	325.2	0.1923	0.0962
5	0	160	4.45	0.5	0	80	2.23	0	12800	0	0	356	0.6864	0.3432
6	0	200	3.89	0.5	0	100	1.95	0	20000	0	0	389	0.7705	0.3853
7	0	240	3.17	0.25	0	60	0.79	0	14400	0	0	190.2	1.0146	0.2537
8	40	0	6.28	0.5	20	0	3.14	800	0	0	125.6	0	0.0561	0.028
9	40	40	6.36	1	40	40	6.36	1600	1600	1600	254.4	254.4	-0.4998	-0.4998
10	40	80	5.78	1	40	80	5.78	1600	6400	3200	231.2	462.4	-0.3957	-0.3957
11	40	120	4.87	1	40	120	4.87	1600	14400	4800	194.8	584.4	0.0384	0.0384
12	40	160	4.16	1	40	160	4.16	1600	25600	6400	166.4	665.6	0.2725	0.2725
13	40	200	3.41	1	40	200	3.41	1600	40000	8000	136.4	682	0.5466	0.5466
14	40	240	3.14	0.5	20	120	1.57	800	28800	4800	62.8	376.8	0.3407	0.1704
15	80	0	5.37	0.5	40	0	2.69	3200	0	0	214.8	0	0.2622	0.1311
16	80	40	5.57	1	80	40	5.57	6400	1600	3200	445.6	222.8	-0.4137	-0.4137
17	80	80	5.20	1	80	80	5.20	6400	6400	6400	416	416	-0.5196	-0.5196
18	80	120	4.86	1	80	120	4.86	6400	14400	9600	388.8	583.2	-0.6555	-0.6555
19	80	160	3.93	1	80	160	3.93	6400	25600	12800	314.4	628.8	-0.2014	-0.2014
20	80	200	3.39	1	80	200	3.39	6400	40000	16000	271.2	678	-0.1373	-0.1373
21	80	240	2.95	0.5	40	120	1.48	3200	28800	9600	118	354	-0.1732	-0.0866
22	120	0	4.57	0.5	60	0	2.29	7200	0	0	274.2	0	0.3583	0.1791
23	120	40	4.51	1	120	40	4.51	14400	1600	4800	541.2	180.4	-0.0576	-0.0576
24	120	80	4.25	1	120	80	4.25	14400	6400	9600	510	340	-0.2735	-0.2735
25	120	120	3.68	1	120	120	3.68	14400	14400	14400	441.6	441.6	-0.1794	-0.1794
26	120	160	3.02	1	120	160	3.02	14400	25600	19200	362.4	483.2	0.0047	0.0047
27	120	200	2.62	1	120	200	2.62	14400	40000	24000	314.4	524	-0.0712	-0.0712
28	120	240	2.42	0.5	60	120	1.21	7200	28800	14400	145.2	290.4	-0.3471	-0.1736
29	160	0	3.78	0.5	80	0	1.89	12800	0	0	302.4	0	0.4443	0.2222
30	160	40	3.38	1	160	40	3.38	25600	1600	6400	540.8	135.2	0.3684	0.3684
31	160	80	2.99	1	160	80	2.99	25600	6400	12800	478.4	239.2	0.2825	0.2825
32	160	120	2.99	1	160	120	2.99	25600	14400	19200	478.4	358.8	-0.1934	-0.1934
33	160	160	2.42	1	160	160	2.42	25600	25600	25600	387.2	387.2	-0.0993	-0.0993
34	160	200	1.86	1	160	200	1.86	25600	40000	32000	297.6	372	-0.0151	-0.0151
35	160	240	1.96	0.5	80	120	0.98	12800	28800	19200	156.8	235.2	-0.591	-0.2955
36	200	0	2.76	0.25	50	0	0.69	10000	0	0	138	0	0.7604	0.1901
37	200	40	2.22	0.5	100	20	1.11	20000	800	4000	222	44.4	0.8245	0.4123
38	200	80	2.10	0.5	100	40	1.05	20000	3200	8000	210	84	0.4686	0.2343
39	200	120	2.09	0.5	100	60	1.05	20000	7200	12000	209	125.4	0.0027	0.0014
40	200	160	1.45	0.5	100	80	0.73	20000	12800	16000	145	116	0.1668	0.0834
41	200	200	1.10	0.5	100	100	0.55	20000	20000	20000	110	110	0.0409	0.0205
42	200	240	0.92	0.25	50	60	0.23	10000	14400	12000	46	55.2	-0.255	-0.0637
30	3000	3600	115.62	408000	584000	360000	9651	12067						-0.0444

H  
ix  
iy  
a  
b  
c  
d

[p] H + [p x] i x + [p y] i y - [p z] =0  
[p x] H + [p x x] i x + [p x y] i y - [p x z] =0  
[p y] H + [p y x] i x + [p y y] i y - [p y z] =0

7.04
-0.0176
-0.0119
-0.0444
5.9838
-5.9394
0.000001

**Figure 4-28 Optimization model using least squares method**

For the manual method (use the standard Gauss-Jordan elimination of ordinary

linear algebra) show in Table 5

Table 5 Manual method to solve linear group equation

Item	Calculation	H	ix	iy	Z	Check
1	$[P]H + [PX]ix + [PY]iy - [PZ] = 0$	$[p]H = 30H$	$[PX]ix = 3000ix$	$[PY]iy = 3600iy$	$-[PZ] = -115.58$	$= 0$
2	$[PX]H + [PXX]ix + [PXY]iy - [PYZ] = 0$	$[PX]H = 3000H$	$[PXX]ix = 40820ix$	$[PXY]iy = 3600iy$	$-[PYZ] = -9651.4$	$= 0$
3	$[PY]H + [PXY]ix + [PYY]iy - [PYZ] = 0$	$[PY]H = 3600H$	$[PXY]ix = 36000ix$	$[PYY]iy = 5840iy$	$-[PYZ] = -12066.6$	$= 0$
4	Item 1 $\times$ 100	3000H	30000ix	36000iy	-11558	$= 0$
5	Item 2 - item 4	0	10820ix	0	1906.6	$= 0$
6	Solve item 5		ix =			-0.0176
7	Item 1 $\times$ 120	3600H	36000ix	43200iy	-13869.6	$= 0$
8	Item 3 - item 7	0	0	15200iy	+1803	$= 0$
9	Solve item 9			iy =		-0.0119
10	Bring item 6 & 9 to item 1	30H	-52.80	-42.84	-115.58	$= 0$
11	Solve item 10	H =				7.04

As the result, the manual calculation cross checks the Solver's optimization solution. It should be noted that Solver's solution is usually not unique. Several runs of the Solver are recommended.

As discussed in 4.3.1, there are basically five different types of site grading for heavy industry. The calculation of h will be different for each as well.

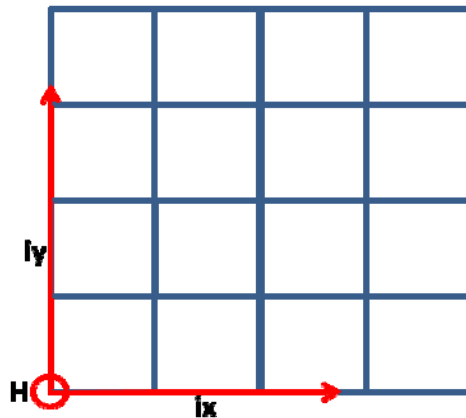
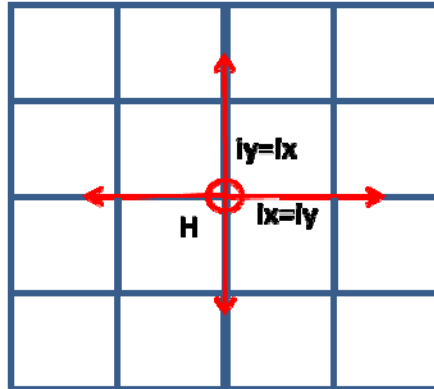


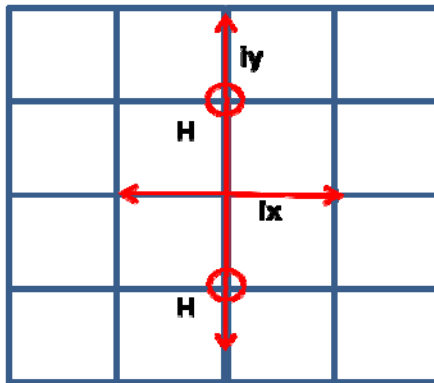
Figure 4-29 The highest point at the site corner

As the highest point at the bottom left corner with the design height  $H$ , the site slope runs down with a slope  $x$  along  $x$  axis and with a slope  $y$  along  $y$  axis. In this type,  $h = H - x \times ix - y \times iy$



**Figure 4-30 The highest point at the site centre**

As the highest point in the center with the design height  $H$ , the site slope runs down to four corners. In this type,  $h = H - x \times ix - y \times iy$

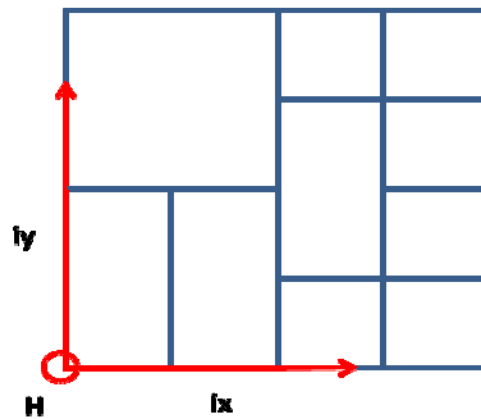


**Figure 4-31 The highest ridge line at site centre**

In this type,  $h = \frac{1}{2} (H - x \times ix - y \times iy + H - x \times ix - y \times iy)$

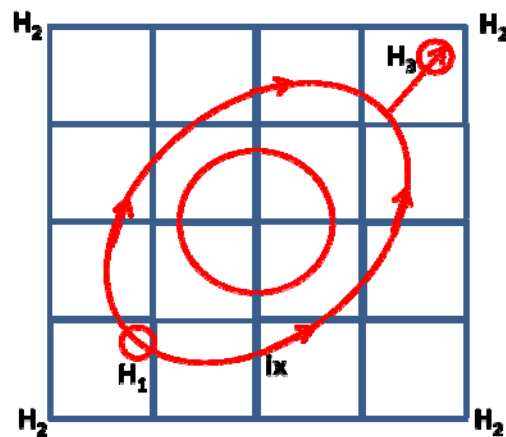
In the traditional least squares optimization model, there are three variables involved:  $h$ ,  $i$ , and  $j$ .  $h$  represents the highest elevation on site,  $i$  represents the slope along  $x$  axis and  $j$  represents the slope along  $y$  axis. For this kind of site, the highest elevation is set up as the ridge line. From there, the elevation splits in four different directions. As such, one site is divided into four pieces. To achieve this

goal, more variables and certain constraints are needed. The variables for this kind of site grading should be  $h$ ,  $i_1$ ,  $i_2$ ,  $i_3$  and  $i_4$ .  $i_1$  to  $i_4$  represents four different slopes in each directions. Before calculating a cell's design elevation, the program must first check which of the four pieces the cell belongs to (to do this, the four corners of the site and ridge line's coordinates need to be entered). Then the program uses one of  $i_1$ ,  $i_2$ ,  $i_3$  or  $i_4$  to determine a cell's design elevation. The last step is to calculate the cut/fill volume for each cell.



**Figure 4-32 The cell's size is varied**

In this type,  $h = H - x \times ix - y \times iy$



**Figure 4-33 the grading along a slope line**

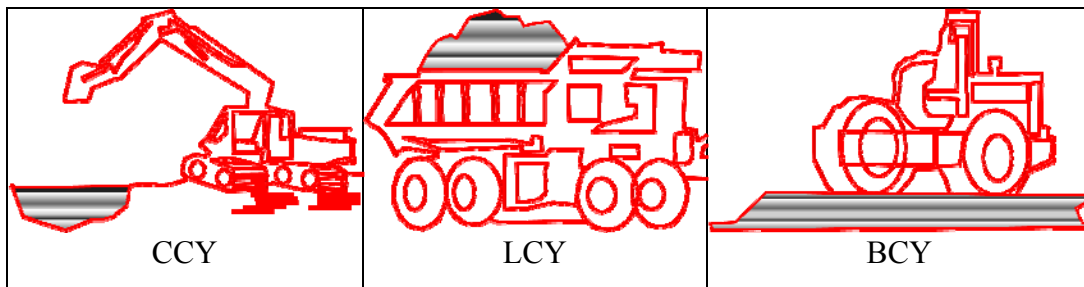
In this type,  $h_3$  (the lowest point's elevation for the whole site) can be manually retrieved from the 3D model.

## Chapter 5 Earthwork Simulation

### 5.1 Earthwork Construction Process and Consideration

#### 5.1.1 Earthwork construction consideration

Traditional earthwork construction can be divided into three sections: cutting, hauling-dumping and filling. Generally speaking, the earth will be loose once it has been excavated. Once the earth is dumped for filling, it will shrink after compaction. These volume changes need to be considered in cost estimation. The following figures and equations show the schema of volume change. The variable and parameters will be defined as they appear.



**Figure 5-1 Soil volume change: bank volume, loose volume and compacted volume**

Notes: Soil volume change: Bank, (bcm)(bcy), Loose, (lcm)(lcy), compacted (ccm)(ccy)



$$V_b = \frac{V_c}{SF} \quad \text{Eq. 5-1}$$

$$V_b = \frac{V_c}{1-s_h} \quad \text{Eq. 5-2}$$

$$V_b = \frac{w_c \times V_c}{w_b} \quad \text{Eq. 5-3}$$

$$SF = \frac{w_b}{w_c} \quad \text{Eq. 5-4}$$

Where

SF =shrinkage factor       $V_c$  =compacted volume

$V_b$  =bank volume       $w_c$  =soil compacted density

$w_b$  =soil bank density

At the same time, Rolling Resistance (RR) and Grade Resistance/Assistance (GR/GA) need to be considered. The basic figures and equations are follows:

$$F_{GR} = W \tan \theta = W \frac{G}{100} \text{ tons} \quad \text{Eq. 5-5}$$

$$FR = (RR)W \quad (20G)W \quad \text{Eq. 5-6}$$

$$TR = RR + GR$$

Eq. 5-7

$$RR = (40 + [30 \times TP]) \times GVW$$

Eq. 5-8

Where

$F_R$  =Force Resistance

TP =Tire Penetration, inches (may be different for haul and return)

GVW =Gross Vehicle Weight, tons

$$T_{travel} = \frac{D}{S \times F_{idle} \times F_{efficiency}} \quad \text{Eq.5-9}$$

Where

D =Distance      S =Truck Speed

$F_{idle}$  =Factor of equipment idle       $F_{efficiency}$  =Factor of equipment efficiency

The standard truck production rate can be calculated as the following equation

$$R = \frac{C}{T} \quad \text{Eq. 5-10}$$

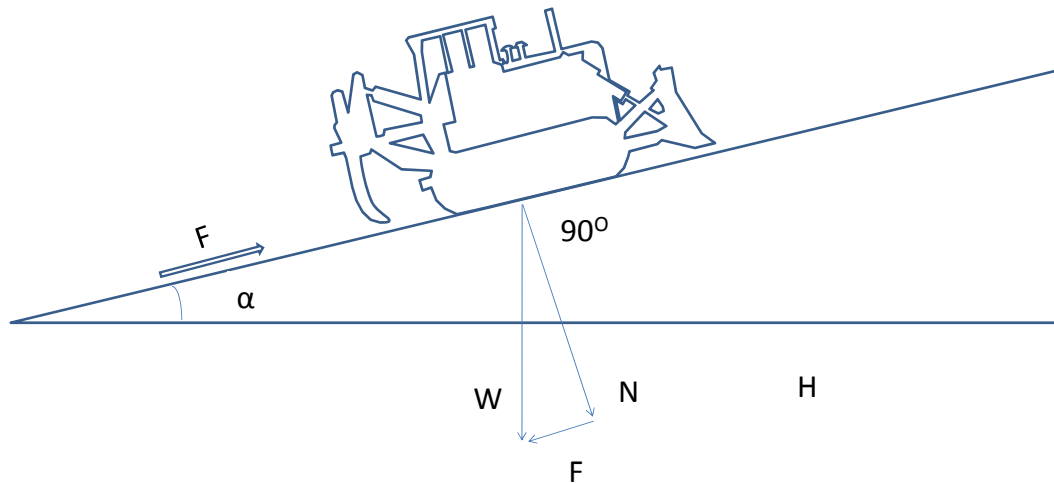
Where

R =Production Rate      C =Cycle capacity

$T$  = Units of time per cycle of operation

The total actual cycle time,  $T_t$  which is the total operation time of the dump truck can be obtained by summing up the actual time of traveling, loading and dumping, as per the following equation

$$T_t = T_{\text{traveling}} + T_{\text{loading}} + T_{\text{dumping}} + T_{\text{returning}} \quad \text{Eq. 5-11}$$

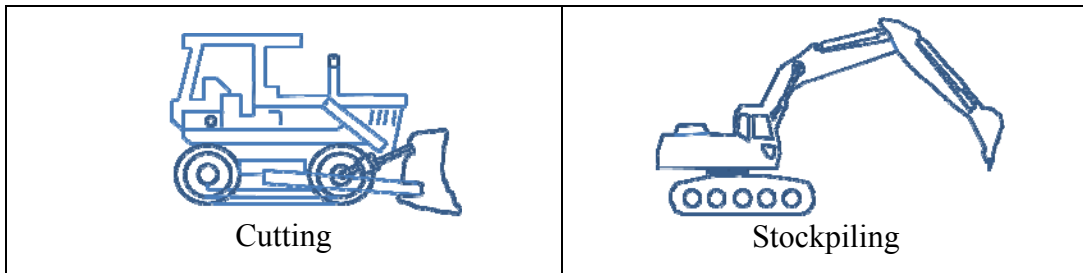


**Figure 5-2 Grade resistance**

### 5.1.2 Earthwork construction cycles

The work cycle consists of repetitive operations for the equipment to undertake the earthwork. The primary work cycle is the earthmoving operation (fleet operation), which includes loading, hauling, dumping, and returning for another load. The secondary work cycle occurs in the cut area, which includes cutting and stockpiling. Another secondary work cycle occurs in the fill (embankment) area and includes spreading, watering and compacting. Each machine has a work cycle that depends on the other equipment's productivity. The most convenient common denominator for analyzing a work cycle is the cycle time (CT). This is true for the economic analysis of an earthwork operation, because the cost of manpower and equipment are mainly time related. Earthwork operations need to meet requirements of location, elevation, density and moisture content.

