Decision Aids for Tunneling

A CATALOGUE FOR APPLICATION TO SMALL TUNNELS

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Abstract

The Decision Aids for Tunneling are a very powerful tool in assisting decision makers. They have been developed and applied over decades. As popular as they have become in big tunneling projects, they remain complicated and less used for small tunnels. The objective of this work is to devise a way to facilitate their use for small tunneling applications.

After considering two different approaches, a "calculator" and a "catalogue", the latter was developed. A Catalogue is arguably the best option to do so, as a compromise between both extremes of completely modeling each project and just not using the DAT. The users only have to consult the proper pre-developed chart in order to obtain the total construction time and cost for their project without using the DAT or running any simulations themselves.

The Catalogue currently consists of 27 charts. Each one presenting results based on 50,000 simulations for each one of five length steps: 1 to 5 km. The results are based on simulating different combinations of geologic conditions representing: lithology, fracturing and water inflow. In terms of construction considerations, the Catalogue's data are for TBM tunnels excavated from one portal only, with a 9 meters diameter.

Future expansions of the Catalogue to more complex geologies, different diameters, construction methods and tunnel configurations are sure to make it even more potent and useful.

Résumé

Les instruments d'aide à la décision pour la construction de tunnels ADCT ou simplement DAT (de l'anglais, Decision Aids for Tunneling) ont été développés il y a des décennies et ont depuis, déjà fait leurs preuves. Leur utilisation dans l'industrie reste néanmoins limitée aux grands projets puisqu'ils sont relativement complexes et par conséquent, moins appréciés pour les tunnels de petite taille. L'objectif principal de ce travail consiste à développer des solutions afin d'encourager l'utilisation des DAT pour des projets de tunnels de taille restreinte.

Afin de venir à bout de cet objectif, l'option de développer un « catalogue » a été retenue suite à une analyse d'autres alternatives notamment celle d'une simplification de l'interface des DAT, nommée « calculatrice ». Un Catalogue constitue la meilleure option puisqu'il présente un compromis parfaitement balancé entre les deux extrêmes, d'une modélisation complète ou au contraire, de totalement négliger l'utilisation des DAT. L'utilisateur n'a qu'à consulter la bonne référence dans le Catalogue afin d'obtenir les valeurs recherchées des coûts et du temps de construction pour un projet, sans devoir passer par les DAT ni lancer des simulations.

A présent, 27 diagrammes forment le contenu du Catalogue. Chaque diagramme présente les résultats basés sur 50,000 simulations pour chacun des cinq incréments de longueur allant de 1 à 5 km. Les résultats simulent différentes combinaisons de conditions géologiques traitant principalement la lithologie, la fracturation et les venues d'eau dans les roches. En ce qui concerne la construction, les résultats du Catalogue sont propres à une excavation au tunnelier, de 9 mètres de diamètre, et pour un avancement en sens unique d'un portail à un autre.

Les développements futurs du Catalogue promettent d'incorporer plus de complexités géologiques, différents diamètres, différentes méthodes d'excavation et différentes configurations de tunnels. Ainsi, le Catalogue verra son potentiel croitre avec la richesse de sa librairie de données.

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Table of Contents

List of Figures

List of Tables

INTRODUCTION

Tunnels remain some of the biggest endeavors in geotechnical engineering. Uncertainties and risks are naturally present and particularly problematic when considering the scale and budget of such projects. Significant time and money are invested in the early design phases in order to foresee and mitigate potential risks and reduce certain variabilities. Consequently, for a single project, numerous alternatives are put forward to be thoroughly analyzed while considering different criteria and their respective uncertainties. Conducting detailed analyses with so many inputs proves to be a very tedious and rigorous task.

The Decision Aids for Tunneling (hence, DAT) allow decision makers to consider the joint effects of the aforementioned criteria, in addition to their respective uncertainties, using simulations and statistical tools. The Decision Aids were first developed decades ago and have been in use ever since in many projects around the world. After more than fifty years of experience with the DAT, observations reveal that it remains mostly used for big projects while small tunnels usually do not warrant their use. This is where the objective of this work emerges. How is it possible to encourage the use of the DAT for small tunneling projects? For the sake of consistency, the terminology "small" will mainly refer to short tunnels. It is therefore a qualification of the length and not of the diameter of a tunnel.

In an attempt to solve this problem, it is necessary to present the DAT and other useful tunneling decision tools. This is the scope of Chapter 1. An illustrative example, in Chapter 2, presents a small application of the DAT in action, reflecting its potential for a real case.

Chapter 3 initiates the reflections around the stated objective and presents different alternatives to adapt the DAT for small tunnels. A Catalogue, consisting of charts with construction cost and time information, is retained as the preferred one and thus, developing it becomes the focal point of the work.

Chapters 4 and 5 encompass all the required inputs, respectively dealing with classical tunneling inputs such as cost-time estimates in Chapter 4 and with the required number of iterations for Monte Carlo simulations in Chapter 5.

Chapter 6 presents the developed Catalogue in one package along with all of its guidelines, recommendations, rules of usage and future potential expansions. It is offered in a ready-to-read format for direct consultation. Additionally, discussions about the results are presented in Chapter 7 with deeper reflections on the obtained data.

CHAPTER 1

1 LITERATURE REVIEW

1.1 DAT and Tunneling Literature

1.1.1 DAT Description

The Decision Aids for Tunneling are a computer-based tool with which one can determine tunnel construction cost and time as well as other information (Einstein, 2004). This set of results can support many potential applications for the DAT that will be further examined in the following section. First, some basic information is provided in order to understand the theoretical background of the system.

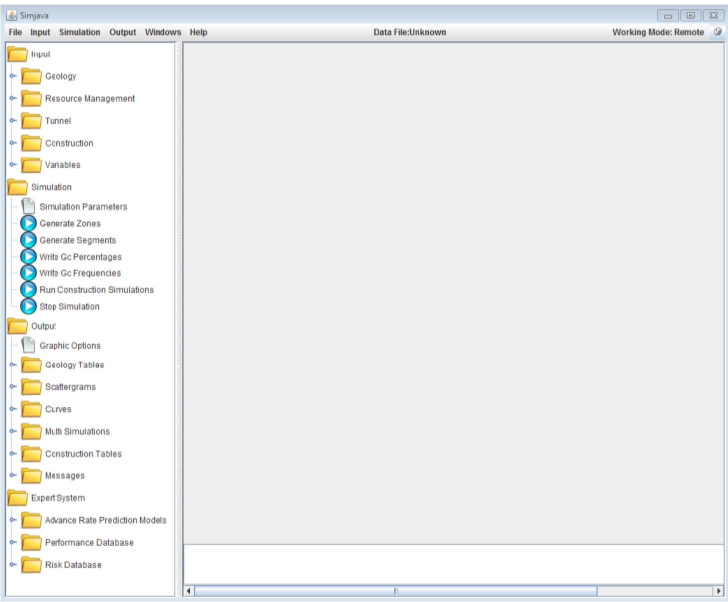


Figure 1.1: DAT computer interface

When seeking to estimate tunnel construction cost and time, numerous factors need to be considered. This is done through three major components also referred to as modules (Einstein et al., 2017).

- Geology description
- Construction simulation
- Resource management

Each module acts like an umbrella covering different sub-fields. With all the inputs in place, the software generates geological profiles, based on the set of probabilistic rules chosen by the user, followed by a Monte Carlo simulation for the construction process. The end results take the form of graphs or tables mostly in the form of "clouds" of dots corresponding to iterations showing the probabilistic distribution of the tunnel construction time and cost. These distributions are referred to as cost-time scattergrams (Einstein et al., 2017). They reflect the overall uncertainty of the results.

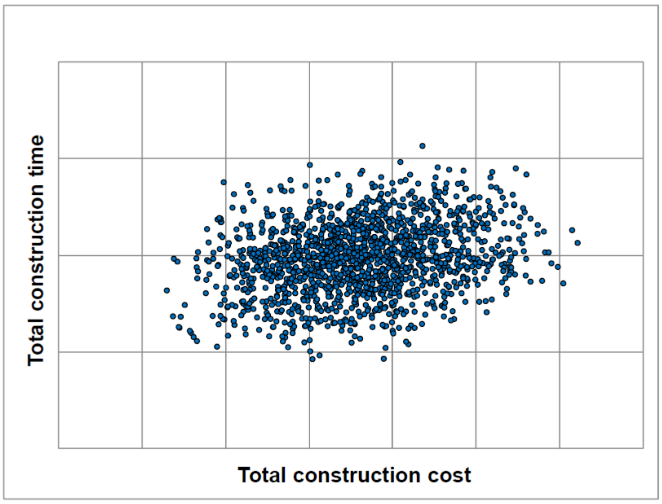


Figure 1.2: Scattergram example

1.1.2 DAT Operation Details

The most important modules (also the ones that are always required for most applications of the DAT) are the Geology and Construction modules. They are treated in a semi-independent fashion by the software; the geology profiles are indeed generated first, regardless of whatever is defined in the construction part.

The theoretical aspect behind these processes is briefly detailed below.

Geology

The description of the geology produces geological and geotechnical profiles along the tunnel (Einstein et al., 2017).

Areas and zones define the "geometry" of the tunnel for which geological and geotechnical parameters are produced according to defined user inputs. Ground Parameters (GP) are defined by the user according to the needs of every case. Examples of ground parameters are: lithology, water, squeezing, spalling etc. Each GP is associated with different states. For instance, GP states for lithology may be: granite, limestone etc. Each GP state is applied along the tunnel areas/zones based on a user defined rule: deterministic, semi-deterministic or probabilistic (Markov, triangular Markov, fixed triangular Markov) each with different required inputs. The latter usually are the average length, minimum and maximum values, transition probabilities etc. These enable a realistic modeling of the tunnel's geology based on multiple levels of uncertainties. Ground Classes (GC) attribute a certain geologic "qualification" to different possible combinations for all GP and GP states. In simple terms, they define the combinations that could for instance be qualified as good or bad and everything in between. A schematic representation appears in Figure 1.3 (Einstein et al., 2017).

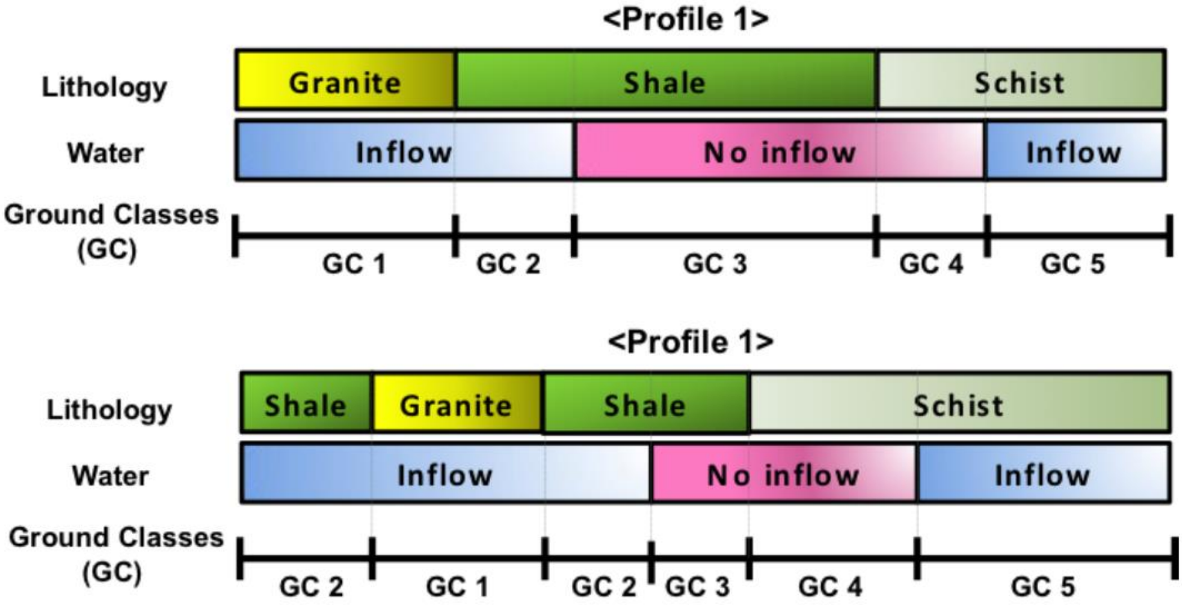


Figure 1.3: GP, GP sets and GC example

Construction

The geological profiles are generated based on what was described in the previous section. In these profiles, construction simulations will be applied using a Monte Carlo procedure. The level of complexity is once again decided by the user, ranging from simple time/cost rates per unit length, to describing all construction activities (such as drilling, loading, blasting etc.) (Min et al., 2003). Geometries and a tunnel network configuration are also needed to simulate factors that may have significant effects such as: multiple tubes, delays, intermediate access tunnels etc. Eventually, each ground class is related to a construction method with associated times and costs, with their respective probabilistic distributions. Method changes, learning curves etc. can also be considered in the simulations.

More complex examples are also shown in other sections of this work. At this stage, the following schematic in Figure 1.4 is used for illustrative purposes (Einstein et al., 2017).

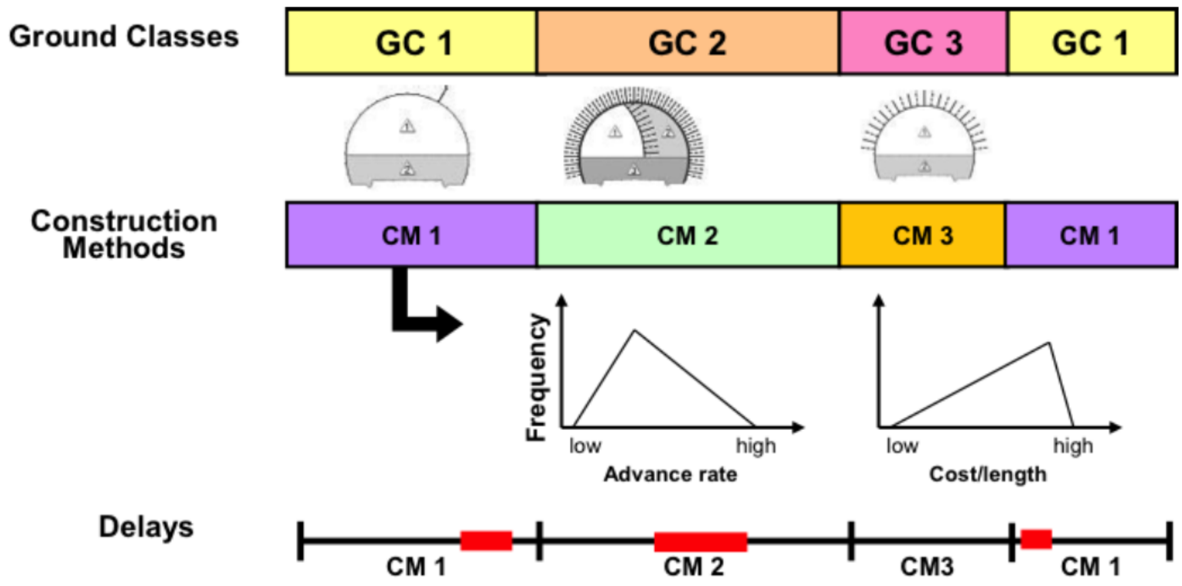


Figure 1.4: Construction methods and delays example

1.1.3 DAT Applications

Uses of the DAT cover a wide spectrum of the needs relative to tunneling projects. These include: finding the best alternative, finding the best construction method, updating and forecasting, managing resources, analyzing risks etc. Recently, new expansions even consider going beyond basic tunneling into more heterogeneous projects that are, like tunnels, based on similar uncertainties and variabilities. Examples of these include linear infrastructure networks and deep wells.

Best Alternative Determination

Perhaps the most basic objective and most popular use of the DAT is to compare different alternatives for the same project in the planning phase, in order to eventually converge towards the most favorable one. This is where decision makers are in need of "decision aids" in order to be able to tackle the large amount of inputs and their variabilities and eventually pick the best solution in a rational and objective manner with a quantified statistical consideration of associated risks.

One example of this use of the DAT, goes back to 1991 in the transalpine context of Switzerland (Einstein, 2004). During the development and design phase of the Gotthard base tunnel, three possible systems were proposed and studied in parallel (Descoeudres and Dudt, 1993). Naturally, each alternative results in a different cost and time of completion, but also in different variabilities in these results based on the associated risks. The conducted DAT simulations appear in Figure 1.5 (Einstein et al., 2017).

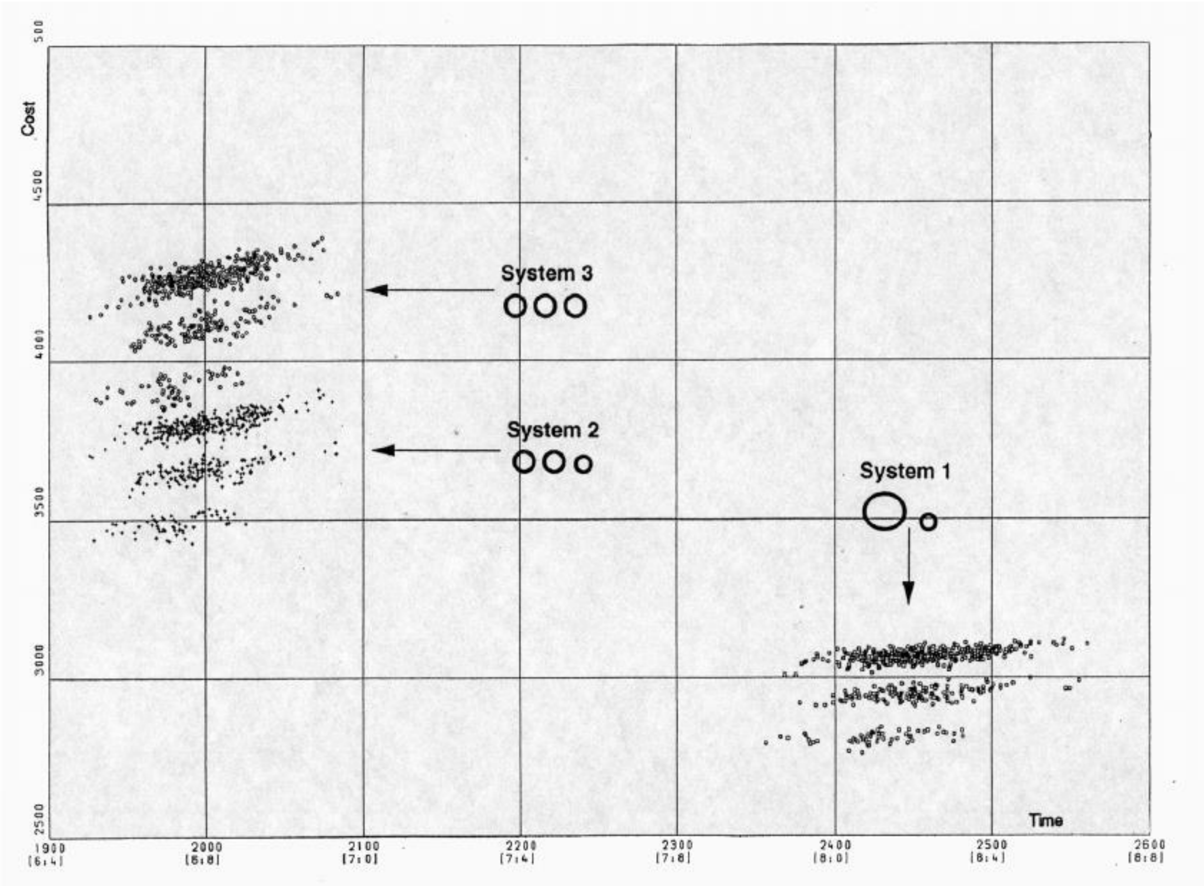


Figure 1.5: Three systems for the Gotthard base tunnel preliminary study in 1991

Clearly, system 1 is the least costly but is associated with the longest completion time. Systems 2 and 3 seem to have comparable completion times, yet system 3 is more expensive. Also, the estimations of time and cost have different associated levels of variability, embodied by the amount of scattering of the points in one cloud. Note that each system appears to have three clouds in the graph. This is relative to another application of the DAT that aims to investigate the effect of encountering, or evading, a particularly problematic geology formation.

Other examples exist, for instance in the case of a 1.9 *km* tunnel in the southern province of Korea, where three models have been developed for the three phases of planning: initial simulation, simulation after feedback from the client and finally a third final simulation (Min et al., 2003).

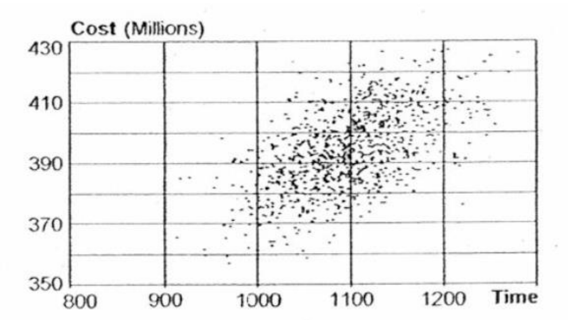
Best Construction Method Determination

When different construction methods need to be compared, a lot of effort revolves around qualitative descriptions based on previous experience. For instance, microtunneling and full face TBM tunneling have been compared (Sinfield and Einstein, 1996). Each method has its own specificities namely: equipment, cycle steps, advance rates, costs and delays. It is seemingly impossible to conduct a quick comparison while considering all the aforementioned information. The DAT are able to simulate the full complexity of the problem, not only once, but for many user defined iterations. This is particularly useful to obtain results, but also to discuss their generalizability based on sensitivity and parametric analyses (Sinfield and Einstein, 1996).

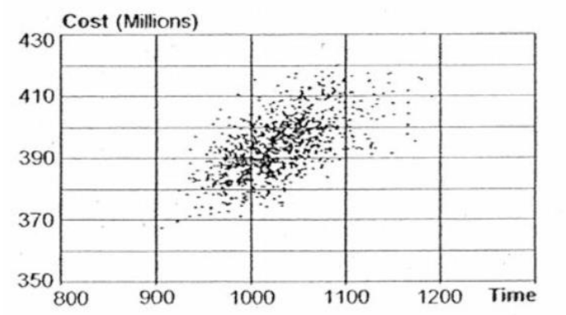
Updating

The concept of updating involves the incorporation of new information in the estimates, leading to a change in the resulting scattergrams (Einstein, 2004). The literature differentiates two types of updating: conducting new exploration in order to reduce the geological uncertainties and narrow the scatter cloud, is one option. The second, is to feed in the model new information obtained from the excavated part of the tunnel, to update the predictions for the yet unexcavated part (Einstein et al., 2017).

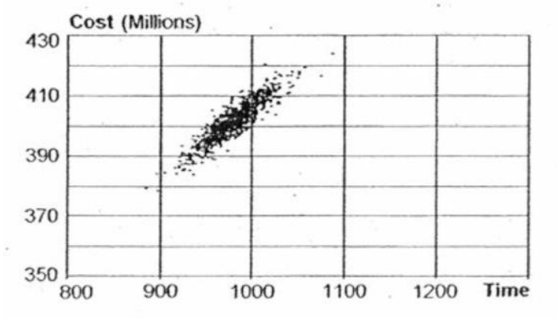
Figure 1.6 shows, respectively, a scattergram before construction, a scattergram with the known excavated parts but without updating of the unexcavated section and finally a scattergram with the known excavated parts used to update the unexcavated section (Einstein, 2004).



a.



b.



c.

Figure 1.6: Scattergram (a) before construction, during construction (b) without updating and (c) with updating

It is clear that the scattering becomes smaller and thus less uncertain.

Another updating example goes back to the Sucheon tunnel in Korea, where two simulations were conducted: one before and one during construction. The latter is based on updated geologic conditions as they were encountered during the excavation process for different construction methods. The results of updating are, as expected, a reduction of the observed uncertainty (Min, et al., 2008).

Resource Management

Another module in the DAT is dedicated to the management of resources. The management of waste or reuse of muck are typical examples, as they too, are subject to uncertainties relative to both the geology and construction process. An example in the literature is related to the Lötschberg tunnel in Switzerland with the intention to reuse the muck, in the attempt to minimize the amount of disposed material. Possible usages range from concrete/shotcrete aggregates to embankments (Einstein, 2004). However not all the muck can be reused, as the shape and size may be inappropriate or even have problems of alkali reactions in concrete mixes. These additional uncertainties can all be implemented in the modeling by defining muck classes and their respective variabilities with different end uses. Figure 1.7 schematizes the south side of the Lötschberg base tunnel with its repositories (Einstein, 2004).

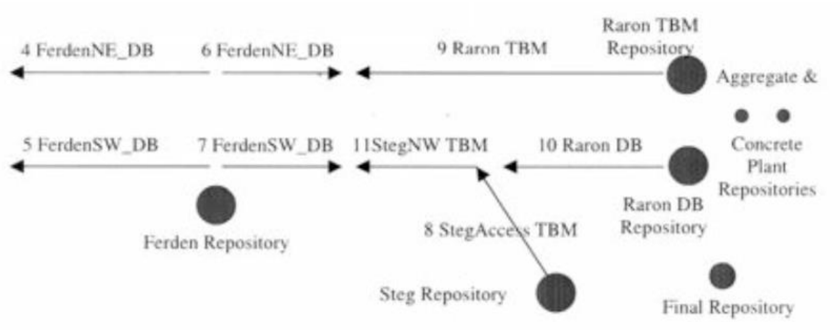


Figure 1.7: Lötschberg base tunnel south side, repositories used for materials management

DAT Extensions

Recent applications are making use of the DAT in a more revolutionary fashion. The most noticeable ones in the literature are the following:

- including optimization
- risk analysis for tunneling
- extension to linear, networked and other infrastructure
- extension to deep well boring

Looking at different alignments and comparing the resulting time-cost scattergrams is certainly possible with the DAT but is usually done "by hand". New extensions aim to include optimization and integration tools that could be combined with the DAT further improving its capabilities, as shown in Figure 1.8 (Einstein et al., 2017).

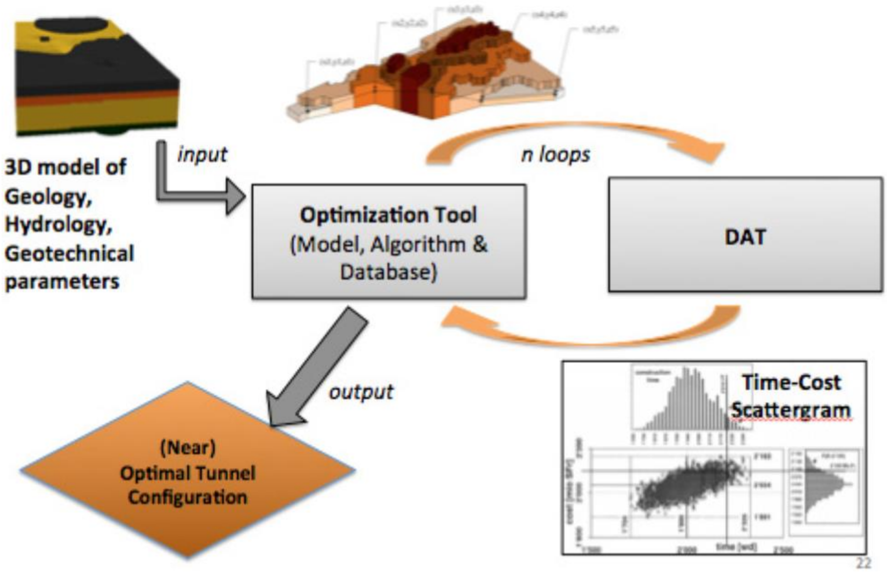


Figure 1.8: Combination of DAT and optimization systems

Risk analysis for tunneling relies heavily on the updating process by making use of recorded inputs during the excavated part in order to alleviate some uncertainties in the yet unexcavated parts. Some extensions aim to use this potential of the DAT to develop a warning system (Einstein et al., 2017).

Extensions of the DAT applications to linear infrastructure is also possible. These may include bridges, viaducts, roads, cuts and embankments etc. Some applications even make use of the DAT for deep geothermal systems where the uncertain factors are: component cost, drilling cost and time, fluid usage, trouble costs, geology and temperature effects (Einstein et al., 2017).

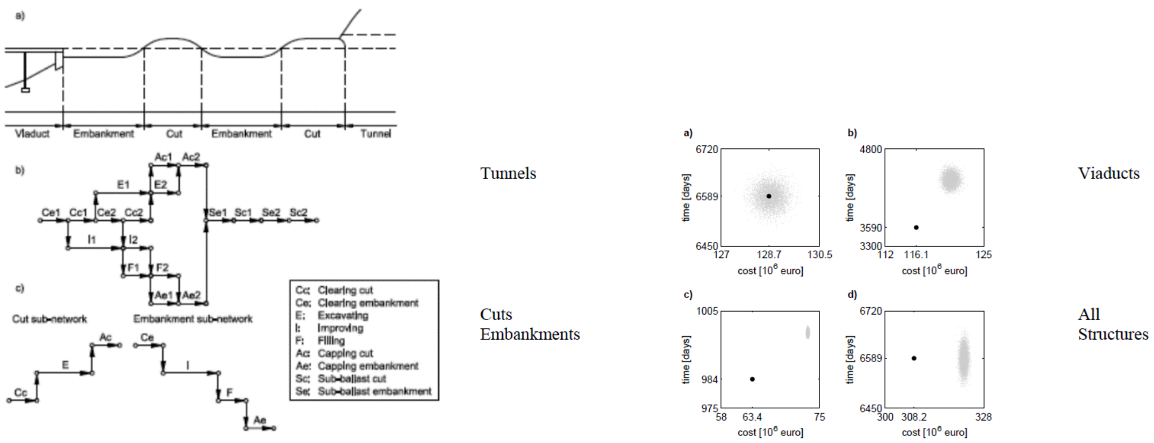


Figure 1.9: Extension of the DAT to linear or networked infrastructure

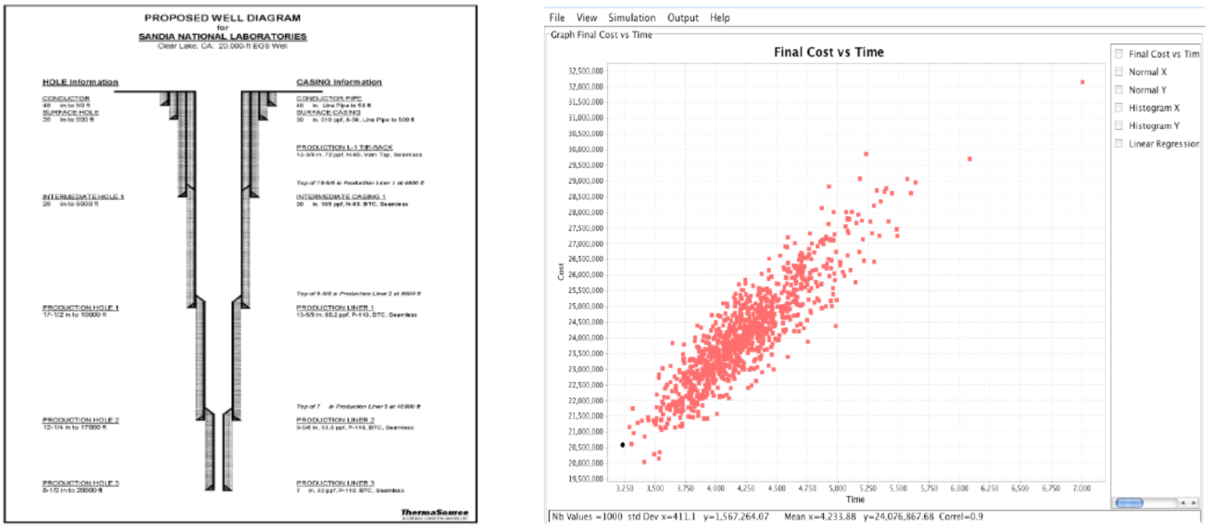


Figure 1.10: Extension of the DAT to deep geothermal systems

1.1.4 Modeling Correlations

In a study, Moret and Einstein, investigate what types of correlation occur in rail line construction, quantify their impact on the distributions of the total cost and the total time, and determine whether repetitions of activities can amplify the effect of correlations on such distributions.

Figure 1.11 shows how the total cost and total time are simulated. Correlated costs are generated with a correlation model, whose inputs are the correlation matrix and the marginal probability distributions; the generated correlated costs are summed to obtain the total cost. Regarding times, the times of activities on the critical path are summed to obtain the total time.

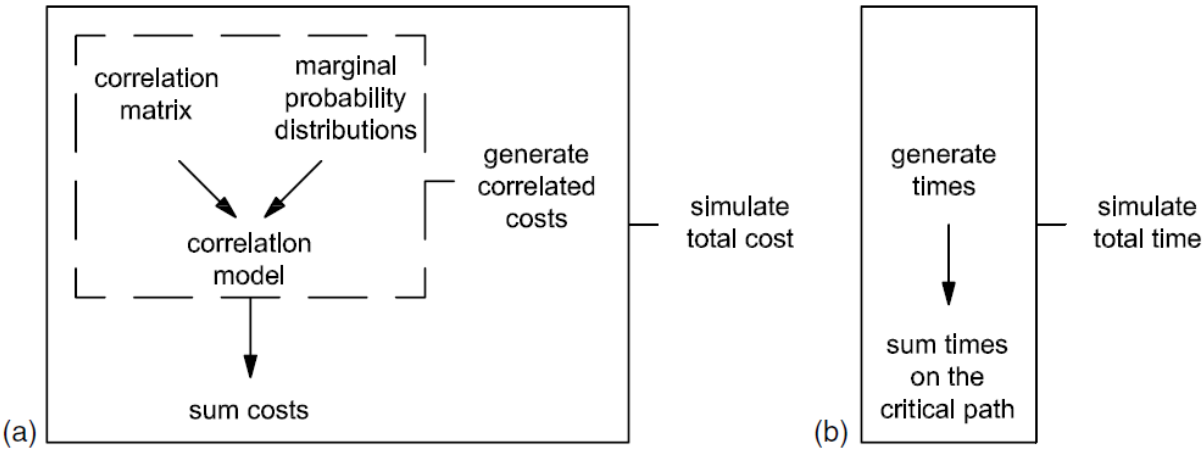


Figure 1.11: Simulations of (a) total cost and (b) total time

Many correlation types are identified, before focusing on two of them. These are (Moret and Einstein, 2012):

1. Correlation between the costs of different activities in a structure. An example can be the correlation between the cost of constructing a viaduct's pier and the cost of constructing its foundations.
2. Correlation between the costs of a repeated activity in a structure. For example, the correlation between the cost excavating the 10^{th} meter and the cost of excavating the 11^{th} meter in a tunnel.

The effect of correlation types 1 and 2 on the standard deviation of the total cost is investigated with two case studies: a viaduct and a tunnel, respectively. Hence, correlation type 1 is demonstrated with a case study with a 395 m long viaduct while the correlation of type 2 is investigated by relying on the case study of a 500 m long tunnel (Moret and Einstein, 2012).

Throughout the paper, a cost distribution C is defined with a lognormal distribution, where μ is the mean and σ is the standard deviation.

$$C \sim Lognormal\ (\mu, \sigma)$$

On the other hand, a triangular distribution is chosen for time T, where $Min, Mode$ and Max are respectively the minimum, mode and the maximum, of the triangular distribution.

$$T \sim Triangular\ (Min, Mode, Max)$$

Figure 1.12 graphically shows the shapes attributed to cost (lognormal) and time (triangular) distributions (Moret and Einstein, 2012).

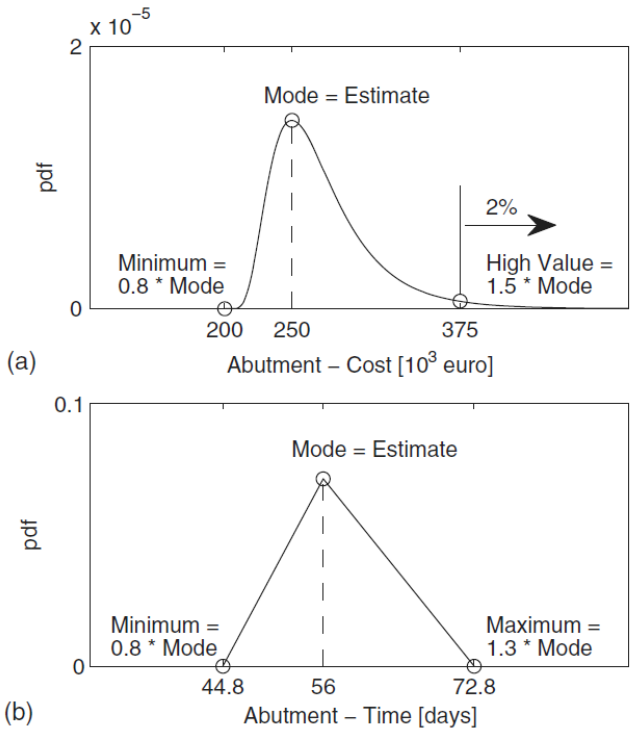


Figure 1.12: Distribution (a) lognormal for cost and (b) triangular for time

Correlation between the costs of different activities in a structure (correlation type 1) and the correlation between the costs of a repeated activity in a structure (correlation type 2) are investigated with NORTA.

In the end, in the viaduct case, correlation type 1 causes an increase in standard deviation of the total cost of 8% for the correlated compared to the independent scenario, whereas in the tunnel case study, correlation type 2 causes an increase in total cost standard deviation of 1,260% for the correlated compared to the independent scenario. The reason for this dramatic difference in the increase of the total cost standard deviation has been explained with the number of correlated costs: correlation type 1 consists of the correlation between few costs, while correlation type 2 consists of the correlation between many. A sensitivity analysis has also shown that the more costs are correlated, the larger the standard deviation of the total cost becomes (Moret and Einstein, 2012).

1.2 Potential New Extensions

Some ideas proposed in the literature may have potential in constituting new modules for the DAT. Two of them are detailed here, especially relative to the accuracy of the results as a function of the number of simulations and a historical data module.

1.2.1 Required Number of Simulations

A question that usually arises in connection with Monte Carlo simulations, is to ask how many iterations are needed? If the simulations were allowed to run for an extremely large number of iterations it is expected that the results would be reasonably accurate whereas for a smaller number of iterations, different results may be obtained. The question asked above may be re-phrased in the form; how many iterations need to be performed in order to obtain a specified accuracy in the result? A study by the Naval Postgraduate School looks at this issue considering the average damage a target sustained when attacked by a specific weapon with a known accuracy of delivery (Driels, 2004).

Through statistical tools such as mean, variance and standard deviation it is possible to define a confidence level, confidence limits and confidence intervals. When associated with a specific distribution, for example normal or t-distributions, it is possible to statistically calculate upper and lower bounds relative to specific error percentages.

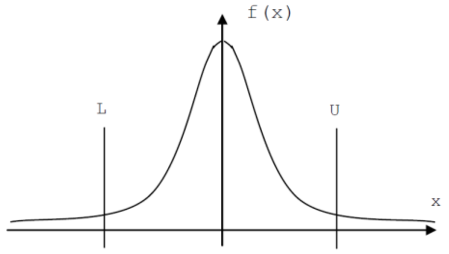


Figure 1.13: Confidence limits for a t-distribution

The mathematical relationships can be rewritten to find n, the number of required simulations.

$$n = \left[\frac{100 z_c S_x}{E\bar{x}}\right]^2$$

For the example solved, where the confidence level is 95%, $z_c = 0.196$, $x = 0.176$, $S_x = 0.3073$ and $E = 5$, the required number of iterations becomes 4684. In words this reads: If the simulation is run for 4684 iterations, there is a 95% confidence that the calculated result will not differ by more than 5% from the true result (Driels, 2004). Since the solution is mathematically correct, it can be applied for any application. For instance, the same formulae are used in a reliability analysis for tunnel supports (Bukaçi et al., 2016).

Some programs can use the methods outlined in the paper to provide the following user assistance (Driels, 2004):

1. For a given number of iterations, give the confidence limits associated with a user supplied confidence level(s) at the end of the run.

2. While the run is executing, provide the user with the number of iterations needed to achieve a bounded error on the result subject to a user specified confidence level.

An example of a dialog box incorporating the features above is shown in Figure 1.14.

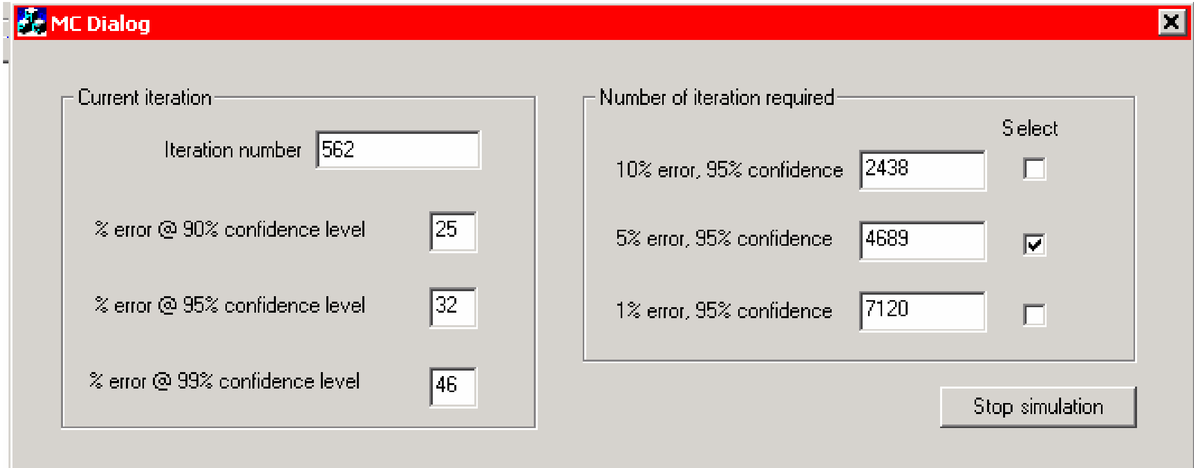


Figure 1.14: Suggested dialog box to display confidence levels

If this dialog box were displayed during the Monte Carlo simulation it would enable the user to determine how accurate the simulation is so far and give an estimate of how many iterations are required to achieve a specific error with known confidence levels. The user may then stop the simulation if sufficient accuracy has been achieved, or let it run to a specific terminal error criterion (Driels, 2004).

1.2.2 Historical Data Module

When estimating construction time and cost, the DAT relies on simulations run for every specific case. Another way of approximating these could be possible by looking at previous existing data. The raw concept goes back to experience. With more knowledge about historical data, some statistical analysis could be applied and thus help estimate the cost and time for new similar projects. One work has been done in this direction, based on the study of nearly 270 projects and applies statistical analysis of the recorded construction inputs in order to yield better cost estimations (Rostami et al., 2012).

In general, it is well-known that the cost a tunnel is a function of the tunnel length and size, geological conditions, support system, mucking, haulage of the excavated material and rate of advance which itself depends on many of the above factors. Also, many non-technical factors such as skills and experience of the workforce, contracting practices, type of funding and cost of financing etc. can affect the cost of tunnel construction. Because of all these complexities, a categorization is applied using the following criteria (Rostami et al., 2012):

- Conventional tunneling methods include drilling and blasting, cut and cover, New Austrian Tunneling Method (NATM), also called sequential Excavation Method (SEM).
- Mechanized hard rock tunneling methods include hard rock TBMs (mainly open face).
- Mechanized soft ground tunneling methods include shielded machines including slurry, and EPB TBMs.
- Mixed ground tunneling method includes those tunnels that have combination of hard or soft ground mechanized tunneling with conventional methods.
- Micro-tunneling.

The results are also presented following a categorization by four applications, namely: highway, wastewater, subway and water. Each set of results is presented in both graphical and tabular form, with the data, the fits and analyses. A brief summary is presented in Table 1.1 (Rostami et al., 2012).

Table 1.1: Brief summary of cost estimations based on historical data

Summary of unit cost and multi-variable regression analyses.

Application	Type of excavation	Number of data	$\frac{P_c}{A_c}$	R^2 (%)	Multi-variable regression equation
Highway	Conventional	12	1.04	95	Cost (M$) = 10^(1.51 + 1.02 log (L) + 0.374 log (D))
Waste water	Conventional	5	1.13	90	Cost (M$) = 10^(−0.391 + 1.63 log (0 + 1.11 log of (D))
Waste water	Mixed	9	1.22	90	Cost (M$) = 10^(1.03 + 0.761 log (L) + 0.804 log (D))
Waste water	Hard rock mechanized	34	0.89	95	Cost (M$) = 10^(0.319 + 0.901 log (L) + 1.35 log (D))
Waste water	Soft ground mechanized	46	0.94	90	Cost (M$) = 10^(0.377 + 1.02 log (L) + 1.53 log (D))
Waste water	Micro-tunneling	46	0.8	94	Cost (M$) = 10^(0.553 + 0.975 log (L) + 0.374 log (D))
Subway	Conventional	13	0.91	77	Cost (M$) = 10^(1.10 + 0.933 log (L) + 0.614 log (D))
Subway	Mixed	22	0.47	45	Cost (M$) = 10^(1.47 + 0.760 log (L) + 0.527log (D))
Subway	Hard rock mechanized	7	0.81	68	Cost (M$) = −97.2 + 11.7L + 28.3D
Subway	Soft ground mechanized	28	0.91	90	Cost (M$) = 10^(1.23 + 1.05 log (L) + 0.636 log (D))
Water	Conventional	7	0.94	66	Cost (M$) = 10^(0.917 + 0.669 log (L) + 0.658 log (D))
Water	Mixed	6	0.8	73	Cost (M$) = 10^(1.94 + 0.414 log (L) + 0.053 log (D))
Water	Hard rock mechanized	21	0.86	98	Cost (M$) = 10^(0.553 + 0.866log (L) + 1.23 log (D))
Water	Soft ground mechanized	16	0.62	60	Cost (M$) = 10^(1.07 + 0.725 log (L) + 1.02 log (D))

L: Length of the tunnel (km).
D: Equivalent diameter (m).

In addition, a simple computer interface has been developed and goes by the name of Tunnel Cost Estimator (TCE). This software puts into practice the findings of the study in a user-friendly way as it appears in Figure 1.15 (Rostami et al., 2012).

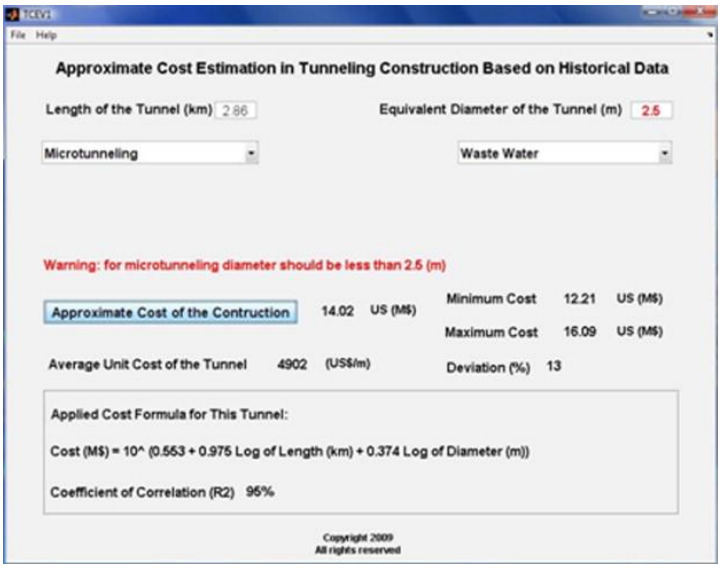


Figure 1.15: Main page of Tunnel Cost Estimator (TCE) software

CHAPTER 2

2 ILLUSTRATIVE DAT EXAMPLE

2.1 Purpose

Perhaps the potential of the DAT is best illustrated with a simple tunnel example; different from the cases in the literature when the DAT was used for the longest, most expensive and extremely challenging tunnels in the world. This strategy is also in line with the overall work aiming to apply the DAT for small tunnels. Instead of referring to complex cases, this section establishes the potential of the DAT with a small extension of a metro line in Cambridge Massachusetts of roughly $2600\ ft$ ($\sim 800\ m$). The project is part of the course "Underground Construction" given at the Massachusetts Institute of Technology by Prof. Einstein.

2.2 Scope

The main question to be answered for this problem is the following: should the stations be constructed in rock or in soft ground (soil), and, if the tunnels should be constructed by "cut and cover" or be "mined"? This array of options and their different possible combinations means only one thing in the tunneling world: alternatives must be established and studied from different points of view (technical, economical etc.) before picking the most suitable one. Traditionally, and especially for small tunnels of this scale, the preliminary investigations are done "by hand". They rely mainly on deterministic approximations and the end results (cost and time estimates) appear as fixed numbers with no consideration whatsoever to any uncertainties. This will now be done in a first step. In a second step, the same analysis is conducted using the DAT. The latter encompasses a consideration of the uncertainties of the problem. The end results obtained surpass the deterministic ones in terms of precision but also by conveying a certain level of trust associated with the numerical values related to a certain "spread" of the results in the simulations' scattergrams.

2.3 Available Information and Constraints

2.3.1 Geology

Following a study of the existing boring profiles (~15 borehole logs), a preliminary subsurface profile is established.

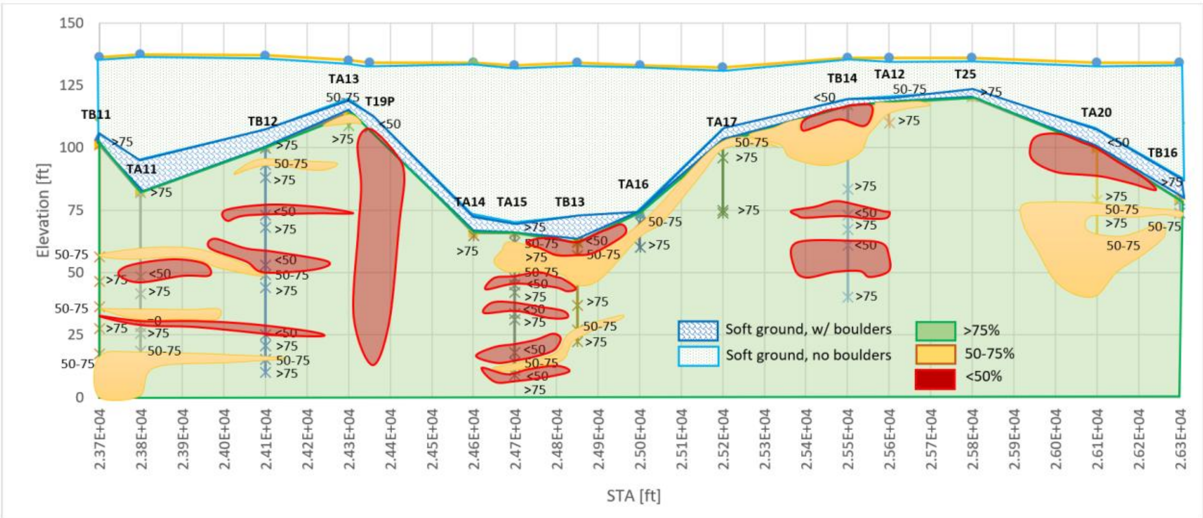


Figure 2.1: Subsurface geology

2.3.2 Construction

Other considerations relative to construction practices include the following:

- Two single track tunnels of $20\ ft$ ($6.1\ m$) outside diameter are to be driven if mined tunneling is used (horseshoe or circular shape). A double track rectangular tunnel, $30\ ft$ ($9.15\ m$) wide, $20\ ft$ ($6.1\ m$) high, is to be used for cut and cover tunneling (all dimensions 'outside').
- Davis Square Station is constructed by cut and cover method. Invert level at El. 80 ft.
- Porter Square Station can be either constructed by cut and cover (invert El. 80 ft) or as a mined station (invert El. 14 ft).
- Mined tunnels in soft ground have to be driven with a minimum 20 ft distance between ground surface and crown; mined tunnels in rock should have 10 ft ($3.05\ m$) of rock above the crown if $RQD > 75\%$, 15 ft ($4.6\ m$) if $75\% < RQD < 50\%$ and 25 ft ($7.62\ m$) if $RQD < 50\%$ (if the rock cover is less, mixed face excavation applies).
- Maximum gradient is 4%.

For all these considerations, a total of four feasible scenarios have been proposed in Figure 2.2. They constitute the four alternatives for which, the analysis is conducted.

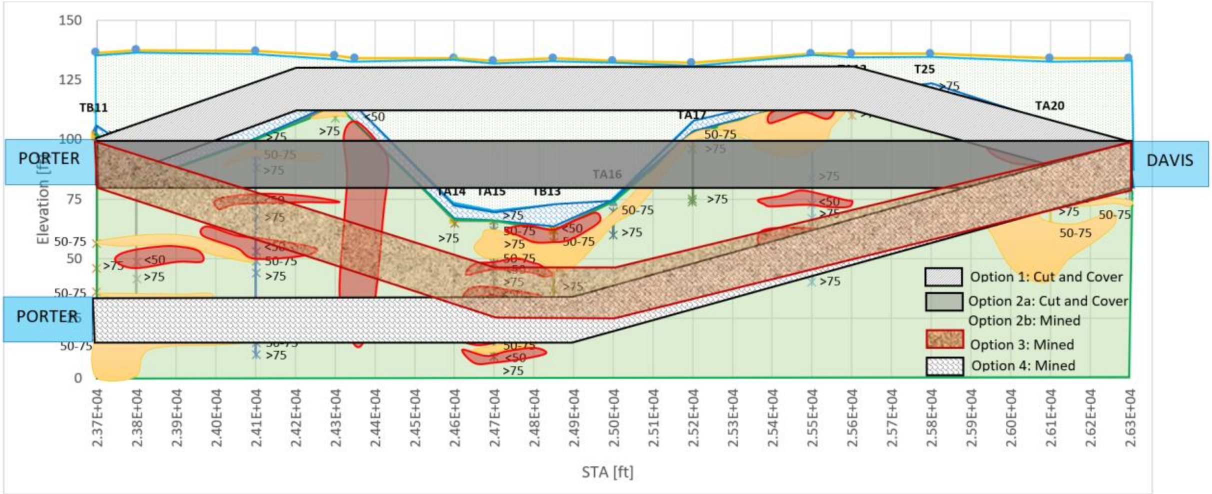


Figure 2.2: Four proposed alternatives

2.3.3 Costs

Concerning the cost estimations, the following considerations apply. All cost values are expressed in $ per linear ft.

- Soft ground mined 20 ft diameter:
    - Above g.w. table, no boulders: 5,000
    - Below g.w. table, no boulders: 7,500
    - Above g.w. table, with boulders: 6,000
    - Below g.w. table, with boulders: 10,000

- Soft ground cut and cover 30 $ft \times 20\ ft$:
    - Above g.w. table, no boulders: 6,000
    - Below g.w. table, no boulders: 7,000
    - Above g.w. table, with boulders: 7,000
    - Below g.w. table, with boulders: 9,000

  If depth of excavation is greater than 25 ft, increase unit cost of cut and cover construction by 25%, if depth of excavation is greater than 50 ft, increase unit cost by 50%.

- Rock mined 20 ft diameter:
    - RQD $>$ 75: 4,500
    - RQD 50 to 75 above g.w. table: 4,500
    - RQD 50 to 75 below g.w. table: 5,000
    - RQD $<$ 50 above g.w. table: 7,000
    - RQD $<$ 50 below g.w. table: 9,000

- Mixed face:
    - Mined 20 ft above g.w. table: 7,500
    - Mined 20 ft below g.w. table: 10,000
    - Cut and cover 20 $ft \times 30\ ft$ above g.w. table: 7,000
    - Cut and cover 20 $ft \times 30\ ft$ below g.w. table: 9,000

If depth of excavation in mixed face cut and cover is greater than 25 ft, increase unit costs by 25%, if greater than 50 ft, increase by 50%.

- Notes:
    - If only a part of the cross-section tunnel is below the g.w. table, the cost for 'below g.w. table' applies.
    - Analogous for boulders
    - If different RQD values are encountered in the same cross-section, the cost of the lowest RQD applies.

A separate quick manual approximation, considering only the costs, was preliminarily conducted for all the alternatives. Its results are summarized in Table 2.1.

Table 2.1: Preliminary cost summary prior to the analysis

Alternative	Cost
#1 - Cut and Cover	**$24 350 000**
#2a - Cut and Cover	$34 020 000
#2b - Mined	$49 200 000
#3 - Mined	$34 130 000
#4 - Mined	**$32 770 000**

It is clear that two alternatives are the most interesting, namely: alternative 1 (cut and cover in soils) and alternative 4 (mined in rock). For sake of simplicity, these are the two alternatives that will be retained for the rest of the analysis. The others will henceforth no longer be considered.

2.4 Alternative 1

Recall that alternative 1 involves constructing the tunnel by cut and cover in soft ground (soil) with both stations being at relatively shallow depth. For a finer analysis, this alternative is described as shown in Figure 2.3.

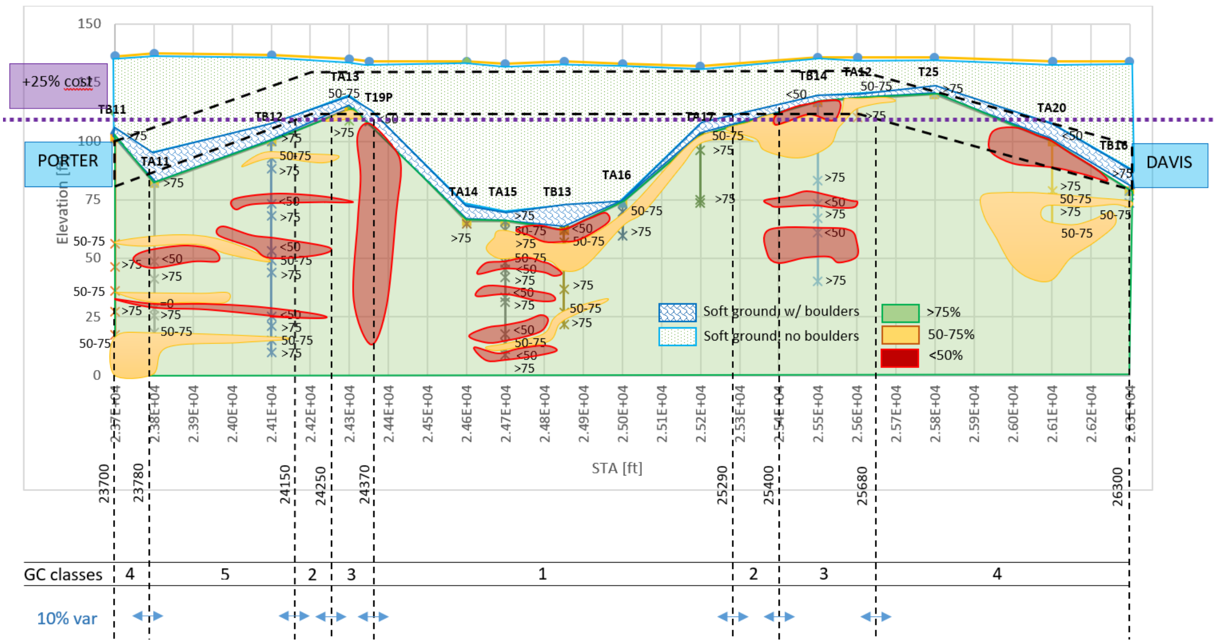


Figure 2.3: Geology section and zones for alternative 1

2.4.1 Deterministic

From a deterministic point of view, the tunnel is subdivided into zones, each associated with a corresponding couple of unit cost and unit advance rate as they appear in Table 2.2. Simple calculations, based on the length of each zone, yield total cost and time estimates for the whole tunnel.

Table 2.2: Deterministic calculations for Alternative 1

STA [ft] From	STA [ft] To	Linear Dist. [ft]	Strata	Cost [$/Liner ft]		Time [ft/d]	Section cost [$]	Section Time [d]
23700	23780	80	Mixed Cost+	$9000 x 1.25	11250	5	900000	16
23780	24150	370	Soft Bolders Cost+	$9000 x 1.25	11250	10	4162500	37
24150	24250	100	Soft Bolders	$9000	9000	8	900000	12.5
24250	24370	120	Mixed	$9000	9000	6	1080000	20
24370	25290	920	Soft NO Bolders	$7 000	7000	20	6440000	46
25290	25400	110	Soft Bolders	$9 000	9000	12	990000	9.17
25400	25680	280	Mixed	$9000	9000	6	2520000	46.7
25680	26300	620	Mixed Cost+	$9000 x 1.25	11250	5	6975000	124
extra costs/ delays								40
TOTAL COST							$23 967 500	351.33

The cut and cover option which is a double track tunnel produces the following results.

$$Total\ Cost = 23{,}967.5\ k\$ \qquad Total\ Time = 352\ days$$

2.4.2 Probabilistic

In reality, all the values considered in the previous section have an inherent uncertainty. Solving the problem deterministically as it was done, does not account for these variations. In this section, the same problem is revisited using the DAT. The uncertainties of the problem are thus incorporated in the analysis and the end results are statistical values from numerous simulations.

The main uncertainties for this example are:

- Geology zones: uncertainty with regard to the limits of each zone
- Cost and time inputs: they may end up varying more or less than budgeted

By making use of the DAT, these variabilities are rather incorporated into the model. For illustrative purposes, the zones lengths vary by a constant percentage of 10% of each zone's length. The values of the End Positions (E.P.) appear in Table 2.3.

Table 2.3: Zones definition in the DAT by E.P. values for alternative 1

STA	E.P.	Delta Dist [ft]	10% of Dist [ft]	Min E.P.	Mean E.P.	Max E.P.
23700	0			*0*	*0*	*0*
23780	80	80	8	*72*	*80*	*88*
24150	450	370	37	*413*	*450*	*487*
24250	550	100	10	*540*	*550*	*560*
24370	670	120	12	*658*	*670*	*682*
25290	1590	920	92	*1498*	*1590*	*1682*
25400	1700	110	11	*1689*	*1700*	*1711*
25680	1980	280	28	*1952*	*1980*	*2008*
26300	2600	620	62	*2600*	*2600*	*2600*

With regard to the cost and time inputs, their uncertainties are dealt with by using a set of values $[Min;\ Mode;\ Max]$ for each category. The adopted inputs appear in Table 2.4.

Table 2.4: Cost and time inputs Alternative 1

	GC	GC names	Min	Mean	Max	Unit
Advance Rate	1	Soft No Boulders	15	20	30	ft/d
	2	Soft + Boulders	9	12	18	
	3	Mixed	4	6	8	
	4	Mixed Cost+	3	5	7	
	5	Soft + Boulders Cost+	8	10	16	
Cost	1	Soft No Boulders	5	7	9	k$/ft
	2	Soft + Boulders	7	9	11	
	3	Mixed	7	9	11	
	4	Mixed Cost+	9.25	11.25	13.25	
	5	Soft + Boulders Cost+	9.25	11.25	13.25	

Other variabilities have not been considered in the context of this example. For instance, the tunnel network was kept simple assuming a linear excavation from one end to the other, without including intermediate access or other position/time delays, except for the starting point delay.

Table 2.5: Starting delay for alternative 1

Delay	Min	Mean	Max	Unit
Initial Position	30	40	50	days

The number of simulations consists of 100 geology and 10 construction simulations. For more than one thousand points, the graph becomes too cluttered and thus for the sake of clarity, the number of simulations is fixed at 1000.

The end result is a scattergram of time and cost; it appears in Figure 2.4.

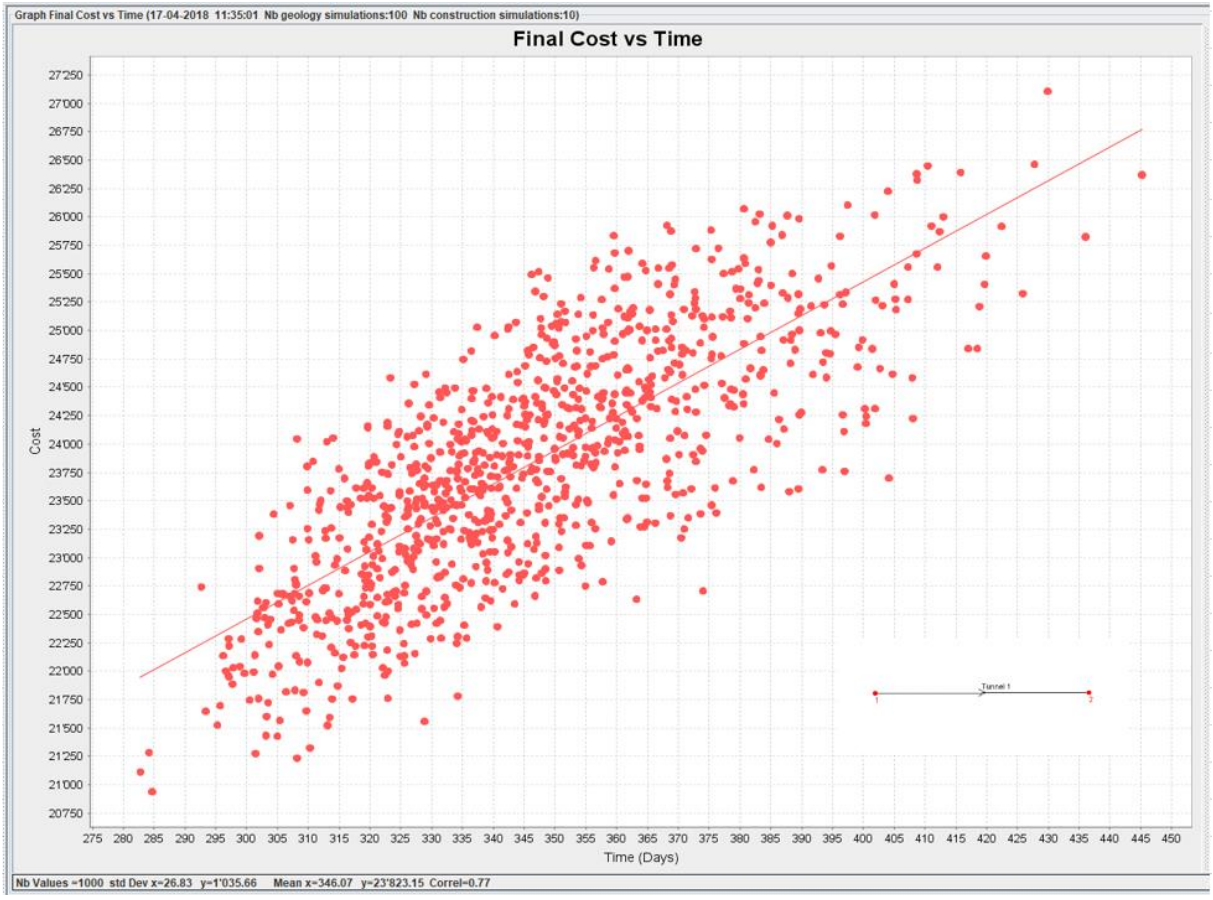


Figure 2.4: Alternative 1 scattergram

On average the obtained results are:

$$Total\ Cost = 23{,}823.15\ k\$ \qquad Total\ Time = 346\ days$$

Extreme results also exist for the absolute most favorable and pessimistic scenarios that occurred for the 1000 simulated cases. Note that the couples of extreme values $[Min; Max]$ for cost and time do not correspond to the same point. They are the absolutely highest and lowest values recorded on the scattergram separately for each category.

$$Max\ Cost = 27{,}106.52\ k\$ \qquad Max\ Time = 445\ days$$

$$Min\ Cost = 20{,}936.53\ k\$ \qquad Min\ Time = 283\ days$$

Not only are the values important, but also, the distribution of the points on the graph is crucial. Indeed, these recorded extreme values are associated with a lower probability of occurrence. These can be seen with the histograms using the DAT (not shown in Figure 2.4 but visible in Figure 2.8), or just observed visually with a higher clustering of values around the mean position, while very few events fall close to the lower or upper bounds of cost and time.

2.5 Alternative 4

Alternative 4 involves mining the tunnel in rock with the Porter station being placed deep underground. The analysis follows the same pattern as was done with the previous section. It starts similarly with a finer division of the tunnel into zones as they appear in Figure 2.5.

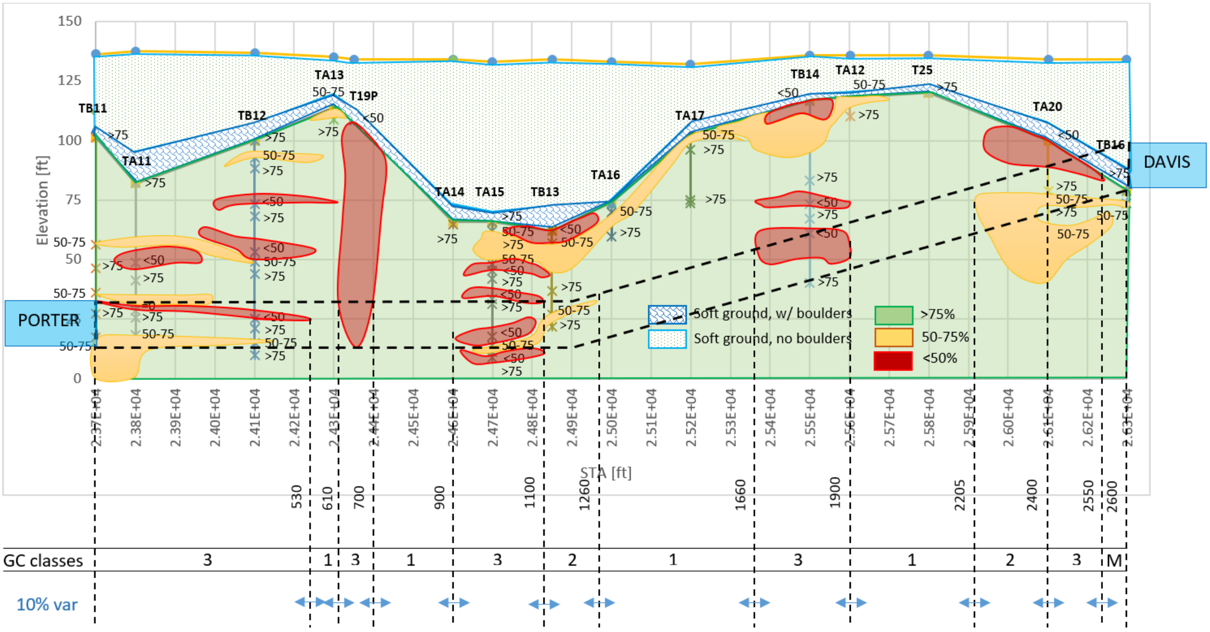


Figure 2.5: Geology section and zones for alternative 4

2.5.1 Deterministic

In a deterministic setting, this alternative has the following results, assuming the unit cost and time that appear in Table 2.6.

Table 2.6: Deterministic calculations for Alternative 4

STA [ft] From	STA [ft] To	Linear Dist. [ft]	Strata	GC	Cost [$/Liner	Time [ft/d]	Section cost [$]	Section time [d]
23700	24230	530	RQD<50%	3	9000	7	4770000	75.7
24230	24310	80	RQD>75%	1	4500	35	360000	2.3
24310	24400	90	RQD<50%	3	9000	7	810000	12.9
24400	24600	200	RQD>75%	1	4500	35	900000	5.7
24600	24810	210	RQD<50%	3	9000	7	1890000	30.0
24810	24960	150	RQD 50-75%	2	5000	15	750000	10.0
24960	25360	400	RQD>75%	1	4500	35	1800000	11.4
25360	25600	240	RQD<50%	3	9000	7	2160000	34.3
25600	25905	305	RQD>75%	1	4500	35	1372500	8.7
25905	26100	195	RQD 50-75%	2	5000	15	975000	13.0
26100	26250	150	RQD<50%	3	9000	7	1350000	21.4
26250	26300	50	Mixed		10000	10	500000	5.0
Extra costs/delays							0	80.0
COST 1 Tunnel		2600					$17 637 500	310.4285714
TOTAL COST							**$35 275 000**	**155.2**
							2 tubes	2 ways excav.

For this case, the inputs are related to one tube, while the metro requires two. Therefore, the total cost has to be doubled. Construction time will depend on the selected tunnel network: for a simple excavation from one end to another, the total time is either kept the same or divided by two if it is excavated from both ends.

$$Total\ Cost = 17{,}637.5\ k\$ \qquad Total\ Time = 311\ days\ (ONE\ tube\ ONE\ way)$$

$$Total\ Cost = \ 35{,}275.0\ k\$ \qquad Total\ Time = 156\ days\ (TWO\ tubes\ TWO\ ways)$$

2.5.2 Probabilistic

For the same types of uncertainties (geology, cost and time inputs), the same approach is simulated in the DAT in order to include these uncertainties.

Again, the End Positions (E.P.) of the zones are defined based on the same 10% variability of the zones' lengths as before. The values appear in Table 2.7.

Table 2.7: Zones definition in DAT by E.P. values for alternative 4

E.P.	delta Dist [ft]	10% of Dist [ft]	Min E.P.	Mean E.P.	Max E.P.
0			*0*	*0*	*0*
530	530	53	*477*	*530*	*583*
610	80	8	*602*	*610*	*618*
700	90	9	*691*	*700*	*709*
900	200	20	*880*	*900*	*920*
1110	210	21	*1089*	*1110*	*1131*
1260	150	15	*1245*	*1260*	*1275*
1660	400	40	*1620*	*1660*	*1700*
1900	240	24	*1876*	*1900*	*1924*
2205	305	30.5	*2174.5*	*2205*	*2235.5*
2400	195	19.5	*2380.5*	*2400*	*2419.5*
2550	150	15	*2535*	*2550*	*2565*
2600	50	5	*2600*	*2600*	*2600*

Also similarly to the previous alternative, the uncertainties of cost and time inputs are introduced with a range of variability as follows in Table 2.8.

Table 2.8: Cost and time inputs Alternative 4

	GC	GC names	Min	Mean	Max	Unit
Advance Rate	1	Exc-1	28	35	42	ft/d
	2	Exc-2	10	15	20	
	3	Exc-3	5	7	10	
	4	Exc-mix	7	10	15	
Cost	1	Exc-1	3.5	4.5	5.5	k$/ft
	2	Exc-2	4	5	6	
	3	Exc-3	8	9	10	
	4	Exc-mix	8	10	12	

In contrast to what was done with the first alternative, for alternative 4, two tunnel networks are analyzed separately: a single tube with one-way excavation or double tubes excavated from both sides. The same delays are applied at the start position of the excavation.

Table 2.9: Starting delay for alternative 4

Delay	Min	Mean	Max	Unit
Initial Position	30	40	50	days

Simulations are still fixed at 1000 for the same aforementioned reasons.

The scattergrams of both tunnel networks appear respectively in Figure 2.6 and Figure 2.7.

