UNIVERSITI PUTRA MALAYSIA

EFFECTS OF SOIL AND FAULT PROPERTIES ON TUNNEL DISPLACEMENT INDUCED BY NORMAL AND REVERSE FAULTS

MEHDI GHAFARI

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By

MEHDI GHAFARI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2020

DEDICATION

I would like to dedicate this thesis to my dearest wife for her endless love, support and encouragement. Also, to my parents for their support and pray make me able to get such success for this journey. Moreover, this thesis is dedicated to my father and mother in law for their support and encouragement in this journey.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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August 2020

Chairman : Associate Professor Haslinda binti Nahazanan, PhD
Faculty : Engineering

As the world population increasing considerably in tandem with the growing cities, economies, and businesses, there is a need for effective and efficient public transportation. One of the fastest, and most convenient public transport is subway. However, it has become a major concern to geotechnical engineers as the development and construction of subways are held underground where faults exist. Several seismic events such as the earthquakes in Taiwan in 1999, China in 2008, and Malaysia (Sabah) in 2015 caused by fault ruptures signify the importance of this study. Although many studies have been conducted on fault ruptures, most researchers only considered a free field (a field without tunnels) and on homogeneous cohesionless soil (sand). In this study, a gigantic physical model 1000 mm in height, 3000 mm in length, and 1000 mm in width was fabricated in Geotechnical Engineering laboratory, Universiti Putra Malaysia (UPM) to evaluate the influence of various soil properties on tunnels affected by both normal and reverse faults, as well as the effects of various fault angles and tunnel depths. Three different soil cohesion have been selected, cohesionless soil , 10 kPa and 20 kPa which due to the reason that cohesionless soil has been used in most of previous studies, and other studies (in soil stability), cohesion values of less than 23 kPa has been used. Three different soil friction angles have been investigated in this study,

27°, 33° and 39°. Previous studies have showed that range of soil friction angle between 28° and 39° indicated density of up to 80%. Results revealed that increasing the soil cohesion and friction angle resulted in reducing tunnel displacements by as much as 64% and 39% respectively. Investigation on the differences and similarities between normal and reverse faults revealed that reverse faults can bring approximately 60% more tunnel displacements compared to normal faults because a normal fault released less energy than a reverse fault. Another aspect considered is the influence of fault angles in which results showed that vertical movements due to a fault angle of 90° could bring major displacements of more than two times the displacements caused by a fault angle of 30°. Evaluation of the effects of various distances between a tunnel and a fault revealed that tunnel displacements could be reduced by more than 22% when the tunnel is located 250 mm away from the fault. In addition, finite element analyses were also performed using PLAXIS to simulate and compare the results with physical model. The results of the current study could be of benefit to society considering the fault ruptures. Many metropolitan cities with underground structures are exposed to risks to many lives if fault ruptures occurred. This study asserts that besides the structural design of a tunnel, the geotechnical design also has a major impact on the safety and robustness of the tunnel. It is also shown that geotechnical engineering aspects such as soil properties, type of fault, tunnel depth, and fault angle have a strong influence on tunnel damages in which those aspects were not considered in previous research despite their importance.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KESAN SIFAT TANAH DAN SESAR KE ATAS ANJAKAN TEROWONG YANG DIDORONG OLEH SESAR NORMAL DAN SONGSANG

Oleh

MEHDI GHAFARI

Ogos 2020

Pengerusi : Profesor Madya Haslinda binti Nahazanan, PhD
Fakulti : Kejuruteraan

Peningkatan pesat jumlah penduduk dunia yang berlaku seiring dengan pertumbuhan bandar, ekonomi, dan perniagaan mewujudkan keperluan kepada pengangkutan awam yang berkesan dan efisien. Salah satu pengangkutan awam yang paling pantas, dan mudah ialah kereta api bawah tanah. Namun begitu, ia menimbulkan kebimbangan kepada jurutera geoteknik berikutan pembangunan dan pembinaan laluan kereta api dibuat di bawah tanah di tempat terdapatnya sesar. Beberapa peristiwa seismik seperti gempa bumi di Taiwan pada tahun 1999, China pada tahun 2008, dan Malaysia (Sabah) pada tahun 2015 yang disebabkan oleh pemecahan sesar menunjukkan kepentingan kajian ini. Walaupun banyak kajian telah dijalankan terhadap pemecahan sesar, kebanyakan pengkaji hanya mengambil kira medan lapang (medan tanpa terowong) dan tanah homogen tanpa jeleket (pasir). Dalam kajian ini, model fizikal gergasi berukuran 1000 mm tinggi, 3000 mm panjang, dan 1000 mm lebar dibina di dalam makmal Kejuruteraan Geoteknik, Universiti Putra Malaysia (UPM) untuk menilai pengaruh pelbagai sifat tanah terhadap terowong yang mengalami kesan sesar normal dan songsang, termasuk kesan pelbagai sudut sesar dan kedalaman terowong di bawah tanah. Tiga nilai kejeleketan tanah: tanpa kejeleketan, 10 kPa dan 20 kPa telah dipilih berikutan tanah tanpa kejelekatan telah digunakan di dalam banyak kajian yang lepas, dan kajian lain (kestabilan tanah), nilai kejeleketan tanah kurang daripada 23 kPa telah digunakan. Tiga nilai sudut geseran iaitu 27°, 33° dan 39° telah disiasat di dalam kajian ini. Kajian lepas telah menunjukkan bahawa julat sudut geseran tanah antara 28° dan 39° menandakan kepadatan sehingga 80%. Keputusan menunjukkan bahawa peningkatan kejeleketan tanah dan sudut geseran menyebabkan pengurangan anjakan terowong sebanyak masing-masing 64% dan 39%. Penyiasatan terhadap perbezaan dan persamaan antara sesar normal dengan songsang menunjukkan bahawa anjakan terowong yang disebabkan oleh sesar songsang ialah kira-kira 60% lebih tinggi berbanding sesar normal kerana sesar

normal mengeluarkan tenaga yang lebih rendah berbanding sesar songsang. Satu lagi aspek yang dipertimbangkan ialah pengaruh sudut sesar dan hasil kajian menunjukkan bahawa pergerakan menegak yang disebabkan oleh sudut sesar 90° boleh menyebabkan anjakan besar iaitu lebih daripada dua kali ganda anjakan yang disebabkan oleh sudut sesar 30°. Penilaian kesan pelbagai jarak di antara terowong dan sesar menunjukkan bahawa anjakan terowong boleh dikurangkan sebanyak lebih daripada 22% apabila terowong terletak 250 mm dari kedudukan sesar. Di samping itu, analisis unsur terhingga telah dijalankan menggunakan PLAXIS untuk mensimulasikan dan membandingkan situasi yang biasanya tidak diuji terhadap model fizikal. Hasil kajian ini boleh memberikan manfaat kepada masyarakat berkaitan pemecahan sesar. Banyak bandar raya metropolitan dengan struktur bawah tanah terdedah kepada risiko yang mengancam banyak nyawa jika berlaku kejadian pemecahan sesar. Kajian ini menekankan yang selain daripada reka bentuk struktur terowong, reka bentuk geoteknik juga memberikan kesan yang besar terhadap keselamatan dan keteguhan terowong. Ia juga menunjukkan aspek-aspek kejuruteraan geoteknik seperti sifat tanah, jenis sesar, kedalaman terowong, dan sudut sesar memberikan pengaruh yang besar tehadap kerosakan terowong di mana aspek-aspek penting ini tidak dipertimbangkan dalam kajian terdahulu.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

c	Cohesion
Dr	Relative density
D	Diameter of the tunnel
D_{50}	Diameter of the soil particles for which 50 % of the particles are finer
E	Void ratio
E	Elastic modulus
B	Length of physical model
G	Shear modulus
T	Tunnel depth from the ground surface
ΔH	Soil displacement by a vertical component
H	Soil thickness in the physical model
N	g-Level
t	Time
V_S	Soil shear velocity
h	Displacement by vertical component
$\propto$	Fault angle
ν	Poisson ratio
ϕ	Friction angle
ψ	Dilatancy angle
ω	Moisture content

CHAPTER 1

INTRODUCTION

1.1 Introduction

Fault ruptures are caused by sudden movement on a fault when stress on the edge overcomes the friction and energy in waves are released and travel through the soil. In recent years, there has been an increasing amount of research on this topic due to several major incidents such as fault ruptures in Taiwan in 1999, Turkey in 1999, USA in 2002, Japan in 2004, China in 2008, and Iran in 1990. Furthermore, in 2015, an earthquake with a magnitude of 6 occurred in Sabah, Malaysia, which was recorded as the second largest earthquake in the country after the 1991 earthquake in Ranau which was also in Sabah. Tectonic map of fault activity revealed that Sabah's fault was part of a 200 km-long system of normal fault that crosses the eastern side of the Crocker Range parallel to Sabah's northwest coastline.

Two types of physical models, namely, centrifuge and 1g models have been used in previous studies on fault ruptures. Centrifuge model has the ability to change the centrifuge's acceleration, *Ng,* where *N* stands for the scaling factor and g stands for the acceleration of gravity. It is involves changing gravity to simulate a real situation. However, fault simulations with centrifuge tests were mostly used to investigate free fields (fields without any structures) and cohesionless soil (Ng & Asce, 2012;). Several studies have examined the relationship between shear zone and damages, and the findings show that soil experiences the highest stress and strain in the shear zone, which causes damages to soil. Lee (2003) used centrifuge model for an experimental investigation to explore the shear zone when faults happen in a free field, and he showed that soil density can have major influence on ground surface displacements. 1g model is more preferred to be used for simulating the effect of soil properties on tunnels induced by faults. Firstly, unlike centrifuge model which is very sensitive to achieve certain gravity, natural gravity is used in 1g model. Secondly, the process of increasing vertical component in 1g model can be manipulated and also more gauges can be installed in 1g model due to its larger size. Thirdly, the effects of various soil properties can be investigated more accurately as it involves greater mass of soil.

Investigation on the effects of soil properties alone shows that soil friction angles are important aspect of soil failure. The shear zone in low-density soil is typically more complex than in high-density soil and as the relative density of the ground model becomes more significant, the number of rupture planes decrease because soil strength does not let more fractures in the soil (this fact also showed in this study 4.2.4). Furthermore, soil properties such as cohesion, friction angle, particle size, density and soil moisture are very important in any simulation and analysis involving with soil (Ertugrul, 2010). Previous studies revealed that changing of soil friction angles and cohesion could affect bearing capacity of soil. The results from Khezri (2015) showed cohesion is very important to be measured in underground structures because cohesion increases with the depth and each layer has different cohesion. Furthermore, soil particle size and moisture content have been claimed to have critical impact in designing foundation, road and other infrastructure (Sudarsan et al., 2018; Pöhlitz et al., 2019). Moreover, normal and reverse faults would also have different impacts on soil deformations. For instance, normal faults tent to bend over the hanging walls and reverse faults tend to bend over the footwalls. When a normal fault happens, at least one rupture propagation reaches the ground surface and damages building foundations and there could be more impacts on the soil. In this study, 1g model has been used for evaluating the effect of faults (normal and reverse) on tunnels. Various soil properties including soil moisture content, particle size cohesion and friction angle have been used. Furthermore, differences and similarity of normal and reverse faults have been tackled. Also, the effects of various fault angles and tunnel depth on tunnels have been investigated.

Two types of software are often used in this field, namely PLAXIS and ABAQUS, both of which are based on the finite element model (FEM). PLAXIS is a useful tool for analyzing two- and three-dimensional models and has been used for different circumstances such as modeling rock mass parameters, tunnels, foundations and many more. Likewise, ABAQUS has ability to model tunneling in dynamic and slopped zones. In this study PLAXIS software had been used for simulating and comparing the results of physical model with the software.

1.2 Problem statement

Fault rupture studies have been receiving more attention after the occurrence of severe disasters globally, particularly in metropolitan areas as they caused casualties and damages to large-scale structures. For instance, Chi–Chi reverse fault in Taiwan in 1999 (Figure 1.1), Kocaeli strike fault in Turkey in 1999, Central Alaska reverse fault in the USA in 2002, and Mid Niigata reverse fault in Japan in 2004. It has been suggested not to build any structure on a fault trace to avoid severe damages (Stanton, 2013). However, it is very unlikely to avoid any constructions including underground structures where fault existed. This is due to rising population in cities that cause the need for more public transportation especially subways which have been required as the first choice in megacities.

Tunnels and subways would be the first structure to experience damages when any movements happened before the forces caused by faults reach the ground surface. Hence, the stability of tunnel structures should be given more consideration by designers and engineers. Millions of people use underground public transportation every day, and hence, fault ruptures could pose a major hazard to their lives. Restoration of structures is another challenge because it would be very costly and sometimes impossible. Thus, more research in this area is needed to reduce the damages to tunnels and buildings. Besides fault characteristics, soil properties also have major influence and need particular attention. Several studies have previously been conducted in fault ruptures in which none have considered soil properties as one of the major aspects of tunnel displacement. For instance, cohesion is known to has a major influence on forces nevertheless most studies have only been conducted on cohesionless soil. In this study, an experimental investigation was conducted to explore the effects of various soil properties such as cohesion, friction angle and various fault properties such as fault types, angles and tunnel depth by using a 1g model. Furthermore, unlike other studies that only investigated free fields, this research focus on field with tunnel. The outcome of this study can help engineers in understanding the level of damage that might be imposed on tunnels at the area of fault with various properties of soil and faults.

Figure 1.1 : Damages caused by 6m displacements reverse fault in 1999 Chi-Chi Taiwan (after Stanton, 2013)

1.3 Objectives of study

This study aims to evaluate the important factors that influence tunnel deformations due to dip-slip faults (normal and reverse) using a physical model and simulation in computer software. The following objectives have been identified for the successful completion of the aim of this research:

- To analyze the effects of various soil properties (cohesion and friction angle) on soil deformation and hence tunnel displacement due to fault ruptures.
- To assess the differences and similarities of the effects of dip-slip faults (normal and reverse) on soil deformation and tunnel displacement.