The cut area work cycle can be further divided into two work cycles. And the first cycle in cut area can be divided into two steps: Cutting and Stockpiling



**Figure 5-3 Machinery used for Cutting and stockpiling**

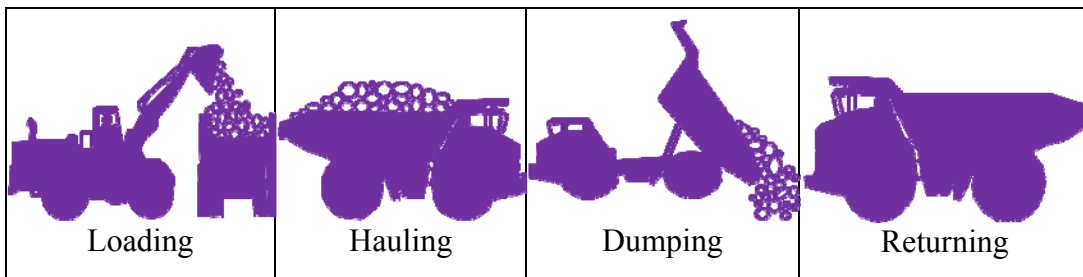
**Step1 Surface digging and cutting**

After the clearing, grubbing, and topsoil removal have been completed, dozers work in the cutting area to push the unnecessary earth to a certain place for the next loading process. Digging and cutting are the first step in removing materials from its natural location. The materials must be in a manageable form and size. They must fit into the bucket or dipper of excavating equipment and the bowl or dump body of hauling equipment.

**Step 2 Stockpiling**

The cutting material will be piled up for further loading process.

The second cycle connecting cut and fill areas is the truck cycle which can be divided in four steps: Loading, Hauling, Dumping and Returning



**Figure 5-4 Truck cycle**

**Step1 Loading**

Following digging and cutting, the material is moved from its original location

and deposited at the temporary storage site. The excavator sits at the loading area and loads the earth onto trucks.

#### Step2 Hauling

The Truck travels from the loading area to the dumping area. The haul time (HT) is the time it takes to haul the material from the loading point to the dumping point. It varies with the haul distance, the condition of the haul route, the power of the hauling equipment.

#### Step3 Dumping

The Truck then dumps the earth at the dumping area. The earth will be spread to a uniform thickness and compacted by other equipment. The dumping time (DT) depends on the condition of the material, that is, whether it is free flowing or very sticky such as moisture saturated clay. Dumping time is also influenced by the kind of equipment and the method of dumping. Is it all dumped in one spot? Is it roughly spread? Is it carefully spread, or is it placed in a windrow, that is, a ridge of material? In any case the dumping time is only a small fraction of the total cycle time.

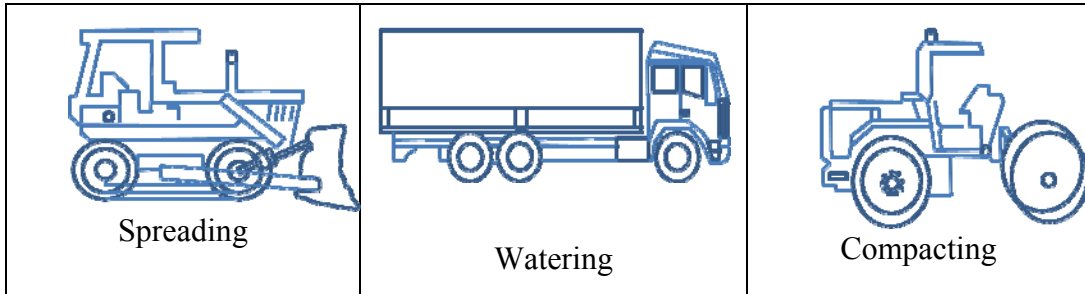
#### Step4 Returning

The truck returns to the loading area. The return distance is likely to be similar to the haul distance. However, the profile of the haul road will change and the travel speed of the empty unit may be quite different from that of the loaded machine. Therefore, the return time (RT) of the empty machine must also be considered. The returning haul unit may need to join a waiting line before it can be loaded again, and it may have to wait for assistance to be spotted in a position where it can be loaded. If this time is considered at all, it is generally assumed to be a fixed time known as spotting time (ST).

$$CT = LT + HT + DT + RT + ST$$

Eq. 5-12

The cycle in the fill area can be divided in three steps: Spreading, Watering and Compacting



**Figure 5-5 Machinery used in the filling area process**

**Step1 Spreading**

Dozer or spreader spreads the dump material in the fill area in a uniform layer, usually every 150mm or 200mm lift per cycle.

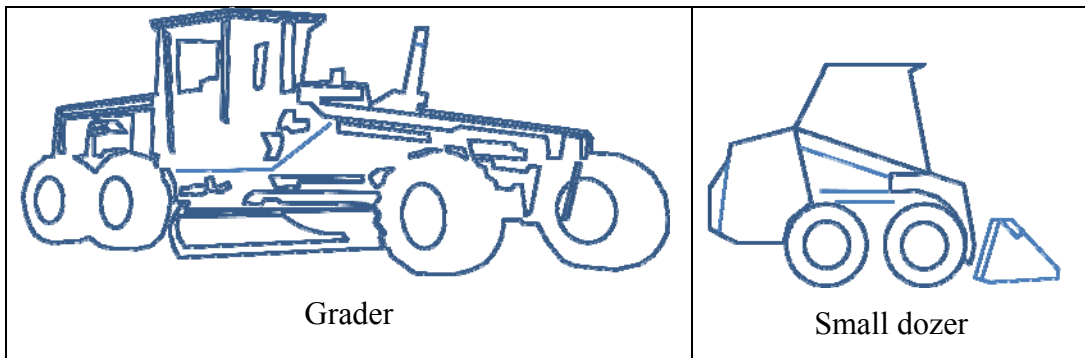
**Step2 Watering**

The water truck then waters the soil to archive the soil optimal moisture content.

**Step3 Compacting**

A compactor compacts the soil in about 150mm or 200mm per lifts to the final grade and specified density.

During these three processes cycles, other equipment being is used as well, such as graders and small dozers.



### **Figure 5-6 Grader and small dozer**

Although the grader is not in the process loop, it keeps the haul roads smooth and equipment running. If haul roads are well maintained, rolling resistance is less and production improves. Good haul roads require graders and water trucks. The small dozer or cat can reach confined spaces where big equipment cannot reach or it can perform side works.

## ***5.2 Earthwork Construction Simulation***

In the current earthwork planning practice, one of the most important tasks is to optimize the mass-haul balance, as either borrowing the material from outside or transporting the surplus material to a landfill site is expensive, especially for borrowing the material from outside. At the same time, both cost and time involved in the load-haul process can be reduced by optimizing the transport direction and routes. For these reasons, an optimization process will be integrated to find the optimal allocation of the earth mass satisfying the constraints described above. For the simulation section, simulation modeling is applied to enhance flexibility in the planning of earthwork production activities. Further earthwork specific simulation components, such as fill, watering and compacting processes are also taken into consideration.

### **5.2.1 Mass transportation problem**

The mass transportation problem is one of the first formalized operation research problems, which is named Monge-Kantorovich Problem. This problem, originally presented by Monge in 1781 in *Mémoire sur la théorie des déblais et des remblais* (Monge. G. 1781), was further updated by Kantorovich in 1942 (Kantorovich L.V. 1948) and formalized by Dantzig in 1949 (Dantzig 1949). The problem consists of a set of resources traveling between blocks located on a linear axis. Starting from an initial altimetric profile of the construction site, earthwork involves moving earth from “excavations” to dump it into “fills.” The Monge-Kantorovich problem can be described as the following equation.

$$W(\psi) = \int_R \int_R r(x, y)\psi(de, de') \quad \text{Eq. 5-13}$$

Assume given two mass distributions determined by additive set functions  $\phi(e)$  and  $\phi'(e)$  with  $\phi(R) = \phi'(R) = 1$ . A translocation of masses is a function  $\Psi(e, e')$  that determines the mass translocated from a set  $e$  to a set  $e'$  with  $[\Psi(e, R) = \phi(e); \Psi(R, e) = \phi'(e)]$ .  $R(x, y)$  is the distance between points  $x$  and  $y$ .

In most recent years, Ignizio (1982), Easa (1988), Moreb (1996) proposed using the linear programming to finding optimal roadway grades that minimize earthwork cost. This method is called Weighted Ground Elevation (WGE) method. The term WGE is a hypothetical center elevation where cut and fill areas are balanced within the cross section if the center of template is set onto it. The mathematical representation of WGE is shown as the following equation.

$$\sum_{i=1}^n S_C(i) = \sum_{i=1}^n S_F(i), \text{ for } y = h_w \quad \text{Eq. 5-14}$$

$h_w$       weighted ground elevation

$S_C(i)$     cut areas for WCSL in cross section

$S_{(F)}(i)$  fill areas for WCSL in cross section

$n$         number of cut areas in cross section

$m$         number of fill areas in cross section

The objective of their function that minimizes the total cost of the haul is:

$$\text{Min}Z = \sum_{i=1}^n \sum_{j=1}^n C_{ij}T_{ij} \quad \text{Eq. 5-15}$$

$n$         number of sections in the road

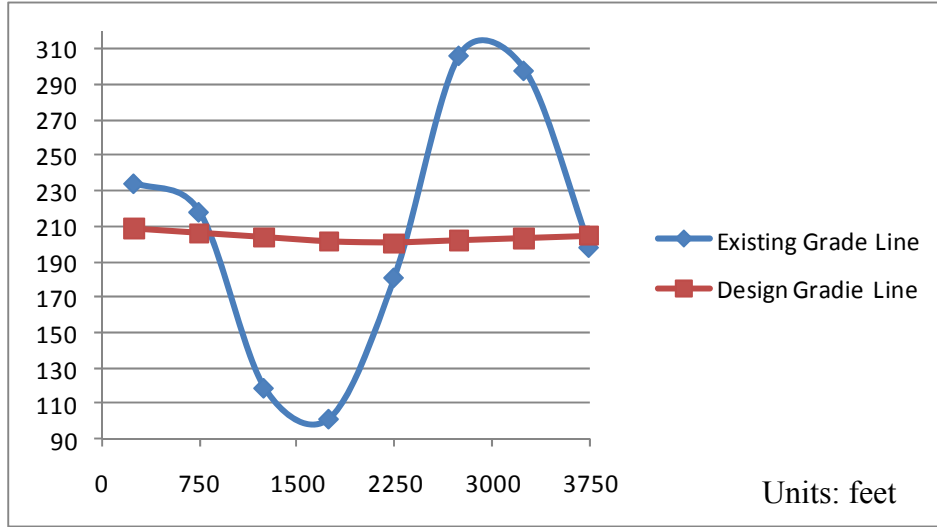
$C_{ij}$      cost of transporting one cubic unit of earth from section  $i$  to section  $j$

$T_{ij}$      number of cubic units of earth to be transported from section  $i$  to section  $j$

Easa (1988) and Moreb (1996) presented a sample as described as follows

One road is 24ft wide and 3750 ft long, which is divided in 8 sections, the horizontal coordinates  $x_i$  in feet ( $x_1=250, x_2=750, x_3=1250, x_4=1750, x_5=2250, x_6=2750, x_7=3250$  and  $x_8=3750$ ). The average heights  $h_i$  (in ft) at the various sections are ( $h_1=234.062, h_2=217.973, h_3=118.564, h_4=101.125, h_5=180.938, h_6=306.343, h_7=297.85, h_8=198.007$ ). The thickness of cuts and fills ( $u$  and  $v$  in

feet) are ( $u_1=25.3265$ ,  $u_2=11.7666$ ,  $v_3=85.1164$ ,  $v_4=100.0234$ ,  $v_5=19.5854$ ,  $u_6=104.5406$ ,  $u_7=94.7686$ ,  $v_8=6.35048$ ). Haul cost crossing one section is  $\$1.05/\text{yd}^3$ .



**Figure 5-7 Existing and design grade**

The objective function is

$$\text{Min}Z = \sum_{i=1}^8 \sum_{j=1}^8 C_{ij}T_{ij} \quad \text{Eq. 5-16}$$

$$A = 24\text{ft} \times 500\text{ft} = 12000 \text{ ft}^2 \quad \text{Eq. 5-17}$$

$$12000u_1 - 12000v_1 = \sum_{j=2}^8 T_{1j} - \sum_{j=2}^8 T_{j1} + T_{1d} - T_{b1} \quad \text{Eq. 5-18}$$

$$12000u_2 - 12000v_2 = \sum_{j=2}^8 T_{2j} - \sum_{j=2}^8 T_{j2} + T_{2d} - T_{b2} \quad \text{Eq. 5-19}$$

$$12000u_3 - 12000v_3 = \sum_{j=2}^8 T_{3j} - \sum_{j=2}^8 T_{j3} + T_{3d} - T_{b3} \quad \text{Eq. 5-20}$$

$$12000u_4 - 12000v_4 = \sum_{j=2}^8 T_{4j} - \sum_{j=2}^8 T_{j4} + T_{4d} - T_{b4} \quad \text{Eq. 5-21}$$

$$12000u_5 - 12000v_5 = \sum_{j=2}^8 T_{5j} - \sum_{j=2}^8 T_{j5} + T_{5d} - T_{b5} \quad \text{Eq. 5-22}$$

$$12000u_6 - 12000v_6 = \sum_{j=2}^8 T_{6j} - \sum_{j=2}^8 T_{j6} + T_{6d} - T_{b6} \quad \text{Eq. 5-23}$$

$$12000u_7 - 12000v_7 = \sum_{j=2}^8 T_{7j} - \sum_{j=2}^8 T_{j7} + T_{7d} - T_{b7} \quad \text{Eq. 5-24}$$

$$12000u_8 - 12000v_8 = \sum_{j=2}^8 T_{8j} - \sum_{j=2}^8 T_{j8} + T_{8d} - T_{b8} \quad \text{Eq. 5-25}$$

The quantity of earth to be moved from one section to another:

$$T_{1d}=11,256.23 \text{ yd}^3 \quad T_{73}=30,592.30 \text{ yd}^3$$

$$T_{23}=5,229.58 \text{ yd}^3 \quad T_{75}=8,704.62 \text{ yd}^3$$



$$T_{63}=2,007.64 \text{ yd}^3 \quad T_{78}=2,822.44 \text{ yd}^3$$
$$T_{64}=44,454.84 \text{ yd}^3$$

The quantity of soil excavated and embanked at a section is equal to the quantity transported from this section minus the quantity that is transported into the section

The excavated earth has swelling potential once it has been excavated. And the excavated earth can rarely be used as 100% as a fill, because the entire cut volumes are not homogeneous and some of this volume (particularly topsoil) is not suitable as fill material and there may be loss of material during transportation from cut to fill. Goktepe (2004) suggested adding two more factors,  $P_S$  (Potential swell) and  $P_A$  (Appropriateness percentage) in the calculation consideration.

Kataria et al., (2005) proposed the use of the ant colony optimization to do the earthwork allocation for road project. Karimi et al., (2007) suggested using a fuzzy optimization model to do the earthwork allocation.

However, since the earthwork occurs only along the linear axis for road earthwork construction, the problem can be solved with a group of equations. In other words, this method only works for road earthwork construction. To solve the site grading earthwork construction problem, we need consider two more factors.

In the road earthwork construction the travel distance is known by comparing the chainage differences. But in the grading earthwork construction, it must be calculated. Ignizio and Moreb only presented a hand calculation method to use a simple sample to do the demonstration, since the calculation is very heavy. The calculation should be carried out by computer programming.

