# NUMERICAL SIMULATION OF PULL-OUT TEST ON CABLEBOLTS

MAJOR PROJECT – II

MASTER OF TECHNOLOGY
IN
**GEOTECHNICAL ENGINEERING**

SUBMITTED BY
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**2K18/GTE/11**

UNDER THE GUIDANCE OF
PROF A K SHRIVASTAVA

**CIVIL ENGINEERING DEPARTMENT**
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BAWANA ROAD, DELHI – 110042

AUGUST 2020

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# DECLARATION

I, Shikha Singh (2K18/GTE/11), student of M.Tech. (Geotechnical Engineering), hereby declare that the Major Project II titled "NUMERICAL SIMULATION OF PULL-OUT TEST ON CABLEBOLTS" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement of the award of the degree of Master of Technology, is original and is not copied from any source without proper citation. This work has not previously formed the basis of the award of any degree, diploma associateship, fellowship or any similar title of recognition.

Place: Delhi

Date: 31 August 2020

Shikha Singh

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi – 110042

# CERTIFICATE

I hereby certify that the Major Project II titled "NUMERICAL SIMULATION OF PULL-OUT TEST ON CABLEBOLTS" by Shikha Singh, belonging to Master of Technology, Geotechnical engineering, Civil Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi — Prof. A K Shrivastava

Date: 31 August 2020 — Supervisor

# ACKNOWLEDMENT

It gives me immense pleasure in expressing our gratitude to all those people who supported us and have had their contribution in making this major project possible. We would like to express our gratitude to my mentor Prof. A K Shrivastava. He consistently allowed this project to be my own work, but steered me in the right the direction whenever I needed it. I am gratefully indebted to his very valuable comments on this project.

I am extremely thankful to Prof. A K Shrivastava for incorporating in us the idea of a creative Major Project, helping me in undertaking this project and for being there whenever I needed his assistance. I am immensely grateful to all those who have helped us in making this project better, by providing us their valuable comments and guidance. I am grateful to Prof. Nirendra Dev, Head of Department, Department of Civil Engineering, Delhi Technological University (Formerly Delhi College of Engineering) and all other faculty members of our department, for their astute guidance, constant encouragement and sincere support for this project work.

Place: Delhi

Date: 31 August 2020 Shikha Singh

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# ABSTRACT

Bolting is an effective method for providing temporary and permanent support to roofs of tunnels, steep slopes, cliffs and vertical cuts and also for reinforcing dam structures. This report deals with the study of behaviour of grouted as well as non-grouted cable bolt using various models developed over time by various researchers.

Due to presence of external loads, the bolt providing stability to the structure may fail which may create a hazardous situation in case of mining and construction activities. The failure may be due to the failure of bolt itself or the failure of grout (in case of grouted bolt) along the bolt grout interface or the grout rock interface. It is thus necessary to study the effect of variation of a number of factors on the pull-out resistance and hence the failure of bolt.

The objective of this project is to study the pull-out behaviour of cablebolt. The model developed in the software focuses on understanding the influence of various dimensional and material properties of the bolt as well as grout on the pull-out test of the bolt. The factors include diameter and length of bolt, confining pressure, thickness of grout annulus and fiction angle for the grout material etc. As a part of the initial stage of the work, a thorough literature review had been conducted in the previous project.

# CHAPTER 1

# INTRODUCTION

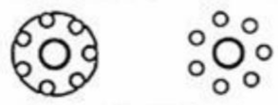
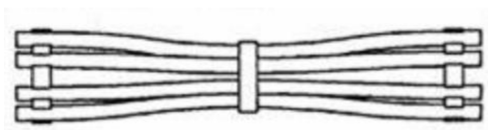
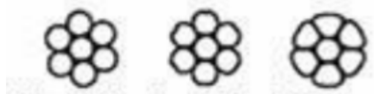
## 1.1 Cablebolts

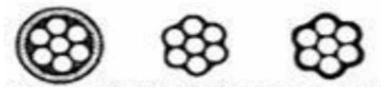
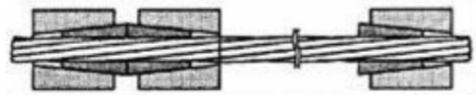
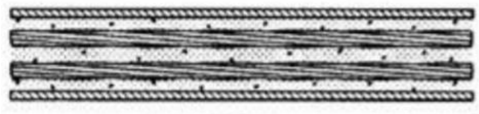
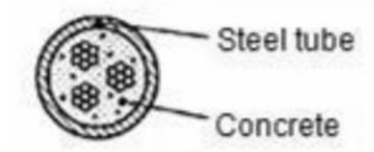
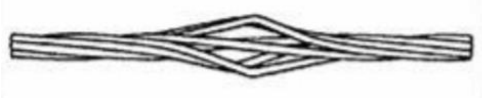
A cablebolt is a reinforcement made up of a number of steel wires, tied together into strand, which makes it flexible in nature. It is a very flexible form of support, since the cable can bend in any direction, it makes installation of bolts from confined places easier. Also, they can be obtained using a number of different varieties of the steel wires for a range performance analysis. More than one cablebolt strand can be easily placed in a single borehole, to increase tensile capacity, if the borehole diameter is sufficiently large to occupy both. Additionally, plates, straps and meshes can be used to provide surface strength. Cablebolts can be used in collaboration with other systems to provide support, examples include shotcrete, grouted rebar and bolts.

Cablebolts are used in underground mines to:

- provide safe environment for the working miners,
- increase stability of the rock mass

Table 1: Development of cables as a reinforcing element [23]

| TYPE | LONGITUDINAL SECTION | CROSS SECTION |
|---|---|---|
| **Multi-wire tendon (Clifford, 1974)** |  Figure 1 |  Figure 2 |
| **Birdcaged multi-wire tendon (Jirovec, 1978)** |  Figure 3 |   Figure 4 |
| **Single strand (Hunt & Askew, 1977)** |  Figure 5 |   Figure 6 |

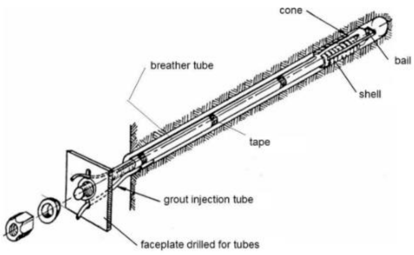
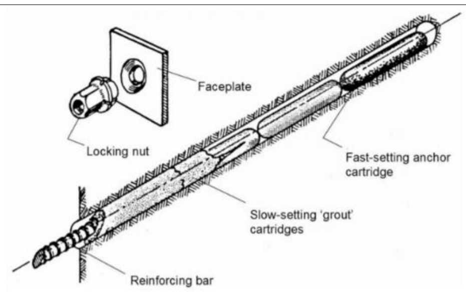
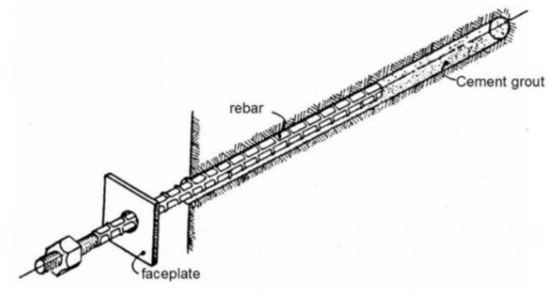
| | | |
|---|---|---|
| **Coated single strand (Hunt & Askew, 1977)** |  Figure 7 |  Sheathed Coated Encapsulated Figure 8 |
| **Barrel and wedge anchor on strand (Mathews et al, 1984)** |  Double Stranded Single Stranded Figure 9 |  3 component 2 component Figure 10 |
| **Swaged anchor on strand (Schmuck, 1979)** |  Figure 11 |  Square Circle Figure 12 |
| **High capacity shear dowel (Mathews et al, 1986)** |  Figure 13 |   Figure 14 |
| **Birdcaged strand (Hutchins et al, 1990)** |  Figure 15 |  Antinode Node Figure 16 |
| **Bulbed strand (Garford, 1990)** |  Figure 17 |  Antinode Node Figure 18 |
| **Ferruled strand (Windsor, 1990)** |  Figure 19 |  Antinode Node Figure 20 |

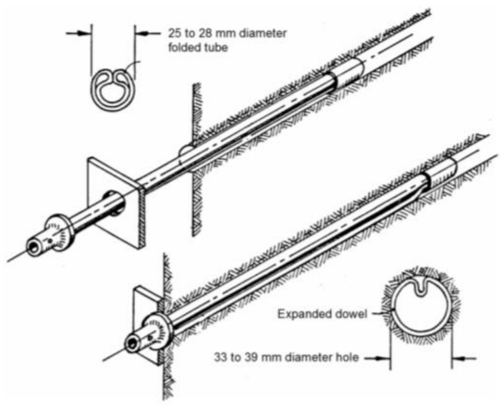
## 1.2 Rock bolts and dowels

Generally, rock bolts consist of steel rods which have not been deformed along with a chemical or mechanical anchor and a face plate with nut may or may not be present. After installation, they may or may not be tensioned. For temporary applications the bolts are generally non-grouted. For long term applications resin or cement grout maybe used to fill up the space between the host rock and the bolt.

Dowels or anchor bars comprise of deformed kind of steel bars which are grouted. It is not possible to provide tension to the dowels and the load is generated because of movements in the host rock mass to which it is grouted. For efficiency, they are installed before significant movement in the rock mass has occurred.

Table 2: Various kinds of rockbolts and dowels [6]

| TYPE | LONGITUDINAL SECTION | PROPERTIES |
|---|---|---|
| **Mechanically anchored rockbolts** | <br>Figure 21 | ⇒ Suitable for hard rock<br>⇒ Not effective in closely jointed or soft kind of rock<br>⇒ Prevents corrosion<br>⇒ Locks mechanical anchor in a fixed place |
| **Resin anchored rockbolts** | <br>Figure 22 | ⇒ Works in most rocks<br>⇒ Most resin systems have limited shelf life pertaining to storage conditions esp. temperature<br>⇒ Uncertaninty about long term corrosion protection |
| **Grouted dowels** | <br>Figure 23 | ⇒ If stress change anticipated, use grouted dowels instead of grouted rock bolts<br>⇒ Complex and more time consuming process of installing as compared to grouted rock bolts |

| | | |
|---|---|---|
| **Friction dowels or 'Split Set' stabilisers** [17] | <br>Figure 24 | ⇒ Less time consuming<br>⇒ Simple to install<br>⇒ Corrosion is primary issue which can be reduced but not prevented by galvanising |
| **'Swellex' dowels (Atlas Copco)**[21] | <br><br>Figure 25 | ⇒ No pushing force required during insertion<br>⇒ Activated by injection of high pressure water<br>⇒ Corrosion is of prime concern which can be overcome by coating<br>⇒ Major advantage is speed of installation |

## 1.3 Rock mass classification

Terzaghi (1946) which is one of the earliest methods of rock mass classification gave rock loads carried by steel sets which have been estimated on the basis of descriptive classification. He classified the rock mass broadly into following seven categories.