- To identify the influence of various fault angles and tunnel depth on displacements and the forces induced, which will then be transferred to tunnels.
- To perform 3D finite element analysis on deformation of tunnel considering factors such as soil properties, fault angles and tunnel depth.

1.4 Scope and limitations

This study focused on four important aspects. Firstly, the study investigated the effects of various soil properties on soil deformation due to fault ruptures. Soil properties such as cohesion and friction angle were assessed in this study. To achieve this goal, each property was changed in three different proportions. Rain method which involves filling strong box with a certain distance of unloading soil was chosen for compacting soil due to large amount of soil required. Secondly, normal and reverse faults and their differences and similarities were investigated under the same conditions, i.e., the same soil properties and displacements by a vertical component. Other important aspects that have been undertaken in experimental investigation in this study are fault angles and tunnel depth, which were evaluated by choosing three different fault angles (30°, 60°, and 90°) and two different tunnel depths from the ground surface (250 and 500 mm) for both normal and reverse faults. Different displacements by vertical component (20, 40, and 60 mm) were used for all the tests. Maximum displacement and boundary conditions for fabrication of the physical model were suggested to be 8% and B=4H respectively (Anastasopoulos et al., 2007). Tunnel thickness was maintain at 10mm and tunnel diameter of 80mm in all the tests, similar to SMART tunnel in Kuala Lumpur, Malaysia because some parts of the tunnel had to be constructed in soil deposit similar to soil used in this study. In addition, PLAXIS software was used to analyze tunnel displacement due to faults in rock that could not be simulated in physical model. Moreover, the effects of foundation on tunnels were also evaluated. Mohr-Columns theory was used for software analysis.

1.5 Thesis organization

This thesis consists of five chapters which present the flow of the research involved. The outline of the thesis is as follows:

- Chapter One provides a brief introduction to the research background. The research requirements as well as the problem statement are stated to define the key research aspects used. The objectives and aims of the study are listed to set the focus of the research. Subsequently, the scope of the study is highlighted.
- Chapter Two is a literature review of past studies. In this chapter, the author explains the history of tunnels affected by fault ruptures and discusses previous works in this area. Moreover, an explanation of the

fault process and fault protection is provided in this chapter.

- Chapter Three describes the methodology in designing a tunnel influenced by fault ruptures. In addition, the processes of designing in software and fabricating the physical model that can simulate normal and reverse fault are explained. Also, the details of the tests are mentioned in this chapter.
- Chapter Four forms the major part of this thesis, in which the experimental results and the data for each objective are explained in details. Also, data comparison with previous researchers and software analyses are discussed.
- Chapter Five presents the conclusion of the research in terms of the design process and analysis of the results of the physical model. Also, this chapter includes several recommendations for future researchers who are interested in this field.

REFERENCES

Abou Romieh, M., Westaway, R., Daoud, M., & Bridgland, D. R. (2012). First indications of high slip rates on active reverse faults NW of Damascus, Syria, from observations of deformed Quaternary sediments: Implications for the partitioning of crustal deformation in the Middle Eastern region. *Tectonophysics*, *538–540*, 86–104. https://doi.org/10.1016/j.tecto.2012.03.008

Ahmadi, M., Moosavi, M., & Jafari, M. K. (2018). Experimental investigation of reverse fault rupture propagation through wet granular soil. *Engineering Geology*, *239*, 229–240. https://doi.org/10.1016/j.enggeo.2018.03.032

Ahmed, W., & Bransby, M. F. (2009). Interaction of Shallow Foundations with Reverse Faults. *Journal of Geotechnical and Geoenvironmental Engineering*, *135*(7), 914. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000072

Alexandr, G. (2018). the Impact of Earthquakes of Tunnel Linings: a Case Study From the Hanoi Metro System. *International Journal of GEOMATE*, *14*(41), 151–158. https://doi.org/10.21660/2018.41.15309

Alshameri, B., Bakar, I., Madun, A., Abdeldjouad, L., & Dahlan, S. H. (2016). Effect of Coarse Materials Percentage in the Shear Strength. *IOP Conference Series: Materials Science and Engineering*, *136*(1). https://doi.org/10.1088/1757-899X/136/1/012017

Anastasopoulos, I., Antonakos, G., & Gazetas, G. (2010). Slab foundation subjected to thrust faulting in dry sand: Parametric analysis and simplified design method. *Soil Dynamics and Earthquake Engineering*, *30*(10), 912–924. https://doi.org/10.1016/j.soildyn.2010.04.002

Anastasopoulos, I., Callerio, A., Bransby, M. F., Davies, M. C. R., El Nahas, A., Faccioli, E., … Rossignol, E. (2008). Numerical analyses of fault-foundation interaction. *Bulletin of Earthquake Engineering*, *6*(4), 645–675. https://doi.org/10.1007/s10518-008-9078-1

Anastasopoulos, I., Gerolymos, N., Gazetas, G., & Bransby, M. F. (2008). Simplified approach for design of raft foundations against fault rupture. Part I: free-field. *Earthquake Engineering and Engineering Vibration*, *7*(2), 147–163. https://doi.org/10.1007/s11803-008-0835-6

Anastasopoulos, I., Zarzouras, O., Georgarakos, T., Drossos, V., & Gazetas, G. (2013). Caisson Foundations subjected to Seismic Faulting : Reduced-scale Physical Modeling The two components of an Earthquake. *SERIES Concluding Workshop - Joint EU-NEES*.

Anastasopoulos, I, Gazetas, G., Asce, M., Bransby, M. F., Davies, M. C. R., & Nahas, a El. (2007). Fault Rupture Propagation through Sand : Finite-Element Analysis and Validation through Centrifuge Experiments. *Journal of Geotechnical and Geoenvironmental Engineering*, (August), 943–958. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:8(943)

Anastasopoulos, Ioannis, & Gazetas, G. (2010). Analysis of cut-and-cover tunnels against large tectonic deformation. *Bulletin of Earthquake Engineering*, *8*(2), 283–307. https://doi.org/10.1007/s10518-009-9135-4

Anastasopoulos, Ioannis, Gerolymos, N., Drosos, V., Georgarakos, T., Kourkoulis, R., & Gazetas, G. (2008). Behaviour of deep immersed tunnel under combined normal fault rupture deformation and subsequent seismic shaking. *Bulletin of Earthquake Engineering*, *6*(2), 213–239. https://doi.org/10.1007/s10518-007-9055-0

Athanasopoulos, G. A., Pelekis, P. C., & Anagnostopoulos, G. A. (2000). Effect of soil stiffness in the attenuation of Rayleigh-wave motions from field measurements. *Soil Dynamics and Earthquake Engineering*, *19*(4), 277–288. https://doi.org/10.1016/S0267-7261(00)00009-9

Babaahmadi, A., Mohajjel, M., Eftekhari, A., & Davoudian, A. R. (2012). An investigation into the fault patterns in the Chadegan region, west Iran: Evidence for dextral brittle transpressional tectonics in the Sanandaj-Sirjan Zone. *Journal of Asian Earth Sciences*, *43*(1), 77–88. https://doi.org/10.1016/j.jseaes.2011.08.012

Bäckblom, G., Munier, R., & Kärnbränslehantering, S. (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results, 115. Retrieved from https://books.google.com/books/about/Effects_of_Earthquakes_on_the_Deep_Repos.html?id=9wZSAAAAMAAJ&pgis=1

Bäckblom, G., Stockholm, S. K., & Munier, R. (2002). *Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results*.

Baziar, M. H., Nabizadeh, A., Jung Lee, C., & Yi Hung, W. (2014). Centrifuge modeling of interaction between reverse faulting and tunnel. *Soil Dynamics and Earthquake Engineering*, *65*, 151–164. https://doi.org/10.1016/j.soildyn.2014.04.008

Baziar, M. H., Nabizadeh, A., Mehrabi, R., Lee, C. J., & Hung, W. Y. (2016). Evaluation of underground tunnel response to reverse fault rupture using numerical approach. *Soil Dynamics and Earthquake Engineering*, *83*, 1–17. https://doi.org/10.1016/j.soildyn.2015.11.005

Beeson, J. (2001). The Setback Distance Concept and 1999 Chi-Chi (Taiwan) Earthquake. In *International conferences on recent advances in geotechnical earthquake engineering and soil dynamics* (pp. 10-56`). Retrieved from http://scholarsmine.mst.edu/icrageesd/04icrageesd/session10/29%0AThis

Bransby, M. F., Davies, M. C. R., El Nahas, A., & Nagaoka, S. (2008). Centrifuge modelling of reverse fault-foundation interaction. *Bulletin of Earthquake Engineering*, *6*(4), 607–628. https://doi.org/10.1007/s10518-008-9080-7

Bransby, P., & Smith, A. (1975). Side Friction in Model Retaining Wall Experiments. *Journal of the Geotechnical Engineering Division*, 615–632.

Bray, J. D. (2001). Developing mitigation measures for the hazards associated with earthquake surface fault rupture. *A Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities*, 55–80. Retrieved from http://www.aegsc.org/meetings/Bray 2001- EQ Faulting.pdf

Bray, J. D., Seed, R. B., & Bolton Seed, H. (1989). *The effects of tectonic movements on stresses and deformations in earth embankments (UCB/EERC-90/13 Report)*.

Bray, J. D., Seed, R. B., Cluff, L. S., & Bolton Seed, H. (1990). Earthquake Fault Rupture Propagation Through Soil. *Journal of Geotechnical Engineering*, *16*(2), 543–561. https://doi.org/10.2118/72060-PA

Bray, J. D., Seed, R., & Cluff, L. S. (1994). Earthquake fault rupture propagation through soil, *120*(3), 543–561.

Burridge, P. B., Scott, R. F., & Hall, J. F. (1989). Centrifuge Study of Faulting Effects on Tunnel. *Journal of Geotechnical Engineering*, *115*(7), 949–967. https://doi.org/10.1061/(ASCE)0733-9410(1989)115:7(949)

by M.Hamada, E., & T.O'Rourke. (2002). *Proceedings from the Fourth Japan - U.S Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction*. Retrieved from c:$%5C$CS$%5C$all%5Cnrefs$%5C$technical$%5C$MCEER%5Cnreports$%5C$92-0019.pdf

Cai, Q. P., Hu, P., Laak, P. Van, Ng, C. W. W., & Chiu, A. C. F. (2010). Investigation of boundary conditions for simulating normal fault propagation in centrifuge. In *The 4th International Conference on Geotechnical Engineering and Soil Mechanics* (Vol. 614, pp. 1–8).

Cai, Q. P., & Ng, C. W. W. (2014). Effects of the tip depth of a pre-existing fracture on surface fault ruptures in cemented clay. *Computers and Geotechnics*, *56*, 181–190. https://doi.org/10.1016/j.compgeo.2013.12.005

Causse, L., Cojean, R., & Fleurisson, J.-A. (2015). Interaction between tunnel and unstable slope – Influence of time-dependent behavior of a tunnel excavation in a deep-seated gravitational slope deformation. *Tunnelling and Underground Space Technology*, *50*, 270–281. https://doi.org/10.1016/j.tust.2015.07.018

Chakeri, H., Ozcelik, Y., & Unver, B. (2015). Investigation of ground surface settlement in twin tunnels driven with EPBM in urban area. *Arabian Journal of Geosciences*, *8*(9), 7655–7666. https://doi.org/10.1007/s12517-014-1722-2

Chang, Y. Y., Lee, C. J., Huang, W. C., Hung, W. Y., Huang, W. J., Lin, M. L., & Chen, Y. H. (2015). Evolution of the surface deformation profile and subsurface distortion zone during reverse faulting through overburden sand. *Engineering Geology*, *184*, 52–70. https://doi.org/10.1016/j.enggeo.2014.10.023

Chen, W. S., Lee, K. J., Lee, L. S., Ponti, D. J., Prentice, C., Chen, Y. G., … Lee, Y. H. (2003). Paleoseismology of the Chelungpu Fault during the past 1900 years. *Quaternary International*, *115–116*, 167–176. https://doi.org/10.1016/S1040-6182(03)00105-8

Chung, C. F., Lin, M. L., Jeng, F. S., Tsai, L. S., Chin, C. T., & Chan, S. . (2005). A case study on the response of shield tunnel near a thrust fault offset. In *Geotechnical Earthquake Engineering, Satellite Conference, Osaka, Japan*.

Cluff, L. ., Page, R. ., Slemmons, D. ., & Crouse, C. . (2003). Seismic hazard exposure for the trans-Alaska pipeline. Proceedings of the 6th U.S. *American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering*, *25*, 535–546.

Cole, D. a., & Lade, P. V. (1984). Influence Zones in Alluvium Over Dip- Slip Faults. *Journal of Geotechnical Engineering*, *110*(5), 599–615. https://doi.org/10.1061/(ASCE)0733-9410(1984)110:5(599)

Deyasi, K., Chakraborty, A., & Banerjee, A. (2017). Network similarity and statistical analysis of earthquake seismic data. *Physica A: Statistical Mechanics and Its Applications*, *481*, 224–234. https://doi.org/10.1016/j.physa.2017.04.050

Dönmez, C., & Pujol, S. (2005). Spatial distribution of damage caused by the 1999 earthquakes in Turkey. *Earthquake Spectra*, *21*(1), 53–69. https://doi.org/10.1193/1.1850527

Duffy, B., Campbell, J., & Finnemore, M. (2014). Defining fault avoidance zones and associated geotechnical properties using MASW: a case study on the Springfield Fault, New Zealand. *Engineering Geology*, *183*, 216–229. https://doi.org/10.1016/j.enggeo.2014.10.017

Erickson, S. G., Strayer, L. M., & Suppe, J. (2001). Initiation and reactivation of faults during movement over a thrust-fault ramp: Numerical mechanical models. *Journal of Structural Geology*, *23*(1), 11–23. https://doi.org/10.1016/S0191-8141(00)00074-2

Ertugrul, N. (2010). *Analysis of seismic behavior of underground structures: a case study on bolu tunnels*. *The graduate school of natural and applied sciences*. https://doi.org/10.1093/occmed/kqq062

Faccioli, E., Anastasopoulos, I., Gazetas, G., Callerio, a., & Paolucci, R. (2008). Fault rupture-foundation interaction: Selected case histories. *Bulletin of Earthquake Engineering*, *6*(4), 557–583. https://doi.org/10.1007/s10518-008-9089-y

Fadaee, M., Jafari, M. K., Kamalian, M., Shafiee, a., & Moosavi, S. M. (2013). Feasibility study of fault rupture deviation by slurry wall. *International Journal of Civil Engineering*, *11*(2 B), 90–99.