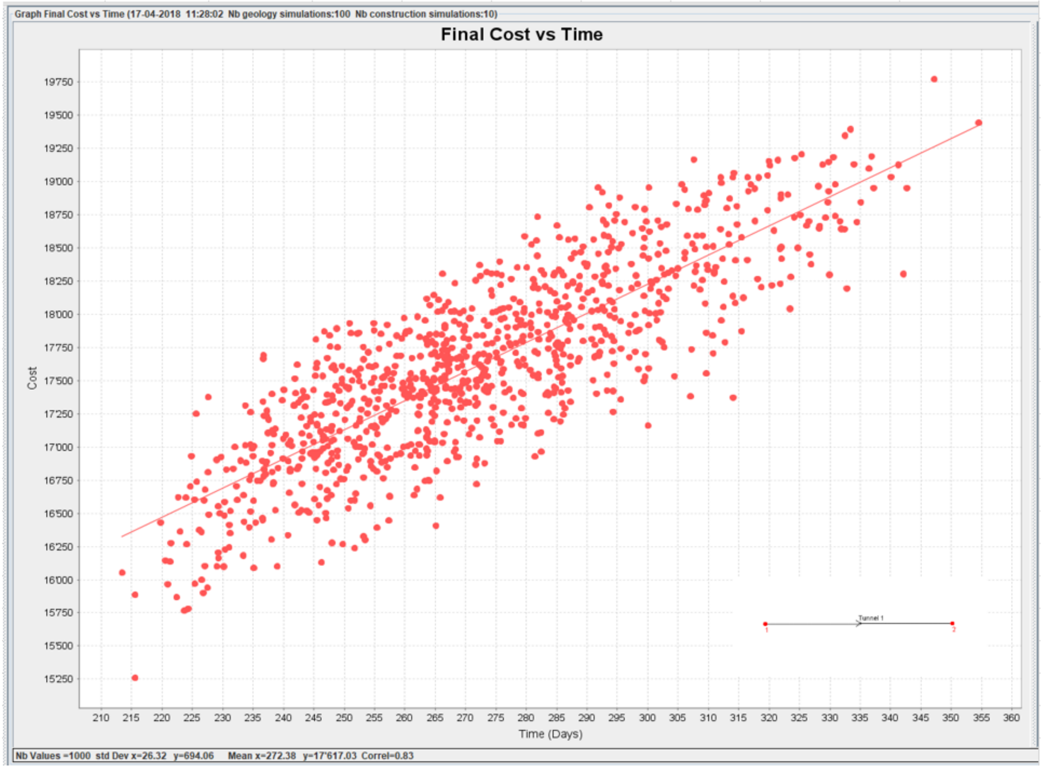


Figure 2.6: Alternative 4 one tube – one way scattergram

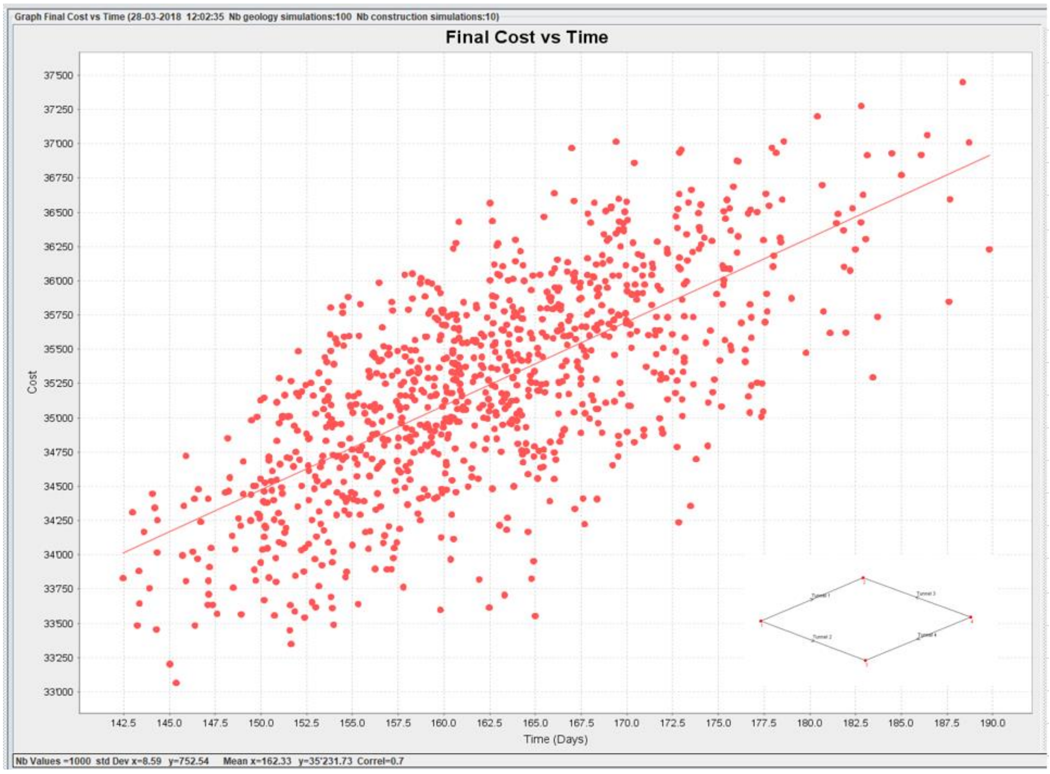


Figure 2.7: Alternative 4 double tubes - two ways scattergram

For a ***single tube, one-way*** excavation the average results are:

$$Total\ Cost = 17{,}617.03\ k\$ \qquad Total\ Time = 273\ days$$

Extreme values are:

$$Max\ Cost = 19{,}771.26\ k\$ \qquad Max\ Time = 355\ days$$

$$Min\ Cost = 15{,}258.98\ k\$ \qquad Min\ Time = 214\ days$$

Identically, for ***double tubes, two-ways*** excavation, average results are:

$$Total\ Cost = 35{,}231.73\ k\$ \qquad Total\ Time = 163\ days$$

Extreme values are:

$$Max\ Cost = 37{,}720.56\ k\$ \qquad Max\ Time = 192\ days$$

$$Min\ Cost = 32{,}864.84\ k\$ \qquad Min\ Time = 140\ days$$

It is worth mentioning again that the extreme values are associated with a lower probability of occurrence, as most of the points cluster around the central value and only very few isolated points occur at both extremes.

2.6 DAT Potential

With all the analyses completed, a quick comparison is sure to reflect the interesting potentials of the DAT even for an example as simple as this small tunnel.

2.6.1 Results Comparison

Table 2.10 summarizes the obtained results of the entire analysis.

Table 2.10: Summary comparison of all variants

	PROBABILISTIC						DETERMINISTIC	
	Cost [k$]			Time [d]			Cost [k$]	Time [d]
	min	mean	max	min	mean	max	fixed	fixed
ALT 1	$ 20 936.53	$ 23 823.15	$ 27 106.52	283	346	445	$ 23 967.50	352
ALT 4 - one way	$ 15 258.98	$ 17 617.03	$ 19 771.26	214	273	355	$ 17 637.50	311
ALT 4 - two ways	$ 32 864.84	$ 35 231.73	$ 37 720.56	140	163	192	$ 35 275.00	156

As can be seen, the mean values for the DAT analyses are very close to the deterministically obtained ones, thus establishing the average probabilistic values as credible. This is where the deterministic information actually ends, while through the DAT, more can be achieved by looking at the distribution of results.

The scattergrams are indeed powerful tools for decision makers. A high scattering on the graph indicates a higher risk of variability. Depending on the extreme recorded values, as well as on the concentration of points, decision makers can better frame the problem and know better what to expect from both pessimistic or optimistic scenarios. With this, they can make finer choices, propose further modifications, rationally take decisions etc. This is clearer in Figure 2.8, showing the distribution of results with histograms.

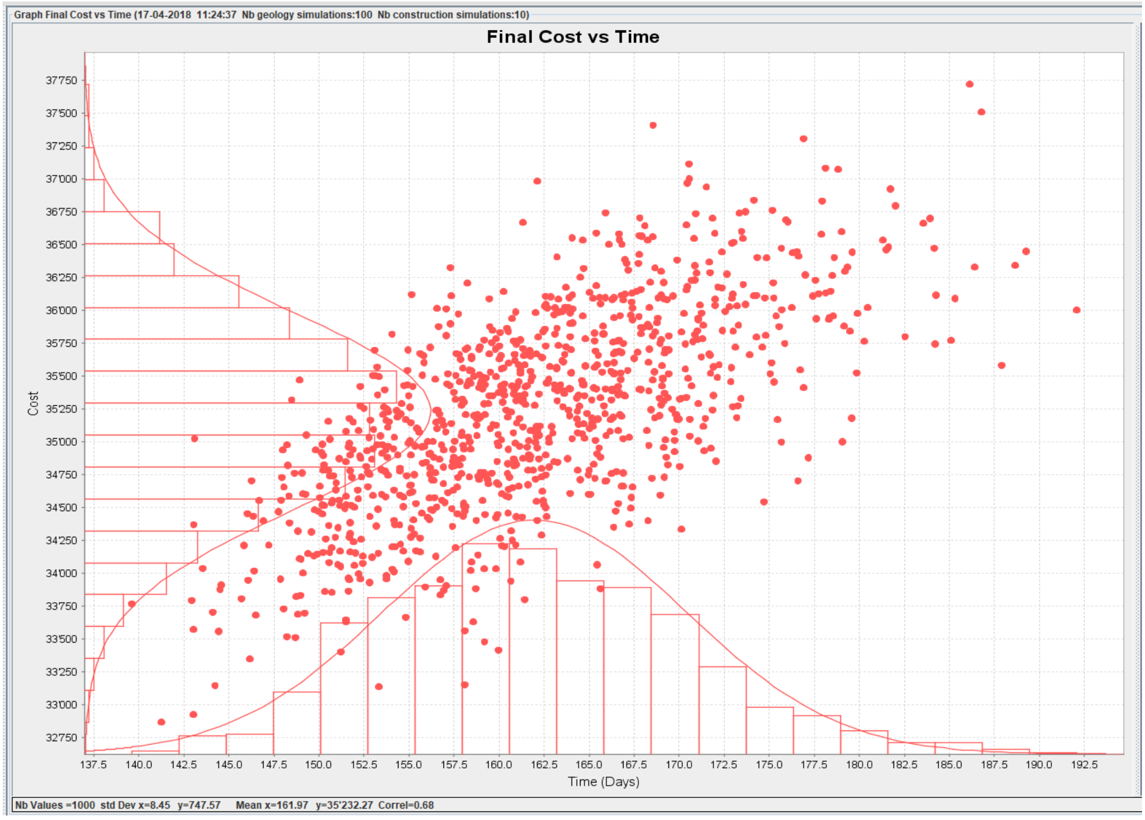


Figure 2.8: Sample scattergram with statistical distributions

2.6.2 Alternative Selection

In the attempt to pick the best alternative, a closer comparison among the options is required. One direct utilization of the DAT for this specific task involves superposing the scattergrams of the different available options. For the specific case of the studied example it is crucial to recall that the cut and cover option automatically yields a double tunnel (excavated from one side), whereas the mined alternative was studied twice, for a single tube (excavated from one end) and for a double tube (excavated from both ends). It is important to keep this in mind when comparing the scattergrams because the construction methods are not entirely identical. The superposed scattergrams appear in Figure 2.9.

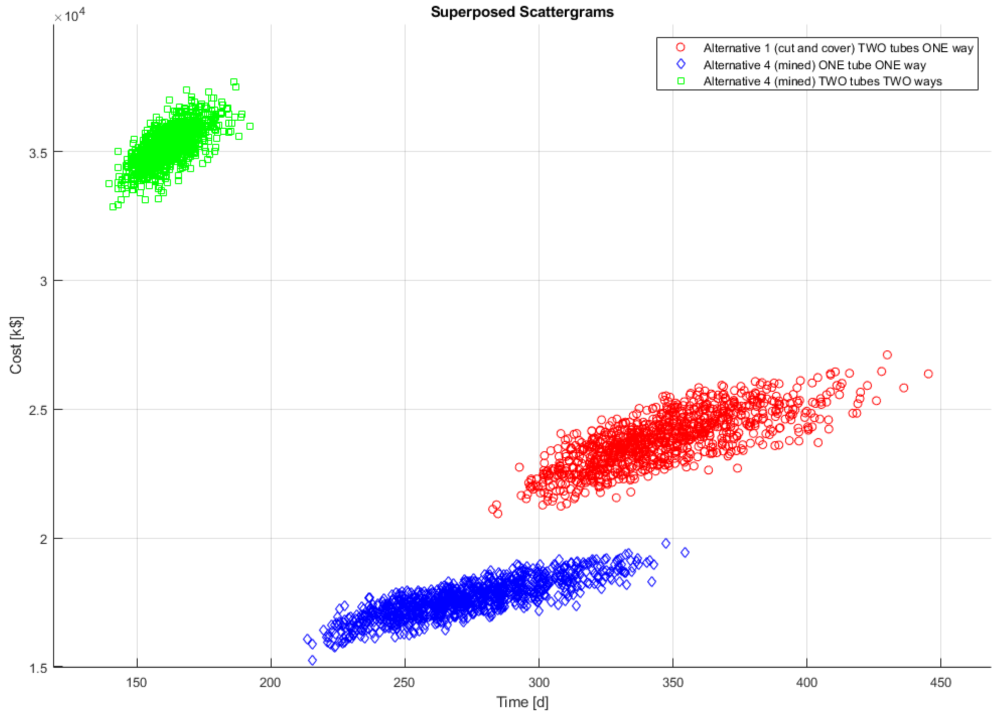


Figure 2.9: Superposed Scattergrams

Figure 2.10 shows only the mean and extrema values recorded for each alternative for the 1000 conducted simulations.

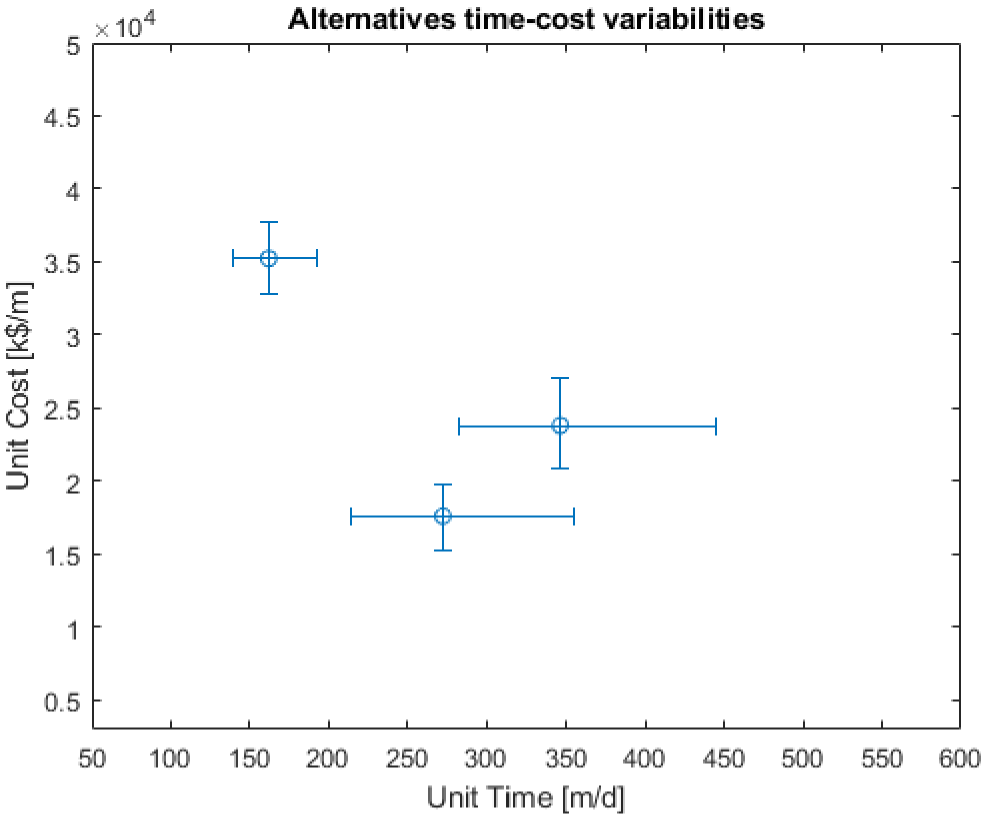


Figure 2.10: Superposed [Max; Mean; Min] values

Clearly for this example, alternative 4 when excavated from both sides in double tubes (green squares in Figure 2.9) is the most expensive while also being the fastest. The other available option would be alternative 1 with cut and cover (red circles in Figure 2.9). It is less expensive but requires a longer construction time, while also showing a higher variability with a wider spread in the end results. Decision makers weigh these implications with respect to other constraining factors such as:

- Variabilities and risk levels
- Available time for the project
- Available resources for the project
- Penalty clauses in the contracts, etc.

With all these considerations and many others specific to every case, they may simply pick the

- least expensive alternative (when the budget is the main limiting factor)
- fastest alternative (when constrained by time)
- most reliable (when contracts are heavily penalizing with regard to variabilities)
- middle alternative (not cheapest nor fastest) but offers a good balance between all the above-mentioned criteria

Alternative 4 with only one tube and one direction of excavation (blue diamonds in Figure 2.9) is presented only for sake of comparison, as it does not satisfy the requirements of the project (two tubes are needed). Nonetheless it shows how the results are not always linear. When going from a single to a double tube or from a one way to two-way excavations, the results are not simply a mere multiplication or division by 2, respectively, as was the case for deterministic approaches. Indeed, the deterministic assumption

$$Cost_{n\ tunnels} = n \times Cost_{1\ tunnel} \qquad Time_{n\ tunnels} = n \times Time_{1\ tunnel}$$

does ***not*** hold true for most tunneling practices.

Constructing $2, 4$ or 10 tunnels based on the forecasts of a single one, is not simply associated with a cost and time that increase by $2, 4$ and 10 respectively. Results may indeed vary much more for the average values (not much for this very simple case because the geology and construction were mostly semi-deterministic) but also for the extrema boundaries and scattering of the points on the scattergrams.

Thus when using the DAT, decision makers do not linearly extrapolate between alternatives but instead are able to simulate different scenarios with their variabilities and, consequently, obtain more accurate results, not only in terms of cost and time but also in terms of a level of confidence associated with different levels of scattering for each alternative.

CHAPTER 3

3 OPTIMIZATION FOR SMALL TUNNELS

Two approaches are presented in this chapter in an attempt to optimize the DAT for small tunnel applications. Respectively referred to as the "Calculator" and the "Catalogue", they constitute two different schools of thought to achieve the original objective, i.e. to encourage the use of the DAT for small tunneling projects.

The Calculator aims to simplify the DAT by dropping off some redundancies and complex rarely used modules and presenting it in a very simple and user-friendly interface. In a few minutes the user can thus model their case in the Calculator, following a tight set of pre-defined rules in order to avoid any mistakes or rely on complicated thinking, run the simulations and finally obtain the desired results.

The Catalogue on the other hand adopts a different path. It is based on the philosophy that the user does not need to run any simulations. As the name indicates, it is based on generating a catalogue with pre-calculated results for so many different cases. Then, the user only needs to refer to the proper chart, table or graph in order to obtain the required information.

Both alternatives are analyzed in their respective sections, before retaining the Catalogue as the adopted solution for the rest of the work.

3.1 DAT Calculator

3.1.1 Concept

This approach proposes a simplification of the existing DAT in order to present a simpler and more user-friendly interface, that could be operated as a simple "calculator". The latter is based on the DAT backbone with some pre-defined elements the user has to pick from. As such the steps follow exactly the same approach as the one used in the DAT, while shielding the user from the complex nomenclature such as: Ground Parameters, GP sets, Ground Classes etc. The following comparison shows roughly how the calculator would be structured both to the user and what is happening inside the black-box in parallel, that the user never actually sees. Later, a full example is solved to better establish this approach.

Inspiration

Commercially used software try to balance between the two opposite poles of effectiveness and flexibility. Indeed, the more limited an interface is, the more efficiently (quickly and reliably) it can be used, but it will only apply to certain pre-defined cases. The calculator cannot be fully adapted for all possible scenarios. It will be optimized for some applications, specifically for small tunnels. For all other purposes, the user can simply revert back to a full fledged DAT analysis.

A simple idea of how it might look like is presented in the following Figure 3.1 that shows the simple and user-friendly interface of the ALIZE software used for pavement design. The details are only for illustrative purposes of showing: a simple presentation, ticking on/off options and drop-down menus (the contents of the picture however have nothing whatsoever to do with our tunneling applications).

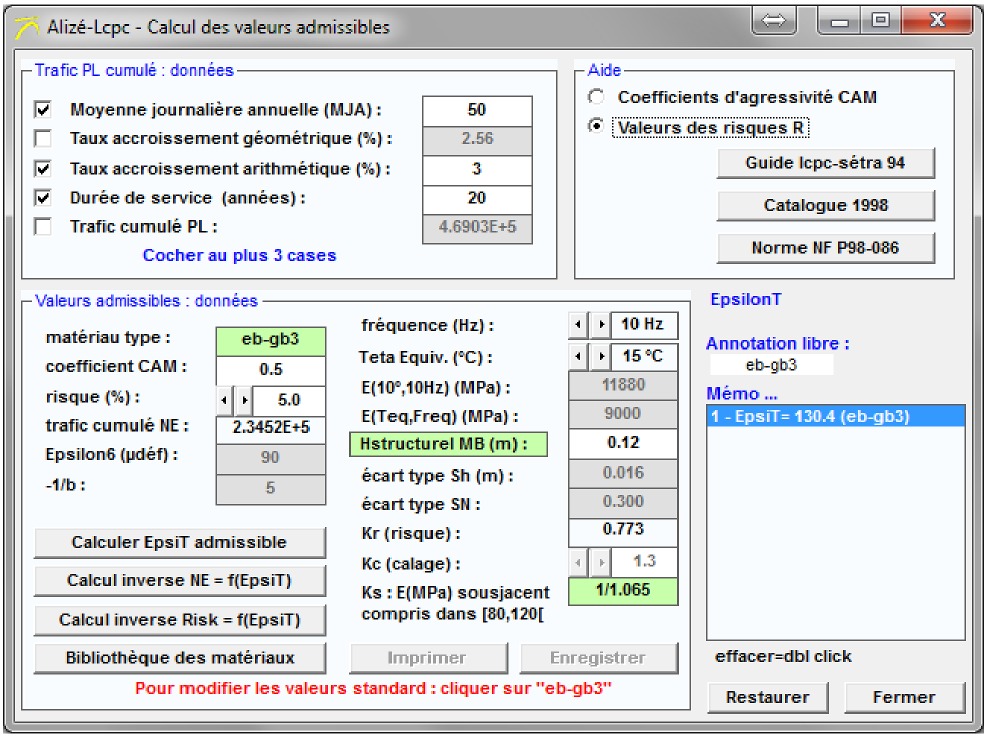


Figure 3.1: Alizé-Lcpc interface used as an illustrative comparison

It is essential to recall that the core concept of the Calculator relies not on reprogramming a new version of the DAT, but on hiding or simplifying the interface for the user instead. Therefore, it is necessary to abide by the specific DAT format when creating this Calculator. Hence, the same internal definition of areas/zones and other core concepts like Ground Parameters, Ground Classes etc. all remain unchanged; but as mentioned before, the user does not have to directly define them.

For small tunnels, it is safe to assume that only two modules are needed in the Calculator. They are the geology and construction modules. As mentioned in Chapter 1, they are treated semi-independently by the DAT. This is why each module is presented separately in Figure 3.2 and Figure 3.3.

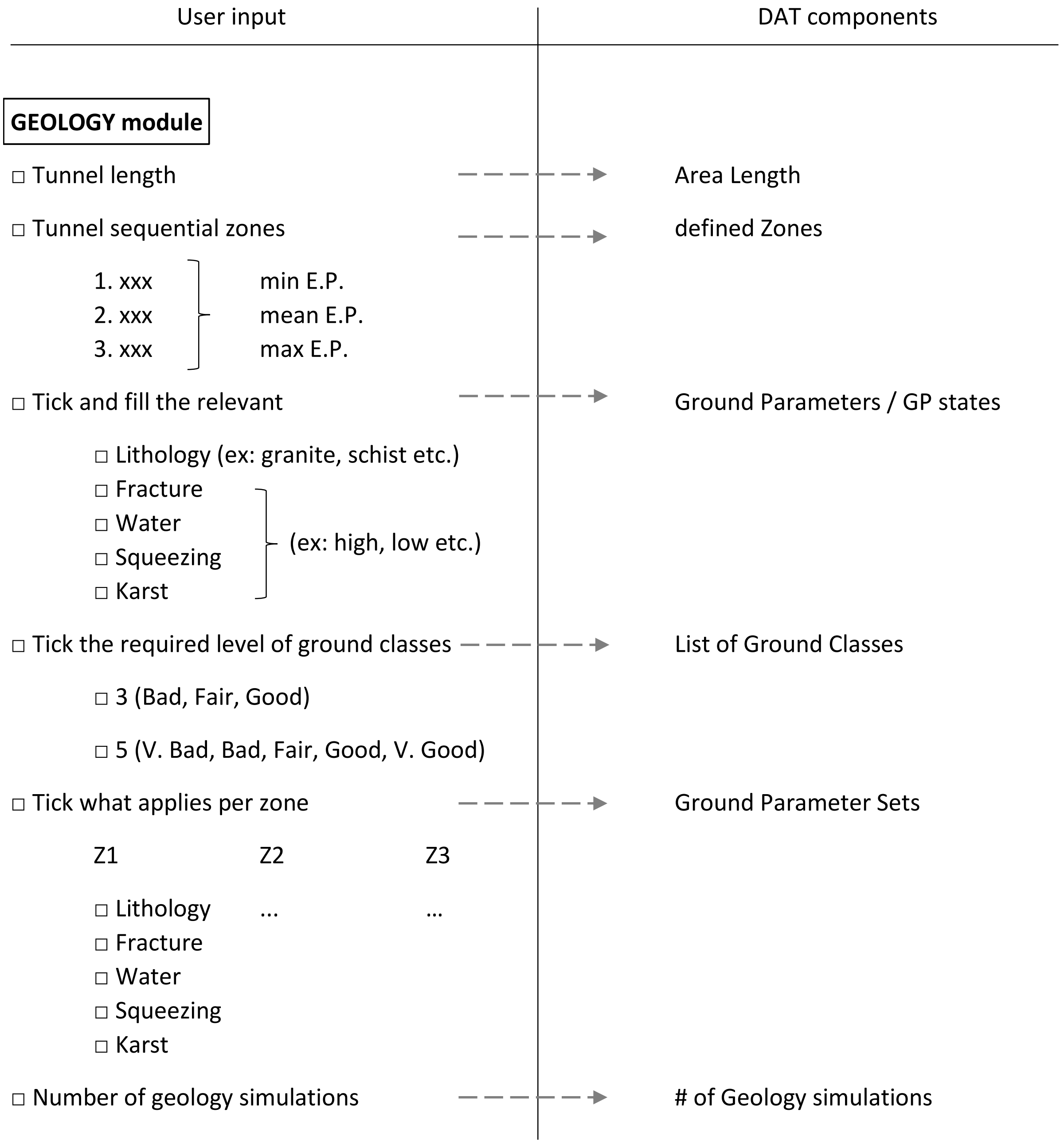


Figure 3.2: Schematic of the geology module in the Calculator and its DAT backbone

Figure 3.2 shows side by side an example of the Calculator's tentative interface and its associated DAT activities. The user no longer has to understand the DAT logic, nomenclature and basis before tailoring his project to fit the DAT. Only the most important steps are retained. When replacing all the tasks by simple "tick what applies" or "enter the value here", the users can model their projects with ease and in a very short time.

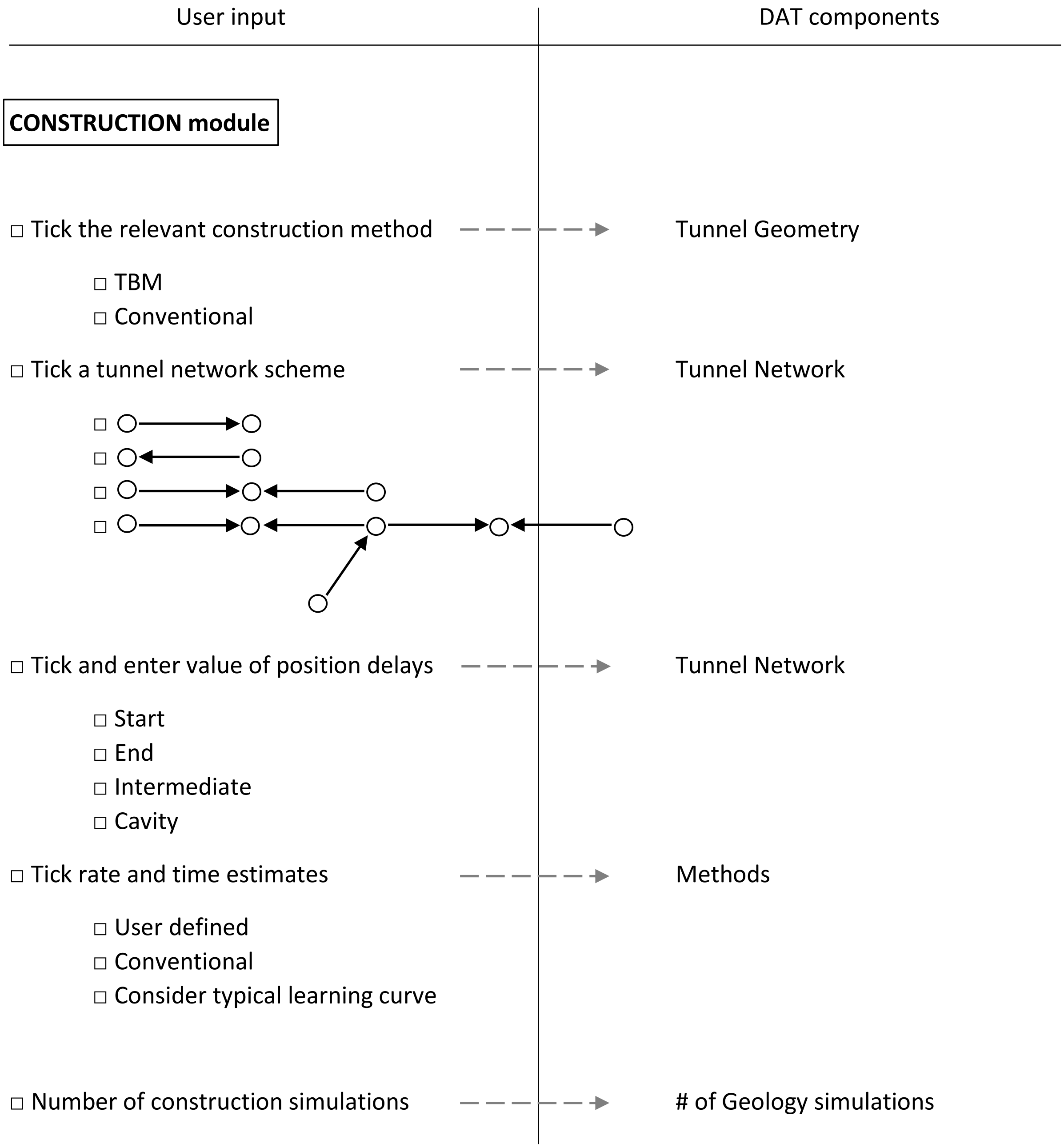


Figure 3.3: Schematic of the construction module in the Calculator and its DAT backbone

In Figure 3.3, the same simple interface applies for the construction module. The user only has to tick or enter a value. This leaves no room for errors and does not require the user to have any form of experience with the DAT beforehand.

One note regarding some features in the Calculator. Some steps that offer the possibility of selecting different options, must be pre-defined in a library within the Calculator. An example is the definition of Ground Classes. A matrix of all possible "pickable" options should be part of the Calculator's database so that it can accommodate any options the user picks among the closed list of Ground Parameters and GP Sets. An example is solved to further illustrate the concept.

3.1.2 Calculator Example

In order to facilitate how the Calculator could work for a real case project, an example is solved using the Calculator's approach. Since the interface has not yet been developed, the solution follows the steps in a text format, accompanied by screenshots from the DAT, showing how the Calculator uses the DAT as a "black box", that the user does not need to see or understand.

Problem Presentation

The fictitious example assumes the construction of a small tunnel with $L = 4000\ m$; considering the following factors: Fracture [F], Water [W] and Squeezing [S] all in a presence/absence or simply YES/NO fashion. The tunnel is excavated from both sides by classical Drill and Blast with initial delays at both portals of 40 to 60 days.

The geometries, positions and other information relative to the project appear in the following Figure 3.4.

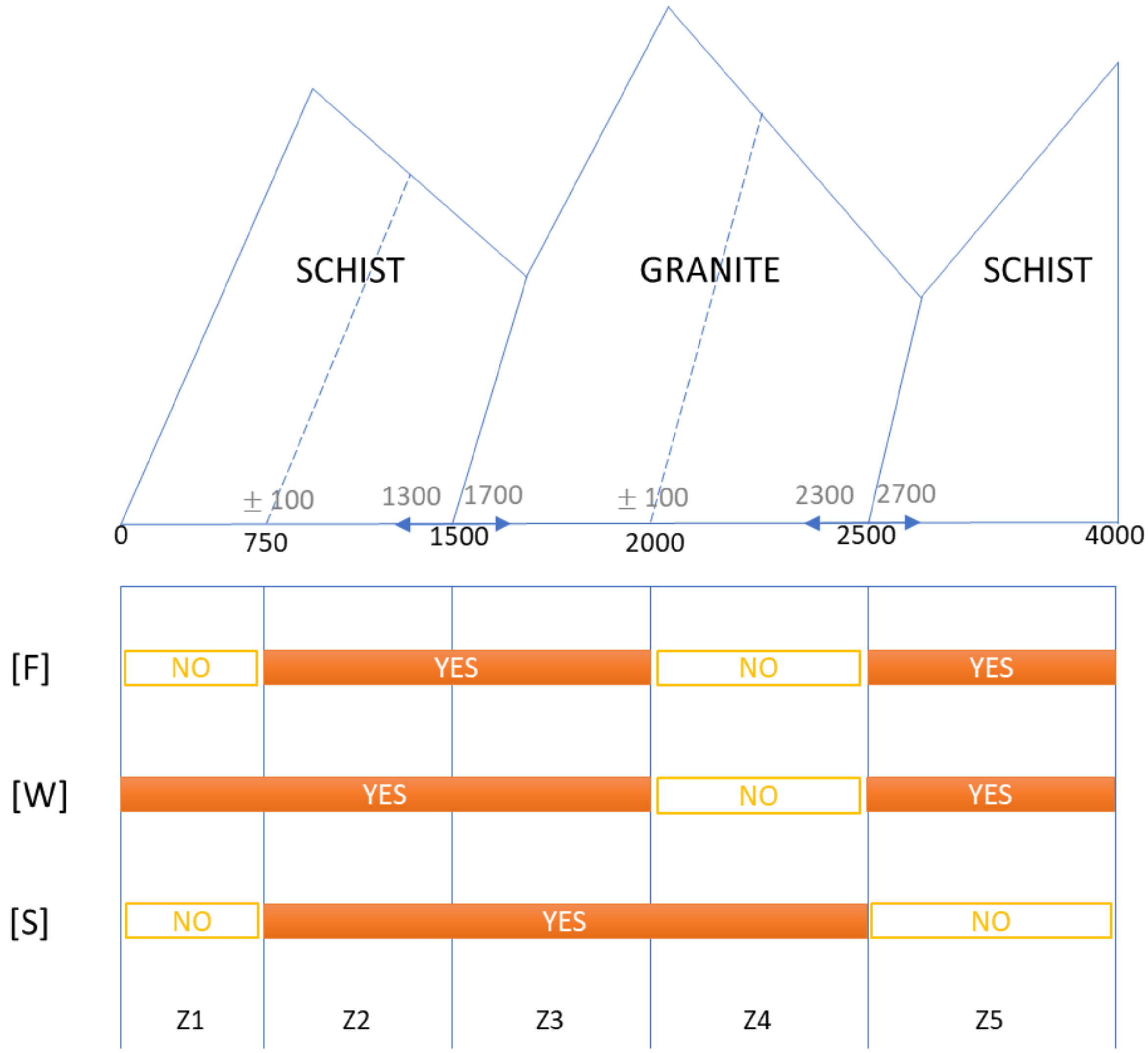


Figure 3.4: Calculator example schematic representation

Problem Solving

All user inputs are filled in orange in the respective sections of the DAT calculator; ticks are shown using the symbol “╲”. Accompanying pictures from the actual DAT show how the calculator abides exactly by the same approach and philosophy in the conventional DAT so that the programming remains the same and can be simply implemented with the user-friendly suggestions and drop-down menus.

GEOLOGY module

1.1. Input tunnel length $L\ [m] = 4000$

1.2. Input the number of zones and define them by end position (E.P.):

- ☑ Z.1: define by E.P. Min E.P. 650 Mean E.P. 750 Max E.P. 850
- ☑ Z.2: define by E.P. Min E.P. 1300 Mean E.P. 1500 Max E.P. 1700
- ☑ Z.3: define by E.P. Min E.P. 1900 Mean E.P. 2000 Max E.P. 2100
- ☑ Z.4: define by E.P. Min E.P. 2300 Mean E.P. 2500 Max E.P. 2700
- ☑ Z.5: define by E.P. Min E.P. 4000 Mean E.P. 4000 Max E.P. 4000

Zones

< | > | Add | Insert | Delete | Delete All

Nb	Name	Area	GP Set	Generation Mode	Min. L.	Mod. L.	Max. L.	Prob. Min. L.	Prob. Max. L.	Min. E.P.	Mod. E.P.	Max. E.P.	Prob. Min. E.P.	Prob. Max. E.P.
1	Zone 1	Area 1	---	End Pos.	0.0	0.0	0.0	0.0	0.0	650.0	750.0	850.0	0.0	0.0
2	Zone 2	Area 1	---	End Pos.	0.0	0.0	0.0	0.0	0.0	1300.0	1500.0	1700.0	0.0	0.0
3	Zone 3	Area 1	---	End Pos.	0.0	0.0	0.0	0.0	0.0	1900.0	2000.0	2100.0	0.0	0.0
4	Zone 4	Area 1	---	End Pos.	0.0	0.0	0.0	0.0	0.0	2300.0	2500.0	2700.0	0.0	0.0
5	Zone 5	Area 1	---	End Pos.	0.0	0.0	0.0	0.0	0.0	4000.0	4000.0	4000.0	0.0	0.0

Areas

< | > | Add | Insert | Delete | Delete All

Nb	Name	Length	First Zone	Last Zone	Ground Parameter Set
1	Area 1	4000.0	Zone 1	Zone 5	-

1.3. Tick what is relevant [from what is pre-defined]

☑ LITHOLOGY ☑ FRACTURE ☑ SQUEEZING □ KARST ☑ WATER

LITHOLOGY:

- ☑ Granite
- □ Shale
- □ Limestone
- ☑ Schist
- □ Sandstone
- □ Gneiss

FRACTURE, SQUEEZING, KARST, WATER:

- ☑ YES/NO
- □ High/medium/Low

Ground Parameters

< | > | Add | Insert | Delete | Delete All

Nb	Ground Parameter Name
1	LITHOLOGY
2	FRACTURATION
3	SQUEEZING
4	WATER

LITHOLOGY (1/4) State List

Nb	GP State\Adv. Rate Coeff
1	Granite
2	Schist

Add GP State

Ground Parameters

< | > | Add | Insert | Delete | Delete All

Nb	Ground Parameter Name
1	LITHOLOGY
2	FRACTURATION
3	SQUEEZING
4	WATER

FRACTURATION (2/4) State List

Nb	GP State\Adv. Rate Coeff
1	YES
2	NO

Add GP State

1.4. Tick level of ground class detail [Note: both predefined in a big table for ALL possible combinations among what is possible to tick for the cases that we define.]

☐ 3 Ground Classes (Good, Fair, Bad)

☑ 5 Ground Classes (Very Good, Good, Fair, Bad, Very Bad)

1.5. Tick what applies per zone [Note: according to what was chosen before, the user should tick where they apply here.]

	Z1	Z2	Z3	Z4	Z5
LITHOLOGY	☐ Granite ☑ Schist	☐ Granite ☑ Schist	☑ Granite ☐ Schist	☑ Granite ☐ Schist	☐ Granite ☑ Schist
FRACTURE	☐ YES ☑ NO	☑ YES ☐ NO	☑ YES ☐ NO	☐ YES ☑ NO	☑ YES ☐ NO
WATER	☑ YES ☐ NO	☑ YES ☐ NO	☑ YES ☐ NO	☐ YES ☑ NO	☑ YES ☐ NO
SQUEEZING	☐ YES ☑ NO	☑ YES ☐ NO	☑ YES ☐ NO	☑ YES ☐ NO	☐ YES ☑ NO

Ground Parameters Sets

< | > | Add | Insert | Copy | Delete | Delete All

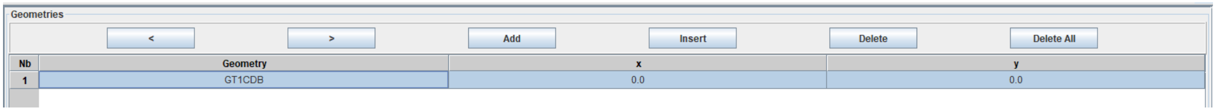
Nb	GP Set	Area 1	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
1	GPSet 1	☐	☑	☐	☐	☐	☐
2	GPSet 2	☐	☐	☑	☐	☐	☐
3	GPSet 3	☐	☐	☐	☑	☐	☐
4	GPSet 4	☐	☐	☐	☐	☑	☐
5	GPSet 5	☐	☐	☐	☐	☐	☑

1.6. Enter value of number of Geology Simulations: 100

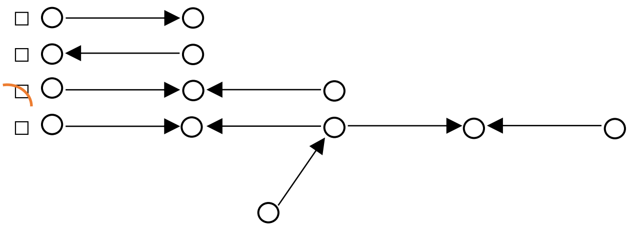
CONSTRUCTION module

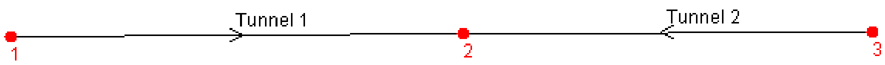
2.1. Tick the relevant construction methods and where they apply

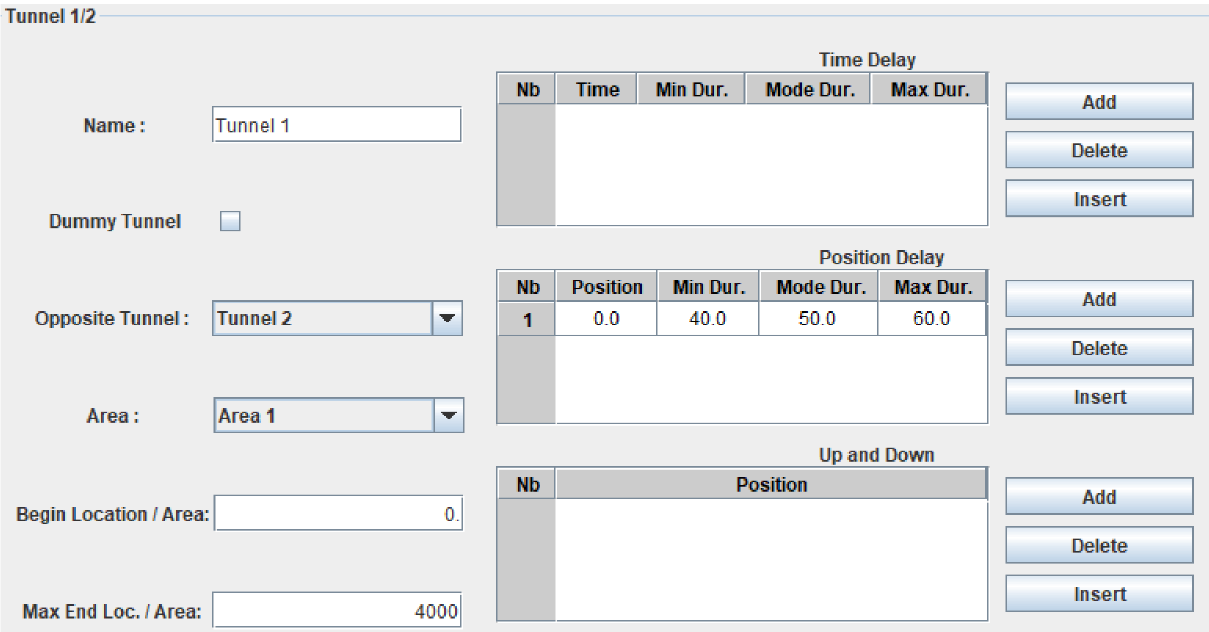
☐ TBM
☑ Conventional D&B: ☑ Z.1 ☑ Z.2 ☑ Z.3 ☑ Z.4 ☑ Z.5
☐ Impact Hammer
☐ NATM



2.2. Tick a Tunnel Network Scheme







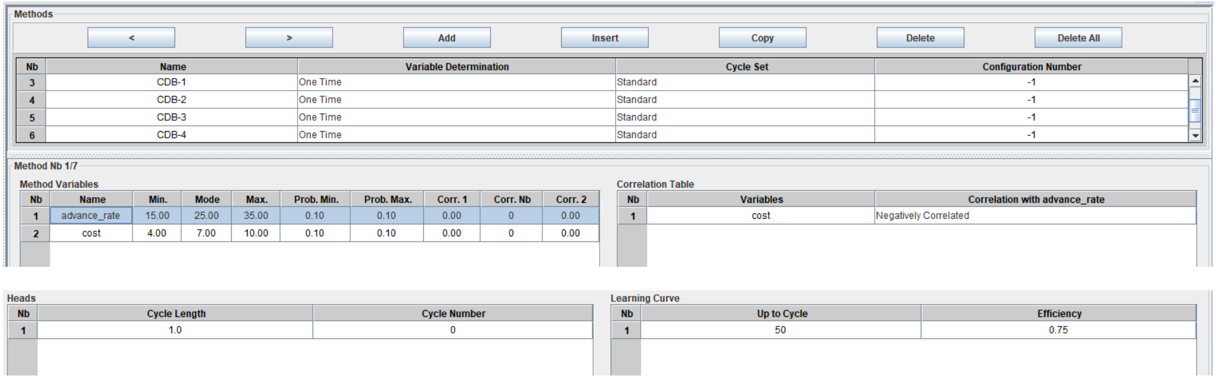
2.3. Tick the relevant delays (in days) and add their values

☑ Start Min = 40 Mean = 50 Max = 60 ☐ One side
☑ Both sides

☐ End
☐ Intermediate
☐ Cavern

2.4. Values for Costs and Advance Rates

□ User defined
□ Usual Values [Note: typical costs for each GC and construction method pre-defined in matrix table for all possible combinations in the calculator.]
□ Include Learning Curve Up to cycle: 50 Efficiency: 0.75



Methods

< | > | Add | Insert | Copy | Delete | Delete All

Nb	Name	Variable Determination	Cycle Set	Configuration Number
3	CDB-1	One Time	Standard	-1
4	CDB-2	One Time	Standard	-1
5	CDB-3	One Time	Standard	-1
6	CDB-4	One Time	Standard	-1

Method Nb 1/7

Method Variables

Nb	Name	Min.	Mode	Max.	Prob. Min.	Prob. Max.	Corr. 1	Corr. Nb	Corr. 2
1	advance_rate	15.00	25.00	35.00	0.10	0.10	0.00	0	0.00
2	cost	4.00	7.00	10.00	0.10	0.10	0.00	0	0.00

Correlation Table

Nb	Variables	Correlation with advance_rate
1	cost	Negatively Correlated

Heads

Nb	Cycle Length	Cycle Number
1	1.0	0

Learning Curve

Nb	Up to Cycle	Efficiency
1	50	0.75

2.5. Enter value of number of Construction Simulations: 10

3.1.3 Verdict: pending

The Calculator's concept is acceptable and is perfect in meeting the user halfway between their needs and the complexity of the DAT.

The task of developing it is however more programming oriented than anything else. Not only does it have to be operational but also it needs to be user-friendly. The process of developing it has to rely on an intense iterative process, between programming, designing and optimizing. These steps are both time consuming and fall outside the main tasks of the objectives set for this work. It will not be immediately developed. The thesis carries on to examine a second alternative of optimizing the DAT for small tunnels called the Catalogue.

Since the Calculator's concept has been defined, it can be eventually developed in the future.

3.2 DAT Catalogue

3.2.1 Concept

In this approach, the idea is to make use the DAT to run numerous simulations eventually producing graphs/tables/charts that can be consulted by the user, thus bypassing the complexity of the DAT. In order to achieve this objective, the inputs (and their uncertainties) need to be analyzed and re-ordered in order to have a list of variables. All this has to be done while keeping in mind the desired end-results and the forms that they can take.

The most crucial part is the definition of inputs in order to obtain the desired results. The choice of Geology and then the corresponding Ground Classes remains particularly problematic. Three main paths are possible:

1. Generate the graphs/tables/charts for ONE type of lithology or ground class at a time (deterministic)
    - o Pros: easier and more realistic representation
    - o Cons: the problem is all deterministic and may not even require the DAT

2. Generate graphs/tables/charts for a certain geologic setting (ex: swiss alps…) considering the uncertainties (probabilistic)
    - o Pros: more realistic distribution using Markov successions and variabilities
    - o Cons: end results only useful for projects whose geology resembles most the same inputs and which fall within the same geologic setting

3. Generate graphs/tables/charts for a set of predefined combinations of geologies and construction methods, so users can refer directly to, for estimates about their tunnel.
    - o Pros: more realistic distribution using Markov successions and variabilities; more relatable than the previous option 2 to most tunnels, ensuring a wider use of the catalogue
    - o Cons: have to limit the available options otherwise the number of needed tables to cover them is too big

Inspiration

As engineers, one very efficient and widely used form of data presentation is in the form of graphs/tables/charts. These are often empirically based and thus have an inherent imprecision. However, this is totally acceptable especially for those intended to be used in preliminary design. The ease of access to information and the approximations of results obtained almost instantly, warrant the acceptance of the imprecisions.

One simple idea of how our end results may look like is presented in the following Figure 3.5 showing a column interaction diagram from structural engineering. A modification of the original appears in Figure 3.6 showing how different variables could be presented and iterated on using the DAT. It is only for illustrative purposes showing how for example

- the column type could be replaced by the tunnel geometry,
- the structural parameters replaced by geologic properties (with certain defined proportions)
- the load pattern replaced by the tunnel configuration (one or two way excavation etc.)
- the axes modified to accommodate the required Cost, Time and Length
- superposition of different plots on the same graph (perhaps for min and max boundaries etc.)

The contents of the picture shown have however nothing to do with our tunneling applications.

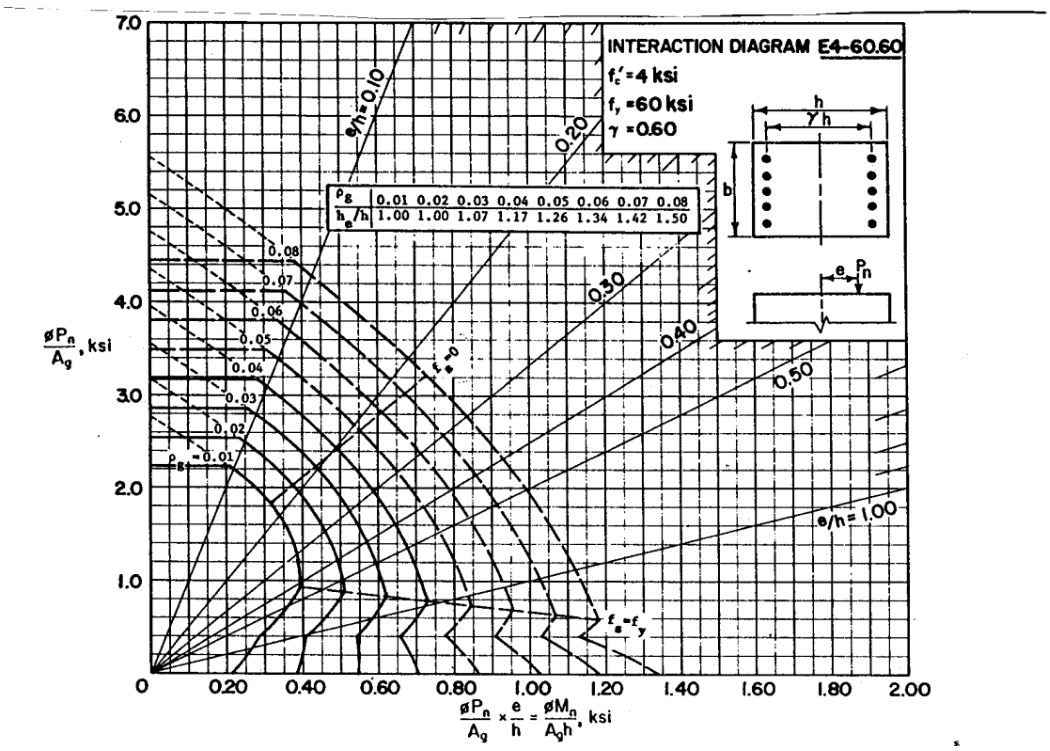


Figure 3.5: Column interaction diagram

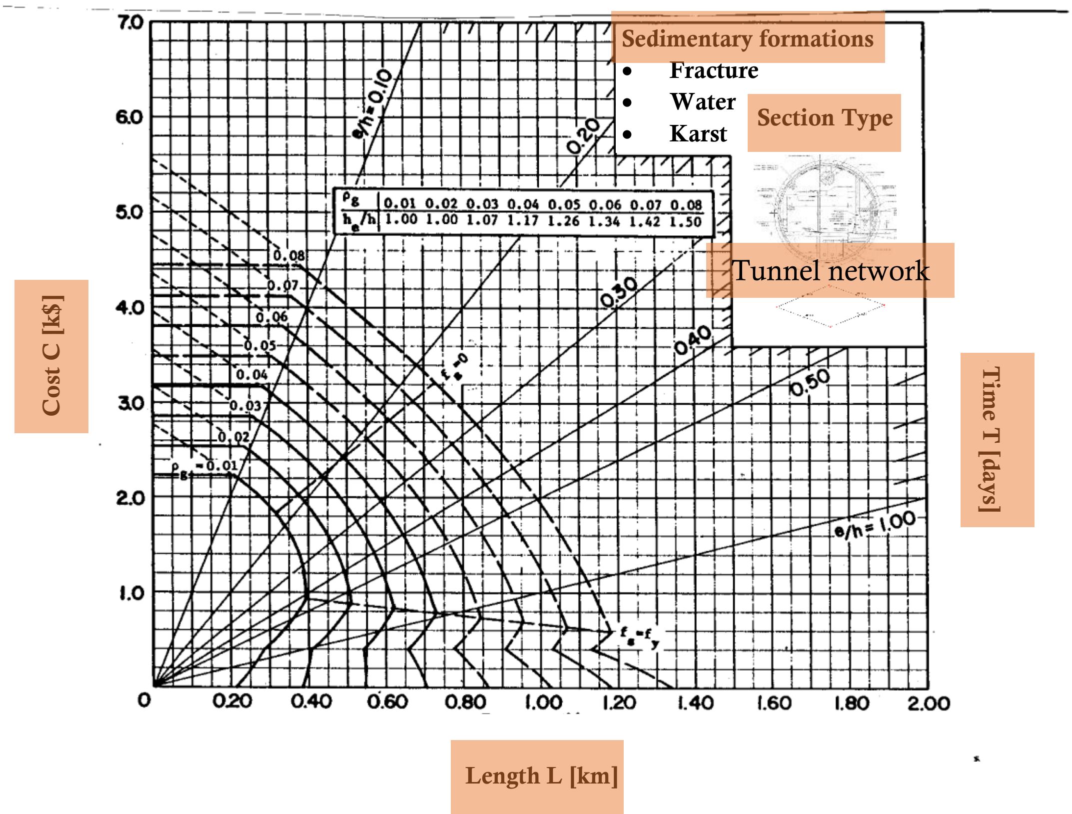


Figure 3.6: Modified column interaction diagram for tunneling applications

For ***option 1*** (deterministic modeling), the Catalogue is too simplistic and relies only on linear approximations and linear superpositions of different ground parameter states. The DAT is somehow not needed as the calculations can be simply done using other spreadsheet calculating software. This option is not retained any further.

For ***option 2*** (modeling with uncertainties in a specific setting), the following steps are to be considered:

1. select a context (ex: alpine arc).
2. study the type of rock families encountered in that specific geological context (ex: sedimentary, igneous etc.).
3. converge towards the most probable lithologies to be retained in the analysis.
4. select probability distributions between them (define the Markov transition matrix).
5. select the other appropriate ground parameters (water, fracture, karst, squeezing, spalling etc.) and their uncertainties (again by defining Markov transition matrices).

Iterate along these lines by changing one at a time of the following variables, namely:

- The dominant lithology
- Tunnel length
- Construction methods and tunnel geometries

For ***option 3*** (modeling for generic general cases), the following steps need to be considered:

1. select the geologic settings that will be retained in the analysis (igneous, sedimentary, etc.).
2. select other ground parameters (water, fracture, karst, squeezing, spalling etc.) and their respective states (high/low, high/medium/low, etc.).
3. select probability distributions for each along the tunnel length (define the Markov proportions instead of transition matrices).

Similarly, iterate along these lines by changing one at a time of the following variables, namely:

- The dominant lithology
- Tunnel length
- Construction methods and tunnel geometries

3.2.2 Catalogue Example

***Example Option* 2**

Among many possible options, the picked geologic context to illustrate the example, is the one of alpine Switzerland. This settles step 1. Now, in order to investigate the dominant families of rocks, it is possible to refer to geologic maps. Numerous sources are possible (confederation hydro-geologic maps, NAGRA website etc.). Even the underground water and aquifers' locations can be consulted in order to see if they are to be considered or not in the analyses. With this step 2 completed, the other steps can be carried on. This is not done here since option 2 is eventually not adopted.

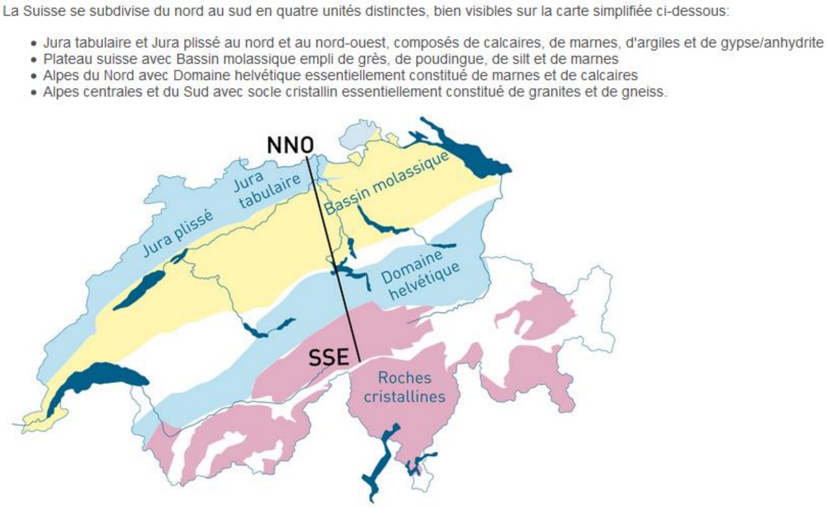


Figure 3.7: Four settings of Swiss geology (NAGRA, 2018)

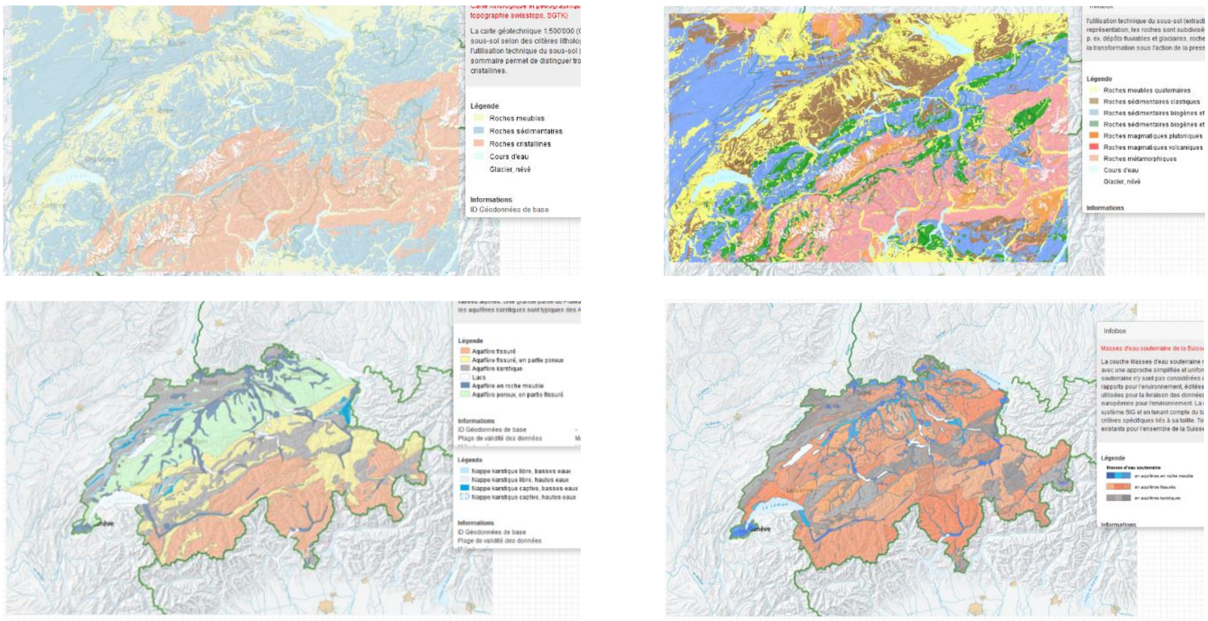


Figure 3.8: Hydrogeologic maps of Switzerland and the alpine region (map.geo.admin, 2018)

Example Option **3**

The third option (numerous tables for different combinations of possible conditions) is the best alternative and will hence be retained. It ensures a wider application, more realistic representation and easier usage than the other options.

The final product is a catalogue composed of different charts and/or tables, each showing the cost and time $[Min; Mean; Max]$ as a function of small tunnel lengths (up to $5\ km$) for certain conditions. For example, these could include: lithology, fracture, water, squeezing, spalling, karst, etc. defined probabilistically in Markov successions based on chosen proportions along the whole tunnel.

Defining GP by Markov distributions can be done in the DAT by defining proportions and not requiring the use of transition probabilities and mean lengths. This is described in the manual (Indermitte et al., 2015).

Proportions – It may be simpler for the project Geologist to know the relative proportion of each parameter state, instead of the mean segment lengths and the transition probabilities. For this purpose, a new option "Proportions" has been introduced. The program converts then the given proportions into an equivalent Markov distribution.

Button "Display Proportions" of Figure 4-17: this changes the right part of the bottom panel (see Figure 4-18) to allow the user to input the proportions in decimal format. The proportions may be fixed, or have themselves triangular distributions, defined by min, mode and max values. To compute the equivalent Markov mean lengths, the program needs a "Minimum zone length" and a "Number of occurences", which is set by default to 5.

Button "Compute Proportions" of Figure 4-17: this changes also the right part of the bottom panel (see Figure 4-18), but the proportions are automatically computed from the Markov mean lengths and transition probabilities.

Button "Display Markov Values" of Figure 4-18: this allows coming back to the Markov panel (see Figure 4-17), without taking into account the proportions.

Button "Compute Markov Values" of Figure 4-18: this allows also coming back to the Markov panel (see Figure 4-17), but the Markov mean lengths and transition probabilities are automatically computed from the given proportions, and the preceding values are overwritten.

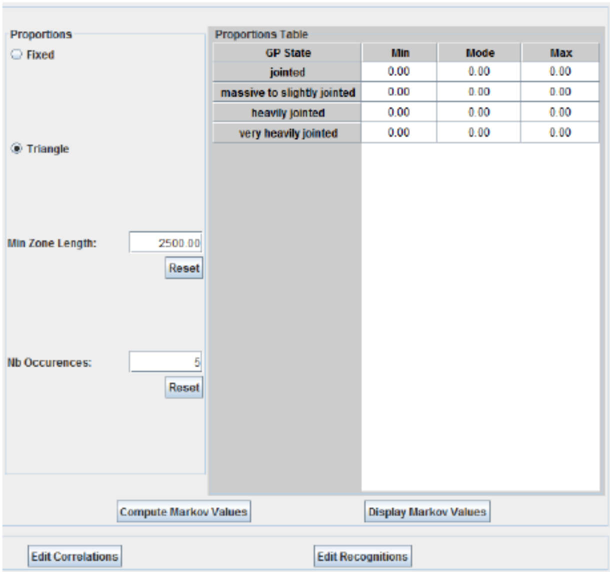


Figure 4-18 *Table allowing to input the parameter states as Proportions.*

Figure 3.9: Markov distributions using proportions instead of a transition matrix

3.2.3 Verdict: retained

Following the analysis of both alternatives (Calculator vs. Catalogue), the Catalogue is the retained option. Its concept is more practical, shielding the user from the DAT complexity while at the same time offering immediate results without the need to run any simulations.

With this concept in mind, the tedious task of practically materializing the Catalogue becomes the next objective. Indeed, thorough reflections on its definition, format, contents and presentation are needed if the Catalogue is to ever see the light. Following the general outline of option 3, briefly discussed earlier, the next section will define all the conceptual foundations in in developing the Catalogue.

3.3 Catalogue Philosophy

3.3.1 Applicability

A catalogue is always anchored in a clearly defined setting, outside of which, it should not be used. It is therefore essential as a first step in developing the DAT Catalogue, to start by establishing the frame within which it is intended to be used.

Two classes of parameters are involved in generating the Catalogue:

- Direct inputs: are critical parameters in the DAT without which the results cannot be obtained. They may or may not be of specific interest to the user, but they need to be defined nevertheless if any simulations are to take place. An example of these would be the Ground Classes.
- Indirect inputs: are not directly required to run the simulations, because they are considered indirectly or simply bypassed by other parameters. For example, the DAT does not need to see the diameter of the tunnel as long as the proper time and cost rates have been defined in accordance with the diameter in mind. These inputs need to be nonetheless clearly labeled, not for the DAT, but so that the user can relate to them when using the Catalogue.

As mentioned, some parameters appear directly in the DAT inputs while others simply affect the selected unit cost and advance rates. Also, future expansions of the Catalogue can later be produced by having the same geology but different other inputs (construction method, tunnel network etc.).

What follows is a checklist of all the parameters needed in order to run the simulations that constitute the backbone of the Catalogue. Not only are they identified and explained, they are also already assigned a certain value. The origin of these values can be found in different dedicated sections throughout the chapters of this work. They are only presented in a summary form here for sake of convenience and simplicity of consultation by the user.

Direct DAT Inputs

- Tunnel network
  - Number of tubes: **1**
  - Intermediate tunnels: **0**
  - Delays (to simulate a blocked TBM): **5 to 55 days** and **no other delays** considered
  - Tunnel configuration: **one-way excavation**

- Ground classes
  - **5 GC** (very good, good, fair, bad, very bad)
  - Big table with all possible combinations: Table 4.19.
  - Imported every time for all simulations

- Excavation classes
  - Same as GC so **5** in total (one each)
  - TBM-1, TBM-2, TBM-3, TBM-4, TBM-5

- Advance rate and unit cost
  - Need to be realistic otherwise the catalogue is useless
  - Consider only the structural support
  - Function of the excavation method
  - Function of the tunnel diameter
  - Final inputs summarized in Table 4.20.

- Number of simulations
  - Total number per entry: $\mathbf{50,000}$
  - Distribution among geology /construction: **129 for geology/388 for construction**
  - Affect the computation time
  - Affect the accuracy of results

Indirect Parameters

- Excavation method
  - Method selection: ***TBM***
  - Possibility to generate new data for different methods

- Excavation diameter
  - For single highway lane or single railroad track: $7 - 9\ m$
  - For two lanes: $8.5 - 13.2\ m$
  - Almost same for both applications (road/rail)
  - Retained value: $\mathbf{9\ m}$

- Length steps in one chart
  - **5** data entries per table
  - Increments of $\mathbf{1, 2, 3, 4}$ and $\mathbf{5\ km}$

3.3.2 Small Tunnels

Since the Catalogue is intended for projects dealing with small tunnels, a question then naturally arises: what is a small tunnel?

There is no definition of what a small tunnel is, neither in the industry nor in academia. It is then decided take the length of the tunnel as the selected criterion upon which the definition of size is based. Therefore, the diameter of a tunnel does not play a role in defining it as “small” or not. A small tunnel is simply defined as:

$$L_{tunnel} \leq L_{threshold}$$

Picking a relatively high value as the limit, will limit the Catalogue as many simplifications become problematic for long tunnels. On the other hand, going for an extremely low threshold value, will make the results not applicable to the majority of tunnels intended to be constructed and thus render the Catalogue useless.

Two possible options are available, both satisfying the aforementioned balance between the extremes of excessively long and short:

- $L_{threshold} = 3\ km$, with the Catalogue charts showing results for 6 increments of $500\ m$
- $L_{threshold} = 5\ km$, with the Catalogue charts showing results for 5 increments of $1000\ m$

In the context of the European Alps, two countries have a particularly abundant inventory of well documented tunnels. They are Switzerland and Austria. Table 3.1 respectively shows roughly sixty well-known tunnels of Switzerland (67 tunnels) and Austria (64 tunnels).

Table 3.1: Well-known tunnels of Switzerland (67) and Austria (64)

	SWITZERLAND		
	Name	Length (Km)	Type
1	Bubenholz Tunnel	0.6	road
2	Maroggia Tunnel	0.6	rail
3	Schöneich Tunnel	0.6	road
4	Lopper I Rail Tunnel	1.2	rail
5	Wipkingen Tunnel	1.2	rail
6	Cassanawald Tunnel	1.2	road
7	Cholfirst Tunnel	1.3	road
8	Glion Tunnel	1.4	road
9	Baregg Tunnel	1.4	road
10	Monte Ceneri Road Tunnel	1.4	road
11	Rosenberg Tunnel	1.5	road
12	Rosenberg Tunnel	1.5	rail
13	Zermatt–Sunnegga Tunnel	1.5	rail
14	Sonnenberg Tunnel	1.6	road
15	Lopper Road Tunnel	1.6	road
16	Monte Ceneri Rail Tunnel	1.7	rail
17	San Nicolao Tunnel	1.7	road
18	Lopper II Rail Tunnel	1.7	rail
19	Felskinn–Mittelallalin Tunnel	1.7	rail
20	Girsberg Tunnel	1.8	road
21	Furka Summit Tunnel	1.9	rail
22	Milchbuck Tunnel	1.9	road
23	Giswil Tunnel	2.1	road
24	Letten Tunnel	2.1	rail
25	Käferberg Tunnel	2.1	rail
26	Hirschengraben Tunnel	2.1	rail
27	Crapteig Tunnel	2.2	road
28	Aescher Tunnel	2.2	road
29	Sierre Tunnel	2.5	road
30	Hauenstein Summit Tunnel	2.5	rail
31	Bözberg Rail Tunnel	2.5	rail
32	Arrissoules Tunnel	3.0	road
33	Bure Tunnel	3.1	road
34	Belchen Tunnel	3.2	road
35	Gubrist Tunnel	3.3	road
36	Munt la Schera Tunnel	3.4	road
37	Wasserfluh Tunnel	3.6	rail
38	Bözberg Road Tunnel	3.7	road
39	Kerenzerberg Rail Tunnel	4.0	rail
40	Weinberg Tunnel	4.8	rail
41	Heitersberg Tunnel	4.9	rail
42	Zürichberg Tunnel	5.0	rail
43	Sachseln Tunnel	5.2	road
44	Adler Tunnel	5.3	rail
45	Mappo–Morettina Tunnel	5.5	road
46	Kerenzerberg Road Tunnel	5.8	road
47	Great St Bernard Tunnel	5.8	road
48	Albula Tunnel	5.9	rail
49	Mont d'Or Tunnel	6.1	rail
50	Grauholz Tunnel	6.3	rail
51	San Bernardino Tunnel	6.6	road
52	Jungfrau Tunnel	7.1	rail
53	Hauenstein Base Tunnel	8.1	rail
54	Grenchenberg Tunnel	8.6	rail
55	Ricken Tunnel	8.6	rail
56	Seelisberg Tunnel	9.3	road
57	Zimmerberg Base Tunnel	9.4	rail
58	Lötschberg Tunnel	14.6	rail
59	Gotthard Rail Tunnel	15.0	rail
60	Ceneri Base Tunnel	15.4	rail
61	Furka Base Tunnel	15.4	rail
62	Gotthard Road Tunnel	16.9	road
63	Vereina Tunnel	19.1	rail
64	Simplon Tunnel	19.8	rail
65	Large Hadron Collider	27.0	other
66	Lötschberg Base Tunnel	34.6	rail
67	Gotthard Base Tunnel	57.1	rail

	AUSTRIA		
	Tunnel	Length (m)	Type
1	Rottenmann Tunnel	0.4	road
2	Pretallerkogel Tunnel	0.5	road
3	Gratkorn Tunnel Nord and Süd	0.8	road
4	Selzthal Tunnel	1.0	road
5	Schartnerkogel Tunnel	1.2	road
6	Bruck Tunnel	1.3	road
7	Ofenauer Tunnel	1.4	road
8	Bartl Kreuz Tunnel	2.0	road
9	Hiefler Tunnel	2.0	road
10	Herzogberg Tunnel	2.0	road
11	Geißwand Tunnel	2.1	road
12	Brandberg Tunnel	2.1	road
13	Ganzstein Tunnel	2.1	road
14	Klaus Tunnel	2.1	road
15	Gräbern Tunnel	2.1	road
16	Lainberg Tunnel	2.3	road
17	Langen Tunnel	2.4	road
18	Tanzenberg Tunnel	2.5	road
19	Harpfnerwand Tunnel	2.6	road
20	Spital Tunnel	2.6	road
21	Letze Tunnel	2.6	road
22	Spering Tunnel	2.9	road
23	Wald Tunnel	2.9	road
24	Amberg Tunnel	3.0	road
25	Schönberg Tunnel	3.0	road
26	Perjen Tunnel	3.0	road
27	Falkenberg Tunnel	3.0	road
28	Lermoos Tunnel	3.2	road
29	Achrain Tunnel	3.3	road
30	Ehrentalerberg	3.3	road
31	Pfaffenboden Tunnel	3.4	road
32	Semmering Scheitel Tunnel	3.5	road
33	Ganzstein Semmering Tunnel	3.5	road
34	Oswaldiberg Tunnel	4.3	road
35	Tschirgant Tunnel	4.3	road
36	Unterweitersdorfer Berg Tunnel	4.5	road
37	Roppener Tunnel	5.1	road
38	Schmitten Tunnel	5.1	road
39	Felbertauern Tunnel	5.3	road
40	Felbertauern Tunnel	5.3	road
41	Katschberg Tunnel	5.4	road
42	Katschberg Tunnel	5.4	road
43	Bosruck Tunnel	5.5	road
44	Bosruck Tunnel	5.5	road
45	Erzberg Tunnel	5.7	road
46	Strenger Tunnel	5.9	road
47	Tauern Road Tunnel	6.4	road
48	Pfänder Tunnel	6.7	road
49	Landecker Tunnel	7.0	road
50	Karawanken Tunnel	7.9	road
51	Karawanken Tunnel	8.0	rail
52	Gleinalm Tunnel	8.3	road
53	Tauern Railway Tunnel	8.6	rail
54	Plabutsch Tunnel	9.9	road
55	Arlberg Tunnel	10.2	rail
56	Arlberg Railway Tunnel	10.2	rail
57	Inntal Tunnel	12.7	rail
58	Lainzer Tunnel	12.8	rail
59	Wienerwald Tunnel	13.4	road
60	Wienerwald Tunnel	13.4	road
61	Arlberg Straßen Tunnel	14.0	road
62	Arlberg Road Tunnel	14.0	road
63	Koralm Tunnel	32.9	rail
64	Koralm Tunnel	32.9	rail

A brief comparison of these tunnels' lengths appears in Table 3.2.

Table 3.2: Comparison between lengths of Swiss and Austrian tunnels

	Switzerland	Austria
% tunnels smaller than 3 km	49%	42%
% tunnels smaller than 5 km	63%	58%

For $L_{threshold} = 5\ km$, a higher percentage of tunnels fall under the umbrella of "small tunnels", which gives the Catalogue a wider spectrum of application. Also, when generating the results, considering increments of 1,000 m is more interesting than 500 m, because the longer the step, the more variability is introduced in the simulations which yields more heterogenous results.

Thus, the Catalogue is best tailored for small tunnels, having a **Length $\boldsymbol{L \leq 5\ km}$**.

3.3.3 Tunnel Diameter

It has been assumed that the diameter of a tunnel does not affect its qualification as small or not. Nonetheless, a tunnel diameter must be selected for the simulations. Indeed, the size of the tube will have a direct influence on other inputs such as the unit time and cost estimates. If the user is to consult the Catalogue, the results must clearly show to which diameter they apply.

Picking tunnel diameter sizes is a function of many parameters, most importantly:

- Type of tunnel: railway vs. motorized traffic
- Traffic class: traffic volume (qualitatively: high, medium or low)
- Number of lanes: one or multiple

In order to get an idea about the usual diameter sizes of tunnels, some external sources need to be consulted. One publication aiming to find an optimal diameter for railway tunnels runs a parametric assessment on diameter sizes ranging from 7.95 m to 9 m (Abdi and Ghanbarpour, 2016). On another hand, Table 3.3 and Table 3.4 show respectively the recommendations of the Norwegian Standard (Norwegian Public Roads Administration, 2004) and the ones of the U.S. Department of Transportation (U.S. Federal Highway Administration, 2009) for road tunnel width dimensions.

Table 3.3: Norwegian Standard for road tunnel width recommendations

Tunnel Type	Total Width [m]	Description
T4	4	pedestrian and cycle paths
T5.5	5.5	single lane without requirements that a broken-down vehicle may be passed
T7	7	single lane with possibilities for a broken-down vehicle to be passed
T8.5	8.5	two-way traffic with medium traffic density
T9.5	9.5	two-way traffic with high traffic density
T11.5	11.5	requirement for three lanes or an emergency lay-by with medium traffic density
T12.5	12.5	requirement for three lanes or an emergency lay-by with high traffic density

Table 3.4: U.S. Federal Highway Administration road tunnel width recommendations

	two-lane tunnel width	
	[ft]	[m]
minimum	30	9
desirable	44	13.2

The type of tunnel (railway or road) seems to affect the section of the tunnel but not change it dramatically. They are roughly of the same size. The factor that is considerably changing the diameter is the number of lanes.

As far as the Catalogue is concerned, if it is to be widely used, it should then follow the trends of whatever is most common in real life. Most of the tunnels tend to accommodate at least two lanes in different configurations:

- two lanes, in one way
- two lanes, in a two-ways direction
- one full lane, with an emergency lane or wide shoulder, safety sidewalk etc.