The objective of the earthwork relocation optimization model is to provide the minimum total fleet effort in handling the earthwork:

### Objective Function

$$\text{Min}Z = \sum_{i=1}^n \sum_{j=1}^m D(C_i F_j) \times V(C_i F_j) \quad \text{Eq. 5-26}$$

D Distance from cell  $C_i$  to cell  $F_j$

V Earthwork relocation volume from cell  $C_i$  to cell  $F_j$

### Constraints

The following constraints guarantee regardless of how excavated material is transported from a cut area to a fill area, the fill area is only to receive the material volume as needed.

$$V C_i = \sum_{n=1}^j V C_i F_j \quad \text{Eq. 5-27}$$

$$V F_j = \sum_{n=1}^i V F_j C_i \quad \text{Eq. 5-28}$$

As the object described as above, the new approach tries to use the Transportation Simplex Method to solve this problem. The basic transportation simplex method can be described as the following equation:

$$\text{Min} \sum_{i=1}^m \sum_{j=1}^n C_{ij} x_{ij} \quad \text{Eq. 5-29}$$

$$\sum_{j=1}^n x_{ij} = s_i, \forall i \quad \text{Eq. 5-30}$$

$$\sum_{i=1}^m x_{ij} = d_{ij}, \forall j \quad \text{Eq. 5-31}$$

$$x_{ij} \geq 0, \forall i, j \quad \text{Eq. 5-32}$$

### Sample of the traditional Transportation Simplex Method

There are three warehouses to supply goods to four retailers, warehouse No. 1 has 500 items of this kind of goods, warehouse No. 2 has 700 items and warehouse No. 3 has 800 items. retailer No.1 needs 400 items of this kind of goods, retailer No.2 needs 900 items, retailer No.3 needs 200 items and retailer No.4 needs 500 items. Transport one item from warehouse No.1 to retailer No.1 cost \$12. Transport one item from warehouse No.1 to retailers No.2 cost \$13, so long and so for. Assume that the total supply equals the total demand. Thus, exactly one equality constraint is redundant. At each step, the Simplex method attempts to send units along a route that is unused (non-basic) in the current BFS, while eliminating one of the routes that is currently being used (basic).

1. Start with the cell in the northwest corner cell (Northwest Corner Rule).
2. Allocate as many units as possible, consistent with the available supply and demand
3. Move one cell to right if there is remaining supply; otherwise, move one cell down.
4. Goto step2
5. Determine the shadow prices for each supply side  $u_i$  and each demand side  $v_j$  such that  $u_i + v_j = c_{ij}$  for every used cell (basic variable), that is, solving  $A_N y = c_N$ . One can always set  $v_n = 0$
6. Calculate the reduced costs (Russell's method)  $r_{ij} = c_{ij} - u_i - v_j$  for the unused cells (non-basic variable), that is, computing  $r_N = c_N - A_N y$ .  
If the reduced cost for unused cell is nonnegative, then STOP: declare OPTIMAL.
7. Select an unused cell with the most negative reduced cost. Using a chain reaction cycle, determine the maximum number of units ( $\theta$ ) that can be allocated to the cell and adjust the allocation appropriately. Update the values of the new set of used cells (BFS).
8. Goto step 5.

	R1	R2	R3	R4	supply	stage1																
W1	12	13	4	6	500					500		400				100	400	100			0	
W2	6	4	10	11	700	→				700	→					700	→				700	
W3	10	9	12	4	800					800						800					800	
demand	400	900	200	500	2000		400	900	200	500		0	900	200	500		0	800	200	500		
	400	100			0		400	100		0		400	100		0		400	100			0	
		700			0	←		700		0	←		700		0	←		700			0	
		100	200	500	0			100	200	500			100		700						800	
	0	0	0	0			0	0	0	500		0	0	200	500		0	100	200	500		
	↓ stage2-1																					
	12	13			u1		12	13		u1		12	13		u1		12	13			u1	
		4			u2	→		4		u2	→		4		u2	→		4			u2	
		9	12	4	u3			9	12	4	u3=4			9	12	4	u3=4		9	12	4	u3=4
	v1	v2	v3	v4=0			v1	v2	v3	v4=0		v1	v2	v3=8	v4=0		v1	v2=5	v3=8	v4=0		
	↓ stage2-2																					
	12	13	4	6	u1=8		12	13		u1=8		12	13		u1=8		12	13			u1	
	6	4	10	1	u2=1	←		4		u2=1	←		4		u2=1	←		4			u2=1	
	10	9	12	4	u3=4			9	12	4	u3=4			9	12	4	u3=4		9	12	4	u3=4
	v1=4	v2=5	v3=8	v4=0			v1=4	v2=5	v3=8	v4=0		v1	v2=5	v3=8	v4=0		v1	v2=5	v3=8	v4=0		
	↓ stage2-3																					
	12/0	13/0	4/-12	6/-2	u1=8		400	100(-)	(+)		0	400		100		0						
	6/3	4/0	10/3	11/12	u2=1	→		700			0	→	700			0						
	10/2	9/0	12/0	4/0	u3=4			100(+)	200(-)	500	0		200	100	500	0						
	v1=4	v2=5	v3=8	v4=0			0	0	0	0		0	0	0	0							

**Figure 5-8 Transportation simplex method solutions**

Stage 1 defines the supply chain network, Stage2-1 constructs the initial BFS, Stage2-2 determine the shadow prices and Stage2-3 calculate the reduced cost coefficients

### Terminology

**Northwest Corner rule**, the upper left-hand corner of the tableau is called northwest corner. The rule is to select the uncrossed cell closest to the northwest corner. This is the simplest rule to apply.

**Shadow price** is the terminology used in constrained optimization in economics, which is the change in the objective value of the optimal solution of an optimization problem obtained by relaxing the constraint by one unit – it is the marginal utility of relaxing the constraint, or equivalently the marginal cost of

strengthening the constraint.

**Vogel's method** looks ahead one step and constructs a penalty for not being able to assign a flow to the remaining cells in a row or column whose cost is the smallest, but instead having to pick the cell with the second smallest cost. In economic terms, the idea is to determine the opportunity cost associated with each possible assignment and then pick the cell with the greatest opportunity cost. To begin with, compute for each uncrossed row the difference between the smallest cost in the row and the second smallest cost. Do the same for uncrossed columns. Select the row or column with the greatest difference. The rule is to choose the uncrossed cell in the selected row or column with the smallest cost. When done by hand, Vogel's method is usually performed directly on the tableau. The selection of basic variables in each iteration is accompanied by crossing out of a row or column and the recalculating of differences as well as supplies and demands. The tableau becomes so messy, however, each row of the table lists the row and column differences, the basic variable assigned, the adjustment of demands and supplies, and the row or column crossed out.

**Russell's method** makes use of the reduced costs associated with cells not yet assigned. At each iteration, compute for the uncrossed rows and columns

$u_i$  = value of the largest uncrossed cost in row  $i$

$v_j$  = value of the largest uncrossed cost in column  $j$

for each uncrossed cell compute  $r_{ij} = c_{ij} - u_i - v_j$ . The rule is to choose the uncrossed cell with the largest negative value of  $r_{ij}$ .

From stage 1 to stage 2, \$1,200 dollar has been saved.

4800	1300				4800		400	
	2800					2800		
	900	2400	2000	→		1800	1200	2000
			14200					13000

**Figure 5-9 Cost saving from stage 1 to stage 2**

As it shows, if the supply warehouse changes to the cut area, the demand retailer changes to the fill area and the cost for transferring goods from a warehouse to a retailer changes to the distance from a cut spot to a fill spot. The traditional transportation simplex method can be used for earthwork construction planning optimization.

	R1	R2	R3	R4	supply			C1	C2	C3	C4	Cut
W1	12	13	4	6	500		F1	12	13	4	6	500
W2	6	4	10	11	700	→	F2	6	4	10	11	700
W3	10	9	12	4	800		F3	10	9	12	4	800
demand	400	900	200	500	2000		Fill	400	900	200	500	2000

**Figure 5-10 Apply Traditional Transportation Simplex Method to Earthmoving**

### 5.2.2 Simulation with SDESA

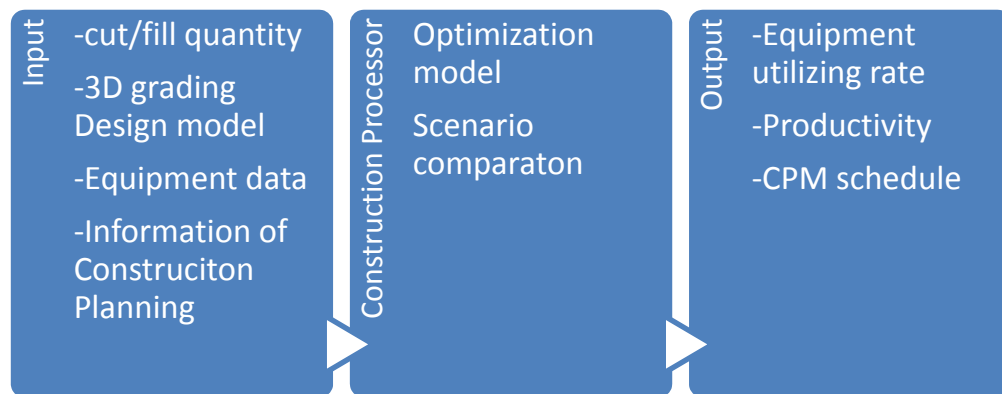
SDESA, developed By Dr. Ming Lu, is a construction management simulation tool that provides a promising alternative solution to do construction planning by predicting the future state of a real construction system based on the real life statistics and operation. At the same time, this powerful simulation tool works as an electronic realistic prototype for engineers to experiment on and, eventually, lead to productive, efficient and economical field operation. SDESA is process-interaction (PI) based modeling paradigm instead of an Activity Cycle Diagrams (ACD) based simulation tool.

SDESA characterizes construction activities into transit activities and production activities. A transit activity engages a machinery or manpower resource from certain time duration in moving a material unit from an origin location to a destination location in the site space. For example, in the transit activity of “haul one truck of dirt from cut area to fill area”, a truck moves certain amount (1 truck load) of soil from cut area to fill area. On the other hand, a production activity occurs at one relatively fixed location involving the use of manpower and machinery resources for certain time duration to place a material unit. SDESA has

also defined the disposable resources for representing either materials or signals, which are generated as intermediate products by one activity, and requested and consumed by the other activity. The disposable resources can only be utilized for one time and serve as the logical linkage between different activities and work flows.

SDESA modeling methodology is reminiscent of the resource-loaded CPM: Activities are defined with time and resource requirements identified, followed by articulation of activities into work flows according to construction technology. However, activity definition in SDESA differs from CPM by (1) highlighting activity locations; (2) specifying generation of disposable resources; and (3) adding disposable resources to resource requirements. Moreover, through associating a diamond node with the first activity of each work flow, a SDESA model specifies what type of work units (flow entities) and how many are to be handled by each work flow. The flow entity can be physical machine (e.g. truck or loader) or a certain amount of material (e.g. 10 cu.m. soil).

The proposed earthwork simulation process can be simply shown as the following figure.



**Figure 5-11 SDESA simulation process**

As shows on the above simulation process diagram, terminologies as describe as

below.

### 3D Grading Design Model

The 3D geometrical model comprises a host of graphical objects or triangle meshes representing entities to be constructed or those related directly to construction activities.

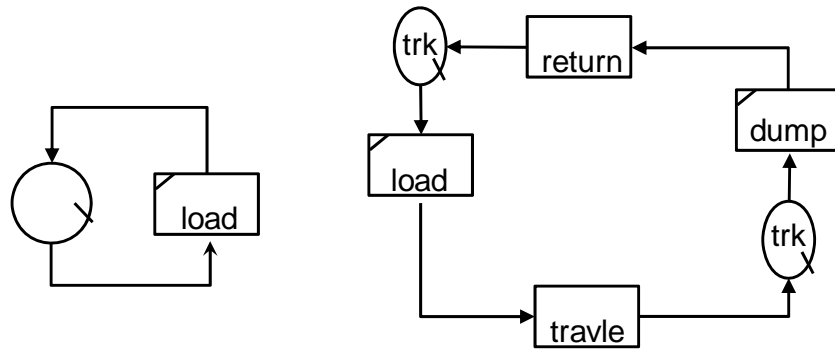
### Information of Construction Planning

Information of construction planning has data concerning the duration of individual construction activity, sequence relationships amongst various activities and symbolic site plan details.

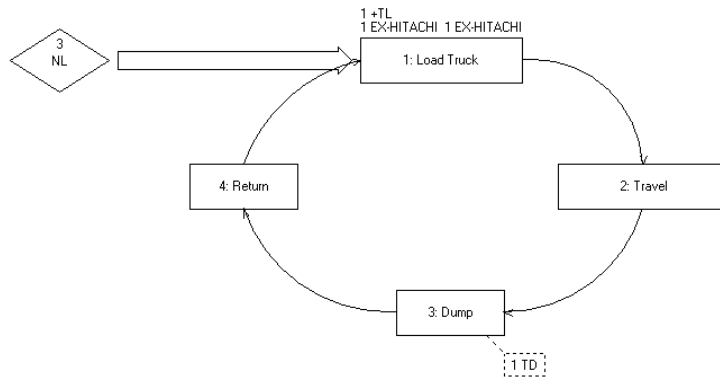
### Construction Processor

The task of construction processor is to animate simulation of activities, to evaluate the resources requirements for a specific construction activity such as labor, material, equipment, workspace, cost and to represent site facilities layout versus time dynamically.

Traditional simulation map for Load-Dump process, which does not represent the detailed operations of the loader or excavator.







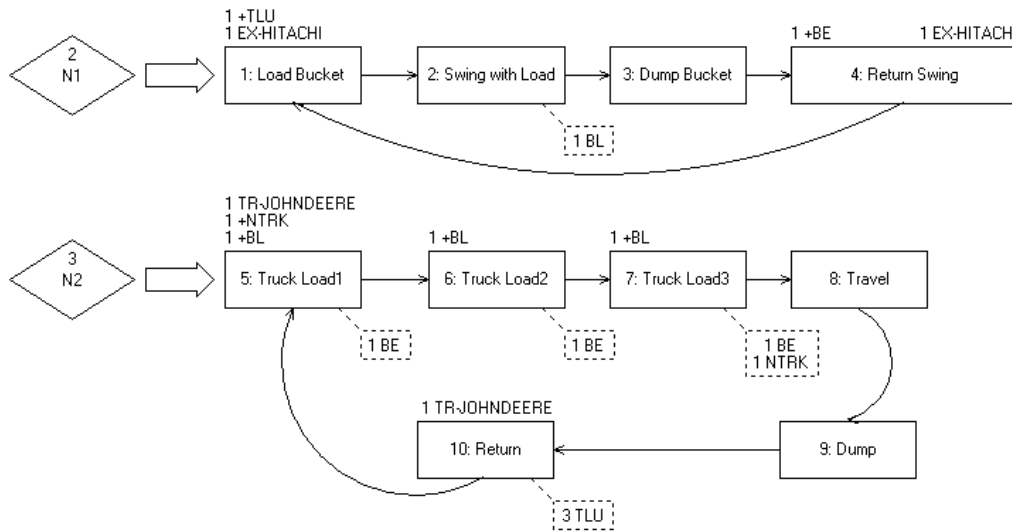
**Figure 5-12 Traditional simulation map for Load-Dump process by CYCLONE and SDESA**

When the loading time is relatively long or comparable to travel time, simplifying loader cycle modeling into resource activity cycles as shown in Figure 5-12 (Halpin and Leland 1992) is not justified. The loading activity event times are generally recorded by tracking “truck moving into loading position” and “truck moving out of loading position”; the “truck departure to travel” event concurs with the “loader swing back” event. Thus, the “loader swing back” is overlooked in the simulation model, which could build up over loader cycle repetitions. Second, the simple model only considers truck waiting before “truck moving into loading position” in tallying “unproductive” time and calculating utilization percent. But, the truck waiting during the loading process due to repetitive loader cycles are ignored, which could be significant loss of accuracy. An improved simulation technique is desired to select truck type vs. loader type by reducing or increasing the truck volume, thus fewer loading cycles are required to fill one truck load. This would improve truck utilization more effectively than simply changing truck quantities.

The newly suggested process mapping for simulating the Load-Dump process models the detailed steps in both the loader cycle and the truck cycle, as shown in Fig. 6-13. As such, the non-productive time of a truck includes not only the time for waiting for the previous truck to finish, but also waiting for “loader return

swing” and “loader load bucket”, and “loader swing with load” during the loading process.

This basic model is based on a normal dump truck (12 m<sup>3</sup> capacity) and a loader (4 m<sup>3</sup> bucket capacity). It also applies to the “giant holders” used for earthmoving in surface mining, such as 115 ton excavator and 345 ton sump truck. Therefore, three loading cycles will fill one truck. The number of loading cycle repeats depends on the volume capacities of specific trucks and loaders (or excavators).



**Figure 5-13 the new suggest simulation map by SDESA**

The new approach separates the Loader and the Truck in two different cycles and uses disposable resources to link the logically. In the loader’s process cycle, the first step is to load the bucket, then to swing and load the truck, once this step is done, generate a “BL” (short for bucket load) signal to control the start on truck loading. Then dump bucket, this step require a disposable resource “TLU” (short for truck loading unit) which is equivalent to one third of truckload quantity, then the last step for this loop is to return swing. In the truck load-dump cycle, the first step is to load the truck; this step requires one disposable resource “NTRK” and one disposable resource “BL-bucket load”. The signal “BL” is generated from loader the loop, only after loader load the material then the truck can receive that load. Since three loader’s load can fill one truck. The truck load step need to be

done for two more times. Once the truck is filled up, it will general a signal “NTRK” to allow the other truck to go to the loading position. Then the current truck goes through following steps, namely: traveling, then dumping, then returning back to the loading position. Once the truck returns, three disposable resources (3 TLU’s representing an empty truck ready for loading, each TLU being one third of the truck volume or the volume of the loader’s bucket) will be released. Then process follows to the next loop.