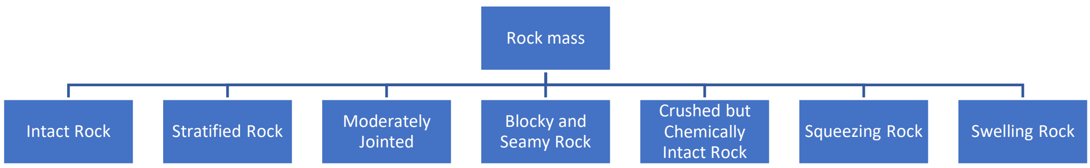



Figure 26: Rock mass classification as per Terzaghi [18]

He outlined the characteristics especially when gravity acts as a dominant driving force, which govern rock mass behaviour. The specific definitions and the practical comments included in his paper are good examples of the type of information pertaining to geology, which is functional for engineering design although they don't particularly provide valuable insight into the design of support systems.

Since, in this paper, the pull-out tests are conducted on models of intact rock mass hence, the classification of this category of rock mass is of significance.

The classification of intact rock mass [3] is based on their UCS values and Modulus ratio values. As per UCS they classified intact rocks into five classes while on the basis of Modulus ratio they were classifies into three classes. Combining these two gave the category of intact rock mass.

The modulus ratio is defined as[3]

$$MR = E_{t50} / \sigma_{ult} \qquad \text{...... equation (1)}$$

Where

MR = Modulus Ratio

$E_{t50}$ = Tangent modulus at 50% ultimate compressive strength of rock

$\sigma_{ult}$ = Uniaxial ultimate compressive strength

Table 3: Classification of Intact rock as per UCS [3]

| Class | Description | UCS (MPa) |
|---|---|---|
| A | Very high strength | > 224 |
| B | High strength | 112 - 224 |
| C | Medium strength | 56 - 112 |
| D | Low strength | 28 - 56 |
| E | Very low strength | < 28 |

Table 4: Classification of Intact rock as per Modulus Ratio [3]

| Class | Description | Modulus Ratio |
|---|---|---|
| H | High Modulus Ratio | > 500 |
| - | Average Modulus Ratio | 200 - 500 |
| L | Low Modulus Ratio | < 200 |

## 1.4 Reinforcement system

A reinforcement system[24] comprises four principal components which include the rock (intact or jointed), the reinforcing element i.e. bolt, cables or dowels, the internal structure which refers to the medium or mechanical action at the interface of the bolt and the rock and lastly, the external fixture which refers to the face plate and the nut. In this project all the components are present in the model except the external fixture.

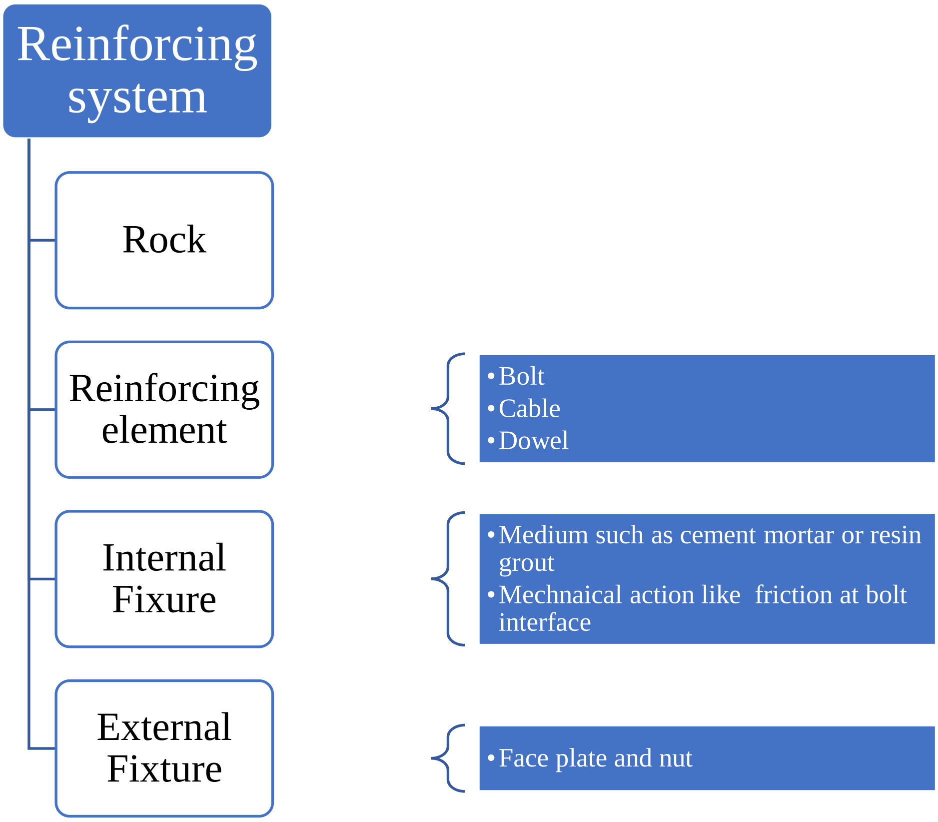



Figure 27: Components of reinforcing system[24]

## 1.5 Modes of failure of bolt

The pull-out capacity of a bolt depends mainly on the mechanism of the failure of the reinforcement system. For a non-grouted bolt and grouted bolt, the possible failure modes are mentioned below.

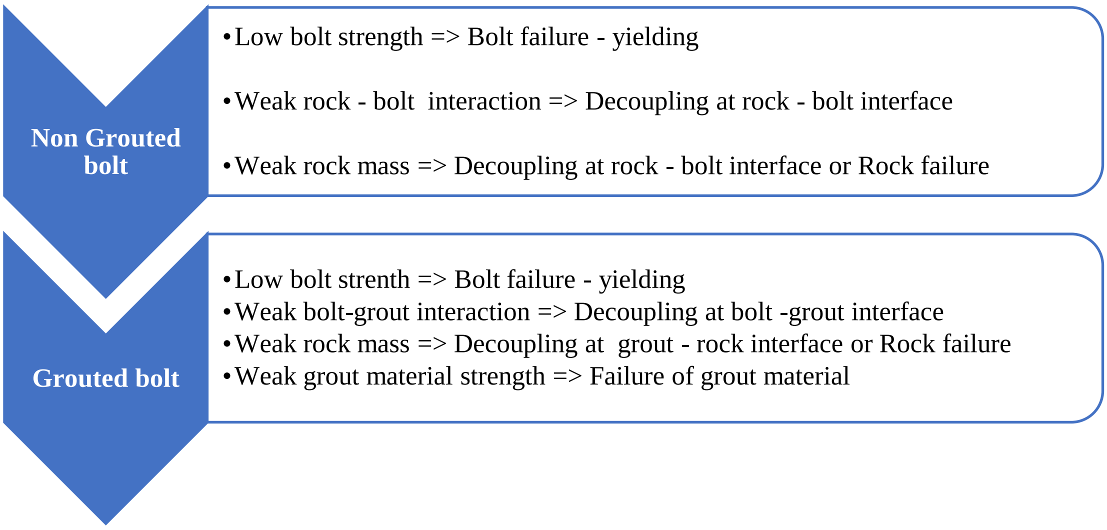



Figure 28: Modes of failure of bolt [11]

In this project, the mode of failure is taken to be debonding at the interface of the bolt and grout surface so as to obtain the pull-out load of the bolt.

## 1.6 Discrete Element Modelling

Discrete-based methods represent the model material to be comprising of independent elements, which interact with each other to give suitable results. The model represents discontinuities to be of discrete nature, which are then depicted as the required boundary of single element. Discrete Element Method (DEM) refers to the numerical method for discrete systems where individual elements are non-deformable in nature. Although this method is more suitable for granular natured material, many geomaterials, like rocks, which definitely do not appear to be like granular material, make use of discrete models however. They are often utilised to understand their behavior, by assuming that the material can be approximated as group of discrete elements combined together by different cohesive forces or maybe cementing effects. Thus, the mechanical behavior of the model material can be calculated via the overall contributions of the discrete elements under prescribed loading or unloading processes as the case maybe to exhibit motion or displacement or sliding or inter-element. The Discrete Elements (DE) can be rigid in nature (or deformable), with rough or smooth edges and surfaces of varying shapes and sizes.

## 1.7 3DEC Software [10]

*3DEC* is a 3-dimensional program for numerical simulation primarily based on the distinct element method for evaluating discontinuum models. *3DEC* calculates the response of discontinuous model materials (for example jointed rock mass) undergoing either static or dynamic loading. The deformable blocks are converted into a mesh of finite difference elements. Each element acts as per already well known linear or nonlinear stress-strain law.

*3DEC* has built-in behavior models for various materials i.e. for intact blocks and for the jointed rock mass, the discontinuities, that allow the simulation of tests and corresponding outcomes comparable to results in fields.

## 1.8 Objective of this project

The prime objective of this project is to study the pull-out behaviour of cablebolt. The model developed in the software focuses on understanding the influence of various dimensional and material properties of the bolt as well as grout on the pull-out test of the bolt. The factors include diameter and length of bolt, confining pressure, thickness of grout annulus and fiction angle for the grout material etc.

# CHAPTER 2

# LITERATURE REVIEW

Li et al (1999) gave an analytical model that takes into account elastic, debonding and softening zones for the distribution of shear stress for fully grouted kind of bolts in tension. He established the formulas for shear and axial stress along axis of loading for fully grouted and fully frictionally coupled kinds of bolts. The models were prepared for bolt subjected to uniform nature of rock deformation and another for bolt subjected to discrete opening of a rock joint for in situ cases. Bolts with and without face plate were considered and other factors that were taken into account are Young's modulus of elasticity, Poisson's ratio of both rock and bolt, diameter of bolt and bolt spacing. It was observed that for fully frictional bolts that shear stress was less and even reached zero but for the case of a fully frictional kind of bolt, the shear strength was close to ultimate shear strength only. The bolt had a pickup, anchor length and neutral point as was given by Freeman (1978). Face plate induced a direct stress of tensile nature which enhanced reinforcement effect and reduced shear strength on bolt surface. In jointed rock mass, opening displacement induces axial stress peaks in bolt. The drawback was that the influence of the grout material property was not considered.

Killic et al (2002) gave an experimental test conducted to obtain the influence of grout material and bolt material on the pull-out capacity of bolt. He established the expression for ultimate bearing capacity of the bolt as given by Aldorf and Exner (1986). The experiment was conducted on rebars, grouted into basalt rocks using cement mortar. The variation of bolt bond strength with water-cement ratio was studied and best fit curves were obtained by regression process. It was observed that the maximum pull-out increases linearly with section of bolt (embedment length constant). Also, the pull-out resistance of bolt increases linearly with embedment length. On increasing grout's uniaxial compressive strength, Young's modulus of grout and shear strength increases bond strength of bolts was obtained from the results. One of the shortcomings was model size restricted due to lab constraints. Also, as per Hoek & Wood (1989), the most dominant failure mode is shear at bolt grout interface. Thus, for the experiment, only this failure has been focused on while other failures are those of the bolt and grout material or failure at grout rock interface have been ignored.