Based on the recommendations in the sources and recalling that the Catalogue is considering a tunnel excavation by TBM only, the retained diameter is $\boldsymbol{d = 9\ m}$. This ensures that the Catalogue can be consulted for both road and railway tunnels with two ways, in whatever configuration may they be in.

3.3.4 Format and Nomenclature

The charts or tables constitute the end-results of the Catalogue. They are what needs to be consulted in order to obtain the construction cost and time estimates. They are presented in a Reference Table labeled by geology considerations. More details about the Reference Table appear in a dedicated section in Chapter 6.2.

Tables have two ways to be referred to:

- a number (from 1 to 27) that depends on their position in the Reference Table. This is the simplest way to refer to them for now.
- a universal nomenclature that is independent of their position in the Reference Table as the latter is expected to change with new expansions of the Catalogue.

The universal nomenclature always follows the same scheme, with each letter or number here referring to a position in the name:

$$A\,B - 1.2.3 - 44.55.66$$

Each position could be filled with one of many options and bears a certain significance. It is tailored to the current Catalogue but also leaves room for future additions. Abbreviation options are summarized in the non-exhaustive Table 3.5.

- A: a letter referring to the excavation method
- B: a letter referring to the geologic setting

- 1: a one-digit number referring to the number of GP states in the first GP (Geology)
- 2: a one-digit number referring to the number of GP states in the second GP (Fracture)
- 3: one-digit number referring to the number of GP states in the third GP (Water)

- 44: a double-digit number quantifying the percentage of the first GP state of Geology
- 55: a double-digit number quantifying the percentage of the first GP state of Fracture
- 66: a double-digit number quantifying the percentage of the first GP state of Water

Table 3.5: Summary of the nomenclature abbreviations

position A: Excavation Method		position B: Geologic Setting	
Abbreviation	Meaning	Abbreviation	Meaning
T	TBM	I	Igneous
D	Drill & Blast	S	Sedimentary
E	Excavator	M	Mixed

For further clarification, consider the following example for Table 1. In the general nomenclature it is:

$$T\,I - 2.2.2 - 75.75.75$$

Where:

- T for TBM
- I for Igneous setting
- 2 is the number of possible GP states for geology: Igneous Good / Igneous Bad
- 2 is the number of possible GP states for fracture: High / Low
- 2 is the number of possible GP states for water: High / Low
- 75 is the percentage of GP state 1 of geology: $IG = 75$
- 75 is the percentage of GP state 1 of fracture: $H = 75$
- 75 is the percentage of GP state 1 of water: $H = 75$

Similarly, Table 26 is:

$$T\,M - 4.2.2 - 38.25.25$$

- T for TBM
- $M$for Mixed setting
- 4 is the number of possible GP states for geology:
  Igneous Good / Igneous Bad / Sedimentary Good / Sedimentary Bad
- 2 is the number of possible GP states for fracture: High / Low
- 2 is the number of possible GP states for water: High / Low
- 38 is the percentage of GP state 1 of geology: $IG = 38$
- 25 is the percentage of GP state 1 of fracture: $H = 25$
- 25 is the percentage of GP state 1 of water: $H = 25$

This nomenclature, being independent of the position of the table in the Reference Table, is needed when expanding the Catalogue and having new charts generated for intermediate conditions that would otherwise ruin the simplistic numbering that currently goes from 1 to 27.

Table 3.6 summarizes all the current (27) table numbers in the Reference Table with their associated absolute name following the defined format.

Table 3.6: Summary of the table numbers and their absolute name

	Table Number	position A	position B	position 1	position 2	position 3	position 44	position 55	position 66	Absolute table name
Igneous setting	1	T	I	2	2	2	75	75	75	T I - 2.2.2 - 75.75.75
	2	T	I	2	2	2	50	75	75	T I - 2.2.2 - 50.75.75
	3	T	I	2	2	2	25	75	75	T I - 2.2.2 - 25.75.75
	4	T	I	2	2	2	75	50	50	T I - 2.2.2 - 75.50.50
	5	T	I	2	2	2	50	50	50	T I - 2.2.2 - 50.50.50
	6	T	I	2	2	2	25	50	50	T I - 2.2.2 - 25.50.50
	7	T	I	2	2	2	75	25	25	T I - 2.2.2 - 75.25.25
	8	T	I	2	2	2	50	25	25	T I - 2.2.2 - 50.25.25
	9	T	I	2	2	2	25	25	25	T I - 2.2.2 - 25.25.25
Sedimentary setting	10	T	S	2	2	2	75	75	75	T S - 2.2.2 - 75.75.75
	11	T	S	2	2	2	50	75	75	T S - 2.2.2 - 50.75.75
	12	T	S	2	2	2	25	75	75	T S - 2.2.2 - 25.75.75
	13	T	S	2	2	2	75	50	50	T S - 2.2.2 - 75.50.50
	14	T	S	2	2	2	50	50	50	T S - 2.2.2 - 50.50.50
	15	T	S	2	2	2	25	50	50	T S - 2.2.2 - 25.50.50
	16	T	S	2	2	2	75	25	25	T S - 2.2.2 - 75.25.25
	17	T	S	2	2	2	50	25	25	T S - 2.2.2 - 50.25.25
	18	T	S	2	2	2	25	25	25	T S - 2.2.2 - 25.25.25
Mixed setting	19	T	M	4	2	2	25	75	75	T M - 4.2.2 - 25.75.75
	20	T	M	4	2	2	38	75	75	T M - 4.2.2 - 38.75.75
	21	T	M	4	2	2	12	75	75	T M - 4.2.2 - 12.75.75
	22	T	M	4	2	2	25	50	50	T M - 4.2.2 - 25.50.50
	23	T	M	4	2	2	38	50	50	T M - 4.2.2 - 38.50.50
	24	T	M	4	2	2	12	50	50	T M - 4.2.2 - 12.50.50
	25	T	M	4	2	2	25	25	25	T M - 4.2.2 - 25.25.25
	26	T	M	4	2	2	38	25	25	T M - 4.2.2 - 38.25.25
	27	T	M	4	2	2	12	25	25	T M - 4.2.2 - 12.25.25

Regarding the presentation of the data, each Table of the Catalogue in Chapter 6, is actually a collection of different results, enumerated here and annotated on Figure 3.10:

1. Five independent scattergrams: showing the results for each length step: 1,2,3,4 and 5 km
2. One graph with all the superposed scattergrams
3. One summary table: showing the results $[Min;\ Mean;\ Max]$ of cost and time
4. Two summary charts: respectively with linear and second degree polynomial fits

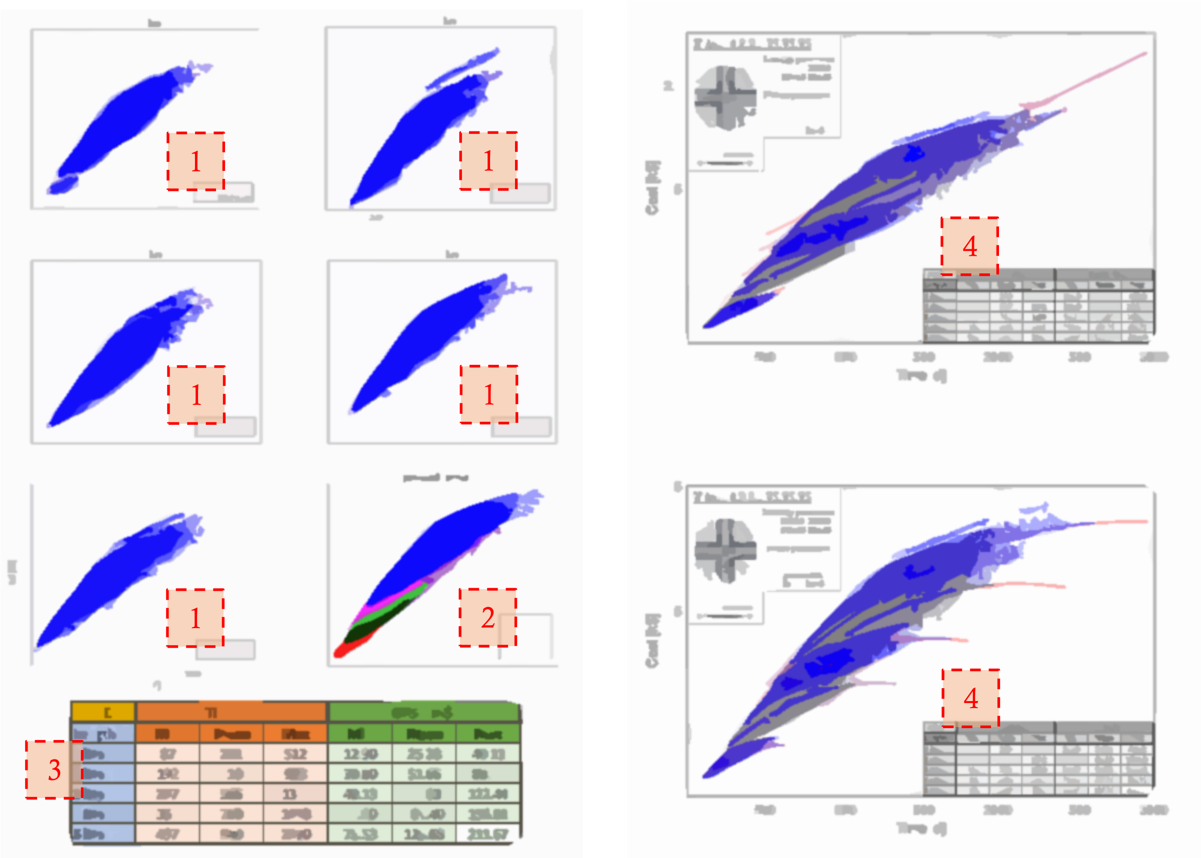


Figure 3.10: Template of a typical Catalogue Table

As mentioned, two models are proposed for the summary charts. Basically, the same layout applies to both with only the data presentation differing between a linear fit and a second-degree polynomial. They are presented respectively in Figure 3.11 and Figure 3.12.

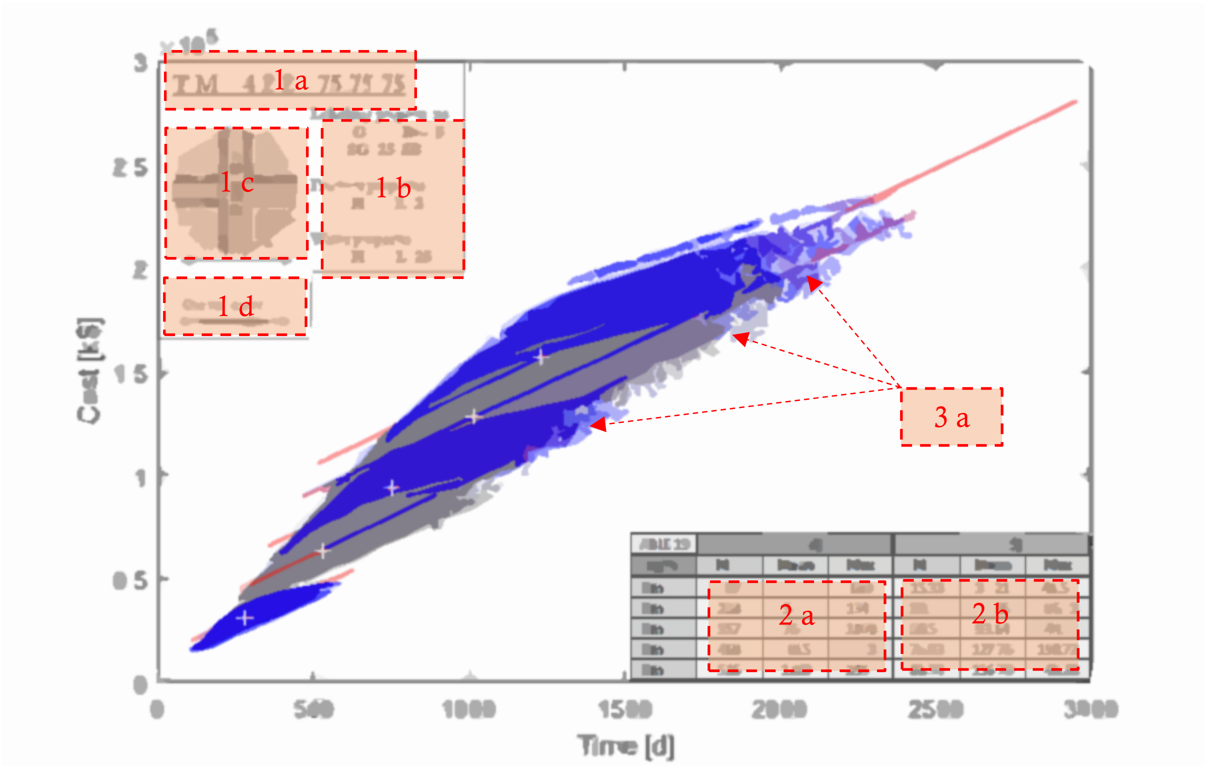


Figure 3.11: Chart layout with linear fitting of the data

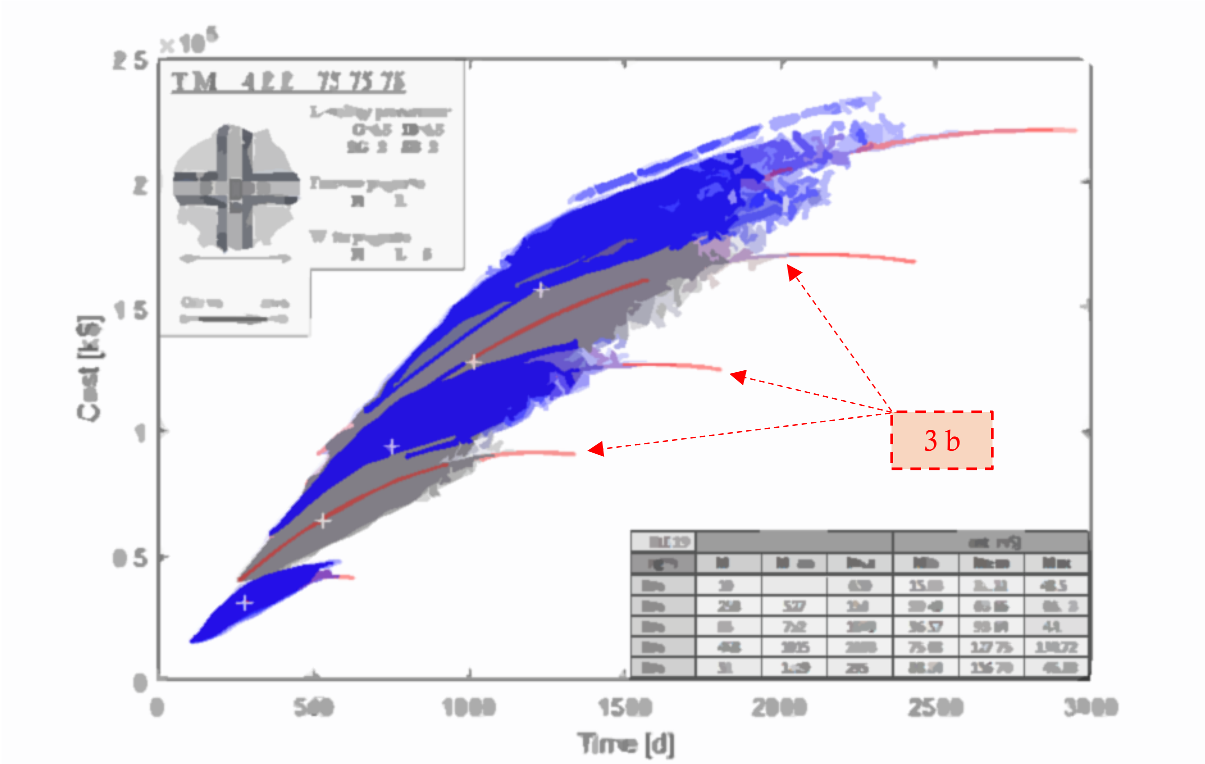


Figure 3.12: Chart layout with second degree polynomial fitting of the data

Each summary chart has within the following components, labeled on Figure 3.11 and Figure 3.12 using the following enumeration:

1. A summary of the simulated conditions at the top left-hand side:
    a. Complete name of the chart
    b. GP and GP states summary with proportions
    c. Section dimensions and construction method
    d. Tunnel network configuration

2. A summary table at the bottom right hand-side:
    a. $[Min;\ Mean;\ Max]$ values of time for every length step
    b. $[Min;\ Mean;\ Max]$ values of cost for every length step

3. Superposed scattergrams and fits
    a. Linear fit model
    b. Second degree polynomial fit model

The linear fit model in Figure 3.11 presents the scattergrams with an individual fit for each. Time and cost appear respectively on the x-axis and y-axis. The particularity of this fit is that most slopes are comparable. As such, it becomes much easier to approximate values in between simulated data entries by simply finding the centerline (white crosses on the data that are almost equally spaced) and drawing a line parallel to the rest. This interpolation process is detailed in Chapter 6.6. One possible addition (not implemented on the current graphs) proposes two confidence boundaries on both sides. They appear roughly schematized in Figure 3.13. The internal region delimits a high probability domain, where basically most of the results appear. The intermediate hatched region delimits a low probability domain, where only a few points appear out of the total 50,000 per length step. And finally, the outer region is the extremely improbable domain, where basically no results have been observed.

The preference for this initially proposed fit was halted when the results have been obtained. Indeed, as can be seen in Chapter 6 and discussed in Chapter 7, the scattergrams are not best approximated by a linear fit. A second-degree polynomial fit is then proposed.

This second-degree polynomial fit model appears in Figure 3.12. The same axes configurations apply as abovementioned for the first model. The confidence boundaries are replaced by simpler upper and lower bounds shown in Figure 3.14. Also, interpolations become less simple, as curved lines need to be drawn for best estimates.

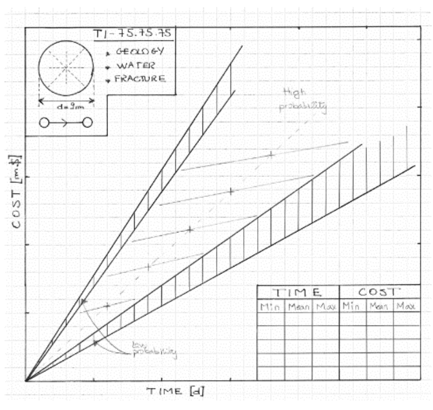


Figure 3.13: Schematic linear fit

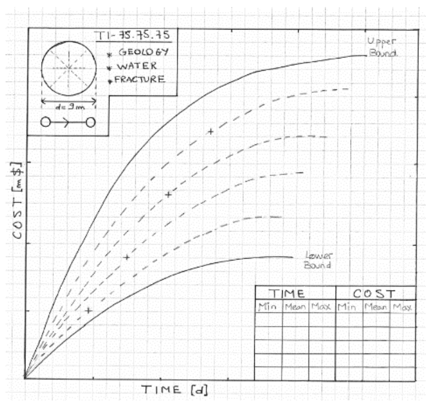


Figure 3.14: Schematic polynomial fit

CHAPTER 4

4 CATALOGUE INPUTS

4.1 Cost Estimates

4.1.1 Sources

Among different inputs required for the simulations, cost estimates and their variabilities are perhaps the most crucial values. Simple estimates by speculations are thus not the best approach to abide by, especially when trying to gain the user's confidence in the Catalogue.

Data might be gathered from contractors in the form of short surveys and the results statistically analyzed in order to estimate the spread $[Min;\ Mean;\ Max]$ of unit excavation costs for different specified construction methods. However, contractors are often reluctant to divulge such information about their estimates, especially of unit costs, on which they extensively rely during the bidding phases of contracts. Therefore, a different but often practiced approach is used, ensuring a proper balance between the accuracy of results and the time constraints.

Estimates are based on two studies. Fermilab Tunnels published a report by CNA Consulting Engineers and Hatch-Mott-MacDonald (CNA Consulting Engineers, 2001) detailing the cost estimates of 30 tunnel cases similar to the ones being simulated in the Catalogue. The following are the considered assumptions in the source. More details are available in Appendix A.

- 4800 m of tunnel from shaft to shaft
- Two 10 hours shifts undertaken daily, 5 days per week
- Tunnels excavated using 3.66 m and 4.88 m finished diameter rock TBM
- Labor rates based on a Minneapolis Project in Year 2001
- 3 ground class categories considered

Another study, upon which the estimates rely, is a publication entitled "Tunnel Construction Costs for Tube Transportation Systems" (Sinfielf and Einstein, 1998). The latter summarizes the results of 52 cases of tunnel diameters ranging from $0.4\ m \leq d \leq 4.8\ m$, as they appear in Appendix B. Its results, that are much less detailed compared to the ones of first source, are best used to back-check the validity of the estimated results from the Fermilab cases.

A discrepancy exists however in the specifications between what is needed and what is available in the sources. Therefore, corrections are needed in order to make use of the available data. They are the following:

- Cost corrections for **diameter**
- Cost corrections for cross sectional **area**
- Cost extrapolation for new **ground classes**
- Cost corrections for **years**

4.1.2 Geometry Correction

The available cost estimates require some corrections in order to respect the overall needed scale. Primarily, the length of tunnels is taken out of the equation because all values are unit costs normalized in [$\$/m$]. Yet one may suggest that studies based on tunnels many kilometers in length are less representative of the targeted small tunnels of this study. For the Fermilab case, at $4800\ m$, the scale is almost perfectly tailored for the tunnels of the Catalogue with lengths ranging from $1000 \leq L \leq 5000\ m$. Thus, the length does not require any corrections.

On the other hand, the diameter is off scale by roughly a factor of two. The available estimates apply to 3.66 m and 4.88 m diameters while the required one is 9 m.

The raw values extracted from the Fermilab Tunnels report appear in Table 4.1. For the rest of the analysis, the results are reorganized in the form of [$Min;\ Mean;\ Max$] values, in order to yield the final results in this sought-after format.

Table 4.1: Original values Fermilab

FERMILAB ESTIMATE SUMMARY

DATA VALUES IN 2001

Diameter 3.66 m				
Rock	Total [$]	Unit cost [$/m]	summary values	
A	8560000	1783		
	6270000	1306	A min	1208
	6110000	1273	A mean	1356
	5800000	1208	A max	1783
	5800000	1208		
B	19330000	4027		
	16550000	3448	B min	3315
	16340000	3404	B mean	3502
	15910000	3315	B max	4027
	15910000	3315		
C	27030000	5631		
	23390000	4873	C min	4715
	23140000	4821	C mean	4951
	22630000	4715	C max	5631
	22630000	4715		

Diameter 4.88 m			
Total [$]	Unit cost [$/m]	summary values	
11330000	2360		
7560000	1575	A min	1400
7280000	1517	A mean	1650
6720000	1400	A max	2360
6720000	1400		
24810000	5169		
20360000	4242	B min	4021
20010000	4169	B mean	4324
19300000	4021	B max	5169
19300000	4021		
33760000	7033		
28030000	5840	C min	5573
27600000	5750	C mean	5954
26750000	5573	C max	7033
26750000	5573		

The first intuition would be to linearly extrapolate the existing values in order to obtain the required ones. The results appear in Table 4.2, based on the following approach and solving for $Unit\ Cost_{d=9}$.

$$\frac{4.88\ m - 3.66\ m}{Unit\ Cost_{d=4.88} - Unit\ Cost_{d=3.66}} = \frac{9\ m - 4.88\ m}{Unit\ Cost_{d=9} - Unit\ Cost_{d=4.88}}$$

Table 4.2: Results for d=9m by diameter correction

Costs in	BY DIAMTER [m]		
2001	**3.66**	**4.88**	**9**
GC	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]
A min	1208	1400	2047
A mean	1356	1650	2645
A max	1783	2360	4309
B min	3315	4021	6406
B mean	3502	4324	7102
B max	4027	5169	9024
C min	4715	5573	8472
C mean	4951	5954	9341
C max	5631	7033	11768

However, other studies suggest that the increase in unit cost is not linear. Figure 4.1 shows the cost variation as a function of diameter increase (Sinfield and Einstein, 1995).

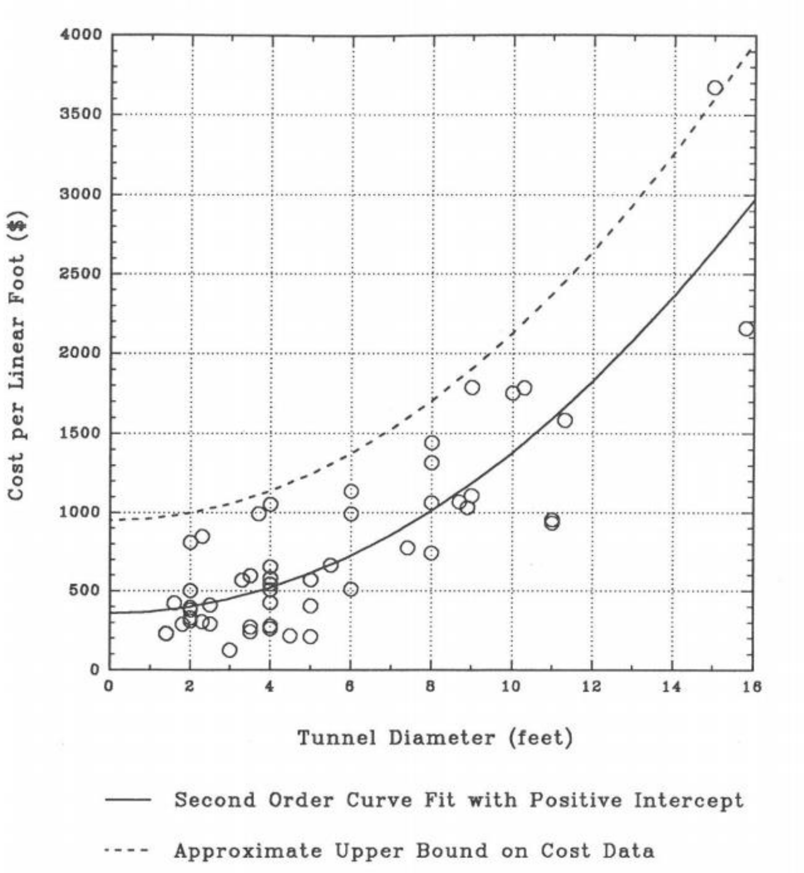


Figure 4.1: Tunnel cost per linear foot and tunnel diameter

An alternative to correct for the needed geometry, instead of directly extrapolating by diameter values, is to do so using a correction by area. The same concept holds true but resorts to using ratios of cross section areas with a squared effect of diameter. Results appear in Table 4.3.

Table 4.3: Results for d=9m by area correction

Costs in	BY AREA [m2]		
2001	**10.52**	**18.70**	**63.62**
GC	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]
A min	1208	1400	2452
A mean	1356	1650	3267
A max	1783	2360	5528
B min	3315	4021	7897
B mean	3502	4324	8839
B max	4027	5169	11435
C min	4715	5573	10284
C mean	4951	5954	11458
C max	5631	7033	14729

Results obtained using the correction by area are slightly larger than the ones obtained by diameter correction by an average ratio of 1.24. Referring to Figure 4.1, higher costs are actually more plausible, which is why a correction by area is the preferred option. The ratio between costs obtained by area correction with respect to the one by diameter is equal to 1.24. The details appear in Table 4.4.

Table 4.4: Results 9m by both corrections

Costs in	BY DIAMTER [m]			BY AREA [m2]			COMPARISON
2001	**3.66**	**4.88**	**9**	**10.52**	**18.70**	**63.62**	of both corrections
GC	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	ratio of costs Area/Dia
A min	1208	1400	2047	1208	1400	2452	1.20
A mean	1356	1650	2645	1356	1650	3267	1.24
A max	1783	2360	4309	1783	2360	5528	1.28
B min	3315	4021	6406	3315	4021	7897	1.23
B mean	3502	4324	7102	3502	4324	8839	1.24
B max	4027	5169	9024	4027	5169	11435	1.27
C min	4715	5573	8472	4715	5573	10284	1.21
C mean	4951	5954	9341	4951	5954	11458	1.23
C max	5631	7033	11768	5631	7033	14729	1.25

4.1.3 Ground Classes Correction

Three ground classes are used in the Fermilab cases, namely: A, B and C. According to the provided description of each, it is possible to link the construction practices to a qualitative description of the ground classes (5) used for the Catalogue, namely: *very good*, *good*, *fair*, *bad* and *very bad*. More information about the ground classes used in the Catalogue is presented later in Chapter 4.4.

In the Fermilab records, ground class **A** is described as follows:

- No areas of difficult excavation
- Total of 400 rock bolts installed sporadically in tunnel crown in jointed or weak zones
- No lining required
- Average advance rate 225 *m* per week

Ground class **B** is described as follows:

- No areas of difficult excavation
- Three rock bolts installed every 4.5 m of the tunnel (more than 1000 in total)
- Secondary cast-in-place concrete lining to prevent long term degradation
- Average advance rate 195 m per week

Ground class **C** is described as follows:

- Areas of difficult excavation encountered, slowing normal advance rate by 20% over 20% of the tunnel length
- 225 mm thick segmental concrete lining installed immediately behind TBM
- Average advance rate 102 m per week

Note that only the unit costs are being approximated from this source. The unit advance rates are the subject of Chapter 4.2 and are estimated from another source.

Upon inspection of the construction conditions governing the three ground classes, it is somehow clear that they are respectively analogous to ground classes 1, 2 and 3 of the Catalogue's ground classes, namely: *very good*, *good* and *fair*. The two additional ground classes that are not covered in the available data are: *bad* and *very bad* conditions. These need to be determined based on the existing information.

For the three diameters of data (following the previous correction), and three cross sections, it is possible to calculate a ratio of cost increase when passing from one ground condition to another. For instance, when going from ground classes A to B and from ground classes B to C, for all [Min; $Mean$; Max] values. The results and their averages, appear in Table 4.5.

Table 4.5: Ground class transition factors

		BY DIAMTER [m]			BY AREA [m2]			Average
		3.66	**4.88**	**9**	**10.52**	**18.70**	**63.62**	
A to B	min	2.74	2.87	3.13	2.74	2.87	3.22	2.58
	mean	2.58	2.62	2.68	2.58	2.62	2.71	
	max	2.26	2.19	2.09	2.26	2.19	2.07	
B to C	min	1.42	1.39	1.32	1.42	1.39	1.30	1.36
	mean	1.41	1.38	1.32	1.41	1.38	1.30	
	max	1.40	1.36	1.30	1.40	1.36	1.29	

Calculated ratios are respectively:

- when going from ground class A (very good) to B (good): 2.58
- when going from ground class B (good) to C (fair): 1.36

A reasonable option is to maintain the same ratios for the two additionally required ground classes; using the larger ratio for the extreme condition and the smaller one for the regular increase from one ground class to another. Basically, the two ratios are chosen as follows:

- when going from ground class C (fair) to D (bad): 1.36
- when going from ground class D (bad) to E (very bad): 2.58

Figure 4.2 shows the ratio repartitions in order to extrapolate results for the new ground classes with: (1) observed ratios from the given data and (2) chosen values to mimic what was found.

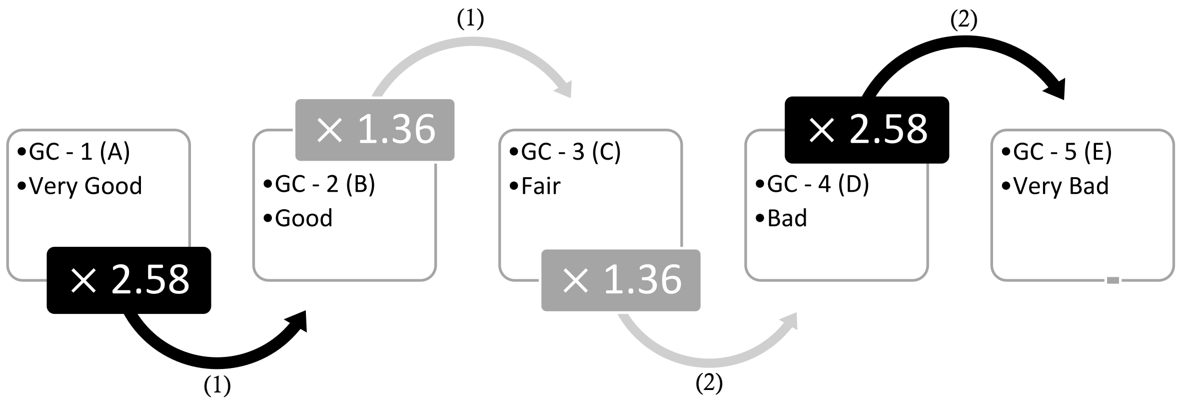


Figure 4.2: Ground classes extrapolation cost ratios

The calculated results for the two extra ground classes appear in Table 4.6 for the 9 m diameter and its cross section.

Table 4.6: Cost for ground classes D and E for diameter 9 and area

Costs in	BY DIAMTER [m]			BY AREA [m2]			COMPARISON
2001	**3.66**	**4.88**	**9**	**10.52**	**18.70**	**63.62**	of both corrections
GC	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	ratio of costs Area/Dia
A min	1208	1400	2047	1208	1400	2452	1.20
A mean	1356	1650	2645	1356	1650	3267	1.24
A max	1783	2360	4309	1783	2360	5528	1.28
B min	3315	4021	6406	3315	4021	7897	1.23
B mean	3502	4324	7102	3502	4324	8839	1.24
B max	4027	5169	9024	4027	5169	11435	1.27
C min	4715	5573	8472	4715	5573	10284	1.21
C mean	4951	5954	9341	4951	5954	11458	1.23
C max	5631	7033	11768	5631	7033	14729	1.25
calculated values				calculated values			calculated values
D min	not needed		11552	not needed		14023	1.21
D mean			12737			15625	1.23
D max			16047			20084	1.25
E min			29800			36176	1.21
E mean			32857			40307	1.23
E max			41396			51811	1.25

4.1.4 Years Correction

All the aforementioned costs in the original and computed data represent costs in 2001. One alternative would be to simply keep these values unchanged, assuming that few changes have occurred in the market and that corrections are negligible.

On the other hand, the changes may be significant and some correction is indeed needed to represent inflation. One simple way of doing so is through the use of the CPI (Consumer Price Index). Arguably some may contest that this is mainly accurate for goods and services purchased by households but less so applicable to the tunneling industry. Also, economists differentiate between CPI and inflation as two related but not entirely identical concepts. Nonetheless, the differences are negligible for such a small application. Also, the correction through barely a few decades remains fairly accurate.

CPI values are provided by the U.S. Department of Labor Bureau of Labor Statistic (U.S. Inflation Calculator, 2018) as follows:

$CPI_{2001} = 177.1$ (all 12 months average) $CPI_{2018} = 249.2$ (first 4 available months average)

The new costs are calculated based on the following relation as defined by the US Inflation Calculator (U.S. Inflation Calculator, 2018):

$$2018\,price = 2001\,price\ \times \frac{2018\,CPI}{2001\,CPI}$$

All the costs previously calculated for 2001 are thus corrected for the year 2018 as they appear in the following Table 4.7.

Table 4.7: All values corrected for time in 2018

Costs in	BY DIAMTER [m]			BY AREA [m2]			COMPARISON
2018	**3.66**	**4.88**	**9**	**10.52**	**18.70**	**63.62**	of both corrections
GC	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	unit cost [$/m]	ratio costs Area/Dia
A min	1701	1970	2881	1701	1970	3451	1.20
A mean	1908	2323	3723	1908	2323	4598	1.24
A max	2510	3322	6065	2510	3322	7780	1.28
B min	4665	5659	9015	4665	5659	11114	1.23
B mean	4928	6086	9995	4928	6086	12439	1.24
B max	5667	7274	12700	5667	7274	16093	1.27
C min	6635	7843	11922	6635	7843	14473	1.21
C mean	6967	8379	13145	6967	8379	16126	1.23
C max	7925	9898	16562	7925	9898	20729	1.25
calculated values				calculated values			calculated values
D min	not needed		16257	not needed		19736	1.21
D mean			17925			21989	1.23
D max			22584			28266	1.25
E min			41938			50911	1.21
E mean			46241			56725	1.23
E max			58259			72916	1.25

4.1.5 Preliminary Results

From the obtained analysis it is possible to regroup the results for an easier representation and comparison. They appear in the following tables.

Table 4.8: 4 summary tables: both diameter and area corrections for both time and no time corrections

Candidate table 1

TBM d= 9m (2001)		Unit costs [$/m]		
by diameter		**min**	**mean**	**max**
GC-1	Very Good	2047	2645	4309
GC-2	Good	6406	7102	9024
GC-3	Fair	8472	9341	11768
GC-4	Bad	11552	12737	16047
GC-5	Very Bad	29800	32857	41396

Candidate table 2

TBM d= 9m (2001)		Unit costs [$/m]		
by area		**min**	**mean**	**max**
GC-1	Very Good	2452	3267	5528
GC-2	Good	7897	8839	11435
GC-3	Fair	10284	11458	14729
GC-4	Bad	14023	15625	20084
GC-5	Very Bad	36176	40307	51811

Candidate table 3

TBM d= 9m (2018)		Unit costs [$/m]		
by diameter		**min**	**mean**	**max**
GC-1	Very Good	2881	3723	6065
GC-2	Good	9015	9995	12700
GC-3	Fair	11922	13145	16562
GC-4	Bad	16257	17925	22584
GC-5	Very Bad	41938	46241	58259

Candidate table 4

TBM d= 9m (2018)		Unit costs [$/m]		
by area		**min**	**mean**	**max**
GC-1	Very Good	3451	4598	7780
GC-2	Good	11114	12439	16093
GC-3	Fair	14473	16126	20729
GC-4	Bad	19736	21989	28266
GC-5	Very Bad	50911	56725	72916

Before selecting the definitive results, a quick comparison with the second source of data is required in order to check that its results fall within the defined limits.

4.1.6 Checking Results

As previously mentioned, a second less detailed source (Sinfielf and Einstein, 1998) is used as a check in order to both make sure that the estimates are representative and to help pick the most accurate table as the definitive one. This publication shows the unit costs of 52 cases and their adjusted values in the year 1998. The complete set of data appears in Appendix B.

In order to compare these given 52 case results to the 4 candidate unit cost tables, they need to be converted to an equivalent 9 m diameter and brought forward to the year 2018. Adjusting for years is done similarly to what was done before using the CPI with a $CPI_{1998} = 163$.

Geometry corrections on the other hand are slightly different. Since for each case there is now only one value to extrapolate from (recall before each had two values: for 3.66 m and 4.88 m diameters), then the linear extrapolation goes simply as follows:

$$Corrected\ cost = \frac{9\ m\ section \times Original\ cost}{Original\ section}$$

This is the first method of correcting for geometry by making use of the cross-sectional areas as was done previously. However, many of the cases in the publication have excessively small diameters (more than half of them have a diameter $d \leq 1.5\ m$) that produce very small areas which in turn yield huge corrected costs (being the denominator of in the equation).

A second method can be applied based only on the diameter (not the area) and is perhaps more appropriate for values as small as the ones here. The correction applies the same principle as previously mentioned:

$$Corrected\ cost = \frac{9\ m\ diameter \times Original\ cost}{Original\ diameter}$$

However, it has already been established in Figure 4.1 that basing corrections solely on diameters is inexact. The obtained value when using this method is then inflated by a factor of 1.24. This is actually the ratio of area correction results to diameter correction results observed previously in Table 4.4.

Respective results for method 1 (area correction) and method 2 (diameter correction) appear in Table 4.9 and Table 4.10.

Table 4.9: Results method 1 (area correction)

Project Number	Diameter	Cost 1998 [$/m]	Area [m2]	9m Cost 1998 [$/m]	9m Cost 2018 [$/m]
1	0.4	748	0.1257	378675	579023
2	0.4	755	0.1257	382218.75	584442
3	0.5	1384	0.1963	448416	685662
4	0.5	945	0.1963	306180	468173
5	0.6	1083	0.2827	243675	372598
6	0.6	1247	0.2827	280575	429021
7	0.6	1299	0.2827	292275	446911
8	0.6	1014	0.2827	228150	348859
9	0.6	2661	0.2827	598725	915496
10	0.6	1664	0.2827	374400	572486
11	0.7	994	0.3848	164314.2857	251249
12	0.7	2782	0.3848	459881.6327	703194
13	0.8	958	0.5027	121246.875	185396
14	0.8	1342	0.5027	169846.875	259709
15	0.9	410	0.6362	41000	62692
16	1	1867	0.7854	151227	231238
17	1.1	892	0.9503	59712.39669	91305
18	1.1	791	0.9503	52951.23967	80967
19	1.1	1959	0.9503	131139.6694	200523
20	1.1	3255	0.9503	217896.6942	333181
21	1.2	1781	1.1310	100181.25	153185
22	1.2	856	1.1310	48150	73625
23	1.2	915	1.1310	51468.75	78700
24	1.2	1906	1.1310	107212.5	163936
25	1.2	1667	1.1310	93768.75	143380
26	1.2	2146	1.1310	120712.5	184579
27	1.2	3455	1.1310	194343.75	297166
28	1.2	1391	1.1310	78243.75	119641
29	1.4	709	1.5394	29300.5102	44803
30	1.5	692	1.7671	24912	38092
31	1.5	1325	1.7671	47700	72937
32	1.5	1870	1.7671	67320	102937
33	1.7	2178	2.2698	61044.29066	93341
34	1.8	1673	2.5447	41825	63954
35	1.8	3255	2.5447	81375	124429
36	1.8	3727	2.5447	93175	142472
37	2.3	2539	4.1548	38876.93762	59446
38	2.4	3487	4.5239	49035.9375	74980
39	2.4	2438	4.5239	34284.375	52423
40	2.4	4731	4.5239	66529.6875	101729
41	2.4	4321	4.5239	60764.0625	92913
42	2.7	3504	5.7256	38933.33333	59532
43	2.7	3389	5.7256	37655.55556	57578
44	2.7	5866	5.7256	65177.77778	99662
45	2.7	3632	5.7256	40355.55556	61707
46	3	5748	7.0686	51732	79102
47	3.1	5860	7.5477	49392.29969	75525
48	3.4	3133	9.0792	21952.68166	33567
49	3.4	3068	9.0792	21497.23183	32871
50	3.4	5197	9.0792	36414.9654	55681
51	4.6	12054	16.6190	46142.43856	70555
52	4.8	7080	18.0956	24890.625	38060

Table 4.10: Results method 2 (diameter correction)

Project Number	Diameter	Cost 1998 [$/m]	9m Cost 1998 [$/m]	1.24 x 9m Cost 1998 [$/m]	9m Cost 2018 [$/m]
1	0.4	748	16830.0000	20869.2	25734
2	0.4	755	16987.5000	21064.5	32209
3	0.5	1384	24912.0000	30890.88	47235
4	0.5	945	17010.0000	21092.4	32252
5	0.6	1083	16245.0000	20143.8	30801
6	0.6	1247	18705.0000	23194.2	35466
7	0.6	1299	19485.0000	24161.4	36945
8	0.6	1014	15210.0000	18860.4	28839
9	0.6	2661	39915.0000	49494.6	75681
10	0.6	1664	24960.0000	30950.4	47326
11	0.7	994	12780.0000	15847.2	24232
12	0.7	2782	35768.5714	44353.02857	67819
13	0.8	958	10777.5000	13364.1	20435
14	0.8	1342	15097.5000	18720.9	28626
15	0.9	410	4100.0000	5084	7774
16	1	1867	16803.0000	20835.72	31859
17	1.1	892	7298.1818	9049.745455	13838
18	1.1	791	6471.8182	8025.054545	12271
19	1.1	1959	16028.1818	19874.94545	30390
20	1.1	3255	26631.8182	33023.45455	50495
21	1.2	1781	13357.5000	16563.3	25327
22	1.2	856	6420.0000	7960.8	12173
23	1.2	915	6862.5000	8509.5	13012
24	1.2	1906	14295.0000	17725.8	27104
25	1.2	1667	12502.5000	15503.1	23705
26	1.2	2146	16095.0000	19957.8	30517
27	1.2	3455	25912.5000	32131.5	49132
28	1.2	1391	10432.5000	12936.3	19781
29	1.4	709	4557.8571	5651.742857	8642
30	1.5	692	4152.0000	5148.48	7872
31	1.5	1325	7950.0000	9858	15074
32	1.5	1870	11220.0000	13912.8	21274
33	1.7	2178	11530.5882	14297.92941	21863
34	1.8	1673	8365.0000	10372.6	15861
35	1.8	3255	16275.0000	20181	30858
36	1.8	3727	18635.0000	23107.4	35333
37	2.3	2539	9935.2174	12319.66957	18838
38	2.4	3487	13076.2500	16214.55	24793
39	2.4	2438	9142.5000	11336.7	17335
40	2.4	4731	17741.2500	21999.15	33638
41	2.4	4321	16203.7500	20092.65	30723
42	2.7	3504	11680.0000	14483.2	22146
43	2.7	3389	11296.6667	14007.86667	21419
44	2.7	5866	19553.3333	24246.13333	37074
45	2.7	3632	12106.6667	15012.26667	22955
46	3	5748	17244.0000	21382.56	32696
47	3.1	5860	17012.9032	21096	32257
48	3.4	3133	8293.2353	10283.61176	15724
49	3.4	3068	8121.1765	10070.25882	15398
50	3.4	5197	13756.7647	17058.38824	26084
51	4.6	12054	23583.9130	29244.05217	44716
52	4.8	7080	13275.0000	16461	25170

The obtained corrected results in Table 4.9 and Table 4.10 will be used to measure how "accurate" each candidate table from 1 to 4 is, by counting how many results fall within the predicted limits of each candidate table. Thus, a simple counting of the number of cells that fall within the "correct" margin proposed in each candidate table, is capable of determining the most accurate one. It will be the one retained for the simulations. This accuracy measure is established for each candidate table considering both the results of approaches 1 and 2; the results appear in Table 4.11.

In Table 4.11, the first method (area correction) yields poorer results compared to the second one (correction by diameter); meaning that less cells in Table 4.9 are within the proposed boundaries of the candidate tables compared to the results in Table 4.10. The second method (results in Table 4.10) seems to show a certain satisfaction level with a majority of the data falling within the margins. Apparently, the best results are obtained for candidate table 4 which considers both a correction by area and an update of costs with respect to time.

A second similar round is needed but only looking at the tunnels with a diameter $d \geq 1.5\ m$. The motivation is the fact that all the correction methods are much more accurate for closer ranges of diameters. It is only "fair" to neglect the extremely small diameters $d \leq 1.5\ m$ compared to the desired $9\ m$. The results also appear in the second part of Table 4.11.

As predicted the percentage of accuracy has improved for both methods. The principle of obtaining a better accuracy when dropping off extreme values from the analysis holds true. A third round is thus justified, looking this time at tunnels with a diameter $d \geq 3\ m$. Its results appear in the third part of Table 4.11.

In the third round, method 2 barely shows any improvement when considering only diameters $d \geq 3\ m$, because it has already capped at 100% for the cases falling within the proposed margins in the tables. Method 1 exhibits significant improvement up to a point where a confidence is established for the case of candidate table 4. In other words, using the unit cost approximations in candidate table 4 is accurate to more than 70%, at worst, and 100%, at best, for all the cases of tunnels with a diameter of comparable scale (even if $d = 3\ m$ is till three times smaller than the targeted $d = 9\ m$).

Table 4.11: Results falling within the margins for all 3 cases

METHOD 1			METHOD 2		
cells within boundaries			cells within boundaries		
All diameters			All diameters		
Candidate Table 1	4	8%	Candidate Table 1	45	87%
Candidate Table 2	5	10%	Candidate Table 2	50	96%
Candidate Table 3	8	15%	Candidate Table 3	50	96%
Candidate Table 4	14	27%	Candidate Table 4	51	98%
Only d > 1.5 m			Only d > 1.5 m		
Candidate Table 1	4	18%	Candidate Table 1	21	95%
Candidate Table 2	4	18%	Candidate Table 2	22	100%
Candidate Table 3	7	32%	Candidate Table 3	22	100%
Candidate Table 4	12	55%	Candidate Table 4	22	100%
Only d > 3 m			Only d > 3 m		
Candidate Table 1	3	43%	Candidate Table 1	6	86%
Candidate Table 2	3	43%	Candidate Table 2	7	100%
Candidate Table 3	4	57%	Candidate Table 3	7	100%
Candidate Table 4	5	71%	Candidate Table 4	7	100%

4.1.7 Final Cost Results

Based on the results of the analysis, the retained unit cost estimates are based on the rounded results of candidate table 4. The final end results that are retained and will thus be used for the Catalogue simulations appear in Table 4.12.

Table 4.12: Final cost results: candidate table 4 with results rounded

TBM d= 9m (2018)		Unit costs [$/m]		
by area		**min**	**mean**	**max**
GC-1	Very Good	3000	5000	8000
GC-2	Good	11000	13000	16000
GC-3	Fair	14000	16000	21000
GC-4	Bad	20000	23000	29000
GC-5	Very Bad	51000	57000	73000

4.2 Time Estimates

4.2.1 Sources

Advance rate estimates are required as inputs for the simulations if the end results are to include tunnel construction times. The choice of representative inputs is thus crucial in order to obtain reliable end results in the Catalogue.

Similar to the limitations in deriving cost estimates, this study cannot rely on obtained surveys from tunneling contractors. The issues are primarily the lack to time and the reluctance of contractors to share sensitive knowledge upon which they rely in the bidding phase to ensure a competitive edge. Once again, the analysis avoids this problem by evaluating other sources and filtering out the contents that best describes the targeted case.

One particularly detailed documentation is available by AlpTransit for the Gotthard Base Tunnel (AlpTransit Gotthard AG, 2016). Data is organized for four different tunnels, namely:

- Erstfeld east and Erstfeld west
- Amsteg east and Amsteg west
- Faido
- Bodio

More information about the raw data appear in Appendix C. The data are not exactly given in the sought-after form of $[Min;\ Mean;\ Max]$ time estimates. Inevitably some manipulations are needed in order to formulate the final results intended for the simulations.

4.2.2 Corrections

In the most general form, corrections apply when the available data are based on tunnels whose specifications diverge from the one selected for the Catalogue. For instance,

- Diameter
- Length
- Time
- Ground Classes etc.

For the Gotthard Base Tunnel, all four TBMs have diameters of the same scale as the targeted 9 m diameter. The precise values appear in Table 4.13.

Table 4.13: Gotthard excavation diameter in tunnel sections with TBM drive

Gotthard Tunnels	d [m]
Erstfeld	9.58
Amsteg	9.58
Faido	9.43
Bodio	8.83

Therefore, there is no need to correct the advance rate for diameter size.

From another point of view, advance rates are expressed in $[m/d]$ and thus are independent of the tunnel length. So technically there is no need to consider any corrections for lengths. Nonetheless, the major scale difference may keep the question relevant. The targeted tunnels for the Catalogue simulations are roughly $1 - 5\ km$ long. The Gotthard Base Tunnel on the other hand, is to date, the longest tunnel in the world at roughly $60\ km$ in length (but only partially excavated using TBM with these sections being in the order of $15\ km$ in length). Despite this scale difference, it is still possible to neglect any length correction. The Gotthard Base Tunnel, apart from certain problematic zones, resembles most tunnels without showing radical differences. As mentioned, when keeping aside these particularly troublesome areas, most of the tunnel's geology and construction practices are generalizable to other cases with no major impediments.

Thus, there is no need to correct the advance rate for tunnel length.

Time correction is mostly relevant to cost estimates, when accounting for inflation for instance. It is much less significant with respect to advance rates. The values in $[m/d]$ are not affected by the year the project was undertaken but instead depend on the encountered geologies and the adopted construction method. There is however an argument according to which construction technologies evolve with time. For instance, TBMs today are more efficient compared to machines 50 years ago. The Gotthard Base Tunnel has been inaugurated in 2016 and it is safe to assume very little improvements have affected today's TMBs.

Hence, there is no need to correct the advance rate relative to time differences.

The raw data of the Gotthard Base Tunnel does not associate the values to significantly labeled ground classes. Therefore, it can only be assumed that the lowest recorded rates occur in the worst ground conditions and the highest values are relative to the best ones. The intermediate values need to be approximated as shown in the next sections.

4.2.3 Given Values

The purpose of the analysis is to obtain significant results in the form of $[Min;\ Mean;\ Max]$ advance rates for all ground classes. Perhaps the easiest to delimit are the extreme cases, respectively, the fastest and slowest possible rates. Performance values are reported in Table 4.14 (AlpTransit Gotthard AG, 2016).

Table 4.14: Table performance values Gotthard

	Avg rate incl. downtime [m/wd]	Avg rate exlc. downtime [m/wd]	Max rate [m/wd]
Erstfeld east	14.27	18.06	39
Erstfeld west	14.21	17.57	56
Amsteg east	11.5	14.07	N.A.
Amsteg west	10.6	15.83	40.1
Faido 1	10.5	12.41	N.A.
Faido 2	9.92	12.5	36
Bodio 1	10.83	12.47	N.A.
Bodio 2	11.76	14.04	38.4
Average	*12*	*15*	*42*

The average of the maximum rates is roughly $42\ m/d$. A similar value was recorded for the FermiLab case (CNA Consulting Engineers, 2001) with an average of $45\ m/d$ for the most favorable ground class (GC-1 Very Good).

For the other extreme case, in the worst conditions (GC-5 Very Bad), the advance rate is equal to $0\ m/d$; which physically actually translates as a blocked TBM. A null advance rate value may however have unpredictable results in the simulations. Therefore, the adopted minimal value is $1\ m/d$. The event of a blocked TBM can still be simulated differently, by introducing semi-deterministic delays in the tunnel network configuration.

On the other hand, the provided average values can probably be associated with the mid-ground condition (GC-3 Fair). The Gotthard average advance rate is (AlpTransit Gotthard AG, 2016) $12\ m/d$ and $15\ m/d$ when respectively including and excluding downtime. A slightly more optimistic estimate was recorded in the FermiLab (CNA Consulting Engineers, 2001) at $20\ m/d$ for the same ground class.

The rest of the required values need to be subjectively interpolated, based on the aforementioned results, both for the extreme ground classes (GC-1 and GC-5) and at the in-between ground class (GC-3).

4.2.4 Final Time Results

The aforementioned analysis produces the entries in the final results table. As for the intermediate values, they have been filled in a way that respects both the given values in the sources and common sense. They are based on an engineering judgement and have been checked to be mostly realistic by Prof. Einstein.

Table 4.15 provides a summary of the values retained for the Catalogue simulations.

Table 4.15: Final advance rates results

TBM d = 9 m		Advance Rates [m/d]		
GC	GC names	**Min**	**Mean**	**Max**
1	Very Good	22	28	42
2	Good	13	18	20
3	Fair	8	12	15
4	Bad	3	7	9
5	Very Bad	1	2	3

4.3 Tunnel Configuration

4.3.1 Tunnel Network

In addition to the unit time and cost, another crucial input for the simulations is the tunnel network; i.e. how many tunnels are simulated and how they are related to each other. The DAT have in theory no limitation and can technically accommodate all possible network arrangements. The choice of the configuration to model is then governed by the application of the Catalogue. In order to ensure a wide range of relevance for this work, a linear system is perhaps the best option. Therefore, complexities such as the following are not considered.

- intermediate access tunnels
- caverns for dismantling the TBM
- vertical or inclined shafts
- delays (covered in the next section)

Two typical examples appear in the following figures. Figure 4.3 shows a simple tunnel configuration for a single tube, one-way excavation. Figure 4.4 shows a double tube tunnel excavated from both sides.

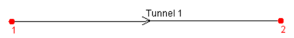


Figure 4.3: Single tube one-way excavation

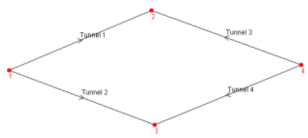


Figure 4.4: Double tubes two-way excavation

It is essential to note that the scatter of the end results and the complexity of the network go hand in hand. Indeed, more complex networks (with their respective variabilities), provide more heterogeneous cases for the Monte Carlo simulations, eventually yielding a higher scatter of the points on the scattergrams. The latter may more or less affect the average values of total completion cost and time but will most probably alter the absolute maximum and minimum values. This effect of tunnel network complexity on the scattering of results was briefly addressed in Chapter 2 of this work.

If the most realistic scenarios are to be modeled, many of these complexities need to be considered in order to yield the best results. However, this also implies that the Catalogue becomes more and more restrictive: more accurate for some specific cases that resemble what is simulated but quite useless for all the rest of the situations. As previously mentioned earlier in the work, the philosophy governing the generation of this Catalogue is based around practicality and universality at the expense of specificity. Therefore, a more general configuration is favored for the Catalogue. If some users have particular problematic complexities they need to assess, they can always use the DAT, that can handle any possible real-life scenario and obtain more accurate specific results for their case.

Consequently, the modeled tunnel has the simplest possible configuration:

- single tube
- excavated from only one portal
- using only one construction method (only TBM for now)
- excavated from one end only

These assumptions are not only simple and thus ensure a wider application of the Catalogue as aforementioned, but they are also quite realistic for small tunnels as they have been previously defined in Chapter 3; namely relative to diameter size, network configuration and excavation method.

Thus, the simplifications made are all within a totally defendable rationale. The final adopted tunnel network is the same one appearing in Figure 4.3.

4.3.2 Delays

Delays constitute an additional type of complexity that is not simulated in the Catalogue. Time and position delays are typically caused by:

- procurement and delivering of materials
- schedule delays because of previous activities
- weather conditions
- unexpected ground conditions (water, geology etc.)
- capacity of repositories and muck management

In line with what was mentioned, no delays are included in the model. However, recall for the advance rate estimates in Chapter 4.2, a null value for the absolute worst case cannot be introduced in the simulations, but needs to be somehow considered. An alternative to handle this issue is possible by using a non-zero value in the inputs and applying a certain delay, practically simulating a blocked TBM. This delay can be applied semi-deterministically by defining it through a set of $[Min;\ Mean;\ Max]$ values instead of a constant one.

For the chosen tunnel network, the position of the applied delay along the length of the tunnel does not make any difference on the end results. For the sake of consistency, it will be applied in the middle of the tunnel. The chosen values appear in Table 4.16.

Table 4.16: Delays simulating a blocked TBM

	Min	Mean	Max
delay [d]	5	25	55

The minimal value of 5 $days$, physically refers to a case where the TBM is very rarely blocked. The mean blocking at 25 $days$ is reasonable when the TBM may be blocked a cumulative time of almost a month for the entire small tunnel. On the other hand, the maximum considered total blocking time for the whole project is a bit less than two months, at 55 $days$.

4.4 Ground Classes

Ground Classes constitute the link that brings together the geology and construction modules (see Chapter 1). All the geologic conditions are superposed and eventually attributed a ground class, and all the construction processes are applied based on the same ground class basis. For example, the unit advance rate and unit costs, are all defined by ground class. Consequently, a delicate definition of the ground class library upon which all simulations will run is crucial.

The inventory of geologic conditions that need to be simulated are the following:

- Igneous: good and bad
- Sedimentary: good and bad
- Fracturing: high and low
- Water: high and low

Metamorphic rocks are not considered independently since they have cost and time estimates similar to igneous rocks. This is more detailed in Chapter 6 when explaining the rules of the Catalogue and how to simplify the geologies before consulting the charts.

Table 4.17 shows the total inventory of ground parameters and their possible respective states.

Table 4.17: Inventory of ground parameters and ground parameter sets

Ground Parameter	STATE
Lihtology	Igneous Good
	Igneous Bad
	Sedimentary Good
	Sedimentary Bad
Fracture	High
	Low
Water	High
	Low

The number of ground classes is user defined and it is possible to have as many ground classes as desired. Too few ground classes, and the problem becomes too simple to mimic real conditions. There is however also a limit beyond which, too many ground classes stop adding value to the results and simply make the model more complex for no justifiable reason. Typically, models have either

- 3 ground classes for simple cases: good, fair and bad
- 5 ground classes for more elaborate cases: very good, good, fair, bad and very bad

Despite being intended for small tunnels, the Catalogue can handle relatively complex geologies. In order to better represent a more realistic behavior, 5 ground classes are used for the simulations. They appear summarized in Table 4.18.

Table 4.18: Five ground classes

GC classes	Qualification
GC-1	Very Good
GC-2	Good
GC-3	Fair
GC-4	Bad
GC-5	Very Bad

Associating the geologic conditions to their respective qualification, as defined in Table 4.17, is done by relying on an engineering judgement and the consultation of tunneling experts such as Prof. Einstein.

The reference inventory table containing all combinations of ground classes for the simulations appears in the following Table 4.19.

Table 4.19: Inventory ground classes used in the Catalogue simulations

FRACTURE	WATER	LITHOLOGY			
combinations couples of High and Low		IGNEOUS Good	IGNEOUS Bad	SEDIMENTARY Good	SEDIMENTARY Bad
H	H	4	5	4	5
L	L	1	2	1	2
H	L	3	4	3	4
L	H	2	3	3	4

In Table 4.19, all possible combinations of fracture and water both high (H) or low (L) are associated with the available lithologies.

Naturally, bad conditions in lithology are attributed a worse ground class grade. Also, with more fracturing and/or water, the ground class gets worse. In between fracture and water, the one with the slightly more degrading effect is the fracturing, as can be seen in the igneous setting for alternating Low and High couples of these two. The reason is that in a closed TBM the water is less of an issue compared to an open Drill and Blast excavation for example. However, highly fractured rocks slow down the TBM as the cutting process is partially jeopardized.

4.5 Inputs Summary

Following the thorough analysis and estimations, the entire inputs required for the simulations are summarized as follows.

The retained values for unit cost and advance rate appear in Table 4.20.

Table 4.20: Final unit time and cost estimates

TBM	GC	GC names	Min	Mean	Max	Unit
Advance Rate	1	Very Good	22	28	42	m/d
	2	Good	13	18	20	
	3	Fair	8	12	15	
	4	Bad	3	7	9	
	5	Very Bad	1	2	3	
Cost	1	Very Good	3	5	8	k$/m
	2	Good	11	13	16	
	3	Fair	14	16	21	
	4	Bad	20	23	29	
	5	Very Bad	51	57	73	

The same inputs can be better visualized in graphical form as they appear in Figure 4.5.

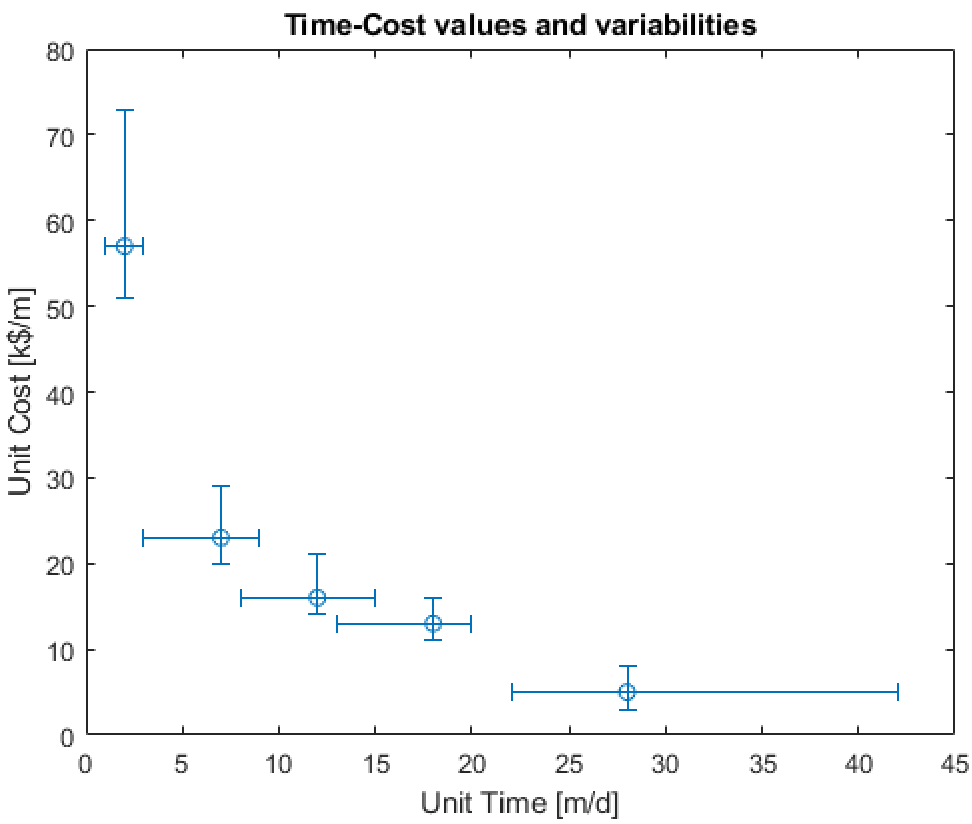


Figure 4.5: Visual representation of the input values for cost and time

On Figure 4.5, the leftmost point corresponds to the worst ground conditions (GC-5 Very Bad) with the slowest advance rate and the highest associated unit cost. The rightmost point represents the best conditions (GC-1 Very Good) with the largest advance rate and lowest cost. In between appear respectively from left to right the remaining conditions: GC-2 Good, GC-3 Fair and GC-4 Bad.

The retained configuration for the tunnel network is a single tube excavated from one side using one unchanged construction method (TBM for now) as it appears in Figure 4.6.

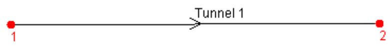


Figure 4.6: Tunnel network configuration

Only one complexity is considered in the simulations: the potential delay caused by a blocked TBM and defined at the mid length of the tunnels by the following values showed in Table 4.21.

Table 4.21: TBM blocking delays

	Min	Mean	Max
delay [d]	5	25	55

As per Chapter 5, every entry point in the Catalogue is based on a total of 50,000 simulations; For each geology simulation, there are 3 construction simulations. Results are summarized in Table 4.22.

Table 4.22: Number and distribution of retained simulations

simulations total	geology simulations	construction simulations	ratio Const/Geol	real simulations
50000	129	388	3	50052

CHAPTER 5

5 NUMBER OF REQUIRED SIMULATIONS

5.1 Procedure

For any Monte Carlo based analysis, the number of simulations is crucial to ensure accurate and reliable results. The Catalogue is no exception to this consideration. The question this chapter aims to answer is: how many simulations are needed in order to ensure trustworthy values in the Catalogue's results?

Ideally, a certain minimal number of required simulations can be calculated. Some publications tackle precisely this issue for any Monte Carlo application as was mentioned in the literature review in Chapter 1 (Driels, 2004). Most approaches are based on purely statistical analyses. They quantify a certain percentage error between a computed parameter and its exact value and establish a relationship with the number of simulations. Clearly, an inverse proportionality exists between the error value and the number of simulations. Thus, it is possible to back calculate a minimal number of simulations that corresponds to a certain acceptable error margin.

For the Catalogue, the previous analyses do not really apply as the sought-after $[Min;\ Mean;\ Max]$ values for time and cost do not have a pre-defined exact value to compare to. Another method is then needed in order to ensure the reliability of results aside from the existing statistical tools.

A need for a parametric analysis tailored specifically for the Catalogue inputs is thus justified. The procedure involves picking a representative example and assessing its end-results when changing the number of simulations for all other inputs being equal.

The retained example upon which the analysis is applied is the first entry point of the first table/chart (Table 1) of the Catalogue. Its inputs, visible in the Reference Table 6.1, are specifically:

- GEOLOGY: Igneous setting with ratios (%): $IG/IB = 80/20$
- FRACTURE: high to low ratio (%): $H/L = 80/20$
- WATER: high to low ratio (%): $H/L = 80/20$
- Length considered $L = 1\ km$

These specific conditions, along with all the rest of the inputs as per Chapter 4, are simulated identically for all the cases of this analysis. If any variability in the results is observed, it is only due to the change in the number of simulations, *ceteris paribus*.

Results will be evaluated for the following number of simulations: 1,000; 5,000; 10,000; 50,000 and 100,000. The values cap at 100,000 because it is the largest number of simulations that the DAT can handle in a single run.

Each one of the total simulations mentioned is a product of two values: geology and construction simulations that are, recall Chapter 1, independently generated. If T is the total number of simulations, it is actually defined as the product:

$$T = C \times G$$

where, C is the number of construction simulations and G is the number of geology simulations. If the cases are to be compared, they need to have a similar relation between geology and construction simulations. Hence, a ratio defined as

$$\frac{C}{G} = cte$$

has to be respected. The fixed ratio of 3, intended to be used in the Catalogue, is thus also retained for the parametric analysis. In essence, for each one of the total simulation values (1,000; 5,000; 10,000; 50,000 and 100,000), there are three times more construction simulations compared to geology ones.

$$\frac{C}{G} = 3$$

In reality, 1,000; 5,000; 10,000; 50,000 and 100,000 simulations cannot be exactly simulated while keeping the same internal ratio of 3. For the rest of the analysis, the runs will be designated by their rounded value and not the exact one. This is detailed in the following Table 5.1.

Table 5.1: Summary of the runs for parametric analysis

Simulations total	Geology simulations	Construction simulations	ratio C/G	real total simulations
1000	18	55	3	990
5000	41	122	3	5002
10000	58	173	3	10034
50000	129	387	3	49923
100000	183	548	3	100284

5.2 Results

For each case, the results are presented in both graphical and tabular form.

Figure 5.1 to Figure 5.10 show the variability of $[Min;\ Mean;\ Max]$ values of time and cost as a function of the number of simulations, respectively for the cases: 1,000; 5,000; 10,000 and 50,000 simulations. Graphical results are also summarized in Figure 5.11 side by side in order to facilitate their comparison. The 50,000 case is displayed twice: The first representation shows the results unchanged, in the similar format as the previous plots. The second representation shows faded individual dots (in blue) so that a clearer mean curve distribution is visible underneath.

Table 5.2 and Table 5.3 show the summary of the recorded absolute $[Min;\ Mean;\ Max]$ values of time and cost.