A trail case has been performed to show the different between the simple and complex model. Assume one earthwork project need move 60 truck load soil from one place to the other place. The trucks versus loader rate is three. That means three loader’s load will fill one truck. Loader’s load bucket, swing and, return swing time are 0.5 minus. The truck’s travel, dump and, return time are 2 minus. To run both simple and complex model, the results shows on the following chart.

	1 Truck and 1 Loader		2 Trucks and 1 Loader		3 Trucks and 1 Loader	
	Simple	Complex	Simple	Complex	Simple	Complex
Truck Total Busy Time(min.)	690	360	690	360	690	360
Truck Total Idle Time(min.)	0	150	11.5	186.5	310.5	453
Truck Utilization Rate	100.00%	70.59%	98.36%	65.87%	68.97%	44.28%
Loader Total Busy Time(min.)	330	270	330	270	330	270
Loader Total Idle Time(min.)	354	236	0	0	0	0
Loader Utilization Rate	48.25%	53.36%	100.00%	100.00%	100.00%	100.00%

The simple model is only average idle time at truck cycle. This leads to overlook the efficiency loss during the truck loading process due to truck-loader type mismatch. As the results shows, the truck utilization rate is higher than it suppose to be and the loader utilization rate is lower than it suppose to be. The complex model accounts average idle time separately from truck cycle and loader cycle.

As an activity based simulation system or ACD (activity-cycle diagrams), SDESA modeling treats earthwork construction as a material handling system, the efficiency of which dictates whether productivity and economical objectives of the whole project can be attained. Nonetheless, the interactive, complicated system environment of a construction site renders conventional site layout

planning and scheduling techniques to be inadequate in coping with materials handling system design in construction. At the meantime, the lack of an accepted practical technique for evaluating the efficiency of a chosen materials handling system design makes it difficult to choose objectively between possibilities.

This SDSEA earthwork construction model for site grading can be used in road construction earthmoving as well. The table and figure below shows a sample of rational mass diagram for road earthwork construction.

Table 6 Traditional mass diagram

TRADITIONAL MASS DIAGRAM												
ccy-bcy	11.29%											
Station (1)	End-area cut(sf) (2)	End-area fill (sf) (3)	Volume of cut (bcy) (4)	Volume of fill (ccy) (5)	Stripping cut (bcy) (6)	Stripping fill (ccy) (7)	Total cut (bcy) (8)	Total fill (ccy) (9)	Adj. fill (bcy) (10)	Algebraic sum (bcy) (11)	Mass ordinate (12)	
1	0+00	0	0									
2	0+50	0	115	0	106	0	18	0	124	138	-138	
3	1+00	0	112	0	210	0	30	0	240	267	-405	
4	2+00	0	54	0	307	0	44	0	351	391	-796	
5	2+50	64	30	59	78	0	22	59	100	111	-52	
6	3+00	120	0	170	28	26	0	144	28	31	113	
7	4+00	160	0	519	0	76	0	443	0	0	443	
8	5+00	317	0	883	0	74	0	809	0	0	809	
9	6+00	51	0	681	0	60	0	621	0	0	621	
10	6+50	46	6	90	6	21	0	69	6	7	62	
11	7+00	0	125	43	121	0	25	43	146	162	-119	
12	8+00	0	186	0	576	0	81	0	657	731	-731	
13	8+50	0	332	0	480	0	69	0	549	611	-611	

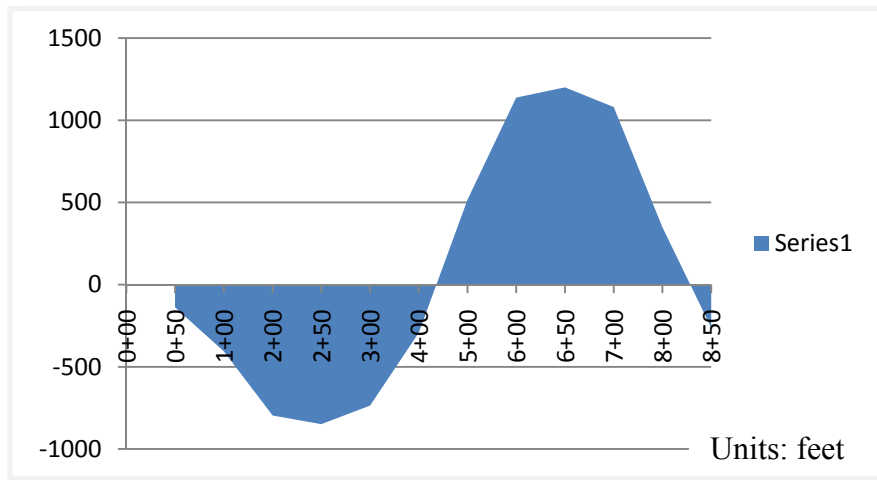


Figure 5-14 Mass Diagram

The SDSEA model given in Fig 6-13 can be applied to earthwork construction on

a road project. The difference between a road earthwork construction and a site grading earthwork construction is for a road earthwork construction, the truck load-dump cycle only happens in one direction which is along the road design chainage, but for a site grading earthwork construction, the truck load-dump cycle happens in two directions. That difference can be readily tackled with resource relocation features available in SDSEA.

Table 7 Earthmoving direction

Truck Capacity		9	cu. yard	
Loader Capacity		3	cu. yard	
		bcy	truck load	bucket loa
2+50	0+50	59	7	20
3+00	0+50	79	9	26
3+00	1+00	65	7	22
4+00	1+00	202	22	67
4+00	2+00	241	27	80
5+00	2+00	150	17	50
5+00	2+50	111	12	37
5+00	3+00	31	3	10
5+00	6+50	7	1	2
5+00	7+00	510	57	170
6+00	7+00	221	25	74
6+00	8+00	400	44	133
6+50	8+00	69	8	23
7+00	8+00	43	5	14

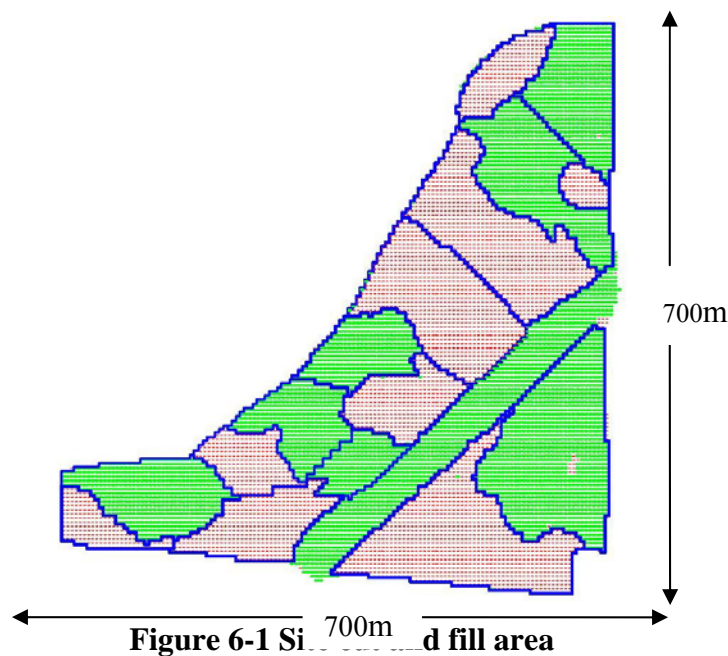
## Chapter 6 Case Study

### 6.1 Project introduction

This research presents a case study for improving the effectiveness of an earthwork construction system by (1) using the modified least squares method to balance cut and fill quantities, (2) applying the Transportation Simplex Method to minimize the total fleet distance and (3) implementing the simplified discrete event simulation approach (SDESA) to analyze operations efficiency and fleet utilization. How to apply the simulation methodology of SDESA is elaborated step by step, illustrated with the case study of designing and evaluating the material handling system for an earthwork construction site. Particular emphasis

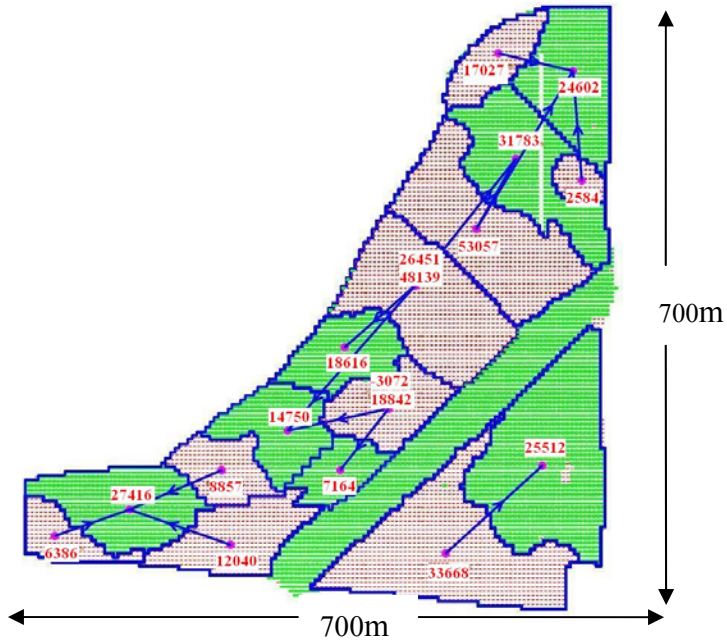
is placed on procedures for establishing a simulation model, validation of the simulation, design of simulation experiments, and analysis of simulation results.

The site is about 244,000 m<sup>2</sup> with a triangle shape. The total earthwork for rough grading has been designed as: bank cut volume 200,000 cu.m and compacted fill volume is 150,000 m<sup>3</sup>. Since the shrinkage factor for the soil is about 0.75. So, the cut and fill are balanced. The following figure shows the cut and fill area in the site: Red indicates that area is a cut area and green indicates a fill area.



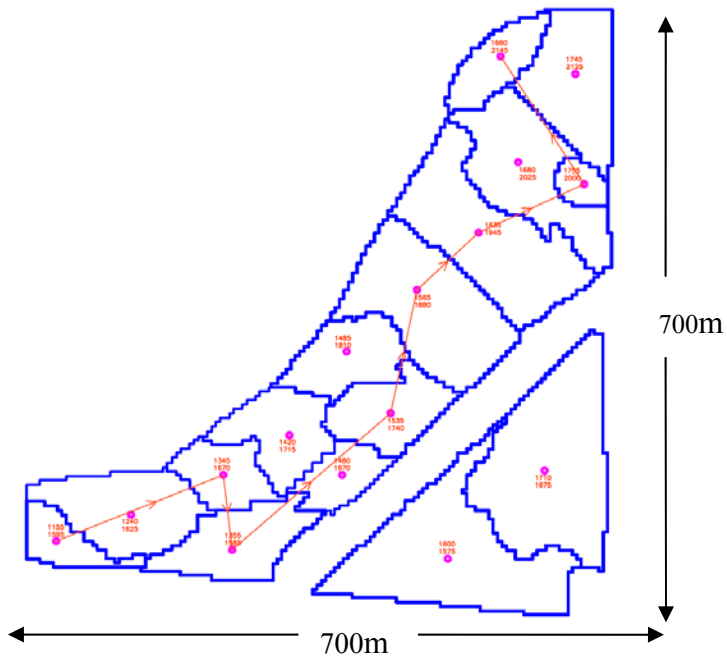
## 6.2 Earthwork Quantity Balance and Equipment Relocation

Since each area has certain cut or fill volumes, the earth should be moved from the cut area to the fill area. And also the process will try to keep the moving distance as short as possible. After considering above factors, the flowing earthmoving sketch has been created to show the earth relocation plan. The blue arrow shows the earth moving direction and the red text indicated the earthwork volume.



**Figure 6-2 Earth moving operation**

Then earthmoving start and end points are defined and earthwork volumes are balanced. Then the equipment allocation route map (resource transit) has been setup as shown below.



**Figure 6-3 Equipment relocation route**

To demonstrate mass-haul optimization and SDESA simulation, the south-east corner has been selected as a detailed case study. First, the demonstrated area is separated by  $40 \times 40\text{m}$  grid cell and retrieved each cell's earthwork is given in the following table.

Table 8 Earthmoving balance sheet

Cell Space	40	by	40	m	Truck Cap.	24	cu.m
Swell	1.1	Shrinkage	0.95		Loader Cap.	2	cu.m
						1.62	
						2592	
						125	
						1.14	2.37
						1824	3792
						88	183
						0.75	0.63
						1200	1008
						58	49
						0.33	0.36
						528	576
						25	28
						0.72	0.24
						1267	422
						53	18
						0.69	1.27
						1104	2032
						53	98
						0.13	2.49
						208	3984
						10	166
						0.87	2.82
						1531	4963
						64	207
						1.06	0.11
						1866	194
						78	8
						0.62	0.94
						194	992
						41	63
						1.77	0.84
						1504	2832
						63	137
						0.84	0.62
						1478	1091
						62	45
						1.68	1.9
						2957	3344
						123	139
						1.14	0.34
						2006	598
						84	25
						1.04	0.84
						1830	1344
						76	65
						0.77	1.81
						1355	3186
						56	133
						1.57	2.15
						2763	3784
						158	55
						0.75	1.1
						1320	1936
						81	81
						1.11	0.69
						1954	1104
						81	53
Total Fill	1656	truck load					
Total Cut	1660	truck load					
Total Fill	19867	bucket load					
Total Cut	19923	bucket load					

The traditional civil earthwork planning is based on rule of thumb, such as the travel distance is not too short. The new method is based on the optimization model. Before the simulation, the earthmoving directions and quantities need to be optimized. Again, the Solver has been used to find out the optimum solution. The first matrix shows each distance from a cut cell to a fill cell.



Table 9 Distance matrix1

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
		1579	1619	1539	1579	1619	1659	1499	1539	1579	1619	1659	1699	1739	1499	1539	1579	1619	1659	1699	1739
		1644	1644	1604	1604	1604	1604	1564	1564	1564	1564	1564	1564	1564	1524	1524	1524	1524	1524	1524	1524
F1	1779	256	226	312	283	256	233	369	339	312	288	268	253	243	396	369	344	322	305	291	283
	1804																				
F2	1739	200	170	256	226	200	179	312	283	256	233	215	204	200	339	312	288	268	253	243	240
	1764																				
F3	1779	233	200	288	256	226	200	344	312	283	256	233	215	204	369	339	312	288	268	253	243
	1764																				
F4	1699	144	113	200	170	144	126	256	226	200	179	165	160	165	283	256	233	215	204	200	204
	1724																				
F5	1739	179	144	233	200	170	144	288	256	226	200	179	165	160	312	283	256	233	215	204	200
	1724																				
F6	1779	215	179	268	233	200	170	322	288	256	226	200	179	165	344	312	283	256	233	215	204
	1724																				
F7	1659	89	57	144	113	89	80	200	170	144	126	120	126	144	226	200	179	165	160	165	179
	1684																				
F8	1699	126	89	179	144	113	89	233	200	170	144	126	120	126	256	226	200	179	165	160	165
	1684																				
F9	1739	165	126	215	179	144	113	268	233	200	170	144	126	120	288	256	226	200	179	165	160
	1684																				
F10	1779	204	165	253	215	179	144	305	268	233	200	170	144	126	322	288	256	226	200	179	165
	1684																				
F11	1659	80	40	126	89	57	40	179	144	113	89	80	89	113	200	170	144	126	120	126	144
	1644																				
F12	1699	120	80	165	126	89	57	215	179	144	113	89	80	89	233	200	170	144	126	120	126
	1644																				
F13	1739	160	120	204	165	126	89	253	215	179	144	113	89	80	268	233	200	170	144	126	120
	1644																				
F14	1779	200	160	243	204	165	126	291	253	215	179	144	113	89	305	268	233	200	170	144	126
	1644																				
F15	1699	126	89	160	120	80	40	204	165	126	89	57	40	57	215	179	144	113	89	80	89
	1604																				
F16	1739	165	126	200	160	120	80	243	204	165	126	89	57	40	253	215	179	144	113	89	80
	1604																				
F17	1779	204	165	240	200	160	120	283	243	204	165	126	89	57	291	253	215	179	144	113	89
	1604																				
F18	1779	215	179	243	204	165	126	280	240	200	160	120	80	40	283	243	204	165	126	89	57
	1564																				
F19	1779	233	200	253	215	179	144	283	243	204	165	126	89	57	280	240	200	160	120	80	40
	1524																				

The second matrix shows from each cut cell, how many truck loads of soil will be removed to a certain fill area.