Grasselli (2005) conducted experimental tests using strain gauge as well as numerical analysis by finite element modelling for shearing strength tests on fully grouted kind of bolt. Large-scale shearing test was conducted with two symmetrical joints, formed by three large concrete blocks, all symmetrically reinforced. Joints were smoothened and five strain gauges were used. Passive cement grouted bolts were used. Bolts at different inclinations to the normal to the joint were used in the model. Shear force, force normal to joint, vertical displacement of central block, deformation of steel bolt were noted down. A 3D FEM model was also created for the bolt wherein the contours of deviator stress was studied. Curve for dimensionless bolt contribution to shear strength T* vs displacement was plotted. Similar shapes were observed for both types of bolts. Formation of plastic hinge was analysed and resistance mobilised by bolt was obtained to be directly proportional to area of steel. In the 3D model, the contours of second invariant of stress was studied, to obtain traction between two plastic hinge as the cause for failure (for full steel bolt) and shear concentrated on joint plane as the cause for failure (for tube).

Thevenin et al (2017) conducted experimental pull-out tests on three different kinds of rock bolts and three different kinds of cable bolts for various embedment length and confining pressures. Two grouting material used were cement and resins with debonding at interface of grout surface and bolt surface. Herein, the significance of plain and threaded surface had been studied such that the influence of adhesion and friction has been observed. Effect of confining pressure and pull-out load on the bolt has the main factors which have been varied. The results obtained for both cable bolts and rock bolts indicated similar behaviour in terms of the pull-out loads obtained for various cases.

Teymen et al (2018) conducted experimental test using strain gauge, computer-controlled data logger with 8 channels, hydraulic pull for load application. For loads exceeding yield point, voltage change is converted to strain reading via date logger. He established the relation of voltage change in strain gauges to the actual strain values. Double shear strength and UCS of grout was calculated simultaneously. Axial and shear stress distribution diagrams were plotted with respect to the distance from rock surface wherein the loading was applied. Elastic load transfer behaviour from bolt to surrounding grout for each grout type. Bolt divided into four parts and decoupling of various portions with respect to loading conditions were studied. Ultimate bond stress occurred near loading point of bolt. The shortcomings include model being of lab size. Also, only effect of grout property variation was considered and the effect of rock strength was not considered. Moreover, rock – grout interface was not studied for failure analysis, only grout bolt interface was studied.

# CHAPTER 3

# 3D NUMERICAL SIMULATION

The major difficulty faced while designing reinforcement system is the existence of various kinds of elements which differ drastically in terms of material properties. These elements are the rock, grout (may or may not be present), face plate and nut (may or may not be present) and the reinforcement itself. The mechanical properties such as elasticity, plasticity, strength, toughness as well as stiffness of each of these elements is different from the other making it necessary to consider properties of each element while designing. The contact surfaces of the different elements also play a significant role in the design.

To obtain a comparable analysis to the one obtained in the field, 3-dimensional design is much more reliable than a 2-dimensional analysis which basically involves plane strain analysis. Hence, in this paper, a 3-dimensional model for conducting the pull-out test on the bolt is prepared for grouted and ungrouted bolts Variation of the pull-out force with the variation in bolt length, diameter, rate of extraction, confining pressure and length of the edge of the tetrahedral for the model, of bolt has been studied for grouted as well as non-grouted cases. In addition to this, the pull-out load on the bolt has also been obtained for variation in thickness of grout and friction angle for the case of grouted bolt only.

## 3.1 Validation of proposed framework

The simulation of a pull-out load for grouted bolts obtained from the software are compared with the pull-out loads obtained via analytical model [1] for plain cable bolts as well as the experimental results obtained for the same. As per the software, when the shear reaction at the bolt – grout interface reaches zero value, the corresponding load obtained gives value of pull-out load. The material properties that have been used for simulation are same as has been used to obtain the pull-out load via the analytical model and the experimental analysis. The result obtained from the software is in good agreement as compared to the pull-out load that has been obtained via the analytical method as has been tabulated below for reference.

Table 5: Comparision of pull-out load for validation of proposed framework

| **Length (mm)** | Pull out load as per software (kN) | Pull out load as per analytical model (kN) | Pull out load as per experimental model (kN) |
|---|---|---|---|
| **150** | 43.32 | 41.8 | 43.4 |
| **200** | 56.40 | 55.7 | 55.8 |
| **300** | 84.10 | 83.2 | 85.2 |
| **400** | 109.96 | 110.4 | 115.6 |
| **500** | 141.87 | 137.3 | 145.5 |
| **600** | 166.82 | 163.6 | 168.6 |
| **700** | 194.34 | 189.3 | 187.2 |

## 3.3 Numerical Model

A 3-dimesional model was created consisting of a block of size 15 cm x 19 cm x 60 cm [20] with a bolt placed at the centre along the z - axis. The number of nodes provided to the bolt are two which are present at the extreme ends of the reinforcement. The velocity is applied to the bolt until shear force at the bolt – grout interface becomes zero.

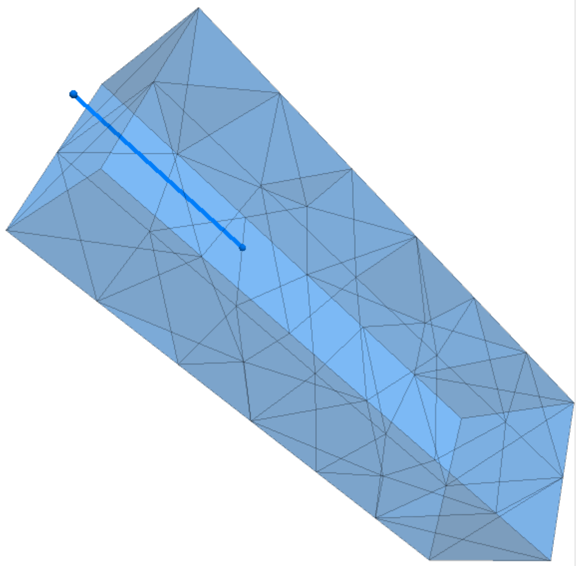


Figure 29: The 3D Model post pull out of bolt

## 3.4 Material Properties

The properties of the rock material as well as that of the grout material and the dimensional properties of the bolt and rock have been mentioned below for reference. The material properties have been taken up from various research papers whose references have been mentioned while the dimensional properties have been assumed to obtain suitable results for the comparative analysis.

Table 6: Material properties

| Element | Property | Values |
|---|---|---|
| Reinforcement | Diameter (cross sectional area) | 32 mm (804 $mm^2$),<br>25 mm (491 $mm^2$),<br>20 mm (314 $mm^2$),<br>16 mm (201 $mm^2$),<br>12 mm (113 $mm^2$). |
| | Bond length | 40 cm, 35 cm, 30 cm, 25 cm, 20 cm. |
| | Young's Modulus of elasticity [20] | 193 GPa |
| | Tensile capacity [20] | 600 MPa |
| | Rate of extraction | 0.01, 0.1, 1, 2, 4 |
| Interface | Bond stiffness [10] | 112 x $10^6$ N/m/m |
| | Cohesive Strength [10] | 175 x $10^3$ N/m |
| Rock | Young's modulus [20] | 25.6 GPa |
| | UCS Value [20] | 62.4 MPa |
| | Poisson's ratio [20] | 0.26 |
| | Density [20] | 2310 kg/$m^3$ |
| | Category as per classification of intact rock mass [3] | Medium Strength Rock |
| Grout Material | Angle of friction | $15^O$, $25^O$, $30^O$, $45^O$, $60^O$ |
| | Thickness | 5 mm, 10 mm, 15 mm, 20 mm, 50 mm |

Table 7: Model properties

| Property | Value |
|---|---|
| Kind of rock | Intact Rock |
| Material Model | Mohr-Coulomb (Basic) |

## 3.5 Flowchart

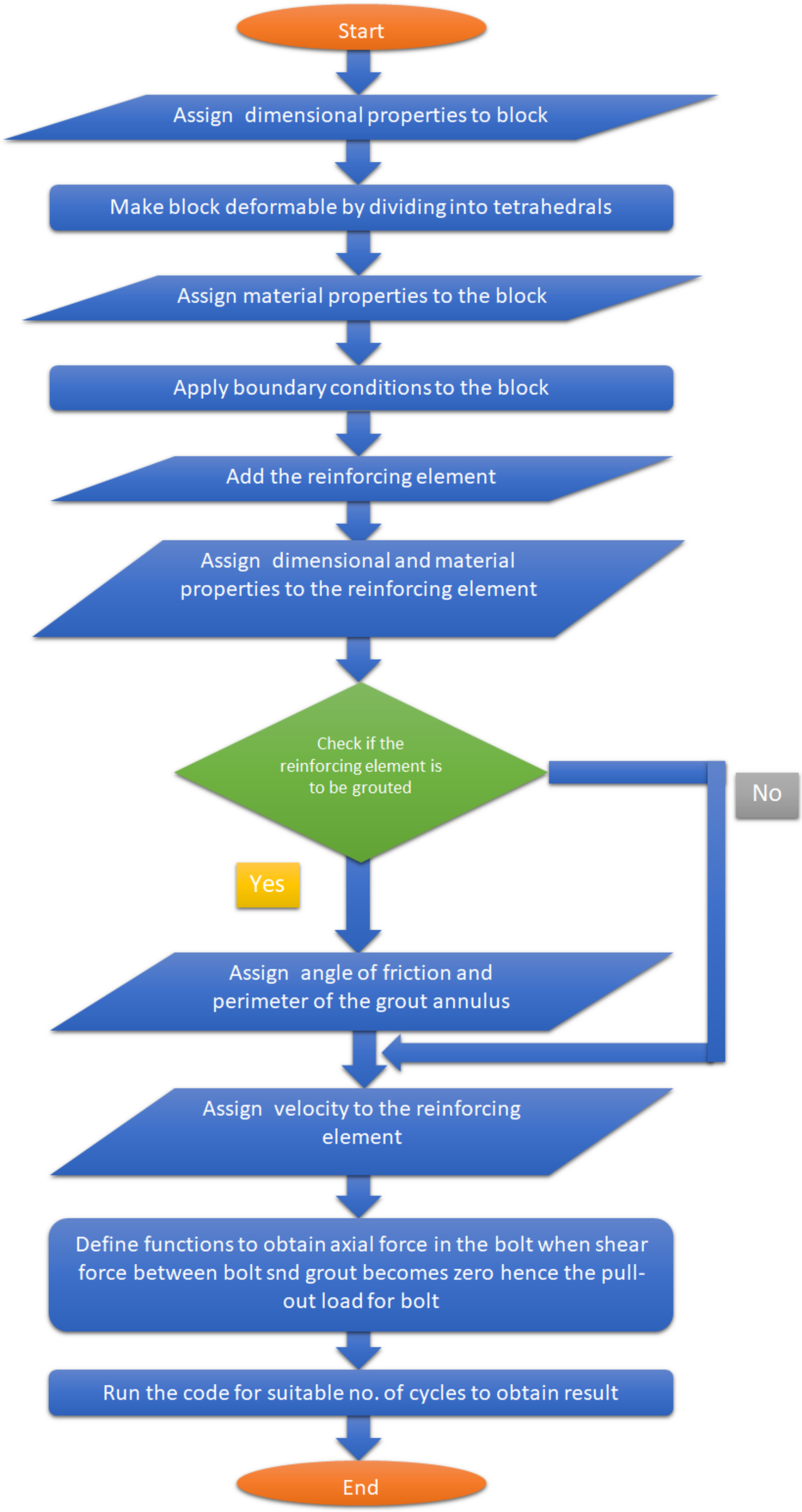



Figure 30: Flow chart

# CHAPTER 4
# OUTCOMES

## 4.1 Results

### 4.1.1 Variation with length

The variation in pull out load has been obtained for both grouted and non-grouted bolts with respect to the variation in the length of the bolt. The parameters whose values have been kept constant are