Table 5.2: Time results for all runs

Run	Min time [d]	Mean time [d]	Max time [d]
1000	120.43	207.90	333.66
5000	113.66	217.60	436.07
10000	102.55	206.03	417.16
50000	94.12	208.12	446.16
100000	94.42	207.94	496.96

Table 5.3: Cost results for all runs

Run	Min cost [k$]	Mean cost [k$]	Max cost [k$]
1000	18183.88	25447.95	32711.12
5000	17492.84	26454.69	38643.06
10000	16947.33	25214.78	37960.88
50000	15319.28	25478.38	39444.89
100000	14884.40	25454.60	42155.29

Time results graphs

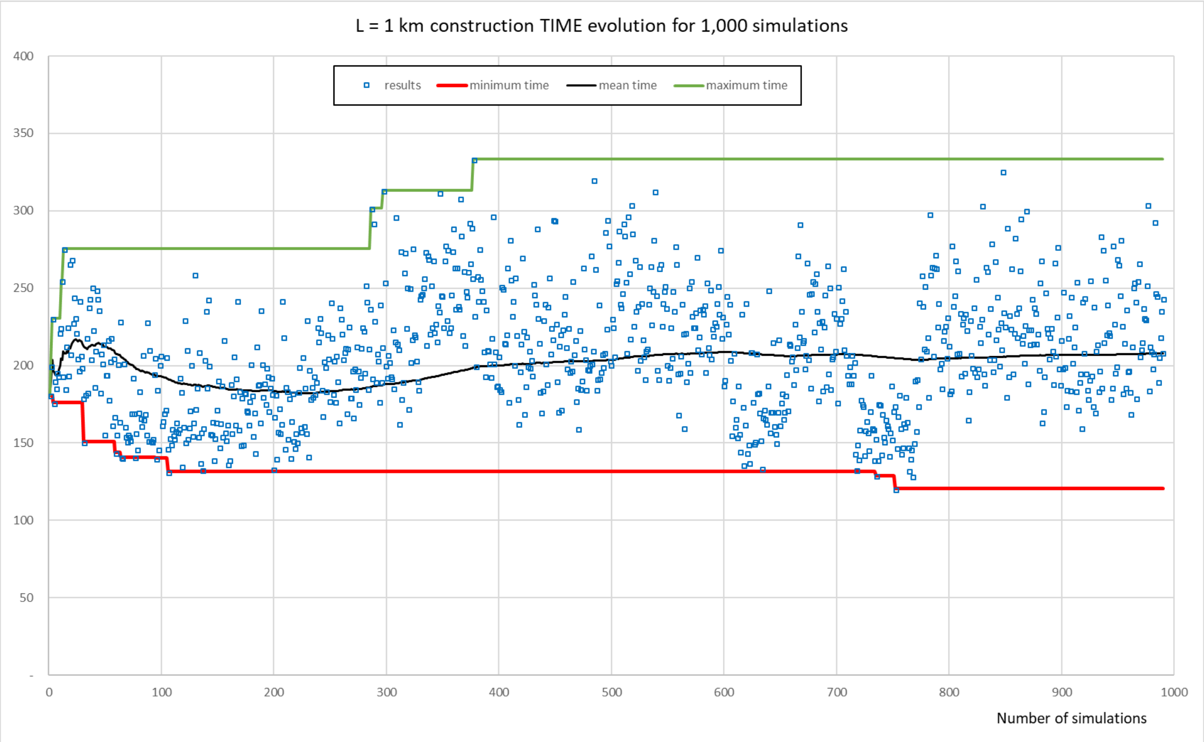


Figure 5.1: Construction time variability for 1,000 simulations

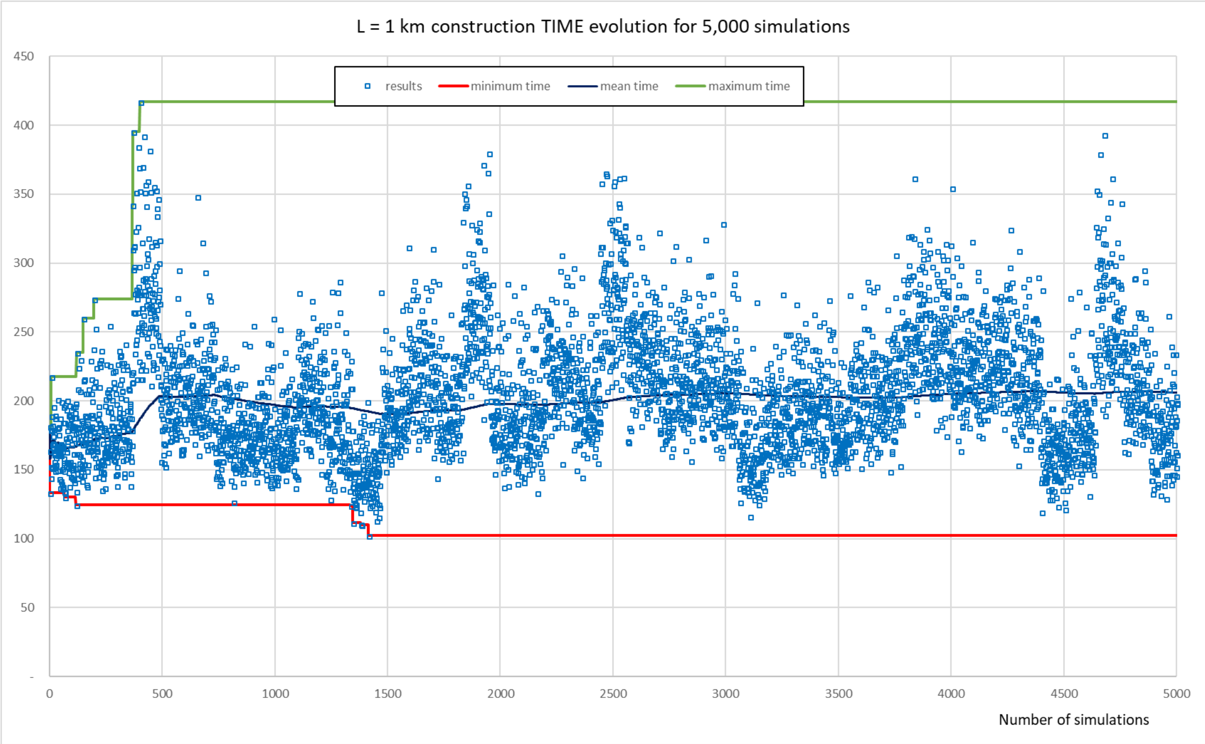


Figure 5.2: Construction time variability for 5,000 simulations

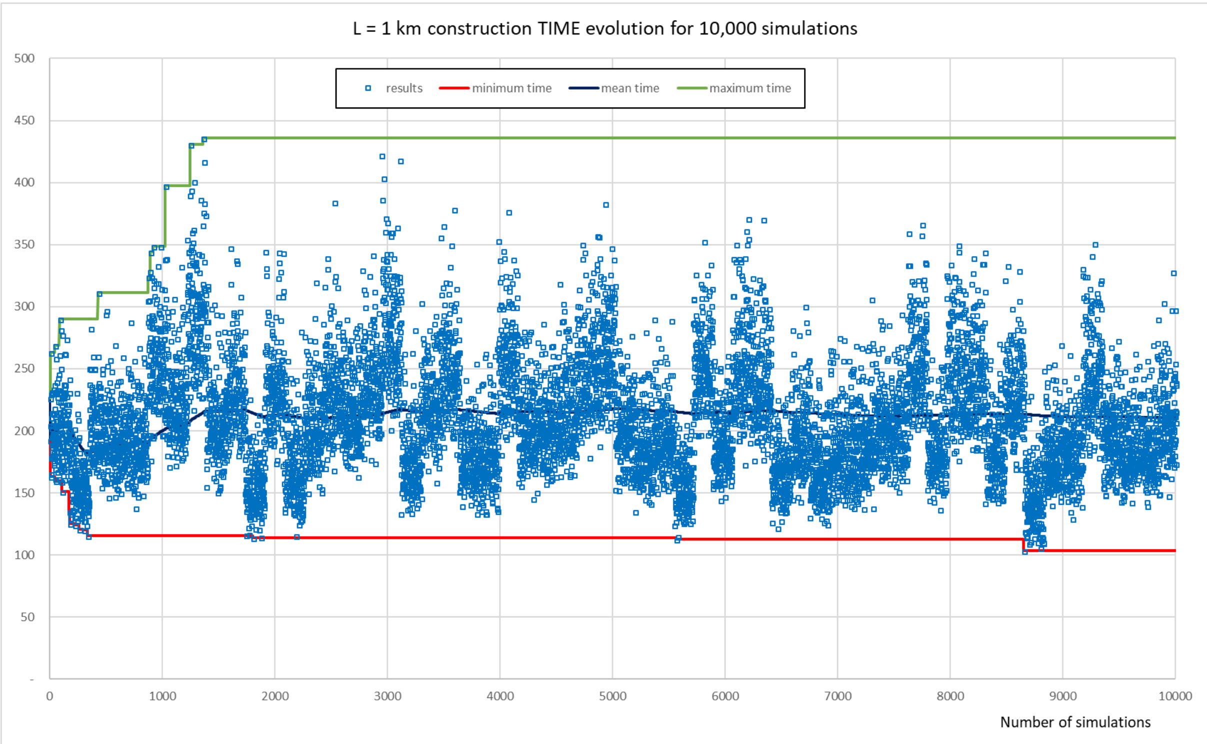


Figure 5.3: Construction time variability for 10,000 simulations

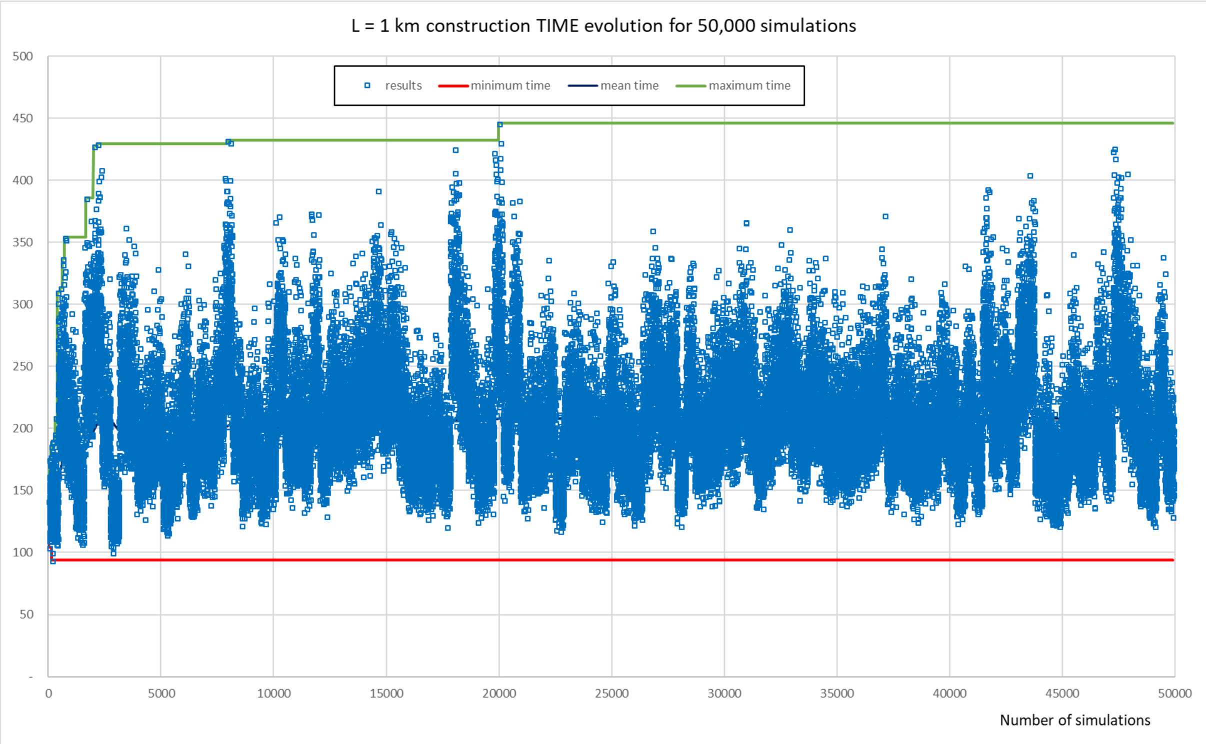


Figure 5.4: Construction time variability for 50,000 simulations

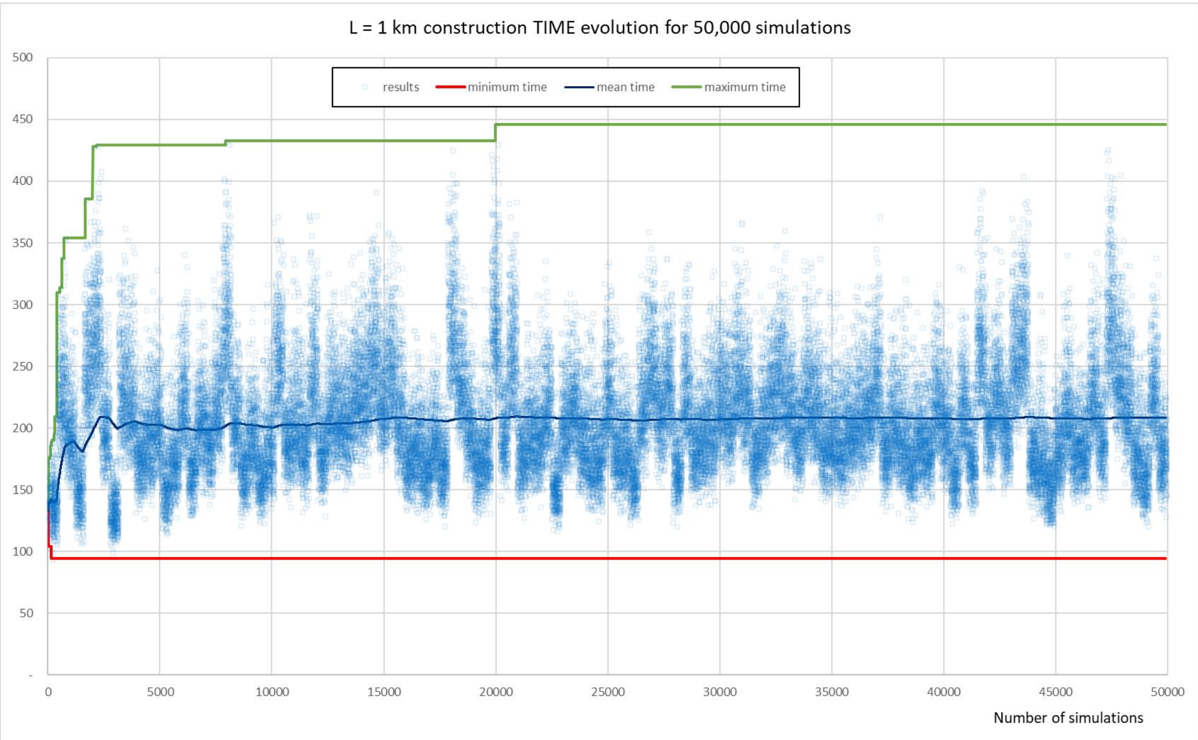


Figure 5.5: Construction time variability for 50,000 simulations faded results

Cost results graphs

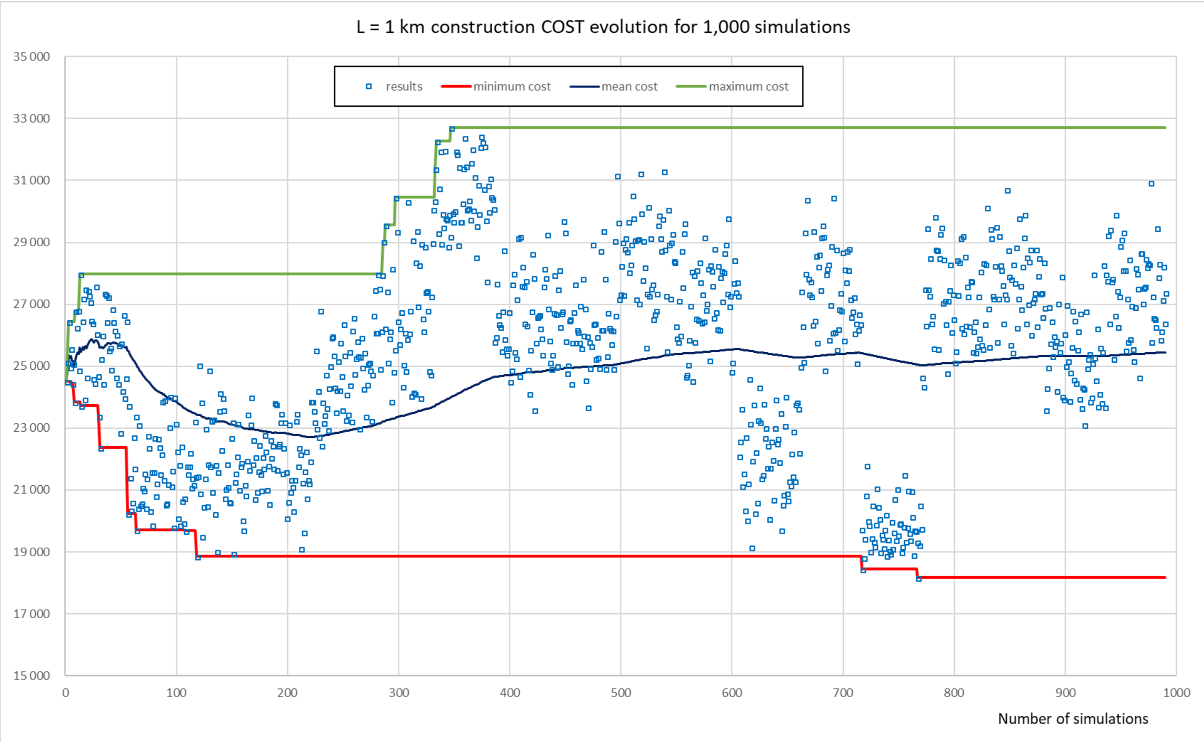


Figure 5.6: Construction cost variability for 1,000 simulations

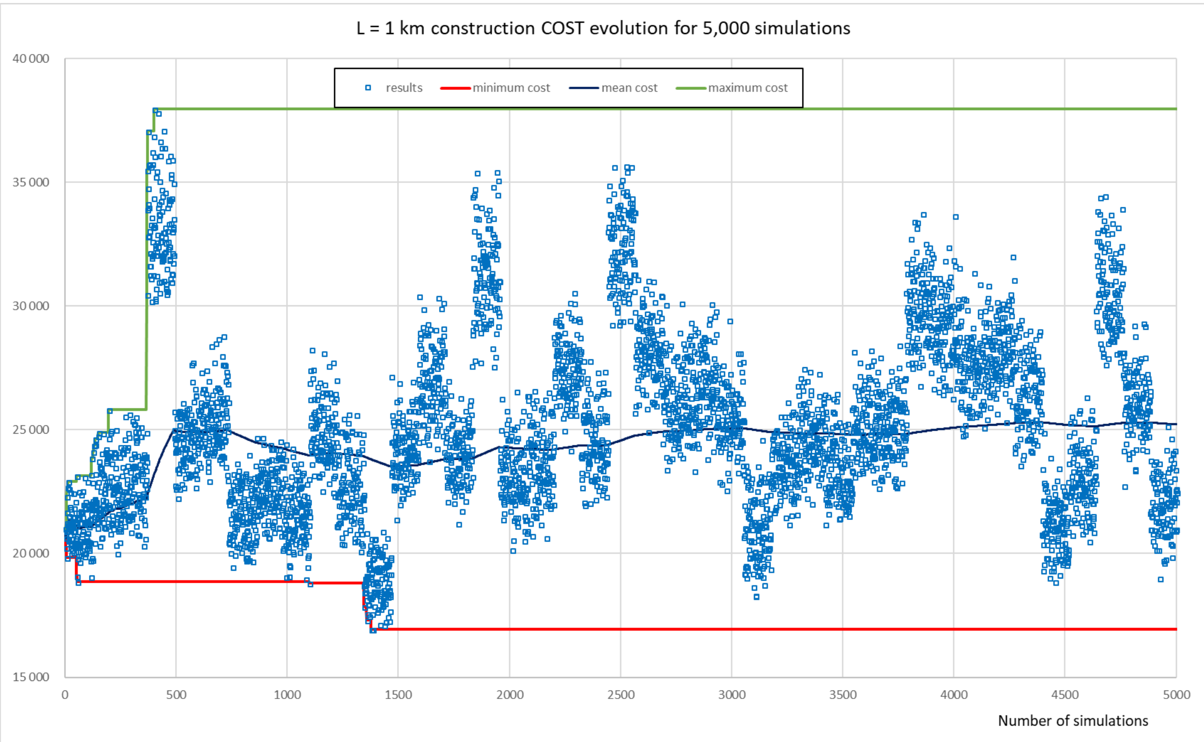


Figure 5.7: Construction cost variability for 5,000 simulations

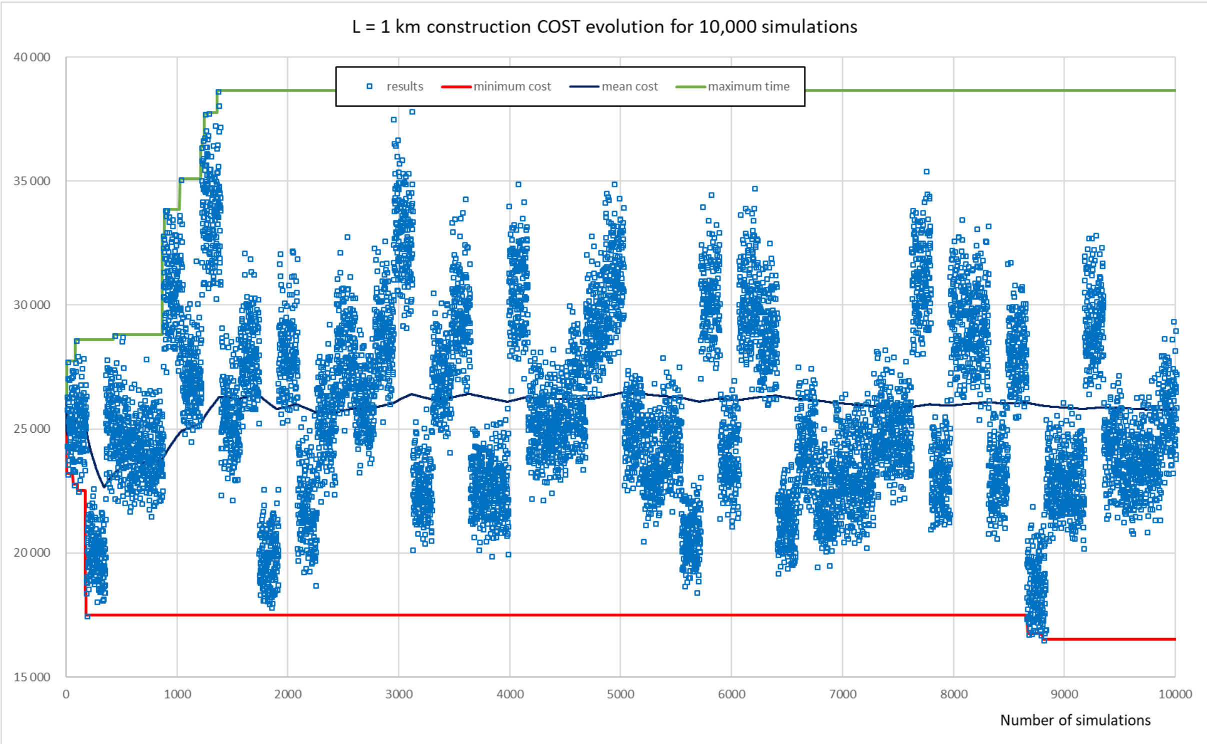


Figure 5.8: Construction cost variability for 10,000 simulations

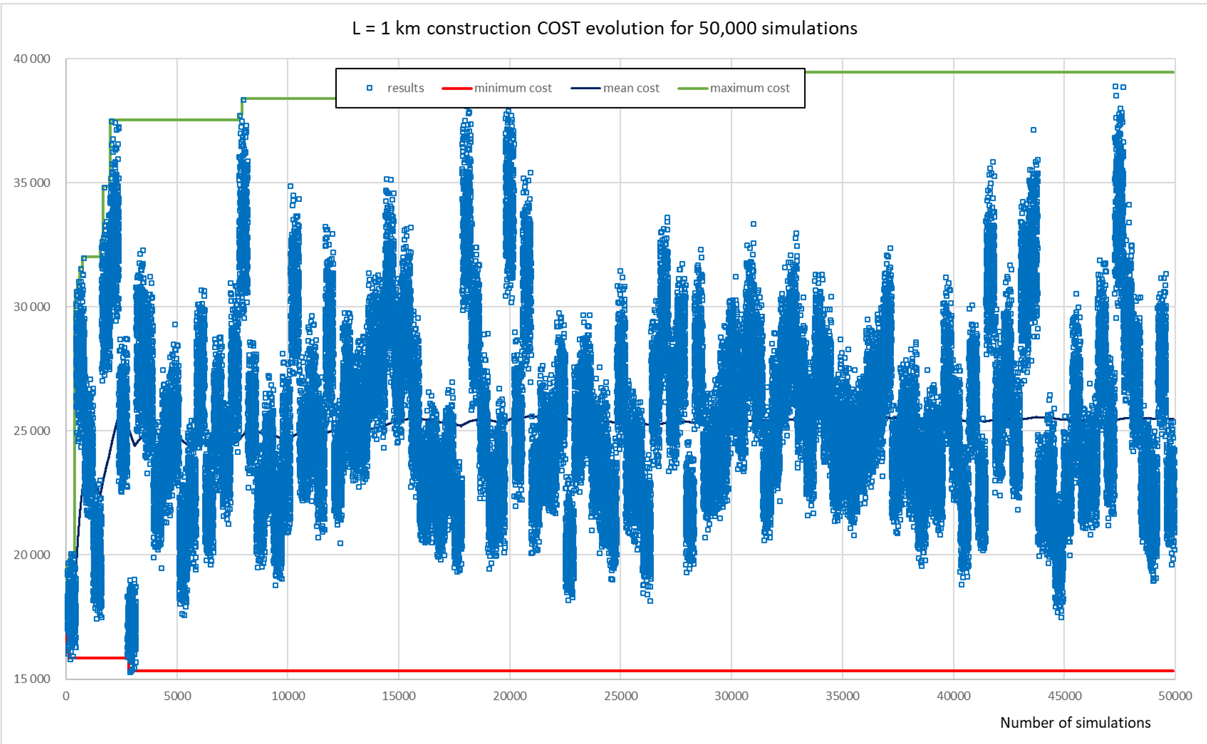


Figure 5.9: Construction cost variability for 50,000 simulations

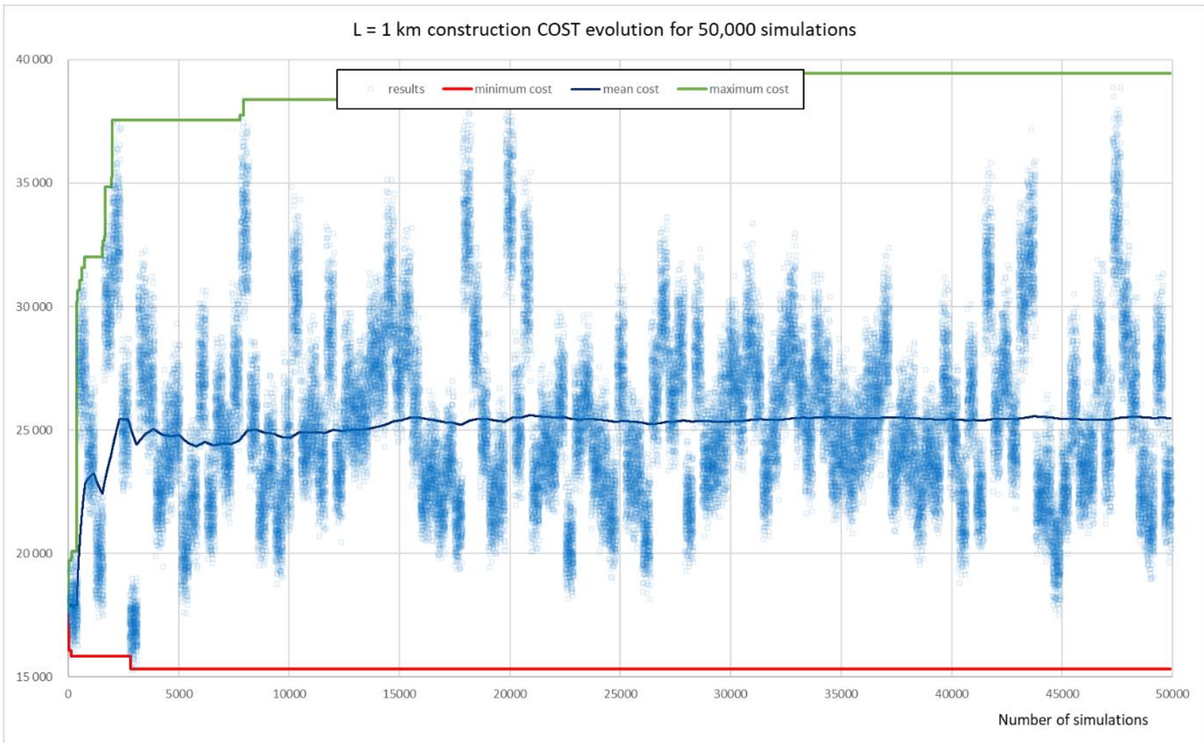


Figure 5.10: Construction cost variability for 50,000 simulations faded results

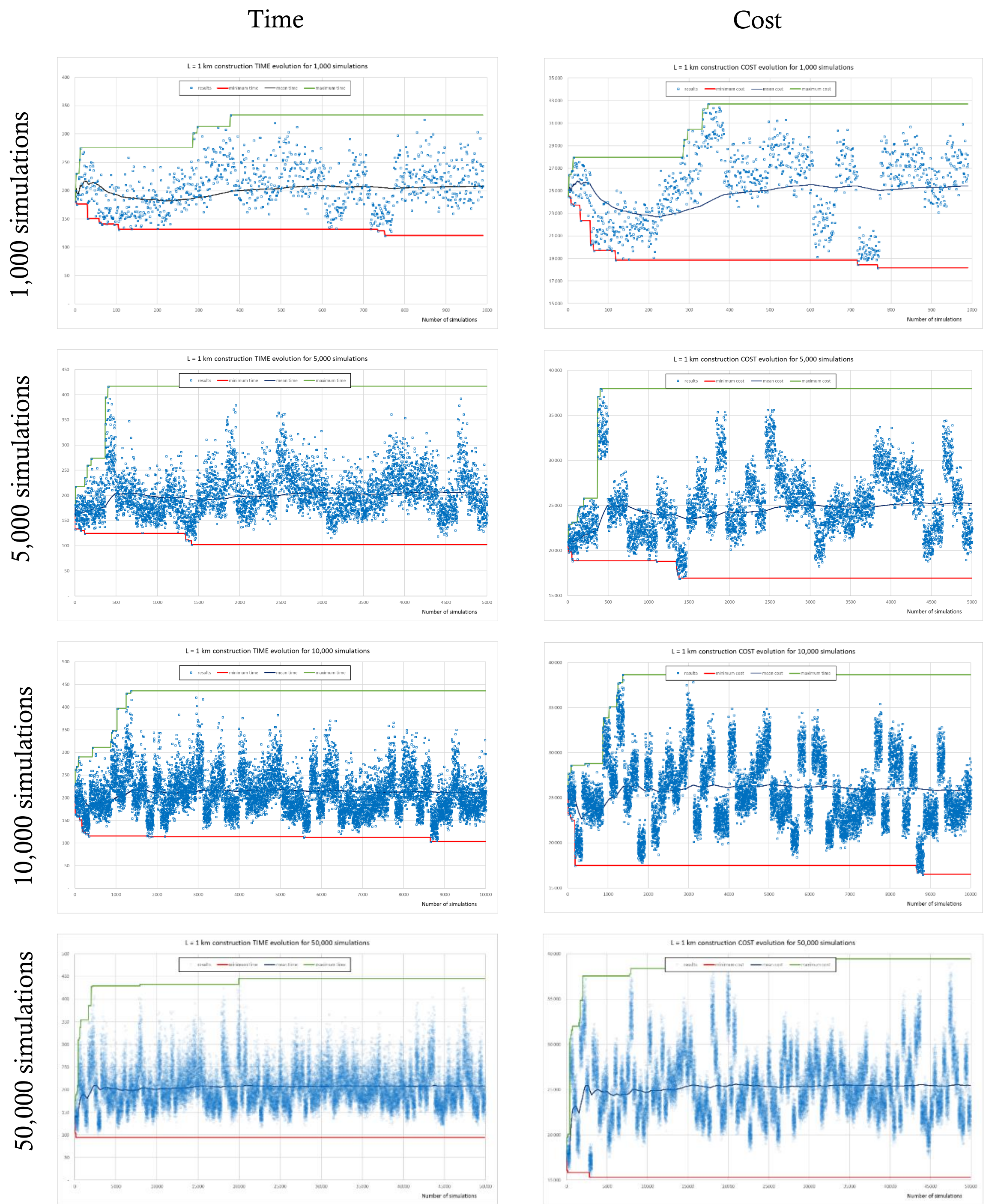


Figure 5.11: Side-by-side results summary

5.3 Analysis

Both construction cost and time exhibit the same trend in the results.

First, a starting note concerning the specificity of the scatter in the form of clouds. These are in fact similar geology cases upon which different construction simulations are applied, as shown in Figure 5.12.

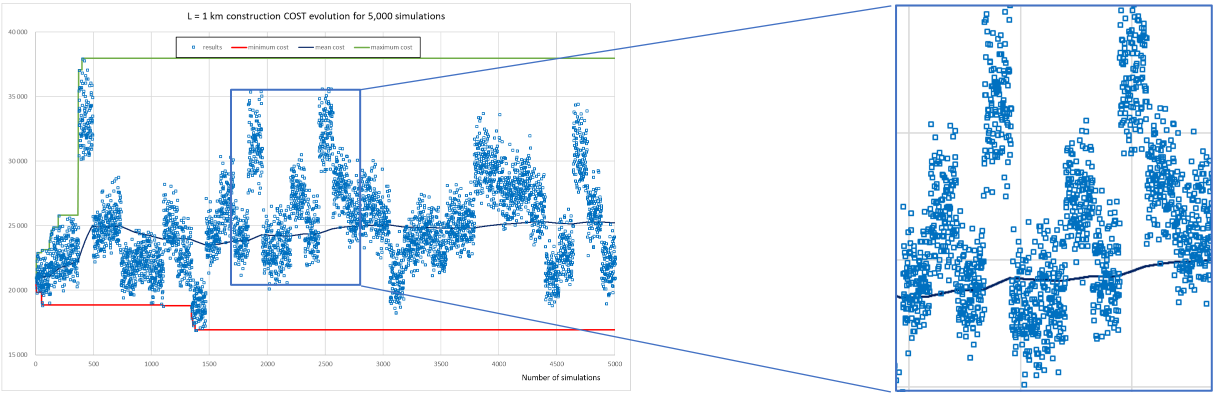


Figure 5.12: Results in the form of packet clusters

Recall that the DAT independently generates the geology sections and then applies to them the construction simulations. Thus, the visual representation of these processes involves a scatter of points in the form of packet clusters.

When first looking only at the mean value, it is somehow possible to differentiate its behavior into three phases. For a low simulation number, the mean is unreliable. It remains highly dependent on the first few clouds of encountered results. In a second phase, the mean is more stable but fluctuating. It is characterized by much less extreme swiveling and seems to oscillate around a central position in wave like pattern. The wavy aspect attenuates with more simulations until eventually stabilizing in the third phase of behavior. The beginning of the third phase is hard to pinpoint on the graph but basically concerns the stable quasi static shape of the curve.

The behavior of the extrema values, basically the absolute maximum and minimum values, is much harder to qualify. These values do not seem to follow a specific trend or shape. The only generalizable trend related to the extrema points is that they tend to get refined with a larger number of simulations. Basically, a value is thought to be the maximum or minimum, until it is replaced by a new extremum revealed during the recording of data with more and more simulations. But even this basic trend does not always hold true. For the run of 50,000 simulations in Figure 5.5, the absolute construction time minimum has been recorded as early as a few hundred simulations and has remained unchanged ever since. The same applies for the absolute cost minimum Figure 5.10. Thus, the general established rule according to which, results are always refined with more simulations is debatable. For the specific case of cost and time at 50,000 simulations, simulating a few hundred or many thousand times did not improve the minimal value. The same skepticism could be applied for the maximum value regardless if the four runs exhibit this behavior or not.

The graphical representations reveal that more simulations enhance the overall quality of the results. This statement is undeniably true for the average values of both construction time and cost. The Catalogue entries need to be based on a certain minimal "safe" number of simulations in order for the results to be statistically correct. The extrema values remain harder to confine within a predictable behavior. They remain volatile, dependent on the randomness of the simulated clouds of results. It takes the worst or best geological case to coincide respectively with the worst or best construction case to yield the most extreme results for cost and time. These extremely optimistic or pessimistic scenarios could come out relatively early on in the simulations or extremely late and even not show up at all for all 100,000 simulations in one run. The results are simply random.

Some ways around this issue surely exist if one was absolutely keen on reaching the finest extreme results. However, it is important not to fall too deep in statistical analyses and instead, make use of an engineering judgement for the rest of the analysis, especially since the objective is to develop a Catalogue for design guidelines not work on applied mathematics.

In response to the original problematic of this chapter, the safest answer would entitle generating all the input points of the Catalogue using 100,000 simulations since this is the technical limitation of the DAT. However, some rational forecasting must be applied. Each table entry has a minimum of 5 lengths entries and tens of tables (some 30 tables in a first stage) are needed. In addition to that, plotting 100,000 points on a chart is sure to clutter everything and make the results harder to generate, more so to work with. For sake of practicality, a compromise has to be found between computing/working time and ideal results. The question now is: how much can the minimal number of simulations go down from the ideal (DAT limit value) 100,000 simulations?

A comparison between the available options is thus needed. The run with 100,000 simulations is now the reference with presumably the best results to which all the rest will be compared to. So, where can the line be drawn for the number of simulations, beyond which the marginal extra precision is no longer worth the effort?

Table 5.4 and Table 5.5 show the absolute difference respectively for tunnel construction time and cost for all runs against the 100,000 case reference values.

Table 5.4: Time difference with respect to the 100,000 simulations run

Run	Min time [d]	Mean time [d]	Max time [d]
1000	26	0	163
5000	19	10	61
10000	8	2	80
50000	0	0	51

Table 5.5: Cost difference with respect to the 100,000 simulations run

Run	Min cost [k$]	Mean cost [k$]	Max cost [k$]
1000	3299	7	9444
5000	2608	1000	3512
10000	2063	240	4194
50000	435	24	2710

Table 5.6 and Table 5.7 show the same information but in percentage values compared to the value at 100,000 simulations.

Table 5.6: Percentage time difference with respect to the 100,000 simulations run

Run	Min time [d]	Mean time [d]	Max time [d]
1000	28%	0%	33%
5000	20%	5%	12%
10000	9%	1%	16%
50000	0%	0%	10%

Table 5.7: Percentage cost difference with respect to the 100,000 simulations run

Run	Min cost [k$]	Mean cost [k$]	Max cost [k$]
1000	22%	0%	22%
5000	18%	4%	8%
10000	14%	1%	10%
50000	3%	0%	6%

Based on the observed results in Table 5.6 and Table 5.7, simulating results based on 1,000 or 5,000 simulations, leaves a relatively big margin for imprecision. This is particularly true for the extreme values that have an error percentage ranging from roughly 10 to 30% for both cost and time. The mean values seem accurate enough based on the specificity of these results but it has been established earlier that for a low number of simulations, the mean is unstable or oscillating. It is safer not to use a number of simulations smaller than 5,000. In order to consider larger simulation number values, more information is needed about the computing time required for each.

Table 5.8 shows the recorded computational time for each run depending on the number of simulations. Note that this is specific to this particular case of simulated geological conditions and constant length $L = 1\ km$. The displayed computational time for this case is used as a reference for the parametric analysis. For the rest of the cases, it is expected to be much higher for longer lengths and more complex geologies in the Catalogue (for example the run for $L = 5\ km$ is expected to take at least 5 times longer).

Table 5.8: Computational times and marginal increases for all runs

Run	run time [s]	run time [min]	ΔT increase [min]	ΔT increase [%]
1000	9	0.15		
5000	44	0.73	0.58	389
10000	88	1.47	0.73	100
50000	435	7.25	5.78	394
100000	867	14.45	7.20	99

As expected, simulating all the points in the Catalogue based on 100,000 simulations, is impossible due to a limitation in time. Comparing the gains with the computational time of the two remaining options, it is possible to see that:

- Moving from 5,000 to 10,000 simulations has a positive effect on the accuracy of results especially on the mean whose error falls to 1%. This comes at a cost of a 100% increase in computational time.
- Moving from 10,000 to 50,000 simulations drops most errors to a range between 0% and 5%. This comes at the expense of a 394% increase in computational time.

It remains essential to note that percentages may mean a lot in terms of statistics but they may be much less representative when looking practically at their physical significance for engineering applications. Indeed, predicting a tunnel construction time and cost is never expected to satisfy surgical precision, especially not for preliminary phases, like the ones the Catalogue aims for.

Hence, the following conclusive remarks relative to the number of simulations for the Catalogue are noted:

- picking any number of simulations higher than 50,000 simulations is not justified
- picking any number of simulations below 10,000 simulations is not recommended
- any value in between is a fair compromise between practicality and accuracy
- the closer the value is to the lower bound of 10,000 simulations, the more practical it is
- the closer the value is to the upper bound of 50,000 simulations, the more accurate it is

The retained number of simulations for the Catalogue entries is: **50,000 simulations**.

CHAPTER 6

6 DAT CATALOGUE

6.1 Rules of Usage

Following the developments of Chapter 3, a Catalogue was developed for small tunnels when the use of the DAT is not justified. This Catalogue is addressed to decision makers working on small tunnels (with a total length $L \leq 5\ km$) in order to help them numerically quantify approximate construction cost and time for their project given a set of pre-defined boundary conditions relative to geology and excavation method.

It is essential to note that these estimates are not absolute. They allow decision makers to have a clearer idea about the expected end results, especially in early phases of a project during preliminary studies, when not much effort or resources are necessarily invested in studying alternatives that might simply end up being discarded. This is where the Catalogue is most useful, in providing a rational basis to confirm or reject certain propositions based not on intuition but on numbers obtained from simulations. The fact that it is available for immediate consultation and does not require the decision makers to run any simulations themselves means that the sought-after results can be obtained in a record time, as long as their inputs are conforming to the Catalogue's format. Nonetheless, some "rules" for using the Catalogue apply and need to be carefully considered.

How does the Catalogue work?

Defined steps to be followed systematically can ensure that the Catalogue is properly utilized and avoid misusing the available data and thus leading to a fallacy in judgements for the decision makers.

1. **Simplify the available geology**

   Geological and/or geotechnical reports can be extremely detailed and span hundreds of pages. The Catalogue however, unlike the DAT itself, considers only three geologic conditions:
   - Lithology
   - Fracture
   - Water

All other considerations are not part of the Catalogue in its first form (2018) presented here. If any major geology conditions are particularly important and cannot be simplified, one has to revert back to an analysis using the DAT.

2. Simplify the available lithologies

The lithology of the project has to be associated with one of three proposed families:

- Igneous
- Sedimentary
- Mixed: where both igneous and sedimentary rocks are considered

Metamorphic rocks are not considered as an independent family in the Catalogue, since they may, in this simplified approach, be approximated by igneous (mostly) or sedimentary conditions. Recall in Chapter 4.4, metamorphic rocks have cost and time estimates similar to igneous rocks.

Within each family, internal differentiations exist. For instance:

- Igneous setting: differentiates between igneous good and igneous bad conditions
- Sedimentary setting: differentiates between sedimentary good and sedimentary bad
- Mixed setting: differentiates between igneous good and bad on one side and sedimentary good and bad on another side

These internal differentiations have attributed proportions, in order to mimic real conditions, by assuming a predominance of one over the rest along the length of the tunnel. Predominance, which in this context means more common, is practically modeled as a proportion along the whole length of the tunnel. For sake of consistency, when one situation is called "predominant" it means it is modeled to apply over 75% of the tunnel length, while the remaining 25% represent the other conditions. When not one condition is predominant, an equal repartition of 50% is assumed for each.

Hence, the following combinations exist:

- Igneous setting with a predominance of good conditions ($IG = 75\%$; $IB = 25\%$)
- Igneous setting with a predominance of bad conditions ($IG = 25\%$; $IB = 75\%$)
- Igneous setting with no predominance; equally probable good and bad conditions ($IG = 50\%$; $IB = 50\%$)

- Sedimentary setting with a predominance of good conditions ($SG = 75\%$; $SB = 25\%$)
- Sedimentary setting with a predominance of bad conditions ($SG = 25\%$; $SB = 75\%$)
- Sedimentary setting with no predominance; equally probable good and bad conditions ($SG = 50\%$; $SB = 50\%$)

- Mixed setting with a predominance of igneous conditions; with equally good and bad ($IG = 38\%$; $IB = 38\%$; $SG = 12\%$; $SB = 12\%$)
- Mixed setting with a predominance of sedimentary conditions; equally good and bad ($IG = 12\%$; $IB = 12\%$; $SG = 38\%$; $SB = 38\%$)
- Mixed setting with no predominance; equally probable igneous and sedimentary both good and bad ($IG = 25\%$; $IB = 25\%$; $SG = 25\%$; $SB = 25\%$)

Figure 6.1 shows a roadmap on how to simplify the lithologies to fit the Catalogue's format.

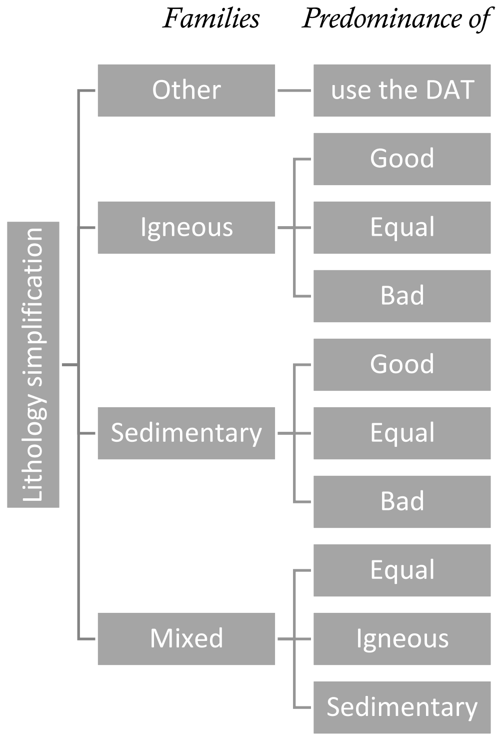


Figure 6.1: Lithology simplification breakdown diagram

3. **Simplify Fracture and Water conditions**

As previously mentioned, only two other geological conditions are considered in addition to the lithology: fracturing in the rocks and inflow of water. Both are presented as interdependent concepts, assuming that with more fractures in rocks under the water table, more inflow of water is expected during excavation. Based on this rationale, the fracture and water considerations vary hand-in-hand between two possible options: high and low.

Similarly to what was done in the previous section, three overall states are defined with regard to fracturing and water:

- Predominance of High fracture and water (75% high and 25% low), associated with any lithology that is independently determined
- Predominance of Low fracture and water (75% low and 25% high), associated with any lithology that is independently determined
- No predominance; equal distribution of fracture and water (50% high and 50% low), associated with any lithology that is independently determined

The 9 lithology possibilities, visible in Figure 6.1, multiplied by 3 possible fracture and water conditions, yields a total of 27 different situations that the current Catalogue encompasses. Future extensions of the Catalogue will consider other conditions.

All these steps are summarized in one Catalogue Reference Table, presented in the next section.

6.2 Reference Table

The Reference Table summarizes all the data of the Catalogue. When consulted properly, it directs the user directly to the proper table. As mentioned before, the current 2018 Catalogue includes 27 tables.

Table 6.1: Catalogue reference table quantitative

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	GP			IGNEOUS SETTING			SEDIMENTARY SETTING			MIXED SETTING					GP
B		GP State		IG/IB			SG/SB			IG/IB/SG/SB				GP State	
C			Percent	75/25	50/50	25/75	75/25	50/50	25/75	25/25/25/25	38/38/12/12	12/12/38/38	Percent		
D	FRACTURE	H/L	75/25	*Table 1*	*Table 2*	*Table 3*	*Table 10*	*Table 11*	*Table 12*	*Table 19*	*Table 20*	*Table 21*	75/25	H/L	WATER
E			50/50	*Table 4*	*Table 5*	*Table 6*	*Table 13*	*Table 14*	*Table 15*	*Table 22*	*Table 23*	*Table 24*	50/50		
F			25/75	*Table 7*	*Table 8*	*Table 9*	*Table 16*	*Table 17*	*Table 18*	*Table 25*	*Table 26*	*Table 27*	25/75		

The following is the same reference table but expressed qualitatively. Instead of showing the real proportions, this second reference table translates into words what the numbers practically mean.

Table 6.2: Catalogue reference table qualitative

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	Family			IGNEOUS SETTING			SEDIMENTARY SETTING			MIXED SETTING					Family
B		State		Igneous Good / Igneous Bad			Sedimentary Good / Sedimentary Bad			Igneous Good and Bad / Sedimentary Good and Bad				State	
C			Predomina nce	Good	Equal	Bad	Good	Equal	Bad	Equal	Igneous	Sedimenta ry	Predomina nce		
D	FRACTURE	High / Low	High	*Table 1*	*Table 2*	*Table 3*	*Table 10*	*Table 11*	*Table 12*	*Table 19*	*Table 20*	*Table 21*	High	High / Low	WATER
E			Equal	*Table 4*	*Table 5*	*Table 6*	*Table 13*	*Table 14*	*Table 15*	*Table 22*	*Table 23*	*Table 24*	Equal		
F			Low	*Table 7*	*Table 8*	*Table 9*	*Table 16*	*Table 17*	*Table 18*	*Table 25*	*Table 26*	*Table 27*	Low		

How to find the needed chart?

In order to find the proper chart, one should:

Horizontally

1. Pick a lithology family in row A
2. Read about the different possible states in row B
3. Pick a suitable distribution from row C

Vertically

4. Both fracture and water appear respectively in columns 1 and 15
5. Read about the possible states in columns 2 and 14
6. Pick a suitable distribution from columns 3 and 13

On charts, (format detailed in Chapter 3.3.4)

7. Verify the selected conditions on the top left-hand side of the chart (for example, on page C-2 for Table 1)
8. Read immediate $[Min;\ Mean;\ Max]$ results in the summary table at the bottom right
9. Examine the distribution for visual results and other tasks (linear and polynomial)

The following section is the DAT Catalogue as it has been developed. It has a special numbering of pages, ranging from C-1 to C-54. It includes all 27 tables, with each being allocated two pages.

As detailed in Chapter 3.3.4, the first page of every table shows five scattergrams (one for every length step), the superposed scattergrams and a summary table with the recorded results. These appear on page C-1 for Table 1 for example. Every first page of a Table can be consulted for more details, beyond what is shown in the summary charts on the second page. It shows the data in an isolated simple form and presented side by side for an easier comparison.

The second page displays two charts with all the superposed results, a summary of the geologic and construction conditions that they are generated for on the top left side and a summary of the results in a small table on the bottom right side. The color scheme is based on simply alternating between blue and grey for successive scattergram length steps, for the sake of clarity. The top chart always shows the data with linear fits while the second shows the exact same data but fitted with second degree polynomial curves instead. These appear on page C-2 for the same example of Table 1.

6.3 CATALOGUE

TABLE1

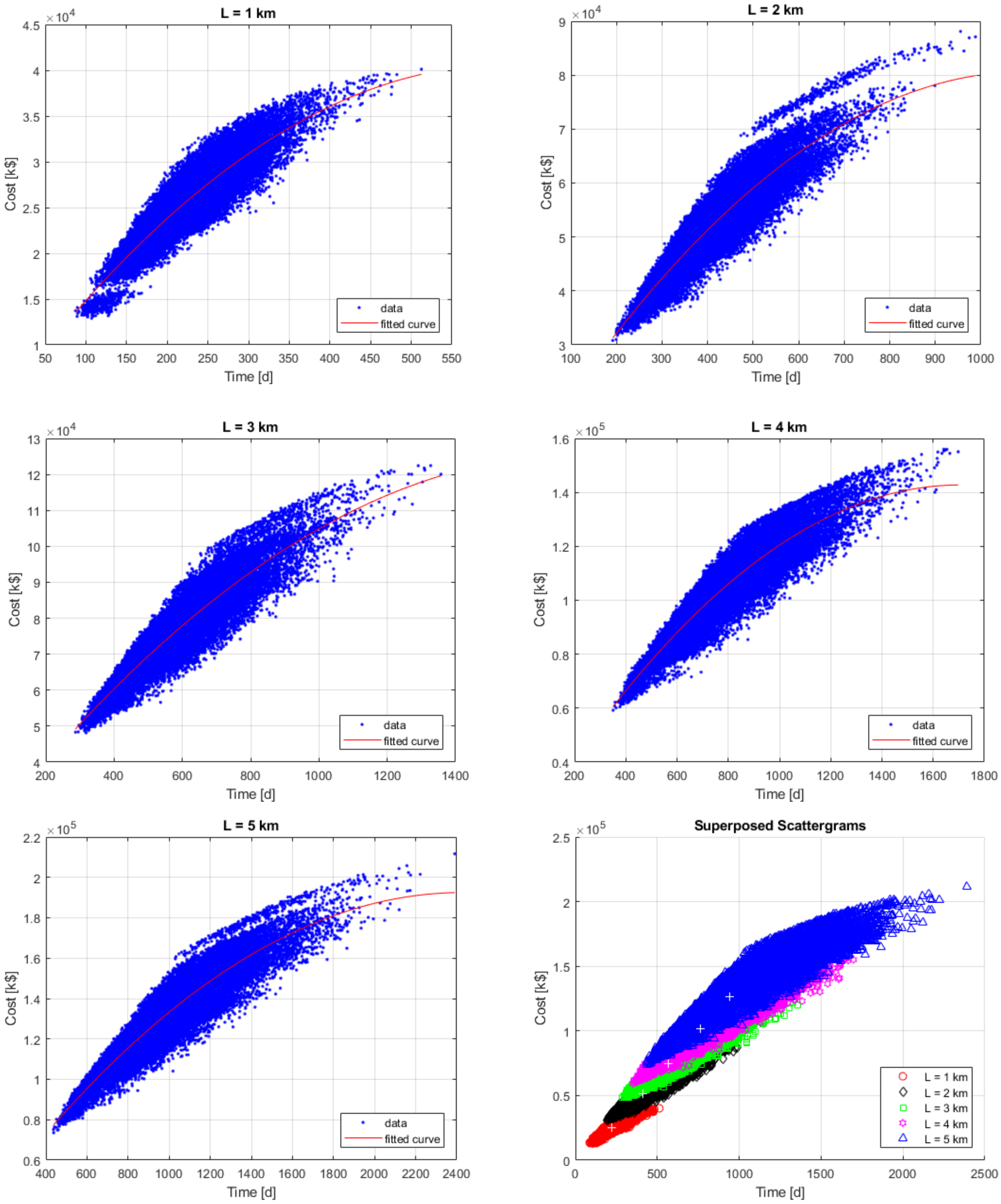
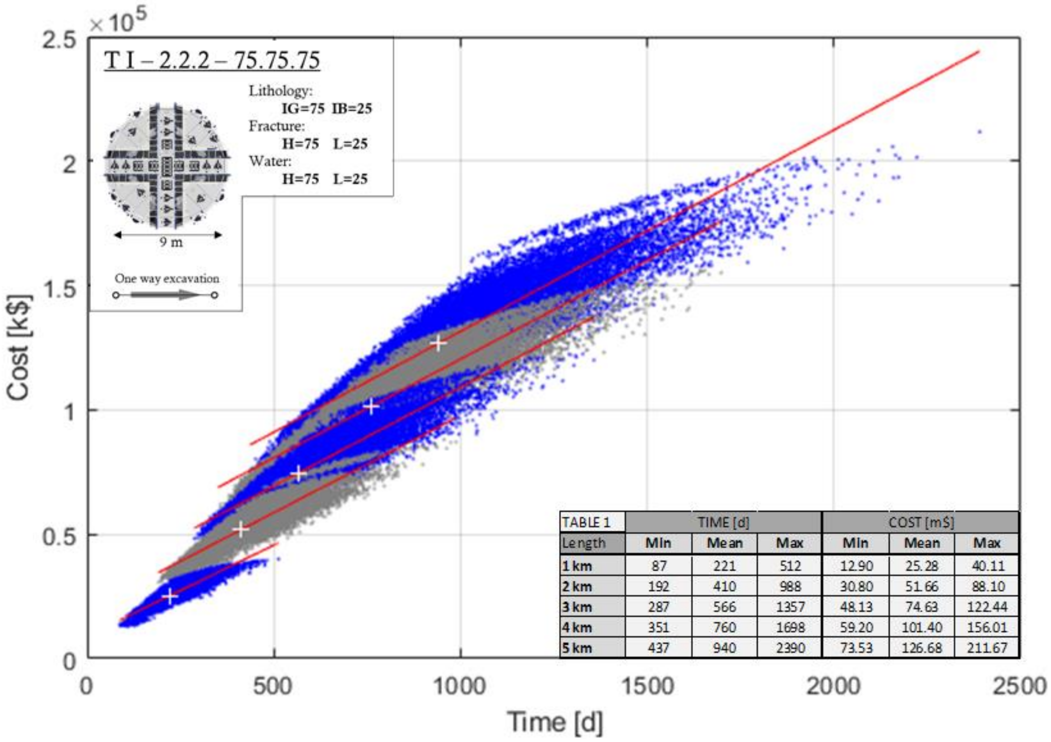


TABLE 1	TIME [d]			COST [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	87	221	512	12.90	25.28	40.11
2 km	192	410	988	30.80	51.66	88.10
3 km	287	566	1357	48.13	74.63	122.44
4 km	351	760	1698	59.20	101.40	156.01
5 km	437	940	2390	73.53	126.68	211.67

TABLE1



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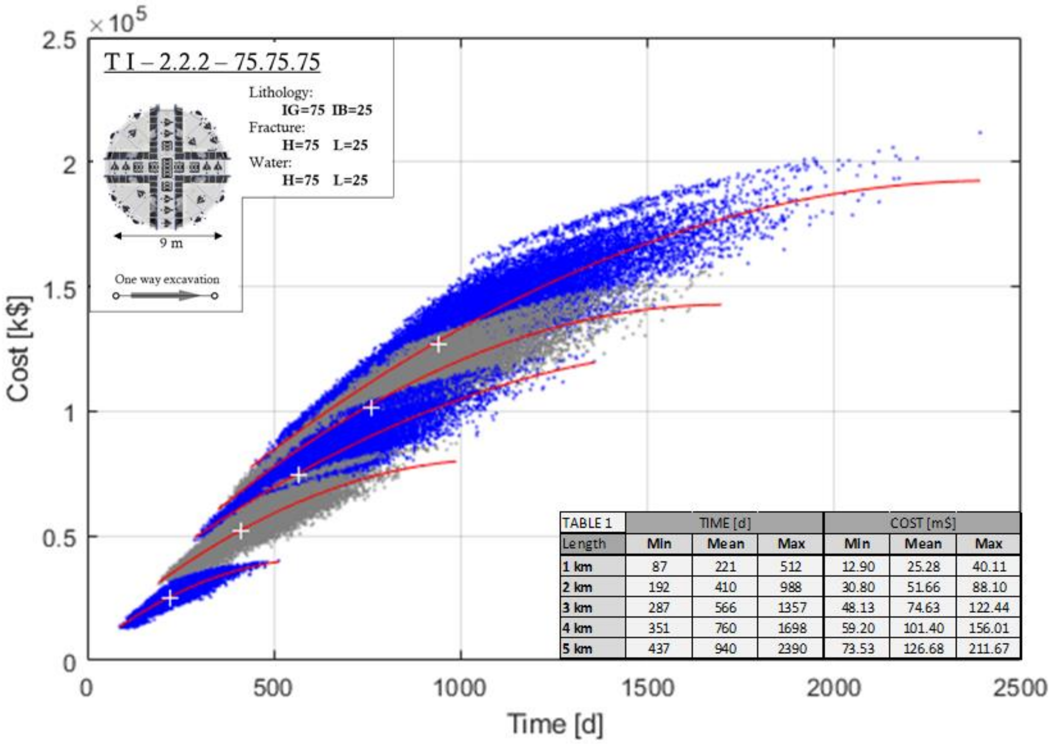

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TABLE 2

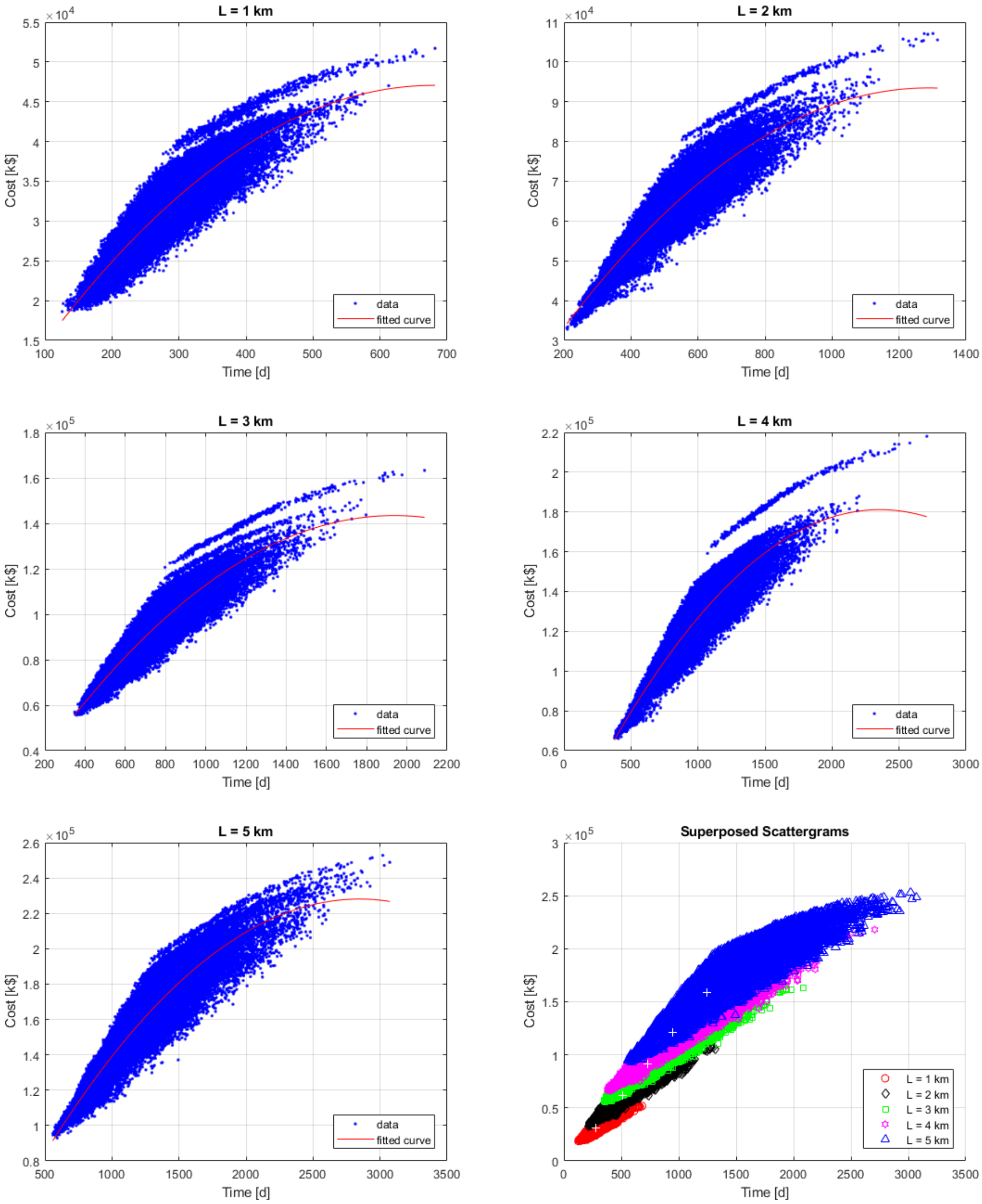
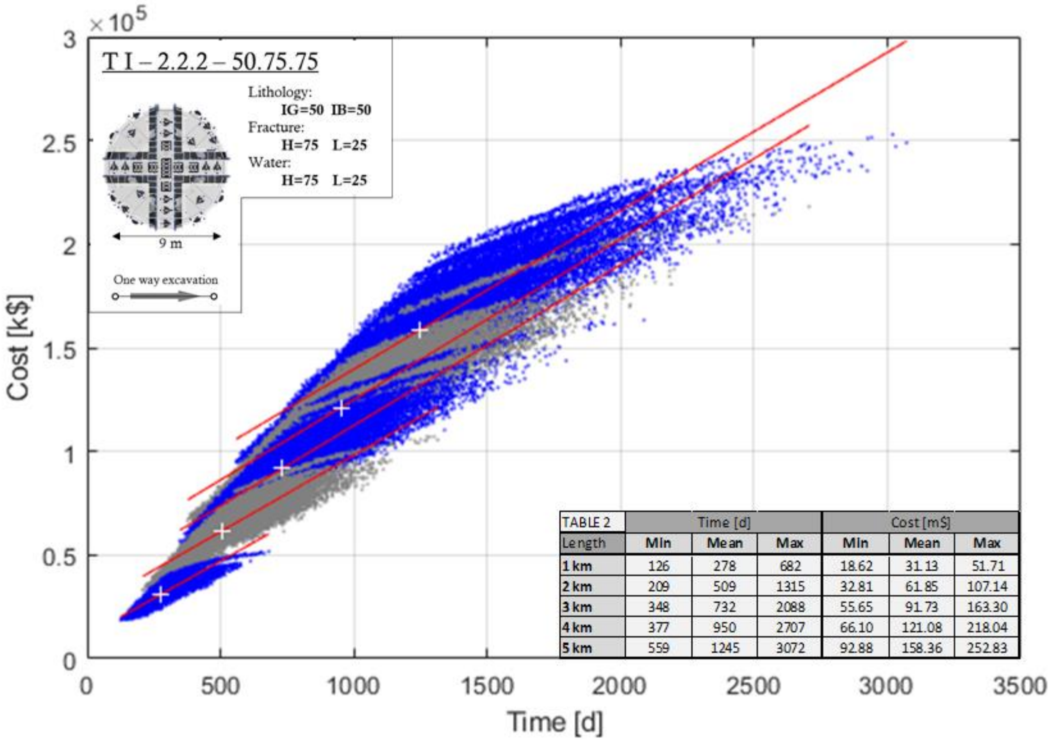


TABLE 2	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	126	278	682	18.62	31.13	51.71
2 km	209	509	1315	32.81	61.85	107.14
3 km	348	732	2088	55.65	91.73	163.30
4 km	377	950	2707	66.10	121.08	218.04
5 km	559	1245	3072	92.88	158.36	252.83

TABLE 2



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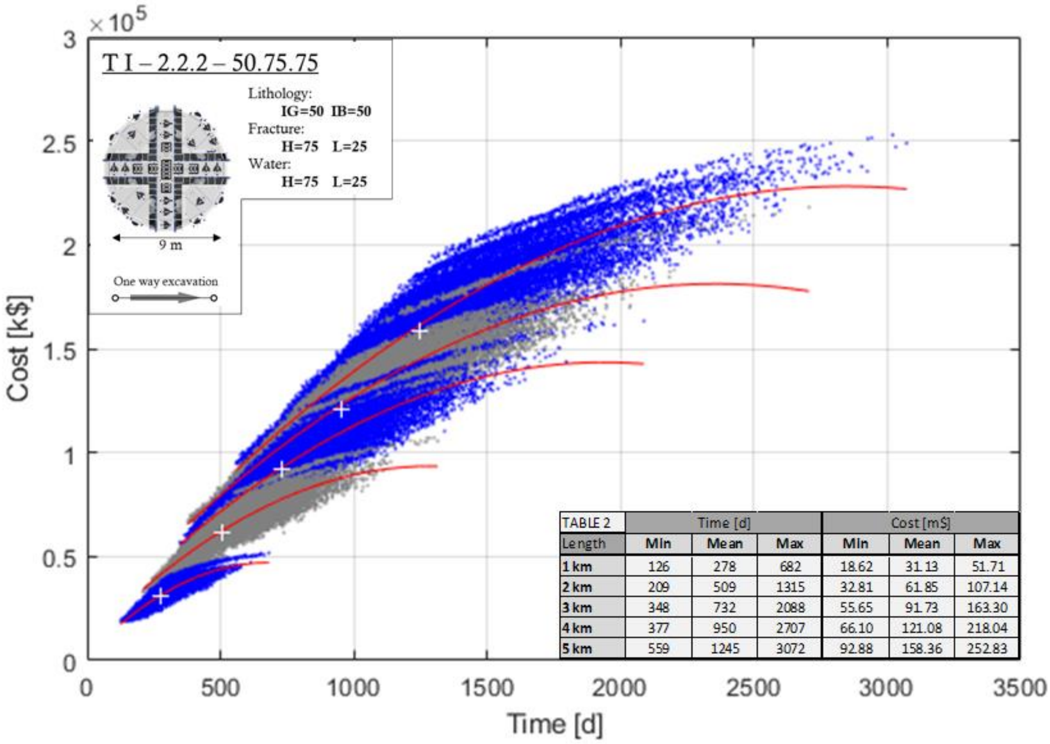

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TABLE 3

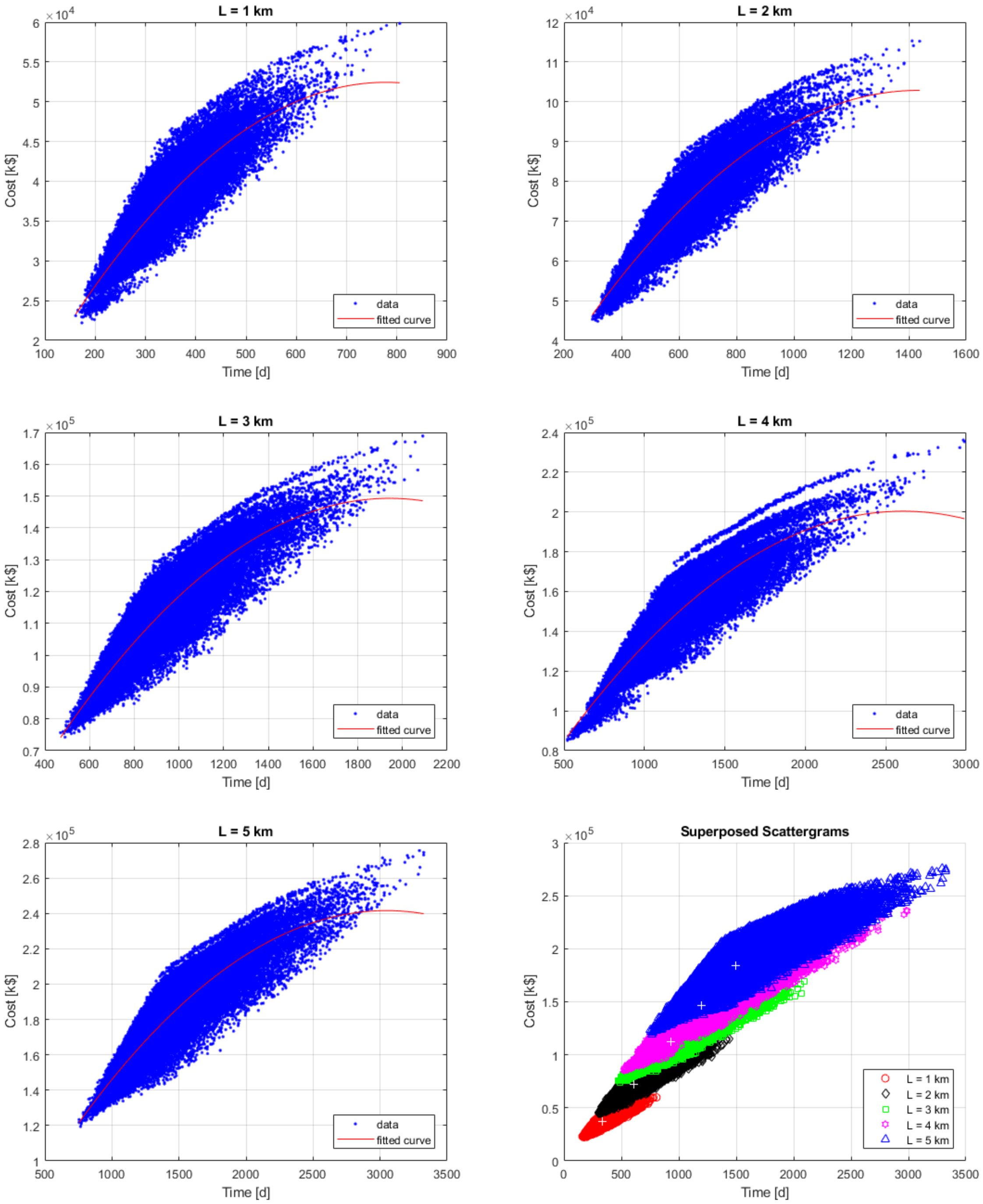
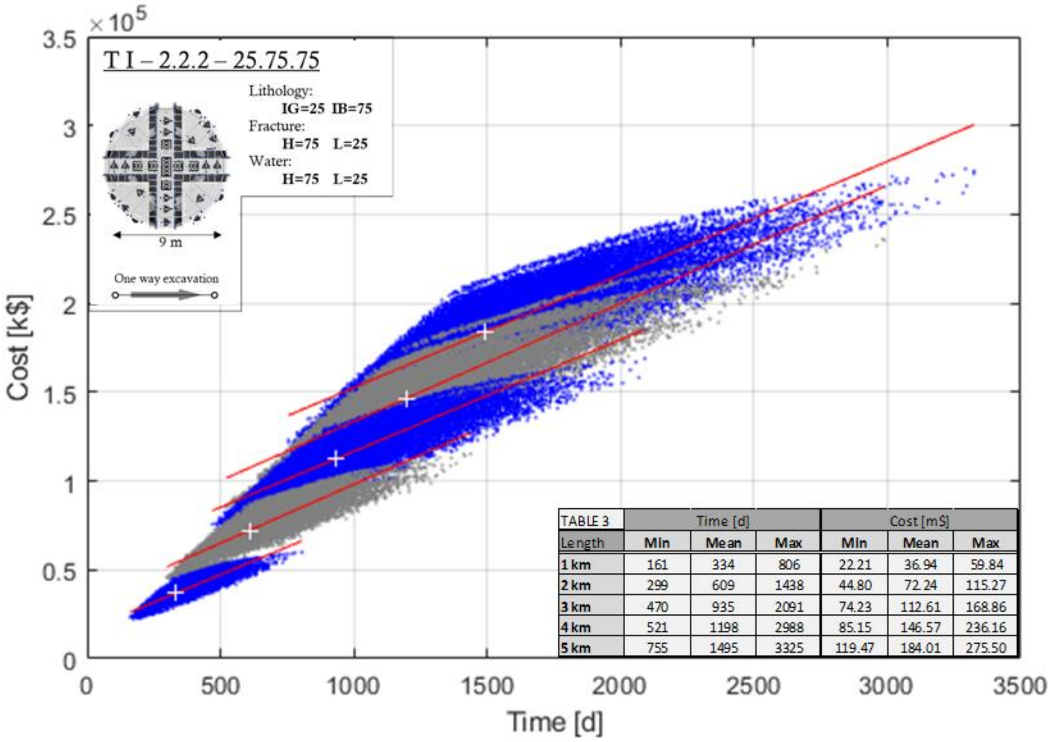


TABLE 3	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	161	334	806	22.21	36.94	59.84
2 km	299	609	1438	44.80	72.24	115.27
3 km	470	935	2091	74.23	112.61	168.86
4 km	521	1198	2988	85.15	146.57	236.16
5 km	755	1495	3325	119.47	184.01	275.50

TABLE 3



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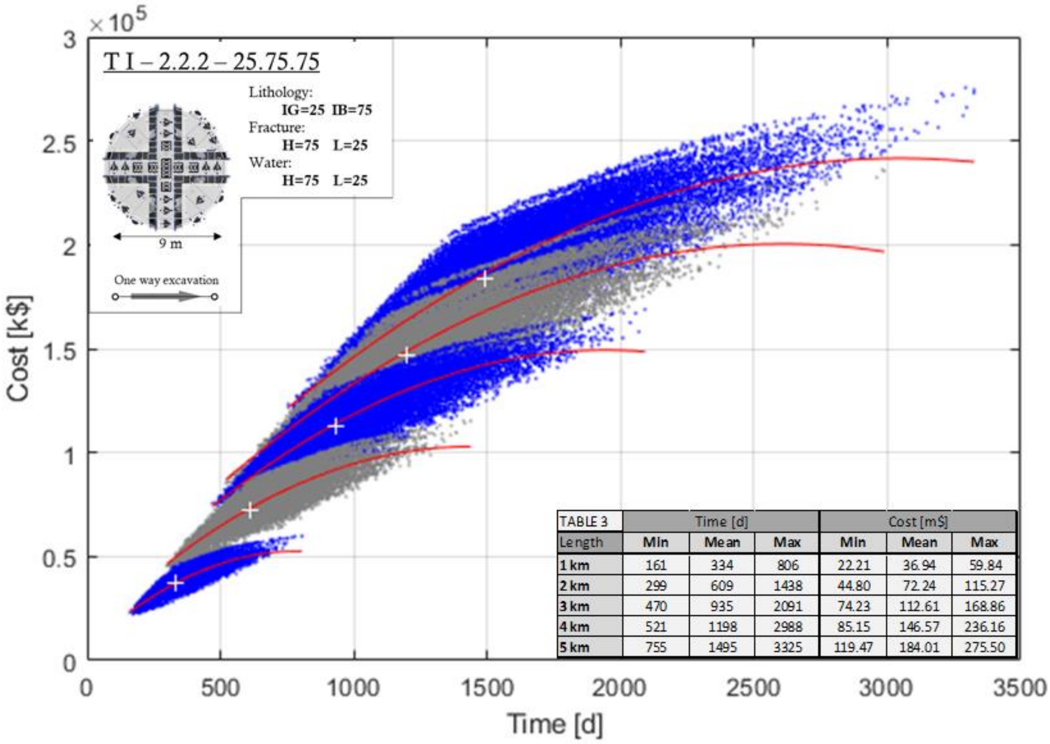

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TABLE 4

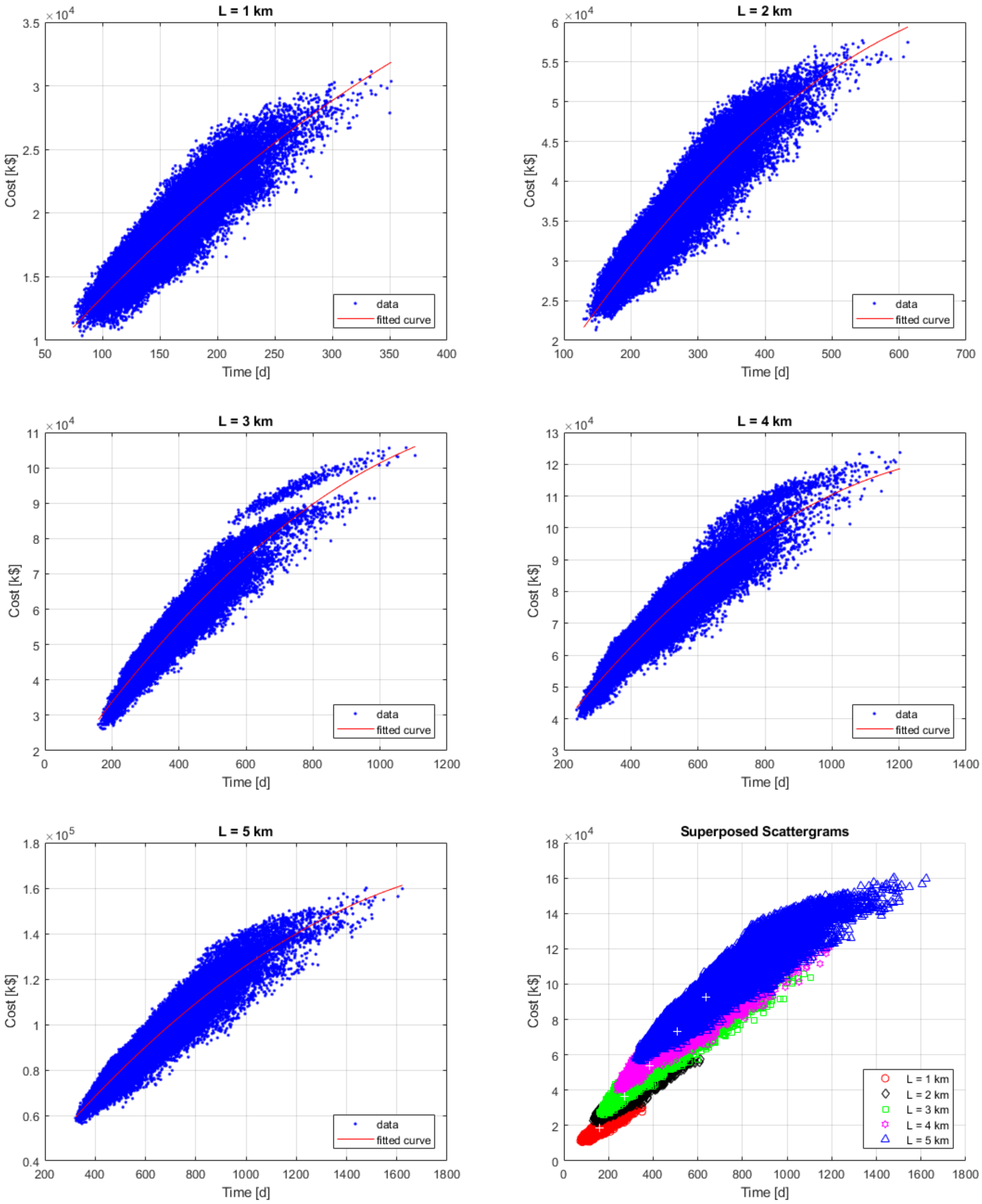
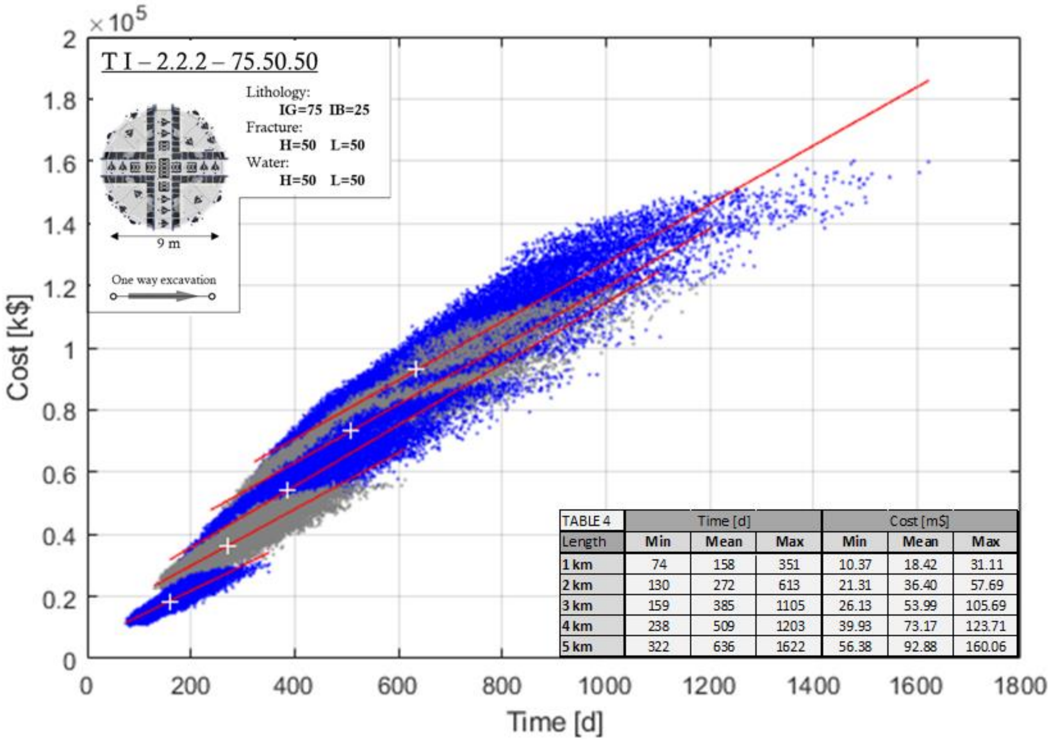