Table 10 Distance matrix2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
F1	<b>256</b>	226	<b>312</b>	283	256	<b>233</b>	369	339	312	288	268	253	243	396	369	344	322	305	291	283
F2	200	<b>170</b>	256	226	<b>200</b>	179	312	283	256	233	215	204	200	339	312	288	268	253	243	240
F3	233	200	288	<b>256</b>	<b>226</b>	200	344	312	283	256	233	215	204	369	339	312	288	268	253	243
F4	144	113	200	<b>170</b>	144	126	256	226	200	179	165	160	165	283	256	233	215	204	200	204
F5	179	144	233	200	170	144	288	256	226	200	179	165	160	312	283	256	233	215	<b>204</b>	200
F6	215	179	268	233	200	170	322	288	256	226	200	<b>179</b>	<b>165</b>	344	312	283	256	233	<b>215</b>	<b>204</b>
F7	89	57	144	113	89	80	200	170	144	126	<b>120</b>	126	144	226	200	179	165	160	165	179
F8	126	89	179	144	113	89	233	200	170	144	<b>126</b>	120	126	256	226	200	179	165	160	165
F9	165	126	215	179	144	113	268	233	200	170	<b>144</b>	126	120	288	256	226	200	<b>179</b>	165	160
F10	204	165	253	215	179	144	305	268	233	<b>200</b>	170	144	126	322	288	256	226	<b>200</b>	179	165
F11	80	40	126	89	57	40	179	144	113	89	80	89	113	200	170	144	<b>126</b>	120	126	144
F12	120	80	165	126	89	57	215	179	144	113	89	80	89	233	200	170	<b>144</b>	126	120	126
F13	160	120	204	165	126	89	253	215	<b>179</b>	144	113	89	80	268	233	200	<b>170</b>	144	126	120
F14	200	160	243	204	165	126	291	253	<b>215</b>	179	144	113	89	305	268	<b>233</b>	200	170	144	126
F15	126	89	160	120	80	40	204	165	126	89	57	40	57	215	179	<b>144</b>	113	89	80	89
F16	165	126	200	160	120	80	243	<b>204</b>	165	126	89	57	40	253	215	<b>179</b>	144	113	89	80
F17	204	165	240	200	160	120	283	<b>243</b>	204	165	126	89	57	291	<b>253</b>	215	179	144	113	89
F18	215	179	243	204	165	126	<b>280</b>	240	200	160	120	80	40	283	243	204	165	126	89	57
F19	233	200	253	215	179	144	283	243	204	165	126	89	57	<b>280</b>	240	200	160	120	80	40

Table 11 Quantity matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	
F1	53	0	64	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	125
F2	0	18	0	0	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88
F3	0	0	0	176	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	184
F4	0	0	0	31	0	0	0	0	0	0	2	0	0	0	0	0	0	0	25	0	58
F5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	0	49
F6	0	0	0	0	0	0	0	0	0	0	0	25	76	0	0	0	0	0	7	82	190
F7	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	26
F8	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0	28
F9	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	18	0	0	46
F10	0	0	0	0	0	0	0	0	0	139	0	0	0	0	0	0	2	38	0	0	179
F11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0	0	0	53
F12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	98	0	0	0	98
F13	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5	0	0	0	10
F14	0	0	0	0	0	0	0	0	118	0	0	0	0	0	0	48	0	0	0	0	166
F15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0	0	0	0	41
F16	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	26	0	0	0	0	63
F17	0	0	0	0	0	0	0	8	0	0	0	0	0	0	133	0	0	0	0	0	137
F18	0	0	0	0	0	0	62	0	0	0	0	0	0	0	0	0	0	0	0	0	65
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0	0	0	0	0	0	53
	53	18	64	207	78	8	62	45	123	139	84	25	76	56	133	115	158	55	81	81	1661

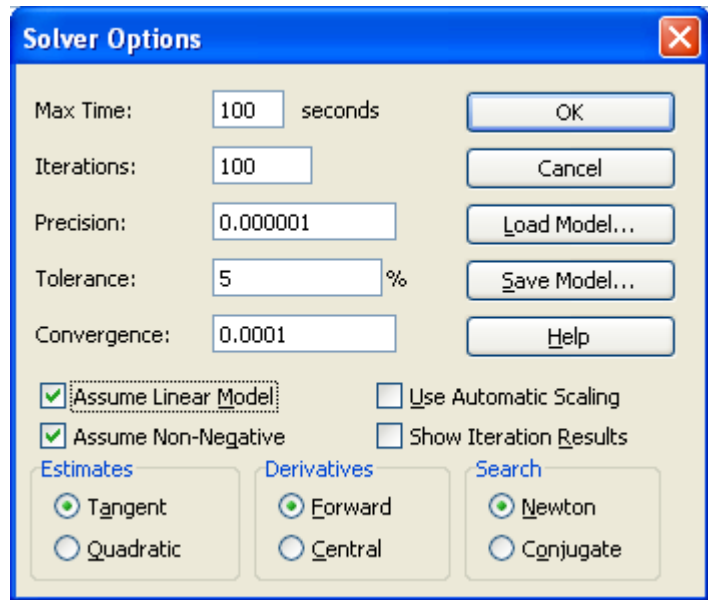
The third matrix shows how much time is needed to take from a cut cell to a fill cell.

Then, set up a  $\Sigma$  which is the summary of all the cells' volume from the third Matrix. The solver's target cell will be this one by changing the cells' in the second matrix's cell volumes.

Table 12 Optimization matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
F1	13575	0	19994	0	0	1866	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0	3055	0	0	14200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F3	0	0	0	45078	1584	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	0	0	0	5261	0	0	0	0	0	0	330	0	0	0	0	0	0	0	5000	0
F5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9994	0
F6	0	0	0	0	0	0	0	0	0	0	0	4472	12534	0	0	0	0	0	1508	16725
F7	0	0	0	0	0	0	0	0	0	0	3120	0	0	0	0	0	0	0	0	0
F8	0	0	0	0	0	0	0	0	0	0	3542	0	0	0	0	0	0	0	0	0
F9	0	0	0	0	0	0	0	0	0	0	4038	0	0	0	0	0	0	3220	0	0
F10	0	0	0	0	0	0	0	0	0	27800	0	0	0	0	0	0	453	7600	0	0
F11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6704	0	0	0
F12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14134	0	0	0
F13	0	0	0	0	0	0	0	0	894	0	0	0	0	0	0	0	849	0	0	0
F14	0	0	0	0	0	0	0	0	25418	0	0	0	0	0	0	11195	0	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5913	0	0	0	0
F16	0	0	0	0	0	0	0	7547	0	0	0	0	0	0	0	4651	0	0	0	0
F17	0	0	0	0	0	0	0	1946	0	0	0	0	0	0	33647	0	0	0	0	0
F18	0	0	0	0	0	0	17360	0	0	0	0	0	0	0	0	0	0	0	0	0
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	14840	0	0	0	0	0	0
	13575	3055	19994	50339	15784	1866	17360	9493	26312	27800	11030	4472	12534	14840	33647	21760	22139	10820	16502	16725

Last, set a cell as the optimization goal as keep this cell's volume as small as possible. And this cell is also the summary of optimization matrix's volume. The detailed solver option setting are as the following figure.



Total **350045.588**

Figure 6-4 Solver option setup

The optimum model need a group of constrains, such as the total cut volume of one cell need to be certain volume and the total fill volume for one cell need to be certain volume as well:

$$C1=(F1C1)+(F2C1)+(F3C1)+ (F4C1) + (F5C1) + (F6C1) + (F7C1) + (F8C1) + (F9C1) + (F10C1) + (F11C1) + (F12C1) + (F13C1) + (F14C1) + (F15C1) + (F16C1) + (F17C1) + (F18C1)$$

$$C2=(F1C2)+(F2C2)+(F3C2+ (F4C2) + (F5C2) + (F6C2) + (F7C2) + (F8C2) + (F9C2) + (F10C2) + (F11C2) + (F12C2) + (F13C2) + (F14C2) + (F15C2) + (F16C2) + (F17C2) + (F18C2)$$

$$C3=(F1C3)+(F2C3)+(F3C3)+ (F4C3) + (F5C3) + (F6C3) + (F7C3) + (F8C3) + (F9C3) + (F10C3) + (F11C3) + (F12C3) + (F13C3) + (F14C3) + (F15C3) + (F16C3) + (F17C3) + (F18C3)$$

.....

$$C20=(F1C20)+(F2C20)+(F3C20)+ (F4C20) + (F5C18) + (F6C18) + (F7C18) + (F8C18) + (F9C18) + (F10C18) + (F11C18) + (F12C18) + (F13C18) + (F14C18) + (F15C18) + (F16C18) + (F17C18) + (F18C18)$$

It should be pointed out the Basic Solver can only support up to 200 “By Changing Cells”. The Premium Solver can handle problems with much larger numbers of adjustable cells.

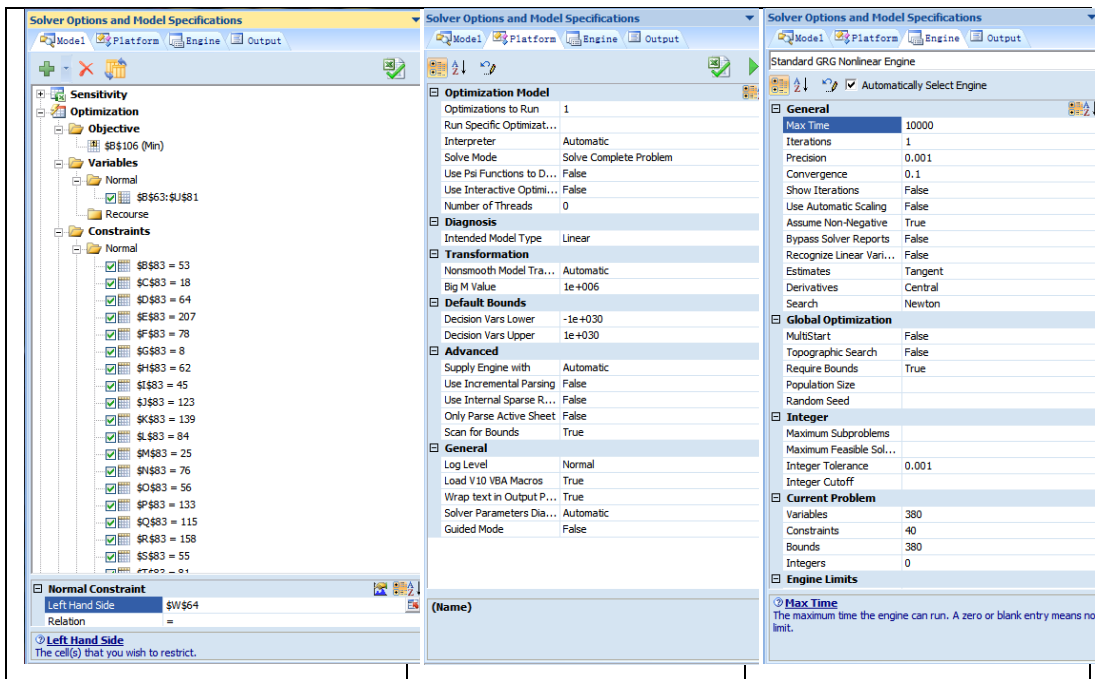


Figure 6-5 Premium solver option setup

To facilitate the visualization of the trend generalized from simulation results, a surface plot and the earthmoving directions are developed for the different scenarios simulated as the following figure.

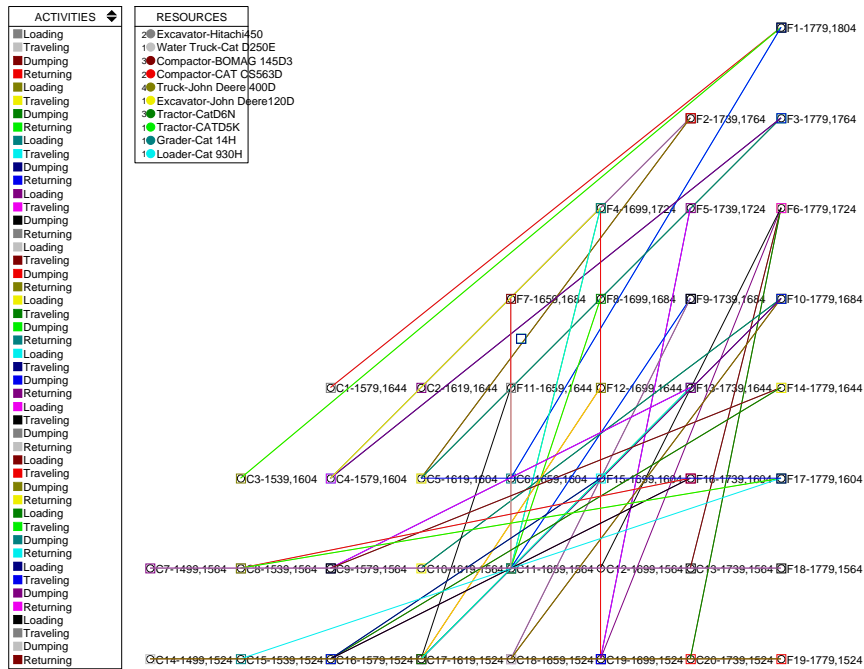


Figure 6-6 Earthmoving directions

### 6.3 Equipment Selection

To achieve the maximum operation productivity, the selected equipment should have proper characteristics and the fleet size should be the most suitable for the specific site condition. For this particular site, the following factors have been considered:

**Safety:** Earthwork sites are amongst the most dangerous because of the variety of work being conducted and because of the speed at which earth moving equipment is operates. However, In excavation and transfer soil from one part of a side to another, the basic idea is avoid the equipment running route intersection as much as possible. If several groups of equipment work in the same site in the same time, try to separate them. Try to keep the equipment running route as simple as

possible.

**Site Size:** This site is about 244,000 sq.m. The earthwork has been designed as: bank cut volume 200,000 cu.m and fill compacted volume is 150,000 cu.m. Since a large quantity of earthwork is required, the equipment size tends to be medium to large size.

**Construction duration:** The earthwork starts in August and needs to be finished before the middle of November. Since the schedule is tight, the contractor tends to bring more equipment to finish the work on time. During this period, the rain might affect the work as well.

**Availability of equipment:** The earthwork construction contractor owns most of the equipment and which are in the good condition. The rental cost of equipment will be determined by equipment capacities and rental rates from “Equipment Rental Rates Guide and Membership Roster” by Alberta Roadbuilders and Heavy Construction Association (ARHCA).

**Equipment Transportation Cost:** The cost is determined by the project size, travel distance and the means of transportation. Ideally, all the equipment will be transported to the site by heavy-trailers except trucks.

**Excavation type:** Since the most adequate equipment to perform one activity may not be suitable to another job, the type should be considered as well. The site’s cut and fill are roughly equal, the excavation mass is relatively large and building / structure foundation excavation evolved as well. This site has no rock or hard material involved.

**Soil type:** The site has about average 200mm depth topsoil on the ground, below which is a sand layer, below the sand layer is either silt or clay. No rock excavation is required. Moreover, excavation pit has different soils at different strata. The typical stratum has the following two features.

**Geometric characteristics of elements to be excavated:** Functional characteristics of different types of equipment makes such considerations necessary.

**Space constraints:** The performance of equipment is influenced by spatial limitations imposed on the movement of excavators.

**Characteristics of haul units:** The size of an excavator will depend on haul units if there is a constraint on the size and / or quantity of these units.

**Location of dumping areas:** The distance between the construction site and dumping areas could be relevant not only for selecting the type and number of haulers, but also the type of excavators.

**Weather and temperature:** Rain, snow and severe temperature conditions affect the job-site productivity of labor and equipment.

**Output of excavator:** This factor will affect the truck operation, the size and characteristics of the excavators selected will determine the output volume excavated per day.

**Distance to dump site:** Sometimes part of the excavated materials may be piled up in a corner at the job-site for use as backfill

**Probable average speed:** The average speed of the truck to and from the dumping site will determine the cycle time for each hauling trip.

**Volume of excavated material:** The volume of excavated materials including the part to be piled up should be hauled away as soon as possible.

**Spatial and weight constraints:** The size and weight of the truck must be feasible at the job site and over the route from the construction site to the dumping area.

The equipment selection is done based on the owning/renting analysis, earthwork volume and site conditions. The equipment availability will be input to SDESA model as resources. Another resource input will be the quantity of earthwork volume. The following table and figure shows the equipment that will be used in the earthmoving processes.



**Figure 6-7 Equipment Selection**

Table 13 Equipment list

#	Description	Type Code	Init Amount
1	Excavator-Hitachi450	EX-HITACHI	2
2	Water Truck-Cat D250E	WT-CAT	1
3	Compactor-BOMAG 145D3	CP-BOMAG	3
4	Compactor-Cat CS563-D	CP-CAT	2
5	Truck-John Deere 400D	TR-JOHNDEERE	4
6	Excavator-John Deere 650D	EX-JOHNDEERE	1
7	Dozer-Cat D6N	DO-CATD6N	3
8	Dozer -Cat D5K	DO-CATD5K	1
9	Grader-Cat 14H	GR-CAT	1
10	Loader -Cat 930H	LD-CAT	1

#### ***6.4 Equipment Production***

Hauler – John Deere 400D Articulated Truck

The articulated dump truck John Deere 400D with a capacity of 24 cubic meters is used to dispose of excavated materials. The distance from the dump site is 250 meters and the average speed of the dump truck is 30 km/h. Since SDESA only need to enter the net productive activity time, the simulation will determine idle time and efficiency factor as results; it is not needed to apply any idle factor or management factor. If a fleet of such truck is used to haul the excavated material, the quantity of trucks can be calculated. The details of trucks' cycle times are follows.

Truck Load	7.2 min	Travel	0.5 min
Dump	1.0 min	Return	0.5 min

Loader – Hitachi Excavator

The excavator Hitachi 450 has a capacity of 3 cubic meters bucket. The job site productivity of excavator per day is 504 cubic meters, which will be modified by a swell factor of 1.1. The details of loaders' cycle time are follows.