Radius = 25 mm

Rate of extraction = 1

Thickness of grout (for grouted bolt only) = 5 mm

Friction angle (for grouted bolt only) = $25^O$

Table 8: Variation of pull out load with length

| Length (mm) | | 200 | 250 | 300 | 350 | 400 | Equation | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| Pullout load (kN) | Grouted bolt | 42.08 | 56.53 | 63.24 | 78.77 | 77.23 | P = 185.11 * l + 8034.79 | 0.921677 |
| | Non grouted bolt | 17.50 | 21.88 | 26.26 | 30.64 | 35.02 | P = 87.56* l -8.09 | 1 |

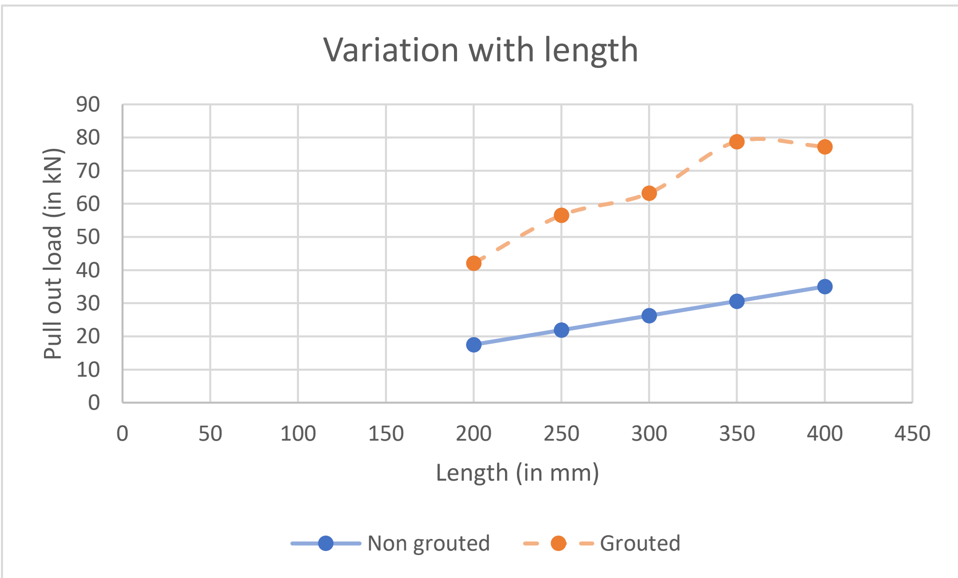



Figure 31: Variation of pull out load with length

The load-displacement curves for the pull out of the bolt with respect to the variation of the length of the bolt has been shown below for reference.

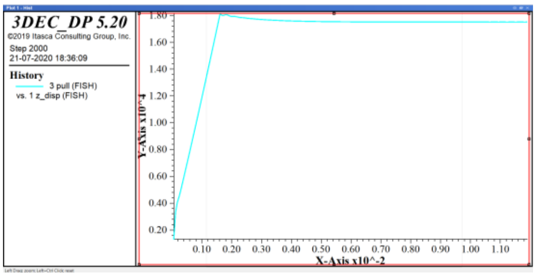



Figure 32: Length = 200 mm (non grouted)

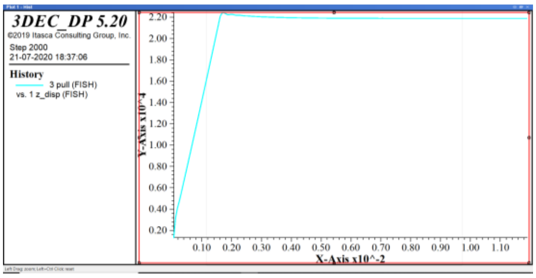



Figure 33: Length = 250 mm (non grouted)

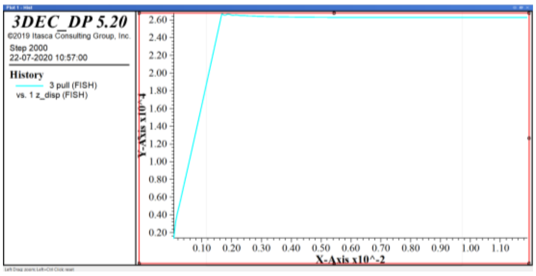



Figure 34: Length = 300 mm (non grouted)

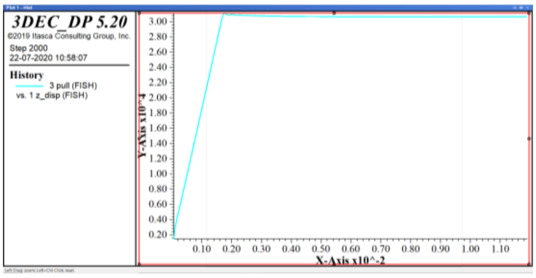



Figure 35: Length = 350 mm (non grouted)

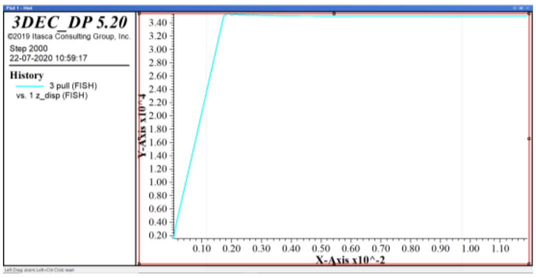



Figure 36: Length = 400 mm (non grouted)

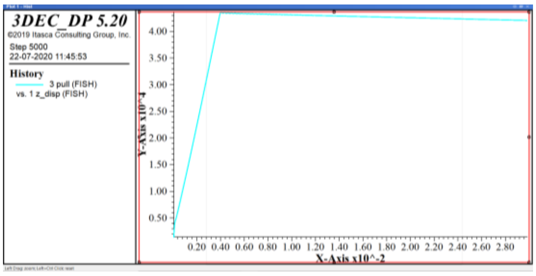



Figure 37: Length = 200 mm (grouted)

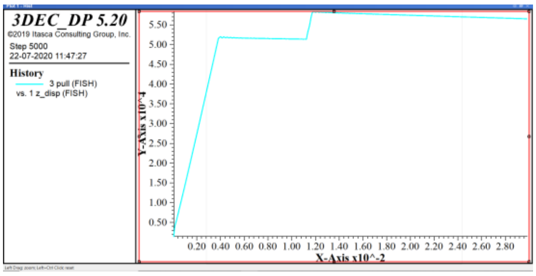



Figure 38: Length = 250 mm (grouted)

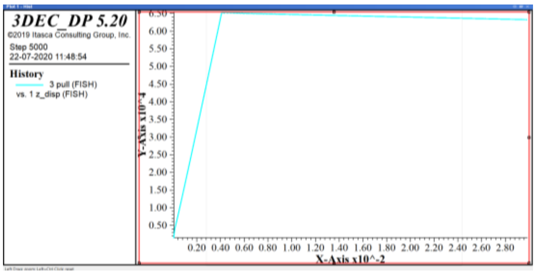



Figure 39: Length = 300 mm (grouted)

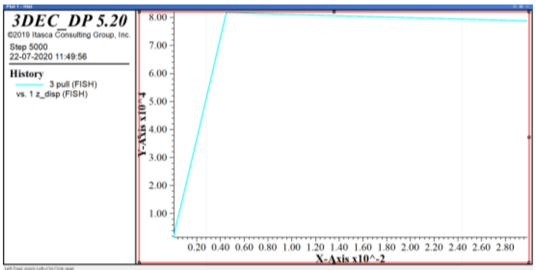



Figure 40: Length = 350 mm (grouted)

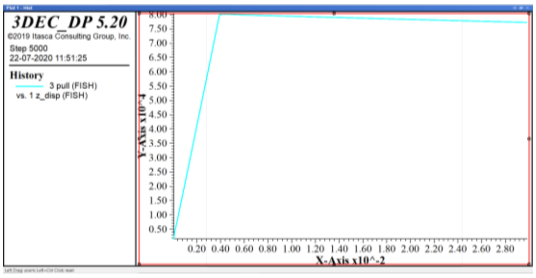



Figure 41: Length = 400 mm (grouted)

### 4.1.2 Variation with diameter

The variation in pull out load has been obtained for both grouted and non-grouted bolts with respect to the variation in the diameter and hence the cross sectional area of the bolt. The parameters whose values have been kept constant are

Length = 200 mm

Rate of extraction = 1

Thickness of grout (for grouted bolt only) = 5 mm

Friction angle (for grouted bolt only) = $25^{O}$

Table 9: Variation of pull out load with diameter

| Diameter (mm) | | 12 | 16 | 20 | 25 | 32 | Equation | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| Pullout load (kN) | Grouted bolt | 33.14 | 35.09 | 38.66 | 42.08 | 46.84 | P = 684.82 * d + 24940.33 | 0.999989 |
| | Non grouted bolt | 17.51 | 17.51 | 17.51 | 17.50 | 17.50 | P = -0.58 * d + 17518.90 | 0.809818 |

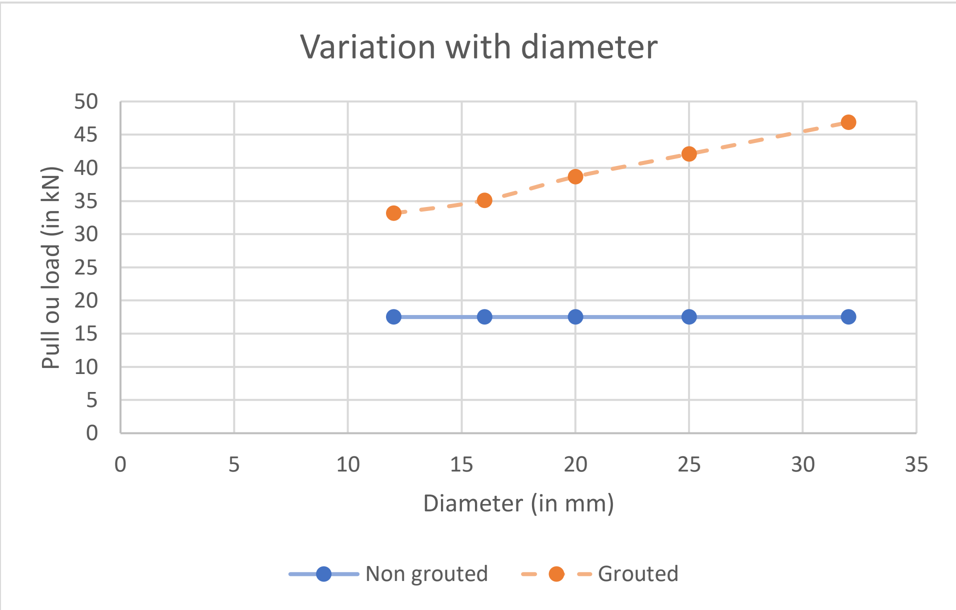



Figure 42: Variation of pull out load with diameter

The load-displacement curves for the pull out of the bolt with respect to the variation of the diameter of the bolt has been shown below for reference.