TABLE 4	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	74	158	351	10.37	18.42	31.11
2 km	130	272	613	21.31	36.40	57.69
3 km	159	385	1105	26.13	53.99	105.69
4 km	238	509	1203	39.93	73.17	123.71
5 km	322	636	1622	56.38	92.88	160.06

TABLE 4



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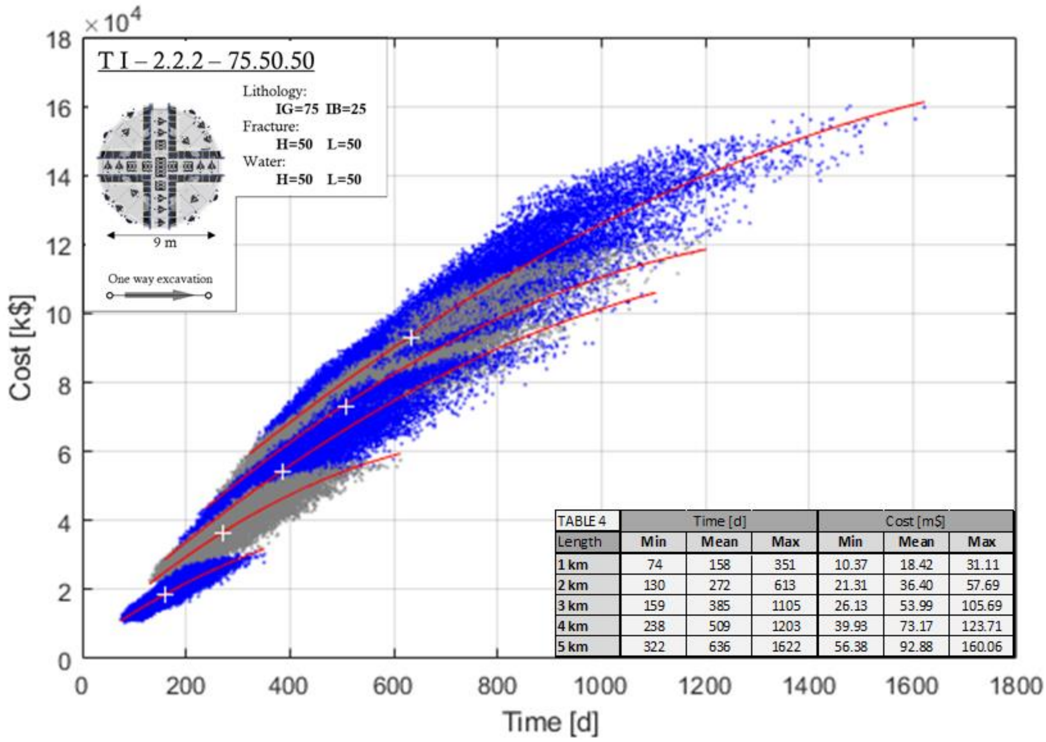

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TABLE 5

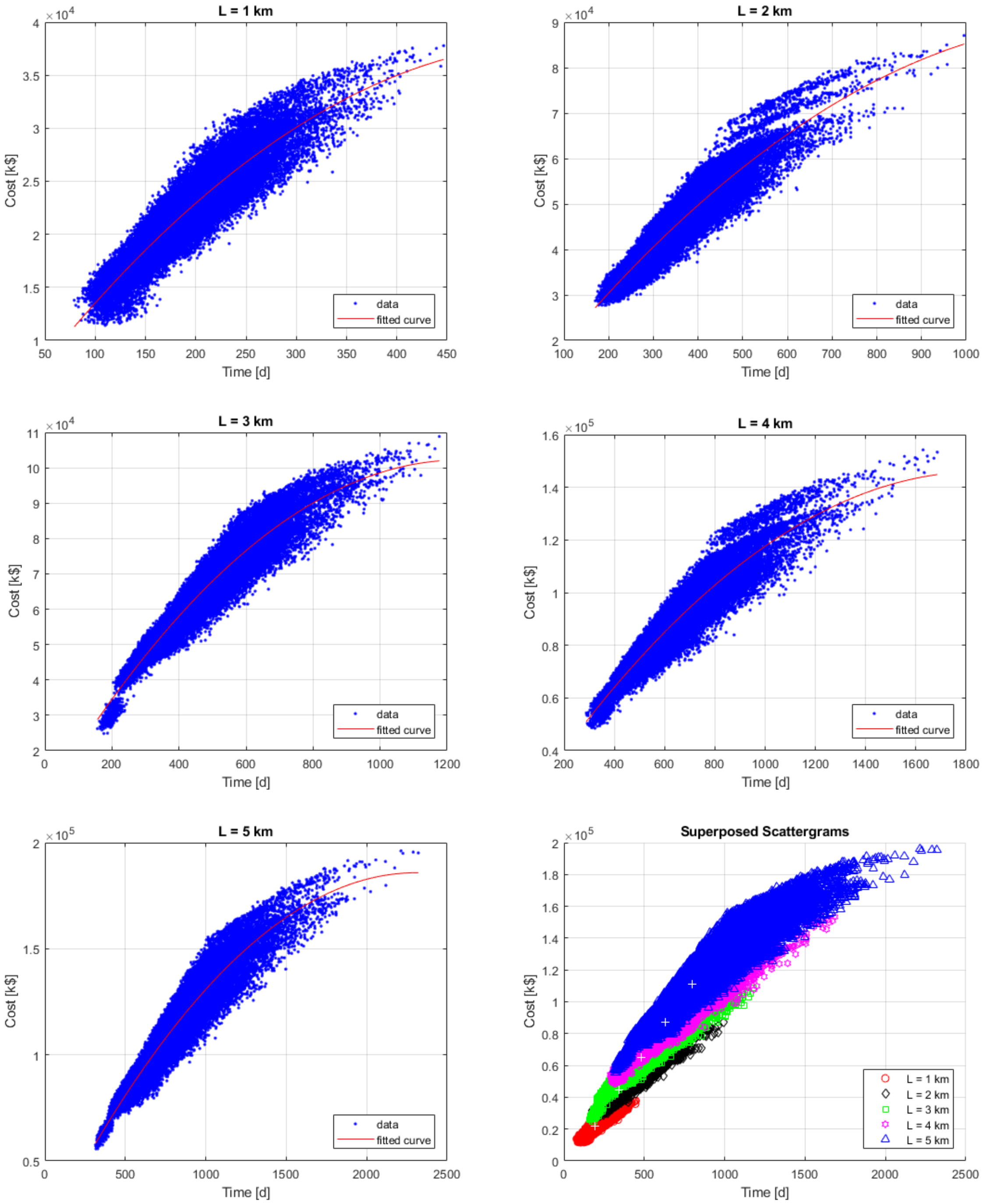
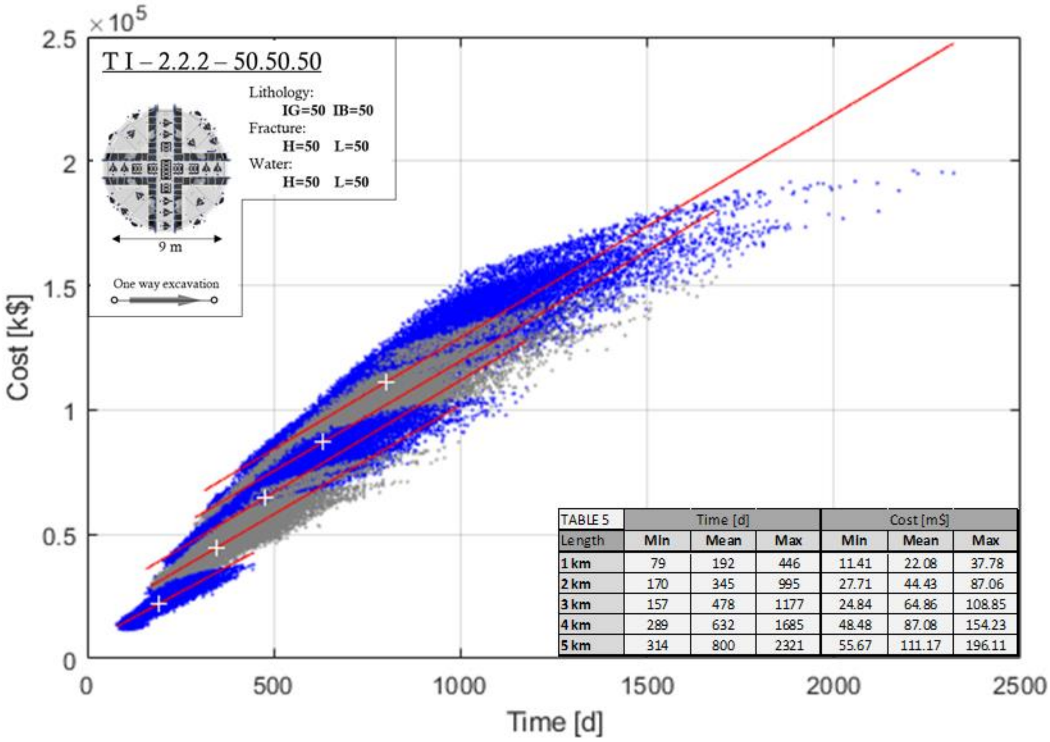


TABLE 5	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	79	192	446	11.41	22.08	37.78
2 km	170	345	995	27.71	44.43	87.06
3 km	157	478	1177	24.84	64.86	108.85
4 km	289	632	1685	48.48	87.08	154.23
5 km	314	800	2321	55.67	111.17	196.11

TABLE 5



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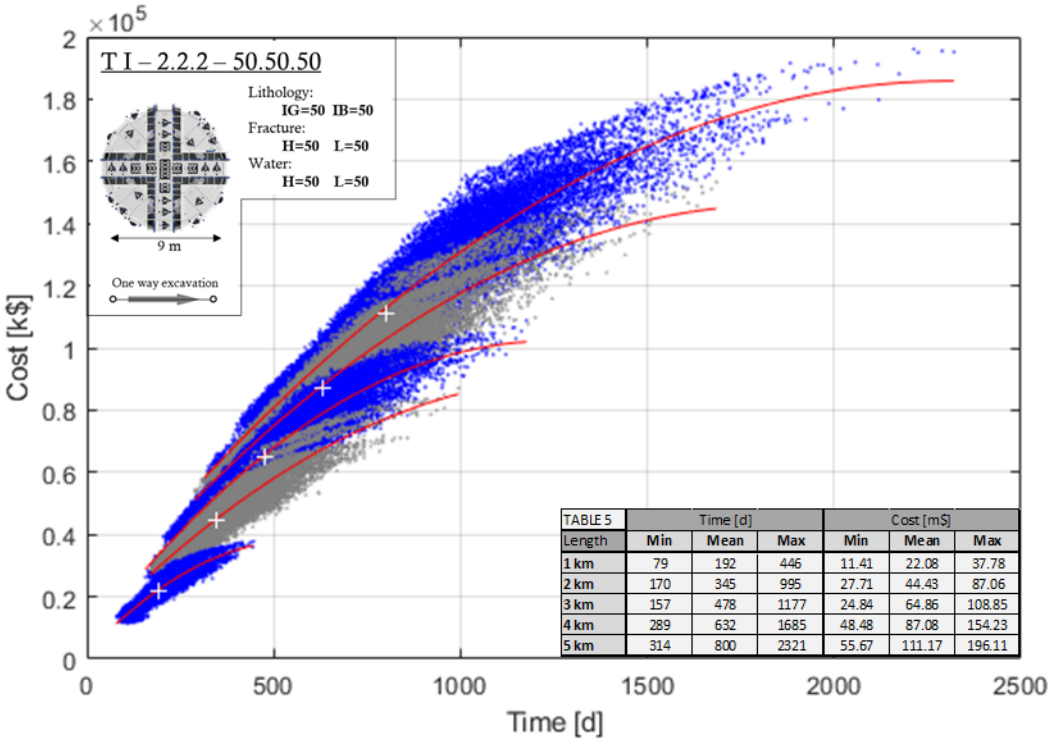

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TABLE 6

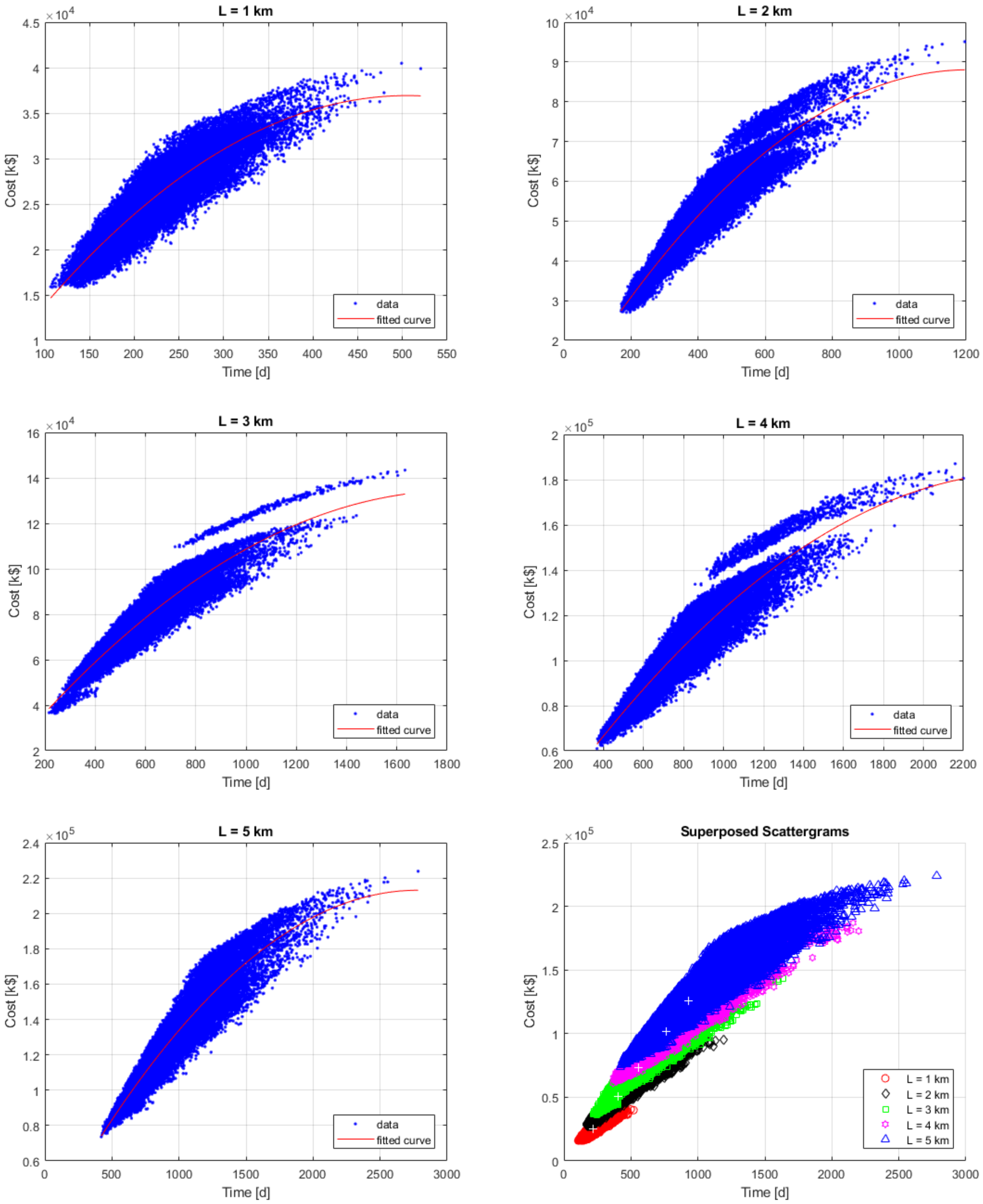
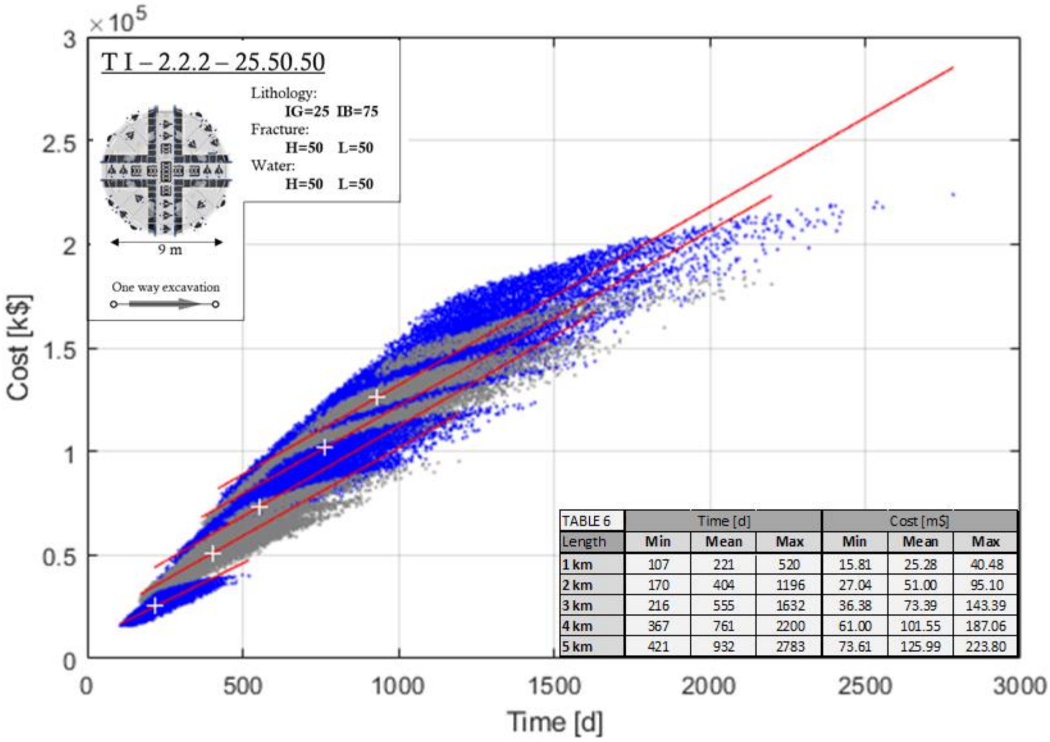


TABLE 6	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	107	221	520	15.81	25.28	40.48
2 km	170	404	1196	27.04	51.00	95.10
3 km	216	555	1632	36.38	73.39	143.39
4 km	367	761	2200	61.00	101.55	187.06
5 km	421	932	2783	73.61	125.99	223.80

TABLE 6



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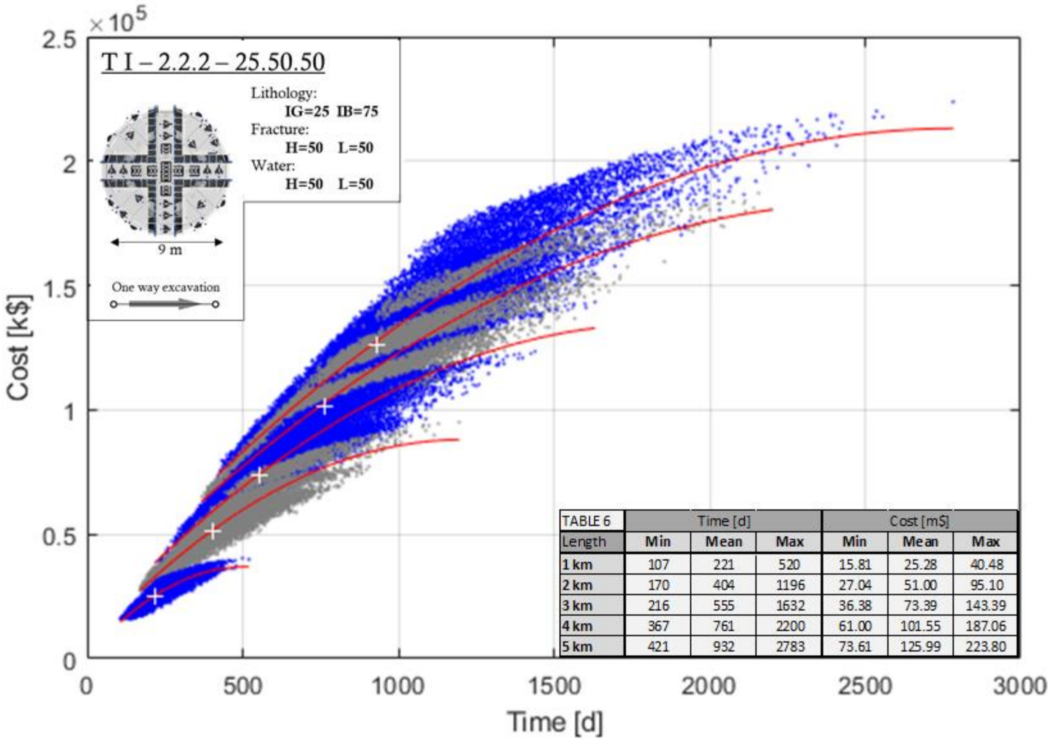

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3 km	216	555	1632	36.38	73.39	143.39
4 km	367	761	2200	61.00	101.55	187.06
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TABLE 7

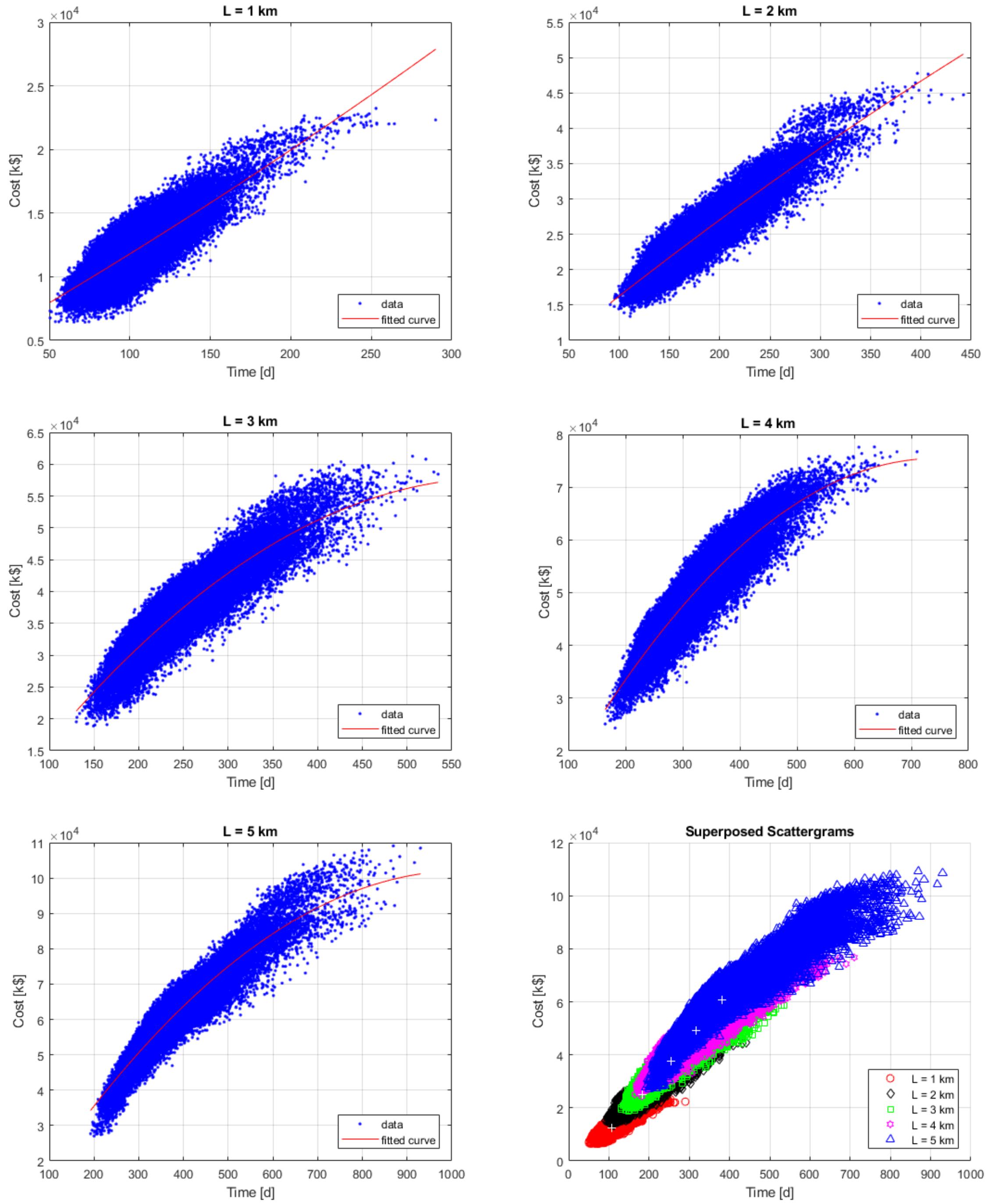
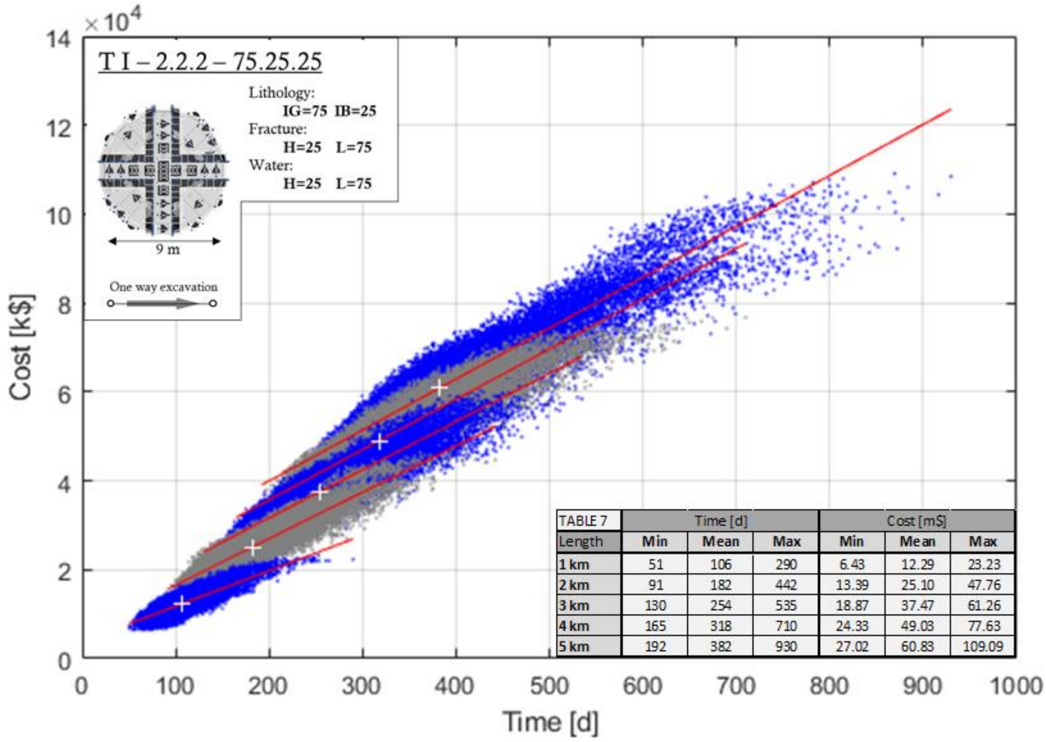


TABLE 7	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	51	106	290	6.43	12.29	23.23
2 km	91	182	442	13.39	25.10	47.76
3 km	130	254	535	18.87	37.47	61.26
4 km	165	318	710	24.33	49.03	77.63
5 km	192	382	930	27.02	60.83	109.09

TABLE 7


T I – 2.2.2 – 75.25.25
Lithology:
IG=75 IB=25
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
×10^4
Cost [k$]
Time [d]
TABLE 7 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 51 | 106 | 290 | 6.43 | 12.29 | 23.23
2 km | 91 | 182 | 442 | 13.39 | 25.10 | 47.76
3 km | 130 | 254 | 535 | 18.87 | 37.47 | 61.26
4 km | 165 | 318 | 710 | 24.33 | 49.03 | 77.63
5 km | 192 | 382 | 930 | 27.02 | 60.83 | 109.09

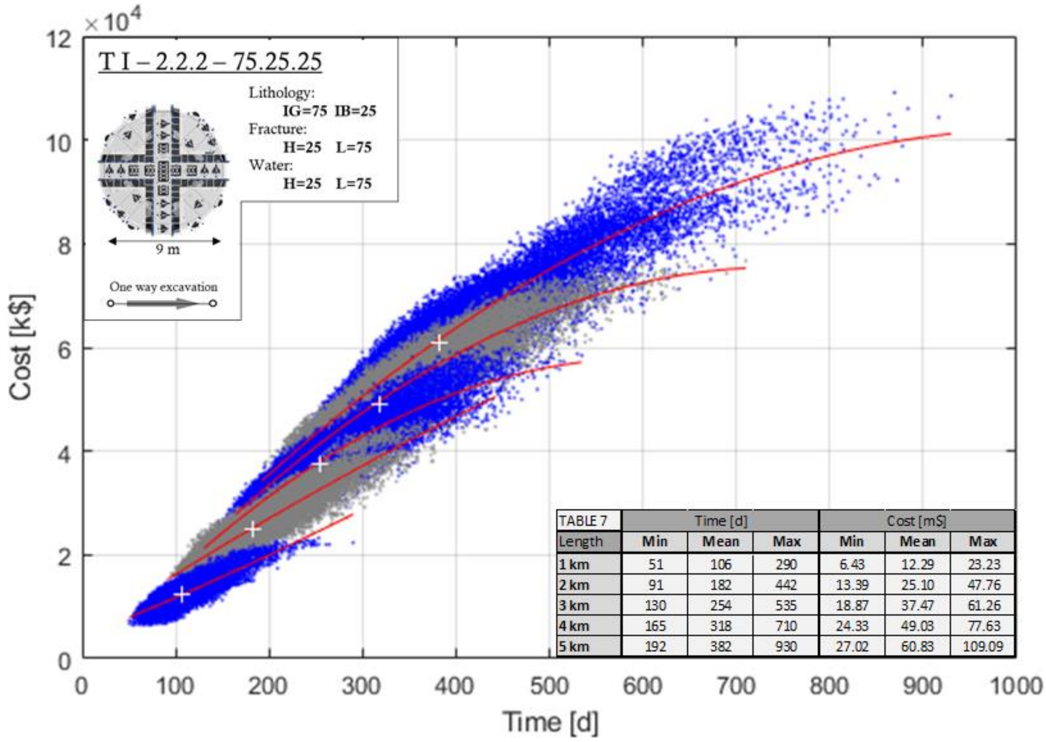

T I – 2.2.2 – 75.25.25
Lithology:
IG=75 IB=25
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
×10^4
Cost [k$]
Time [d]
TABLE 7 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 51 | 106 | 290 | 6.43 | 12.29 | 23.23
2 km | 91 | 182 | 442 | 13.39 | 25.10 | 47.76
3 km | 130 | 254 | 535 | 18.87 | 37.47 | 61.26
4 km | 165 | 318 | 710 | 24.33 | 49.03 | 77.63
5 km | 192 | 382 | 930 | 27.02 | 60.83 | 109.09

TABLE 8

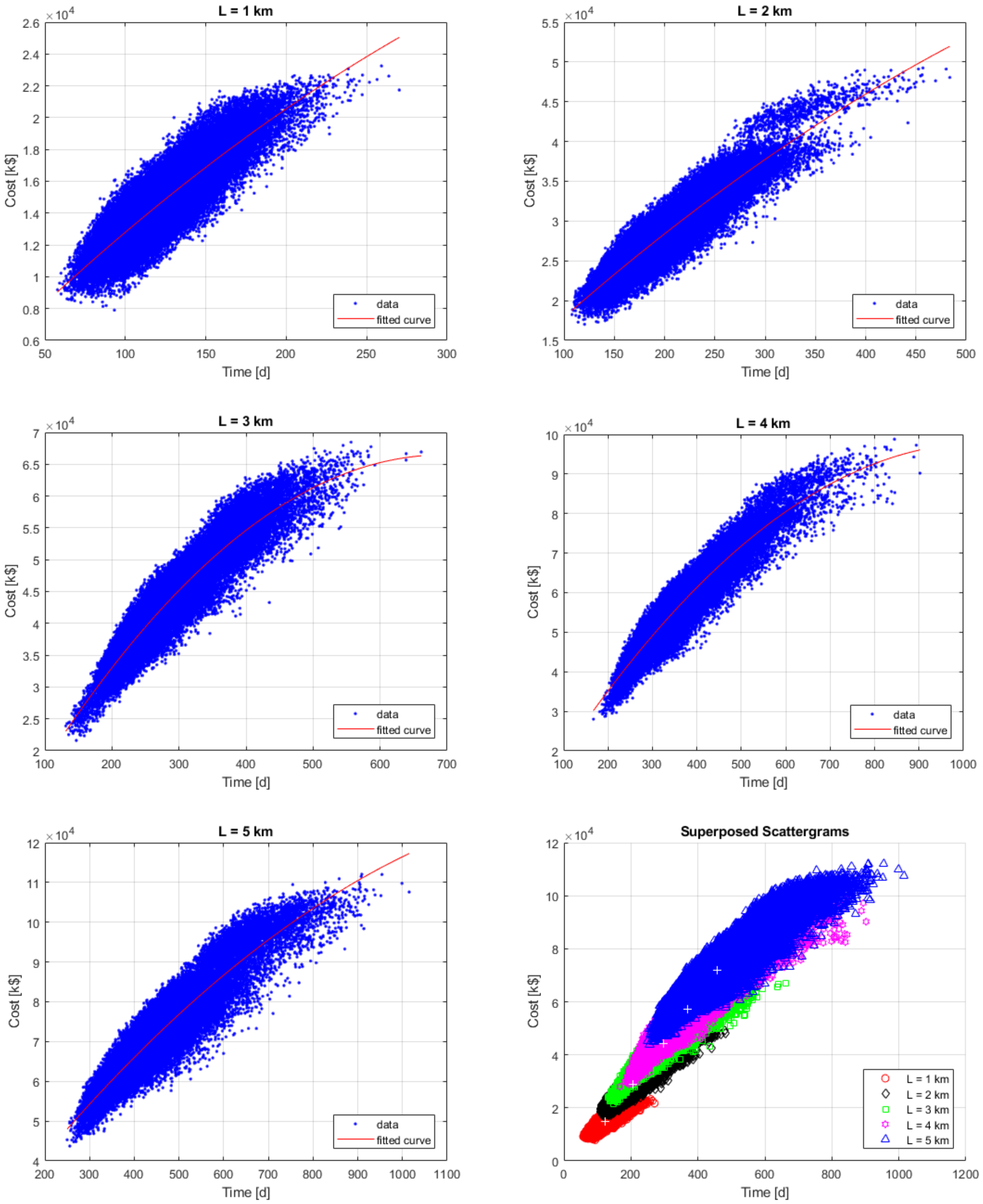
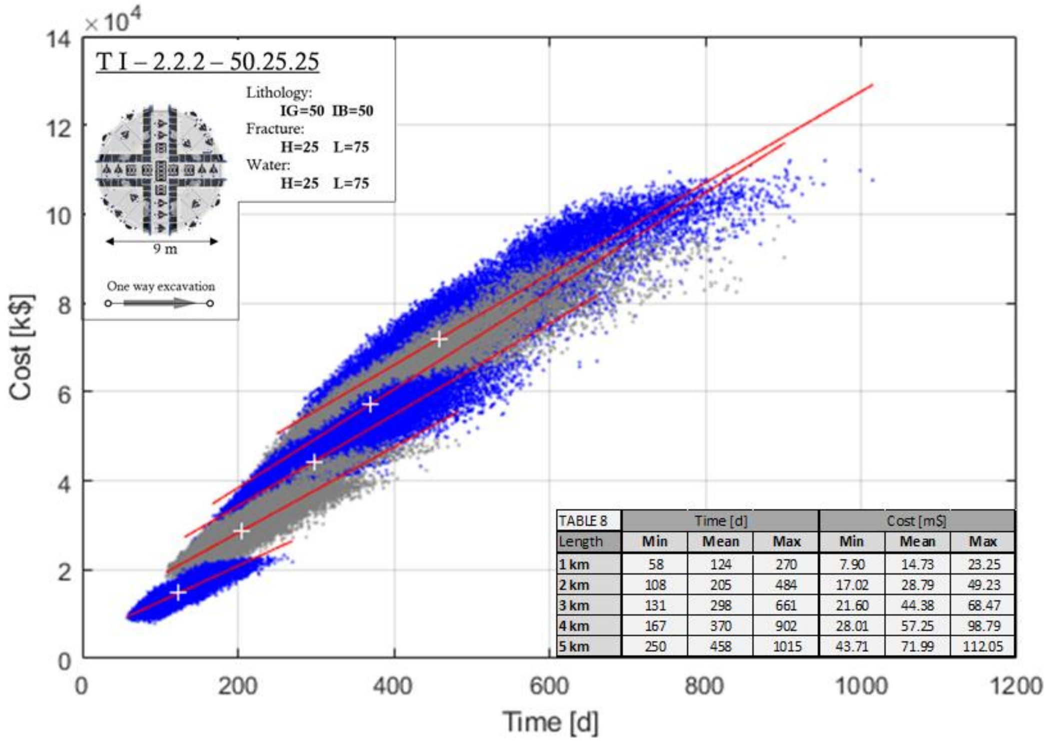


TABLE 8	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	58	124	270	7.90	14.73	23.25
2 km	108	205	484	17.02	28.79	49.23
3 km	131	298	661	21.60	44.38	68.47
4 km	167	370	902	28.01	57.25	98.79
5 km	250	458	1015	43.71	71.99	112.05

TABLE 8


T I – 2.2.2 – 50.25.25
Lithology:
IG=50 IB=50
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
Cost [k$]
Time [d]
× 10^4
TABLE 8 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 58 | 124 | 270 | 7.90 | 14.73 | 23.25
2 km | 108 | 205 | 484 | 17.02 | 28.79 | 49.23
3 km | 131 | 298 | 661 | 21.60 | 44.38 | 68.47
4 km | 167 | 370 | 902 | 28.01 | 57.25 | 98.79
5 km | 250 | 458 | 1015 | 43.71 | 71.99 | 112.05

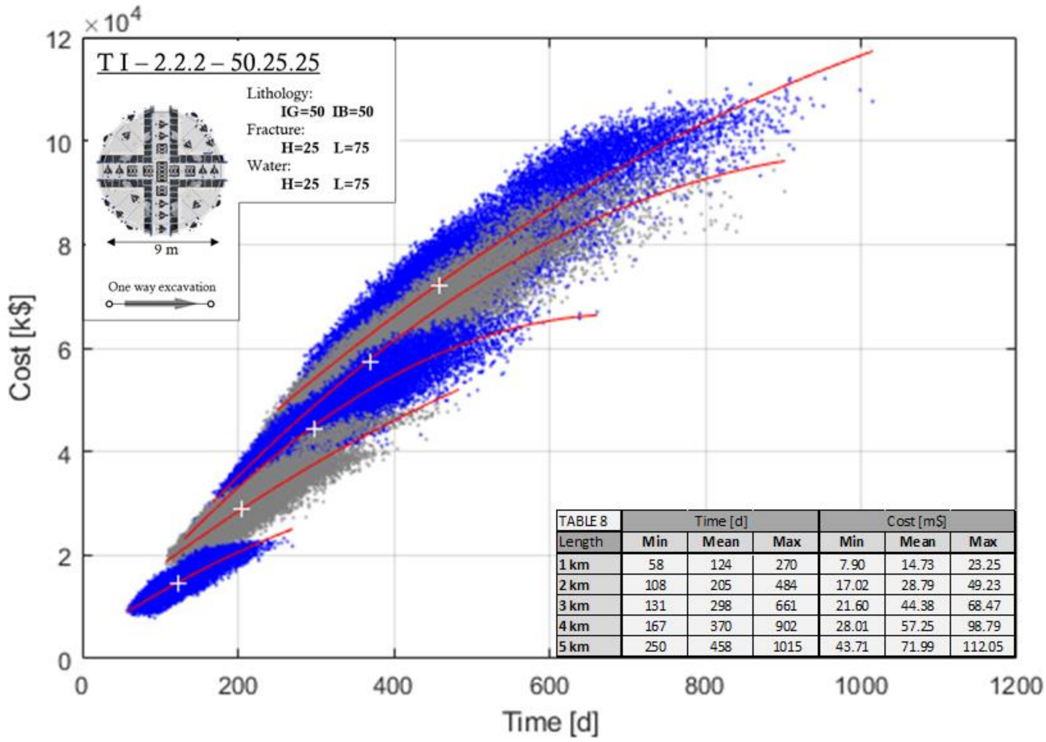

T I – 2.2.2 – 50.25.25
Lithology:
IG=50 IB=50
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
Cost [k$]
Time [d]
× 10^4
TABLE 8 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 58 | 124 | 270 | 7.90 | 14.73 | 23.25
2 km | 108 | 205 | 484 | 17.02 | 28.79 | 49.23
3 km | 131 | 298 | 661 | 21.60 | 44.38 | 68.47
4 km | 167 | 370 | 902 | 28.01 | 57.25 | 98.79
5 km | 250 | 458 | 1015 | 43.71 | 71.99 | 112.05

TABLE 9

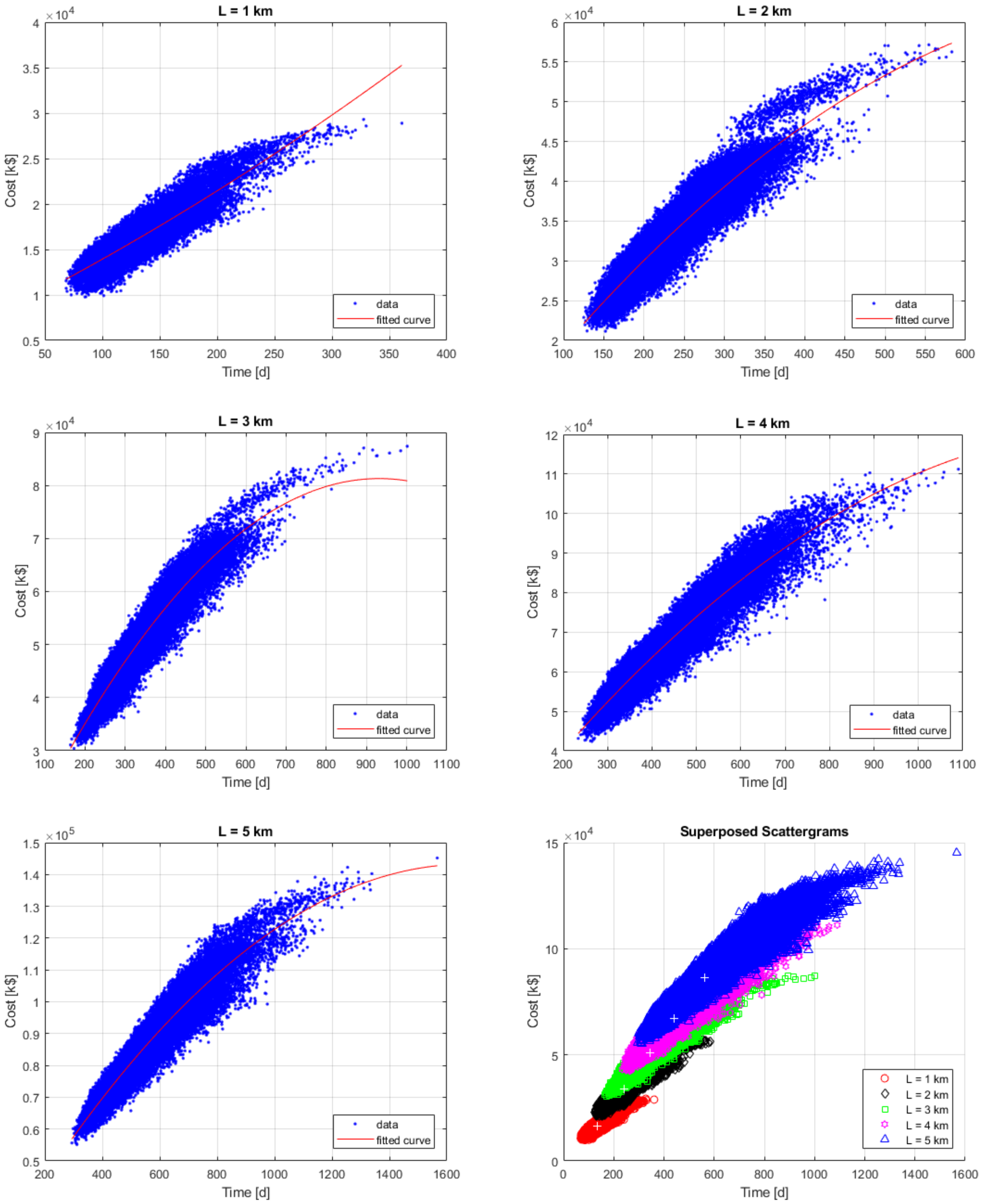


TABLE 9	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	69	135	361	9.77	16.48	29.30
2 km	125	241	583	21.15	33.80	57.16
3 km	164	345	1002	30.41	50.96	87.39
4 km	234	439	1090	42.39	67.17	111.21
5 km	294	562	1566	55.12	86.35	145.20

TABLE 9

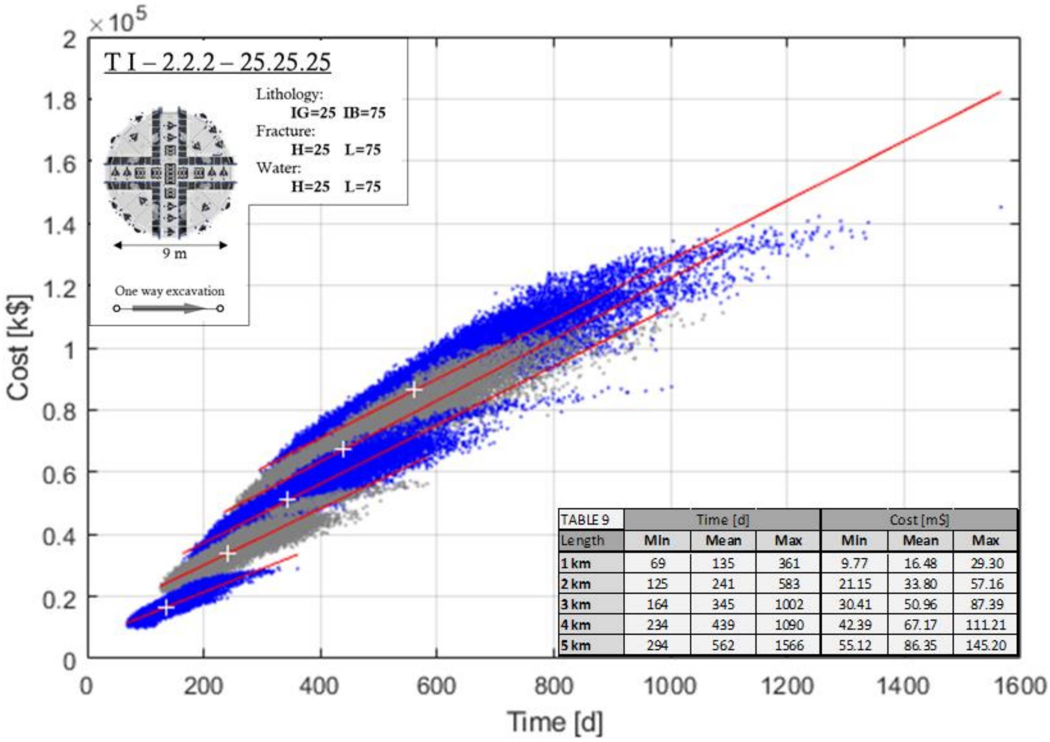


TABLE 9	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	69	135	361	9.77	16.48	29.30
2 km	125	241	583	21.15	33.80	57.16
3 km	164	345	1002	30.41	50.96	87.39
4 km	234	439	1090	42.39	67.17	111.21
5 km	294	562	1566	55.12	86.35	145.20

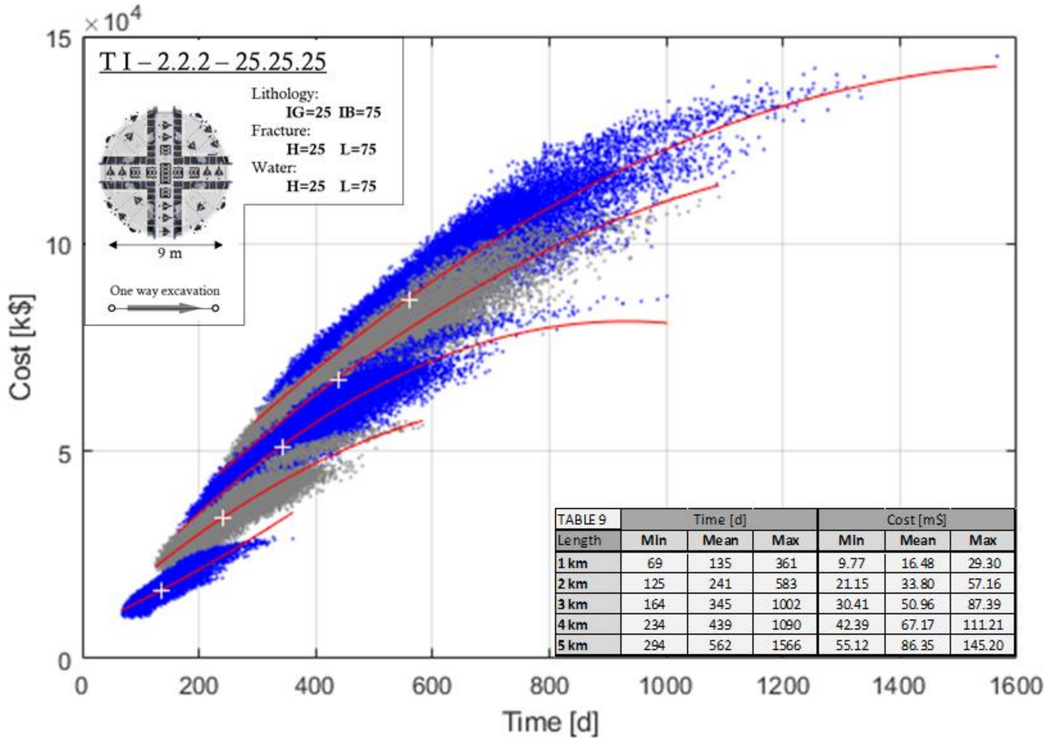


TABLE 9	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	69	135	361	9.77	16.48	29.30
2 km	125	241	583	21.15	33.80	57.16
3 km	164	345	1002	30.41	50.96	87.39
4 km	234	439	1090	42.39	67.17	111.21
5 km	294	562	1566	55.12	86.35	145.20

TABLE 10

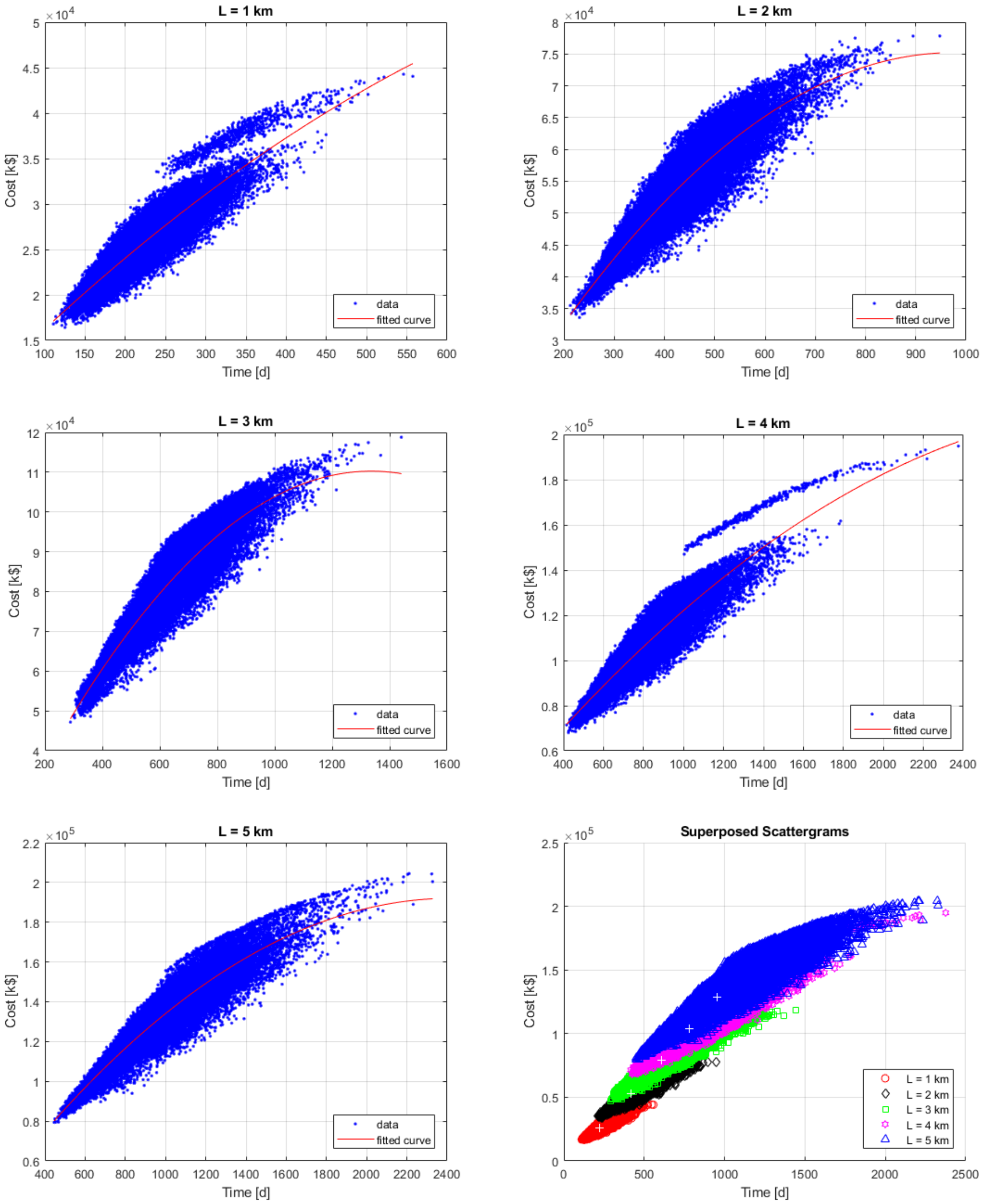


TABLE 10	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	111	223	557	16.42	25.68	44.27
2 km	213	418	948	33.58	52.65	77.83
3 km	289	608	1441	47.17	79.16	118.79
4 km	416	778	2375	68.06	103.70	194.85
5 km	446	956	2328	79.36	128.98	204.45

TABLE 10

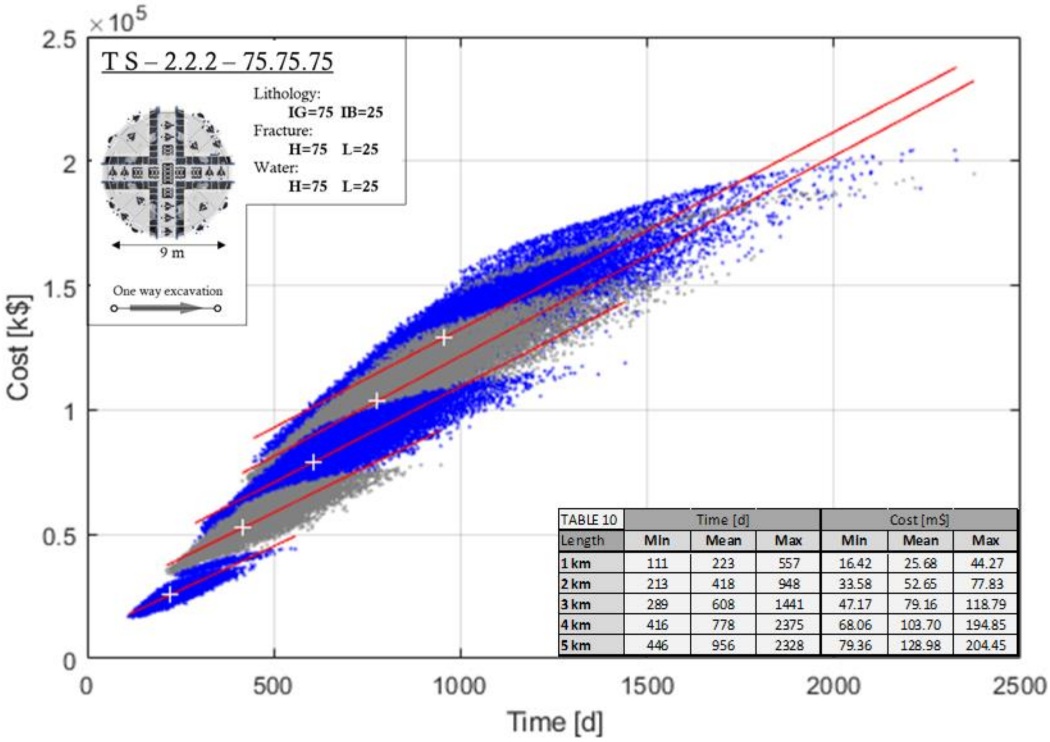


TABLE 10	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	111	223	557	16.42	25.68	44.27
2 km	213	418	948	33.58	52.65	77.83
3 km	289	608	1441	47.17	79.16	118.79
4 km	416	778	2375	68.06	103.70	194.85
5 km	446	956	2328	79.36	128.98	204.45

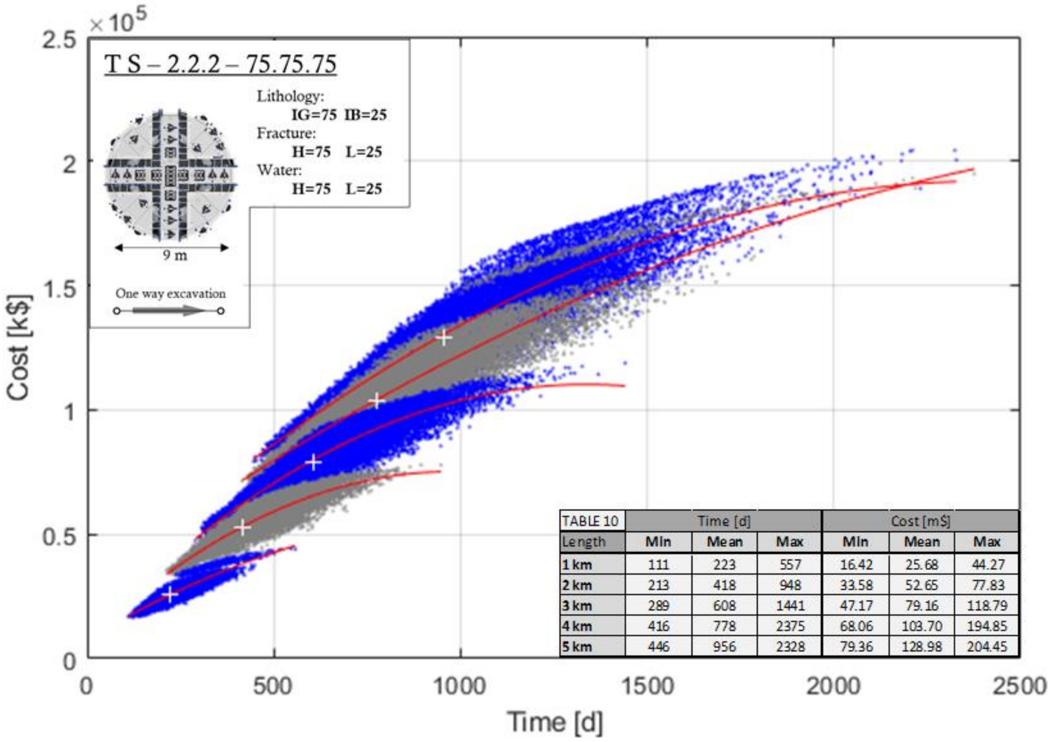


TABLE 10	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	111	223	557	16.42	25.68	44.27
2 km	213	418	948	33.58	52.65	77.83
3 km	289	608	1441	47.17	79.16	118.79
4 km	416	778	2375	68.06	103.70	194.85
5 km	446	956	2328	79.36	128.98	204.45

TABLE 11

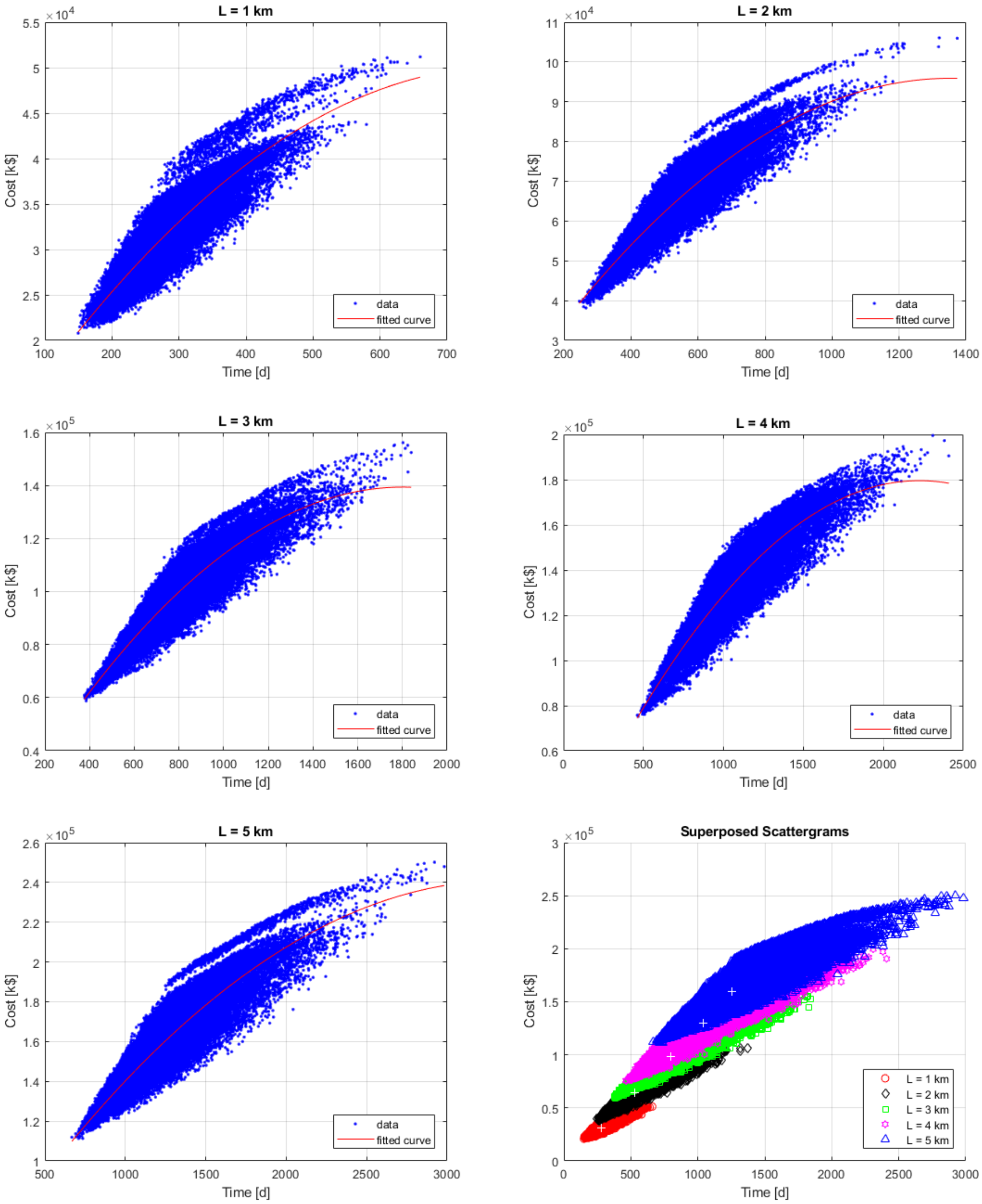


TABLE 11	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	150	279	660	20.79	31.30	51.18
2 km	246	531	1373	38.16	64.03	106.06
3 km	377	796	1840	58.73	98.18	156.13
4 km	462	1039	2409	75.24	130.01	199.54
5 km	668	1254	2982	111.29	159.32	250.16

TABLE 11

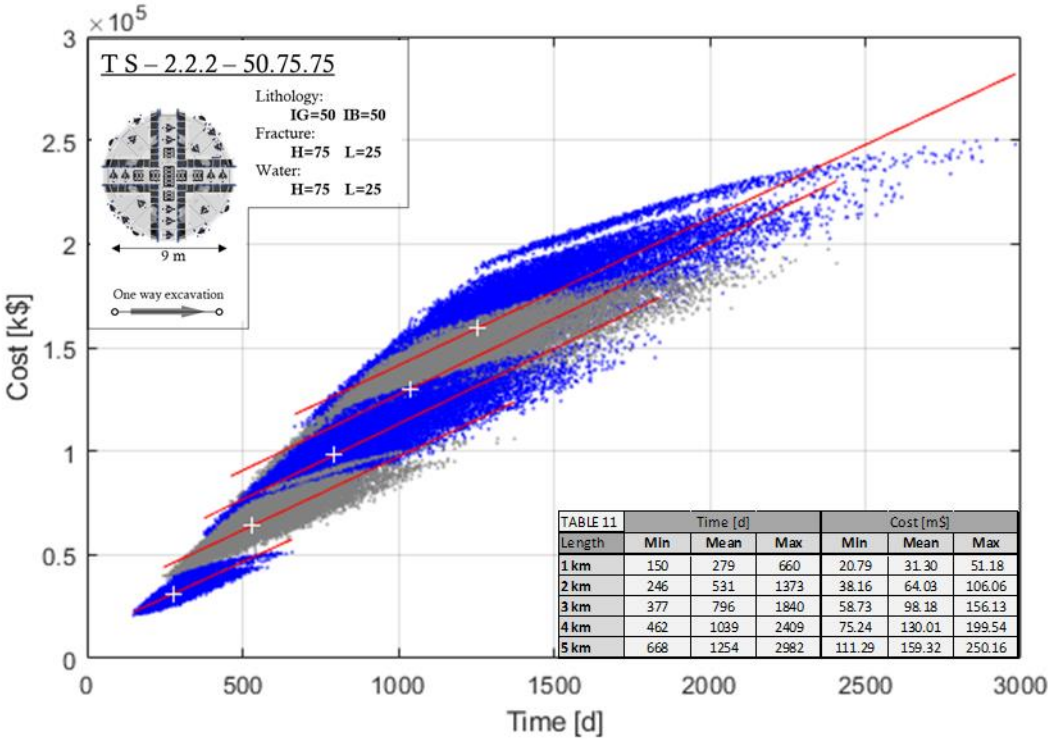


TABLE 11	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	150	279	660	20.79	31.30	51.18
2 km	246	531	1373	38.16	64.03	106.06
3 km	377	796	1840	58.73	98.18	156.13
4 km	462	1039	2409	75.24	130.01	199.54
5 km	668	1254	2982	111.29	159.32	250.16

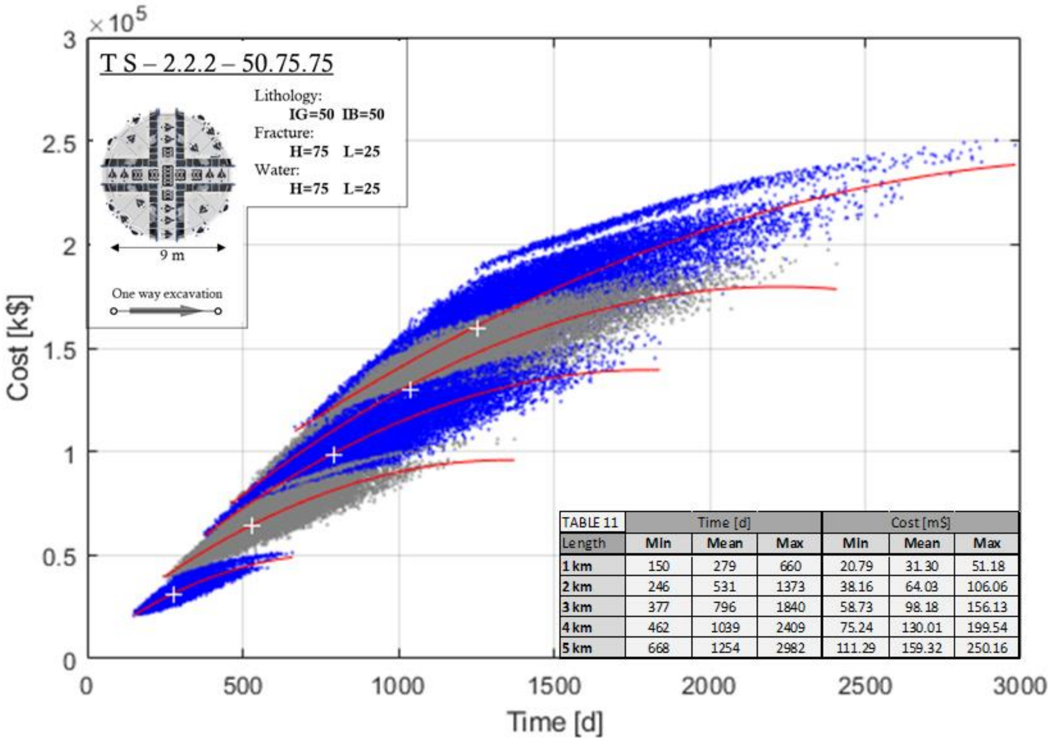

T S – 2.2.2 – 50.75.75
Lithology:
IG=50 IB=50
Fracture:
H=75 L=25
Water:
H=75 L=25
9 m
One way excavation
Cost [k$]
Time [d]
×10^5

TABLE 11	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	150	279	660	20.79	31.30	51.18
2 km	246	531	1373	38.16	64.03	106.06
3 km	377	796	1840	58.73	98.18	156.13
4 km	462	1039	2409	75.24	130.01	199.54
5 km	668	1254	2982	111.29	159.32	250.16

TABLE 12

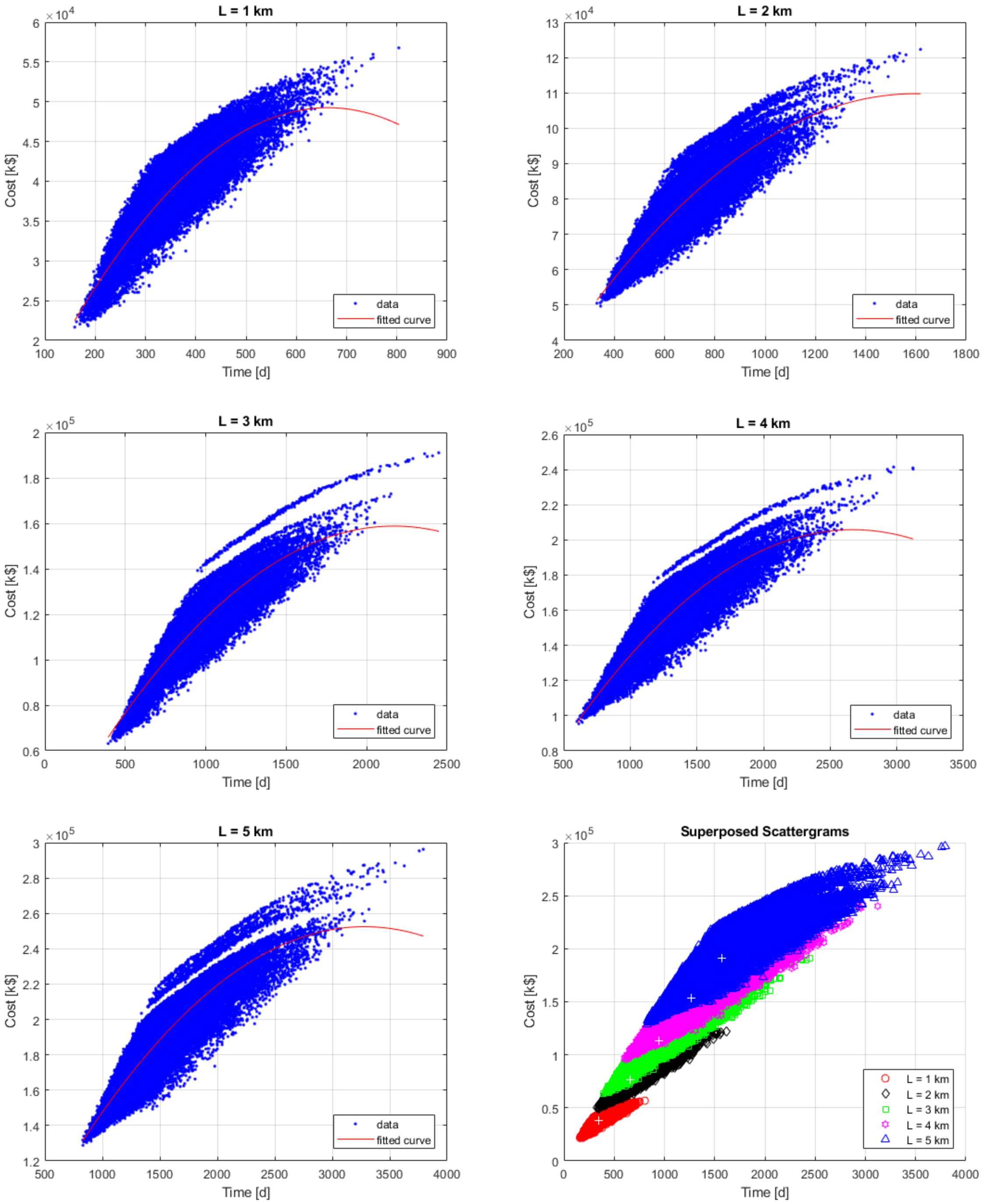


TABLE 12	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	159	346	804	21.67	38.13	56.77
2 km	331	657	1618	49.69	76.83	122.30
3 km	393	944	2447	63.12	113.20	191.05
4 km	600	1265	3122	95.43	153.11	241.45
5 km	830	1568	3792	128.83	190.97	296.24