Load bucket	0.2 min	Swing with load	0.1 min
Dump bucket	0.1 min	Return swing	0.2 min

### ***6.5 Earthwork Construction Activities***

The earthwork construction activities for this site are shown as the following figures



**Figure 6-8 Cutting process**



**Figure 6-9 Stockpiling process**



**Figure 6-10 Loading process**



**Figure 6-11 Dumping process**



**Figure 6-12 Fill and compact process**

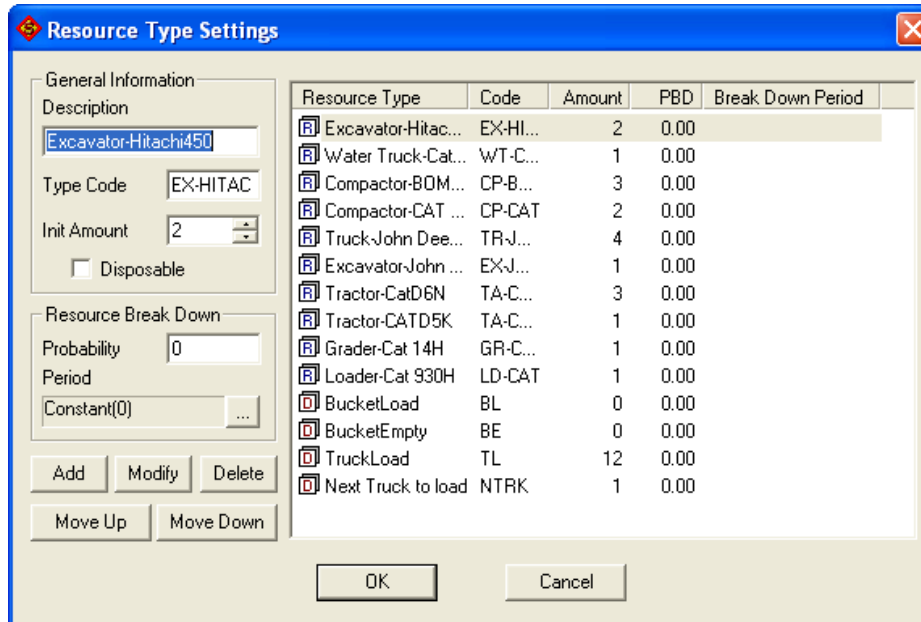


**Figure 6-13 Grader for haul road maintenance**

## ***6.6 SDESA model setup***

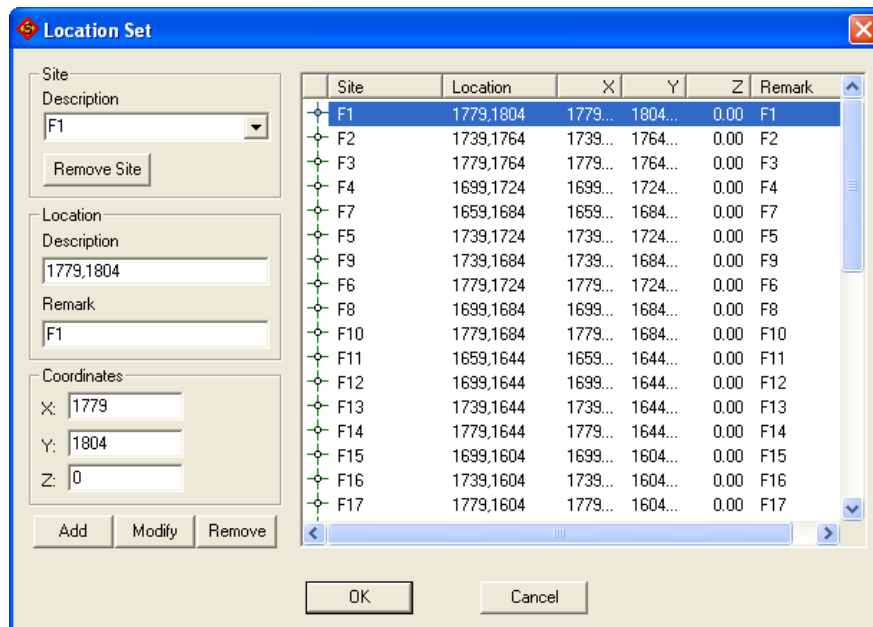
To use the SDESA as a simulation tool, it is important to collect data required by the model. In order to simulate the earthwork construction case, a method statement is prepared. Here is the step by step introduction to set up SDESA model with reference to earthwork case study:

Step1: First, based on the equipment selection, enter those equipments available as resources. And also setup four disposable resource to control the process which are BL, BE, TL and NTRK.



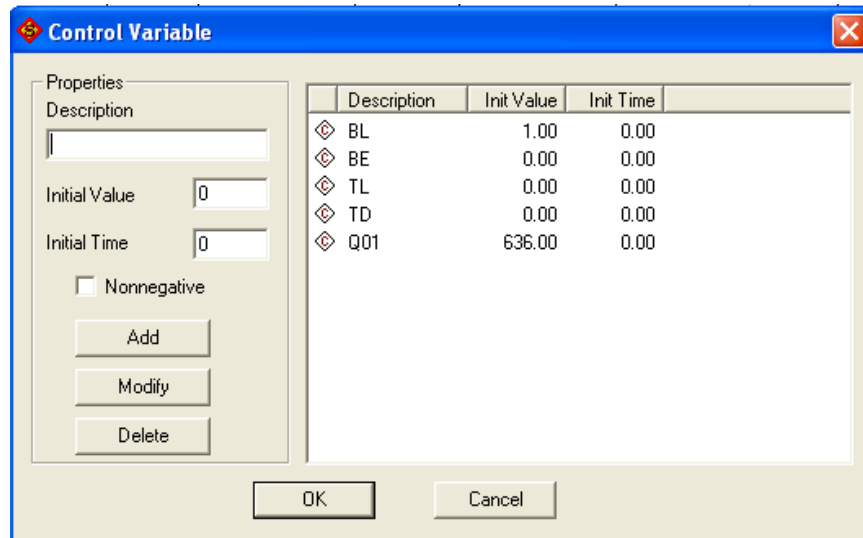
**Figure 6-14 Resource type setting**

Step2: Second, setup each cut/fill cell's center as the location.



**Figure 6-15 Location set**

Step3: Define Control Variables. Five control variables are defined which are BL, BE, TL, TD and Q01.



**Figure 6-16 Control variable set**

Step4: based on the process description as above, the flow entity which is at the head of a chain of activities is determined. From each flow activity in the earthwork moving system, we identify the location in the site and define the activities involved in each work flow. The number in the diamond represents how many trucks or loaders to be processed.

Step5: After drawing the flow entity, link up the flow entity to the activity. The arrow between the flow entity and the activity means the first activity in that flow entity and the arrow between two activities means the finish-to-start logical relationship.

Step6: For the load-dump cycle, as the flow of the processing is running continuously until reaching the target volume, there will be an arrow emanating from the previous activity “dumping” to the first activity “loading”, and this representation is called looping.

Step7: As both flow entity and activity are lined up, resources in the activity should be considered. Not all the resources used in the activity will be added, we need to choose the limited reusable resources including trucks and loaders etc. We

need consider which activity has a low production rate, in another word, which one is the bottle neck of the whole operation system. And after doing the simulation, we may add or reduce such resources based on the model outputs.

Step8: Although flow entity with activity for the earthwork system can be set up in the similar techniques, we establish an interdependent relationship between them. Such that activity “loader” cycle and “hauler” cycle are based on the criteria and constraints we added in. Otherwise, both activities will be start at the beginning and the model is no use. It can be noticed that the use of disposable resources or control variables can activate the load of excavation / cut to the truck once complete one area of excavation / cut has done. In SDESA, disposal resource is defined as either signal or material that is generated from the activity. They are requested and consumed by the other activity. In this case, it can be served as the linkage between two activities. As for activity “loader” cycle and “hauler” cycle are showed in the top left corner of the activity block, it indicated that tow loaders and four trucks were required to execute the activity.

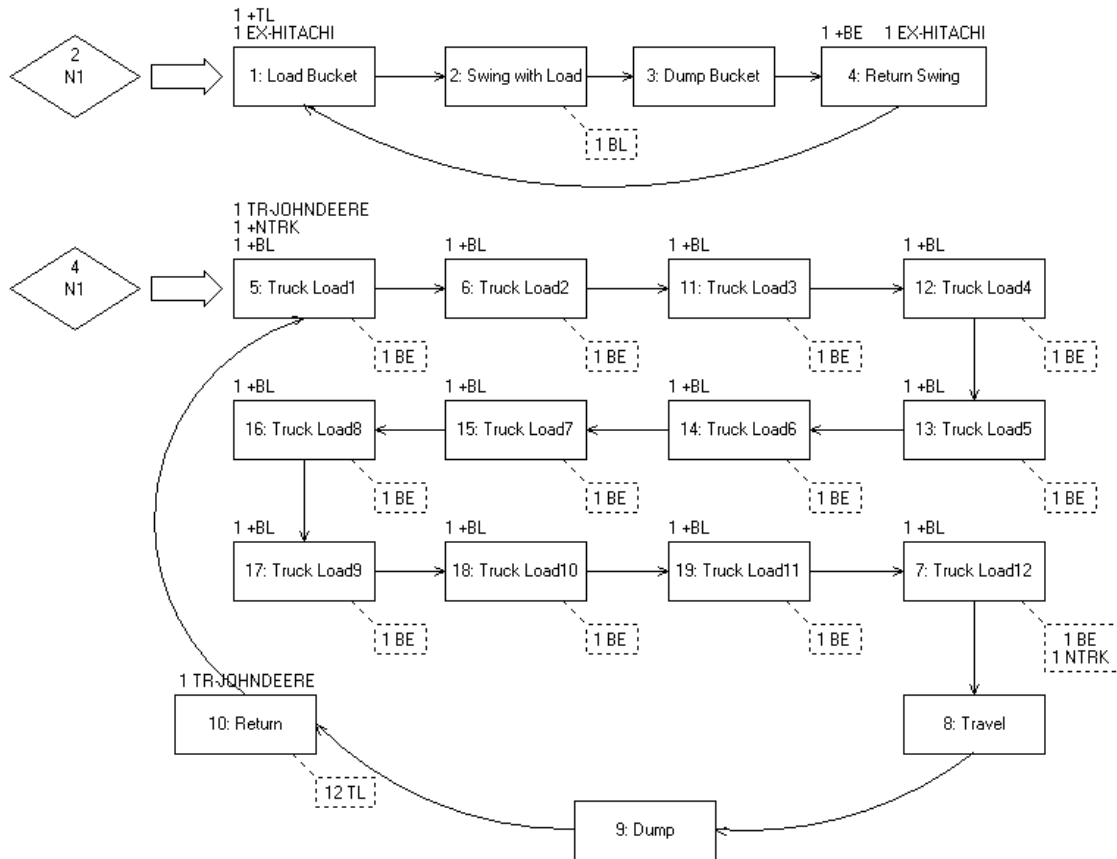
Step9: The BL with quantity equal to “bucket load” is generated at the end of activity “swing the load”, where it is represented with “BL” in the bottom right corner of the activity block. It means that when the “BL” is generated from Swing load activity the quantity equal to 1, the activity “Truck load” can start.

Step10: By setting up the model with the relationship for the remaining flow entities in the similar way, the model is ready to run. However, for the simulation, we toned to decide the time duration of each activity. So, we define the start / finish locations of the activity and input the data on activity duration. These data can be obtained from site experience or actual data on previous projects. By entering the input data, the simulation model can be run to derive data like resources utilization rates, time for completing the project or a certain activity. And the model can be tuned by adding or removing resources, or changing input data so as required to meet the production rate of the earthmoving operation

system.

Step11: By setting the target production rate, we calculate the initial resource required, which is done in grading design stage.

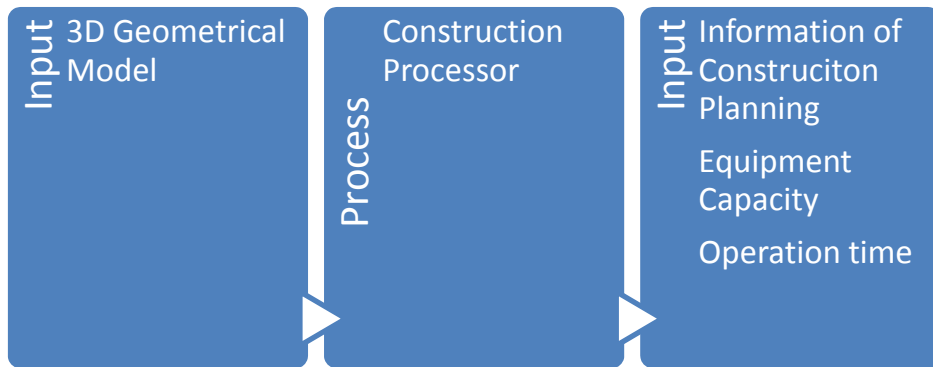
The final model is given as the following figure.



**Figure 6-17 Earthwork construction model**

### 6.7 Analysis and Suggestion

The SDESA model is intended to simulate conventional site management procedures.



**Figure 6-18 Analysis system framework**

#### Equipment Utilization

SDSEA's resource utilization function can provide equipment utilization information once the simulation done. The screen shots for the loader and hauler are shown as following figures.



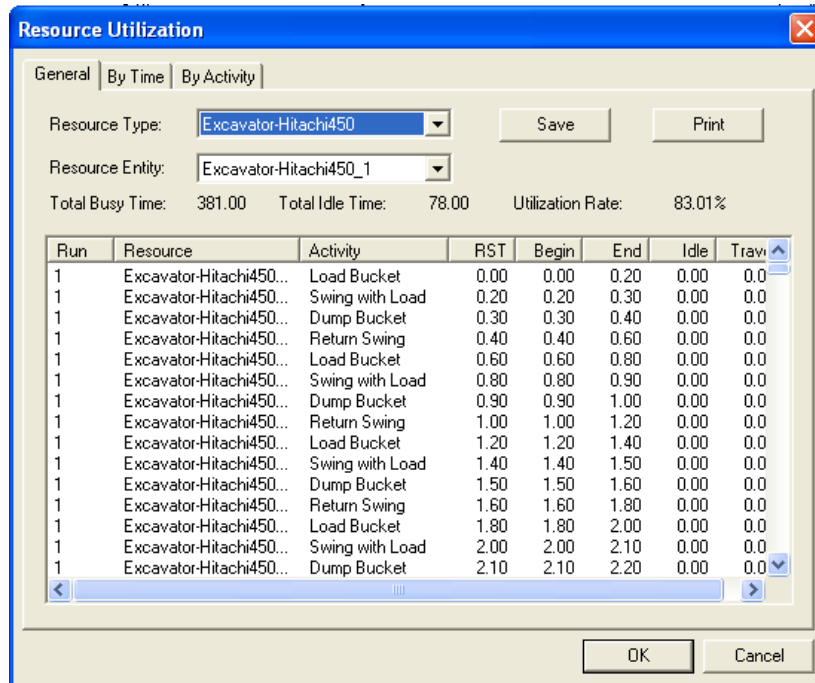


Figure 6-19 Excavator utilization

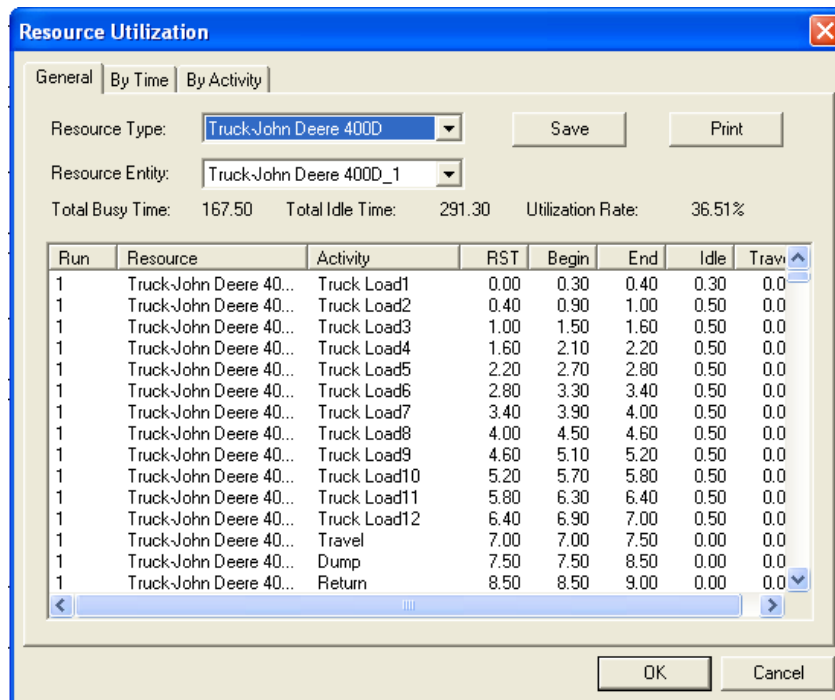


Figure 6-20 Truck utilization

In the base-case scenario for simulation, input factors of the model were arranged to reflect the actual earthwork construction situation. The objective of simulation



experiment design was to evaluate the sensitivity of total cycle duration to various strategies, which are defined by (1) the quantities of loader and truck used; (2) and the travel time from one cut/fill location to the other cut/fill location; and (3) scenarios were postulated and simulated, the results are given in the following table. Note: Excavator's utilization is relatively high, which only idles to wait for the next truck arrival. The truck's utilization is relatively low, as a truck waits for the previous truck to finish loading, while, during the loading process, the truck idles waiting for the excavator to return with fully loaded bucket. The SDESA model is able to capture all the above operations details.