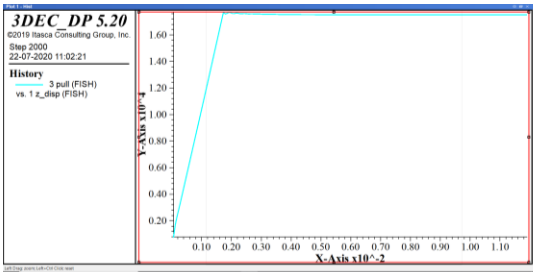



Figure 43: Diameter = 12 mm (non grouted)

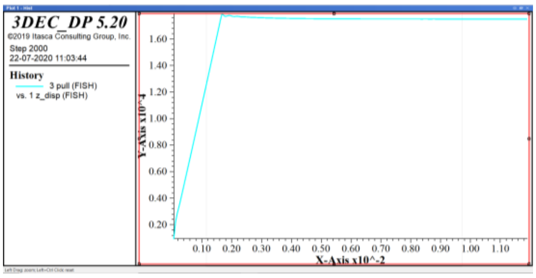



Figure 44: Diameter = 16 mm (non grouted)

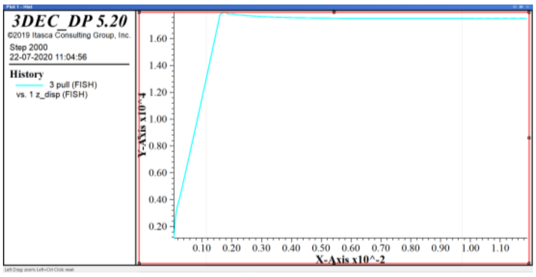



Figure 45 Diameter = 20 mm (non grouted)

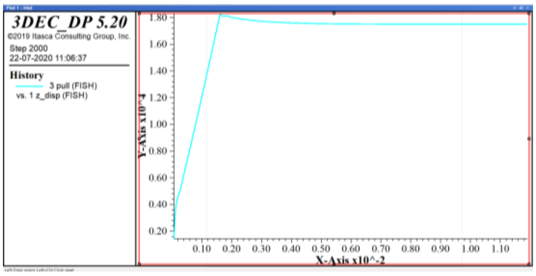



Figure 46: Diameter = 25 mm (non grouted)

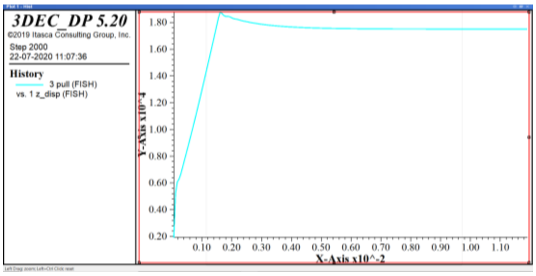



Figure 47: Diameter = 32 mm (non grouted)

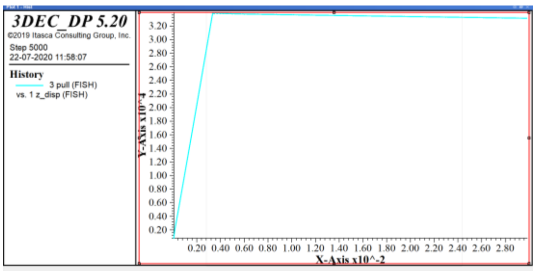



Figure 48: Diameter = 12 mm (grouted)

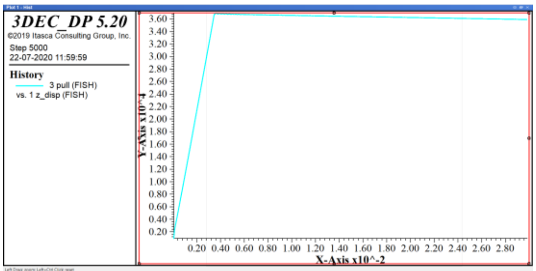



Figure 49: Diameter = 16 mm (grouted)

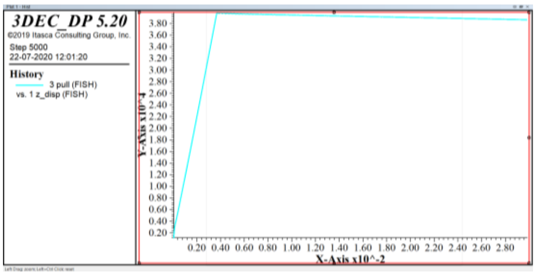



Figure 50: Diameter = 20 mm (grouted)

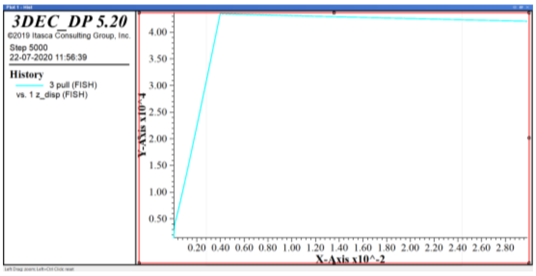



Figure 51: Diameter = 25 mm (grouted)

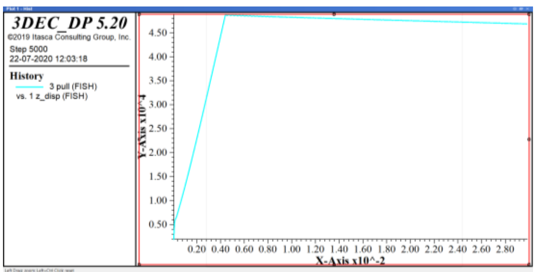



Figure 52: Diameter = 32 mm (grouted)

### 4.1.3 Variation with rate of extraction

The variation in pull out load has been obtained for both grouted and non-grouted bolts with respect to the variation in the rate of extraction (r) of the bolt. The parameters whose values have been kept constant are

Radius = 25 mm

Length = 200 mm

Thickness of grout (for grouted bolt only) = 5 mm

Friction angle (for grouted bolt only) = $25^O$

Table 10: Variation of pull out load with rate of extraction

| **Rate of extraction** | | **0.01** | **0.1** | **1** | **2** | **4** | **Equation** | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| **Pullout load (kN)** | **Grouted bolt** | 33.08 | 33.01 | 32.08 | 31.40 | 31.40 | P = - 430.50 * r + 32812.98 | 0.757799 |
| | **Non grouted bolt** | 17.50 | 17.50 | 17.50 | 17.50 | 17.50 | - | - |

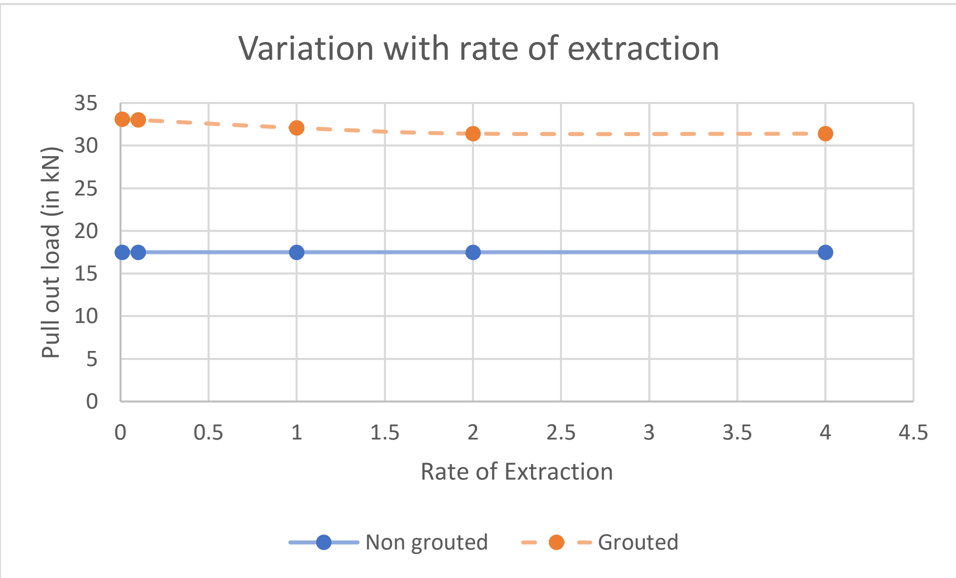



Figure 53: Variation of pull out load with rate of extraction

The load-displacement curves for the pull out of the bolt with respect to the variation of the rate of extraction of the bolt has been shown below for reference.

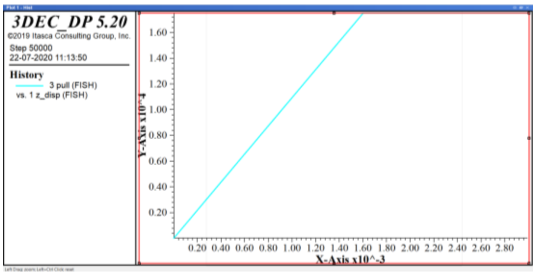



Figure 54: Rate = 0.01 (non grouted)

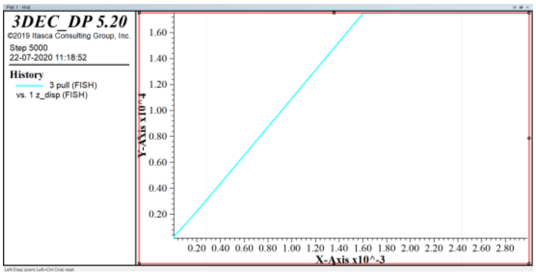



Figure 55: Rate = 0.1 (non grouted)

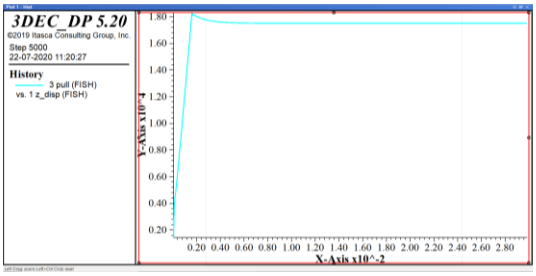



Figure 56: Rate = 1 (non grouted)

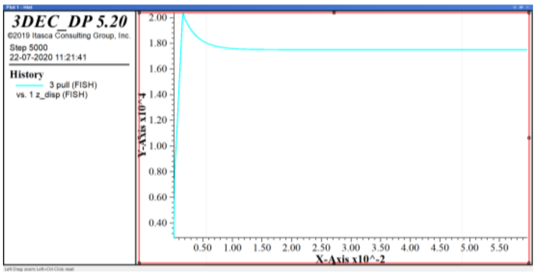



Figure 57: Rate = 2 (non grouted)

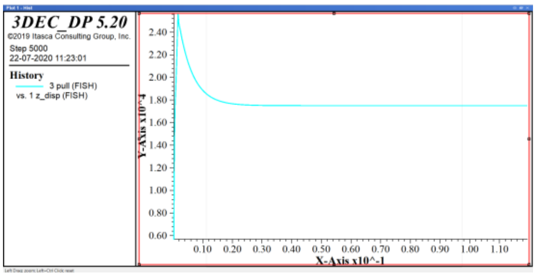



Figure 58: Rate = 4 (non grouted)