Falcucci, E., Gori, S., Moro, M., Pisani, A. R., Melini, D., Galadini, F., & Fredi, P. (2011). The 2009 L'Aquila earthquake (Italy): What's next in the region? Hints from stress diffusion analysis and normal fault activity. *Earth and Planetary Science Letters*, *305*(3–4), 350–358. https://doi.org/10.1016/j.epsl.2011.03.016

Finch, E., Hardy, S., & Gawthorpe, R. (2003). Discrete element modelling of contractional fault-propagation flowding above rigid basement fault blocks. *Journal of Geophysical Research*, *25*, 515–528.

Foti, S., & Socco, L. V. (2014). *Earthquake Geotechnical Engineering Design*. *Geotechnical, Geological and Earthquake Engineering* (Vol. 28). https://doi.org/10.1007/978-3-319-03182-8

Garnier, J., Gaudin, C., Springman, S. M., Culligan, P. J., Goodings, D. J., Konig, D., … Thorel, L. (2007). Catalogue of Scaling Laws and Similitude Questions in Geotechnical Centrifuge Modelling. *International Journal of Physical Modelling in Geotechnics*, *7*, 1-1-23–23. https://doi.org/10.1680/ijpmg.2007.7.3.01

Gazetas, G., Anastasopoulos, I., & Apostolou, M. (2007). Chapter 9 shallow and deep foundations under fault rupture or strong seismic shaking. *Earthquake*, 185–215.

Giambiagi, L., Ghiglione, M., Cristallini, E., & Bottesi, G. (2009). Kinematic models of basement/cover interaction: Insights from the Malargüe fold and thrust belt, Mendoza, Argentina. *Journal of Structural Geology*, *31*(12), 1443–1457. https://doi.org/10.1016/j.jsg.2009.10.006

Gibson, A. D. (1996). Physical scale modeling of geotechnical structures at one-G. Retrieved from http://resolver.caltech.edu/CaltechEERL:1996.SML-97-01

Graff, P., & Bell, F. (1997). The Delivery Tunnel North, Lesotho Highlands Water Project. *Geotechnical and Geological Engineering*, 95–120.

Hamada, M. (2014). *Engineering for Earthquake Disaster Mitigation*. *Engineering for Earthquake Disaster Mitigation* (Vol. 0). https://doi.org/10.1007/978-4-431-54892-8

Hardy, S. (2011). Cover deformation above steep, basement normal faults: Insights from 2D discrete element modeling. *Marine and Petroleum Geology*, *28*(5), 966–972. https://doi.org/10.1016/j.marpetgeo.2010.11.005

Hardy, S. (2013). Propagation of blind normal faults to the surface in basaltic sequences: Insights from 2D discrete element modelling. *Marine and Petroleum Geology*, *48*, 149–159. https://doi.org/10.1016/j.marpetgeo.2013.08.012

Hardy, S., & Finch, E. (2006). Discrete element modelling of the influence of cover strength on basement-involved fault-propagation folding. *Tectonophysics*, *415*(1–4), 225–238. https://doi.org/10.1016/j.tecto.2006.01.002

Hardy, S., & Finch, E. (2007). Mechanical stratigraphy and the transition from trishear to kink-band fault-propagation fold forms above blind basement thrust faults: A discrete-element study. *Marine and Petroleum Geology*, *24*(2), 75–90. https://doi.org/10.1016/j.marpetgeo.2006.09.001

Hashash, Y. M. a., Hook, J. J., Schmidt, B., & I-Chiang Yao, J. (2001). Seismic design and analysis of underground structures. *Tunnelling and Underground Space Technology*, *16*(4), 247–293. https://doi.org/10.1016/S0886-7798(01)00051-7

Heesakkers, V., Murphy, S., & Reches, Z. (2011). Earthquake Rupture at Focal Depth, Part I: Structure and Rupture of the Pretorius Fault, TauTona Mine, South Africa. *Pure and Applied Geophysics*, *168*(12), 2395–2425. https://doi.org/10.1007/s00024-011-0354-7

Huang, F., Zhu, H., Xu, Q., Cai, Y., & Zhuang, X. (2013). The effect of weak interlayer on the failure pattern of rock mass around tunnel - Scaled model tests and numerical analysis. *Tunnelling and Underground Space Technology*, *35*, 207–218. https://doi.org/10.1016/j.tust.2012.06.014

Huang, Y., Yang, S., Qiao, X., Lin, M., Zhao, B., & Kai, T. (2017). Measuring ground deformations caused by 2015 M w7.8 Nepal earthquake using high-rate GPS data and its application to seismology. *Geodesy and Geodynamics*, 4–10. https://doi.org/10.1016/j.geog.2017.03.003

Hughes, A. N., Benesh, N. P., & Shaw, J. H. (2014). Factors that control the development of fault-bend versus fault-propagation folds: Insights from mechanical models based on the discrete element method (DEM). *Journal of Structural Geology*, *68*, 121–141. https://doi.org/10.1016/j.jsg.2014.09.009

Jackson, D. D., & Kagan, Y. Y. (2011). *CHARACTERISTIC EARTHQUAKES AND SEISMIC GAPS* (Vol. 5). https://doi.org/10.1007/978-90-481-8702-7

Jayasree, P., Rajagopal, K., & Gnanendran, C. (2012). Influence of Sidewall Friction on the Results of Small-Scale Laboratory Model Tests: Numerical Assessment. *International Journal of Geomechanics*, *12*(2), 119–126. https://doi.org/10.1061/(ASCE)GM.1943-5622

Johansson, J., & Konagai, K. (2004). Fault Induced Permanent Ground Deformations — Simulations and EXPERIMENTAL VERIFICATION, (479), 1–15.

Johansson, J., & Konagai, K. (2006). Fault induced permanent ground deformations—an experimental comparison of wet and dry soil and implications for buried structures. *Soil Dynamics and Earthquake Engineering*, *26*(1), 45–53. https://doi.org/10.1016/j.soildyn.2005.08.003

Johansson, J., & Konagai, K. (2007). Fault induced permanent ground deformations: Experimental verification of wet and dry soil, numerical findings' relation to field observations of tunnel damage and implications for design. *Soil Dynamics and Earthquake Engineering*, *27*(10), 938–956. https://doi.org/10.1016/j.soildyn.2007.01.007

Jonathan D. Bray, 1 Raymond B. Seed, 2 Lloyd S. Ciuff, H. B. S. (1994). Earthquake fault rupture propagation through soil, *120*(3), 543–561.

Karamitros, D. K., Bouckovalas, G. D., & Kouretzis, G. P. (2007). Stress analysis of buried steel pipelines at strike-slip fault crossings. *Soil Dynamics and Earthquake Engineering*, *27*(3), 200–211. https://doi.org/10.1016/j.soildyn.2006.08.001

Kelson, K. I., Kang, K. H., Page, W. D., Lee, C. T., & Cluff, L. S. (2001). Representative styles of deformation along the Chelungpu Fault from the 1999 Chi-Chi (Taiwan) earthquake: Geomorphic characteristics and responses of man-made structures. *Bulletin of the Seismological Society of America*, *91*(5), 930–952. https://doi.org/10.1785/0120000741

Kemper, W. D., Rosenau, R. C., & Dexter, A. R. (1987). Cohesion Development in Disrupted Soils as Affected by Clay and Organic Matter Content and Temperature1. *Soil Science Society of America Journal*, *51*(4), 860. https://doi.org/10.2136/sssaj1987.03615995005100040004x

Khezri, N., Mohamad, H., HajiHassani, M., & Fatahi, B. (2015). The stability of shallow circular tunnels in soil considering variations in cohesion with depth. *Tunnelling and Underground Space Technology*, *49*, 230–240. https://doi.org/10.1016/j.tust.2015.04.014

Kiani, M., Akhlaghi, T., & Ghalandarzadeh, A. (2016). Experimental modeling of segmental shallow tunnels in alluvial affected by normal faults. *Tunnelling and Underground Space Technology*, *51*, 108–119. https://doi.org/10.1016/j.tust.2015.10.005

Klopčič, J., & Logar, J. (2014). Effect of relative orientation of anisotropy planes to tunnel axis on the magnitude of tunnelling displacements. *International Journal of Rock Mechanics and Mining Sciences*, *71*, 235–248. https://doi.org/10.1016/j.ijrmms.2014.02.024

Ko, Y. Y., & Yang, H. H. (2019). Deriving seismic fragility curves for sheet-pile wharves using finite element analysis. *Soil Dynamics and Earthquake Engineering*, *123*(July 2018), 265–277. https://doi.org/10.1016/j.soildyn.2019.05.014

Kolbuzewski, J. (1948). An experimental study on the maximum and minimum porosities of sand. In *Proceedings of the 2 nd International Conference on Soil Mechanics and Foundation Engineering* (pp. 158–165).

Kontogianni, V. a., & Stiros, S. C. (2003). Earthquakes and seismic faulting: Effects on tunnels. *Turkish Journal of Earth Sciences*, *12*(1), 153–156.

Kouretzis, G. P., Andrianopoulos, K. I., Sloan, S. W., & Carter, J. P. (2014). Analysis of circular tunnels due to seismic P-wave propagation, with emphasis on unreinforced concrete liners. *Computers and Geotechnics*, *55*, 187–194. https://doi.org/10.1016/j.compgeo.2013.08.012

Lazarte, C. ., Bray, J. ., Johnson, A. ., & Lemmer, R. . (1994). Surface breakage of the 1992 Landers Earthquake and its effects on structures. *Bulletin of the Seismological Society of America*, *84*(3), 547–561.

Lazarte, C. A., & Bray, J. D. (1996). A Study of Strike-Slip Faulting Using Small-Scale Models. *Geotechnical Testing Journal*, *19*(2), 118–129.

Lee, J. W., & Hamada, M. (2005). AN EXPERIMENTAL STUDY ON EARTHQUAKE FAULT RUPTURE PROPAGATION THROUGH A SANDY SOIL DEPOSIT, *22*(1).

Lee, J. W., Tabuchi, G., & Hamada, M. (2003). Experimental Approach for Understanding of Fault Rupture Propagation Through an Alluvial Soil. *Journal of Earthquake Engineering Experimental*, 1–4.

Lin, A., Ikuta, R., & Rao, G. (2012). Tsunami run-up associated with co-seismic thrust slip produced by the 2011 M w 9 . 0 Off Pacific Coast of Tohoku earthquake , Japan. *Earth and Planetary Science Letters*, *337–338*, 121–132. https://doi.org/10.1016/j.epsl.2012.04.047

Lin, A., Rao, G., Jia, D., Yan, B., & Ren, Z. (2011). Co-seismic strike-slip surface rupture and displacement produced by the 2010 M W 6 . 9 Yushu earthquake , China , and implications for Tibetan tectonics. *Journal of Geodynamics*, *52*(3–4), 249–259. https://doi.org/10.1016/j.jog.2011.01.001

Lin, A., Ren, Z., Jia, D., & Wu, X. (2009). Co-seismic thrusting rupture and slip distribution produced by the 2008 M w 7 . 9 Wenchuan earthquake , China. *Tectonophysics*, *471*(3–4), 203–215. https://doi.org/10.1016/j.tecto.2009.02.014

Lin, A., Sano, M., Yan, B., & Wang, M. (2015). Co-seismic surface ruptures produced by the 2014 M w 6 . 2 Nagano earthquake , along the Itoigawa – Shizuoka tectonic line , central Japan. *Tectonophysics*, *656*, 142–153. https://doi.org/10.1016/j.tecto.2015.06.018

Lin, M. L., Chung, C. F., & Jeng, F. S. (2006). Deformation of overburden soil induced by thrust fault slip. *Engineering Geology*, *88*(1–2), 70–89. https://doi.org/10.1016/j.enggeo.2006.08.004

Lin, M. L., Chung, C. F., Jeng, F. S., & Yao, T. C. (2007). The deformation of overburden soil induced by thrust faulting and its impact on underground tunnels. *Engineering Geology*, *92*(3–4), 110–132. https://doi.org/10.1016/j.enggeo.2007.03.008

Liu, H. Y., Small, J. C., & Carter, J. P. (2008). Full 3D modelling for effects of tunnelling on existing support systems in the Sydney region. https://doi.org/10.1016/j.tust.2007.06.009

Liu, X., Li, X., Sang, Y., & Lin, L. (2015). Experimental study on normal fault rupture propagation in loose strata and its impact on mountain tunnels. *Tunnelling and Underground Space Technology*, *49*, 417–425. https://doi.org/10.1016/j.tust.2015.05.010

Loukidis, D., Bouckovalas, G. D., & Papadimitriou, A. G. (2009). Analysis of fault rupture propagation through uniform soil cover. *Soil Dynamics and Earthquake Engineering*, *29*(11–12), 1389–1404. https://doi.org/10.1016/j.soildyn.2009.04.003

Mandl, G. (2000). *Faulting in Brittle Rocks* (1st ed.). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-04262-5

Mohammed, S. M. (2015). The Effect of Granular Material on Behaviour of Stone Columns in Soft Clay Under Embankment. *Eng. & Tech. Journal*, *33*(9), 2212–2219. Retrieved from internal-pdf://118.201.166.238/The Effect of Granular Material on Behaviour o.pdf

Mokhtari, M., & Nia, A. A. (2015). The in fl uence of using CFRP wraps on performance of buried steel pipelines under permanent ground deformations. *Soil Dynamics and Earthquake Engineering*, *73*, 29–41. https://doi.org/10.1016/j.soildyn.2015.02.014

Moss, R. E. S., Stanton, K. V, & Buelna, M. I. (2013). The Impact of Material Stiffness on the Likelihood of Fault Rupture Propagating to the Ground Surface. *Seismological Research Letters*, *84*(3), 485–488. https://doi.org/10.1785/0220110109

Murbach, D., Rockwell, T. K., & Bray, J. . (1999). The relationship of foundation deformation to surface and near-surface faulting resulting from the 1992 Landers earthquake. *Earthquake Spectra*, *15*, 121–144.

