LEBANESE AMERICAN UNIVERSITY

**NUMERICAL SIMULATION OF DAMAGE TO MASSIVE
STONE COLUMNS DUE TO EARTHQUAKES**

By

URSULA AREF MERCHAK

A thesis

Submitted in partial fulfillment of the requirements

For the degree of Master of Science in Civil and Environmental Engineering

School of Engineering
June 2012

Thesis Proposal Form

Lebanese American University

School of ENGINEERING - B YBLOS Campus

Thesis Proposal Form

Name of Student: URSULA MERCHAK I.D.#: 200601474

Program / Department: CIVIL ENGINEERING

On (dd/mm/yy): 4-5-2012 has presented a Thesis proposal entitled:

NUMERICAL SIMULATION OF DAMAGE TO MASSIVE STONE COLUMNS DUE TO EARTHQUAKES

in the presence of the Committee Members and Thesis Advisor:

Advisor: DR. MAZEN TABBARA [Redacted Signature]

(Name and Signature)

Committee Member: DR. CAMILLE ISSA [Redacted Signature]

(Name and Signature)

Committee Member: DR. GEBRAN KARAM [Redacted Signature]

(Name and Signature)

Comments / Remarks / Conditions to Proposal Approval: NONE

Date: 5/8/2012 Acknowledged by [Redacted Signature]

(Dean, School of Engineering)

cc: Department Chair
Thesis Advisor
Student
School Dean

Thesis Defense Result Form

Lebanese American University
School of ENGINEERING - B YBLOS Campus

Thesis Defense Result Form

Name of Student: URSULA MERCHAK I.D.: 200601474
Program / Department: CIVIL ENGINEERING
Date of thesis defense: 15-JUNE-2012
Thesis title: NUMERICAL SIMULATION OF DAMAGE TO MASSIVE STONE COLUMNS DUE TO EARTHQUAKES

Result of Thesis defense:

- ☒ Thesis was successfully defended. Passing grade is granted
☐ Thesis is approved pending corrections. Passing grade to be granted upon review and approval by thesis Advisor
☐ Thesis is not approved. Grade NP is recorded

Committee Members:

Advisor: DR. MAZEN TABBARA [Redacted]
(Name and Signature)
Committee Member: DR. CAMILLE ISSA [Redacted]
(Name and Signature)
Committee Member: DR. GEBRAN KARAM [Redacted]
(Name and Signature)

Advisor's report on completion of corrections (if any):

Changes Approved by Thesis Advisor: M. TABBARA Signature: [Redacted]
Date: 15-JUNE-2012 Acknowledged by [Redacted]
(Dean, School of Engineering)

cc: Registrar, Dean, Chair, Advisor, Student

Thesis Approval Form

Lebanese American University

School of ENGINEERING - BYBLOS Campus

Thesis Approval Form

Student Name: URSULA MERCHAK I.D. #: 200601474

Thesis Title : NUMERICAL SIMULATION OF DAMAGE
TO MASSIVE STONE COLUMNS DUE TO EARTHQUAKES

Program / Department CIVIL ENGINEERING

School SCHOOL OF ENGINEERING

Approved by:

Thesis Advisor: DR. MAZEN TABBARA [Redacted]

Committee Member DR. CAMILLE ISSA [Redacted]

Committee Member DR. GEBRAN KARAM [Redacted]

Date 15 - JUNE - 2012

THESIS COPYRIGHT RELEASE FORM

LEBANESE AMERICAN UNIVERSITY NON-EXCLUSIVE DISTRIBUTION LICENSE

By signing and submitting this license, you (the author(s) or copyright owner) grants to Lebanese American University (LAU) the non-exclusive right to reproduce, translate (as defined below), and/or distribute your submission (including the abstract) worldwide in print and electronic format and in any medium, including but not limited to audio or video. You agree that LAU may, without changing the content, translate the submission to any medium or format for the purpose of preservation. You also agree that LAU may keep more than one copy of this submission for purposes of security, backup and preservation. You represent that the submission is your original work, and that you have the right to grant the rights contained in this license. You also represent that your submission does not, to the best of your knowledge, infringe upon anyone's copyright. If the submission contains material for which you do not hold copyright, you represent that you have obtained the unrestricted permission of the copyright owner to grant LAU the rights required by this license, and that such third-party owned material is clearly identified and acknowledged within the text or content of the submission. IF THE SUBMISSION IS BASED UPON WORK THAT HAS BEEN SPONSORED OR SUPPORTED BY AN AGENCY OR ORGANIZATION OTHER THAN LAU, YOU REPRESENT THAT YOU HAVE FULFILLED ANY RIGHT OF REVIEW OR OTHER OBLIGATIONS REQUIRED BY SUCH CONTRACT OR AGREEMENT. LAU will clearly identify your name(s) as the author(s) or owner(s) of the submission, and will not make any alteration, other than as allowed by this license, to your submission.