Table 14 Scenario list

<b>2 Excavator</b>		<b>&amp;</b>	<b>4 trucks</b>			
			Total busy time(min.)	Total Idle time(min.)	Utilizatio Rate	Total time(min.)
Excavator1			190.8	98.8	65.88%	289.6
Excavator2			190.8	98.9	65.86%	289.7
Truck1			44.8	246.7	15.37%	291.5
Truck2			41.6	233.4	15.13%	275
Truck3			41.6	238.9	14.83%	280.5
Truck4			41.6	244.4	14.55%	286
<b>2 Excavator &amp; 3 trucks</b>						
Excavator1			190.8	98.8	65.88%	289.6
Excavator2			190.8	98.9	65.86%	289.7
Truck1			57.6	228.4	20.14%	286
Truck2			57.6	233.9	19.76%	291.5
Truck3			54.4	226.1	19.39%	280.5
<b>2 Excavator &amp; 2 trucks</b>						
Excavator1			190.8	98.8	65.88%	289.6
Excavator2			190.8	98.9	65.86%	289.7
Truck1			86.4	205.1	29.64%	291.5
Truck2			83.2	202.8	29.09%	286
<b>1 Excavator &amp; 1 trucks</b>						
Excavator1			381	93.6	80.28%	474.6
Truck1			167.5	306.9	35.31%	474.4

The above simulation results are in simple, straightforward terms and described as follows:

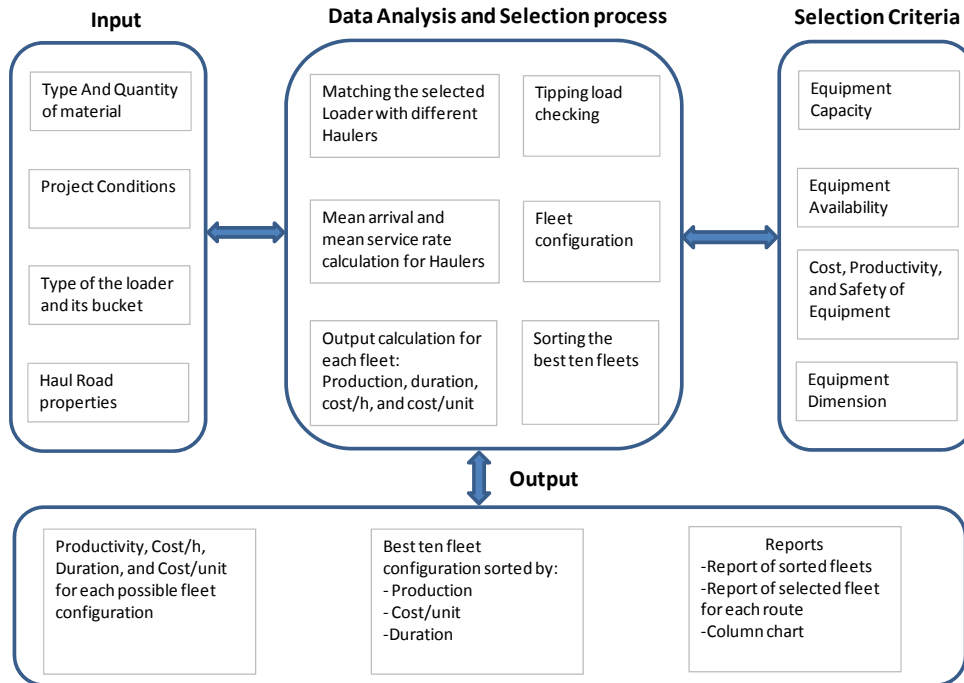
The result shows one excavator with one truck will get the highest efficiency rate.

However, the construction duration is as long as 380 min (60% longer than other scenarios). In order to shorten the project duration as much as possible, chose the two excavators with two trucks solution.

#### Fleet simulation

The simulation results assist in selecting the appropriate fleet of equipment e.g. technically feasible, and allowing for the choice of fleet with optimum output (lease cost, maximum production, or minimum project duration). Based on the input data regarding the project characteristics (hauling road grade type and rolling resistance, type of soil, weather condition, and equipment capacity) and selected type of loaders and bucket, type of trucks, and determine how many loaders to match how many trucks in order to achieve cost efficiency.

Equipment selection for an earthmoving construction is usually based on the production rate required and is often constrained by equipment on hand. Generally speaking, for the best matching the productivity, usually a project requires a single loader with several trucks. However, in this particular case, since the contractor only have those big trucks on hand, even the production rate is not high, it's still more economical to use those trucks instead of rent the small one instead of renting the smaller ones. For the same reason, even the excavator's bucket capacity is small, it is still used. The fleet simulation structure shows as below figure



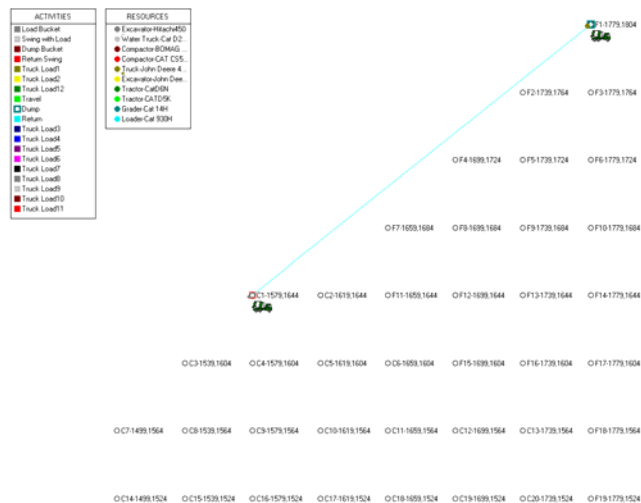
**Figure 6-21 Fleet match analysis system**

**Table 15 Total operation time**

			Total Load	Total Time	Ave. Cycle Time
F1	250	C1	636	279.2	0.439
		C3	768	337.5	0.439
		C6	96	40.7	0.424
F2	176	C2	210	91.9	0.438
		C5	846	372.8	0.441
F3	366	C5	84	35.4	0.421
		C4	2112	931.1	0.441
F4	116	C4	372	162.6	0.437
		C19	300	130.8	0.436
		C11	24	8.9	0.371
F5	97	C19	582	256.2	0.440
F6	380	C13	918	404.6	0.441
		C20	978	431.1	0.441
		C12	300	130.8	0.436
		C19	84	35.4	0.421
F7	51	C11	306	134.3	0.439
F8	56	C11	336	146.7	0.437
F9	91	C11	336	146.7	0.437
		C18	210	91.9	0.438
F10	357	C18	450	197.9	0.440
		C10	1674	738.5	0.441
		C17	18	7.1	0.394
F11	107	C17	642	282.7	0.440
F12	196	C17	1176	517.7	0.440
F13	20	C17	54	23	0.426
		C9	66	28.3	0.429
F14	332	C9	1410	621.9	0.441
		C16	582	256.2	0.440
F15	83	C16	498	219.1	0.440
F16	125	C16	300	130.8	0.436
		C8	450	197.9	0.440
F17	273	C8	96	40.7	0.424
		C15	1590	701.4	0.441
F18	130	C7	738	325.1	0.441
F19	107	C14	678	298.6	0.440
				<b>8756</b> Min	
				<b>146</b> hrs.	

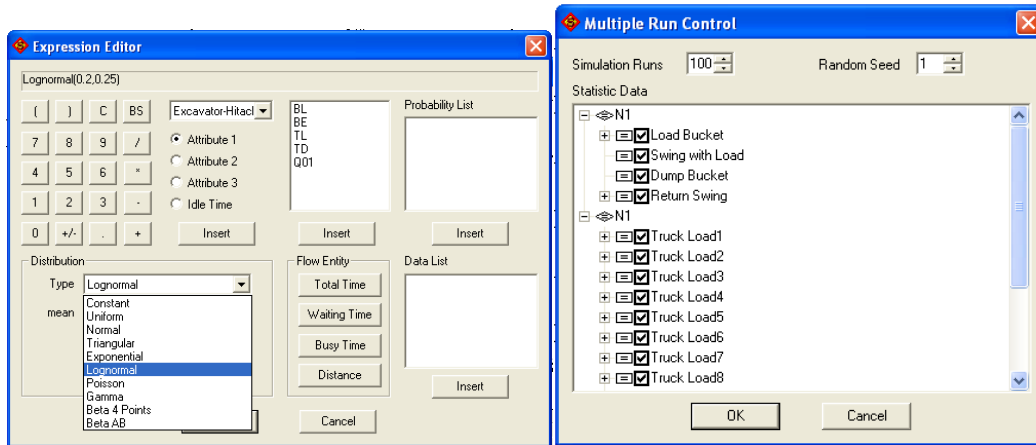
By solving this problem through traditional hand calculation, each truck load-dump cycle takes  $12 \times (0.2 + 0.1 + 0.1 + 0.2) + 0.5 + 1.0 + 0.5 \text{ min} = 9.2 \text{ min}$ . Since we have total 1660 truck loads need to be done, 2 trucks can finish in 7636 min. So, if we use the traditional hand calculation, the earthwork volume will be underestimated. If we consider factors affecting job productivity of the dump truck in addition to those affecting the excavator are 0.80 for equipment idle time and 0.9 for management efficiency, the total time will be  $(7.2 \text{ min} + (2 \text{ min} / 0.8)) \times 1660 / 2 / 0.9 = 8946 \text{ min}$ . But deciding on those efficiency factors is only based on best guess and experience, which is not accurate and subjective.

For the work which is described before, the earthwork operation processes being simulated were replayed through a single run of SDESA model. To further validate the simulation model, 10 Monte Carlo runs on the SDESA model were conducted. SDESA can also provide various statistical parameters common for Monte Carlo simulation such as Triangular, Exponential, lognormal, Poisson, Gamma, Beta 4 Points or Beta etc. This case study has been used Triangular to distribute the variance for the first earthwork movement (cut area c1 to fill area f1, 636 excavator loads, location shows on Figure 6-22). Result is the total operation time is 284 min. with a 99% confidence for that earthwork movement.

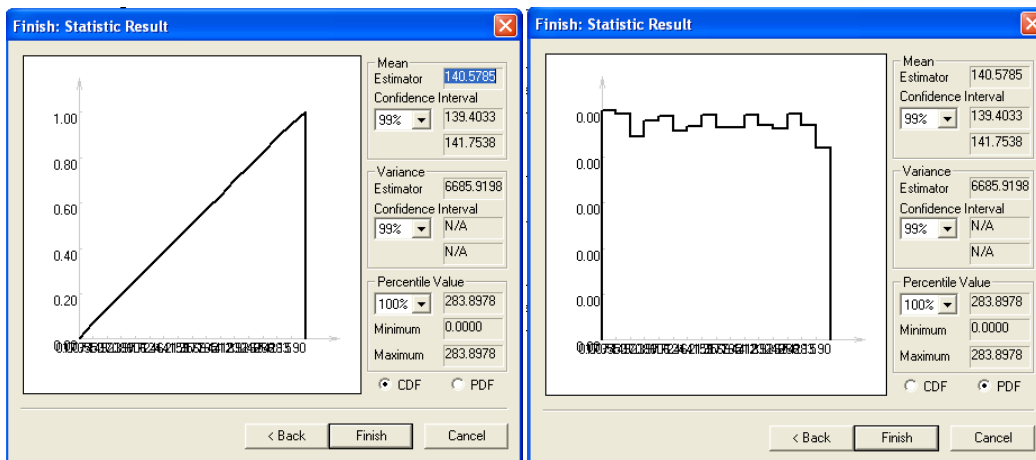


**Figure 6-22 Fleet simulation**

The setting and CDF/PDF result shows on Figure and Figure.



**Figure 6-23 Multiple simulation run set up**



**Figure 6-24 Multiple simulation CDF/PDF results**

Furthermore, to run the SDSEA model base on two other scenarios: 1) assume the contractor has two bigger excavators HITACHI 1200 and two John Deere 400D available, HITACHI 1200's capacity is 8 cu.m. So, three bucket load will fill one John Deere 400D. 2) assume the contractor has two smaller truck Ford L8000 and two excavators HITACHI 450D available, Ford L8000 capacity is 6 cu.m. So, three bucket load of HITACHI 450 will fill one Ford L8000. The results for those two scenarios though SDSEA shows bellow.

Two excavators HITACHI 1200 (8 cu.m.) with two truck John Deere 400D (24

cu.m.)

	Cycle time(min.)	Total busy time(min.)	Total Idle time(min.)	Utilization	Total time(min.)
Excavator1	0.6	48	104	31.58%	152
Excavator2	0.6	48	106.3	31.11%	154.3
Truck1	2	54	99.7	35.13%	153.7
Truck2	2	52	102	33.77%	154

Two excavators HITACHI 450D (2 cu.m.) with two truck Ford L8000 (6 cu.m.)

	Cycle time(min.)	Total busy time(min.)	Total Idle time(min.)	Utilization Rate	Total time(min.)
Excavator1	0.6	190.8	421.7	31.15%	612.5
Excavator2	0.6	190.2	422.3	31.05%	612.5
Truck1	2	212	399.9	34.65%	611.9
Truck2	2	210	402.2	34.30%	612.2

Two excavators HITACHI 450D (2 cu.m.) with two truck John Deere 400D (24 cu.m.)

	Cycle time(min.)	Total busy time(min.)	Total Idle time(min.)	Utilization Rate	Total time(min.)
Excavator1	0.6	95.4	88.4	51.90%	183.8
Truck1	2	54	131.5	29.11%	185.5
Truck2	2	52	130	28.57%	182

As the result shows, the two excavators with two trucks fleet match is not the best fit for this site situation. Then, do other two scenarios: 1) one excavator (8 cu.m.) with one truck (24 cu.m.) 2) one excavator (8 cu.m.) with one truck (40 cu.m.).

For those two scenarios' results though SDSEA shows bellow:

One excavator (8 cu.m) with one truck (24 cu.m.)

	Cycle time(min.)	Total busy time(min.)	Total Idle time(min.)	Utilization Rate	Total time(min.)
Excavator1	0.6	95.4	88.4	51.90%	183.8
Truck1	2	106	79.5	57.14%	185.5

One excavator (8 cu.m) with one truck (40 cu.m.)

	Cycle time(min.)	Total busy time(min.)	Total Idle time(min.)	Utilization Rate	Total time(min.)
Excavator1	0.6	95.4	52.7	64.42%	148.1
Truck1	2	62	85.8	41.95%	147.8

As the result shows, bring the excavator larger will increase the truck utilization rate and shorter the construction duration. However, since the truck travel

distance is relatively short against loading, the truck utilization rate can only reach to about 60%, the other 40% of the time, the truck is waiting before loading and during loading.

### ***6.8 Achievement***

In this case study, the earthwork production design optimization and earthmoving operations optimization have been presented. By considering factors including resource, spatial condition, and the randomness of the construction process, and applying least square methods, the whole site earthwork project duration can be reduced. The result could also guide the equipment selection process and provide quantitative suggestions to determine the project schedule in order to optimize the resource allocation, save resource consumption, and improve construction efficiency. Adopting SDESA to simulate construction, I have been found that the utilization rate is not good enough as the data is estimated only, not the real data gain from the site. But, it should be known that the utilization rate of the resources should maintain within the range between 70% to 95%, so that the resources will not be wasted or idled during the processing, and if there is breakdown or unsatisfactory of one process, the resources will be fully utilized or slow down the whole progress as it becomes a bottleneck. The industry needs the method which is accurate, easy-to-use, and proven. The method that describe above will fit that need.

## **Chapter 7 Conclusion and Future Study**

### ***7.1 Conclusion***

This reach has been getting the following achievements: Firstly, modifications of the least squares method were presented to do the earthwork optimization. Compare the previous researcher work, the new Excel Solver solution is easier to use, by set up slope constrain, define the grid cell's corner elevation and pre-define five (5) different design scenarios, the optimism model will fit for the real practice better. Secondly, transportation simplex method were applying to solve the mass transport minimize solution. In authors visualize, no site grading fleet transport minimization model has been present yet. And since the existing road fleet transport minimization model (Mass diagram and Weight-Grade line Method) is base on one direction mass transport (along the chainage axis), it cannot apply for site grading earthwork which is base on two directions. Thirdly, SDESA were applying to do the simulation for earthwork construction, the new resource based simulation model enrich the modeling consideration and achieved a better result. Also, a case study has been conduct to show the usage of above three advantage quantitative techniques. The case study has been found the new simulation model will get about 14% accurate construction schedule than the traditional hand allocation and the study also found the equipment fleet matching is greatly affect the truck utilization rate (can be as low as 34%), the loader cycle need be included in the simulation model which previous model has been eliminated.

### ***7.2 Future Study of HCCIM***

In recent decades, numerous research studies have been carried out to improve this practice, with most of the research focus on residential and commercial site development. And to date, site development for heavy and civil construction has been studied in detail, but no integration system has been developed to make the site development design and construction in a seamless process.

In present times, during a typical site development process, the engineer usually



uses GIS or CAD for the conceptual planning and civil design software for the detailed geometric design. During these processes, several models or studies need to be taken into account (e.g. digital terrain model, water distribution, hydraulic study, transportation study, etc.). Computer tools are also used for these activities, such as AutoCAD, MicroStation, Civil 3D or InRoads, and calculation software such as stormwater master, culvert master and custom developed tools like Excel spreadsheet.