Namazi, E., Mohamad, H., Jorat, M. E., & Hajihassani, M. (2011). Investigation on the effects of twin tunnel excavations beneath a road underpass. *Electronic Journal of Geotechnical Engineering*, *16 D*, 441–450.

Ng, C. W. W., Asce, F., Cai, Q. P., & Hu, P. (2012). Centrifuge and Numerical Modeling of Normal Fault-Rupture Propagation in Clay with and without a Preexisting Fracture, (December), 1492–1502. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000719.

Nik Norsyahariati, N. D., Ru Hui, K., & Azmi Juliana, A. G. (2016). The Effect of Soil Particle Arrangement on Shear Strength Behavior of Silty Sand. *MATEC Web of Conferences*, *47*, 03022. https://doi.org/10.1051/matecconf/20164703022

Nikkhah, M., & Hosaini, M. M. (2003). Provide a physical model for studying soil landslide under the influence of static and cyclic overlays. *College of Engineering*, 47–62.

Nováková, L. (2014). Evolution of paleostress fields and brittle deformation in Hronov-Poříčí Fault Zone, Bohemian Massif. *Studia Geophysica et Geodaetica*, *58*(2), 269–288. https://doi.org/10.1007/s11200-013-1167-1

Oettle, N., & Bray, J. (2013). Fault rupture propagation through previously ruptured soil. *Journal of Geotechnical and Geoenvironmental …*, (October), 1637–1647. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000919.

Owen, N. G., & Scholl, R. E. (1981). *Earthquake Engineering of Large Underground Structures*.

Perras, M. A., & Diederichs, M. S. (2010). TUNNELLING IN DIFFICULT GROUND : THE NIAGARA TUNNEL PROJECT. In *The Swedish National Rock Mechanics Conference, At Stockholm, Sweden*.

Pistrol, J., Falkner, F.-J., Adam, D., & Adam, C. (2012). Comparison of Constitutive Soil Models for the Simulation of Dynamic Roller Compaction. *6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2012)*, (Eccomas). Retrieved from http://publik.tuwien.ac.at/files/PubDat_210049.pdf

Pitilakis, K. (2007). *Earthquake geotechnical engineering*. 4th International Conference on Earthquake Geotechnical Engineering.

Pöhlitz, J., Rücknagel, J., Schlüter, S., Vogel, H. J., & Christen, O. (2019). Computed tomography as an extension of classical methods in the analysis of soil compaction, exemplified on samples from two tillage treatments and at two moisture tensions. *Geoderma*, *346*(November 2018), 52–62. https://doi.org/10.1016/j.geoderma.2019.03.023

Prentice, C., & Ponti, D. (1997). Coseismic deformation of the wrights tunnel during the 1906 San Francisco earthquake: a key to understanding 1906 fault slip and 1989 surface ruptures in the southern Santa Cruz Mountains, California. *J Geophys Res*, *102*(B1), 635–648.

Prentice, C. S., & Ponti, D. J. (1997). Coseismic deformation of the Wrights tunnel during the 1906 San Francisco earthquake : A key to understanding 1906 fault slip and 1989 surface ruptures in the southern Santa Cruz Mountains , California] Study • Area, *102*, 635–648.

Qi, C., Liu, Q., Chun-Xiao, N., & Changwei, Y. (2005). Numerical modeling of strike-slip fault rupture propagation through soft soil deposit and embankment. *Ninth Asia Pacific Transportation Development Conference*, 662–671.

Rahim, H., Enieb, M., Khalil, A. A., & Ahmed, A. (2015). Seismic Analysis of Urban Tunnel Systems for the Greater Cairo Metro Line No . 4 Seismic Analysis of Urban Tunnel Systems for the Greater Cairo Metro, (4).

Ramancharla, P. K., Hatem, T.-D., & Megur, O. (2004). Dynamic modeling of dip-slip faults for studying ground surface deformation, (832), 4–6.

Rasouli, H., & Fatahi, B. (2019). A novel cushioned piled raft foundation to protect buildings subjected to normal fault rupture. *Computers and Geotechnics*, *106*(November 2018), 228–248. https://doi.org/10.1016/j.compgeo.2018.11.002

Ren, Z., & Lin, A. (2010). Journal of Asian Earth Sciences Deformation characteristics of co-seismic surface ruptures produced by the 1850 M 7 . 5 Xichang earthquake on the eastern margin of the Tibetan Plateau. *Journal of Asian Earth Sciences*, *38*(1–2), 1–13. https://doi.org/10.1016/j.jseaes.2009.12.008

Ridd, M. F. (2012). The role of strike-slip faults in the displacement of the Palaeotethys suture zone in Southeast Thailand. *Journal of Asian Earth Sciences*, *51*, 63–84. https://doi.org/10.1016/j.jseaes.2012.01.018

Roth, W. H., Scott, R. F., & Austin, I. (1981). Centrifuge modeling of fault propagation through alluvial soils. *Geophysical Research Letters*, *8*(6), 561–564. https://doi.org/10.1029/GL008i006p00561

Rourke, T. ., & Palmer, M. . (1996). Earthquake performance of gas transmission pipelines. *Earthquake Spectra*, *12*(3), 493–527.

Russo, M., Germani, G., & Amberg, W. (2002). Design and construction of large tunnel through active faults: a recent application. *Proceedings International Conference of Tunneling and Underground Space Use, Istanbul*, (October), 16–18.

Rutqvist, J., Rinaldi, A. P., Cappa, F., Jeanne, P., Mazzoldi, A., Urpi, L., … Vilarrasa, V. (2016). Fault activation and induced seismicity in geological carbon storage – Lessons learned from recent modeling studies. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(6), 789–804. https://doi.org/10.1016/j.jrmge.2016.09.001

Shen, Y., Gao, B., Yang, X., & Tao, S. (2014). Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after Wenchuan earthquake Yingxiu Longmenshan fault road seven tunnels Pubogou road five tunnels Hanyuan road four tunnels. *Engineering Geology*, *180*, 85–98. https://doi.org/10.1016/j.enggeo.2014.07.017

Stanton, K. (2013). INVESTIGATION OF PARAMETERS INFLUENCING REVERSE FAULT RUPTURE PROPAGATION TO THE GROUND SURFACE.

Stone, K. J. ., & Wood, D. mui. (1992). Effects of dilatancy and particle size observed in model tests on sand. *SOILS AND FOUNDATIONS*, *32*, 43–57. Retrieved from https://www.jstage.jst.go.jp/article/sandf1972/32/4/32_4_43/_article

Sudarsan, B., Ji, W., Adamchuk, V., & Biswas, A. (2018). Characterizing soil particle sizes using wavelet analysis of microscope images. *Computers and Electronics in Agriculture*, *148*(August 2017), 217–225. https://doi.org/10.1016/j.compag.2018.03.019

Taniyama, H., & Watanabe, H. (2001). Deformation of Sandy Deposit by Reverse Faulting. *Doboku Gakkai Ronbunshu*, (591), 135–142. https://doi.org/10.2208/jscej.1998.591_313

Thebian, L., Najjar, S., Sadek, S., & Mabsout, M. (2018). *Numerical investigation of dip-slip fault propagation effects on offshore seabed sediments*. *Engineering Geology* (Vol. 237). Elsevier B.V. https://doi.org/10.1016/j.enggeo.2018.02.008

Tomás, R., & Li, Z. (1992). Large land deformation due to natural phenomena such as earthquakes and subsidence and implication on the natural resources Giorgio Cesari – APAT (Italy), *1992*, 7–9.

Tongkul, F. (1994). The geology of Northern Sabah, Malaysia: Its relationship to the opening of the South China Sea Basin. *Tectonophysics*, *235*(1–2), 131–147. https://doi.org/10.1016/0040-1951(94)90021-3

Varnusfaderani, M. G., Golshani, A., & Majidian, S. (2016). Analysis of cylindrical tunnels under combined primary near-fault seismic excitations and subsequent reverse fault rupture. *Acta Geodynamica et Geomaterialia*, *14*(1), 5–26. https://doi.org/10.13168/AGG.2016.0024

Varnusfaderani, M. gharizade, Golshani, A., & Nemati, R. (2015). Behavior of Circular Tunnels Crossing Active Faults. *Acta Geodynamica et Geomaterialia*, *12*(4), 1–14. https://doi.org/10.13168/AGG.2015.0039

Wang, G., Zhang, S., Wang, C., & Yu, M. (2014). Seismic performance evaluation of dam-reservoir-foundation systems to near-fault ground motions. *Natural Hazards*, *72*(2), 651–674. https://doi.org/10.1007/s11069-013-1028-9

Wang, Y., Wang, Y., Li, J., & Zhan, Y. (2000). Characteristics of ground ruptures caused by the 1999 M 7.3 earthquake of Jiji, Taiwan. *Seismol*, *22*(2), 97– 103.

Wang, Yu, Wei, S., Wang, X., Lindsey, E. O., Tongkul, F., Tapponnier, P., … Sieh, K. (2017). The 2015 M w 6.0 Mt. Kinabalu earthquake: an infrequent fault rupture within the Crocker fault system of East Malaysia. *Geoscience Letters*, *4*(1), 6. https://doi.org/10.1186/s40562-017-0072-9

Wang, Z., Gao, B., Jiang, Y., & Yuan, S. (2009). Investigation and assessment on mountain tunnels and geotechnical damage after the Wenchuan earthquake. *Science in China, Series E: Technological Sciences*, *52*(2), 546–558. https://doi.org/10.1007/s11431-009-0054-z

Wang, Z. Z., Zhang, Z., & Gao, B. (2008). The Seismic Behavior of the Tunnel Across Active Fault. *Proceedings 15th World Conference on Earthquake Engineering*, (1), 1–7.

White, I. R., & Crider, J. G. (2006). Extensional fault-propagation folds: mechanical models and observations from the Modoc Plateau, northeastern California. *Journal of Structural Geology*, *28*(7), 1352–1370. https://doi.org/10.1016/j.jsg.2006.03.028

Wilkinson, M., Roberts, G. P., Mccaffrey, K., Cowie, P. A., Faure, J. P., Papanikolaou, I., … Watson, Z. K. (2015). Slip distributions on active normal faults measured from LiDAR and fi eld mapping of geomorphic offsets : an example from L ' Aquila , Italy , and implications for modelling seismic moment release. *Geomorphology*, *237*, 130–141. https://doi.org/10.1016/j.geomorph.2014.04.026

Yang, H. (2005). *Soil slope stability investigation and analysis in Iowa*. Lowa State University.

Yin, H., Zhang, J., Meng, L., Liu, Y., & Xu, S. (2009). Discrete element modeling of the faulting in the sedimentary cover above an active salt diapir. *Journal of Structural Geology*, *31*(9), 989–995. https://doi.org/10.1016/j.jsg.2008.10.007

Yokoi, H. (1968). Relationship between soil cohesion and shear strength. *Soil Science and Plant Nutrition*, *14*(3), 89–93. https://doi.org/10.1080/00380768.1968.10432750

Yusoff, H. H. M., Razak, K. A., Yuen, F., Harun, A., Talib, J., Mohamad, Z., … Razab, R. A. (2016). Mapping of post-event earthquake induced landslides in Sg. Mesilou using LiDAR. *IOP Conference Series: Earth and Environmental Science*, *37*, 012068. https://doi.org/10.1088/1755-1315/37/1/012068

Zhang, J., Morgan, J. K., Gray, G. G., Harkins, N. W., Sanz, P. F., & Chikichev, I. (2013). Comparative FEM and DEM modeling of basement-involved thrust structures, with application to Sheep Mountain, Greybull area, Wyoming. *Tectonophysics*, *608*, 408–417. https://doi.org/10.1016/j.tecto.2013.09.006

Zhang, P., Xu, X., Wen, X., & Ran, Y. (2008). Slip rates and recurrence intervals of the Longmen Shan active fault zone, and tectonic implications for the mechanism of the May 12 Wenchuan earthquake, 2008, Sichuan, China. *Chin. J. Geophys*, *51*(4), 1066–1073.