Name: Ursula Merchak

Signature

Date: 12 June 2012

PLAGIARISM POLICY COMPLIANCE STATEMENT

I certify that I have read and understood LAU's Plagiarism Policy. I understand that failure to comply with this Policy can lead to academic and disciplinary actions against me.

This work is substantially my own, and to the extent that any part of this work is not my own I have indicated that by acknowledging its sources.

Name: Ursula Merchak

Signature

Date: 12 June 2012

ACKNOWLEDGMENTS

This research would not have been possible without the help and assistance of many persons.

First I would like to express my gratitude to my supervisor Dr. Mazen Tabbara and the committee members Dr. Camille Issa and Dr. Gebran Karam. I am also deeply grateful to my family. Thanks go also to Mr. Salim Jamal Eddine.

NUMERICAL SIMULATION OF DAMAGE TO MASSIVE STONE COLUMNS DUE TO EARTHQUAKES

Ursula Aref Merchak

Abstract

Large seismic events have historically occurred in the Middle East and particularly in Lebanon causing severe deterioration and destruction of historical monuments. In 1202 and 1759, Lebanon experienced two of the strongest earthquakes in the history of the region which led to the collapse of 34 monumental columns at the Jupiter temple of Baalbek. This study simulates the effects of earthquakes of varying magnitudes on massive stone columns in order to predict the potential of damage to such columns. The damage in the modeled columns is compared to the actual damage and chipping of the columns in Baalbek. This comparison enables the estimation of the different magnitudes of past earthquakes felt at that site. Numerical simulations were performed using the ADINA software in order to predict and analyze the damage and the collapse of the modeled columns. Two different models were used: a linear elastic model which allows the prediction of the magnitude at which toppling occurs and a second model that admits cracking and crushing of the stone with the aim of reflecting actual damage. The two models were used in predicting the response of the Baalbek colonnades to earthquakes having different magnitudes, thus serving as an indicator of either the occurrence or non-occurrence of past earthquakes with specific magnitudes.

Keywords: Baalbek, Collapse, Earthquake, Finite Elements, Numerical Analysis

Table of Contents

List of Tables	xi
List of Figures	xii
Chapter One Introduction	1
Chapter Two Computational Model	4
2.1 Dimensions of the Model Column	4
2.2 Finite Element Meshes	5
2.3 Material Models	5
2.3.1 Elastic Model	6
2.3.2 Rock Model	6
2.4 Method of Analysis and Earthquake Loading	6
Chapter Three Results and Discussion	9
3.1 Overview	9
3.2 Collapse Threshold	10
3.2.1 Aqaba EW	10
3.2.2 Aqaba NS	11
3.2.3 Caldiran	11
3.2.4 Dinar	11
3.2.5 Duzce	12
3.2.6 Erzincan	12

3.2.7 Kocaeli	12
3.2.8 Manjil.....	12
3.2.9 Tabas	12
3.3 Sensitivity to mesh element size	13
3.4 Effect of vertical component	13
Aqaba.....	13
3.5 Cracking and Damage	13
3.5.1 Aqaba.....	13
3.5.2 Dinar	15
3.6 Three-Dimensional Analysis	15
3.6.1 One Component of Aqaba	15
3.6.2 One Horizontal and One Vertical Component of Aqaba.....	15
3.6.3 Two Horizontal and One Vertical Components of Aqaba.....	15
3.7 Comparison with previous work	16
Chapter Four Conclusions and Remarks.....	17
Bibliography	19
Appendices.....	22
Appendix I: Tables	22
Appendix II: Figures	25

List of Tables

Table 1: Input parameter for the Linear-Elastic material model.....	22
Table 2: Input parameter for the rock material model	22
Table 3: Ground Motion Parameters for the horizontal earthquake records used in the analysis.....	23
Table 4: Scale factor that multiplies the earthquake loading that initiates collapse of the column.....	24