TABLE 12

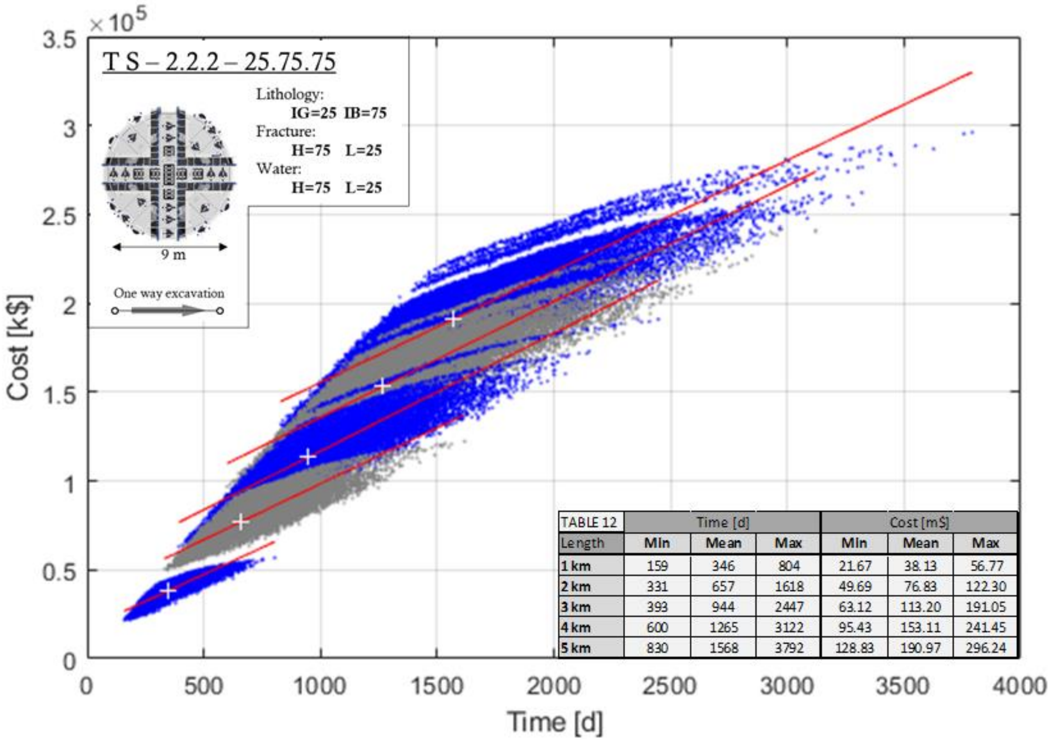


TABLE 12	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	159	346	804	21.67	38.13	56.77
2 km	331	657	1618	49.69	76.83	122.30
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4 km	600	1265	3122	95.43	153.11	241.45
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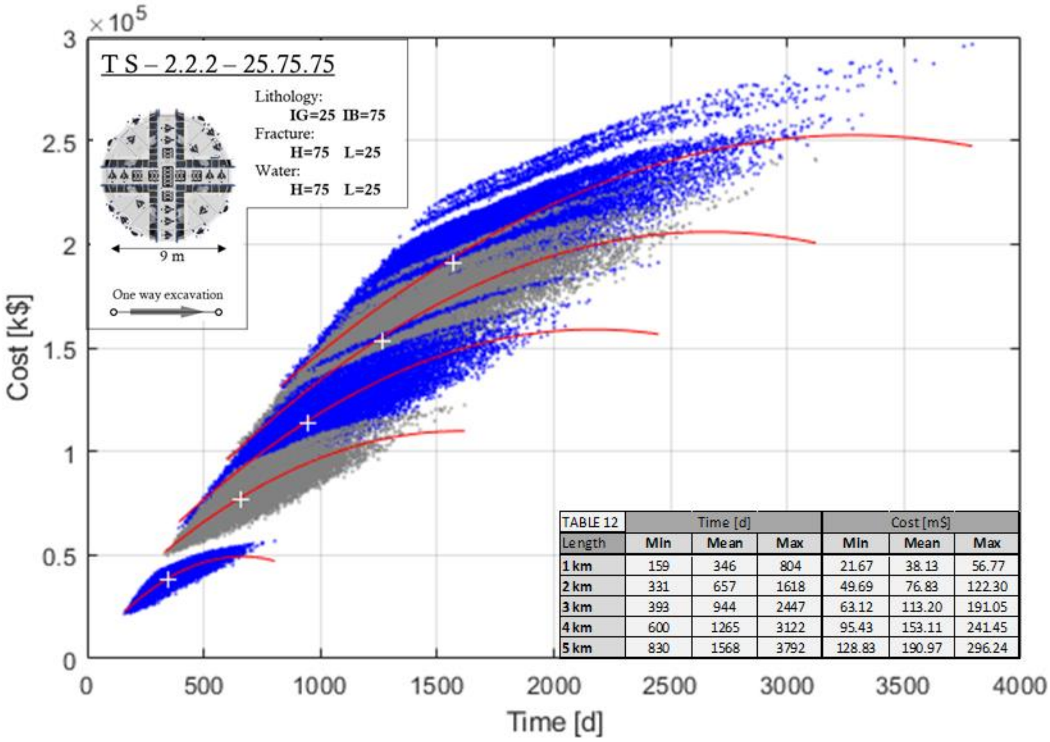


TABLE 12	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	159	346	804	21.67	38.13	56.77
2 km	331	657	1618	49.69	76.83	122.30
3 km	393	944	2447	63.12	113.20	191.05
4 km	600	1265	3122	95.43	153.11	241.45
5 km	830	1568	3792	128.83	190.97	296.24

TABLE 13

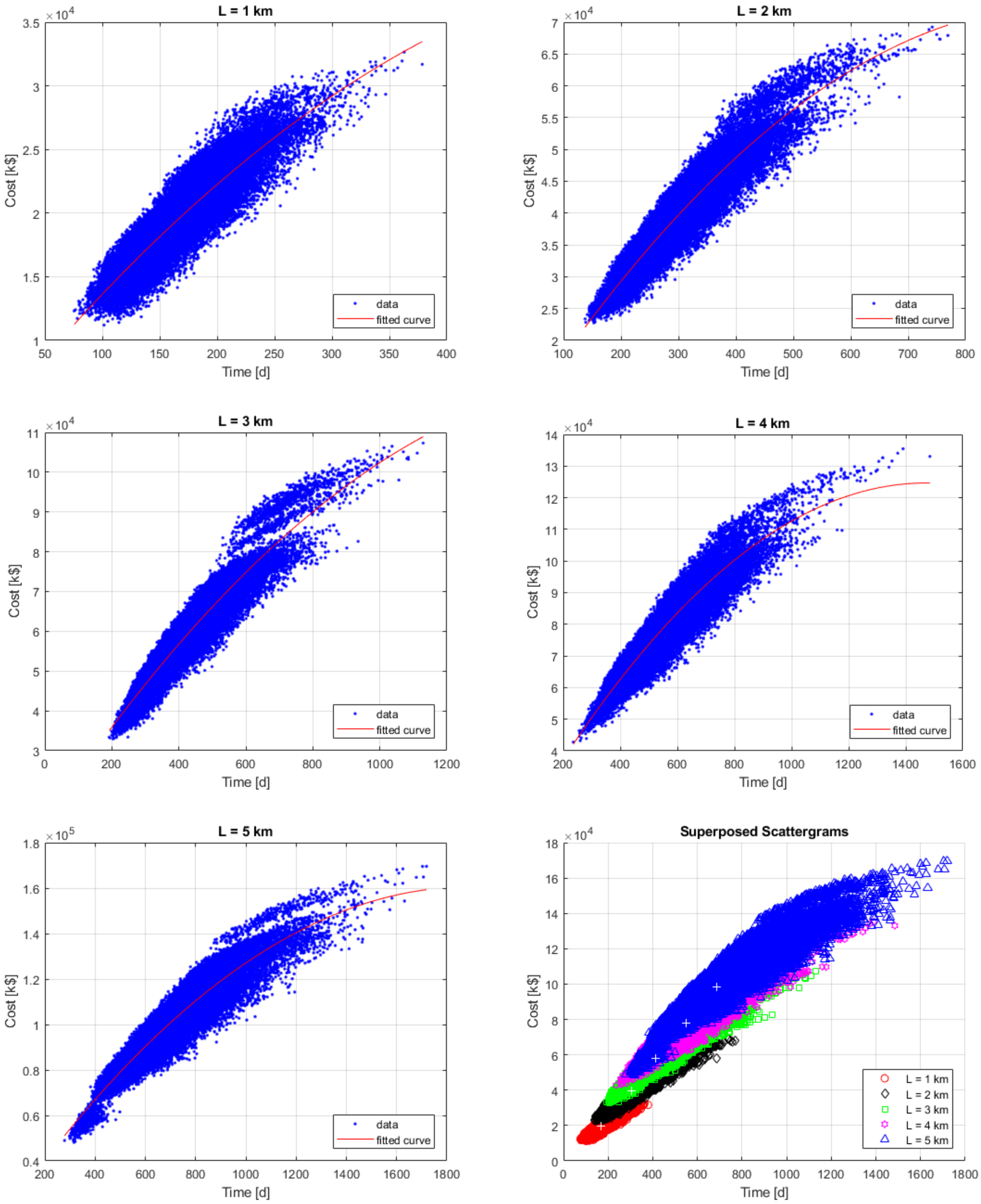


TABLE 13	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	76	167	379	11.20	19.49	32.65
2 km	138	304	769	22.76	39.73	69.22
3 km	192	415	1129	32.94	57.79	107.31
4 km	235	549	1485	42.77	77.76	135.46
5 km	279	687	1719	48.16	98.31	169.57

TABLE 13

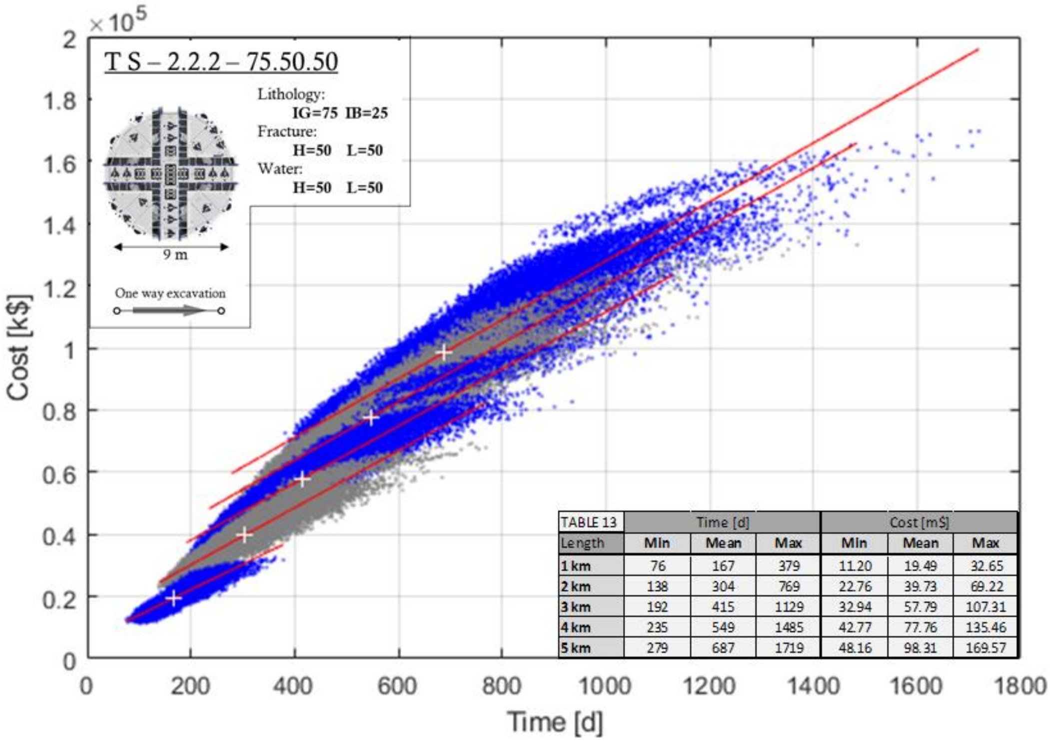


TABLE 13	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	76	167	379	11.20	19.49	32.65
2 km	138	304	769	22.76	39.73	69.22
3 km	192	415	1129	32.94	57.79	107.31
4 km	235	549	1485	42.77	77.76	135.46
5 km	279	687	1719	48.16	98.31	169.57

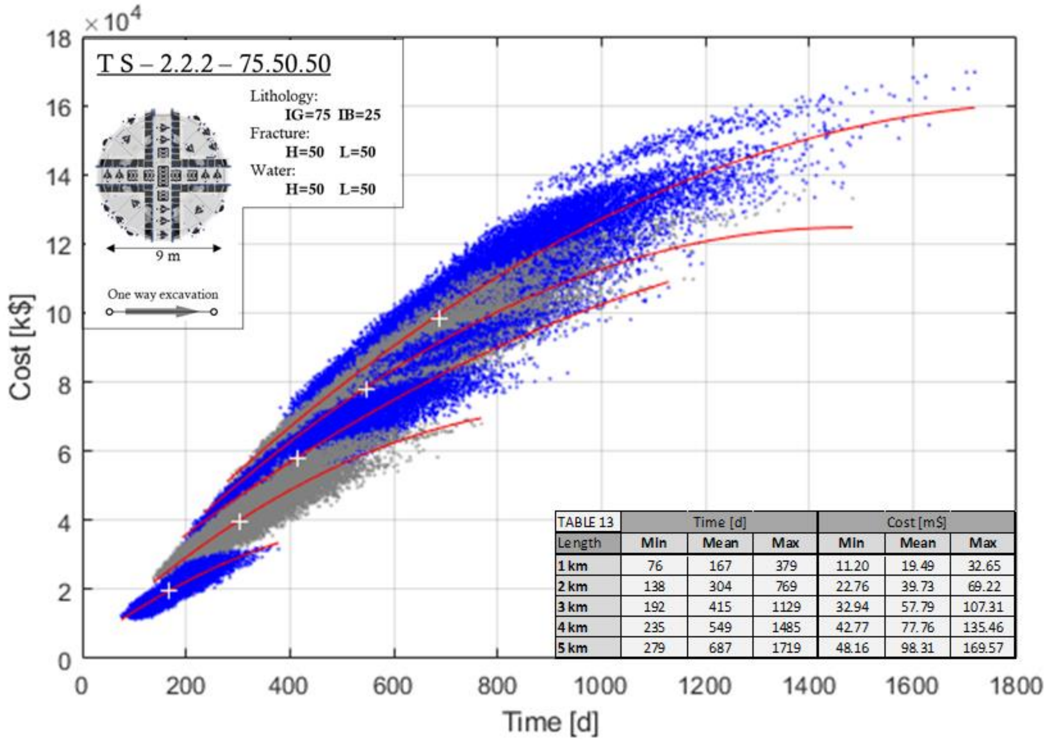


TABLE 13	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	76	167	379	11.20	19.49	32.65
2 km	138	304	769	22.76	39.73	69.22
3 km	192	415	1129	32.94	57.79	107.31
4 km	235	549	1485	42.77	77.76	135.46
5 km	279	687	1719	48.16	98.31	169.57

TABLE 14

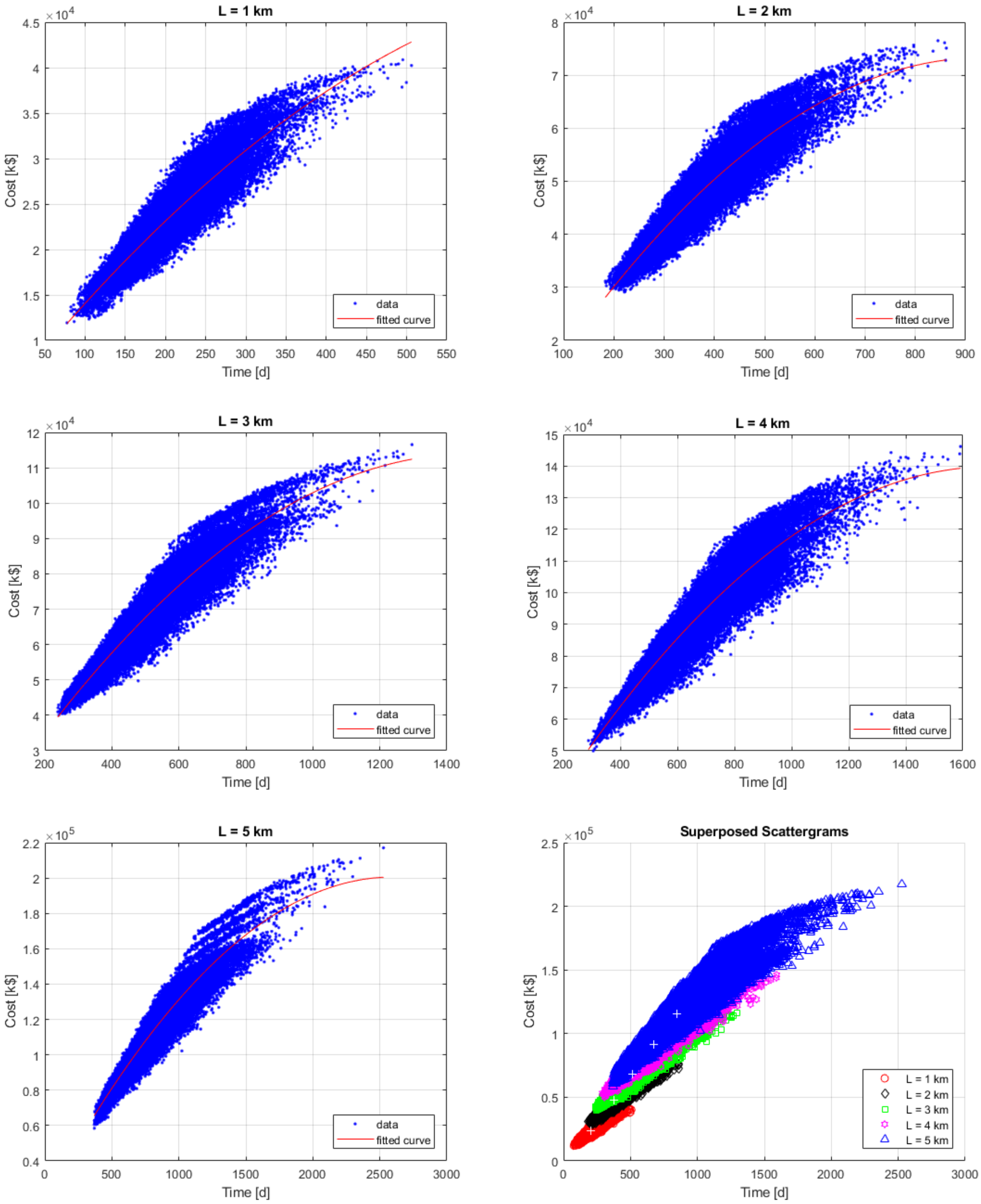
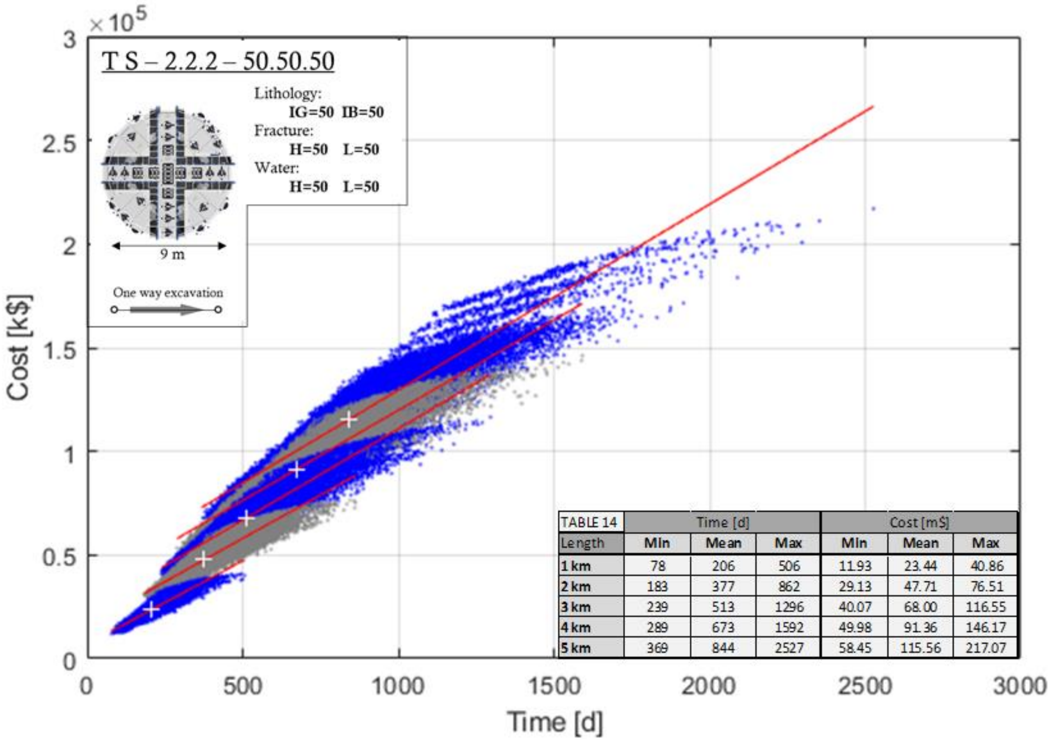


TABLE 14	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	206	506	11.93	23.44	40.86
2 km	183	377	862	29.13	47.71	76.51
3 km	239	513	1296	40.07	68.00	116.55
4 km	289	673	1592	49.98	91.36	146.17
5 km	369	844	2527	58.45	115.56	217.07

TABLE 14



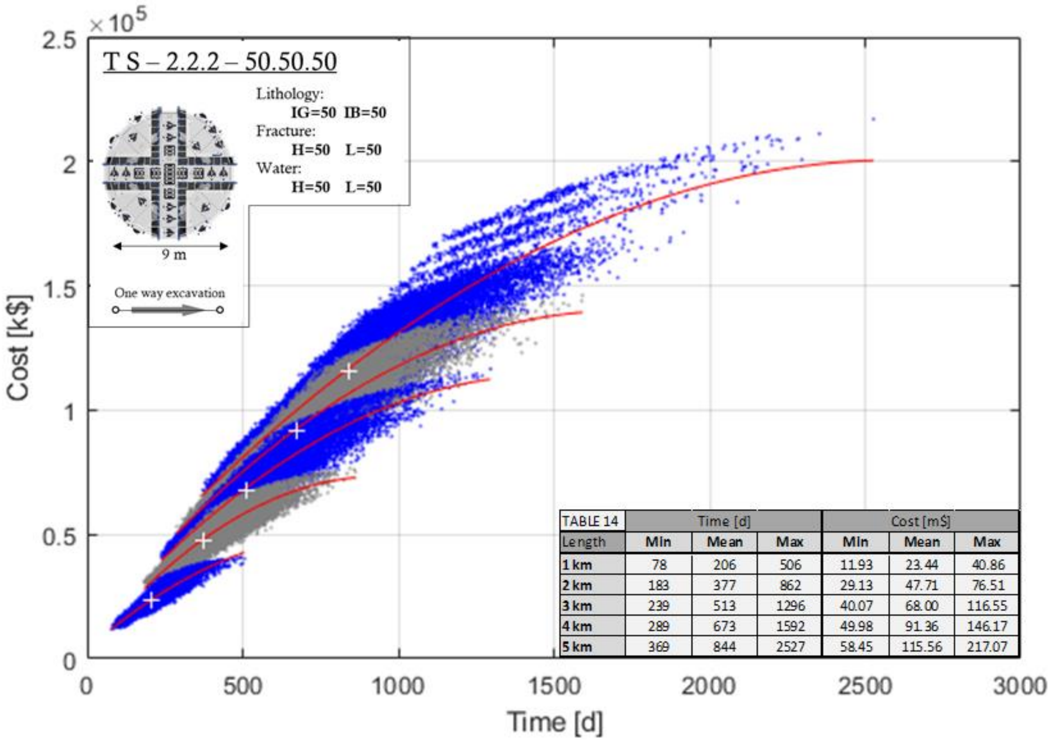

×10^5
T S – 2.2.2 – 50.50.50
Lithology:
IG=50 IB=50
Fracture:
H=50 L=50
Water:
H=50 L=50
9 m
One way excavation
Cost [k$]
Time [d]
TABLE 14 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 78 | 206 | 506 | 11.93 | 23.44 | 40.86
2 km | 183 | 377 | 862 | 29.13 | 47.71 | 76.51
3 km | 239 | 513 | 1296 | 40.07 | 68.00 | 116.55
4 km | 289 | 673 | 1592 | 49.98 | 91.36 | 146.17
5 km | 369 | 844 | 2527 | 58.45 | 115.56 | 217.07

TABLE 15

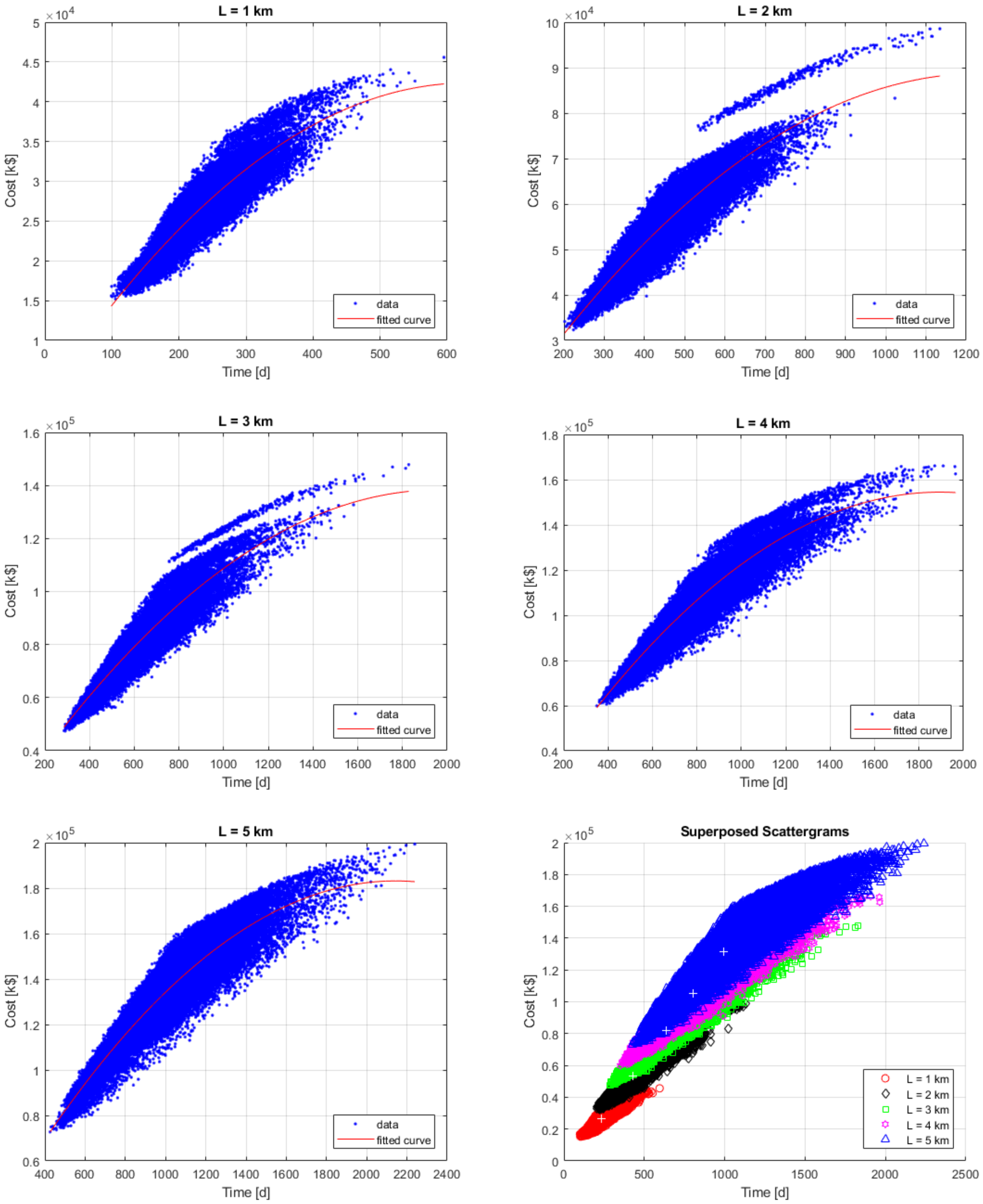


TABLE 15	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	99	234	595	15.19	26.49	45.58
2 km	202	430	1134	32.32	53.39	98.55
3 km	286	638	1828	47.41	81.70	147.86
4 km	350	805	1964	59.91	105.46	166.10
5 km	426	991	2239	72.75	131.32	199.37

TABLE 15

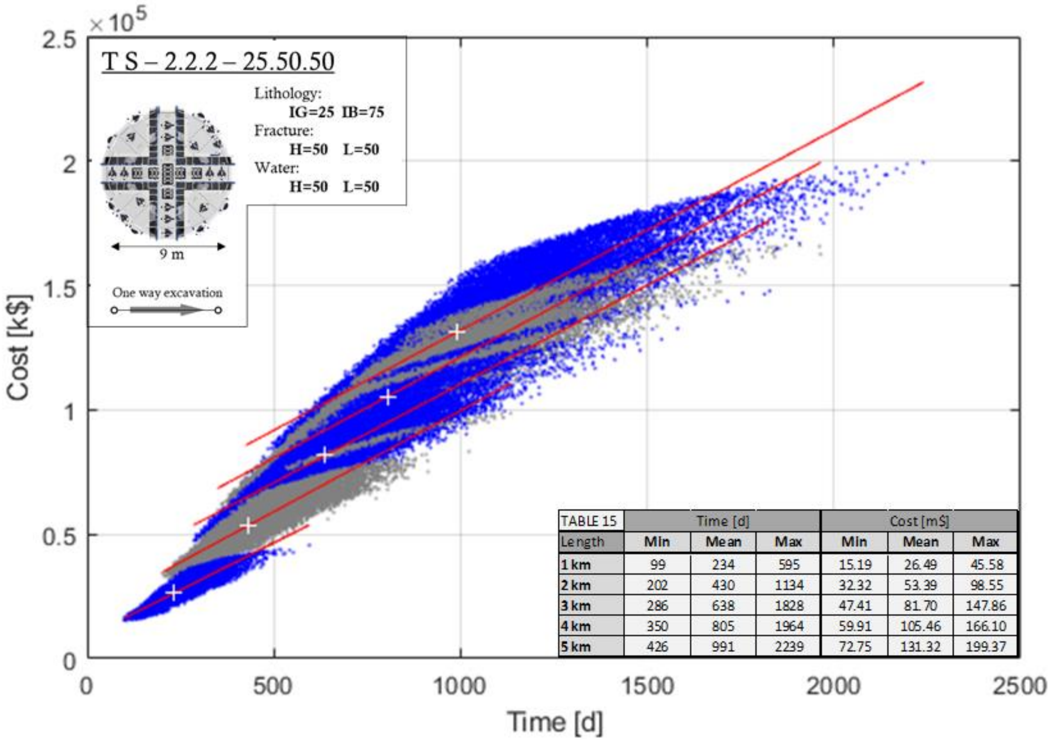


TABLE 15	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	99	234	595	15.19	26.49	45.58
2 km	202	430	1134	32.32	53.39	98.55
3 km	286	638	1828	47.41	81.70	147.86
4 km	350	805	1964	59.91	105.46	166.10
5 km	426	991	2239	72.75	131.32	199.37

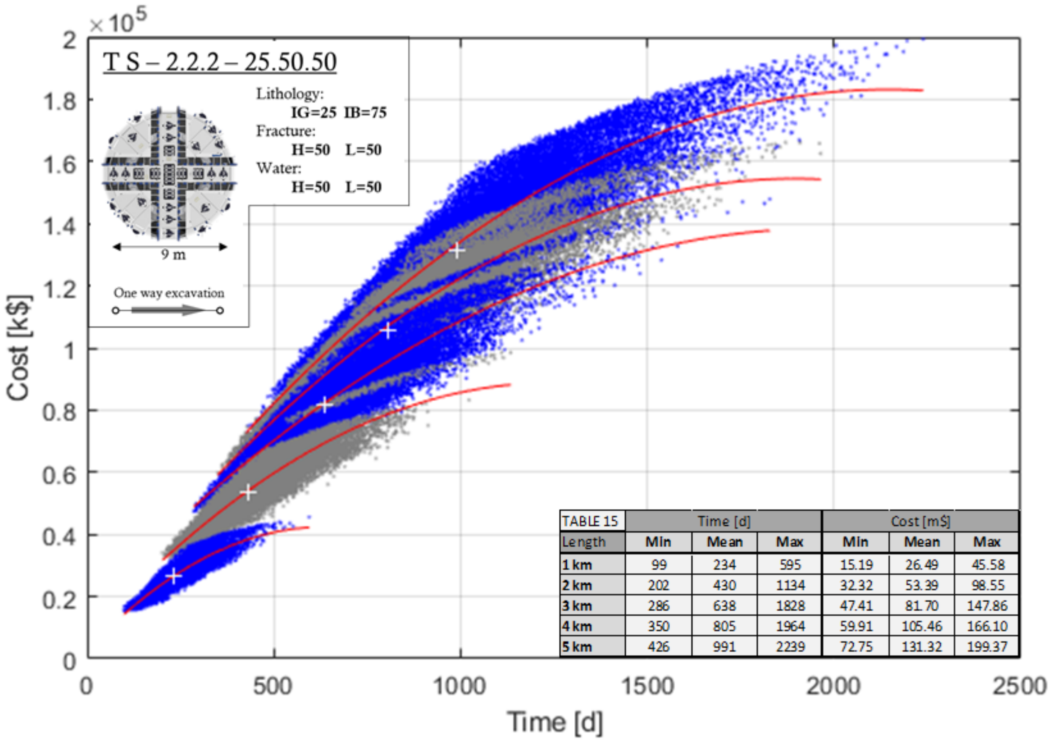


TABLE 15	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	99	234	595	15.19	26.49	45.58
2 km	202	430	1134	32.32	53.39	98.55
3 km	286	638	1828	47.41	81.70	147.86
4 km	350	805	1964	59.91	105.46	166.10
5 km	426	991	2239	72.75	131.32	199.37

TABLE 16

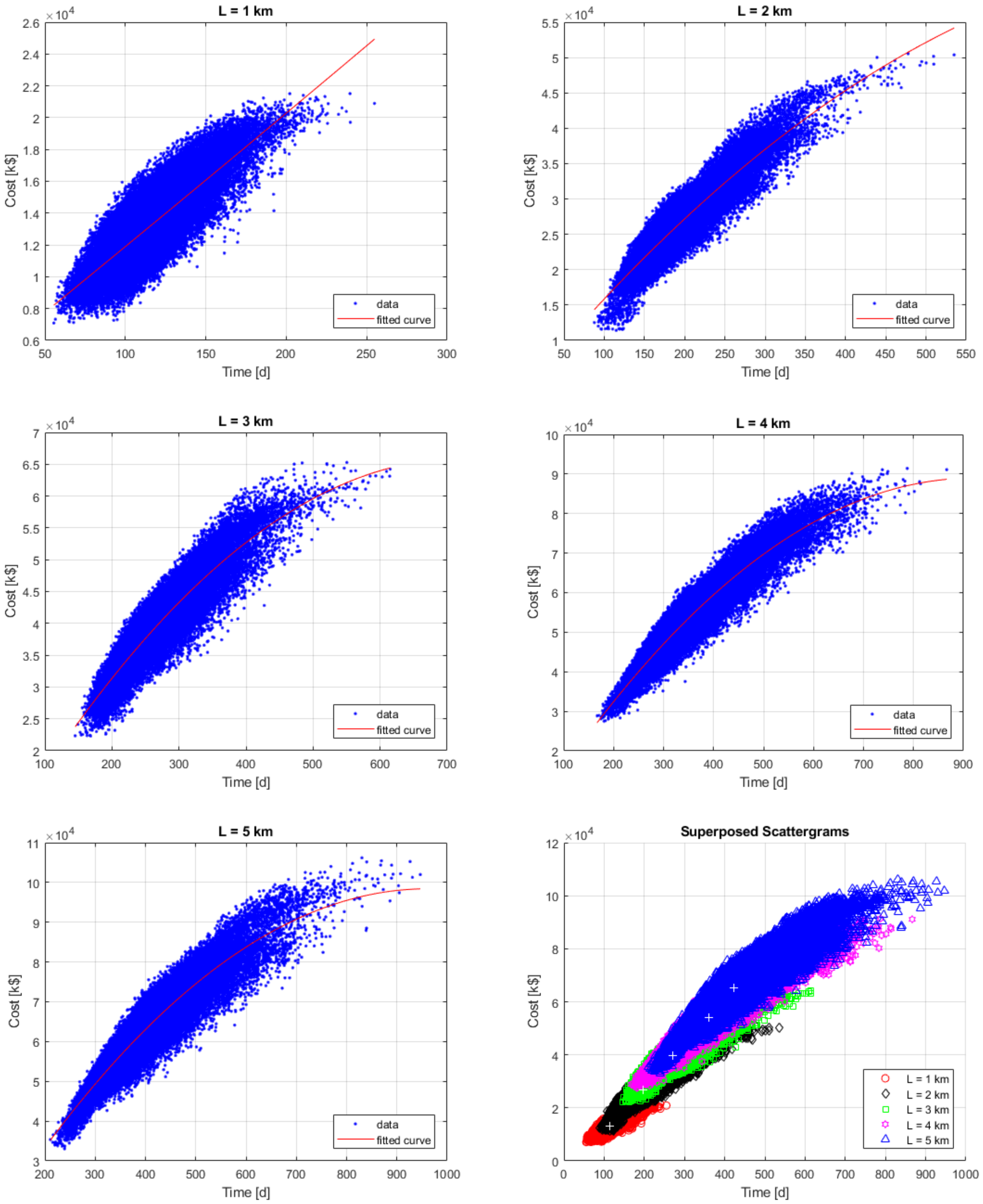


TABLE 16	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	56	114	255	7.09	13.09	21.51
2 km	88	198	535	11.42	26.80	50.54
3 km	145	270	615	22.30	39.65	65.28
4 km	167	360	866	27.49	53.91	91.42
5 km	211	423	947	33.04	65.14	106.18

TABLE 16

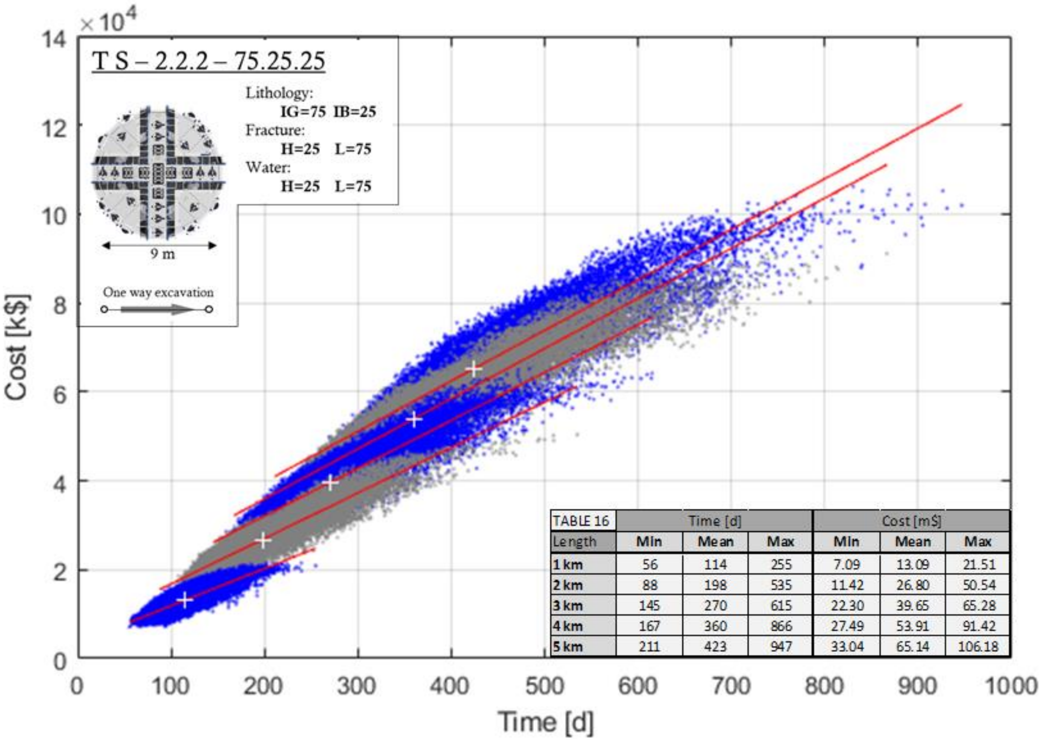


TABLE 16	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	56	114	255	7.09	13.09	21.51
2 km	88	198	535	11.42	26.80	50.54
3 km	145	270	615	22.30	39.65	65.28
4 km	167	360	866	27.49	53.91	91.42
5 km	211	423	947	33.04	65.14	106.18

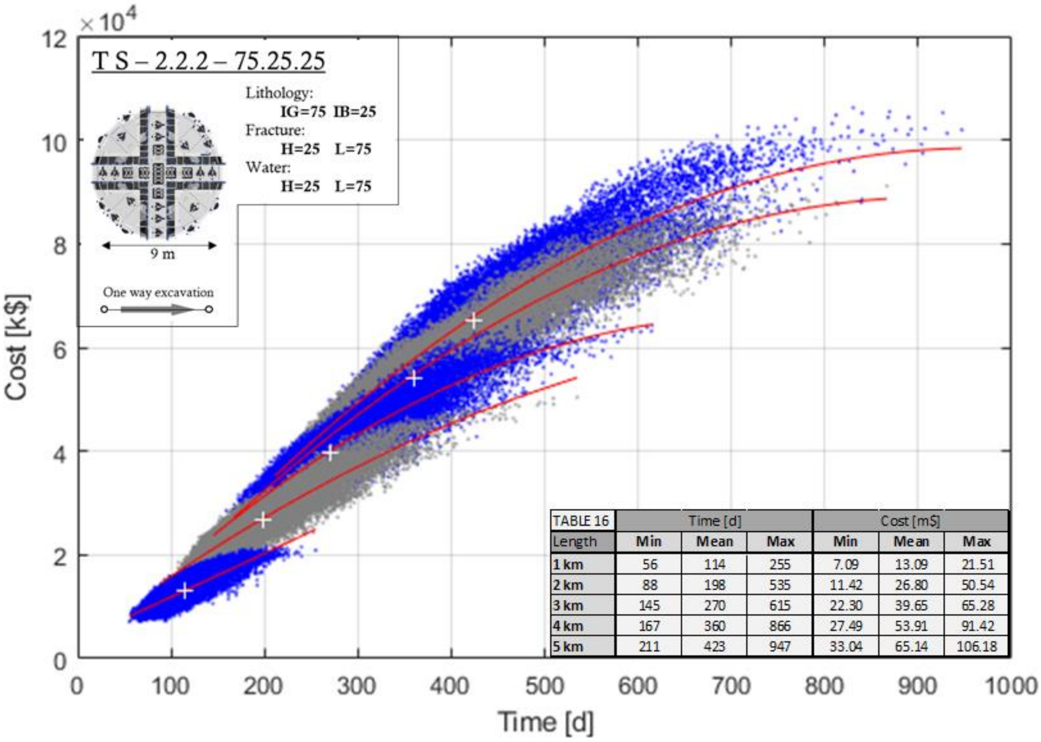


TABLE 16	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	56	114	255	7.09	13.09	21.51
2 km	88	198	535	11.42	26.80	50.54
3 km	145	270	615	22.30	39.65	65.28
4 km	167	360	866	27.49	53.91	91.42
5 km	211	423	947	33.04	65.14	106.18

TABLE 17

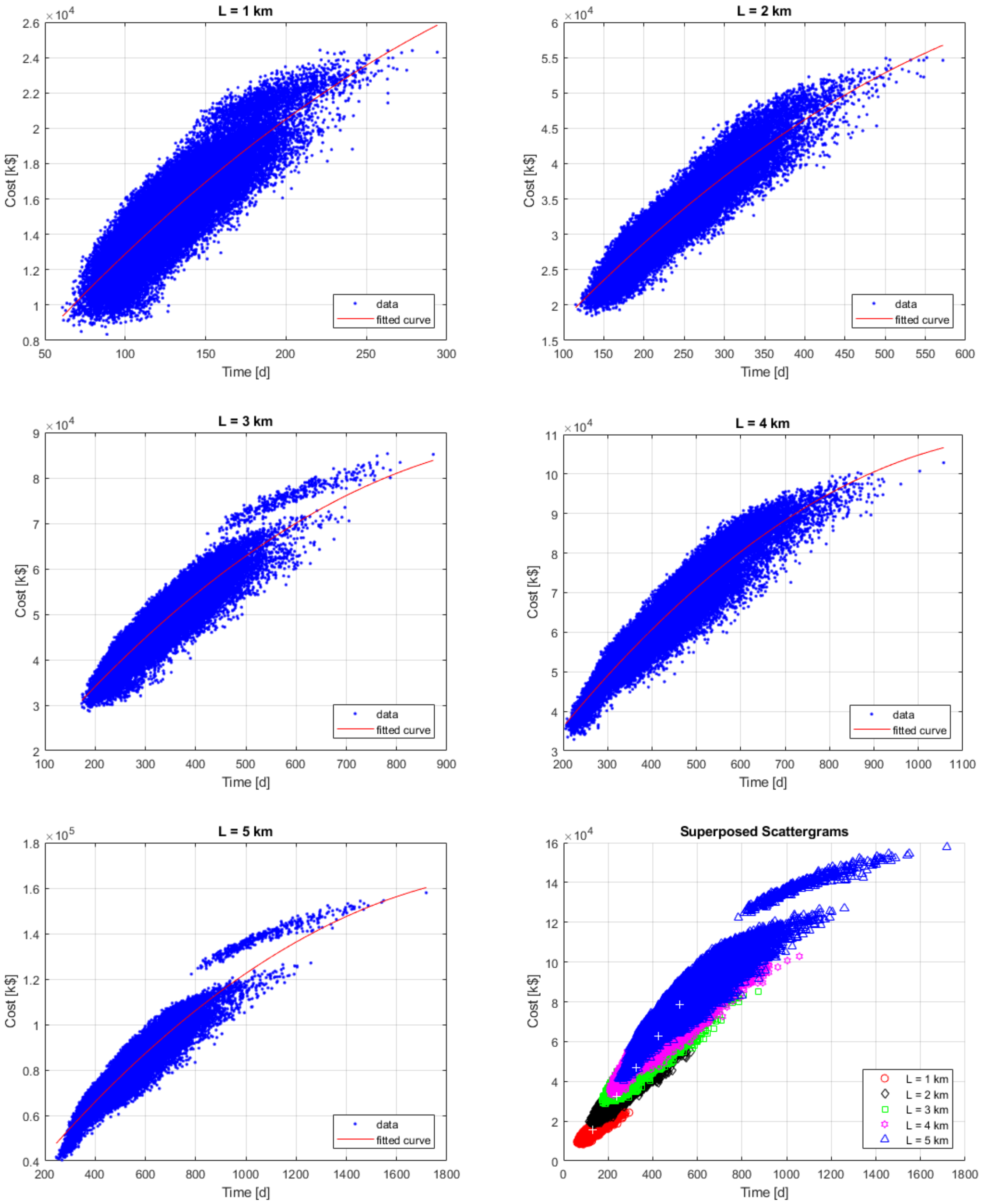


TABLE 17	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	61	132	294	8.34	15.48	24.42
2 km	115	237	572	18.50	32.23	54.98
3 km	173	324	873	28.68	46.95	85.32
4 km	206	425	1057	32.88	62.79	102.85
5 km	246	520	1718	40.39	78.58	157.96

TABLE 17

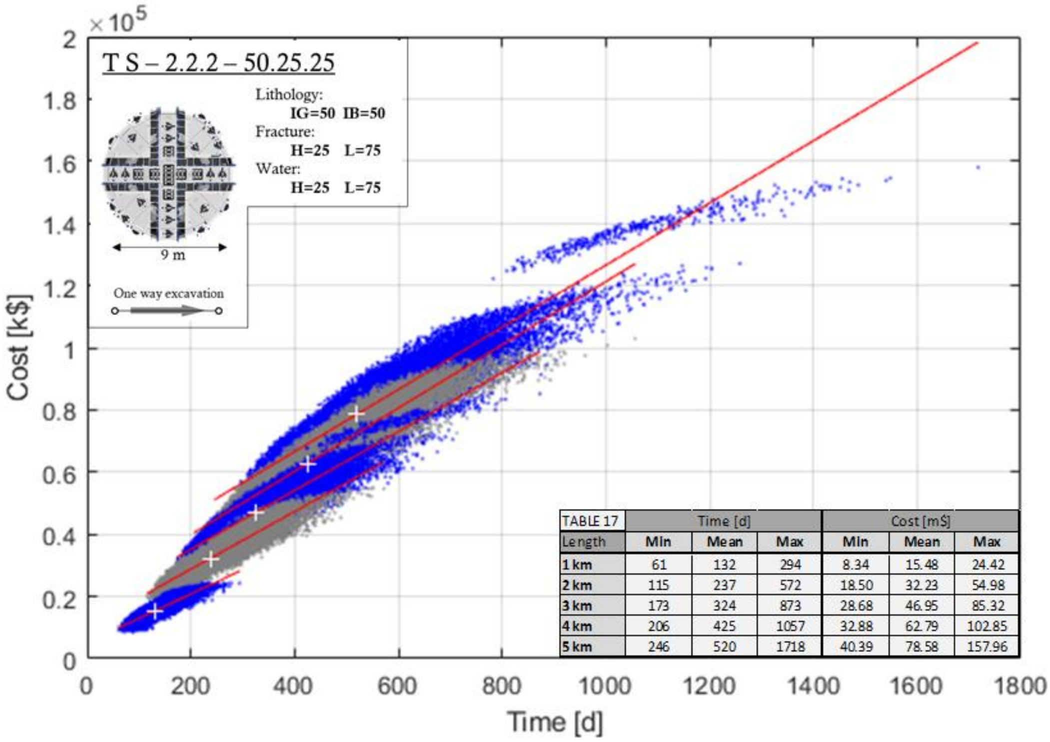


TABLE 17	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	61	132	294	8.34	15.48	24.42
2 km	115	237	572	18.50	32.23	54.98
3 km	173	324	873	28.68	46.95	85.32
4 km	206	425	1057	32.88	62.79	102.85
5 km	246	520	1718	40.39	78.58	157.96

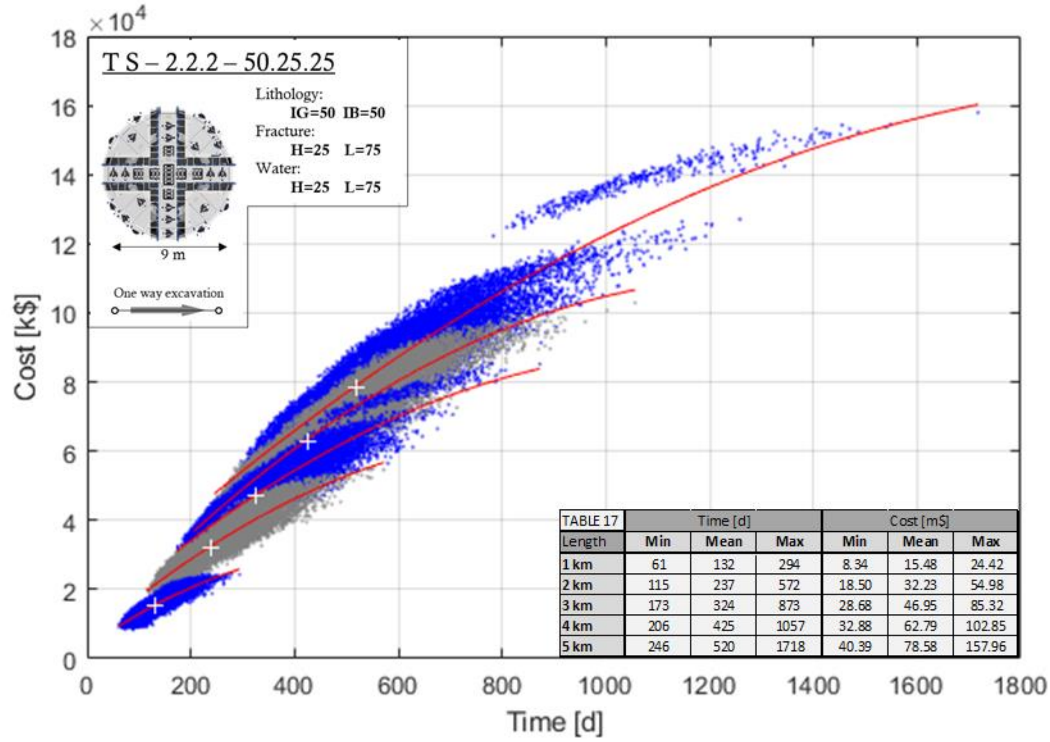


TABLE 17	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	61	132	294	8.34	15.48	24.42
2 km	115	237	572	18.50	32.23	54.98
3 km	173	324	873	28.68	46.95	85.32
4 km	206	425	1057	32.88	62.79	102.85
5 km	246	520	1718	40.39	78.58	157.96

TABLE 18

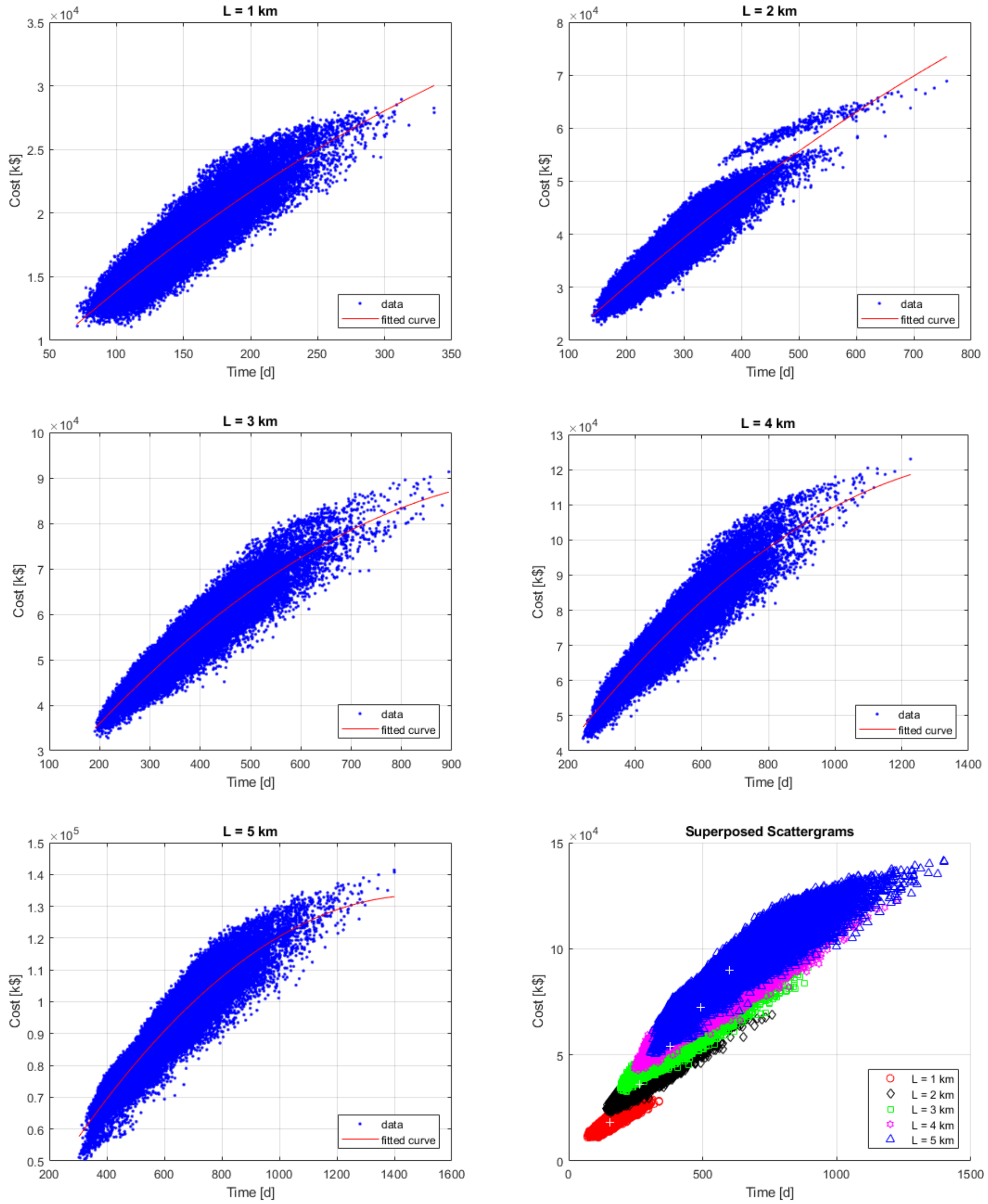
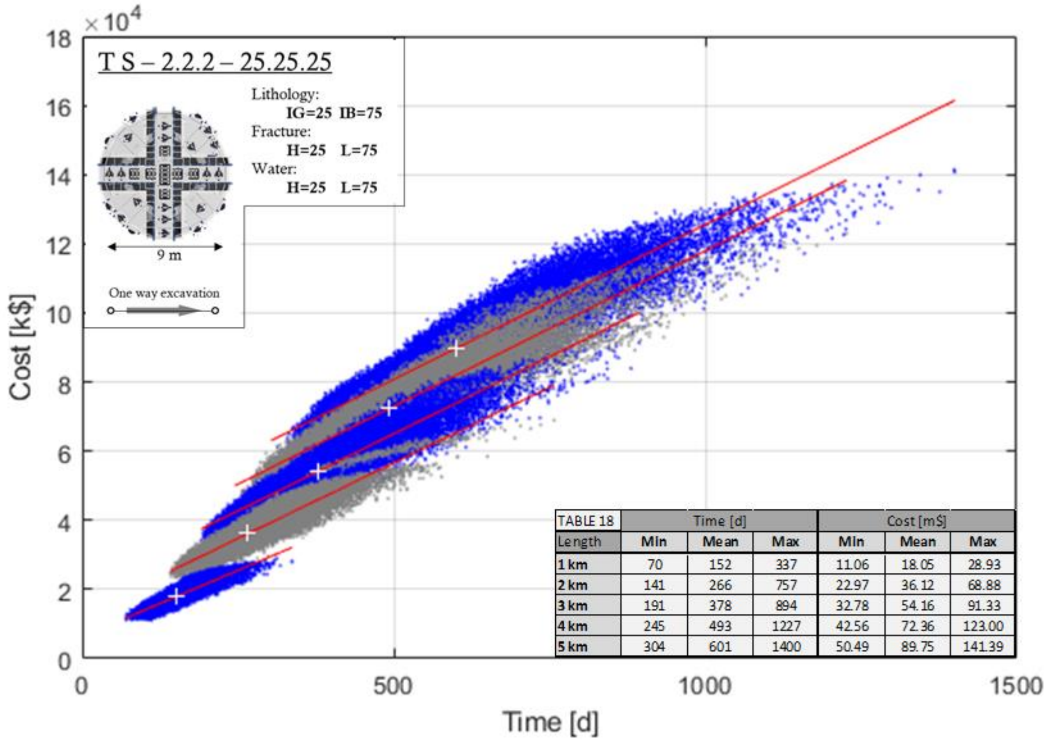
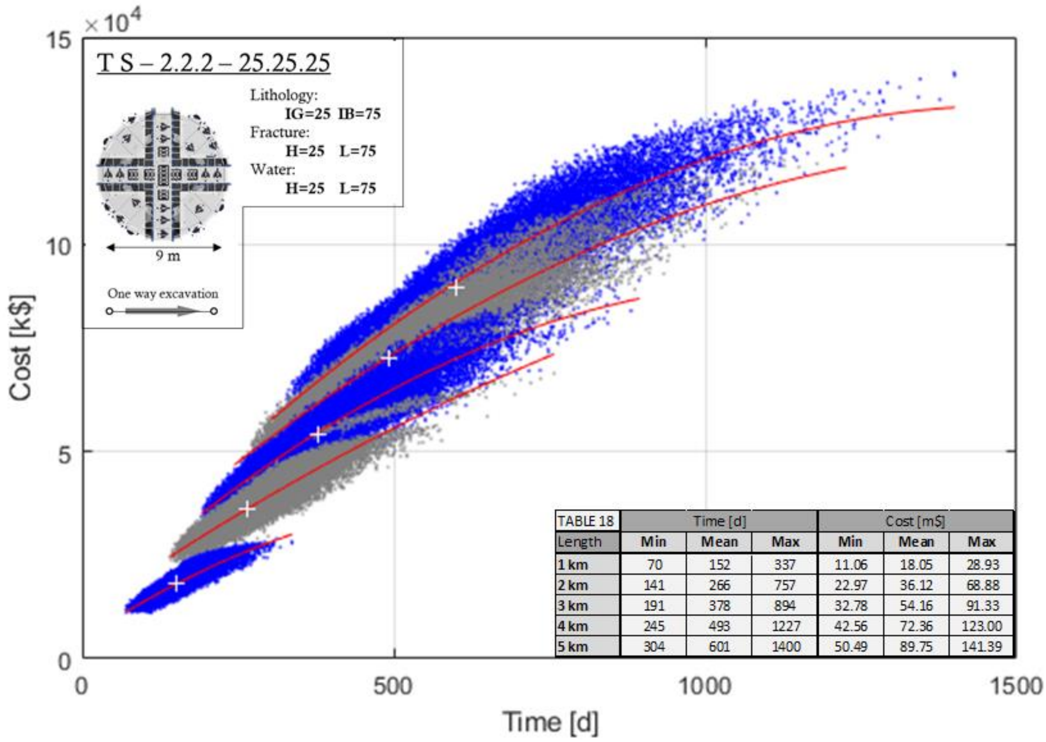


TABLE 18	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	70	152	337	11.06	18.05	28.93
2 km	141	266	757	22.97	36.12	68.88
3 km	191	378	894	32.78	54.16	91.33
4 km	245	493	1227	42.56	72.36	123.00
5 km	304	601	1400	50.49	89.75	141.39

TABLE 18



×10^4
T S – 2.2.2 – 25.25.25
Lithology:
IG=25 IB=75
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
Cost [k$]
Time [d]
0
2
4
6
8
10
12
14
16
18
0
500
1000
1500
TABLE 18 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 70 | 152 | 337 | 11.06 | 18.05 | 28.93
2 km | 141 | 266 | 757 | 22.97 | 36.12 | 68.88
3 km | 191 | 378 | 894 | 32.78 | 54.16 | 91.33
4 km | 245 | 493 | 1227 | 42.56 | 72.36 | 123.00
5 km | 304 | 601 | 1400 | 50.49 | 89.75 | 141.39



×10^4
T S – 2.2.2 – 25.25.25
Lithology:
IG=25 IB=75
Fracture:
H=25 L=75
Water:
H=25 L=75
9 m
One way excavation
Cost [k$]
Time [d]
0
5
10
15
0
500
1000
1500
TABLE 18 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 70 | 152 | 337 | 11.06 | 18.05 | 28.93
2 km | 141 | 266 | 757 | 22.97 | 36.12 | 68.88
3 km | 191 | 378 | 894 | 32.78 | 54.16 | 91.33
4 km | 245 | 493 | 1227 | 42.56 | 72.36 | 123.00
5 km | 304 | 601 | 1400 | 50.49 | 89.75 | 141.39

TABLE 19

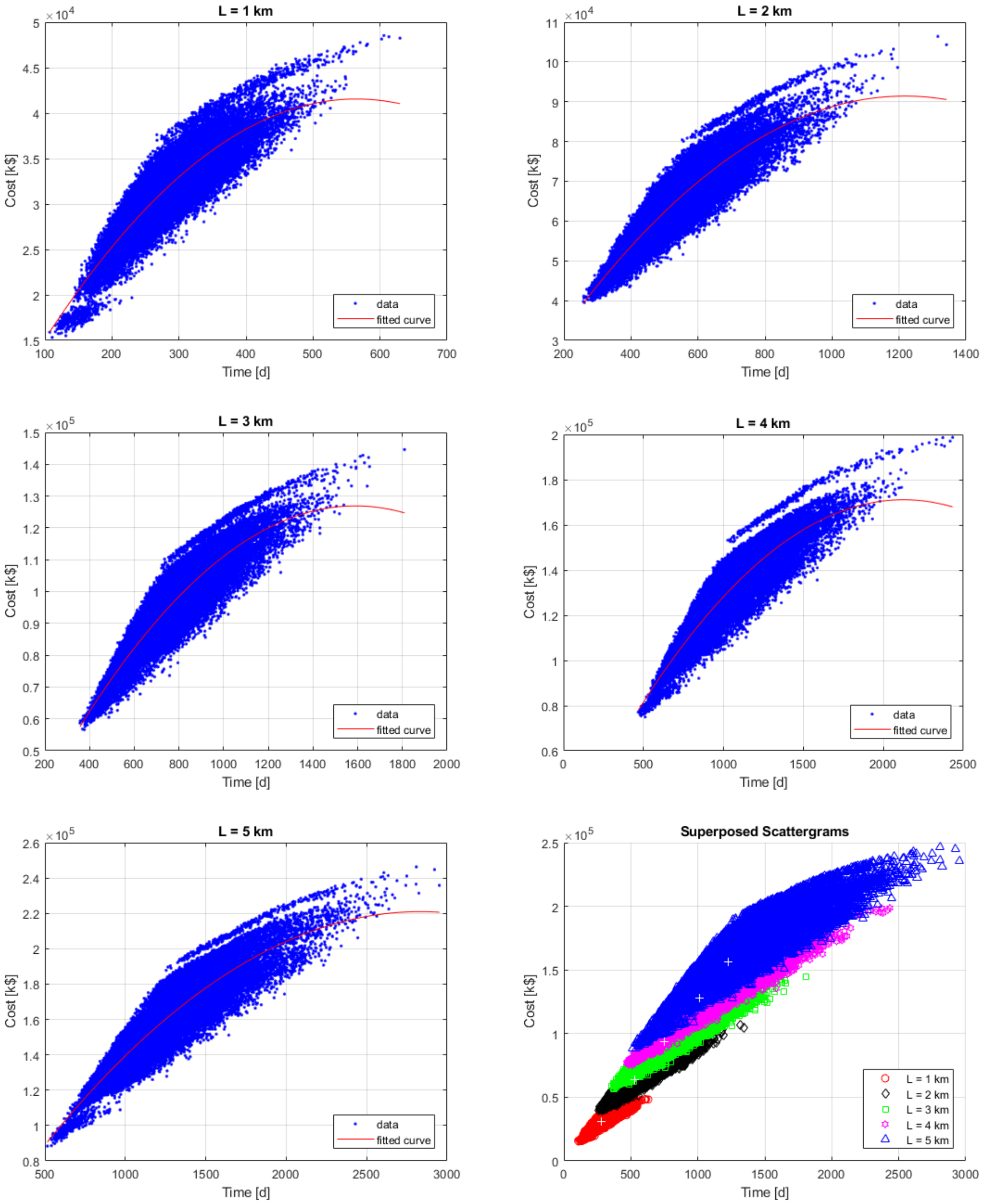
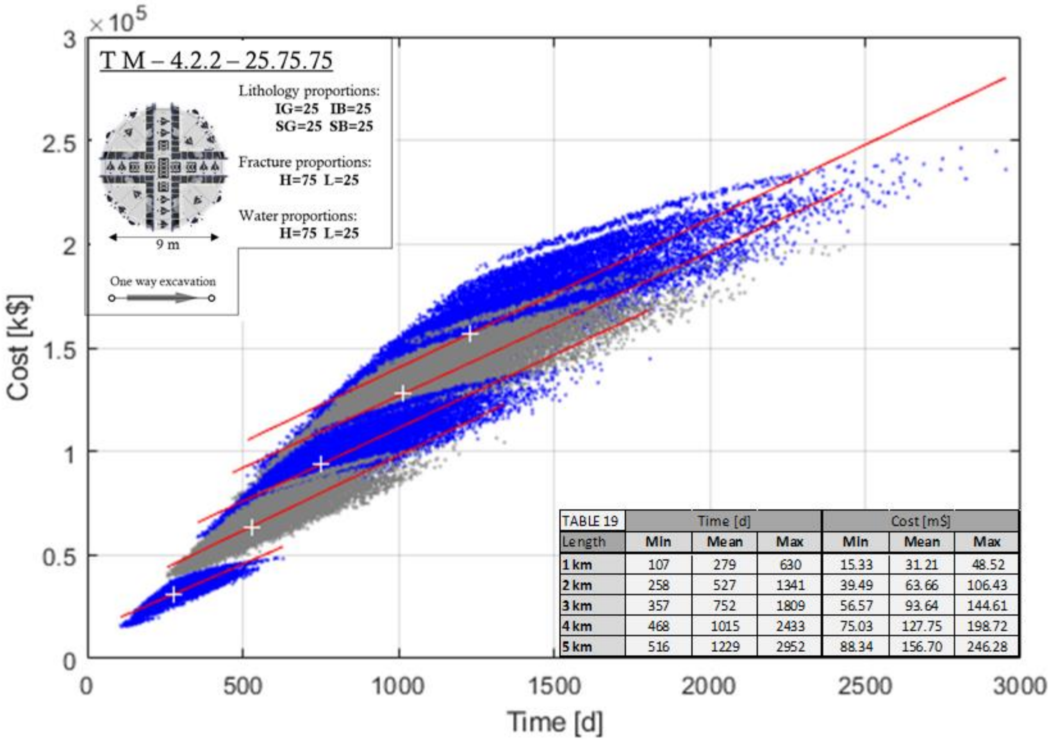


TABLE 19	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	107	279	630	15.33	31.21	48.52
2 km	258	527	1341	39.49	63.66	106.43
3 km	357	752	1809	56.57	93.64	144.61
4 km	468	1015	2433	75.03	127.75	198.72
5 km	516	1229	2952	88.34	156.70	246.28

TABLE 19


T M – 4.2.2 – 25.75.75
Lithology proportions:
IG=25 IB=25
SG=25 SB=25
Fracture proportions:
H=75 L=25
Water proportions:
H=75 L=25
9 m
One way excavation
Cost [k$]
× 10^5
Time [d]
TABLE 19 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 107 | 279 | 630 | 15.33 | 31.21 | 48.52
2 km | 258 | 527 | 1341 | 39.49 | 63.66 | 106.43
3 km | 357 | 752 | 1809 | 56.57 | 93.64 | 144.61
4 km | 468 | 1015 | 2433 | 75.03 | 127.75 | 198.72
5 km | 516 | 1229 | 2952 | 88.34 | 156.70 | 246.28

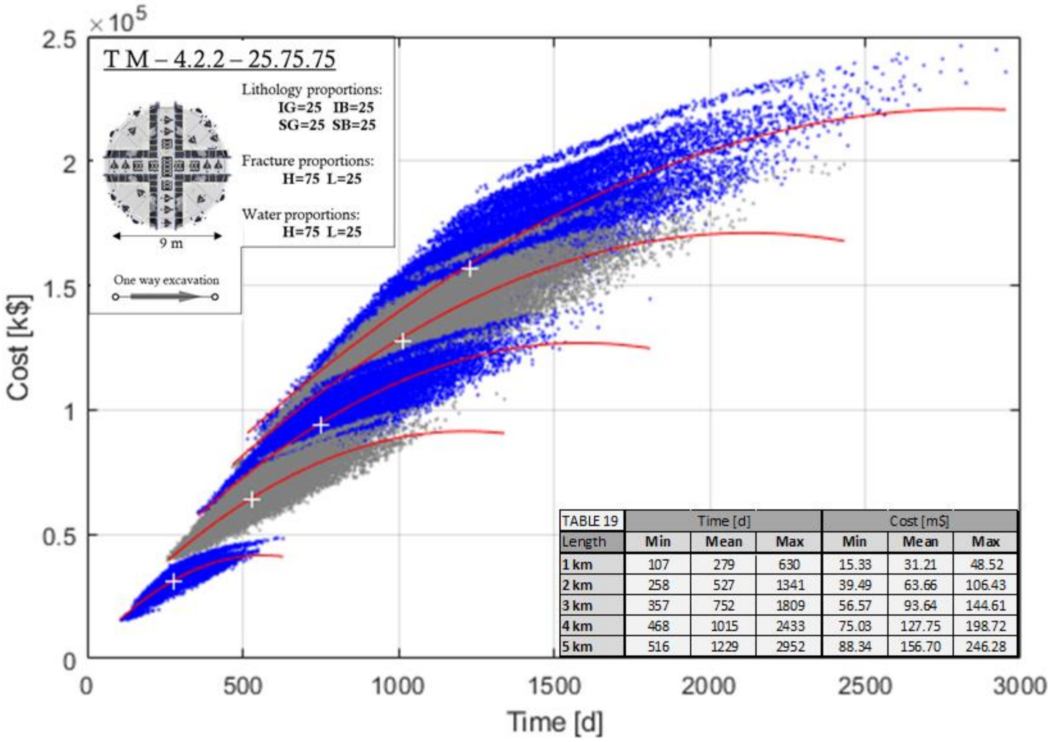

T M – 4.2.2 – 25.75.75
Lithology proportions:
IG=25 IB=25
SG=25 SB=25
Fracture proportions:
H=75 L=25
Water proportions:
H=75 L=25
9 m
One way excavation
Cost [k$]
× 10^5
Time [d]
TABLE 19 | Time [d] | Cost [m$]
Length | Min | Mean | Max | Min | Mean | Max
1 km | 107 | 279 | 630 | 15.33 | 31.21 | 48.52
2 km | 258 | 527 | 1341 | 39.49 | 63.66 | 106.43
3 km | 357 | 752 | 1809 | 56.57 | 93.64 | 144.61
4 km | 468 | 1015 | 2433 | 75.03 | 127.75 | 198.72
5 km | 516 | 1229 | 2952 | 88.34 | 156.70 | 246.28

TABLE 20

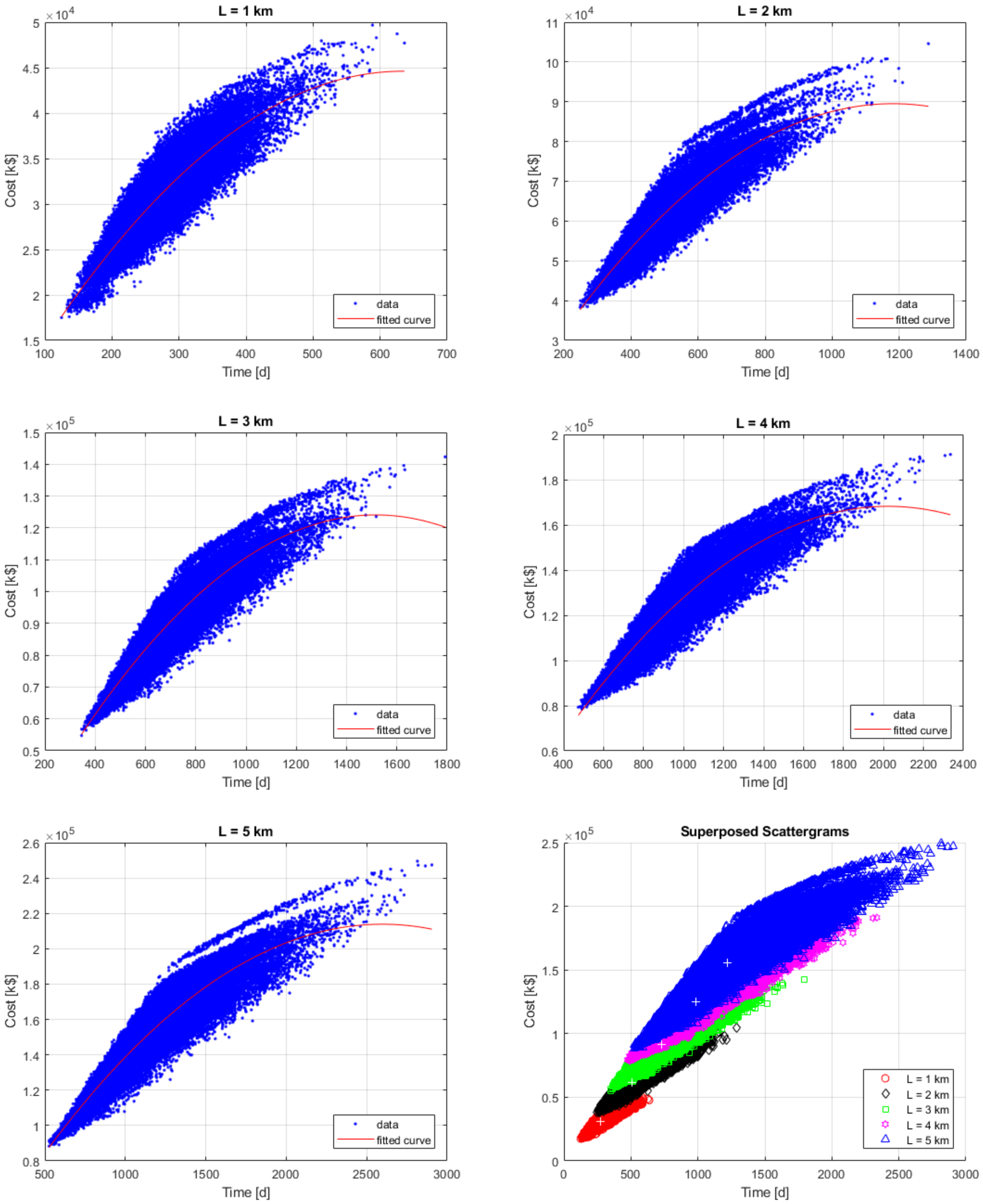


TABLE 20	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	125	275	636	17.50	30.82	49.68
2 km	248	510	1287	38.33	61.88	104.59
3 km	346	731	1792	54.73	91.72	142.31
4 km	474	985	2335	78.47	124.68	191.18
5 km	526	1217	2904	88.30	155.32	249.53