Zhao, C., Alimardani Lavasan, A., Barciaga, T., Kämper, C., Mark, P., & Schanz, T. (2017). Prediction of tunnel lining forces and deformations using analytical and numerical solutions. *Tunnelling and Underground Space Technology*, *64*, 164–176. https://doi.org/10.1016/j.tust.2017.01.015

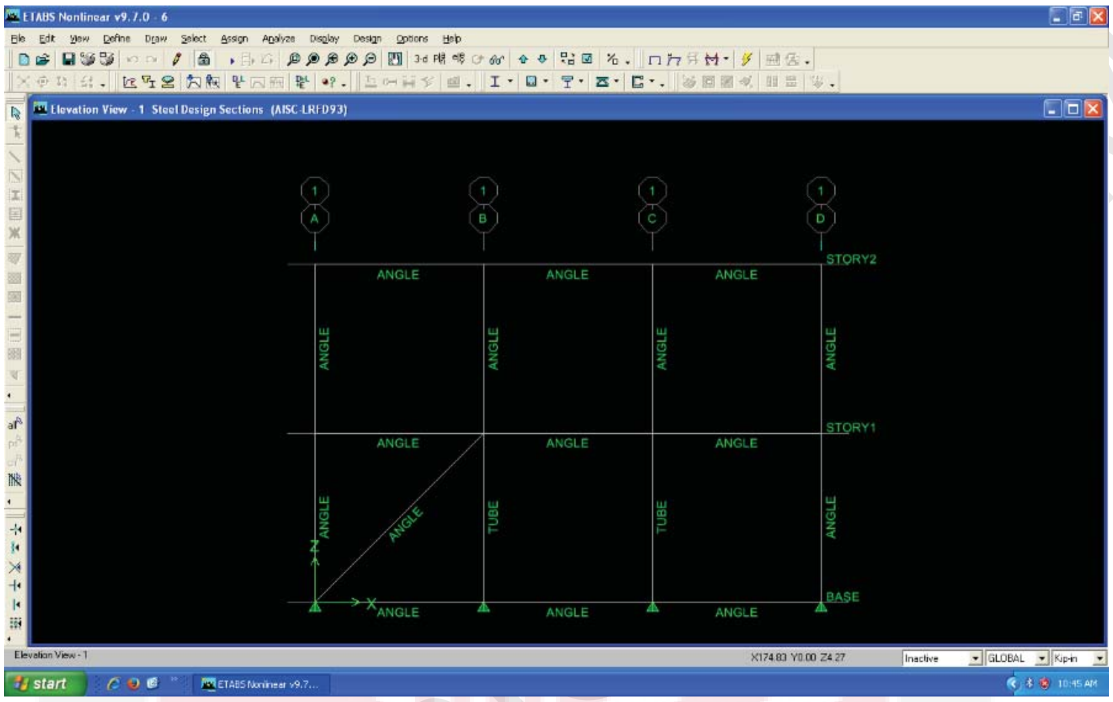
Zidan, a. F., & Ramadan, O. M. O. (2014). Three dimensional numerical analysis of the effects of tunnelling near piled structures. *KSCE Journal of Civil Engineering*, *19*(4), 917–928. https://doi.org/10.1007/s12205-014-0741-6

Zou, J., Chen, G., & Qian, Z. (2019). Tunnel face stability in cohesion-frictional soils considering the soil arching effect by improved failure models. *Computers and Geotechnics*, *106*(August 2018), 1–17. https://doi.org/10.1016/j.compgeo.2018.10.014

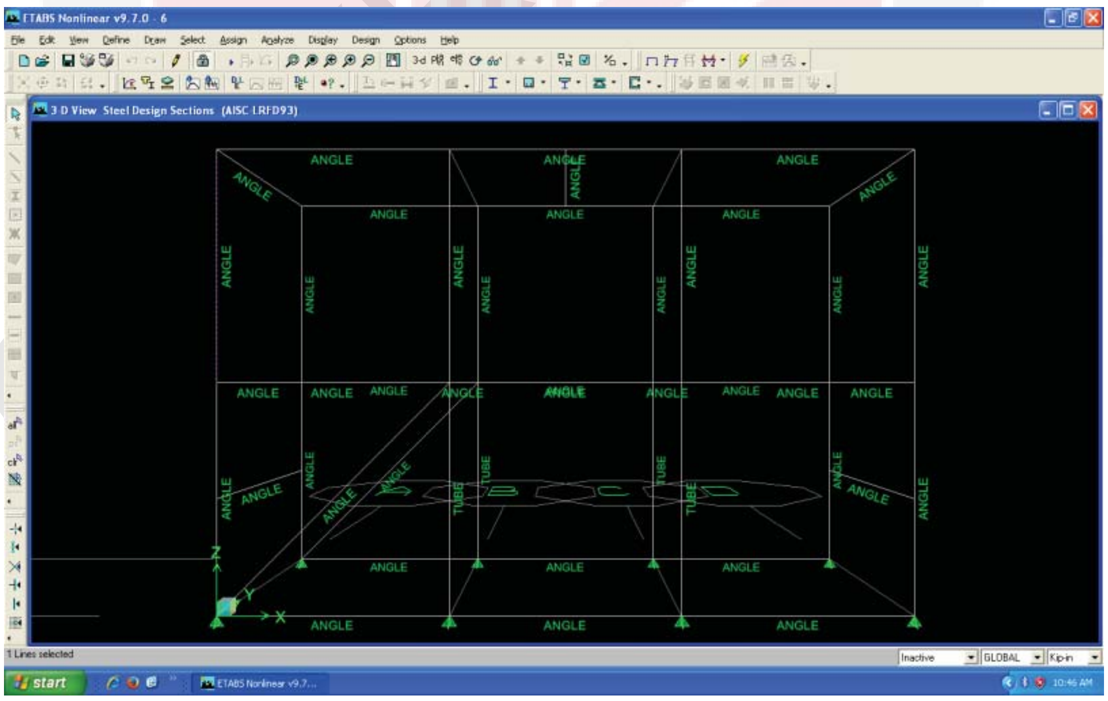
APPENDICES

APPENDIX A

ETABS results

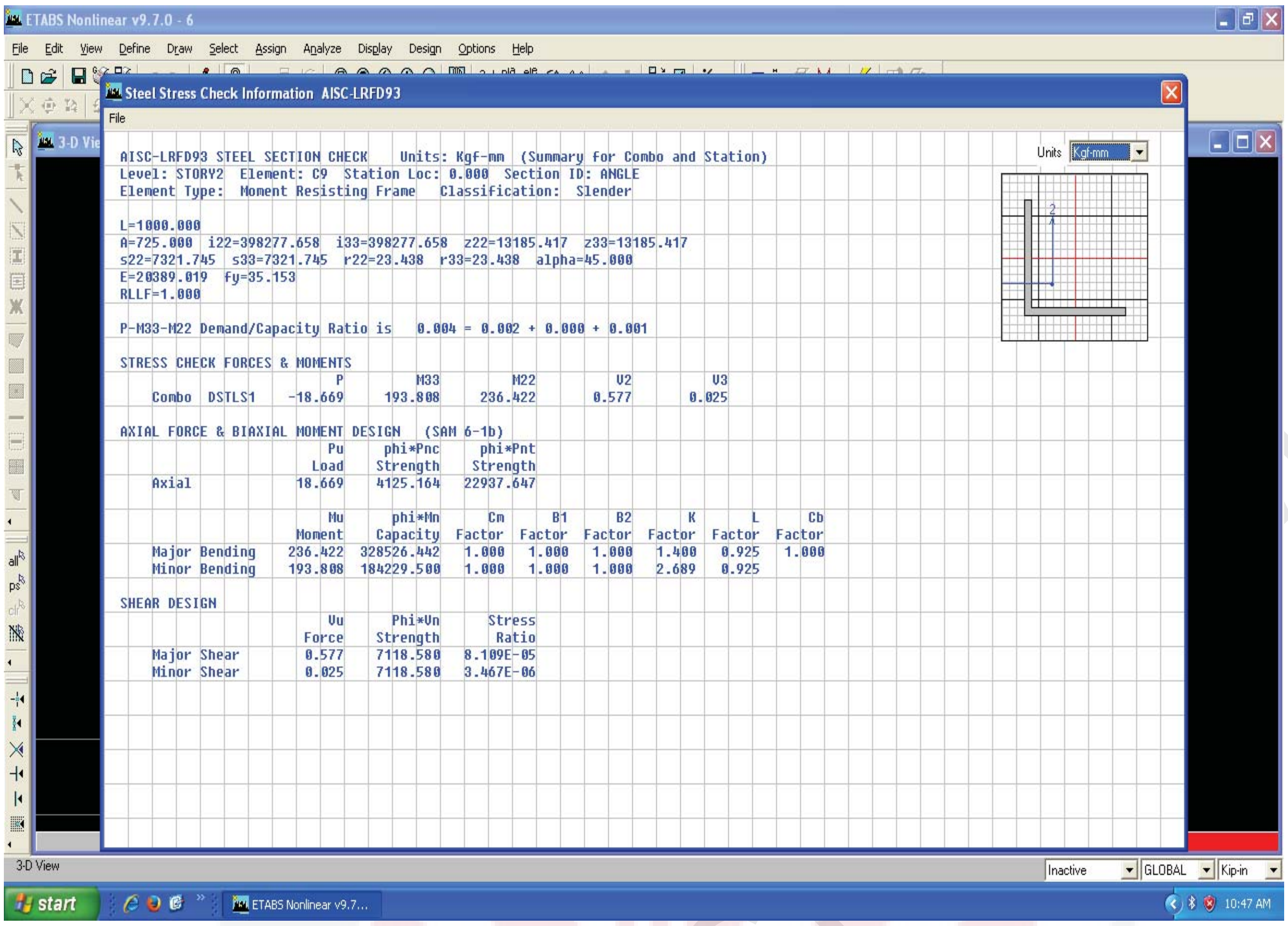


(a)

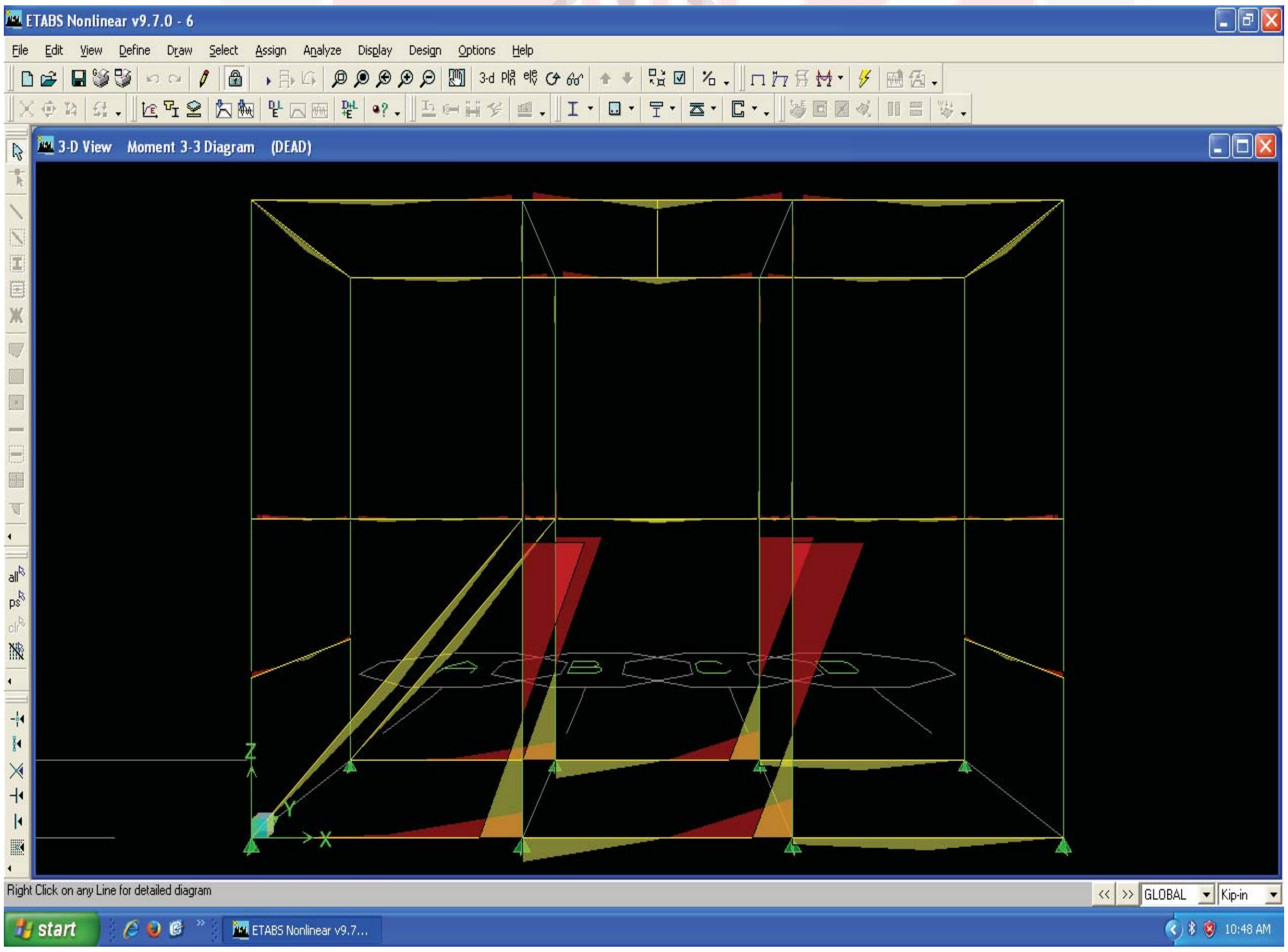


(b)

(a) Frame properties in elevation view (b) in 3D



Results of steel angle column after load induced



Dead statistic load results

Steel beams

Story	ColLine VMinRatio	SecID	PMMRatio	PRatio	MMajRatio	MMinRatio	VMajCombo	VMajRatio	VMinCombo
STORY2	B1	ANGLE	0.006	0.000	0.002	0.004	DSTLS1	0.001	DSTLS2
STORY1	B1	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY1	B2	ANGLE	0.004	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY1	B3	ANGLE	0.004	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY2	B4	ANGLE	0.006	0.000	0.002	0.004	DSTLS1	0.001	DSTLS2
STORY1	B4	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY2	B5	ANGLE	0.004	0.000	0.002	0.002	DSTLS1	0.001	DSTLS2
STORY1	B5	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B5	ANGLE	0.015	0.000	0.005	0.010	DSTLS1	0.001	DSTLS2
STORY2	B6	ANGLE	0.005	0.000	0.002	0.003	DSTLS1	0.001	DSTLS1
STORY1	B6	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B6	ANGLE	0.024	0.000	0.009	0.015	DSTLS1	0.001	DSTLS2
STORY2	B7	ANGLE	0.004	0.000	0.002	0.002	DSTLS1	0.001	DSTLS2
STORY1	B7	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B7	ANGLE	0.008	0.000	0.003	0.005	DSTLS1	0.001	DSTLS2
STORY2	B8	ANGLE	0.004	0.000	0.002	0.002	DSTLS1	0.001	DSTLS2
STORY1	B8	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B8	ANGLE	0.015	0.000	0.005	0.010	DSTLS1	0.001	DSTLS2
STORY2	B9	ANGLE	0.005	0.000	0.002	0.004	DSTLS1	0.001	DSTLS1
STORY1	B9	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B9	ANGLE	0.024	0.000	0.009	0.015	DSTLS1	0.001	DSTLS2
STORY2	B10	ANGLE	0.004	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY1	B10	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
BASE	B10	ANGLE	0.008	0.000	0.003	0.005	DSTLS1	0.001	DSTLS2
STORY2	B13	ANGLE	0.006	0.000	0.002	0.004	DSTLS1	0.001	DSTLS2
STORY1	B14	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS2
STORY1	B15	ANGLE	0.003	0.000	0.001	0.002	DSTLS1	0.001	DSTLS1