List of Figures

Fig. 1: The dominant tectonic feature of the Levant (Ambraseys, 2004)	25
Fig. 2: Faults in Lebanon (Harajli, Sadek, & Asbahan, 2002).....	25
Fig. 3: Chronological applications of different sciences (Galadini, Hinzen, & Stiros, 2006)	26
Fig. 4: Actual Baalbek Colonnade	27
Fig. 5: Dimensions in meters of the Baalbek column used in the analysis.....	27
Fig. 6: 2D and 3D meshes used in the analysis, h represents the typical element size....	28
Fig. 7: Uniaxial Stress-strain relation used for the rock model material 1 (compressive strength = 70 MPa).....	29
Fig. 8: Uniaxial Stress-strain relation used for rock model material 2 (compressive strength = 105 MPa).....	29
Fig. 9: Acceleration time history records for the Aqaba earthquake (two horizontal components and one vertical component).....	30
Fig. 10: Acceleration time history record for the Caldiran earthquake (horizontal component)	30
Fig. 11: Acceleration time history record for the Dinar earthquake (horizontal component)	31
Fig. 12: Acceleration time history record for the Duzce earthquake (horizontal component)	31
Fig. 13: Acceleration time history record for the Erzincan earthquake (horizontal component)	31

Fig. 14: Acceleration time history record for the Kocaeli earthquake (horizontal component)	31
Fig. 15: Acceleration time history record for the Manjil earthquake (horizontal component)	32
Fig. 16: Acceleration time history record for the Tabas earthquake (horizontal component)	32
Fig. 17: Acceleration Response Spectra for the Aqaba earthquake	33
Fig. 18: Acceleration Response Spectrum for the Caldiran earthquake	34
Fig. 19: Acceleration Response Spectrum for the Dinar earthquake	34
Fig. 20: Acceleration Response Spectrum for the Duzce earthquake	35
Fig. 21: Acceleration Response Spectrum for the Erzincan earthquake	35
Fig. 22: Acceleration Response Spectrum for the Kocaeli earthquake	36
Fig. 23: Acceleration Response Spectrum for the Manjil earthquake	36
Fig. 24: Acceleration Response Spectrum for the Tabas earthquake	37
Fig. 25: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 3 using a mesh of element size 0.5m. The images are shown at increasing response time.	38
Fig. 26: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 8 using a mesh of element size 0.25m. The images are shown at increasing response time.	38
Fig. 27: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5 using a mesh of element size 0.125m. The images are shown at increasing response time.	38

Fig. 28: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 8. The images are shown at increasing response time.	39
Fig. 29: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (NS component) scaled by a factor of 8. The images are shown at increasing response time.	39
Fig. 30: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Caldiran earthquake scaled by a factor of 28. The images are shown at increasing response time.	39
Fig. 31: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 3. The images are shown at increasing response time.	40
Fig. 32: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Duzce earthquake scaled by a factor of 1. The images are shown at increasing response time.	40
Fig. 33: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Erzincan earthquake scaled by a factor of 2. The images are shown at increasing response time.	40
Fig. 34: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Kocaeli earthquake scaled by a factor of 7. The images are shown at increasing response time.	41
Fig. 35: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Manjil earthquake scaled by a factor of 1. The images are shown at increasing response time.	41

Fig. 36: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Tabas earthquake scaled by a factor of 1. The images are shown at increasing response time.	41
Fig. 37: Dynamic response of column using the 2D-Elastic model loaded at the base by two components of the Aqaba earthquake (horizontally by the EW component and vertically by the UP component) scaled by a factor of 7. The images are shown at increasing response time.	42
Fig. 38: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 4. The images feature the evolution of cracking at increasing response time.	42
Fig. 39: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5. The images feature the evolution of cracking at increasing response time.	43
Fig. 40: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5.5. The images feature the evolution of cracking at increasing response time.	43
Fig. 41: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 6. The images feature the evolution of cracking at increasing response time.	44
Fig. 42: Dynamic response of column using the 2D-Rock model (Material 2) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 6. The images feature the evolution of cracking at increasing response time.	44