TABLE 20

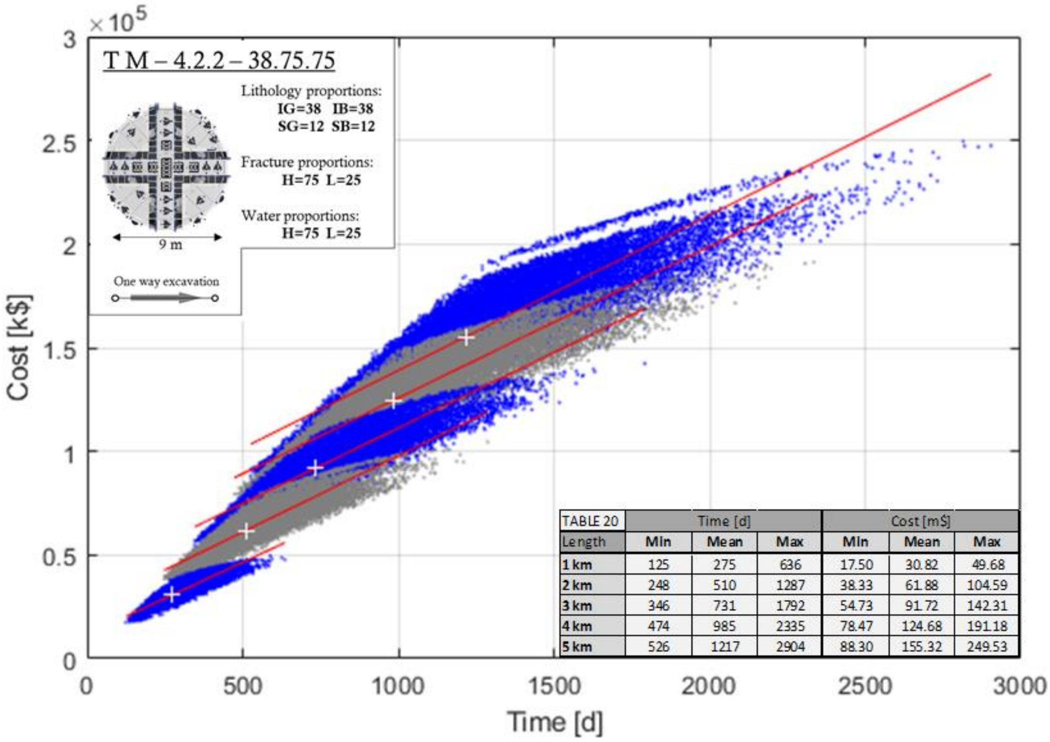


TABLE 20	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	125	275	636	17.50	30.82	49.68
2 km	248	510	1287	38.33	61.88	104.59
3 km	346	731	1792	54.73	91.72	142.31
4 km	474	985	2335	78.47	124.68	191.18
5 km	526	1217	2904	88.30	155.32	249.53

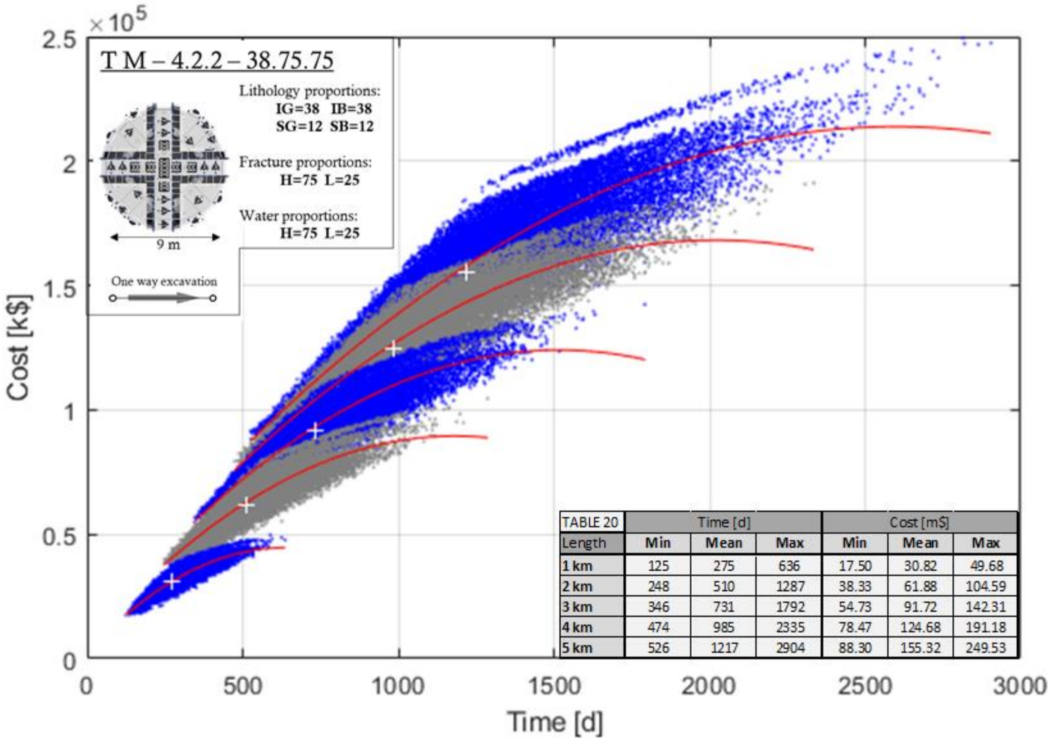


TABLE 20	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	125	275	636	17.50	30.82	49.68
2 km	248	510	1287	38.33	61.88	104.59
3 km	346	731	1792	54.73	91.72	142.31
4 km	474	985	2335	78.47	124.68	191.18
5 km	526	1217	2904	88.30	155.32	249.53

TABLE 21

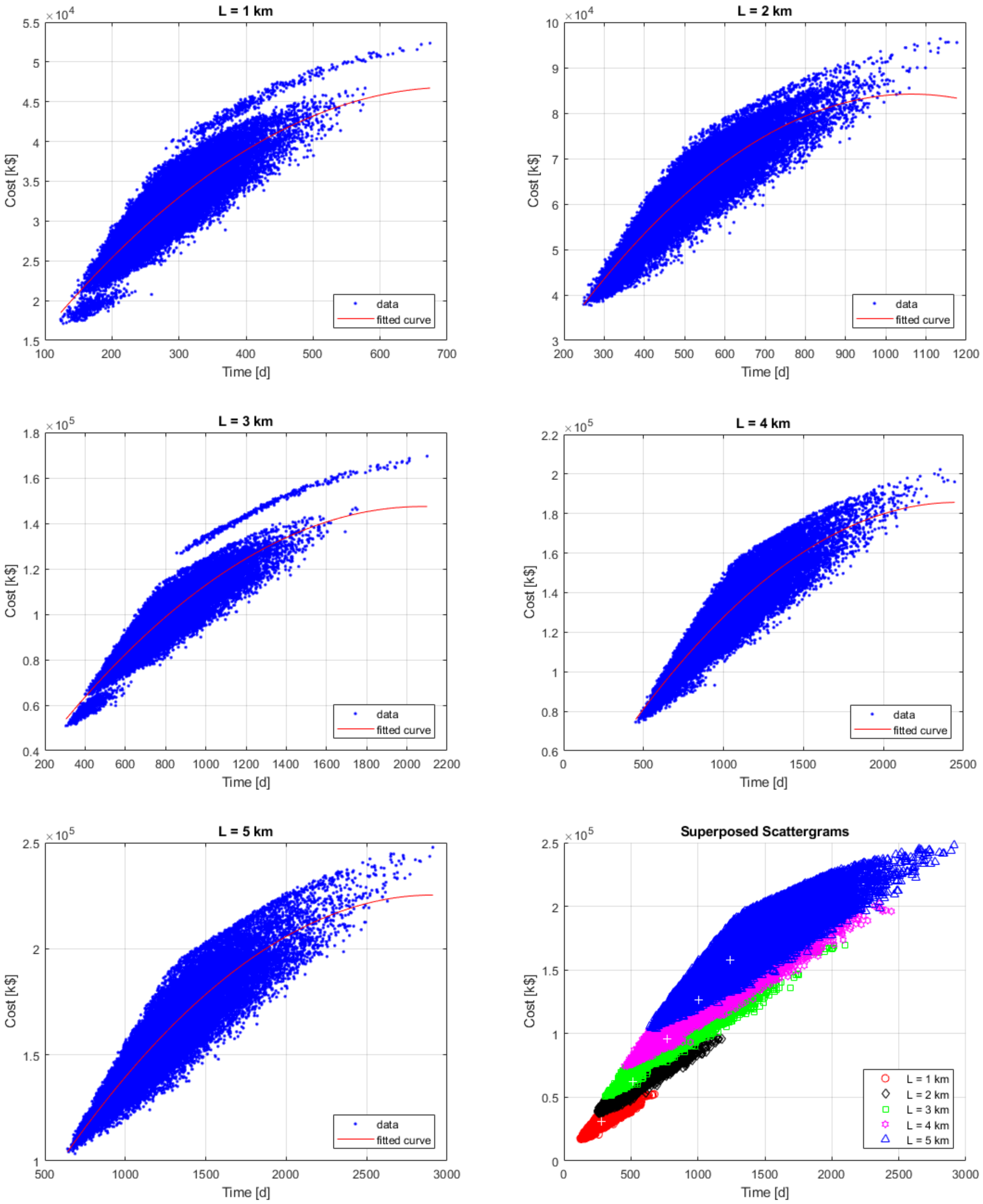


TABLE 21	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	124	279	674	17.12	31.24	52.36
2 km	249	514	1177	37.68	62.30	96.35
3 km	305	773	2100	50.93	95.84	169.54
4 km	451	1006	2445	74.43	126.69	202.27
5 km	641	1241	2911	103.39	157.92	247.75

TABLE 21

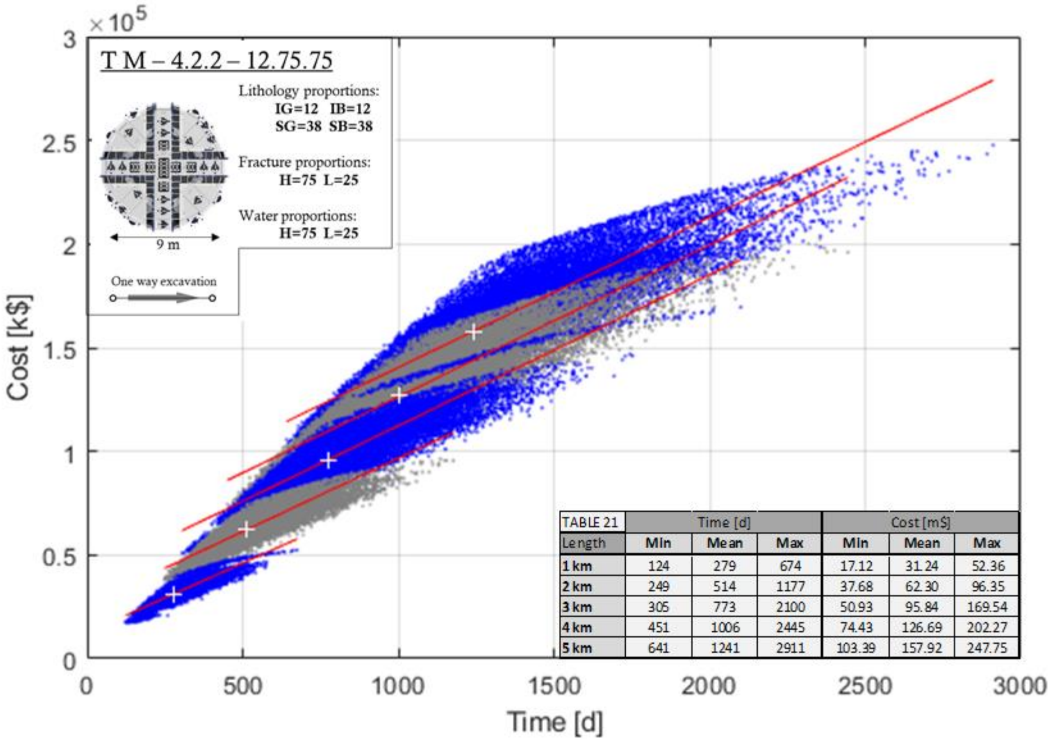


TABLE 21	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	124	279	674	17.12	31.24	52.36
2 km	249	514	1177	37.68	62.30	96.35
3 km	305	773	2100	50.93	95.84	169.54
4 km	451	1006	2445	74.43	126.69	202.27
5 km	641	1241	2911	103.39	157.92	247.75

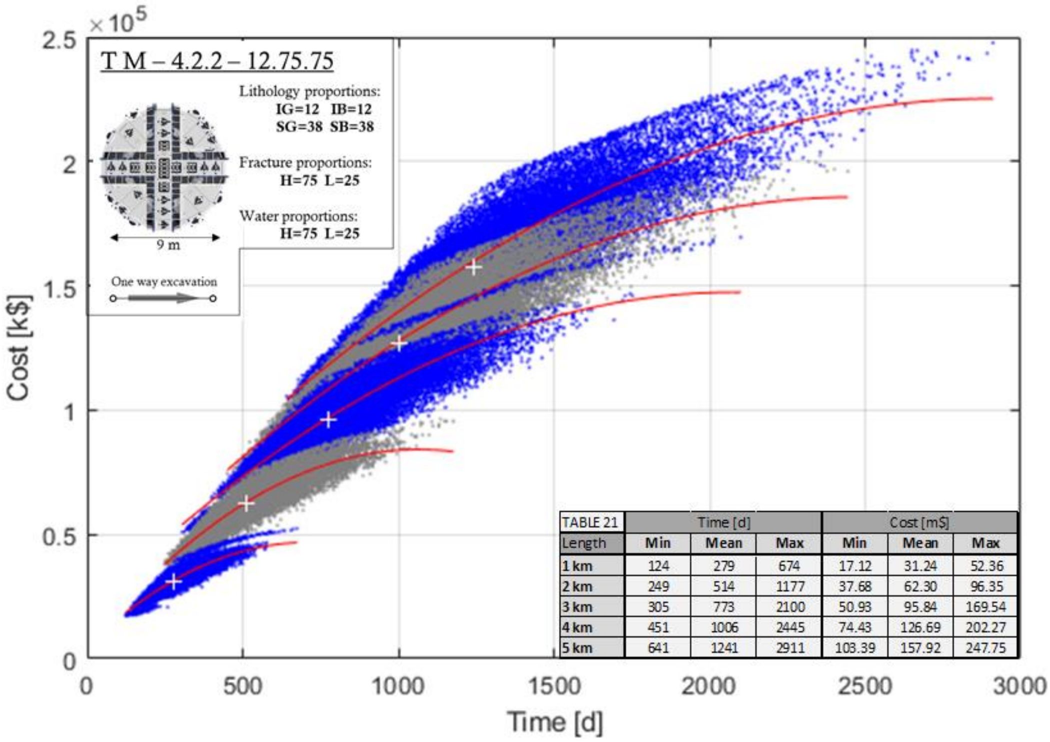


TABLE 21	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	124	279	674	17.12	31.24	52.36
2 km	249	514	1177	37.68	62.30	96.35
3 km	305	773	2100	50.93	95.84	169.54
4 km	451	1006	2445	74.43	126.69	202.27
5 km	641	1241	2911	103.39	157.92	247.75

TABLE 22

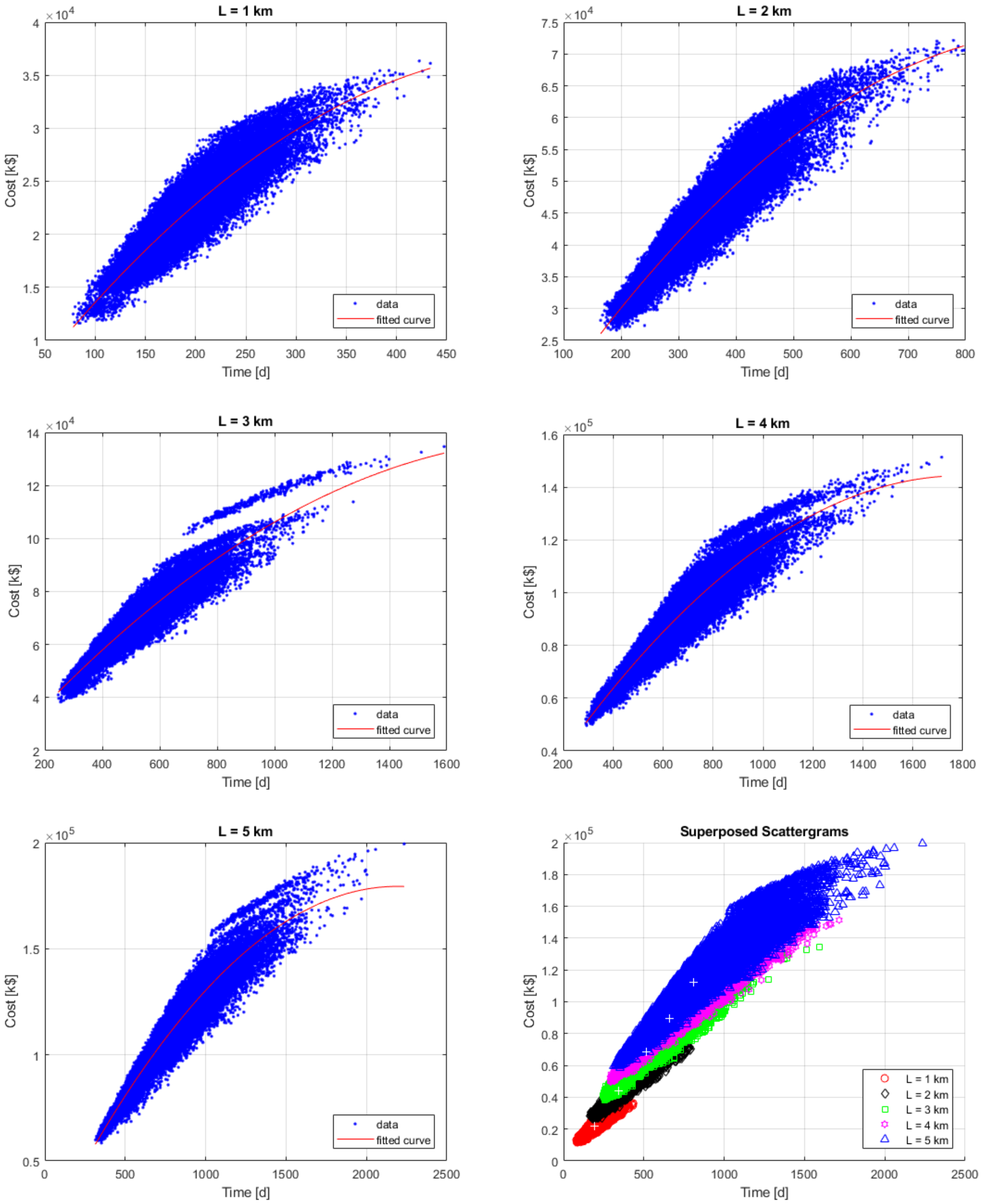


TABLE 22	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	194	434	11.62	22.12	36.35
2 km	164	344	797	26.60	44.20	72.14
3 km	247	515	1591	38.34	68.37	134.64
4 km	290	658	1715	49.58	89.56	151.38
5 km	314	811	2234	58.44	112.02	199.42

TABLE 22

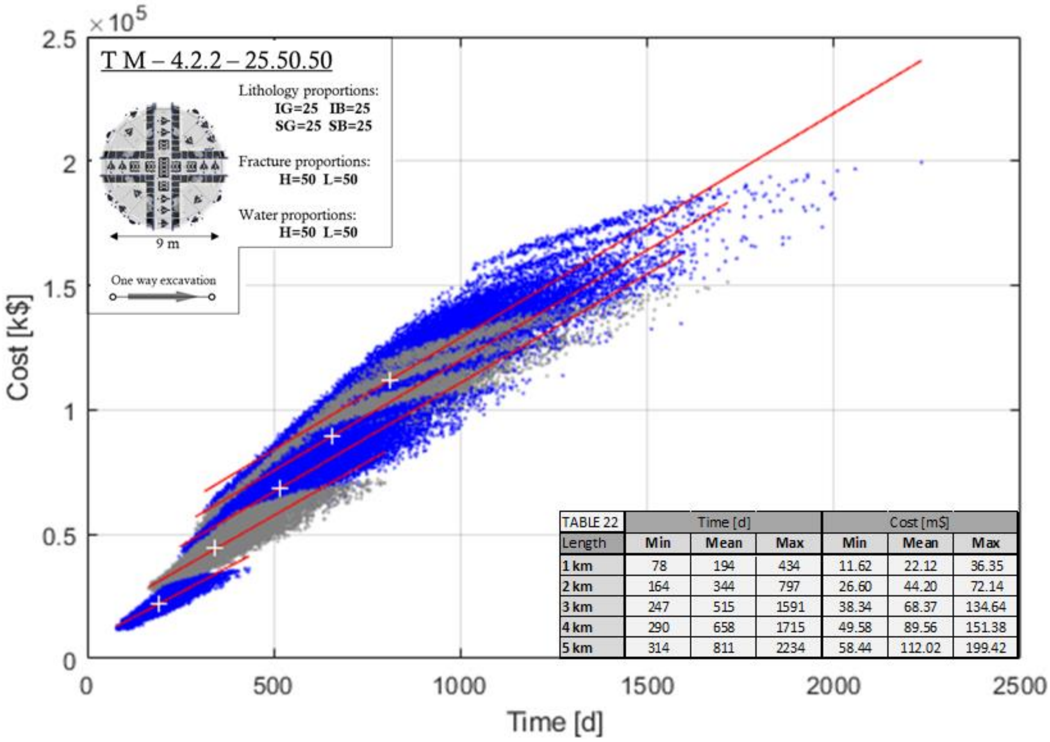


TABLE 22	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	78	194	434	11.62	22.12	36.35
2 km	164	344	797	26.60	44.20	72.14
3 km	247	515	1591	38.34	68.37	134.64
4 km	290	658	1715	49.58	89.56	151.38
5 km	314	811	2234	58.44	112.02	199.42

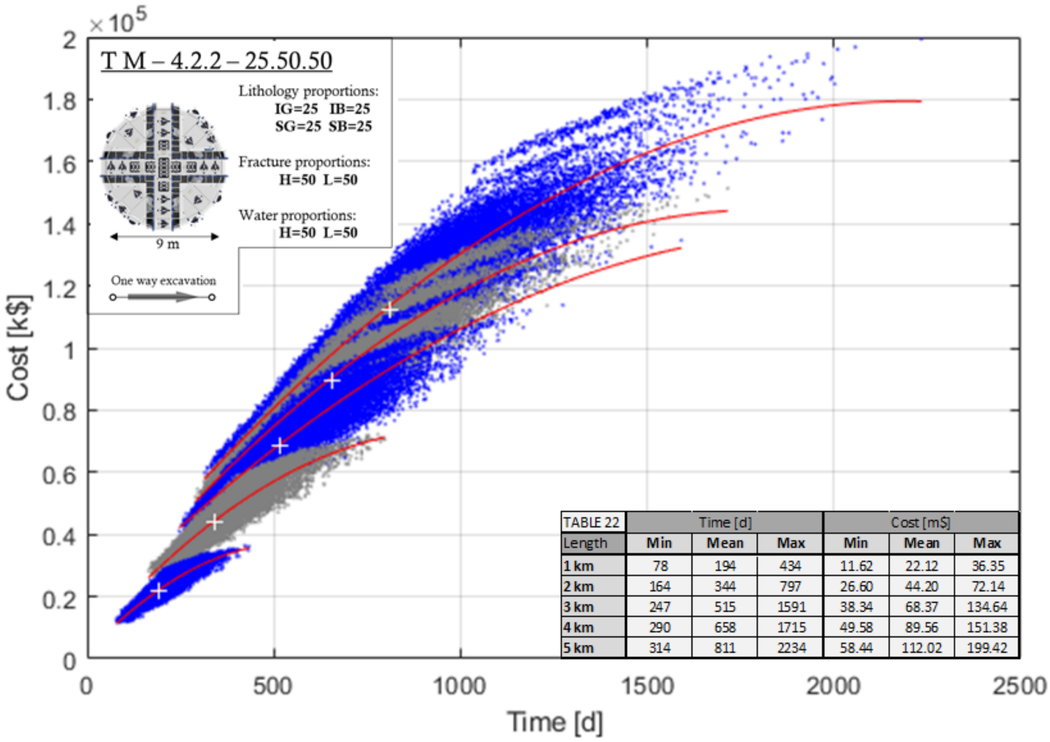


TABLE 22	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	78	194	434	11.62	22.12	36.35
2 km	164	344	797	26.60	44.20	72.14
3 km	247	515	1591	38.34	68.37	134.64
4 km	290	658	1715	49.58	89.56	151.38
5 km	314	811	2234	58.44	112.02	199.42

TABLE 23

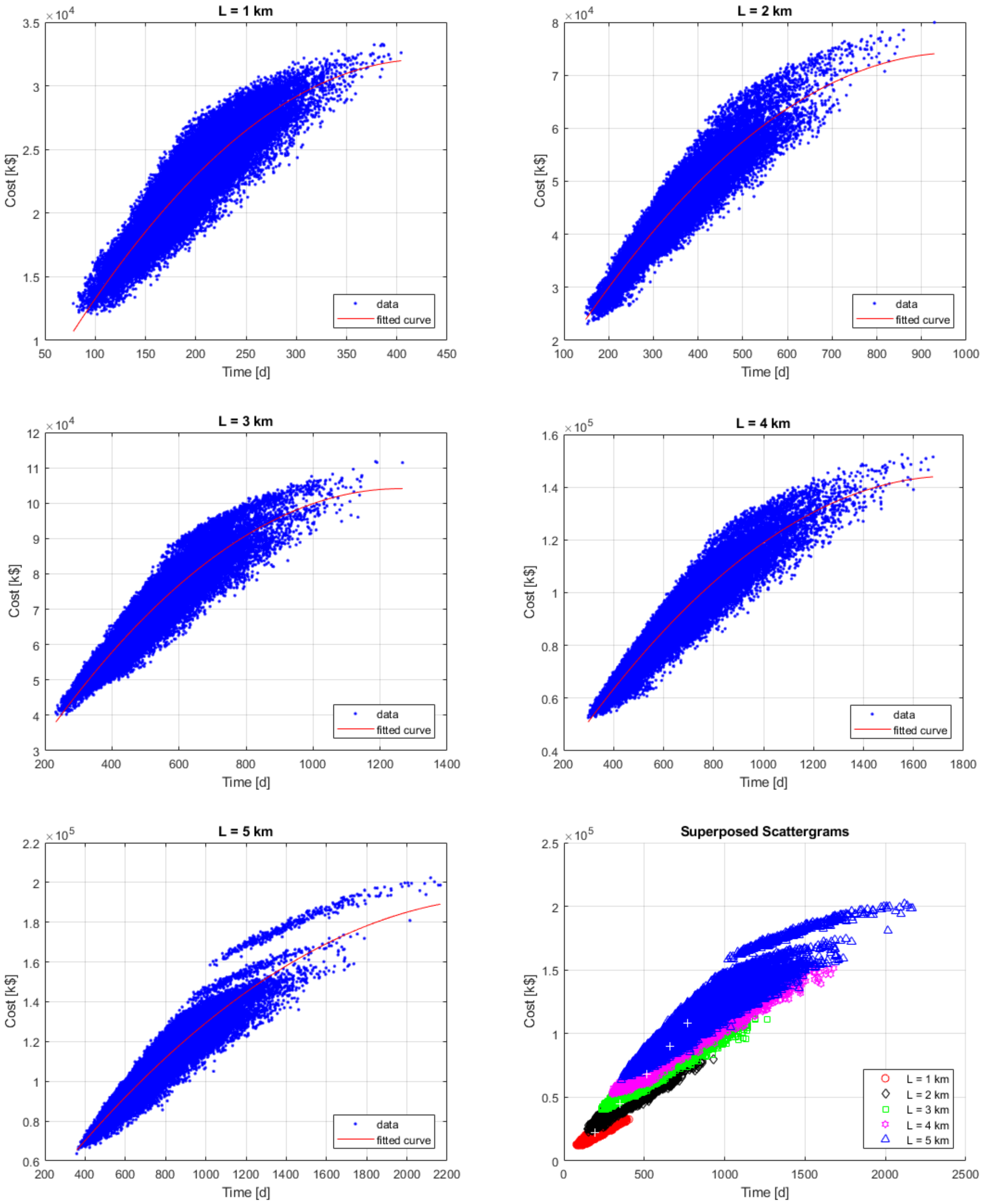


TABLE 23	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	193	404	12.06	22.10	33.27
2 km	149	347	929	23.14	44.54	79.95
3 km	233	513	1267	40.20	68.22	111.76
4 km	299	657	1679	52.58	89.77	152.35
5 km	358	769	2166	63.62	107.88	202.34

TABLE 23

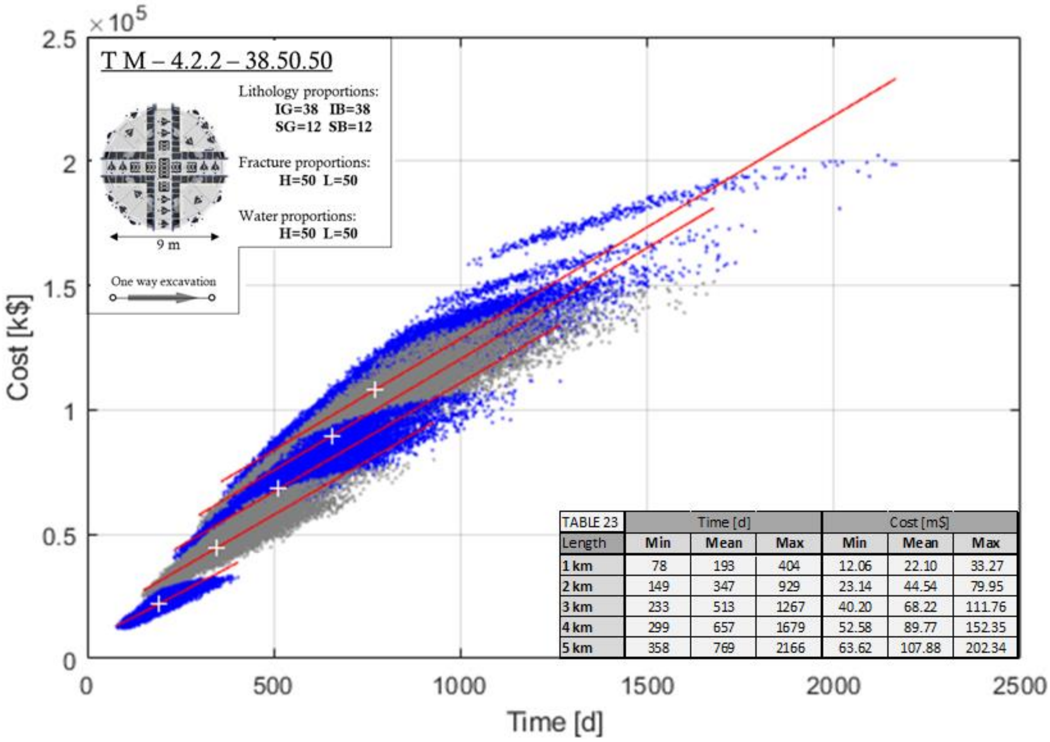


TABLE 23	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
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2 km	149	347	929	23.14	44.54	79.95
3 km	233	513	1267	40.20	68.22	111.76
4 km	299	657	1679	52.58	89.77	152.35
5 km	358	769	2166	63.62	107.88	202.34

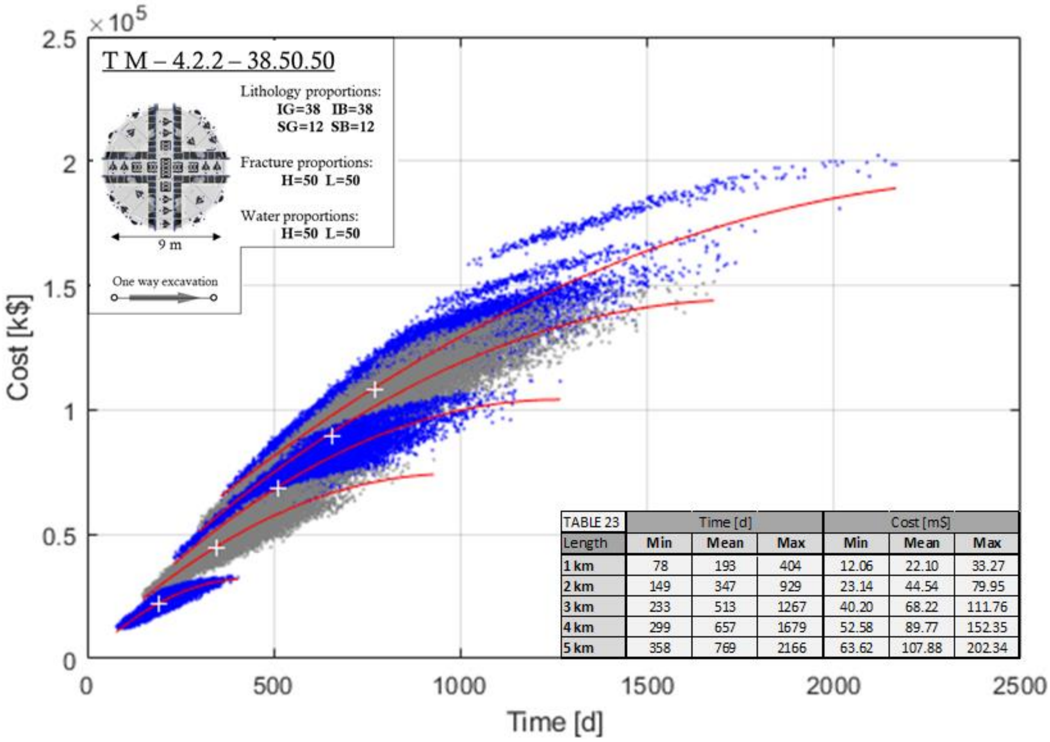

TABLE 23	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	78	193	404	12.06	22.10	33.27
2 km	149	347	929	23.14	44.54	79.95
3 km	233	513	1267	40.20	68.22	111.76
4 km	299	657	1679	52.58	89.77	152.35
5 km	358	769	2166	63.62	107.88	202.34

TABLE 24

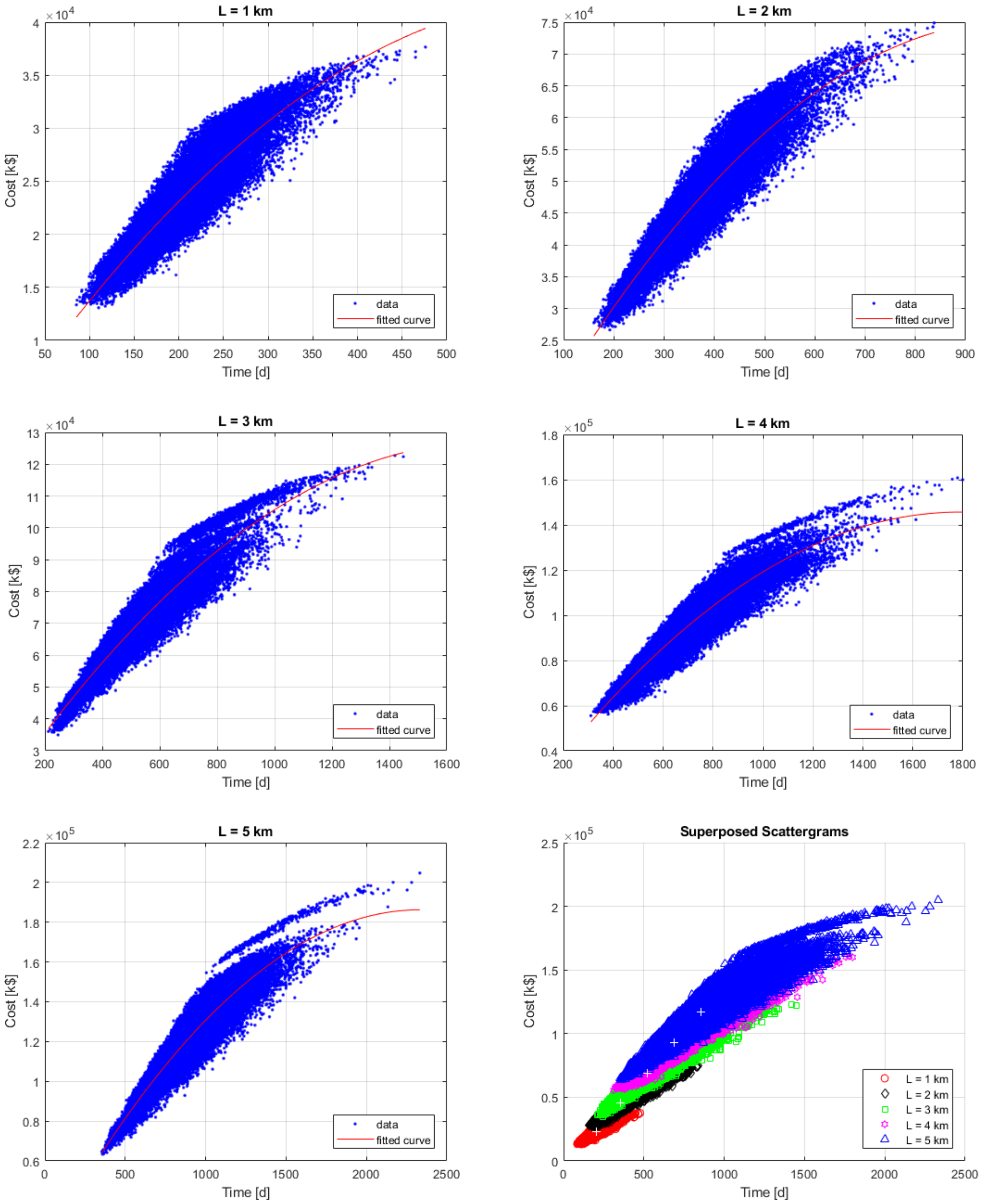

TABLE 24	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	85	203	476	13.08	23.19	37.65
2 km	160	357	838	26.64	45.60	74.88
3 km	213	522	1449	34.94	68.95	122.76
4 km	311	686	1799	55.58	92.72	160.78
5 km	354	856	2332	63.33	116.66	204.73

TABLE 24

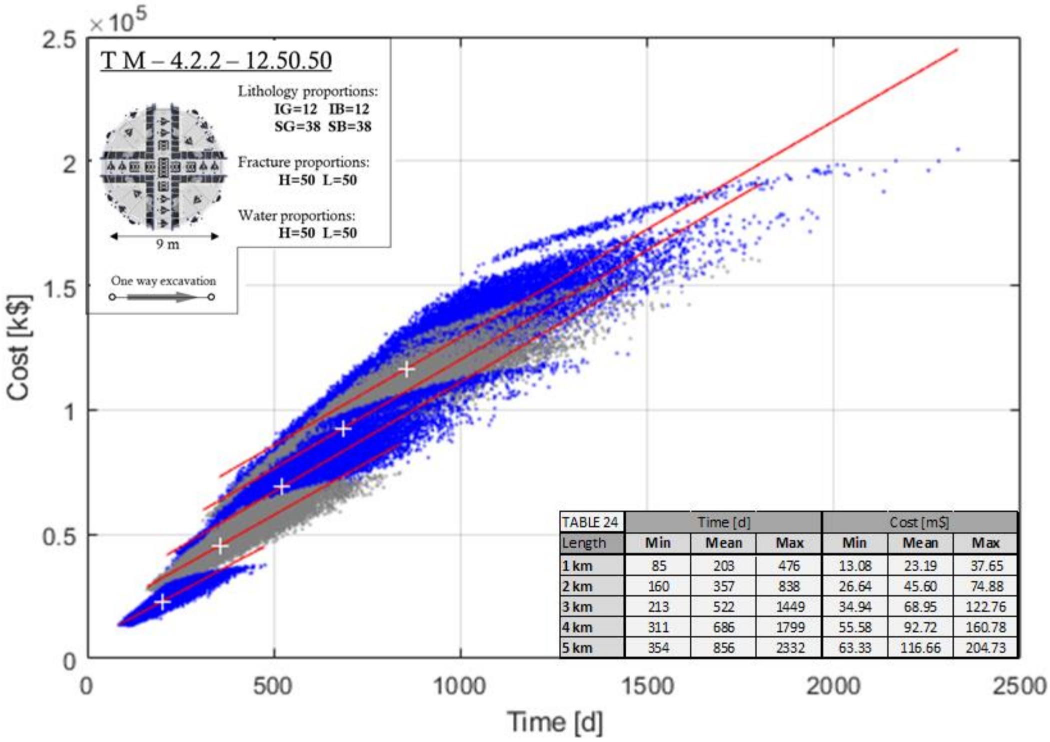

TABLE 24	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	85	203	476	13.08	23.19	37.65
2 km	160	357	838	26.64	45.60	74.88
3 km	213	522	1449	34.94	68.95	122.76
4 km	311	686	1799	55.58	92.72	160.78
5 km	354	856	2332	63.33	116.66	204.73

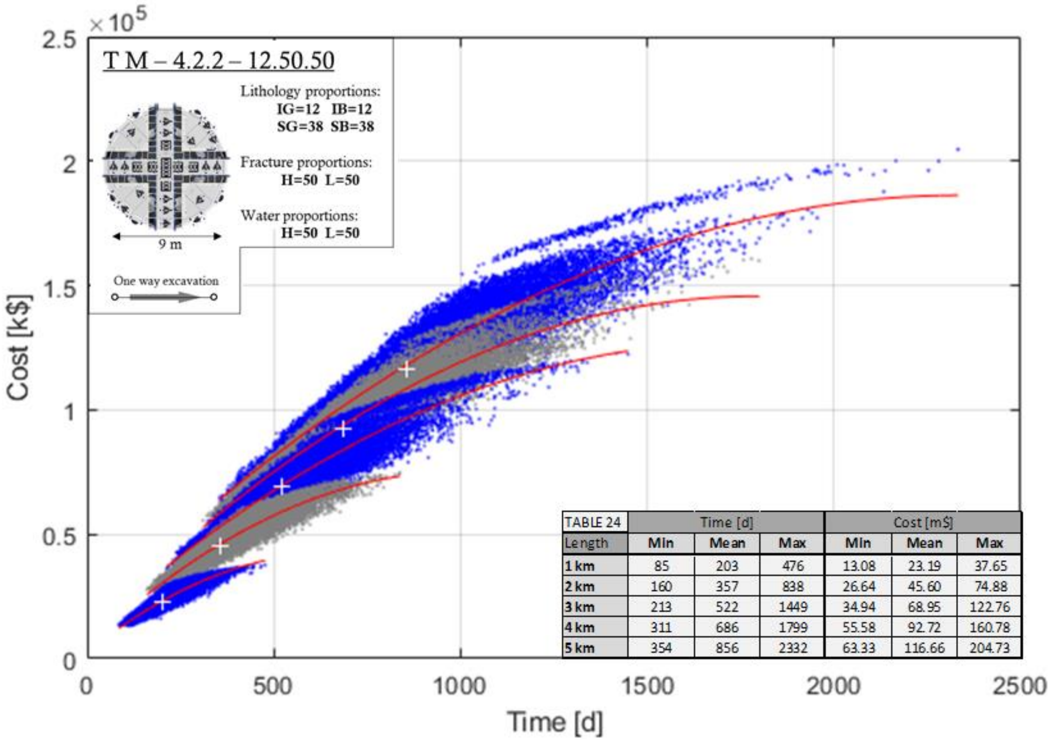

TABLE 24	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
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2 km	160	357	838	26.64	45.60	74.88
3 km	213	522	1449	34.94	68.95	122.76
4 km	311	686	1799	55.58	92.72	160.78
5 km	354	856	2332	63.33	116.66	204.73

TABLE 25

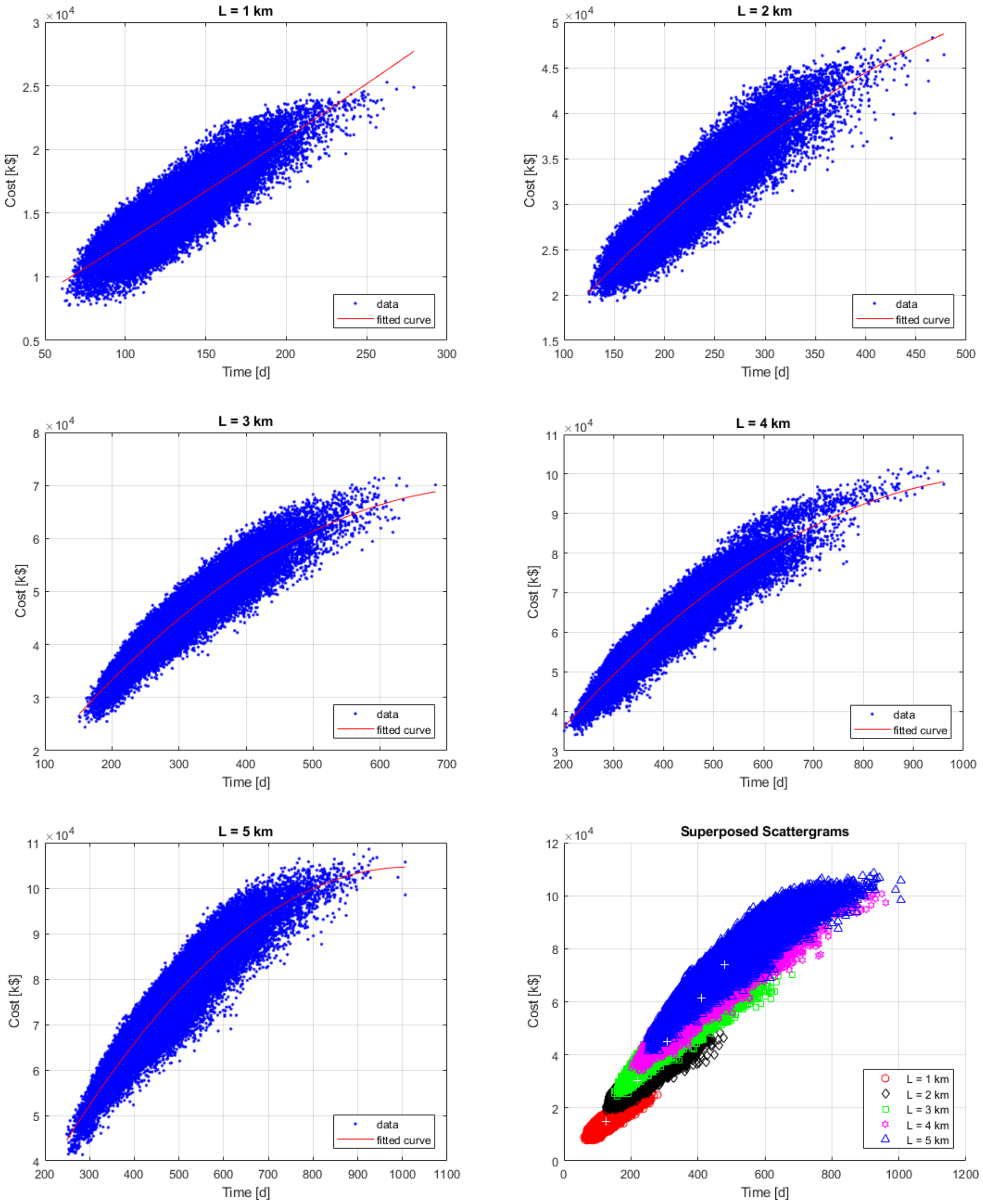

TABLE 25	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	61	126	279	7.75	14.75	25.28
2 km	125	221	478	19.21	30.17	48.29
3 km	151	307	683	24.43	45.09	71.40
4 km	202	412	961	34.06	61.53	101.59
5 km	249	479	1006	41.37	74.14	108.57

TABLE 25

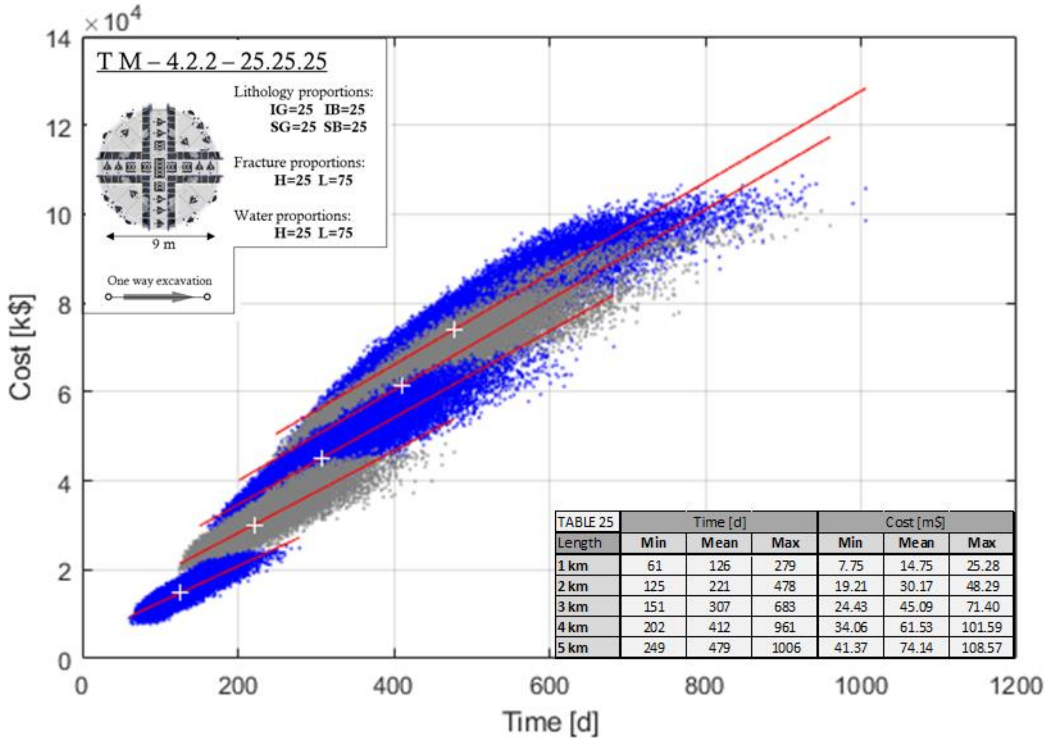

TABLE 25	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	61	126	279	7.75	14.75	25.28
2 km	125	221	478	19.21	30.17	48.29
3 km	151	307	683	24.43	45.09	71.40
4 km	202	412	961	34.06	61.53	101.59
5 km	249	479	1006	41.37	74.14	108.57

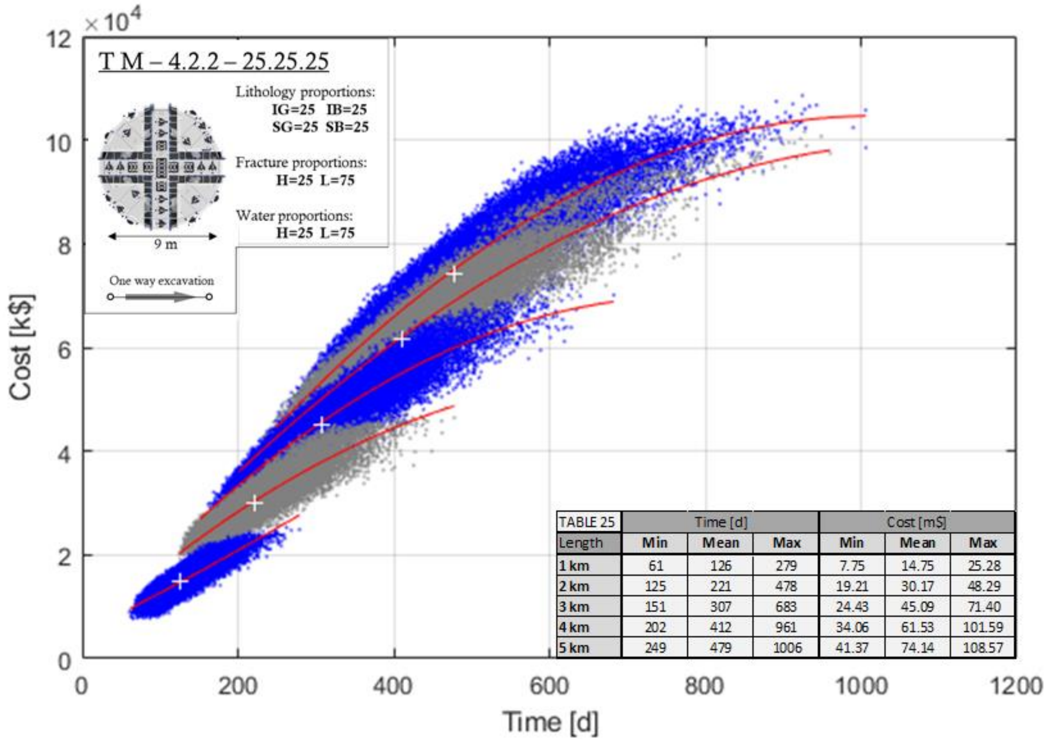

TABLE 25	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	61	126	279	7.75	14.75	25.28
2 km	125	221	478	19.21	30.17	48.29
3 km	151	307	683	24.43	45.09	71.40
4 km	202	412	961	34.06	61.53	101.59
5 km	249	479	1006	41.37	74.14	108.57

TABLE 26

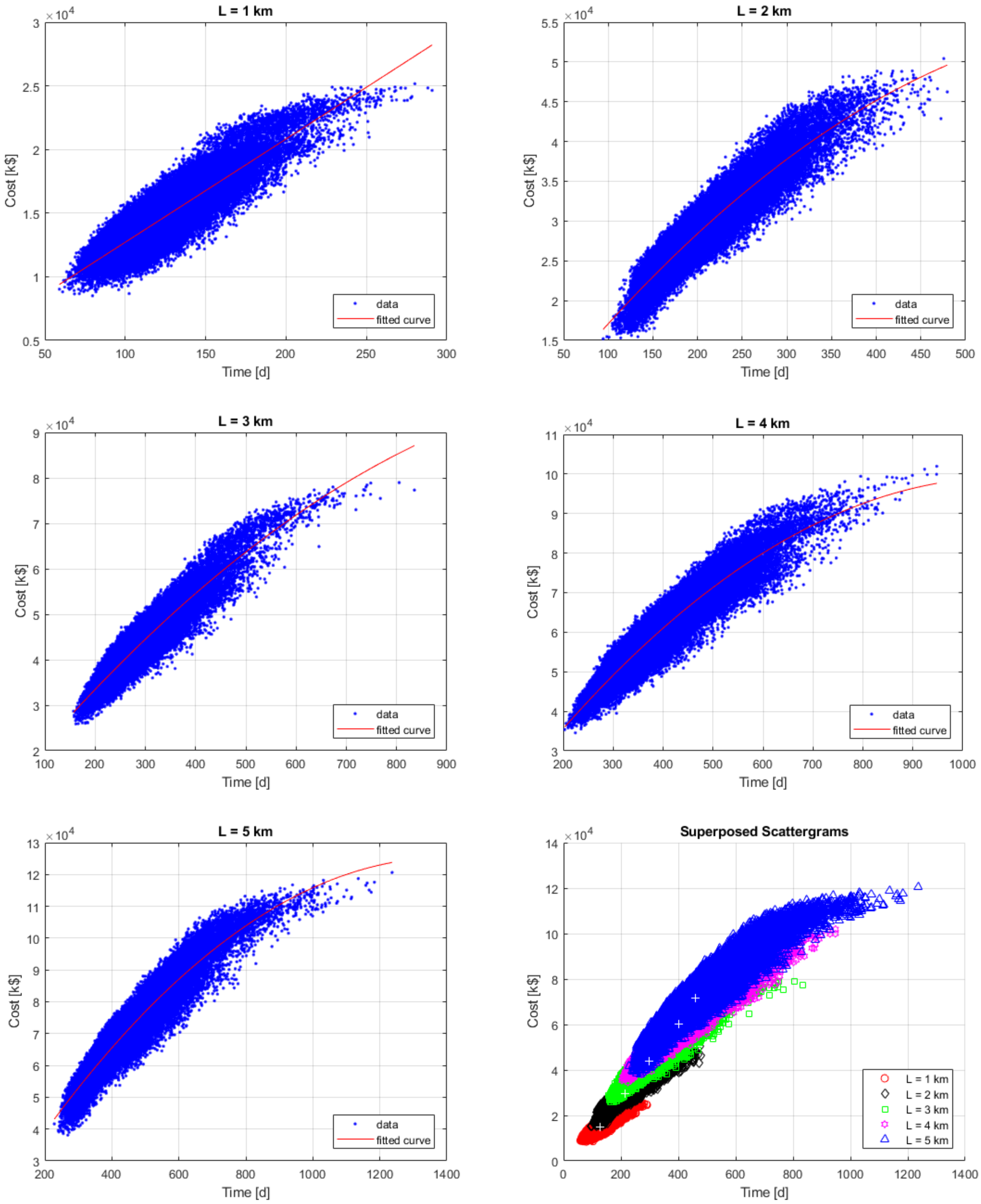

TABLE 26	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	59	128	291	8.51	14.95	25.16
2 km	94	214	480	15.20	29.66	50.43
3 km	157	297	835	25.87	43.96	78.95
4 km	203	401	948	34.55	60.37	101.95
5 km	228	460	1236	38.10	71.78	120.62

TABLE 26

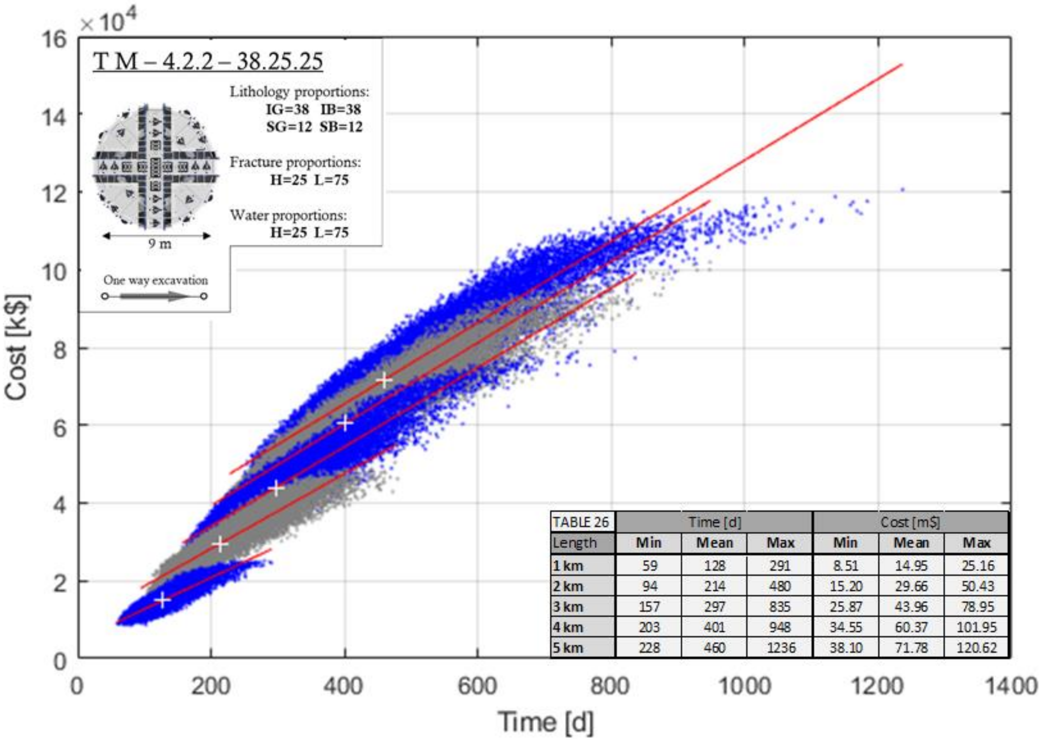

TABLE 26	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	59	128	291	8.51	14.95	25.16
2 km	94	214	480	15.20	29.66	50.43
3 km	157	297	835	25.87	43.96	78.95
4 km	203	401	948	34.55	60.37	101.95
5 km	228	460	1236	38.10	71.78	120.62

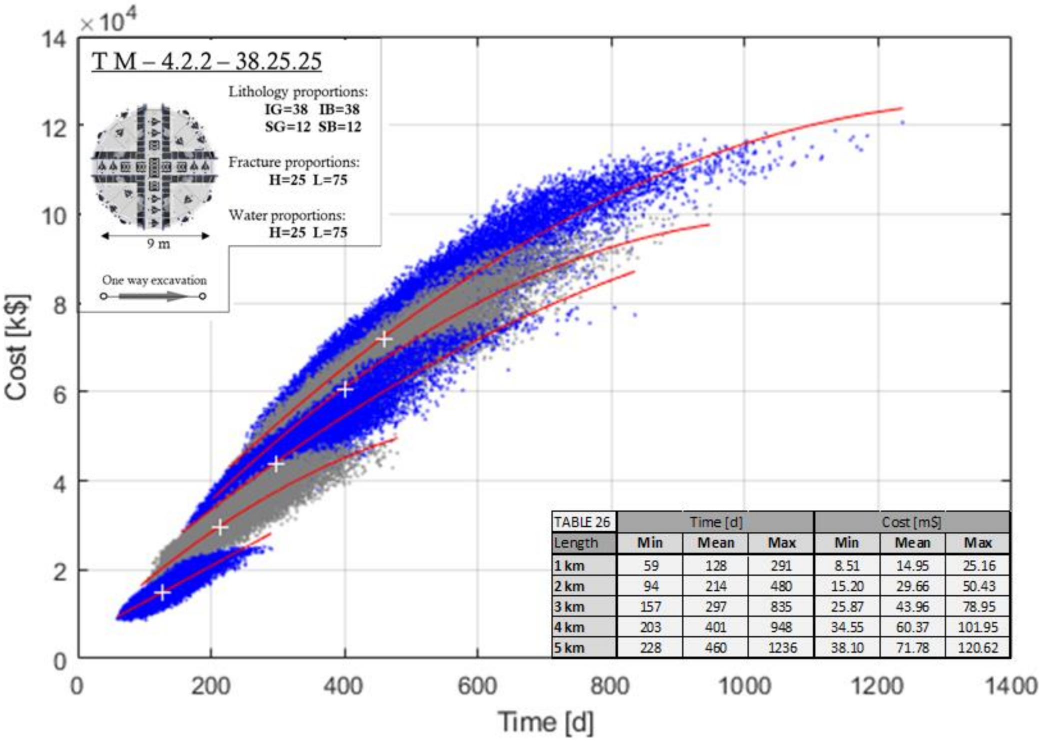

TABLE 26	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	59	128	291	8.51	14.95	25.16
2 km	94	214	480	15.20	29.66	50.43
3 km	157	297	835	25.87	43.96	78.95
4 km	203	401	948	34.55	60.37	101.95
5 km	228	460	1236	38.10	71.78	120.62

TABLE 27

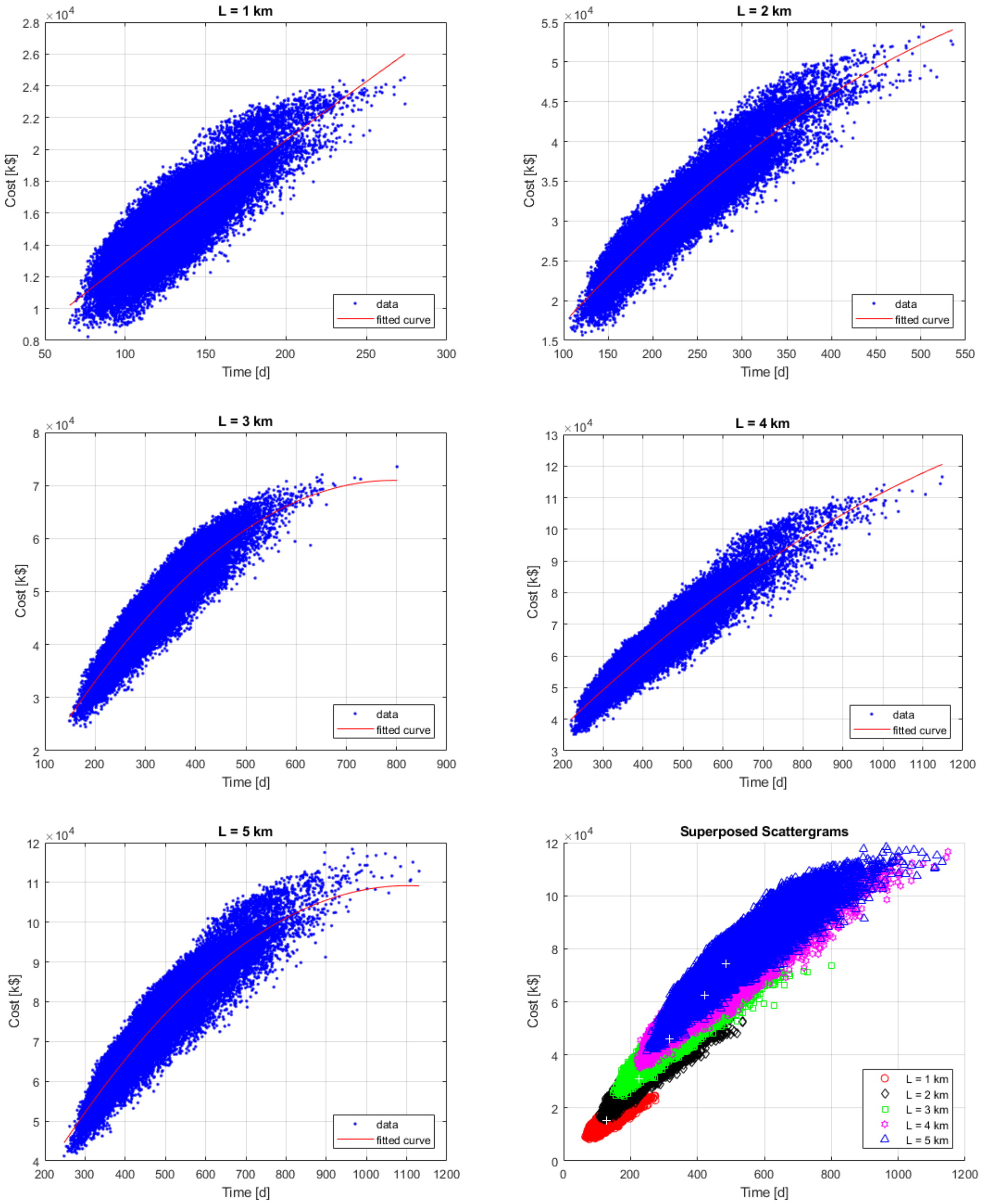

TABLE 27	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	65	129	274	8.22	15.19	24.51
2 km	107	226	536	15.68	30.85	54.41
3 km	149	316	801	24.49	45.92	73.54
4 km	219	422	1148	35.17	62.29	116.61
5 km	248	484	1131	41.22	74.37	118.35

TABLE 27

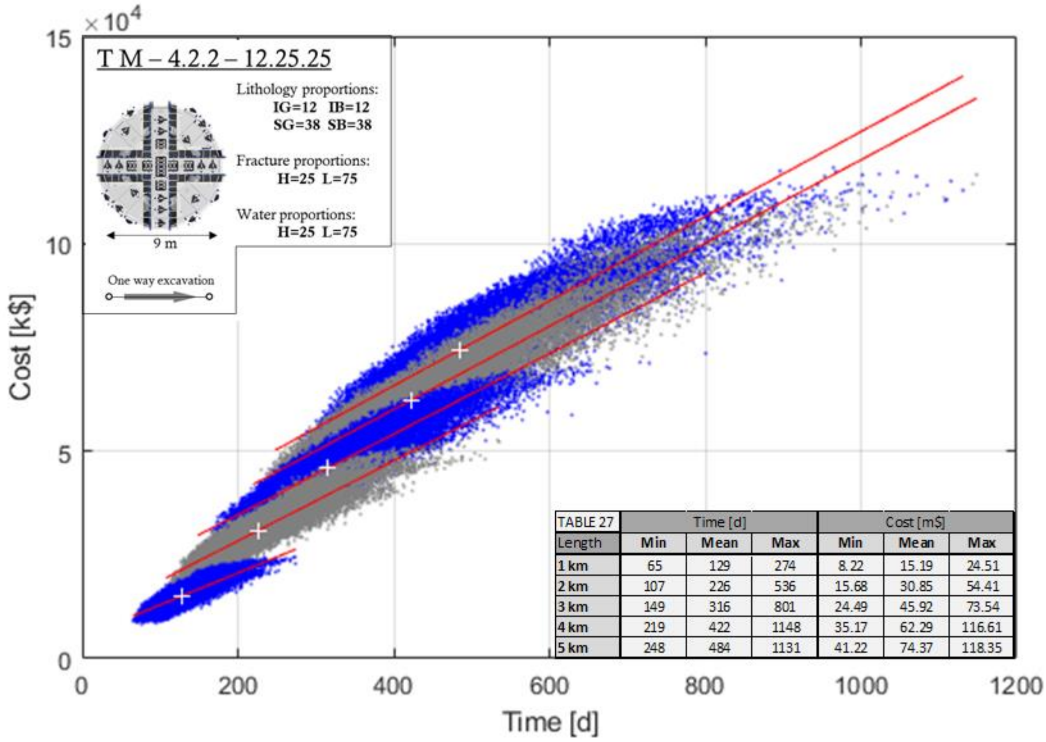

TABLE 27	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	65	129	274	8.22	15.19	24.51
2 km	107	226	536	15.68	30.85	54.41
3 km	149	316	801	24.49	45.92	73.54
4 km	219	422	1148	35.17	62.29	116.61
5 km	248	484	1131	41.22	74.37	118.35

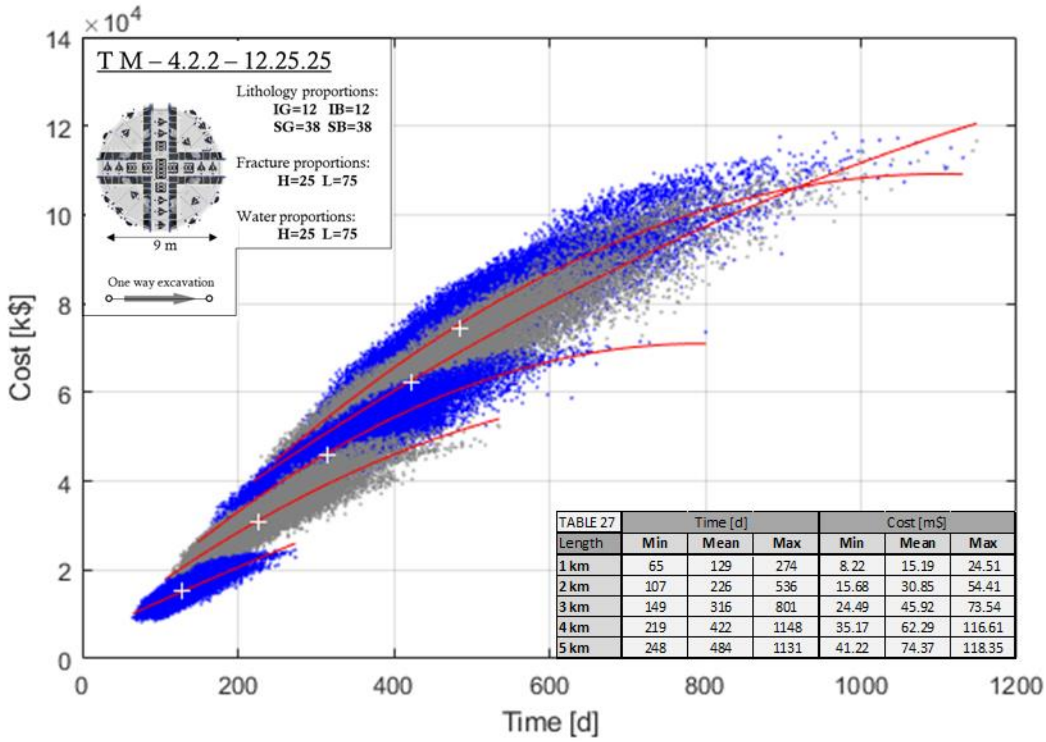

TABLE 27	Time [d]			Cost [m$]		
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1 km	65	129	274	8.22	15.19	24.51
2 km	107	226	536	15.68	30.85	54.41
3 km	149	316	801	24.49	45.92	73.54
4 km	219	422	1148	35.17	62.29	116.61
5 km	248	484	1131	41.22	74.37	118.35

6.4 Catalogue Summary Tables

The tables of each geologic setting are presented side-by-side for an easier comparison.

6.4.1 Igneous setting

Summary of the igneous setting tables (tables 1 to 9)

TABLE 1	TIME [d]			COST [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	87	221	512	12.90	25.28	40.11
2 km	192	410	988	30.80	51.66	88.10
3 km	287	566	1357	48.13	74.63	122.44
4 km	351	760	1698	59.20	101.40	156.01
5 km	437	940	2390	73.53	126.68	211.67

TABLE 2	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	126	278	682	18.62	31.13	51.71
2 km	209	509	1315	32.81	61.85	107.14
3 km	348	732	2088	55.65	91.73	163.30
4 km	377	950	2707	66.10	121.08	218.04
5 km	559	1245	3072	92.88	158.36	252.83

TABLE 3	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	161	334	806	22.21	36.94	59.84
2 km	299	609	1438	44.80	72.24	115.27
3 km	470	935	2091	74.23	112.61	168.86
4 km	521	1198	2988	85.15	146.57	236.16
5 km	755	1495	3325	119.47	184.01	275.50

TABLE 4	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	74	158	351	10.37	18.42	31.11
2 km	130	272	613	21.31	36.40	57.69
3 km	159	385	1105	26.13	53.99	105.69
4 km	238	509	1203	39.93	73.17	123.71
5 km	322	636	1622	56.38	92.88	160.06

TABLE 5	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	79	192	446	11.41	22.08	37.78
2 km	170	345	995	27.71	44.43	87.06
3 km	157	478	1177	24.84	64.86	108.85
4 km	289	632	1685	48.48	87.08	154.23
5 km	314	800	2321	55.67	111.17	196.11

TABLE 6	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	107	221	520	15.81	25.28	40.48
2 km	170	404	1196	27.04	51.00	95.10
3 km	216	555	1632	36.38	73.39	143.39
4 km	367	761	2200	61.00	101.55	187.06
5 km	421	932	2783	73.61	125.99	223.80

TABLE 7	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	51	106	290	6.43	12.29	23.23
2 km	91	182	442	13.39	25.10	47.76
3 km	130	254	535	18.87	37.47	61.26
4 km	165	318	710	24.33	49.03	77.63
5 km	192	382	930	27.02	60.83	109.09

TABLE 8	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	58	124	270	7.90	14.73	23.25
2 km	108	205	484	17.02	28.79	49.23
3 km	131	298	661	21.60	44.38	68.47
4 km	167	370	902	28.01	57.25	98.79
5 km	250	458	1015	43.71	71.99	112.05

TABLE 9	Time [d]			Cost [m$]		
Length	Min	Mean	Max	Min	Mean	Max
1 km	69	135	361	9.77	16.48	29.30
2 km	125	241	583	21.15	33.80	57.16
3 km	164	345	1002	30.41	50.96	87.39
4 km	234	439	1090	42.39	67.17	111.21
5 km	294	562	1566	55.12	86.35	145.20

6.4.2 Sedimentary setting

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	Family			IGNEOUS SETTING			SEDIMENTARY SETTING			MIXED SETTING					Family
B		State		Igneous Good / Igneous Bad			Sedimentary Good / Sedimentary Bad			Igneous Good and Bad / Sedimentary Good and Bad				State	
C			Predominance	Good	Equal	Bad	Good	Equal	Bad	Equal	Igneous	Sedimentary	Predominance		
D	FRACTURE	High / Low	High	*Table 1*	*Table 2*	*Table 3*	***Table 10***	***Table 11***	***Table 12***	*Table 19*	*Table 20*	*Table 21*	High	High / Low	WATER
E			Equal	*Table 4*	*Table 5*	*Table 6*	***Table 13***	***Table 14***	***Table 15***	*Table 22*	*Table 23*	*Table 24*	Equal		
F			Low	*Table 7*	*Table 8*	*Table 9*	***Table 16***	***Table 17***	***Table 18***	*Table 25*	*Table 26*	*Table 27*	Low		

Summary of the sedimentary setting tables (tables 10 to 18)

TABLE 10	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	111	223	557	16.42	25.68	44.27
2 km	213	418	948	33.58	52.65	77.83
3 km	289	608	1441	47.17	79.16	118.79
4 km	416	778	2375	68.06	103.70	194.85
5 km	446	956	2328	79.36	128.98	204.45

TABLE 11	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	150	279	660	20.79	31.30	51.18
2 km	246	531	1373	38.16	64.03	106.06
3 km	377	796	1840	58.73	98.18	156.13
4 km	462	1039	2409	75.24	130.01	199.54
5 km	668	1254	2982	111.29	159.32	250.16

TABLE 12	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	159	346	804	21.67	38.13	56.77
2 km	331	657	1618	49.69	76.83	122.30
3 km	393	944	2447	63.12	113.20	191.05
4 km	600	1265	3122	95.43	153.11	241.45
5 km	830	1568	3792	128.83	190.97	296.24

TABLE 13	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	76	167	379	11.20	19.49	32.65
2 km	138	304	769	22.76	39.73	69.22
3 km	192	415	1129	32.94	57.79	107.31
4 km	235	549	1485	42.77	77.76	135.46
5 km	279	687	1719	48.16	98.31	169.57

TABLE 14	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	206	506	11.93	23.44	40.86
2 km	183	377	862	29.13	47.71	76.51
3 km	239	513	1296	40.07	68.00	116.55
4 km	289	673	1592	49.98	91.36	146.17
5 km	369	844	2527	58.45	115.56	217.07

TABLE 15	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	99	234	595	15.19	26.49	45.58
2 km	202	430	1134	32.32	53.39	98.55
3 km	286	638	1828	47.41	81.70	147.86
4 km	350	805	1964	59.91	105.46	166.10
5 km	426	991	2239	72.75	131.32	199.37

TABLE 16	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	56	114	255	7.09	13.09	21.51
2 km	88	198	535	11.42	26.80	50.54
3 km	145	270	615	22.30	39.65	65.28
4 km	167	360	866	27.49	53.91	91.42
5 km	211	423	947	33.04	65.14	106.18

TABLE 17	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	61	132	294	8.34	15.48	24.42
2 km	115	237	572	18.50	32.23	54.98
3 km	173	324	873	28.68	46.95	85.32
4 km	206	425	1057	32.88	62.79	102.85
5 km	246	520	1718	40.39	78.58	157.96

TABLE 18	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	70	152	337	11.06	18.05	28.93
2 km	141	266	757	22.97	36.12	68.88
3 km	191	378	894	32.78	54.16	91.33
4 km	245	493	1227	42.56	72.36	123.00
5 km	304	601	1400	50.49	89.75	141.39

6.4.3 Mixed setting

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	Family			IGNEOUS SETTING			SEDIMENTARY SETTING			MIXED SETTING					Family
B		State		Igneous Good / Igneous Bad			Sedimentary Good / Sedimentary Bad			Igneous Good and Bad / Sedimentary Good and Bad				State	
C			Predominance	Good	Equal	Bad	Good	Equal	Bad	Equal	Igneous	Sedimentary	Predominance		
D	FRACTURE	High / Low	High	*Table 1*	*Table 2*	*Table 3*	*Table 10*	*Table 11*	*Table 12*	***Table 19***	***Table 20***	***Table 21***	High	High / Low	WATER
E			Equal	*Table 4*	*Table 5*	*Table 6*	*Table 13*	*Table 14*	*Table 15*	***Table 22***	***Table 23***	***Table 24***	Equal		
F			Low	*Table 7*	*Table 8*	*Table 9*	*Table 16*	*Table 17*	*Table 18*	***Table 25***	***Table 26***	***Table 27***	Low		

Summary of the mixed setting tables (tables 19 to 27)

TABLE 19	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	107	279	630	15.33	31.21	48.52
2 km	258	527	1341	39.49	63.66	106.43
3 km	357	752	1809	56.57	93.64	144.61
4 km	468	1015	2433	75.03	127.75	198.72
5 km	516	1229	2952	88.34	156.70	246.28

TABLE 20	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	125	275	636	17.50	30.82	49.68
2 km	248	510	1287	38.33	61.88	104.59
3 km	346	731	1792	54.73	91.72	142.31
4 km	474	985	2335	78.47	124.68	191.18
5 km	526	1217	2904	88.30	155.32	249.53

TABLE 21	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	124	279	674	17.12	31.24	52.36
2 km	249	514	1177	37.68	62.30	96.35
3 km	305	773	2100	50.93	95.84	169.54
4 km	451	1006	2445	74.43	126.69	202.27
5 km	641	1241	2911	103.39	157.92	247.75

TABLE 22	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	194	434	11.62	22.12	36.35
2 km	164	344	797	26.60	44.20	72.14
3 km	247	515	1591	38.34	68.37	134.64
4 km	290	658	1715	49.58	89.56	151.38
5 km	314	811	2234	58.44	112.02	199.42

TABLE 23	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	78	193	404	12.06	22.10	33.27
2 km	149	347	929	23.14	44.54	79.95
3 km	233	513	1267	40.20	68.22	111.76
4 km	299	657	1679	52.58	89.77	152.35
5 km	358	769	2166	63.62	107.88	202.34

TABLE 24	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	85	203	476	13.08	23.19	37.65
2 km	160	357	838	26.64	45.60	74.88
3 km	213	522	1449	34.94	68.95	122.76
4 km	311	686	1799	55.58	92.72	160.78
5 km	354	856	2332	63.33	116.66	204.73

TABLE 25	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	61	126	279	7.75	14.75	25.28
2 km	125	221	478	19.21	30.17	48.29
3 km	151	307	683	24.43	45.09	71.40
4 km	202	412	961	34.06	61.53	101.59
5 km	249	479	1006	41.37	74.14	108.57

TABLE 26	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	59	128	291	8.51	14.95	25.16
2 km	94	214	480	15.20	29.66	50.43
3 km	157	297	835	25.87	43.96	78.95
4 km	203	401	948	34.55	60.37	101.95
5 km	228	460	1236	38.10	71.78	120.62

TABLE 27	Time [d]			Cost [m$]		
Length	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1 km	65	129	274	8.22	15.19	24.51
2 km	107	226	536	15.68	30.85	54.41
3 km	149	316	801	24.49	45.92	73.54
4 km	219	422	1148	35.17	62.29	116.61
5 km	248	484	1131	41.22	74.37	118.35

6.5 Catalogue FAQ

This FAQ section summarizes some of the concepts previously detailed and redirects the user to the targeted section if more information is needed.