Steel braces

Story	ColLine VMinRatio	SecID	PMMRatio	PRatio	MMajRatio	MMinRatio	VMajCombo	VMajRatio	VMinCombo
STORY1	C7	ANGLE	0.010	0.002	0.003	0.005	DSTLS1	0.001	DSTLS2
STORY1	C8	ANGLE	0.010	0.002	0.003	0.005	DSTLS1	0.001	DSTLS2

Steel columns

Story	ColLine VMinRatio	SecID	PMMRatio	PRatio	MMajRatio	MMinRatio	VMajCombo	VMajRatio	VMinCombo
STORY2	C1	ANGLE	0.001	0.001	0.000	0.000	DSTLS2	0.000	DSTLS2
STORY1	C1	ANGLE	0.039	0.037	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY2	C2	ANGLE	0.001	0.001	0.000	0.000	DSTLS2	0.000	DSTLS2
STORY1	C2	ANGLE	0.039	0.037	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY2	C7	ANGLE	0.001	0.001	0.000	0.000	DSTLS2	0.000	DSTLS2
STORY1	C7	ANGLE	0.040	0.038	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY2	C8	ANGLE	0.001	0.001	0.000	0.000	DSTLS2	0.000	DSTLS2
STORY1	C8	ANGLE	0.040	0.038	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY2	C9	ANGLE	0.004	0.002	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY1	C9	TUBE	0.090	0.082	0.007	0.000	DSTLS1	0.001	DSTLS1
STORY2	C10	ANGLE	0.004	0.002	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY1	C10	TUBE	0.088	0.082	0.006	0.000	DSTLS1	0.001	DSTLS1
STORY2	C11	ANGLE	0.004	0.002	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY1	C11	TUBE	0.088	0.082	0.006	0.000	DSTLS1	0.001	DSTLS1
STORY2	C12	ANGLE	0.004	0.002	0.001	0.001	DSTLS1	0.000	DSTLS1
STORY1	C12	TUBE	0.090	0.083	0.007	0.000	DSTLS1	0.001	DSTLS1

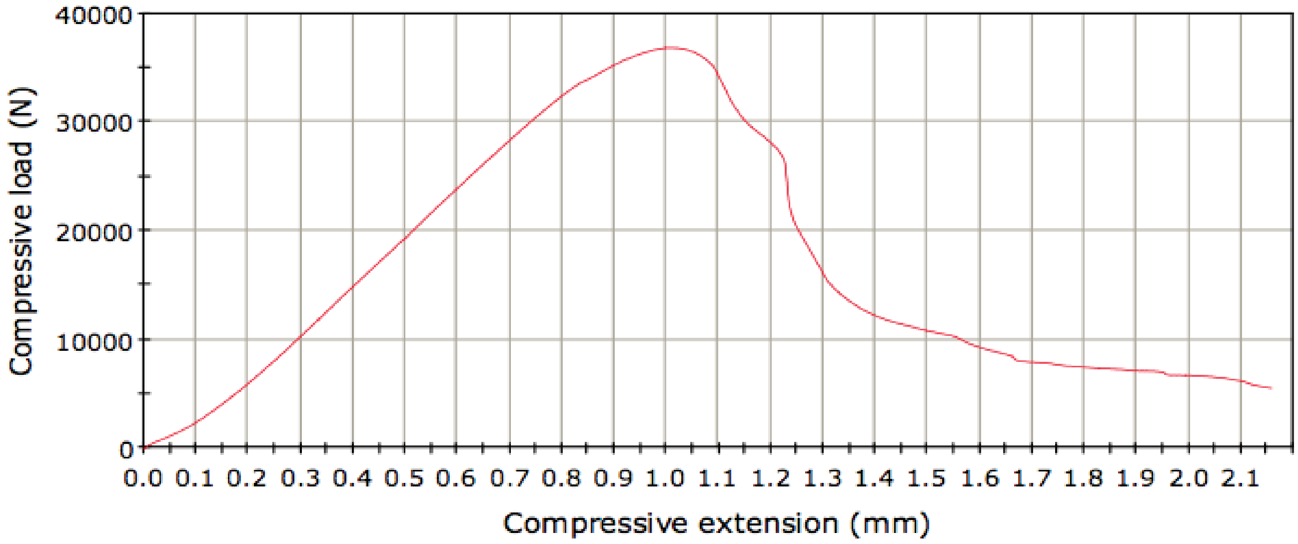
APPENDIX B

Composition limits of Portland cement based on ASTM C 150 – type I, III or BS EN 197-1

Oxide	Content (%)
CaO	60-67
SiO_2	17-25
Al_2O_3	3-8
Fe_2O_3	0.5-6
MgO	0.1-4
Alkalis	0.2-1.3
SO_3	1-3

APPENDIX C

The graph from the compression test



Maximum load and strength compression

	Specimen label	Maximum Load (N)	Compressive Strength (MPa)
1		36864.18	16.40
Mean		36864.18	16.40
Standard Deviation		-----	-----
Minimum		36864.18	16.40
Maximum		36864.18	16.40
Range		0.00	0.00

Results from the compression test

R_1	R_2	ΔR	**δ (MPa)**
28396	35563	7167	16.4

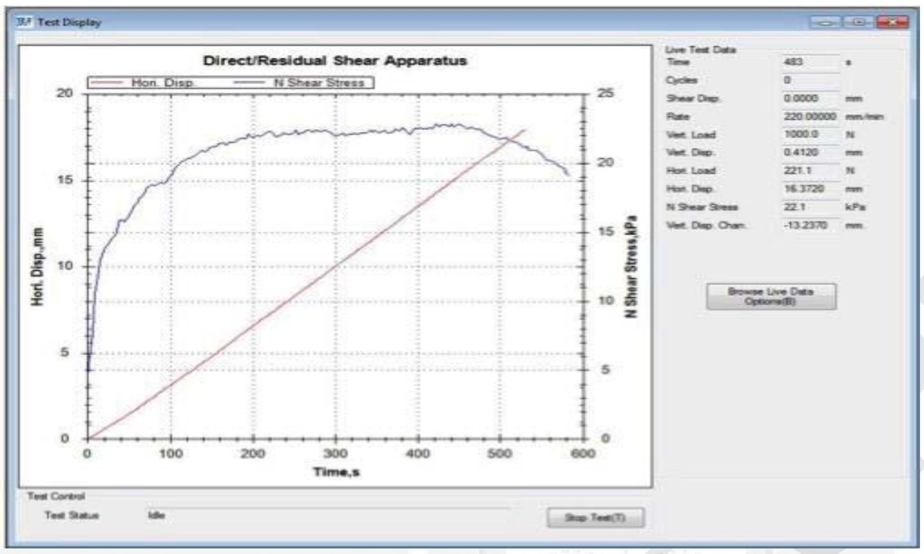
$$\mathrm{GF} = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon}$$

$$2.13 = \frac{0.02}{\epsilon} = 0.009$$

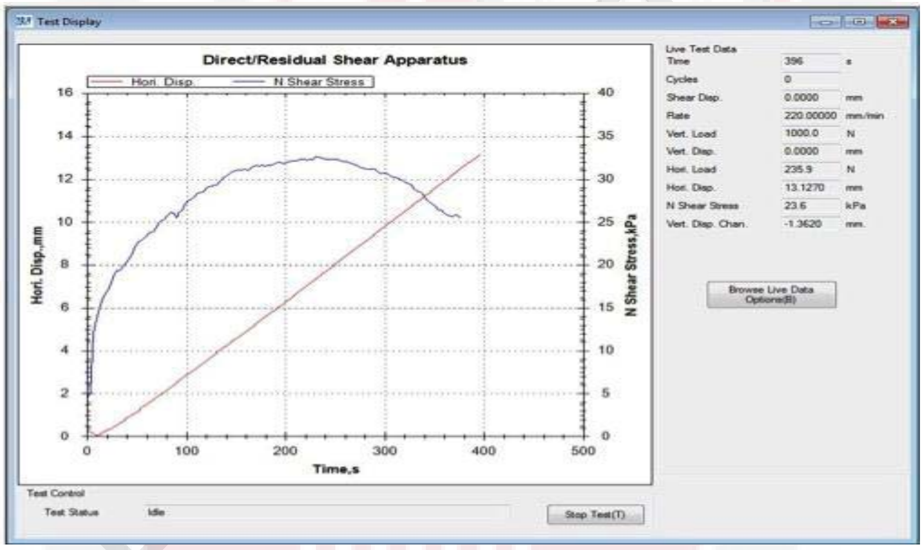
$$\mathrm{E} = \frac{\delta}{\epsilon} = \frac{16.4}{0.009} = 1818 \text{ MPa}$$

APPENDIX D

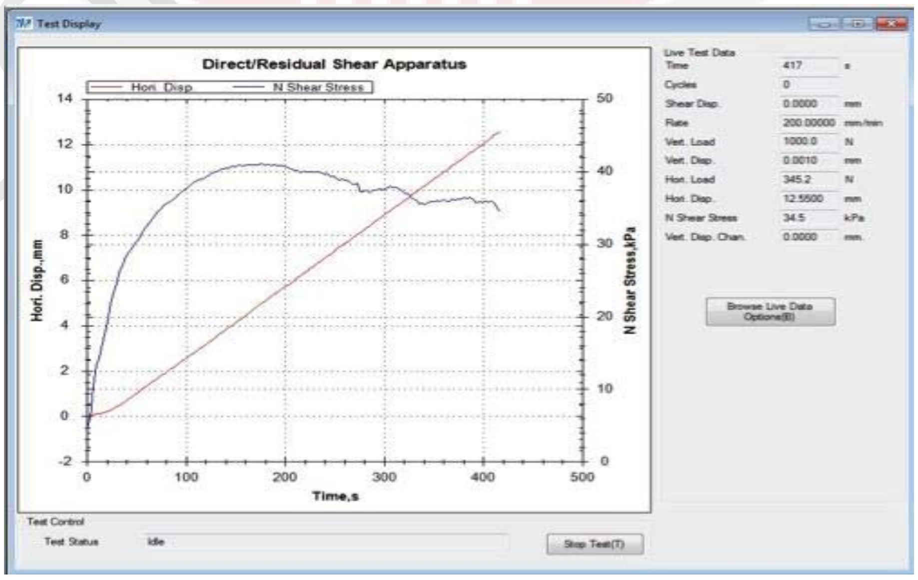
Different soil cohesion



(a)



(b)



(c)

Cohesionless (a), 10kPa (b) and 20kPa (c) results from direct shear box test

Extraction of model development databases from shear box (cohesion of 20kPa)

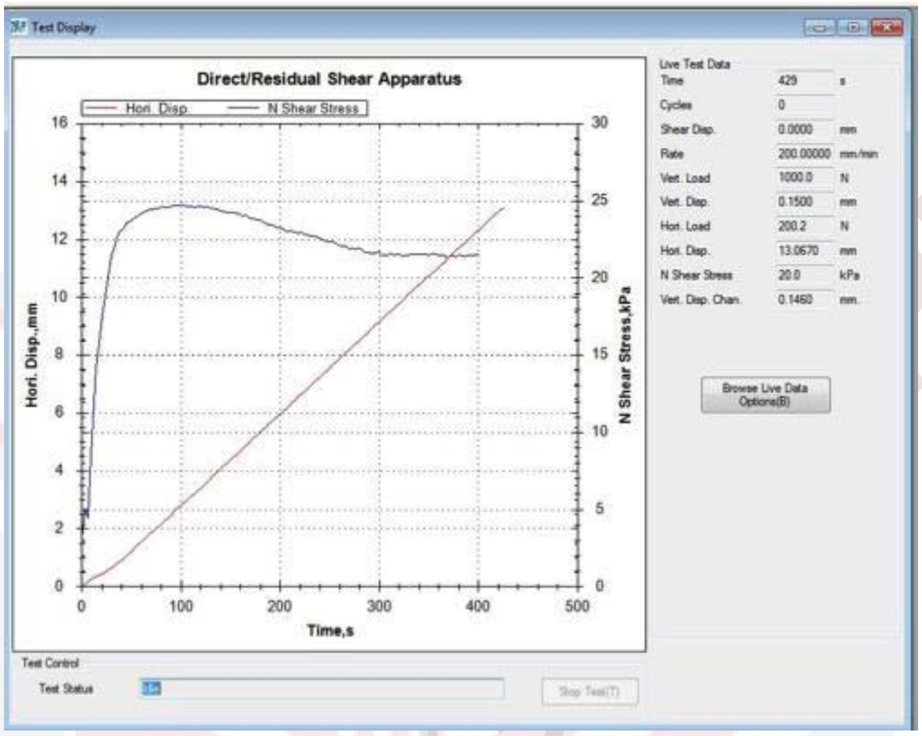
Time,s	Vert. Disp.,mm	Hori. Load,N	Hori. Disp.,mm	N Shear Stress,kPa	Vert. Disp. Chan.,mm.	Shear Force,N
0	0.003	45.6	-0.001	4.55622	0.002	45.5622
3	0.001	60.1	0.044	6.0136	0	60.13596
6	0	103.6	0.082	10.35504	-0.001	103.5504
9	0	132.8	0.104	13.27746	-0.001	132.7746
12	0	143.4	0.116	14.33598	-0.001	143.3598
15	0	157.3	0.131	15.73199	-0.001	157.3199
18	0	174.7	0.159	17.47317	-0.001	174.7317
21	0.001	192.5	0.196	19.24504	0	192.4504
24	0	218	0.25	21.79928	-0.001	217.9928
27	0.001	233	0.335	23.30268	0	233.0268
30	0	246.7	0.423	24.66801	-0.001	246.6801
33	0	262.4	0.499	26.24044	-0.001	262.4044
36	0.001	271.1	0.58	27.11486	0	271.1487
39	0.001	282.3	0.686	28.22708	0	282.2708
42	0.001	289.3	0.766	28.93275	0	289.3275
45	0	294.1	0.848	29.40832	-0.001	294.0832
48	0.001	301.4	0.934	30.14467	0	301.4467
51	0.001	305.1	1.038	30.50518	0	305.0518
54	0.001	310.2	1.123	31.0191	0	310.191
57	0	317.8	1.23	31.77847	-0.001	317.7847
60	0	323.8	1.315	32.37676	-0.001	323.7676
63	0.001	329.7	1.401	32.96738	0	329.6738
66	0.001	334.3	1.513	33.4276	0	334.2761
69	0	339.6	1.6	33.96453	-0.001	339.6453
72	0	345.1	1.684	34.50913	-0.001	345.0913
75	0.001	348.1	1.794	34.80828	0	348.0828
78	0.001	353.9	1.879	35.39123	0	353.9123
81	0.001	356.1	1.963	35.606	0	356.06
84	0.001	358.2	2.069	35.82077	0	358.2077
87	0	362	2.154	36.19662	-0.001	361.9662
90	0.001	365	2.236	36.50344	0	365.0344
93	0.001	368.9	2.335	36.89463	0	368.9463
96	0	372	2.425	37.20144	-0.001	372.0144
99	0.001	375	2.515	37.50059	0	375.0059
102	0.001	378.6	2.602	37.8611	0	378.611
105	0.001	381.7	2.705	38.16792	0	381.6791
108	0.001	384.9	2.784	38.49007	0	384.9007
111	0	387.6	2.895	38.75853	-0.001	387.5853
114	0.001	389.2	2.983	38.91961	0	389.1961
117	0	389.8	3.065	38.98098	-0.001	389.8098
120	0.001	392.8	3.173	39.28012	0	392.8012
123	0.001	394.5	3.265	39.44887	0	394.4887
126	0	398.5	3.352	39.84773	-0.001	398.4773
129	0	399.7	3.445	39.97046	-0.001	399.7046
132	0	399.7	3.56	39.97046	-0.001	399.7046
135	0.001	402.6	3.648	40.26193	0	402.6193
138	0	404.2	3.735	40.41534	-0.001	404.1534
141	0	404.9	3.843	40.49204	-0.001	404.9204
144	0	405.2	3.932	40.51505	-0.001	405.1505
147	0	407.8	4.02	40.77585	-0.001	407.7585
150	0	406.4	4.126	40.63778	-0.001	406.3778
153	0.001	408.8	4.216	40.88323	0	408.8323
156	0	408.4	4.307	40.84488	-0.001	408.4488