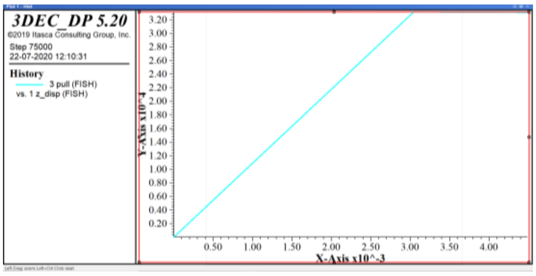



Figure 59: Rate = 0.01 (grouted)

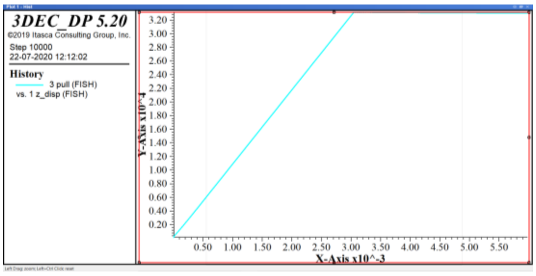



Figure 60: Rate = 0.1 (grouted)

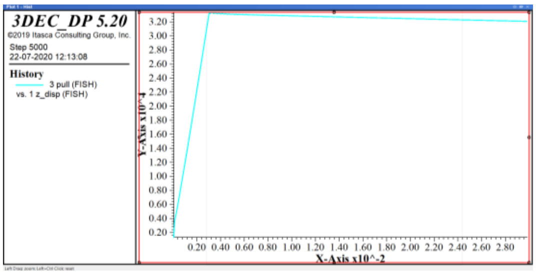



Figure 61: Rate = 1 (grouted)

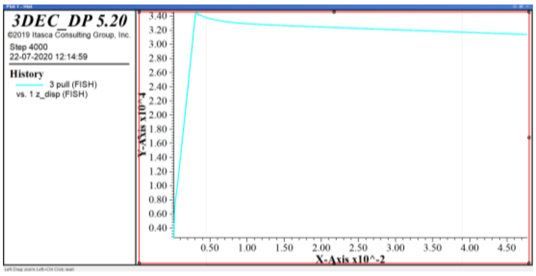



Figure 62: Rate = 2 (grouted)

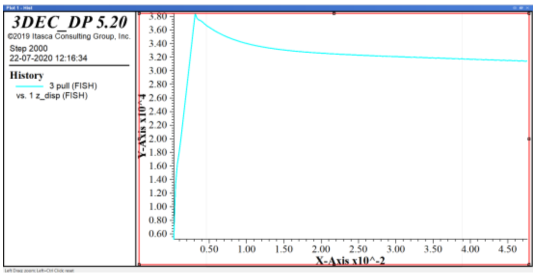



Figure 63: Rate = 4 (grouted)

### 4.1.4 Variation with confining pressure

The variation in pull out load has been obtained for both grouted and non-grouted bolts with respect to the variation in the confining pressure (cp). The parameters whose values have been kept constant are

Radius = 25 mm

Length = 200 mm

Rate of extraction = 1

Thickness of grout (for grouted bolt only) = 5 mm

Friction angle (for grouted bolt only)= $25^O$

Table 11: Variation of pull out load with confining pressure

| **Confining Pressure (MPa)** | | **1.5** | **3** | **5** | **10** | **20** | **Equation** | **$R^2$** |
|---|---|---|---|---|---|---|---|---|
| **Pullout load (kN)** | **Grouted bolt** | 24.57 | 32.08 | 42.08 | 67.12 | 117.24 | P = 5009.407 * cp + 17042.11 | 1 |
| | **Non grouted bolt** | 17.50 | 17.50 | 17.50 | 17.50 | 17.50 | - | - |

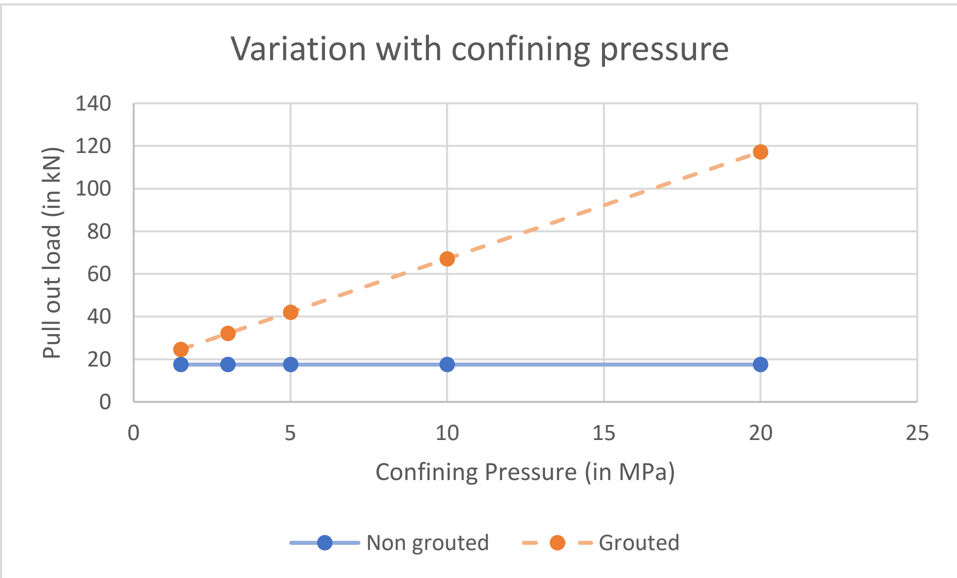



Figure 64: Variation of pull out load with confining pressure

The load-displacement curves for the pull out of the bolt with respect to the variation of the confining pressure (C.P.) has been shown below for reference.

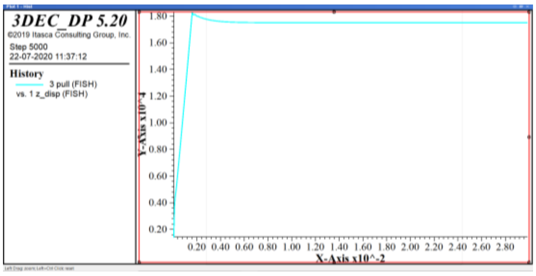



Figure 65: C.P. = 1.5 MPa (non grouted)

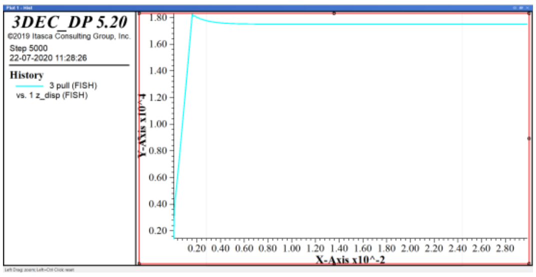



Figure 66: C.P. = 3 MPa (non grouted)

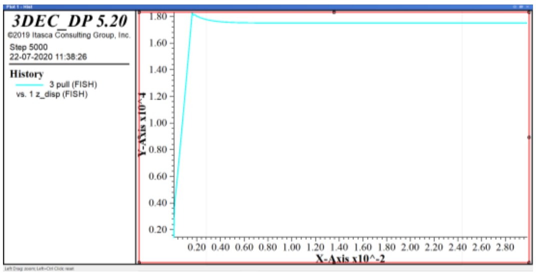



Figure 67: C.P. = 5 MPa (non grouted)

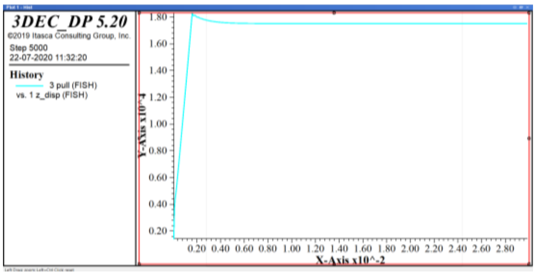



Figure 68: C.P. = 10 MPa (non grouted)

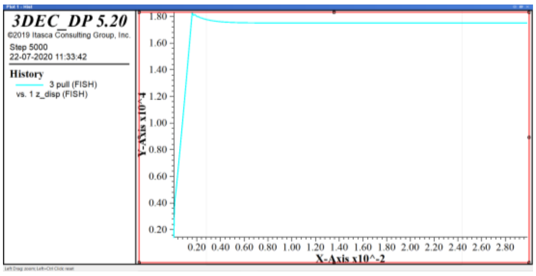



Figure 69: C.P. = 20 MPa (non grouted)

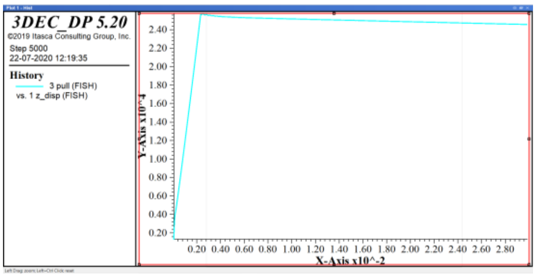



Figure 70: C.P. = 1.5 MPa (grouted)

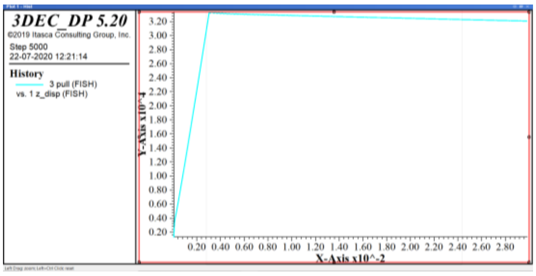



Figure 71: C.P. = 3 MPa (grouted)

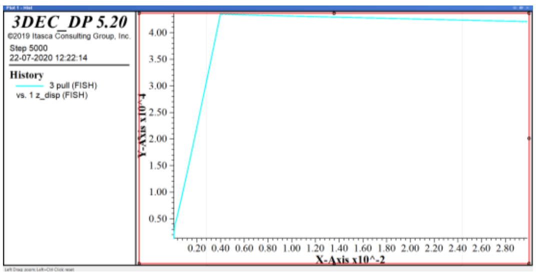



Figure 72: C.P. = 5 MPa (grouted)

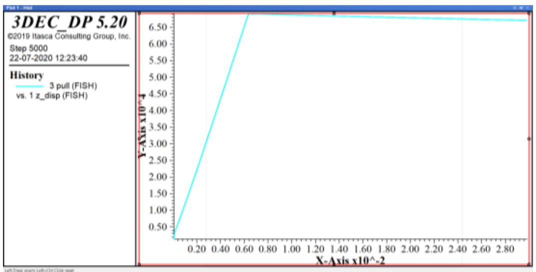



Figure 73: C.P. = 10 MPa (grouted)

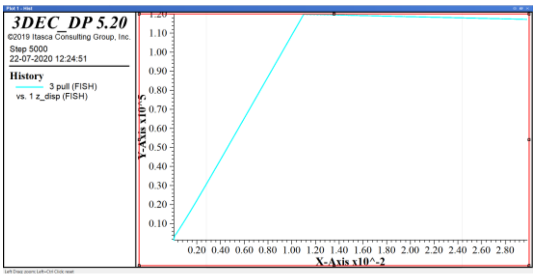



Figure 74: C.P. = 20 MPa (grouted)

### 4.1.5 Variation with edge of the tetrahedral

The variation in pull out load has been obtained for both grouted and non-grouted bolts with respect to the variation in the length of the edge of the tetrahedral (e). The parameters whose values have been kept constant are