Why is the Catalogue useful?

It is tailored to fit the needs of projects dealing with small tunnels. Most of the time, big tunneling projects rely on the DAT itself while it usually remains "not worth it" for small tunnels. The Catalogue is a good compromise between accuracy and efficiency. It is certainly more accurate than manual calculations and at the same time much quicker and easier to use compared to the DAT. It can yield immediate results concerning the construction cost and time for small tunnels in order to assist decision makers with different tasks (alignment selection, finding the best alternative etc.).

How does the Catalogue work?

It is based on generic common conditions that the user may be faced with and presents pre-calculated results for direct consultation by the user without having to run any simulations. For detailed information, refer to Chapter 6.1: Rules of Usage.

How should the Reference Table be used?

It is a table of contents of the Catalogue's charts, but not ordered numerically or alphabetically in a list. Instead, it is a roadmap that allows the user to quickly find the suitable chart they are looking for based on the conditions that best apply to their project. For more detailed information, refer to Chapter 6.2: Reference Table.

How can extra factors be considered?

This depends on the complexity of the required extra factor. If it is something simple to add, like a fixed delay or cost, then it is possible to use the results of the Catalogue and simply add to them whatever is needed. On the other hand, if the user wishes to add a new group of parameters that could change fundamental things (like adding squeezing, spalling etc. that results in altering the definition of the ground classes), then the user must rely on the DAT.

Are the Catalogue's results exact?

The results in the Catalogue are based on simulations. Each set of values $[Min;\ Mean;\ Max]$ for cost and time for a certain tunnel length have been generated using precisely $50{,}052$ simulations. When a project resembles a Catalogue entry, then the results, especially the average ones, are indeed extremely reliable compared to deterministic approximations. The latter can handle at best a few, rather simplistic, estimations while one Catalogue entry has been simulated $50{,}000$ times and for a more complex scheme. However, despite this large number of simulations, it does not mean that all possible combinations have been exhausted. This implies that the absolute maximum and minimum values are not entirely definitive.

Is the Catalogue complete?

This is only the first version of the Catalogue, which only accommodates 27 charts. Future expansions may be implemented considering more geology factors, construction complexities, different TBM diameters and additional construction methods.

6.6 Catalogue Recommendations

Interpolations using the obtained data to forecast other un-simulated conditions are a delicate issue. Chapter 2 partially established that "the whole is greater than the sum of parts". Indeed, when all the complications of a project are simulated in one model, the results vary compared to simply adding the effect of each component. To ensure the best results, it is best to run the simulations for the specifically desired case. This being said, some recommendations can be given if the user would like to obtain quick results from the Catalogue for new not simulated cases. This should only be done when accuracy is usually not the top concern, but rather obtaining rough comparative values.

Ideally, the new Catalogue developments will include more data and so, some of these questions will become obsolete as the exact results would then be available for direct consultation. Meanwhile, relying on estimations is the only thing that can be done at the moment, while remaining vigilant to the limitations of these approximations.

My tunnel has a length that is not exactly simulated

This means that the geologic conditions described in the Reference Table do apply, and that the user was able to find a satisfactory chart. Only the targeted tunnel length is different than exactly $L = 1, 2, 3, 4$ or $5\ km$.

In the targeted length $L \leq 5\ km$, then it is possible to solve this problem through the following:

- Linearly interpolate between two successive rows in the summary tables without considering the distributions or the scattergram shapes. For example, if the required length is $L = 2.5\ km$, then use the results in the table from the correct chart and interpolate between $2\ km$ and $3\ km$.
- Use the linear fit to graphically find the solution by referring to the first layout format of presenting the results in Figure 3.11. The steps to be followed that are presented here are also shown on Figure 6.2. First find an estimate of the mean values (average cost and time) in between two successive white crosses since they follow a linear path. Now for the extreme values (min and max), draw a line with a slope parallel to the rest of the fits and read the extreme values from the intersection with the confidence boundary lines. The confidence boundaries also need to be drawn by the user based on how "strict" the results are needed to be. Be advised that, for most data, a linear fit can overestimate both the minimum and maximum values.
- Use the second-degree polynomial fit to graphically find the solution by referring to the second layout format of presenting the results in Figure 3.12. Graphically, the process is analogous to the linear interpolation that appears in Figure 6.2. First, it is possible to estimate the mean value using the same linear path of the white crosses. The extreme ones (min and max), can be approximated by drawing a curve that resembles the rest and crossing the mean value. Try to mimic the behavior of existing results in terms of shape in order to estimate the extreme minimum and maximum values. Be advised that, for most data, a second-degree polynomial fit can underestimate the maximum value.

If the targeted length $L > 5\ km$, then it is possible to apply the above-mentioned techniques but with caution because there will be no upper bound to frame the solution. Since the Catalogue is not intended for long tunnels, it is not recommended to be used for length exceeding $L > 5\ km$.

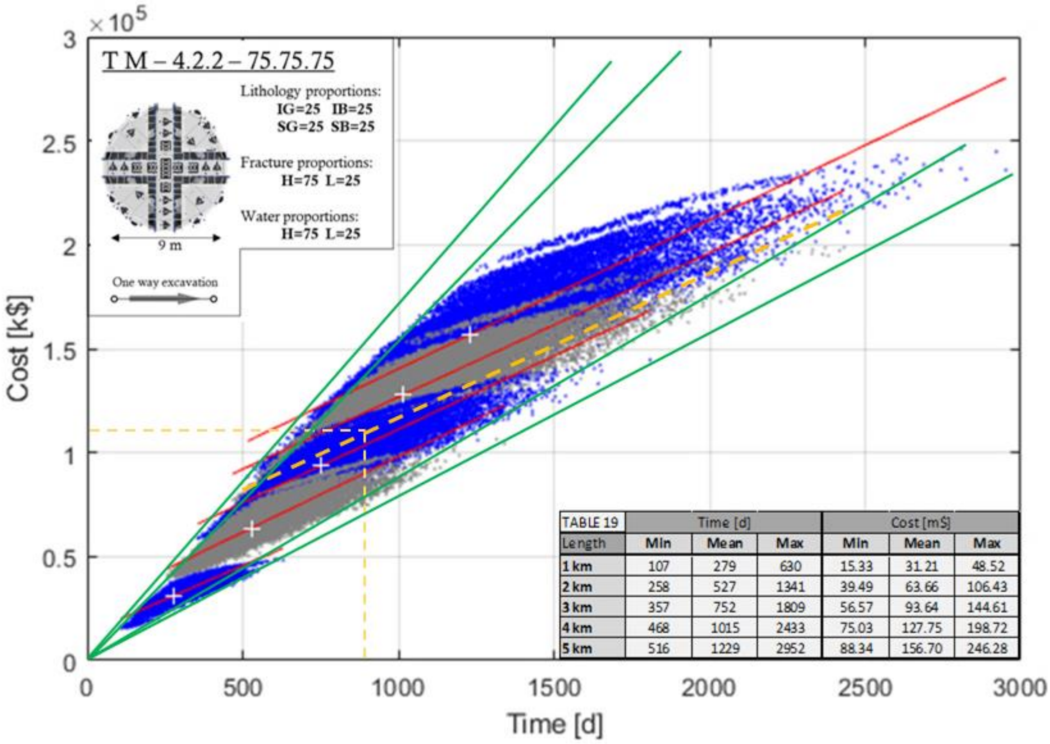

Figure 6.2: Linear interpolation of results

My tunnel has a different diameter

This assumes that the geologic conditions described in the Reference Table do apply, and that the user was able to find a satisfactory chart for their conditions. However, the targeted tunnel diameter is different than exactly $d = 9\ m$.

One way to deal with this problem is to realize that the diameter affects the unit cost and time in the inputs. Therefore, a ratio between the diameter and these inputs could be established. Care must be taken however in not falling into mathematical fallacies, as this concept, when taken into extreme cases, becomes physically impossible. For instance, if the targeted diameter is $d = 1.8\ m$, which is five time smaller than the original $d = 9\ m$, is it really going to cost 5 times less and make the TBM go 5 times faster?

Linear interpolations may be applied only when the time-cost inputs remain within pragmatic limits.

My tunnel has more than one tube

This assumes that the geologic conditions described in the Reference Table do apply, and that the user was able to find a satisfactory chart. However, the targeted tunnel consists of more than one tube.

A simple way is to just assume that the results in the charts are for a single tube and thus for costs, a simple multiplication by the total number of tubes yields the total results. For time, one has to consider if the tunnels are built simultaneously or in sequence. This simplification is acceptable when the tubes are built more or less independently. In reality, this is rarely the case, as the construction activities, deadlines, weather conditions, equipment, teams, geology etc. are seldom totally disconnected. Moreover, when more tubes are built, risks and variabilities are increased, which results in a wider spread of the results on the scattergrams. This effect among others is not properly captured by simple multiplications.

My tunnel is excavated from both sides

This assumes that the geologic conditions described in the Reference Table do apply. However, the targeted tunnel is being excavated from both portals instead of being excavated entirely from one end to the other.

This can be handled similarly to the previous cost problem, by dividing the construction time by half if construction teams are assumed to be working independently.

Another way of approaching this issue, is to replace the case by two tunnels being constructed independently, but with each having half the length of the original. In this case, the Catalogue is consulted twice, once for each tunnel of length $L = 0.5 \times L_{original}$.

6.7 Future Developments

Producing the Catalogue required a lot of reflections and investigations. Different alternatives were assessed before coming up with this approach in order to optimize the DAT for small tunnels. Even so, developing the Catalogue from a simple idea into a useful form within a clearly defined framework required many resources and time. Therefore, this first version of the Catalogue 2018 remains incomplete. With only 27 charts, it is certainly useful but also leaves room for future expansions.

New developments might include the generation of charts for

- Different construction methods: Drill and Blast, for instance, remains a top priority since the construction of small tunnels may not always favor the use of TBMs.
- Different sizes: for both TBM and other construction methods
- Different geology proportions
- Additional geological aspects: considering for example spalling, squeezing, karst etc.
- Different tunnel network configurations: excavations from both portals and/or with an intermediate access tunnel for example.
- Different number of tubes: could also be paired with different tunnel configurations.

Table 6.3 shows a more detailed potential reference table with a finer distribution of the geological features. Also, these same geology inputs could be used to develop yet another parallel version with the same geologies, but with some of the aforementioned modifications; for example: with Drill and Blast instead of TBM, with a different diameter size, etc.

Table 6.3: Expanded Catalogue reference table

GP			IGNEOUS SETTING			SEDIMENTARY SETTING			MIXED SETTING									GP
GP State			IG/IB			SG/SB			IG/IB/SG/SB							GP State		
		Percent	80/20	50/50	20/80	80/20	50/50	20/80	25/25/25/25	50/13/13/13	13/50/13/13	13/13/50/13	13/13/13/50	38/38/12/12	12/12/38/38	Percent		
		70/20/10	*Table 1*	*Table 2*	*Table 3*	*Table 16*	*Table 17*	*Table 18*	*Table 31*	*Table 32*	*Table 33*	*Table 34*	*Table 35*	*Table 36*	*Table 37*	70/20/10		
		50/30/20	*Table 4*	*Table 5*	*Table 6*	*Table 19*	*Table 20*	*Table 21*	*Table 38*	*Table 39*	*Table 40*	*Table 41*	*Table 42*	*Table 43*	*Table 44*	50/30/20		
FRACTURE	H/M/L	33/33/33	*Table 7*	*Table 8*	*Table 9*	*Table 22*	*Table 23*	*Table 24*	*Table 45*	*Table 46*	*Table 47*	*Table 48*	*Table 49*	*Table 50*	*Table 51*	33/33/33	H/M/L	WATER
		20/30/50	*Table 10*	*Table 11*	*Table 12*	*Table 25*	*Table 26*	*Table 27*	*Table 52*	*Table 53*	*Table 54*	*Table 55*	*Table 56*	*Table 57*	*Table 58*	20/30/50		
		10/20/70	*Table 13*	*Table 14*	*Table 15*	*Table 28*	*Table 29*	*Table 30*	*Table 59*	*Table 60*	*Table 61*	*Table 62*	*Table 63*	*Table 64*	*Table 65*	10/20/70		

In the end, the whole value of the Catalogue resembles conceptually a library, where more books increase the overall potential and usefulness. Similarly, with more charts being generated, the Catalogue will be able to both

- provide direct references for more cases
- enhance comparisons between different alternatives

thus, facilitating the daily tasks of decision makers in relatively small tunneling projects, especially in the early phases of conceptual project development and preliminary design.

CHAPTER 7

7 RESULTS ANALYSIS

7.1 Scattergrams Shape Investigation

When developing the Catalogue, many scattergrams have been generated; 5 scattergrams per chart, 135 in total, all presented in Chapter 6. These constitute a basis for the Catalogue and as such need to be closely examined. The general shape of the scattergrams is overall consistent, namely an elliptical shape exhibiting, as expected, an increasing trend in cost when associated with a higher construction time. However, when looking closer, beyond the overall shape, the scattergrams are not exactly identical.

Two noteworthy aspects emerge as somehow peculiar:

- a Bilinear shape in most of the scattergrams
- a Detachment of some data from the main cloud

Indeed, the bilinear aspect is predominant in a majority of the results. Although this does not affect the results in any way, a deeper knowledge of the origin of this bi-linearity is needed for a more profound understanding of the results and a more robust basis for the Catalogue. On the other hand, the detachment of data from the main cloud is not exhibited systematically on all the graphs. It remains however common and especially pronounced at the lower and upper bounds of the scattergrams. A better understanding of its causes is also needed at this stage.

In order to do so, an investigation is carried out, by varying two key parameters, one at a time:

- The cost-time input values
- Proportion of geology to construction simulations, while keeping the same total

The construction cost-time inputs are better visualized in Figure 7.1 with two side-by-side graphs where both the values and their distributions can be seen.

Inputs used in the Catalogue **New symmetric inputs considered**

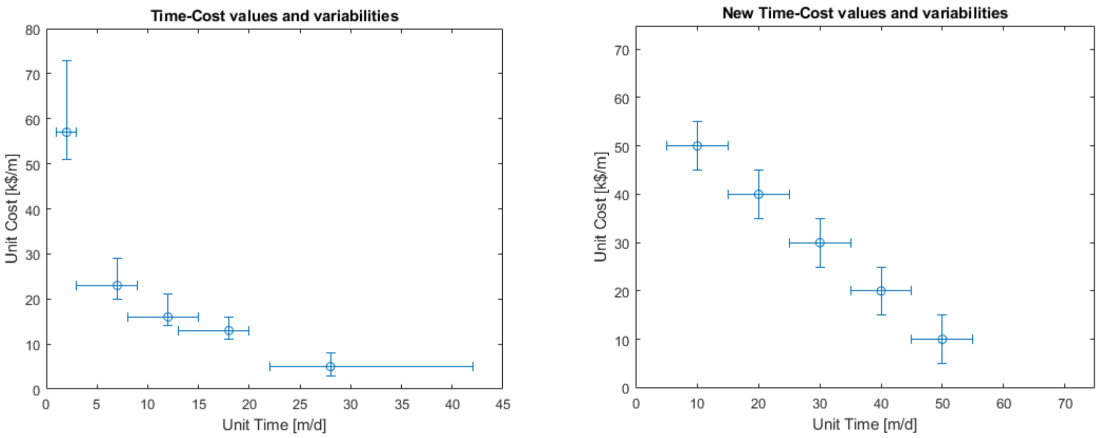

Figure 7.1: Graphical representation of the cost-time inputs for both cases

The inputs used in generating the Catalogue (as they were obtained in Chapter 4), show concave a curve. Their error margins are also not identical. This is because these data have been incorporated from real applications. A conjecture implies that the distinctive shape of the input may have an influence on the overall shape of the scattergram and in particular, on the double curvature behavior. In order to elucidate this issue, the proposed inputs are chosen to be perfectly linear in distribution and their errors perfectly symmetric. If the cost-time inputs have a considerable influence on the end results as is speculated, the new values, chosen to be extremely symmetric, will surely reveal it.

The second analyzed effect in this investigation relates to the number of simulations for geology and construction. The latter are treated semi-independently in the DAT and so, the obtained gap between the data points (visible for example on the first scattergram in Figure 7.2) is attributed to a gap in some geologies that were not generated due to a restricted number of geology simulations. If this statement holds true, then increasing the geology simulations should generate more cases that eventually translates with a better fill on the scattergrams.

The following Table 7.1 shows the number of simulations used both in the Catalogue and during this investigation. The total is always kept equal to 50,000 simulations.

Table 7.1: Number and distribution of simulations for both cases

Simulations	Geology	Construction	Total
used in the Catalogue	129	388	50052
new for investigaton	500	100	50000

The analysis is conducted for chart 2.1 of the Catalogue (Table 2 for $L = 1\ km$; more details about it in the Reference Table), because its scattergram in the Catalogue exhibits both a bilinear shape and a detachment of points. The results appear in four scattergrams presented in Figure 7.2 in a 2×2 matrix disposition for ease of comparison.

Vertically, the first column in Figure 7.2 corresponds to Catalogue cost-time inputs and the second column shows the results using the new inputs.

Horizontally in Figure 7.2, the first row corresponds to results relying on the Catalogue's number of simulations ($129G \times 388C$) while the second row shows the results for the different simulation numbers considered for the investigation ($500G \times 100C$).

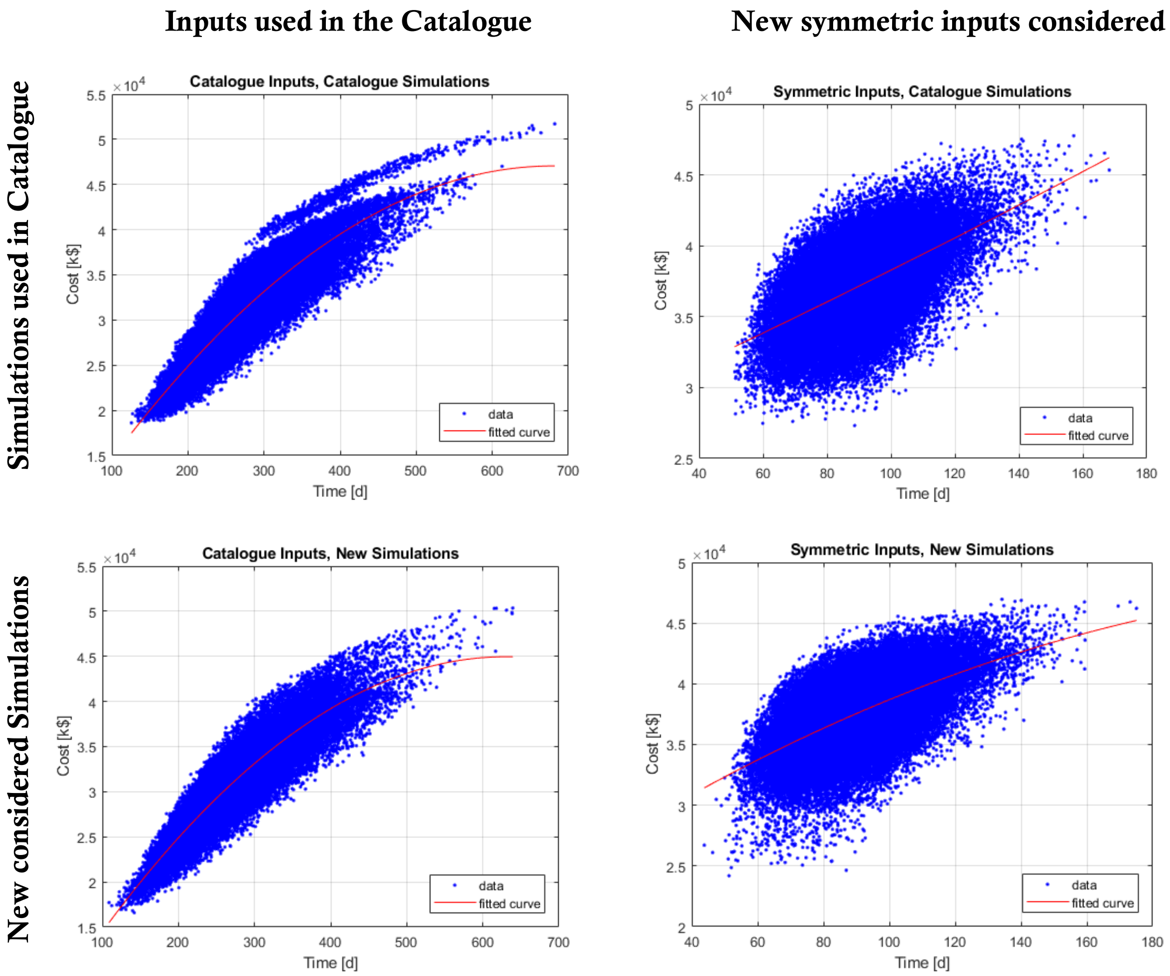

Figure 7.2: Investigation results in a 2×2 *matrix representation*

The scattergrams are labeled in the following fashion:

1	2
3	4

When comparing the figures two by two, it is possible to see the following results:

The **bilinear shape** is best explained as a natural shape governed by the particular **cost-time values** (shown in Figure 7.1) that were used in the simulations of the Catalogue, as it tends to dissipate completely when these inputs are changed. This is visible when comparing scattergrams 1 with 2 and 3 with 4. Indeed when looking at Figure 7.1, the cost-time inputs adopted in the Catalogue are visibly non-symmetric and in a way could be fitted with a bilinear decreasing curve themselves. Eventually on the scattergrams, this means that not "all" combinations are possible. This is why the points accumulate along one side with a certain apparent slope and then seem to suddenly align with another.

The **detachment** is best explained as a gap in geology, since increasing the **number of geology simulations** has generated intermediate results to fill this gap. This is visible when comparing scattergram 1 with 3. With more geology simulations, more heterogenous conditions are simulated, thus filling more continually the space between points on the scattergram.

7.2 Number of Segments Investigation

There are two main approaches in the DAT when defining geologies using Markov distributions:

- Defining directly a matrix for the transition probabilities between GP states
- Defining proportions and number of occurrences for the GP states

Indeed, instead of defining a transition probability matrix and thus generating the geology segments in whatever proportions, it is possible to proceed the other way around. This implies starting by defining a fixed proportion for each Ground Parameter state and let the DAT calculate a corresponding transition matrix for the case. This option was used in generating the Catalogue because it fits the repartition of GP states by proportions over the tunnel length. The number of segments is a required input for the geology module in the DAT, when using the proportions approach in the Markov successions.

In order to apply this approach, a number of occurrences is required so that the geology module can estimate lengths values for the segments. This input is visible in the following Figure 7.3 and is better detailed in an extract from the DAT manual in Figure 3.9, in Chapter 3.2.

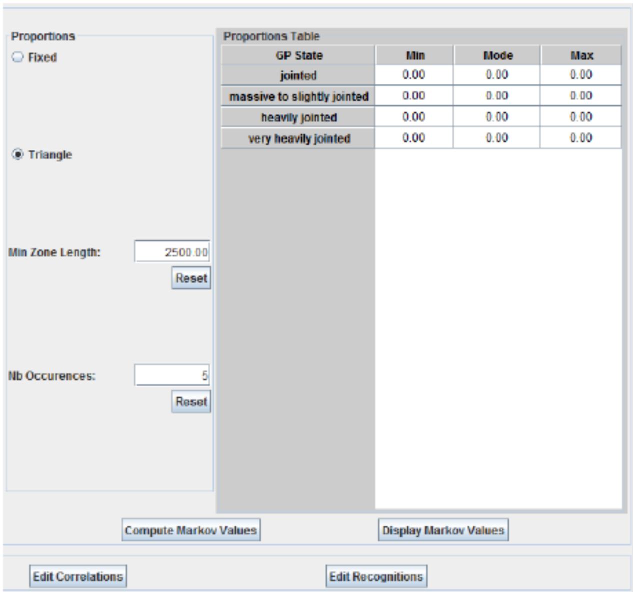

Figure 7.3: DAT screenshot with the Markov proportions inputs

Before proceeding any further, it is important to understand what exactly is this number of occurrences and how is it incorporated in obtaining the results. The number of occurrences is needed when the geology is being generated by Markov proportions instead of relying on the more common practice of directly defining a transition matrix. A direct use of the number of occurrences is the calculation of segment lengths. Specifically, a mode length for each GP state is calculated and applied when generating the geology segments. This length is a function of the tunnel's total length, the proportion of the GP state along this total length and the number of occurrences as follows:

$$Mode\ Length = \frac{Total\ Length}{Number\ of\ occurrences} \times proportion$$

The number of occurrences reflects the number of times a GP State occurs. This, as shown in the previous equation, then produces a segment length.

For all the data in the Catalogue, the default value of 5 $occurences$ has been used. In an attempt to further consolidate the credibility of the results, an investigation is carried out in order to assess the effect of the number of occurrences on the total construction cost and time.

7.2.1 Investigation Setting

This investigation is only useful when it relates to a specific case of the Catalogue's results. Therefore, geologic and construction conditions need to be kept unchanged. Hence, Chart 3.1 (Table 3 for a length $L = 1\,km$) from the Catalogue is the retained case upon which the investigation is carried out. Only the number of occurrences is changed while everything else remains exactly the same. Its core inputs are briefly summarized here:

- Length $L = 1\,km$
- Geology: igneous setting with proportions (%) $IG = 25$ and $IB = 75$
- Fracture: proportions (%) $H = 75$ and $L = 25$
- Water: proportions (%) $H = 75$ and $L = 25$

In order to assess the effect of the number of occurrences on the end-results, five runs are simulated while keeping everything unchanged and only varying the number of occurrences from low to high values: $5, 10, 20, 40$ and 80 occurrences.

For the specific case of the investigation on chart 3.1:

- $Total\ Length = 1'000\ m$
- $proportions$ are either 75% or 25%
- $Number\ of\ occurrences$ varying between: $5, 10, 20, 40$ and 80

Hence, according to the proportion of each GP state, the mode length is calculated as follows:

$$Mode\ Length = \frac{1000}{Number\ of\ occurrences} \times 0.75$$

$$Mode\ Length = \frac{1000}{Number\ of\ occurrences} \times 0.25$$

Applying this for all 5 number of occurrences yields the mode lengths that are summarized in Table 7.2, for both proportions.

Table 7.2: Mode lengths variations for the investigation

Number of occurrences	Mode Lengths [m]	
	for proportion = 0.25	for proportion = 0.75
5	50	150
10	25	75
20	12.5	37.5
40	6.3	18.8
80	3.1	9.4

Mathematically, increasing the number of occurrences, causes the mode length to decrease. This implies that the geology module will apply a certain GP state over a shorter length before changing to another, all while maintaining the total proportion of that GP state fixed, at 75% or 25% depending on which is defined, for the totality of the tunnel length. The results are shown below.

7.2.2 Investigation Results

As previously mentioned, 5 simulations are run respectively for 5, 10, 20, 40 and 80 occurrences, *ceteris paribus*.

The obtained results are summarized in a tabulated form in Table 7.3. Clearly, the construction cost and times have changed with the different occurrence values, even when all the other inputs were kept the same. The number of occurrences has then a non-neglectable effect that requires a closer inspection.

Table 7.3: Summary of the investigation results

Table 3.1	Time [d]			Cost [m$]		
occurrences	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
5	161	334	806	22.21	36.94	59.84
10	163	333	753	23.00	36.75	55.57
20	195	326	619	27.76	36.06	49.02
40	187	321	580	27.46	35.51	46.28
80	195	312	587	27.25	34.43	44.43

Figure 7.4, shows the superposed scattergrams of the five cases. Indeed, a visual representation of the results is more useful at this stage in order to see the differences between them.

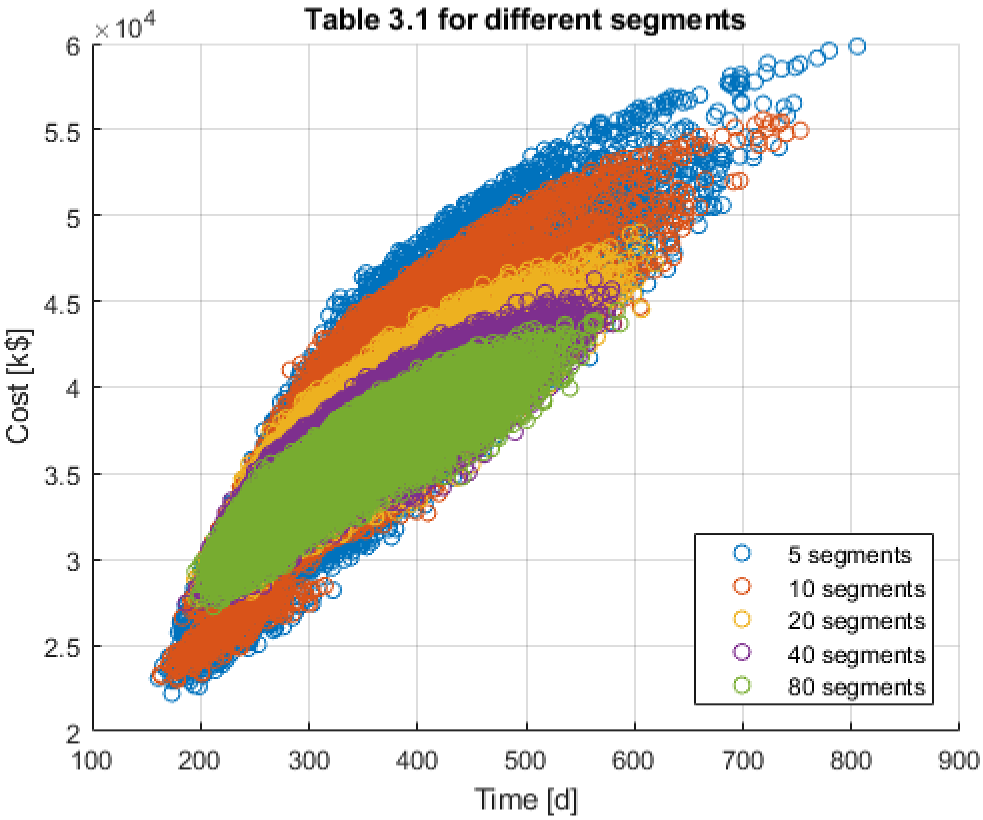

Figure 7.4: Superposed scattergrams for different number of occurrences

It is worth noting that, unlike the superposed scattergrams that appear in the Catalogue, the scattergrams in Figure 7.4 are not related to the same conditions and different lengths. They are for the same conditions and same length ($L = 1\ km$) but with different number of occurrences in the definition of the Markov proportions.

A pattern is undeniably recognizable: a higher number of occurrences decreases the scatter of the results. In other words, the variability of the results is inversely related to the number of occurrences. It has been established that the number of occurrences dictates the value of the mean length. A larger number of occurrences is associated with a smaller mode length for the GP states and consequently, the geology module will shift more frequently between geological conditions.

It is possible to explain the observed behavior: with much smaller mode lengths, the geology segments are much more erratic; they are frequently changing over very small lengths. For example, when comparing the two extremes of 5 vs. 80 occurrences, the lengths are from Table 7.2 in the order of 50 to 3 m and 150 to 9 m respectively. Physically, this means that the unit cost and time values are barely being applied over a few meters before being changed again, while for much longer lengths steps, they are applied consistently enough to accumulate in more extremely favorable or unfavorable scenarios, thus causing a wider scatter and more extremes being recorded on the scattergrams.

This physical understanding attributed to this case is also well-known in statistics and observed in other applications. It is referred to as the **central limit theorem** (Benjamin and Cornell, 1970):

> *Under very general conditions, as the number of variables in the sum becomes large, the distributions of the sum of random variables will approach the normal distribution.*

Considering how the simulations in the DAT are run, it is possible to conclude that this influence of the number of occurrences is indeed governed by the central limit theorem. Clearly, when moving from the 5 to the 80 occurrences cases, the distributions are less spread out and more concentrated. For a lower number of occurrences, a lower peak is reached and more extreme values are recorded. This is visible on Figure 7.5 through Figure 7.8. This same observation is made on the scattergrams.

A closer look at the distributions of the results (cost and time) is still promising, especially when considering the publication on modeling correlations, reviewed in the literature of Chapter 1.

Figure 7.5 shows the time distributions for all $5, 10, 20, 40$ and 80 occurrences while Figure 7.6 filters out the in-between values, to only show the two extremes at 5 and 80 occurrences. The time distributions appear to be skewed in shape, possible to fit with a lognormal behavior as it appears in Figure 7.9.

Similarly, Figure 7.7 shows the cost distributions for all $5, 10, 20, 40$ and 80 occurrences while Figure 7.8 focuses only on the distributions for 5 and 80 occurrences. The overall shape is less skewed and rather more symmetric around a central position, also reminding of a normal/lognormal distribution as it appears in Figure 7.10.

Concerning the shape of the distributions, they are conforming to what is most commonly used as distributions for cost and time, namely by Moret and Einstein (Moret and Einstein, 2012) especially for the cost resembling more a lognormal fit in Figure 7.10.

Time distributions

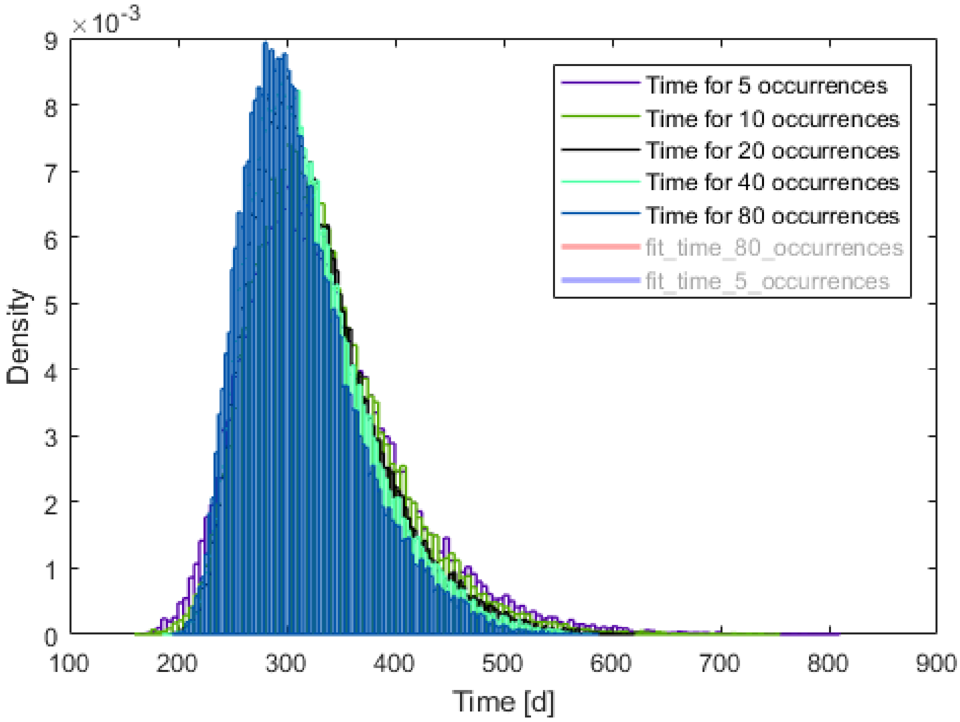

Figure 7.5: Time distribution for all 5, 10, 20, 40 and 80 occurrences

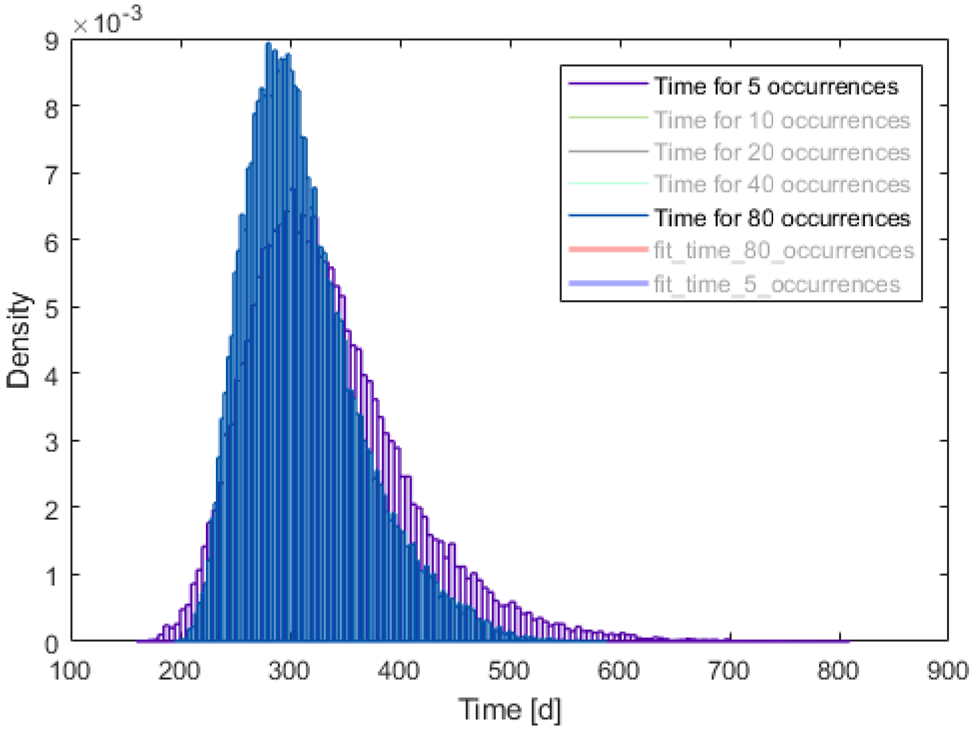

Figure 7.6: Time distribution only for 5 and 80 occurrences

Cost distribution

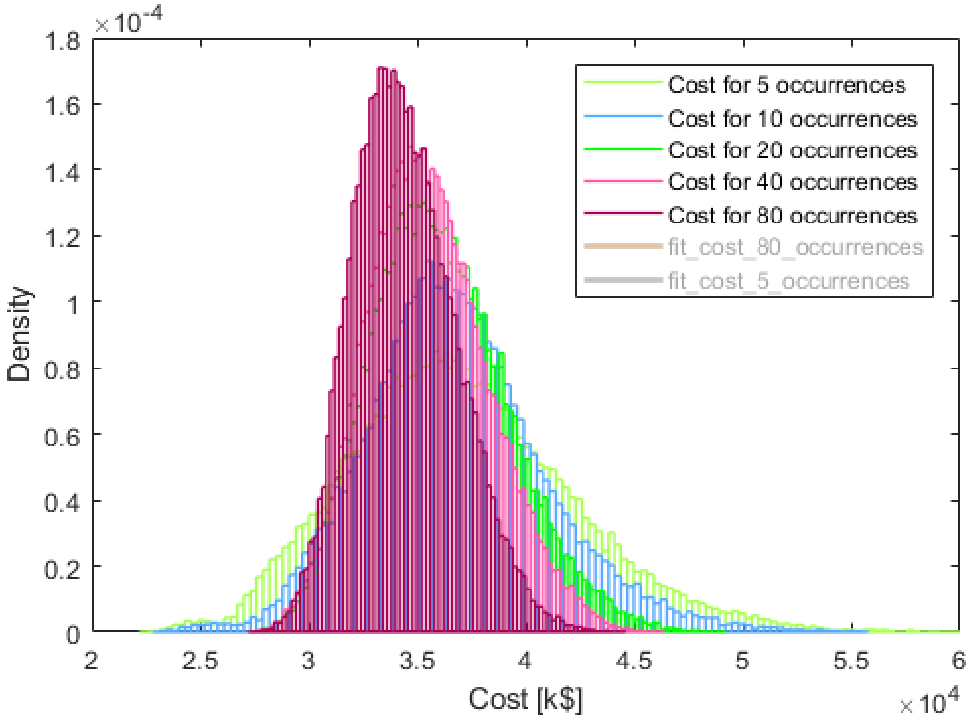

Figure 7.7: Cost distribution for all 5, 10, 20, 40 and 80 occurrences

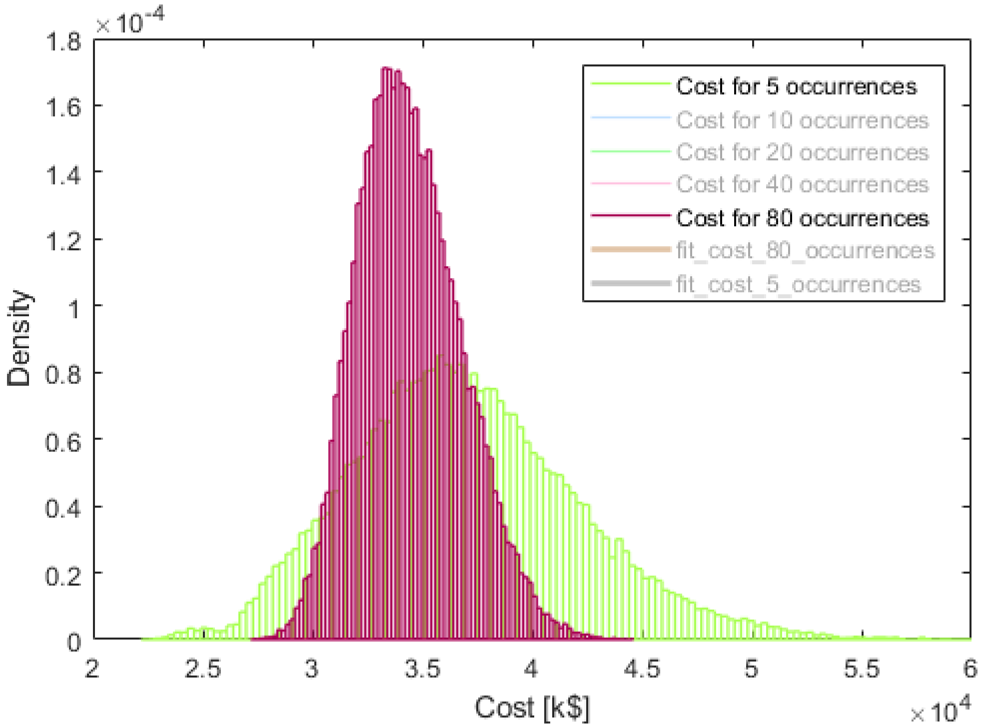

Figure 7.8: Cost distribution only for 5 and 80 occurrences

Cost and Time distributions with fits

The same lognormal fit is used for all distributions in Figure 7.9 and Figure 7.10.

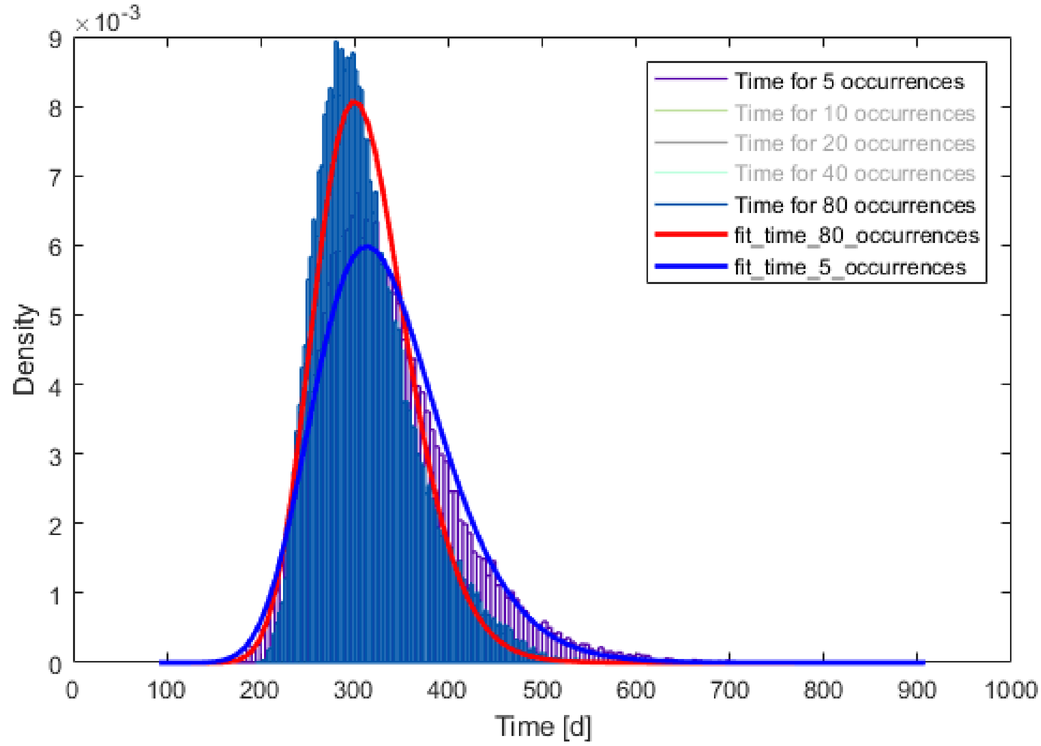

Figure 7.9: Time distribution only for 5 and 80 occurrences with lognormal fits

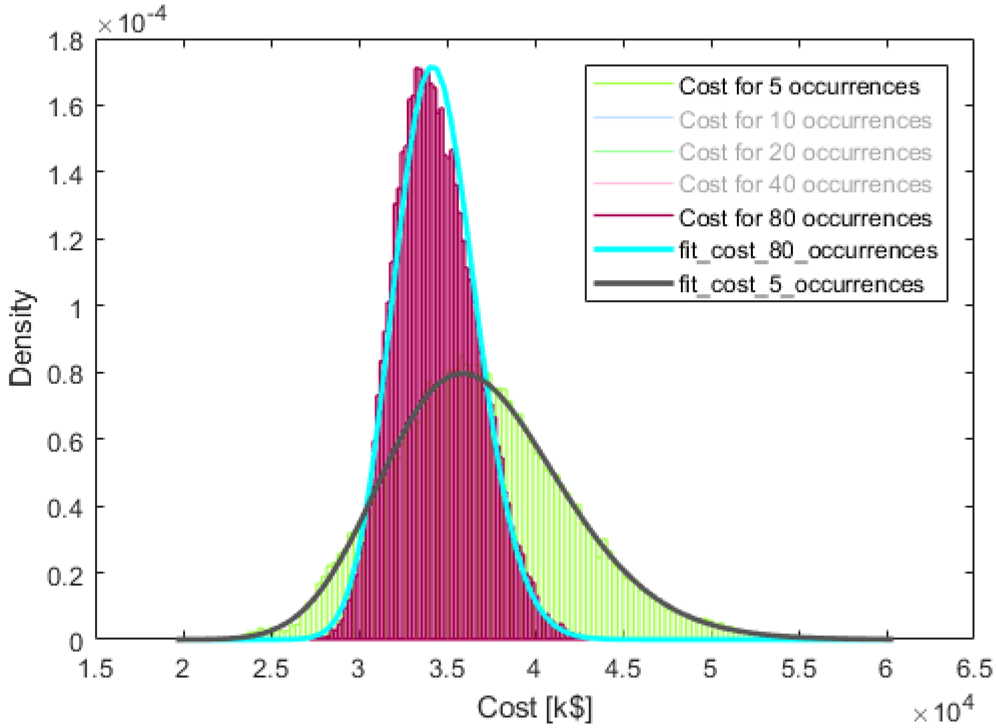

Figure 7.10: Cost distribution only for 5 and 80 occurrences with lognormal fits

More information about the fits are provided. Specifically, the distribution parameters are shown for a lognormal case:

- mu: log location
- sigma: log scale

They are presented respectively for time and cost distributions at both 5 and 80 occurrences, as they appear in Figure 7.9 and Figure 7.10.

Fit for time at 5 occurrences

```
Distribution:     Lognormal
Log likelihood:   -282286
Domain:           -Inf < y < Inf
Mean:             334.078
Variance:         4949.31

Parameter  Estimate  Std. Err.
mu          5.78968  0.000931076
sigma      0.208303   0.00065838

Estimated covariance of parameter estimates:
       mu           sigma
mu     8.66903e-07  2.79273e-19
sigma  2.79273e-19  4.33465e-07
```

Fit for time at 80 occurrences

```
Distribution:     Lognormal
Log likelihood:   -266863
Domain:           -Inf < y < Inf
Mean:             312.081
Variance:         2604.97

Parameter  Estimate  Std. Err.
mu          5.73007  0.000726192
sigma      0.162466  0.000513503

Estimated covariance of parameter estimates:
       mu              sigma
mu      5.27355e-07  -2.61492e-20
sigma  -2.61492e-20   2.63685e-07
```

Fit for cost at 5 occurrences

```
Distribution:     Lognormal
Log likelihood:   -497907
Domain:           -Inf < y < Inf
Mean:             36942.8
Variance:         2.63354e+07

Parameter  Estimate  Std. Err.
mu          10.5076  0.000617946
sigma      0.138249  0.000436961

Estimated covariance of parameter estimates:
       mu            sigma
mu       3.81858e-07  -8.47737e-20
sigma  -8.47737e-20   1.90935e-07
```

Fit for cost at 80 occurrences

```
Distribution:     Lognormal
Log likelihood:   -459028
Domain:           -Inf < y < Inf
Mean:             34429.8
Variance:         5.44968e+06

Parameter  Estimate   Std. Err.
mu           10.4444  0.000302721
sigma      0.0677257  0.000214059

Estimated covariance of parameter estimates:
       mu             sigma
mu        9.164e-08  -1.17448e-19
sigma  -1.17448e-19   4.58214e-08
```

SUMMARY AND CONCLUSIONS

In an attempt to encourage the use of the DAT for small tunnels, two major approaches were proposed and analyzed. The Calculator is a simplification of the existing DAT specifically tailored for small tunnels, that drops certain modules and uses the remaining components in a user-friendly way. This modification of the DAT from its raw form into a simple Calculator for the user to perform quick estimates for decision making, is mainly a programming task; it was investigated but not implemented.

An alternative consists in developing a Catalogue for the user to directly consult, without ever having to learn to run simulations directly on the DAT. This alternative represents a perfect balance between accuracy and efficiency in the results. It will never be absolutely accurate but will provide excellent results within a few minutes when the proper chart is consulted. The current version of the Catalogue is based on TBM excavations of small tunnels (up to 5 km in length), with a diameter of 9 m, excavated from one portal only. It can tackle complexities in geology, with different distributions, relative to: lithology, fracture and water flow. Each result is based on 50,000 simulations conducted using the DAT.

Results are essentially the total construction cost and time. They are presented in scattergrams for graphical inspection of the distribution and in tabular form in a $[Min;\ Mean;\ Max]$ format. In order to ensure reliable results, 50,000 simulations have been selected following a detailed analysis, as a compromise between accuracy and computational time. The results have also been investigated in order to better understood. For instance, the peculiar “bi-linear” shape of the scattergrams is caused by the specific cost-time inputs and the number of internal repartition of the total 50,000 simulations, between geology and construction simulations.

In the future, the Catalogue could be expanded to include additional geology parameters and/or more detailed description of the existing ones. It could also be extended to include other construction methods, different diameter sizes and more complex tunnel networks. Like a library, the wider its spectrum of data ranges, the more useful the Catalogue will be.

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Appendix A

The following are extracted from the FermiLab estimates (CNA Consulting Engineers, 2001): summary results and one detailed estimations sheet for the first drive only.

The tunnel costs were estimated using TBM cost estimating software and cost database developed by Hatch Mott MacDonald. Appendix D contains output from the software for each TBM type and tunnel diameter. Please note the following about the output:

1. 'Rock Types' are called 'TBM Types' in the main body of the report.
2. 'Rock Type A/B' is called 'TBM Type B' in the main body of the report.
3. The costs for concrete inverts were not included in the output in the appendices. These were added in the CNA cost estimating spreadsheet. The inverts are needed to provide a flat working surface. Inverts were added to TBM Types A and C only because it was assumed that the TBM Type B cast-in-place liner could be formed with a flat bottom.
4. The costs of grouting for water control were not included in the appendices. These were added in the CNA cost estimating spreadsheet. Grouting was added to TBM Types A and B only. TBM Type C is a sealed system that does not allow water to enter the tunnel so grouting is not required.

List of Abbreviations:

CIP	Cast-in-place
H	Hour
m2	Square meters of tunnel face
Nr	Number (equivalent to 'Each')
W	Week
mW	per meter per week
kWh	Kilowatt hour
l	Liter
m	Meter
m3	Cubic meter

Fermilab Tunnels

Cost Estimates

Assumptions

General

The following assumptions apply to all tunnel drives:

- 4800 metres of tunnel from shaft to shaft
- 2 ten hours shifts undertaken daily, 5 days per week
- Tunnels excavated using 3.66 metre or 4.88 metre finished diameter rock TBM
- 75 percent of TBM cost written off in first drive, 15 percent in second drive, 10 percent in third drive, and 0 percent in fourth and fifth drives
- Labour rates based on Minneapolis Project for Year 2001. (Similar to Illinois)

Specific

Assumptions used for 3.66m (12ft) diameter tunnel in Rock Type A as follows:

- No areas of difficult excavation
- A total of 400 3 metre long rockbolts installed sporadically in the tunnel crown in jointed or potentially weak zones
- Average tunnel advance rate of 225 metres per week
- No secondary lining required

Assumptions used for 3.66m (12ft) diameter tunnel in Rock Type A/B (requiring CIP liner) as follows:

- No areas of difficult excavation
- Three rockbolts, 3 metres in length, installed in each 6 metre length of tunnel
- Average tunnel advance rate of 211 metres per week
- Secondary cast-in-place concrete lining installed to prevent long term degradation of the rock

Assumptions used for 3.66m (12ft) diameter tunnel in Rock Type C as follows:

- Areas of difficult excavation encountered, slowing normal advance rate by 20 percent, over 20 percent of the tunnel length

- No primary support provided with a 200mm thick segmental concrete lining installed immediately behind the TBM following each excavation cycle
- Average tunnel advance rate of 102 metres per week

Assumptions used for 4.88m (16ft) diameter tunnel in Rock Type A as follows:

- No areas of difficult excavation
- A total of 400 3 metre long rockbolts installed sporadically in the tunnel crown in jointed or potentially weak zones
- Average tunnel advance rate of 225 metres per week
- No secondary lining required

Assumptions used for 4.88m (16ft) diameter tunnel in Rock Type A/B (requiring CIP liner) as follows:

- No areas of difficult excavation
- Three rockbolts, 3 metres in length, installed in each 4.5 metre length of tunnel
- Average tunnel advance rate of 195 metres per week
- Secondary cast-in-place concrete lining installed to prevent long term degradation of the rock

Assumptions used for 4.88m (16ft) diameter tunnel in Rock Type C as follows:

- Areas of difficult excavation encountered, slowing normal advance rate by 20 percent, over 20 percent of the tunnel length
- No primary support provided with a 225mm thick segmental concrete lining installed immediately behind the TBM following each excavation cycle
- Average tunnel advance rate of 102 metres per week

Fermilab Tunnels

Estimate Summary

12 ft dia tunnel (3.66 m)

Rock Type	Tunnel Drive	Tunnel Length (m)	Drive Cost	TBM setup	Total
A	First	4800	8,160,000	400,000	8,560,000
A	Second	4800	6,070,000	200,000	6,270,000
A	Third	4800	5,910,000	200,000	6,110,000
A	Fourth	4800	5,600,000	200,000	5,800,000
A	Fifth	4800	5,600,000	200,000	5,800,000
A/B with CIP	First	4800	18,930,000	400,000	19,330,000
A/B with CIP	Second	4800	16,350,000	200,000	16,550,000
A/B with CIP	Third	4800	16,140,000	200,000	16,340,000
A/B with CIP	Fourth	4800	15,710,000	200,000	15,910,000
A/B with CIP	Fifth	4800	15,710,000	200,000	15,910,000
C	First	4800	26,630,000	400,000	27,030,000
C	Second	4800	23,190,000	200,000	23,390,000
C	Third	4800	22,940,000	200,000	23,140,000
C	Fourth	4800	22,430,000	200,000	22,630,000
C	Fifth	4800	22,430,000	200,000	22,630,000

16 ft dia tunnel (4.88 m)

Rock Type	Tunnel Drive	Tunnel Length (m)	Drive Cost	TBM setup	Total
A	First	4800	10,930,000	400,000	11,330,000
A	Second	4800	7,360,000	200,000	7,560,000
A	Third	4800	7,080,000	200,000	7,280,000
A	Fourth	4800	6,520,000	200,000	6,720,000
A	Fifth	4800	6,520,000	200,000	6,720,000
A/B with CIP	First	4800	24,410,000	400,000	24,810,000
A/B with CIP	Second	4800	20,160,000	200,000	20,360,000
A/B with CIP	Third	4800	19,810,000	200,000	20,010,000
A/B with CIP	Fourth	4800	19,100,000	200,000	19,300,000
A/B with CIP	Fifth	4800	19,100,000	200,000	19,300,000
C	First	4800	33,360,000	400,000	33,760,000
C	Second	4800	27,830,000	200,000	28,030,000
C	Third	4800	27,400,000	200,000	27,600,000
C	Fourth	4800	26,550,000	200,000	26,750,000
C	Fifth	4800	26,550,000	200,000	26,750,000

Hatch Mott MacDonald

Detailed Cost Estimate Report

Tunnel Estimating Database

Version 0.97.3

Estimate #473: Fermilab - 4800 m - 3.66 m (12 ft) dia - good rock

Excavation Method: Rock TBM with Ribs & Lagging

Tunnel Characteristics

Tunnel Length:	4,800	Metres
Finished Diameter:	3.66	Metres
Primary Lining Thickness:	0	Metres
Secondary Lining Thickness:	0	Metres
Grout Thickness:	0	Metres
Invert Concrete Cross-section:	0	Sq.Metres

Excavation Volumes

Total Neat Excavation:	50,500	Cubic Metres
Primary Lining Volume:	0	Cubic Metres
Secondary Lining Volume:	0	Cubic Metres
Theoretical Grout Volume:	0	Cubic Metres
Invert Concrete Volume:	0	Cubic Metres

Advance Rate Calculations

Normal Excavation/Support Cycle

Excavation Cycle Length:	1.5	Metres
Excavate:	15	Minutes
Erect Support:	0	Minutes
Extend Services:	5	Minutes
Total Cycle Tim	20	Minutes

Difficult Excavation/Support Cycle

Length of Difficult Excavation:	0	Metres
Excavate:	0	Minutes
Erect Support:	0	Minutes
Extend Services:	0	Minutes
Total Cycle Time:	0	Minutes

Reduction Factors

Machine Availability:	85%
Back Up Efficiency:	70%
Planned Maintenance:	5%
Learning Curve Efficiency:	50%
Learning Curve Duration:	5 Weeks

Learning Curve Rate:	25.4	m/day
Experienced Advance Rate:	50.9	m/day
Difficult Advance Rate:	0	m/day

	Metres	Days
Learning Curve Drive:	636	25
Experienced Drive:	4,164	82
Difficult Drive:	0	0

Advance Rate and Shift Details

Shift Arrangement: 2 - 10 hour shifts x 5 days per week
Avg. Advance per Shift: 22.50 Metres
Avg. Advance per Week: 225 Metres
Duration of tunneling: 21 Weeks
Total number of shifts: 213

Resource ID	Description	Unit Rate	Unit	Resource Quantity	Unit Quantity	Total
1.0	**Labor**					
1.01	Pit Boss	$66.95	H	0.00	2,133.00	0
1.02	Working Foreman	$61.80	H	1.00	2,133.00	131,819
1.03	Tunnel Miner	$48.66	H	2.00	2,133.00	207,584
1.04	Tunnel Laborer	$39.45	H	1.00	2,133.00	84,147
1.05	Loco Driver	$46.29	H	3.00	2,133.00	296,210

Resource ID	Description	Unit Rate	Unit	Resource Quantity	Unit Quantity	Total
1.06	Shaft Bottom	$39.45	H	2.00	2,133.00	168,294
1.07	TBM Operator	$56.61	H	1.00	2,133.00	120,749
1.08	Tunnel Fitter	$44.89	H	1.00	2,133.00	95,750
1.09	Tunnel Electrician	$55.28	H	1.00	2,133.00	117,912
1.10	Shaft Top	$39.45	H	1.00	2,133.00	84,147
1.11	Crane Operator	$46.29	H	2.00	2,133.00	197,473
1.12	Surface Laborer	$39.45	H	1.00	2,133.00	84,147
1.13	Equipment Laborer	$46.94	H	1.00	2,133.00	100,123
						1,688,355

2.0 Plant

Resource ID	Description	Unit Rate	Unit	Resource Quantity	Unit Quantity	Total
2.01	TBM	$300,000.00	m2	0.75	10.50	2,362,500
2.02	TBM Backup	$250,000.00	Nr	1.00	1.00	250,000
2.03	Face Conveyor	$600.00	W	0.00	21.00	0
2.04	Locomotive	$4,200.00	W	3.00	21.00	264,600
2.05	Muck Cars & Grout Cars	$1,300.00	W	18.00	21.00	491,400
2.06	Flat Cars	$260.00	W	3.00	21.00	16,380
2.07	Manriders	$260.00	W	1.00	21.00	5,460
2.08	Track	$2.00	mW	1.00	51,975.00	103,950
2.09	Air Pipe	$3.00	mW	1.00	51,975.00	155,925
2.10	Water Pipe	$3.00	mW	1.00	51,975.00	155,925
2.11	Pump Main	$2.00	mW	1.00	51,975.00	103,950
2.12	Cabling	$4.00	mW	1.00	51,975.00	207,900
2.13	Lighting	$4.50	mW	1.00	51,975.00	233,888
2.14	Vent Ducting	$3.00	mW	1.00	51,975.00	155,925
2.15	Booster Fans	$550.00	W	3.00	21.00	34,650
2.16	Grout Mixers	$6,000.00	W	0.00	21.00	0
2.17	Grout Pumps	$2,800.00	W	0.00	21.00	0
2.18	Grout Hoses & Pipes	$200.00	W	0.00	21.00	0
2.19	Transformers & Switchgear	$650.00	W	1.00	21.00	13,650
2.20	Small Tools	$500.00	W	1.00	21.00	10,500
2.21	Other Plant	$1,000.00	W	1.00	21.00	21,000
2.22	Hoists	$450.00	W	0.00	21.00	0
2.23	Man Hoists	$1,700.00	W	1.00	21.00	35,700
2.24	Cranes	$4,000.00	W	1.00	21.00	84,000
2.25	Compressors	$800.00	W	1.00	21.00	16,800
2.26	Transformers & Switchgear	$1,700.00	W	1.00	21.00	35,700
2.27	Surface Fans	$1,000.00	W	1.00	21.00	21,000
2.28	Loaders	$1,600.00	W	1.00	21.00	33,600
2.29	Other Surface Plant	$1,500.00	W	1.00	21.00	31,500
						4,845,903

Resource ID	Description	Unit Rate	Unit	Resource Quantity	Unit Quantity	Total
3.01	Electrical Power	$0.10	kWh	1,000.00	2,100.00	210,000
3.02	Gas Oil	$0.60	l	1.00	100,000.00	60,000
3.03	Lubrication Materials	$90.00	W	1.00	21.00	1,890
3.04	TBM Spares, Cutters	$60.00	m	1.00	4,800.00	288,000
3.05	Filters	$400.00	W	1.00	21.00	8,400
3.06	Hydraulic Oil	$1.00	l	1.00	50,000.00	50,000
3.07	Other Consumables	$200.00	W	1.00	21.00	4,200
						622,490
4.0	**Materials**					
4.01	Rockbolts	$60.00	m	0.25	4,800.00	72,000
4.02	Strapping	$90.00	m	0.00	4,800.00	0
4.03	Temporary Materials	$1,000.00	W	1.00	21.00	21,000
						93,000
5.0	**Subcontracts**					
5.01	Muck Disposal	$10.00	m3	1.80	50,500.00	909,000
						909,000

Total Estimated Cost	$8,158,747
Total Estimated Cost per Metre	$1,700
Total Estimated Cost per Week	$388,512
Total Estimated Cost per Shift	$38,304

Appendix B

In this appendix appear the 52 tunnel cases, used in the study of tunnel construction costs (Sinfield and Einstein, 1998).

TABLE 1. Project Data Summary

Project number (1)	Diameter [~m (ft)] (2)	Reported cost[a] [dollars/m (dollars/ft)] (3)	Location index[b] (%) (4)	Year index[c] (%) (5)	Exchange rate[c] (%) (6)	Adjusted cost[a] [dollars/m (dollars/ft)] (7)
1	0.4 (1.4)	712 (217)	0.95	1.00	1.00	748 (228)
2	0.4 (1.4)	718 (219)	0.95	1.00	1.00	755 (230)
3	0.5 (1.6)	1,417 (432)	1.03	0.99	1.00	1,384 (422)
4	0.5 (1.8)	738 (225)	0.95	0.82	1.00	945 (288)
5	0.6 (2.0)	902 (275)	0.95	0.88	1.00	1,083 (330)
6	0.6 (2.0)	1,066 (325)	0.95	0.90	1.00	1,247 (380)
7	0.6 (2.0)	1,148 (350)	0.91	0.97	1.00	1,299 (396)
8	0.6 (2.0)	886 (270)	0.95	0.92	1.00	1,014 (309)
9	0.6 (2.0)	2,297 (700)	0.91	0.94	1.00	2,661 (811)
10	0.6 (2.0)	1,476 (450)	0.95	0.94	1.00	1,644 (501)
11	0.7 (2.3)	1,362 (415)	1.01	1.00	0.74	994 (303)
12	0.7 (2.3)	2,543 (775)	0.91	1.00	1.00	2,782 (848)
13	0.8 (2.5)	1,312 (400)	1.01	1.00	0.74	958 (292)
14	0.8 (2.5)	1,148 (350)	0.95	0.90	1.00	1,342 (409)
15	0.9 (3.0)	328 (100)	0.85	0.94	1.00	410 (125)
16	1.0 (3.3)	2,559 (780)	1.01	1.00	0.74	1,867 (569)
17	1.1 (3.5)	797 (243)	0.90	0.99	1.00	892 (272)
18	1.1 (3.5)	705 (215)	0.90	0.99	1.00	791 (241)
19	1.1 (3.5)	1,863 (568)	0.95	1.00	1.00	1,959 (597)
20	1.1 (3.7)	3,471 (1,058)	1.08	0.99	1.00	3,255 (992)
21	1.2 (4.0)	1,667 (508)	0.97	0.97	1.00	1,781 (543)
22	1.2 (4.0)	801 (244)	0.97	0.97	1.00	856 (261)
23	1.2 (4.0)	833 (254)	0.97	0.94	1.00	915 (279)
24	1.2 (4.0)	1,699 (518)	0.90	0.99	1.00	1,906 (581)
25	1.2 (4.0)	1,499 (457)	0.90	1.00	1.00	1,667 (508)
26	1.2 (4.0)	1,900 (579)	0.89	0.99	1.00	2,146 (654)
27	1.2 (4.0)	3,110 (948)	0.90	1.00	1.00	3,455 (1,053)
28	1.2 (4.0)	1,312 (400)	1.08	0.88	1.00	1,391 (424)
29	1.4 (4.5)	617 (188)	0.90	0.97	1.00	709 (216)
30	1.5 (5.0)	617 (188)	0.90	0.99	1.00	692 (211)
31	1.5 (5.0)	1,194 (364)	0.90	1.00	1.00	1,325 (404)
32	1.5 (5.0)	1,640 (500)	0.96	0.92	1.00	1,870 (570)
33	1.7 (5.5)	1,900 (579)	0.90	0.97	1.00	2,178 (664)
34	1.8 (6.0)	1,460 (445)	0.90	0.97	1.00	1,673 (510)
35	1.8 (6.0)	2,904 (885)	0.90	0.99	1.00	3,255 (992)
36	1.8 (6.0)	3,323 (1,103)	0.90	0.99	1.00	3,727 (1,136)
37	2.3 (7.4)	2,342 (714)	0.95	0.97	1.00	2,539 (774)
38	2.4 (8.0)	4,734 (1,443)	1.00	1.00	0.74	3,487 (1,063)
39	2.4 (8.0)	3,281 (1,000)	1.00	0.99	0.74	2,438 (743)
40	2.4 (8.0)	5,905 (1,800)	1.00	0.92	0.74	4,731 (1,442)
41	2.4 (8.0)	3,209 (978)	0.93	0.80	1.00	4,321 (1,317)
42	2.7 (8.7)	3,281 (1,000)	1.07	0.88	1.00	3,504 (1,068)
43	2.7 (8.9)	4,593 (1,400)	1.03	0.97	0.74	3,389 (1,033)
44	2.7 (9.0)	8,202 (2,500)	1.03	1.00	0.74	5,866 (1,788)
45	2.7 (9.0)	4,029 (1,228)	1.38	0.81	1.00	3,632 (1,107)
46	3.0 (10.0)	3,714 (1,132)	0.95	0.68	1.00	5,748 (1,752)
47	3.1 (10.3)	4,498 (1,371)	0.95	0.81	1.00	5,860 (1,786)
48	3.4 (11.0)	4,016 (1,224)	1.00	0.94	0.74	3,133 (955)
49	3.4 (11.0)	2,628 (801)	0.98	0.88	1.00	3,068 (935)
50	3.4 (11.3)	5,325 (1,623)	1.03	0.99	1.00	5,197 (1,584)
51	4.6 (15.0)	5,249 (1,600)	0.95	0.46	1.00	12,054 (3,674)
52	4.8 (15.8)	6,562 (2,000)	1.08	0.86	1.00	7,080 (2,158)

[a]Measured in 1994 U.S. dollars.
[b]Percentage of national average cost.
[c]Percentage of 1994 U.S. dollar.

50 / JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT / JANUARY/FEBRUARY 1998

Appendix C

In this appendix appear the summary estimates of the Gotthard Base Tunnel (AlpTransit Gotthard AG, 2016).

AlpTransit Gotthard San Gottardo

LZ01-370353-v2

Project data – raw construction Gotthard Base Tunnel

Length, depth and distances	
Total length of tunnel system	151.840 km
Crow flies: Portal north east – portal south east Portal north west – portal south west	 55.782 km 55.704 km
Length of Gotthard Base Tunnel, north portal Erstfeld - south portal Bodio • East tube • West tube Total both tubes	 57.104 km 57.017 km 114.121 km
Length section Erstfeld (excl. cut and cover tunnel) East tube West tube of which - Cut-and-cover tunnel east tube - Cut-and-cover tunnel west tube - Underground east tube (conventional + TBM) - Underground west tube (conventional + TBM)	 7.778 km 7.705 km 0.600 km 0.558 km 7.178 km 7.147 km
Length section Amsteg East tube West tube	 11.330 km 11.350 km
Length access tunnel Amsteg	2.222 km
Length section Sedrun (incl. MFS) East tube West tube	 8.569 km 8.738 km
Length access tunnel Sedrun	909 m
Depth shaft I Sedrun	850 m
Depth shaft II Sedrun	820 m
Length section Faido (incl. MFS)	

East tube West tube	13.456 km 13.523 km
Length access tunnel Faido	2.646 km
Length section Bodio (excl. cut and cover tunnel) East tube West tube of which - Cut-and-cover tunnel and portal east tube - Cut-and-cover tunnel and portal west tube - Underground east tube (loose rock + TBM) - Underground west tube (loose rock and + TBM)	 15.971 km 15.702 km 0.423 km 0.419 km 15.548 km 15.283 km
Length bypass tunnel Bodio	1.336 km
Length muck transportation tunnel Bodio – Buzza di Biasca	3.162 km

Advance rates achieved	
Average advance rate (per theoretical driving day, i.e. incl. downtime) • Erstfeld east / west • Amsteg east / west • Faido • Bodio	 14.27 / 14.21 m/wd 11.05 / 10.60 m/wd 10.50 / 9.92 m/wd 10.83 / 11.76 m/wd
Advance rate excl. downtime (per actual driving day = TBM performance) • Erstfeld east / west • Amsteg east / west • Faido • Bodio	 18.06 / 17.57 m/wd 14.07 / 15.83 m/wd 12.41 / 12.50 m/wd 12.47 / 14.04 m/wd
Maximum performance • Erstfeld (18.07.2009 TBM West) on 18/19.7.2009 in 24 h • Amsteg (09.07.2004 TBM West) • Faido (09.11.2008 TBM West) • Bodio (10.12.2005 TBM East)	 39.0 m/wd 56.0 m/wd 40.1 m/wd 36 m/wd 38.4 m/wd