159	0	407.9	4.414	40.79119	-0.001	407.9119
162	0	409.3	4.499	40.92926	-0.001	409.2926
165	0	408.7	4.613	40.86789	-0.001	408.6789
168	0	409.3	4.705	40.92926	-0.001	409.2926
171	0.001	408.6	4.792	40.86022	0	408.6022
174	0.001	408.8	4.9	40.87556	0	408.7556
177	0.001	410.8	4.988	41.08266	0	410.8267
180	0.001	408.1	5.072	40.8142	0	408.142
183	0	410.7	5.184	41.06733	-0.001	410.6732
186	0	408.5	5.268	40.85255	-0.001	408.5255
189	0	409.1	5.373	40.91392	-0.001	409.1392
192	0	408.1	5.46	40.8142	-0.001	408.142
195	0.001	408.2	5.548	40.82187	0	408.2187
198	0.001	408.4	5.653	40.84488	0	408.4488
201	0	406.1	5.739	40.61477	-0.001	406.1477
204	0	404.8	5.825	40.4767	-0.001	404.767
207	0.001	402	5.931	40.20057	0	402.0057
210	0.001	401.8	6.017	40.17756	0	401.7756
213	0.001	401.2	6.119	40.1162	0	401.162
216	0.001	398.1	6.207	39.80938	0	398.0938
219	0.001	400.1	6.297	40.00881	0	400.0881
222	0	399.8	6.39	39.97813	-0.001	399.7813
225	0.001	398.7	6.504	39.87074	0	398.7074
228	0.001	399.4	6.586	39.93978	0	399.3978
231	0.001	399.2	6.68	39.91676	0	399.1676
234	0.001	399.1	6.79	39.9091	0	399.0909
237	0.001	397.9	6.879	39.78637	0	397.8637
240	0	395.6	6.97	39.56393	-0.001	395.6393
243	0.001	396.6	7.074	39.65597	0	396.5597
246	0.001	392.2	7.164	39.21876	0	392.1876
249	0.001	393.3	7.252	39.33381	0	393.3381
252	0.001	390.3	7.345	39.03467	0	390.3467
255	0.001	388.5	7.461	38.85058	0	388.5058
258	0.001	389	7.55	38.8966	0	388.966
261	0.001	388	7.636	38.79688	0	387.9688
264	0	387.2	7.724	38.72018	-0.001	387.2018
267	0.001	384.1	7.829	38.40569	0	384.0569
270	0	381.9	7.916	38.19093	-0.001	381.9092
273	0.001	383.4	8.019	38.33666	0	383.3666
276	0	372.2	8.107	37.22445	-0.001	372.2445
279	0.001	372.8	8.213	37.27814	0	372.7815
282	0.001	373.5	8.301	37.35485	0	373.5485
285	0	370.9	8.394	37.08639	-0.001	370.8639
288	0.001	373.7	8.485	37.37019	0	373.7019
291	0	373.9	8.597	37.3932	-0.001	373.932
294	0.001	374.5	8.676	37.45457	0	374.5457
297	0.001	375.7	8.78	37.56962	0	375.6962
300	0.001	373.4	8.865	37.33951	0	373.3951
303	0.001	376.7	8.972	37.66933	0	376.6934
306	0.001	379.4	9.061	37.9378	0	379.378
309	0.001	378.3	9.148	37.83041	0	378.3041
312	0.001	378.2	9.256	37.82275	0	378.2274
315	0	375.8	9.342	37.58496	-0.001	375.8496
318	0	374.2	9.429	37.41621	-0.001	374.1621
321	0.001	369.1	9.54	36.90997	0	369.0997
324	0.001	369.3	9.619	36.92531	0	369.2531
327	0.001	363.7	9.707	36.37304	0	363.7304
330	0.001	361.8	9.815	36.18128	0	361.8128
333	0	360.2	9.902	36.0202	-0.001	360.202

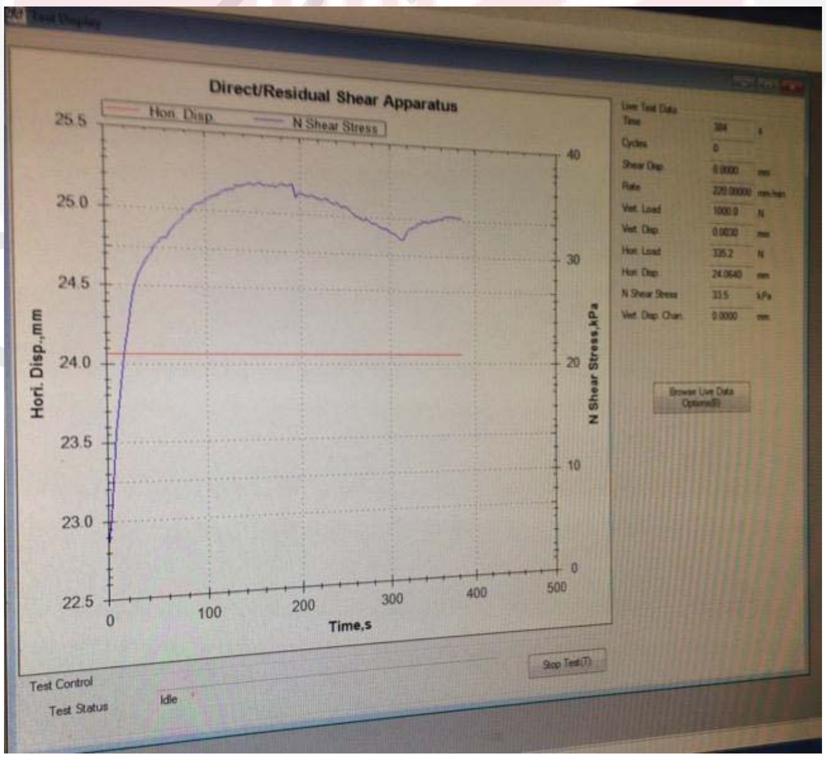
336	0.001	355.7	10.012	35.56765	0	355.6765
339	0.001	356.4	10.098	35.63668	0	356.3668
342	0.001	354.4	10.187	35.44492	0	354.4492
345	0	356.9	10.268	35.69038	-0.001	356.9037
348	0	359	10.386	35.89747	-0.001	358.9747
351	0	358.3	10.478	35.82844	-0.001	358.2844
354	0.001	359.7	10.569	35.96651	0	359.6651
357	0.001	358.8	10.656	35.88213	0	358.8214
360	0.001	361.7	10.764	36.16594	0	361.6594
363	0	358.2	10.853	35.82077	-0.001	358.2077
366	0.001	358.8	10.94	35.88213	0	358.8214
369	0	362	11.05	36.20429	-0.001	362.0429
372	0.001	360.6	11.136	36.05856	0	360.5855
375	0.001	362	11.243	36.19662	0	361.9662
378	0.001	362	11.32	36.20429	0	362.0429
381	0.001	363.7	11.413	36.37304	0	363.7304
384	0.001	362.6	11.526	36.25798	0	362.5798
387	0.001	364.3	11.624	36.4344	0	364.344
390	0.001	362.3	11.709	36.23497	0	362.3497
393	0.001	356.6	11.792	35.65969	0	356.5969
396	0.001	358.5	11.901	35.85145	0	358.5145
399	0.001	357.7	11.988	35.77475	0	357.7475
402	0.001	359.1	12.077	35.91282	0	359.1281
405	0.001	357.6	12.185	35.75941	0	357.5941
408	0.001	359.2	12.274	35.92049	0	359.2049
411	0.001	357	12.38	35.69804	0	356.9804
414	0.001	351.9	12.467	35.1918	0	351.918
417	0.001	345.2	12.55	34.5168	0	345.168
420	0	341.2	12.55	34.11794	-0.001	341.1794
423	0	339.4	12.55	33.94152	-0.001	339.4152
426	0	338.8	12.549	33.88016	-0.001	338.8016
429	0.001	337	12.55	33.70374	0	337.0374
432	0	338.2	12.55	33.81879	-0.001	338.188
435	0.001	336.3	12.55	33.62704	0	336.2704
438	0	335.7	12.55	33.56567	-0.001	335.6567
441	0.001	335.3	12.551	33.52732	0	335.2732

APPENDIX E

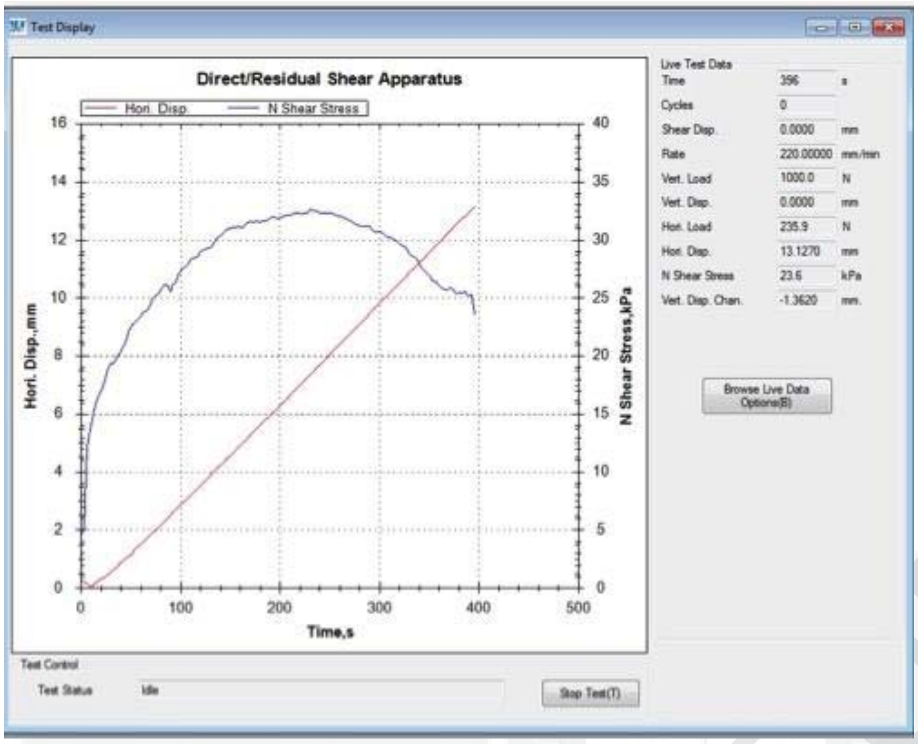
Soil friction angles



(a)



(b)



(c)

Friction angles 27º (a), 33º (b) and 39º (c) results from direct shear box

Extraction of model development databases from shear box (friction angle of 33º)