Radius = 25 mm

Length = 200 mm

Rate of extraction = 1

Thickness of grout (for grouted bolt only) = 5 mm

Friction angle (for grouted bolt only) = $25^{O}$

Table 12: Variation of pull out load with edge of tetrahedral

| **Length of edge of tetrahedral** | | **0.01** | **0.1** | **1** | **Equation** | **$R^2$** |
|---|---|---|---|---|---|---|
| **Pullout load (kN)** | **Grouted bolt** | 29.21 | 32.08 | 32.90 | P = 2584.754 * e + 30436.26 | 0.533293 |
| | **Non grouted bolt** | 17.50 | 17.50 | 17.50 | - | - |
| **No of Zones** | | 103638 | 90 | 6 | - | - |

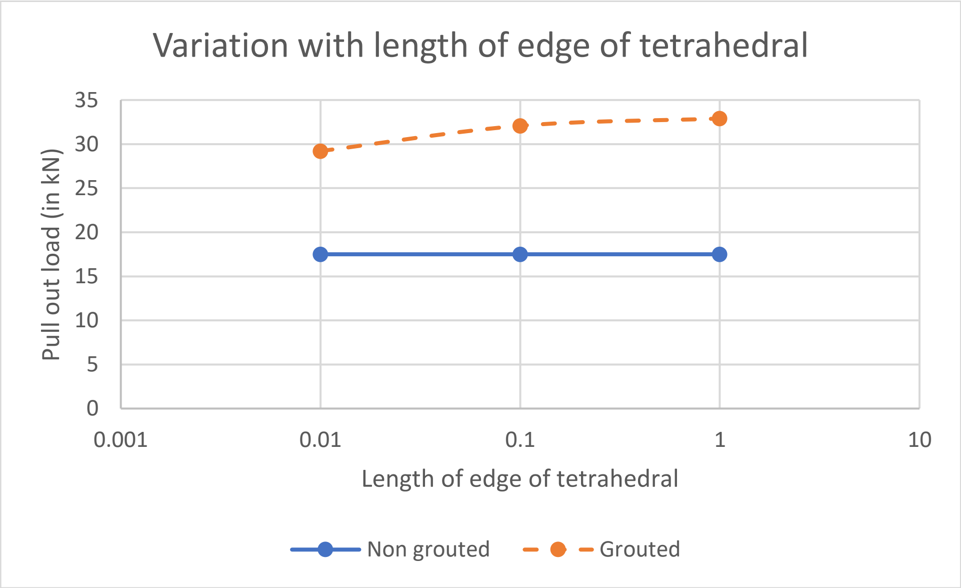



Figure 75: Variation of pull out load with edge of tetrahedral

The load-displacement curves for the pull out of the bolt with respect to the variation of the length of edge of tetrahedral (e) has been shown below for reference.

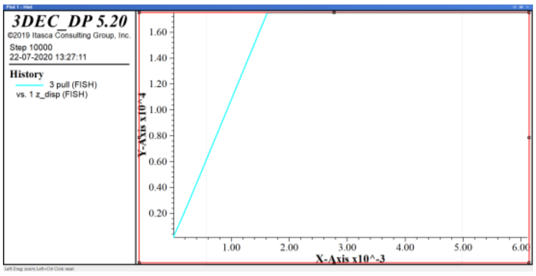



Figure 76: e = 0.01 (non grouted)

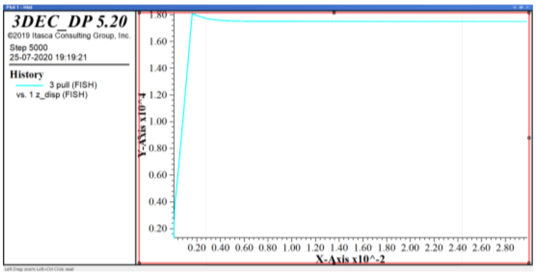



Figure 77: e = 0.1 (non grouted)

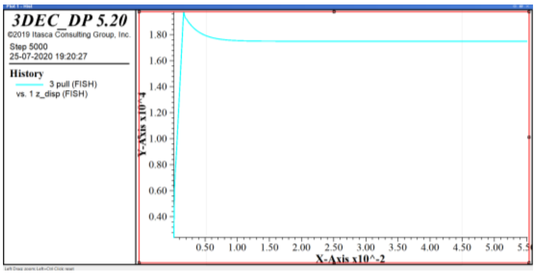



Figure 78: e = 1 (non grouted)

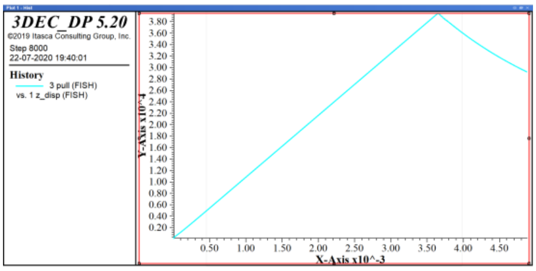



Figure 79: e = 0.01 (grouted)

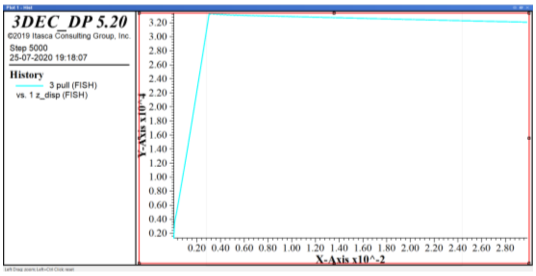



Figure 80: e = 0.1 (grouted)

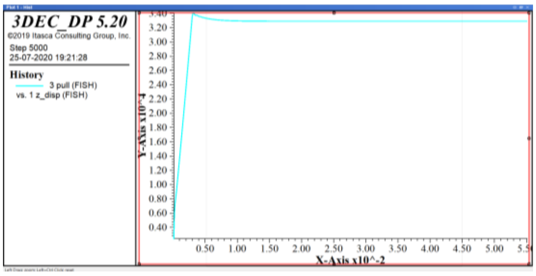



Figure 81: e = 1 (grouted)

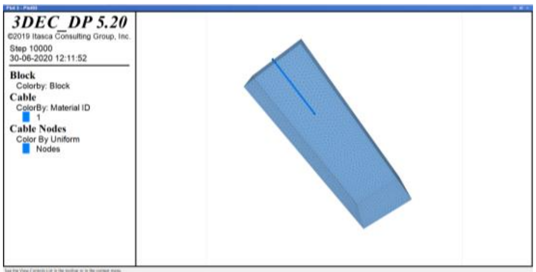



Figure 82: e = 0.01 (model)

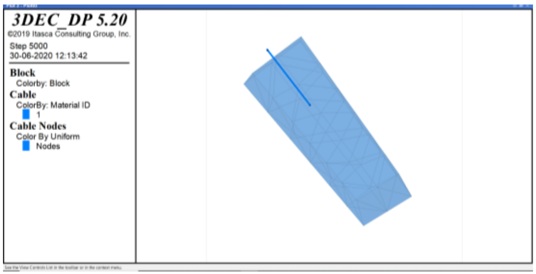



Figure 83: e = 0.1 (model)

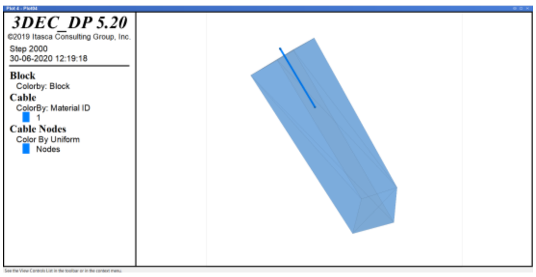



Figure 84: e = 1 (model)

### 4.1.6 Variation with thickness of grout

The variation in pull out load has been obtained for grouted and bolt only with respect to the variation in the thickness of the grout annulus (t). The parameters whose values have been kept constant are

Radius = 25 mm

Length = 200 mm

Rate of extraction = 1

Friction angle (for grouted bolt only)= $25^O$

Table 13: Variation of pull out load with thickness of grout

| Thickness (mm) | Pull out load (kN) |
|---|---|
| **5** | 32.08 |
| **10** | 36.10 |
| **15** | 40.08 |
| **20** | 44.00 |
| **50** | 66.41 |
| **Equation** | P = 759.88 * t + 28536.08 |
| **$R^2$** | 0.999761 |

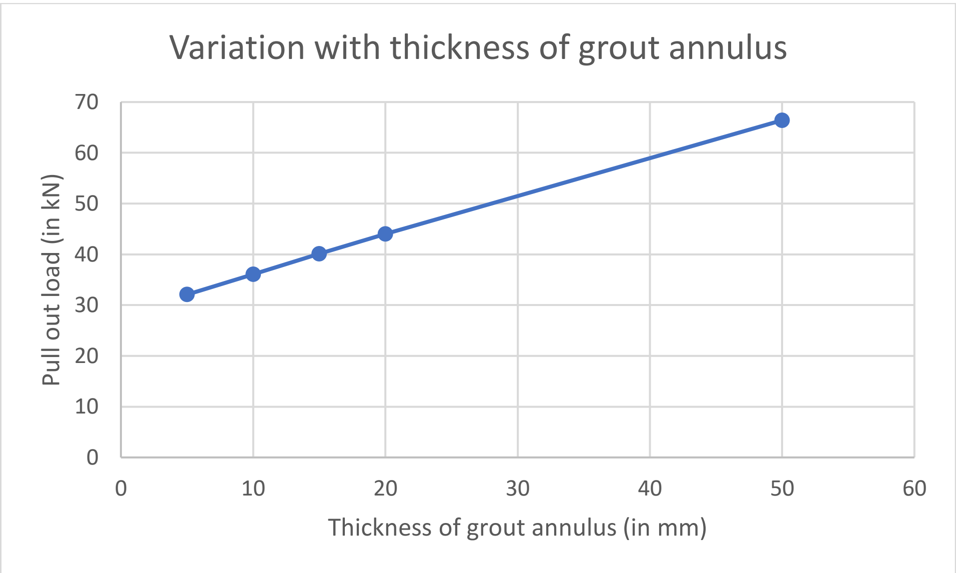



Figure 85: Variation of pull out load with thickness of grout material

The load-displacement curves for the pull out of the bolt with respect to the variation of the thickness of grout annulus (t) has been shown below for reference.