HCCIM (Heavy and Civil Construction Information Modeling) is mainly a combination system that covers the entirety of civil related engineering work for heavy industry land development. The system made engineering calculation and drafting as a seamless process which will minimize the mistake happened in data transfer. In the calculation and analysis part, it provide most of functions for civil design, the data can be automatic transfer to CAD system to produce the drawing. In CAD plug-in part, HCCIM provide series function to make drafting process faster and more accurate. HCCIM will fill the gap between each stage and is able to keep more information in an organized fashion for future use. It will be beneficial for all parties involved, including the engineering consultant, construction contractor and owner. Instead of the traditional way, where certain document papers are used to transfer information to the next stage, this system will create a continuous flow of information in the electronic environment. It will create a task driven process as opposed to a document driven one, to increase job efficiency. Firstly, AutoCAD based software was developed. This software optimizes typical civil design work in the geometric modeling design stage, and it also allows export of geometric information to Excel for future analysis and optimization. Secondly, a series of Excel spreadsheets were created for the design and analysis, which cover civil related areas such as survey, geotechnical, hydrology and hydraulic, structure etc.

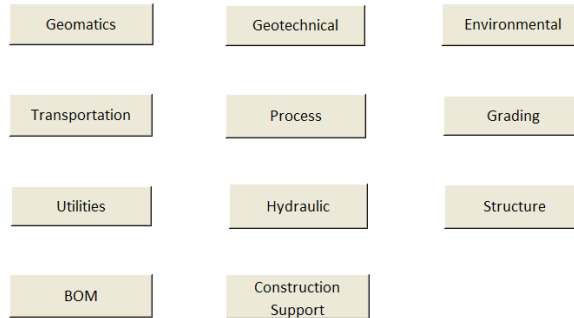
### **7.2.1 Engineering for HCCIM**

Land development civil design involves numerous analysis and calculations in

several fields such as geomatics, geotechnical, environmental, transportation, process, grading, hydraulics, and structure. In current practice, certain analyses and calculations are performed by various software and certain items are still calculated by hand. However, combining both these methods of analysis into an integrating system, HCCIM, would be more beneficial since it has many advantages. Most often, calculations will need certain spatial data as their input, so using the same system will reduce data translation work and provide more accurate results. It also allows the collection of related information and then transfers it to Excel. When using the model's information for calculations, the layers must be taken into account. Through the layer system, filter the information that the calculation does not need. Another advantage is of HCCIM is its features. The features have more functions than CAD elements and can be stored in a database as opposed to a drawing form. The following feature shows the main interface of HCCIM

The traditional civil design software mainly deals with earthwork. First, it sets an original surface from survey data, then builds other design surfaces using 3D elements, alignments (horizontal and vertical), and templates. After that, the surfaces are compared to get the earthwork volume. Usually, existing civil design software provides transportation and hydraulic design tools that can perform calculation tasks such as deciding horizontal and vertical curves or calculating the size of pipe/channel/culvert. However, the analysis functions are limited, so this area needs improvement as well. HCCIM, a computer integrated system, compared to traditional civil design software, provides more analysis functions and collaboration tools for engineering design. HCCIM enhances traditional civil design tools by including elements such as geotechnical, drainage, and structure analysis, among others. To minimize the amount of work and better use the existing resource, HCCIM functions as an add-in to existing software. This paper will build a framework of H.C.C.I.M and focus on the heavy industry civil development engineering process.

**Civil Information Modeling  
(For Heavy Industry Land Development)**



**Figure 7-1 HCCIM main interfaces**



**Figure 7-2 HCCIM CAD Add-ins**

The above figure shows the main interface of HCCIM’s calculation and analysis portion, which is covering most of practices for civil engineering in heavy industry project. Those items generally flow the step of civil engineering procedure. For example, civil engineering is usually starts at geomatics survey and geotechnical investment. In the parallel of survey and geotechnical investment, the environment site assessment/study needs to be accomplished as well. Once the survey map and geotechnical report done, transportation, grading and hydraulic (drainage) design will be performed at the same time. Those three

practices usually affect each other and the engineer need make sure those things work and at the same time cooperate each other. Process, utilities and structure design can be done separately with minor impact with major civil work. The Bill of Material will come up with the final engineering drawing and construction support go afterwards.

### **7.2.2 Construction and maintenance for HCCIM**

The whole HCCIM system includes three major parts- Engineering, Construction and Maintenance. In the construction part, more information on construction needs is required. It is divided into four major functions: model, analysis, scheduling and procurement. The maintenance section involves storage of all the records and ensuring that information is regularly updated for future use.

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## APPENDIX 1 Least squares solution

The following presentation of the details of development of the least squares solution has been reduced to the ultimate useful solution shown in the text. The development begins with Eq.2 (shown earlier) and continues to the final forms of the equation that can be solved by determinants and Cramer's Rule.

Eq. 4, repeated here, is the equation for the sum of squares of the distances between the soil surface at individual grid points within a field to be graded and a plane described by Eq. 1 (also first shown earlier in the text):

$$H(x,y) = a + bx + cy \quad \text{Eq.1}$$

$$R = \sum_{x=1}^m \sum_{y=1}^n [h \times (x_i, y_j) - (a + bx_i + cy_j)]^2 \quad \text{Eq. 2}$$

Where R = the sum of squares of the elevation difference; m and n = the number of points in the x and y directions, respectively, of a rectangular grid enclosing the area to be graded; and h = the elevation of the soil surface at an interior grid point (x<sub>i</sub>, y<sub>j</sub>). The parameter a is the elevation of the plane of Eq. 1 at the origin of the coordinate system, b is the slope of the plane in the x direction, and c is the slope of the plane in the y direction.

A necessary condition for R to be a minimum is that its partial derivatives with respect to a, b, and c be equal to zero.

$$\frac{\partial R}{\partial a} = -2 \sum_{x=1}^m \sum_{y=1}^n [h(x_i, y_j) - (a + bx_i + cy_j)] = 0$$

$$\frac{\partial R}{\partial b} = -2 \sum_{x=1}^m \sum_{y=1}^n (x) [h(x_i, y_j) - (a + b + cy_j)] = 0$$

$$\frac{\partial R}{\partial c} = -2 \sum_{x=1}^m \sum_{y=1}^n (y) [h(x_i, y_j) - (a + bx_i + cy_j)] = 0$$

Eq. 3,

4, 5

The partial derivatives of Eqs. 3-5 result in a series of 3 equations with 3

unknowns a,b, and c that can be solved by determinants and Cramer's Rule:

$$\begin{aligned}
 a\left(\sum_{x=1}^m \sum_{y=1}^n x_i\right) + b\left(\sum_{x=1}^m \sum_{y=1}^n x_i^2\right) + c\left(\sum_{x=1}^m \sum_{y=1}^n y_i\right) &= \sum_{x=1}^m \sum_{y=1}^n h(x_i, y_j) \\
 a\left(\sum_{x=1}^m \sum_{y=1}^n x\right) + b\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) + c\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) &= \sum_{x=1}^m \sum_{y=1}^n (x)[h(x_i, y_j)] \\
 a\left(\sum_{x=1}^m \sum_{y=1}^n y\right) + b\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) + c\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) &= \sum_{x=1}^m \sum_{y=1}^n (y)[h(x_i, y_j)]
 \end{aligned}$$

Eq. 6,

7, 8

The determinant of this system of equations with 3 unknowns a, b, and c is not zero, so the equations have exactly 1 solution. Certain programmable calculators have packaged or internal programs that can perform the computations for a determinant solution from the resulting elements of the matrix and the column vectors.

The solution of the system of Eqs. 33-35 given below follow the Cramer's Rule Formulas:

$$a = \frac{D_1}{D}; b = \frac{D_2}{D}; c = \frac{D_3}{D}$$

Eq. 9

In which D = the determinant of the system of 3 linear equations (Eq. 6-8); and D<sub>k</sub> (K = 1, 2, and 3) = the determinant obtained by replacing the Kth column in D with the column vector. The detail equations for computing D and D<sub>k</sub> (K=1, 2 and 3) from the grid data are given below. The value of N is Eq. 4 (the paper's Eq.4) is the actual number of data points within the area to be graded. The number of points may be much larger. Only the points x<sub>i</sub> and y<sub>j</sub>, which are within the field to be graded, should be used in the computations:

$$\begin{aligned}
D &= (N)\left(\sum_{x=1}^m \sum_{y=1}^n x_i^2\right) + b\left(\sum_{x=1}^m \sum_{y=1}^n y_i^2\right) - \left(\sum_{x=1}^m \sum_{y=1}^n xy_i\right)^2 + 2\left(\sum_{x=1}^m \sum_{y=1}^n x_i\right)\left(\sum_{x=1}^m \sum_{y=1}^n y_j\right)\left(\sum_{x=1}^m \sum_{y=1}^n x_i y_j\right) \\
&\quad - \left(\sum_{x=1}^m \sum_{y=1}^n x^2\right)\left(\sum_{x=1}^m \sum_{y=1}^n y\right)^2 - \left(\sum_{x=1}^m \sum_{y=1}^n y^2\right)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)^2 \\
D_1 &= \left(\sum_{x=1}^m \sum_{y=1}^n h(x, y)\right)\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right)\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) - \left(\sum_{x=1}^m \sum_{y=1}^n xy\right)^2 + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)\left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) \\
&\quad - \left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) + \sum_{x=1}^m \sum_{y=1}^n yh(x, y)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) - \left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) \\
D_2 &= \sum_{x=1}^m \sum_{y=1}^n h(x, y)\left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) - \left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)N\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) \\
&\quad - \left(\sum_{x=1}^m \sum_{y=1}^n y\right)^2 + \left(\sum_{y=1}^n \sum_{x=1}^m yh(x, y)\right)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{y=1}^n \sum_{x=1}^m y\right) - n\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) \\
D_3 &= \sum_{x=1}^m \sum_{y=1}^n h(x_i, y_i)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) - \left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{y=1}^n \sum_{x=1}^m y\right) \\
&\quad - N\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) + \left(\sum_{y=1}^n \sum_{x=1}^m yh(x, y)\right)N\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) - \left(\sum_{x=1}^m \sum_{y=1}^n x\right)^2
\end{aligned}$$

Eq. 10,11,

12,13

In Eq. 10-13 there are a number of recurring factors that can be identified as given below:

$$\begin{aligned}
C_1 &= \left(\sum_{x=1}^m \sum_{y=1}^n x_i^2\right) + \left(\sum_{x=1}^m \sum_{y=1}^n y_i^2\right) - \left(\sum_{x=1}^m \sum_{y=1}^n xy\right)^2 \\
C_2 &= \left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) - \left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n y^2\right) \\
C_3 &= \left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n xy\right) - \left(\sum_{x=1}^m \sum_{y=1}^n y\right)\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) \\
C_4 &= \left(\sum_{x=1}^m \sum_{y=1}^n x\right)\left(\sum_{x=1}^m \sum_{y=1}^n y\right) - N\left(\sum_{x=1}^m \sum_{y=1}^n xy\right)
\end{aligned}$$

Eq. 14,15,

16,17

Therefore, the equations for the determinants for the purposes of computation can be simplified to those which follow. It should again be emphasized that N is the number of points within the actual area to be graded and is not the number of grid points in the x,y grid system. Only the data points within the area to be graded should be used in the computation. One method of avoiding difficulties is to

assign zero elevation values to grid points outside the area to be graded so they can be identified and eliminated from the computations.

The useful equations for determining the values of a, b, and c for the equation of the least squares plane (Eq.1) from Eq. 9 are

$$D = NC_1 + 2\left(\sum_{x=1}^m \sum_{y=1}^n x_i\right)\left(\sum_{x=1}^m \sum_{y=1}^n y_i\right)\left(\sum_{x=1}^m \sum_{y=1}^n x_i y_i\right) - \left(\sum_{x=1}^m \sum_{y=1}^n x^2\right)\left(\sum_{x=1}^m \sum_{y=1}^n y\right)^2 - \left(\sum_{x=1}^m \sum_{y=1}^n y^2\right)\left(\sum_{x=1}^m \sum_{y=1}^n x\right)^2$$

$$D_1 = \sum_{x=1}^m \sum_{y=1}^n h(x, y)C_1 + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)C_2 + \sum_{y=1}^n \sum_{x=1}^m yh(x, y)C_3$$

$$D_2 = \sum_{x=1}^m \sum_{y=1}^n h(x, y)C_2 + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)N\left(\sum_{y=1}^n \sum_{x=1}^m y^2\right) - \left(\sum_{y=1}^n \sum_{x=1}^m y\right) + \left(\sum_{y=1}^n \sum_{x=1}^m y\right) + \left(\sum_{y=1}^n \sum_{x=1}^m yh(x, y)C_4\right)$$

$$D_3 = \left(\sum_{x=1}^m \sum_{y=1}^n h(x, y)C_3 + \sum_{x=1}^m \sum_{y=1}^n xh(x, y)C_4 + \sum_{y=1}^n \sum_{x=1}^m yh(x, y)N\left(\sum_{x=1}^m \sum_{y=1}^n x^2\right) - \left(\sum_{x=1}^m \sum_{y=1}^n x\right)^2\right)$$

Eq. 18,19,

20,21

When the parameters of the least squares plane equation have been determined, the equation of the plane can be used in the land grading design.

## APPENDIX 2 Soil density with compaction

The density in relation to penetrometer and pressure meter-test results for non-cohesive soils

DPH <sup>1</sup>	SPT <sup>2</sup>	CPT <sup>3</sup>	Pressure meter Test		Density
N <sub>10</sub>	N <sub>30</sub>	q <sub>s</sub>	pl	E <sub>m</sub>	
		Kip/ft <sup>2</sup>	Kips/ft <sup>2</sup>		
	<4	50	<4	30	Very loose
3	4-10	50-160	4-10	30-100	Loose
3-15	10-30	160-315	10-30	100-300	Medium dense
15-30	30-50	315-520	30-52	300-520	Dense
>30	>50	>520	>52	>520	Very dense

Dynamic probing heave

Standard penetration test (dynamic)

Cone penetration test (static)

The consistency of cohesive soils in relation to SPT, CPT and pressuremeter-test results is as follows:

SPT <sup>1</sup>	CPT	Pressuremeter Test		Consistency	Undrained shear strength
N <sub>30</sub>	q <sub>s</sub>	pl	E <sub>m</sub>		
	Kips/ft <sup>2</sup>	Kips/ft <sup>2</sup>			Lbs/ft <sup>2</sup>
<2	5	<3	30	Very soft	320
2-4	5-10	3-7	30-110	Soft	320-840
				Soft to firm	840-1050
4-8	10-20	7-12	110-175	Firm	1050-1570
				Firm to stiff	1570-2090
8-15	20-40	12-20	175-420	Stiff	2090-3150
15-30	40-85	20-40	420-840	Very stiff	3150-4175

>30	>85	>40	>840	hard	>4175
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SPT values should not be used to evaluate clay layers.

R.H. Mayer, M.S. Robert. Earthmoving logistics, Journal of the construction division (1981) 297-312.

The correlations between the different methods of soil tests are not based on any standards. Each method gives its own specific classification of subsoil. The tables serve only as an aid to the user to complement their own soils analysis.

## APPENDIX 3 Core AutoLISP code

```
(defun c:aaa(/ h h1 n pnt1 pnt2 c m p1 p2 t pnte pntv fi f ai bi ci d e)
  (graphscr)
  (setq pnt1 (getpoint"\n "))
  (setq pnt2 (getpoint"\n "))
  (setq h (getdist"\n "))
  (setq h1 (- (car pnt2) (car pnt1)))
  (princ
  (setq n (fix(/ (- (cadr pnt2) (cadr pnt1)) h))))
  (setq c 0)
  (repeat n
    (setq p1 (list (car pnt1) (+ (cadr pnt1) c)))
    (setq p2 (list (+ (car pnt1) h1) (+ (cadr pnt1) c)))
    (command"line"p1 p2")
    (setq c (+ c h))
  )
  (setq pntv p1)
  (setq pnte p2)
  (setq t 1)
  (setq c 0)
  (setq m (+ (fix(/ (- (car pnt2) (car pnt1)) h)) 1))
  (repeat m
    (setq p1 (list(+ (car pnt1) c) (cadr pnt1)))
    (setq p2 (list(+ (car pntv) c) (cadr pntv)))
    (command"line" p1 p2")
    (setq c (+ c h))
  )
  (setq fi(getstring"\n "))
  (setq f(open fi "r"))
  (setq ai (list (+ (car pnt1) 1) (+ (cadr pnt1) 1)))
```

```

(setq bi (list (+ (car pnt1) 1) (- (cadr pnt1) 5)))
(setq ci (list (- (car pnt1) 5) (+ (cadr pnt1) 1)))
(repeat n
  (repeat m
    (setq d(read-line f))
    (setq e(read-line f))
    (command"text"ai 3 0 d)
    (setq d(read d))
    (setq ai(list (+ (car ai) h) (cadr ai)))
    (command"text"bi 3 0 e)
    (setq e(read e))
    (setq bi(list (+ (car bi) h) (cadr bi)))
    (command"text"ci 3 0 (- d e))
    (setq ci(list (+ (car ci) h) (cadr ci)))
  )
  (setq ai (list (- (car ai) (* m h)) (+ (cadr ai) h)))
  (setq bi (list (- (car bi) (* m h)) (+ (cadr bi) h)))
  (setq ci (list (- (car ci) (* m h)) (+ (cadr ci) h)))
)
)

```