Time,s	Vert. Disp.,mm	Hori. Load,N	Hori. Disp.,mm	N Shear Stress,kPa	Vert. Disp. Chan.,mm.	Shear Force,N
0	0.003	44.6	24.064	4.46418	0.003	44.64175
3	0.003	66.8	24.064	6.68092	0.003	66.80921
6	0.003	102.9	24.064	10.28601	0.003	102.8601
9	0.003	131.4	24.064	13.1394	0.003	131.394
12	0.003	152.3	24.064	15.22575	0.003	152.2575
15	0.003	163.6	24.064	16.36097	0.003	163.6096
18	0.003	173.3	24.064	17.32743	0.003	173.2744
21	0.003	182.5	24.064	18.24788	0.003	182.4788
24	0.003	188.4	24.064	18.8385	0.003	188.3851
27	0.003	193.5	24.064	19.35242	0.003	193.5242
30	0.003	197	24.064	19.69759	0.003	196.9759
33	0.003	198.7	24.064	19.86634	0.003	198.6634
36	0.003	204	24.064	20.40327	0.003	204.0327
39	0.003	207.9	24.064	20.78679	0.003	207.8679
42	0.003	209.1	24.064	20.90951	0.003	209.0951
45	0.003	209.5	24.064	20.94786	0.003	209.4787
48	0.003	211.9	24.064	21.19332	0.003	211.9332
51	0.003	215.3	24.064	21.53082	0.003	215.3082
54	0.003	216.5	24.064	21.65354	0.003	216.5354
57	0.003	217.5	24.064	21.75326	0.003	217.5326
60	0.003	218.9	24.064	21.89132	0.003	218.9132
63	0.003	222.3	24.064	22.22882	0.003	222.2882
66	0.003	222.4	24.064	22.23649	0.003	222.3649
69	0.003	222.6	24.064	22.2595	0.003	222.595
72	0.003	223.6	24.064	22.35922	0.003	223.5922
75	0.003	226.3	24.064	22.62768	0.003	226.2768
78	0.003	226.8	24.064	22.68138	0.003	226.8138
81	0.003	226.4	24.064	22.64302	0.003	226.4302

84	0.003	227.9	24.064	22.78876	0.003	227.8876
87	0.003	229	24.064	22.90382	0.003	229.0382
90	0.003	229.4	24.064	22.94217	0.003	229.4217
93	0.003	230.6	24.064	23.0649	0.003	230.649
96	0.003	230.6	24.064	23.0649	0.003	230.649
99	0.003	230.8	24.064	23.08023	0.003	230.8024
102	0.003	230.5	24.064	23.04955	0.003	230.4955
105	0.003	230.7	24.064	23.07257	0.003	230.7257
108	0.003	231.6	24.064	23.16461	0.003	231.6461
111	0.003	232.4	24.064	23.24131	0.003	232.4131
114	0.003	231.9	24.064	23.18762	0.003	231.8762
117	0.003	231.5	24.064	23.14927	0.003	231.4927
120	0.003	233.5	24.064	23.3487	0.003	233.487
123	0.003	232.7	24.064	23.272	0.003	232.72
126	0.003	231.8	24.064	23.17995	0.003	231.7995
129	0.003	229.9	24.064	22.98819	0.003	229.8819
132	0.003	232	24.064	23.20296	0.003	232.0296
135	0.003	233.7	24.064	23.37171	0.003	233.7171
138	0.003	232	24.064	23.19529	0.003	231.9529
141	0.003	232	24.064	23.20296	0.003	232.0296
144	0.003	234.9	24.064	23.49444	0.003	234.9444
147	0.003	234.5	24.064	23.44841	0.003	234.4841
150	0.003	233.7	24.064	23.37171	0.003	233.7171
153	0.003	230.3	24.064	23.03421	0.003	230.3421
156	0.003	230.6	24.064	23.0649	0.003	230.649
159	0.003	229.9	24.064	22.98819	0.003	229.8819
162	0.003	230.3	24.064	23.03421	0.003	230.3421
165	0.003	230.2	24.064	23.01887	0.003	230.1887
168	0.003	230.6	24.064	23.0649	0.003	230.649
171	0.003	231.3	24.064	23.12626	0.003	231.2626
174	0.003	230	24.064	22.99586	0.003	229.9586
177	0.003	229.2	24.064	22.91916	0.003	229.1916
180	0.003	229.1	24.064	22.91149	0.003	229.1149
183	0.003	229.4	24.064	22.94217	0.003	229.4217
186	0.003	228.9	24.064	22.88848	0.003	228.8848
189	0.003	228.4	24.064	22.84245	0.003	228.4245
192	0.003	227.8	24.064	22.78109	0.003	227.8109
195	0.003	227.7	24.064	22.77342	0.003	227.7342
198	0.003	228.3	24.064	22.83478	0.003	228.3478
201	0.003	227.9	24.064	22.78876	0.003	227.8876
204	0.003	228.7	24.064	22.87313	0.003	228.7314
207	0.003	228.6	24.064	22.85779	0.003	228.5779
210	0.003	228.2	24.064	22.81944	0.003	228.1944
213	0.003	228.4	24.064	22.84245	0.003	228.4245
216	0.003	226.3	24.064	22.62768	0.003	226.2768
219	0.003	226	24.064	22.60467	0.003	226.0467
222	0.003	227.1	24.064	22.71206	0.003	227.1206
225	0.003	226.4	24.064	22.64302	0.003	226.4302
228	0.003	226.2	24.064	22.62001	0.003	226.2001
231	0.003	225.3	24.064	22.52797	0.003	225.2797
234	0.003	225.6	24.064	22.55865	0.003	225.5865
237	0.003	225.1	24.064	22.51263	0.003	225.1263
240	0.003	225.2	24.064	22.5203	0.003	225.203
243	0.003	225.7	24.064	22.56632	0.003	225.6632

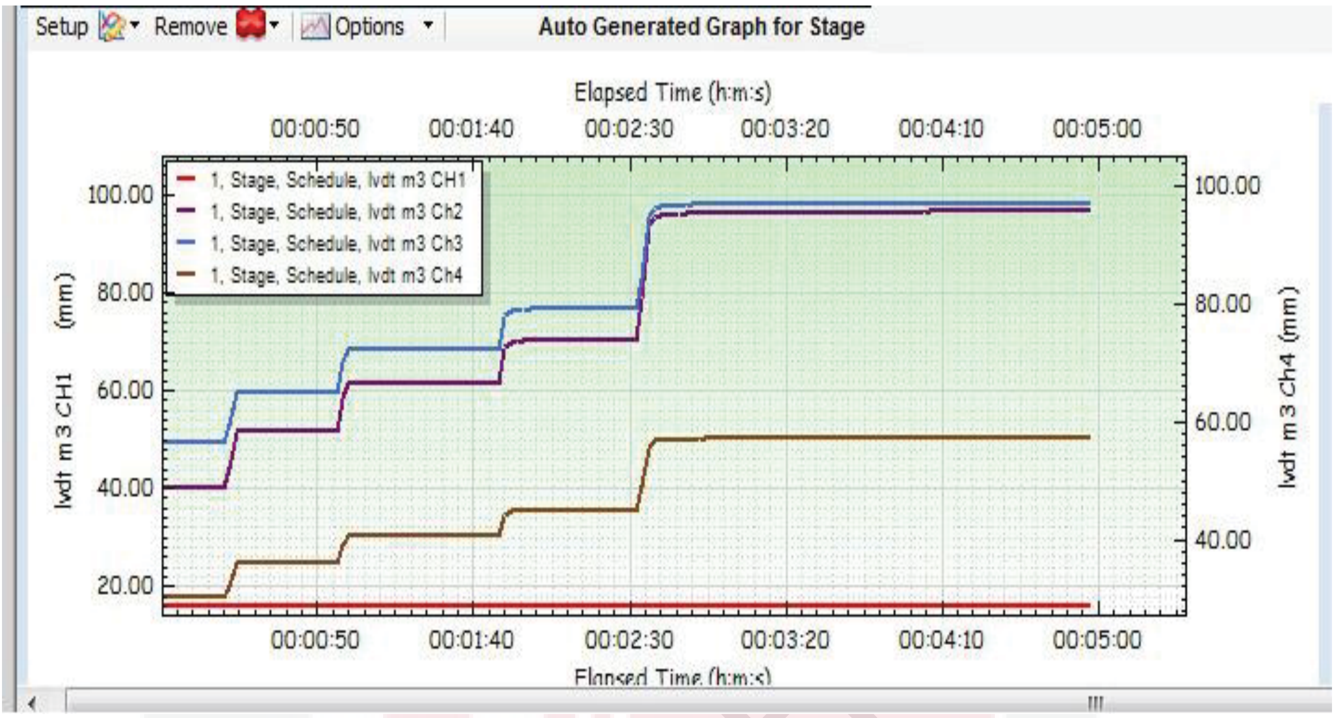
APPENDIX F

LVDTs results for normal fault with D_{50} 0.2mm

M5.11\Spm 1\Stage\Schedule							
	Value	Peak	Trough	Initial	Final		
Elapsed Time	00:06:43			00:00:00	00:06:43		
Logs Record Count	13	13	0	0	13		
Common Data							
lvdt m3 CH1	60.82	61.48	0	60.89	61.26		
lvdt m3 Ch2	51.36	73.28	0	73.26	57.09		
lvdt m3 Ch3	39.53	87.23	0	87.23	49.19		
lvdt m3 Ch4	63.3	86.34	0	86.32	69.43		
lvdt m3 Ch 5	0	51.88	0	0	51.87		
lvdt m3 CH7	29.94	30.04	0	30.03	29.98		
Schedule							
lvdt m3 CH1	lvdt m3 Ch2	lvdt m3 Ch3	lvdt m3 Ch4	lvdt m3 Ch 5	lvdt m3 CH7	Elapsed Time	Logs Record Count
60.89	73.26	87.23	86.32	0	30.03	0	0
61.06	71.52	83.39	85.11	0	30.02	32	1
61.2	69.26	78.52	83.4	0	29.97	81	2
61.26	69.26	78.52	83.4	0	30	83	3
61.09	66.58	73.45	81.49	0	29.95	137	4
61.09	66.58	73.45	81.49	0	29.95	137	5
61.19	63.86	68.39	79.33	0	29.98	168	6
61.19	63.86	68.39	79.33	0	29.98	168	7
61.18	59.95	62	76.23	0	29.98	232	8
61.18	59.95	62	76.23	0	29.98	232	9
60.88	56.3	55.86	73.09	0	29.97	264	10
60.88	56.3	55.86	73.09	0	29.97	264	11
60.96	57.09	49.19	69.43	51.87	29.98	404	12

APPENDIX G

LVDTs results for reverse fault with soil cohesion 10 kPa (C10R60)



APPENDIX H

LVDTs results for reverse fault with friction angle of 39° (F39R60)

M5.11\Spm 1\Stage\Schedule						
	Value	Peak	Trough	Initial	Final	
Elapsed Time	00:06:14	--:--:--	--:--:--	00:00:00	00:04:25	
Logs Record Count	11	11	0	0	10	
Common Data						
lvdt m3 CH1	60.9	61.61	0	61.05	61.39	
lvdt m3 Ch2	17.68	18.48	0	18.25	17.68	
lvdt m3 Ch3	18.23	63.86	0	18.23	63.78	
lvdt m3 Ch4	26.75	27	0	26.78	27	
lvdt m3 Ch 5	0	51.89	0	51.88	0	
lvdt m3 CH7	29.94	30.04	0	29.98	30.03	
Schedule						
lvdt m3 CH1	lvdt m3 Ch2	lvdt m3 Ch3	lvdt m3 Ch4	lvdt m3 Ch 5	lvdt m3 CH7	Elapsed Time
61.05	18.25	18.23	26.78	51.88	29.98	0
61.05	18.41	22.43	26.82	0	29.98	28
61.21	18.46	31.34	26.87	0	29.98	87
61.21	18.46	31.34	26.87	0	29.98	87
61.24	18.48	36.69	26.9	0	29.99	146
61.24	18.48	36.69	26.9	0	29.99	146
61.18	18.48	36.69	26.9	0	29.99	148
61.12	18.46	46.67	26.94	0	29.99	208
61.12	18.46	46.67	26.94	0	29.99	208
61.17	17.68	63.75	27	0	30.02	263
61.39	17.68	63.78	27	0	30.03	265

BIODATA OF STUDENT

Mehdi Ghafari was born in Abadan, IRAN, in 1987. He studied civil engineering course in 2005 and graduated in 2010. He worked as structure engineer in one of the project in Tehran but realized the study was more important for him. He started his master in geotechnical engineering in 2011 and three years after graduated with a distinct result from his viva. He has accepted as a full time student in University Putra Malaysia (UPM) in 2015 and continued his study in geotechnical engineering field. His research interest includes tunneling, excavation, faulting, soil stability and seismic design.

LIST OF PUBLICATIONS

Ghafari, M., Nahazanan, H., Yusoff, Z.M & Nik, N., (2020). A novel experimental study on the effects of soil and faults' properties on tunnels induced by normal and reverse faults. Applied Sciences, 10 (11), 3969, (Published).

Ghafari, M., Nahazanan, H., Yusoff, Z.M & Ghiasi, V., (2019). The effect of soil cohesion and friction angles on reverse faults. Earthquake Engineering & Engineering Vibration. (Accepted)

Ghafari, M., Nahazanan, H., Rostami, V & Ibrahim, A., (2016). The behaviour of peat soil on tunnels against large tectonic deformation. In proceedings of the 3th GEGEU International Research Seminar. Putrajaya, Malaysia.

Ghafari, M., Nahazanan, H., Rostami, V & Salajegheh, A., (2017). Physical models of tunnels and effects of fault ruptures. Global Civil Engineering Conference (GCEC2017). Kuala Lumpur, Malaysia.

Ghafari, M., Nahazanan, H., Rostami, V & Ghafari, M.J., (2017). Difference behavior of shallow and deep foundation induced by fault ruptures. In proceedings of the 4th GEGEU International Research Seminar. Putrajaya, Malaysia.

Ghafari, M., Nahazanan, H., Yusoff, Z.M & Rostami, V., (2018). The effect of soil properties on tunnels against large tectonic deformation. In proceedings of the 5th GEGEU International Research Seminar. Bangi, Malaysia.

Ghafari, M., Nahazanan, H., Ghiasi, V & Rostami, V., (2019). Soil properties impact on normal and reverse faults. Acta Geotechnica. (under review)

Ghafari, M., Nahazanan, H., Ghiasi, V & Rostami, V., (2020). Experimental study on normal and reverse faults through different soil properties. Soil Mechanics and Foundation Engineering. (under review)