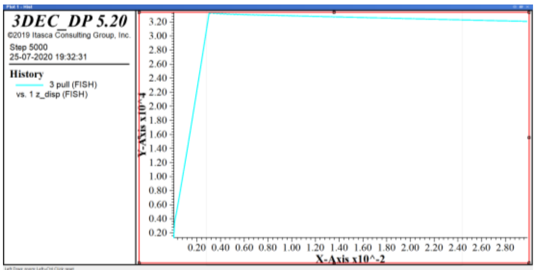



Figure 86: t = 5 mm (grouted)

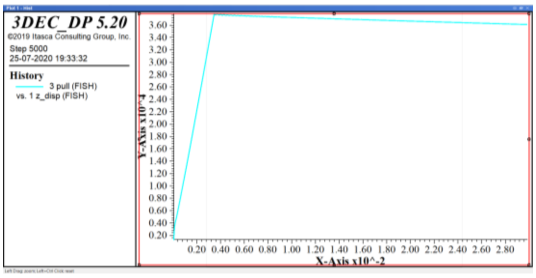



Figure 87: t = 10 mm (grouted)

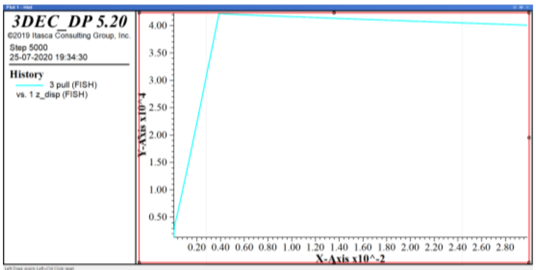



Figure 88: t = 15 mm (grouted)

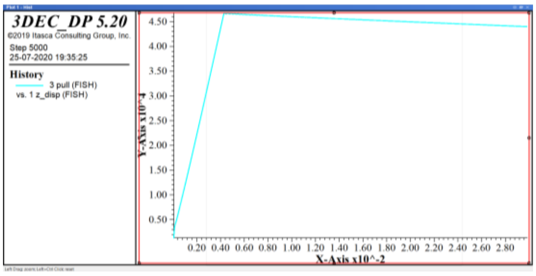



Figure 89: t = 20 mm (grouted)

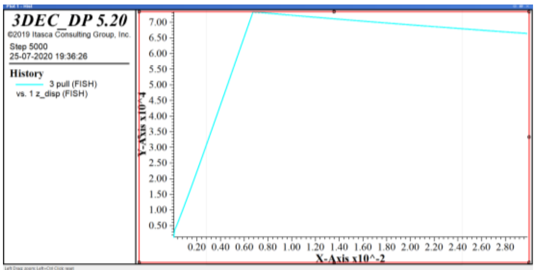



Figure 90: t = 50 mm (grouted)

## 4.1.7 Variation with friction angle

The variation in pull out load has been obtained for grouted and bolt only with respect to the variation in the angle of friction of the grout material (ϕ). The parameters whose values have been kept constant are

Radius = 25 mm

Length = 200 mm

Rate of extraction = 1

Thickness of grout = 5 mm

Table 14: Variation of pull out load with friction angle

| **Friction angle (degrees)** | **Pull out load (kN)** |
|---|---|
| **$15^{O}$** | 25.97 |
| **$25^{O}$** | 32.08 |
| **$30^{O}$** | 35.43 |
| **$45^{O}$** | 47.89 |
| **$60^{O}$** | 68.20 |
| **Equation** | P = 933.33 * ϕ + 9247.24 |
| **$R^2$** | 0.972345 |

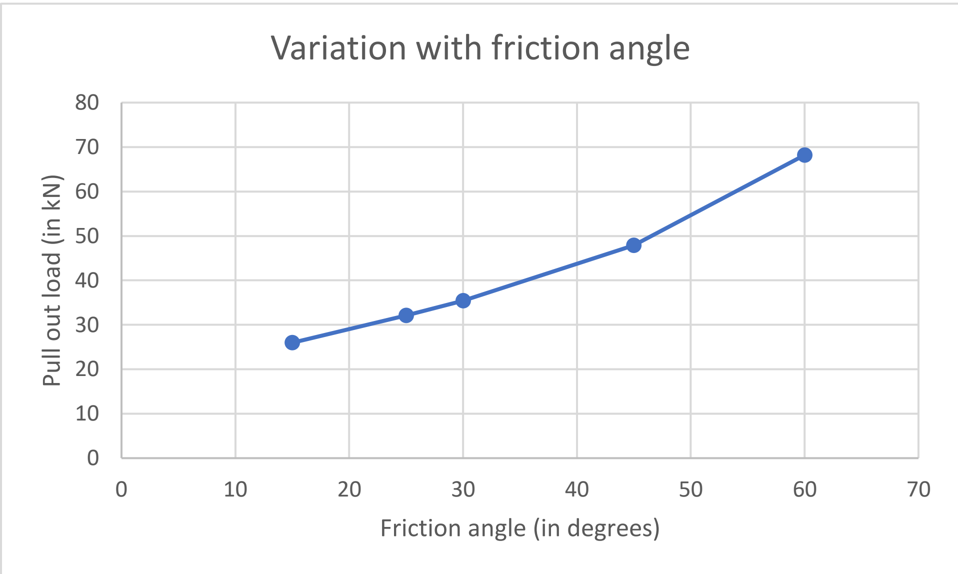



Figure 91: Variation of pull out load with edge of tetrahedral

The load-displacement curves for the pull out of the bolt with respect to the variation of the angle of friction of the grout material (ϕ) has been shown below for reference.

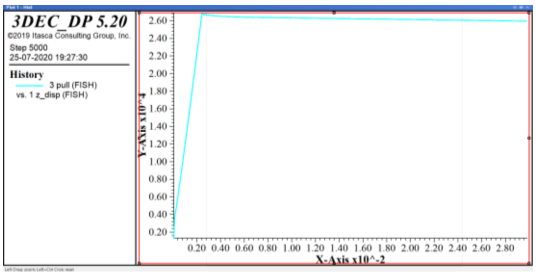



Figure 92: ϕ = $15^{O}$ (grouted)

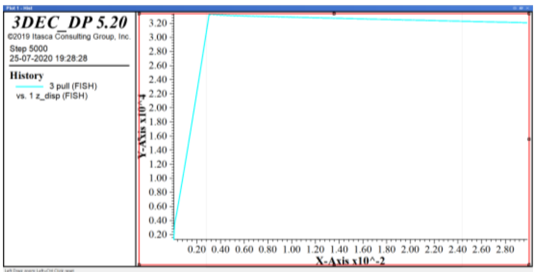



Figure 93: ϕ = $25^{O}$ (grouted)

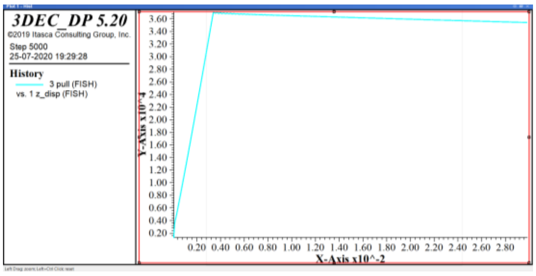



Figure 95: ϕ = 30$^{O}$ (grouted)

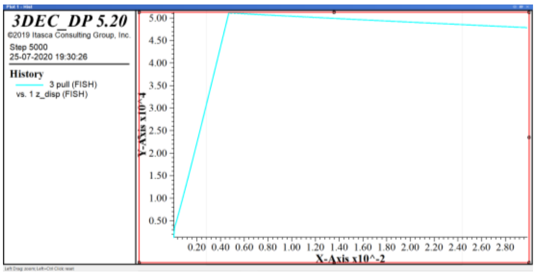



Figure 96: ϕ = 45$^{O}$ (grouted)

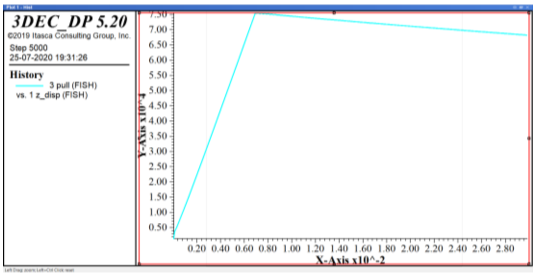



Figure 97: ϕ = 60$^{O}$ (grouted)

# CHAPTER 5
# CONCLUSION

## 5.1 Conclusions

- For the case of grouted bolt, the variation in pull out load with the variation in length was non-linear while for non-grouted bolt, it was observed to be linear. The increment in the pull-out load for grouted bolt was observed to vary between 42.08 kN and 78.77 kN while for non-grouted bolt the variation was from 17.50 kN to 35.02 kN with increment in length of bolt from 200 mm to 400 mm.
- With the variation in diameter and hence in the cross-sectional area, the pull-out load had an almost linearly increasing trend for grouted bolt while for non-grouted, the values remained constant. The increment pull-out load for grouted bolt was observed to be varied from 33.14 kN to 46.84 kN while for non-grouted bolt this value remained at 17.50 kN with increment in diameter of bolt from 12 mm to 32 mm.
- When the rate of extraction was varied, the pull out for grouted bolt reduced slightly while for non-grouted bolt the value remained constant. Here, the decrement in pull-out load for grouted bolt was observed to be varying between 33.08 kN and 31.40 kN while for non-grouted bolt this value remained at 17.50 kN with increment in rate of extraction of bolt from value 0.01 to value upto 4.
- Variation of pull out with confining pressure was observed to be significant only for grouted bolt while the value for non-grouted bolt remained same for all the cases as per the software. For grouted bolt the variation went from 24.57 kN to as high as 117.24 kN (at confining pressure of 20 MPa) i.e. more than four times the value obtained at low confining pressure of 1.5 MPa.
- As the length of the edge of the tetrahedral was reduced the time taken for analysis increased. No significant trend was observed for grouted bolt while for non-grouted bolt the value remained same.
- For grouted bolt only, the pull-out load increased linearly with the thickness of the grout annulus while the variation was non-linear increment when the angle of friction was increased. Considering the thickness of grout annulus, the variation went from 32.08 kN to 66.41 kN as the thickness of grout annulus increases from 5 mm to 50 mm for a bolt of diameter 25 mm. While with increment in the friction

angle the variation went from 25.97 kN to 68.20 kN as the friction angle changed from $15^{O}$ to $60^{O}$.

- For non-grouted bolts, the variation in pull-out load is only observed while varying the length which indicates that the force dominant for the resisting action of non-grouted bolt is the force of friction only. The pull-out load thus increases as the area of contact for the bolt increases with length considerably which in turn increases the force of friction.
- All the results were obtained considering variation of a single factor while all the other involved parameters were taken to be constant for the analysis.

## 5.2 Limitations

Some drawbacks were observed while preparing the software-based model for obtaining the pull-out load for the bolt. It is difficult to obtain the results for various different kinds of bolts as in case of multistrand cablebolt, the software doesn't provide with option to include wires or strands or tendons in the design. It also doesn't account for rockbolts and its variations such as swellex which are hollow in nature, split set, expansion shell etc. Also, ribs on bolts cannot be defined in this software. The properties of the grout material such as density, young's modulus of material etc cannot be incorporated, only the friction angle and the concerned area of grout annulus can be mentioned in the code to accommodate for the properties of the grout. The results thus obtained pertain to very simple kind of plain-surface bolts.

## 5.3 Future scope

The field of cablebolts is comparatively new and hence the research availability in this field currently is not very vast. With advancement in technology as the analysis methods are also shifting to more software-based methods for increased accuracy in results. Thus, this field provides a huge area for further exploration.

The work done in this project has been limited to a very few factors and has also been curbed by the limitations of the software used. The analysis can be compared with laboratory results, by preparing similar models and studying in depth the variation of each mentioned factor respectively to understand the exact behaviour of the software pertaining to a particular parameter and the proximity in results. Moreover, the factors can be extended to consider the influence of the rock material properties too. The design of cable bolt used in this project is a primitive plain one. However, various better kinds of cablebolts such as Birdcage, Garford Bulb strands, Nutcase etc can also be used in models.

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