Fig. 43: Dynamic response of column using the using the 2D-Rock model (Material 2) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 7. The images feature the evolution of cracking at increasing response time...	45
Fig. 44: Dynamic response of column using the 2D-Rock model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 1. The images feature the evolution of cracking at increasing response time.	45
Fig. 45: Dynamic response of column using the 2D-Rock model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 2. The images are shown at increasing response time.	46
Fig. 46: Dynamic response of column using the 3D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 7. The images are shown at increasing response time.	47
Fig. 47: Dynamic response of column using the 3D-Elastic model loaded at the base by two components of the Aqaba earthquake (horizontally by the EW component and vertically by the UP component) scaled by a factor of 3. The images are shown at increasing response time	47
Fig. 48: Dynamic response of column using the 3D-Elastic model loaded at the base by three components of the Aqaba earthquake (horizontally by the EW and NS components and vertically by the UP component) scaled by a factor of 4. The images are shown at increasing response time.	47
Fig. 49: Collapse threshold chart for the column as computed using UDEC for a harmonic ground motion with 25 cycles. The ADINA results of the current study using real earthquakes are represented by the * symbol (Tabbara & Karam, 2011).	48

Chapter One

Introduction

In the Middle East, the rupturing of the Dead Sea Fault system (DSFS) and the southern segment of the East Anatolian fault zone (EAFS) have been the cause of the past tectonic activity of the area, leading to the 12th century seismic paroxysm with severe earthquakes occurring in 1114, 1138, 1157 and 1170 (Ambraseys, 2004). These earthquakes can be seen to be propagating from north to south along the DSFS direction, as shown in Fig. 1, eventually reaching Lebanon by 1170. Although the activity of these faults has been minimal in the last two centuries, the overall activity of the region cannot be concluded solely from this relatively short-term period. Indications of destructive earthquakes are exhibited in currently relatively quiescent areas (Ambraseys, 2006). As depicted in Fig. 2, in Lebanon the DSFS extends into the Yammouneh fault and braids into the Roum, Hasbaya, Rachaya and Serghaya faults. As a result, Lebanon falls in an actively seismic region. Two of the strongest earthquakes in Lebanon occurred in 1202 and in 1759 (Daeron, Klinger, Tapponnier, Elias, Jacques, & Sursock, 2007). In the 1202 earthquake 31 of 40 monumental columns were toppled at the Jupiter temple of Baalbek and in the 1759 earthquake 3 of the 9 remaining columns were toppled. Baalbek is considered to be the largest Roman temple in the world and a UNESCO World Heritage Site.

Whereas no instrumental records for such activities were documented, it would be possible to estimate the magnitudes of these past earthquakes by studying their effect

on the response of massive stone columns. Archaeoseismology is a new science that uses archaeology to collect relevant data regarding past earthquakes from their impact on historical structures (Galadini, Hinzen, & Stiros, 2006). Damage caused to free standing monumental columns such as shifting, leaning and collapse, are stamps that this science can detect (Ambraseys, 2006). In addition, cracking and breaking of corners of building blocks, as well as the aligned collapse of columns are other characteristics to be considered (Marco, 2008). However, it is crucial to focus on the methodology in order to distinguish between earthquake-caused damage and other types of damage, such as wear and tear and anthropogenic damage (Ambraseys, 2006; Marco, 2008). From this, the need for cooperation between different disciplines seems indispensable (Ambraseys, 2006). In fact, other sciences (Fig. 3) such as geology, paleoseismology, historical data and architectural evolution of religious buildings can also be used in order to estimate the characteristics of past earthquakes (Galli & Galadini, 2001). According to Ambraseys (2006), who studied the relation of earthquakes to archaeology, the difficulty of predicting the possibility of an earthquake occurring in the future demonstrates the importance of understanding what happened in the past and of utilizing such understanding for future extrapolation. However, this study is not intended to predict future events but aims on focusing on the responses of monumental columns as a means of enabling the estimation of the peak ground acceleration (PGA) of the earthquakes that occurred. These simulated responses will give us knowledge about the content of the earthquakes that occurred and about those that will cause damage or collapse to existing columns if they were to occur in the future. Baalbek colonnades will be used as a case study to simulate the collapse and damage caused to the columns. Damage can include

cracking and crushing of stone blocks and culminates in the collapse or failure. The collapse of a column is due to large block displacements causing toppling.

Previous investigations on the seismic behavior of columns included experimental methods and numerical methods using the Discrete Element Method (DEM). DEM was originally applied to rock mechanics, and was utilized to model multi-block columns (Papaloizou & Komodromos, 2009; Komodromos, Papaloizou, & Polycarpou, 2008; Psycharis, Lemos, Papastamatiou, Zambas, & Papantonopoulos, 2003). In the analysis, these blocks were assumed to be rigid without taking into consideration the stress development inside the blocks themselves. In order to take block stresses and crushing into account the finite element method was used in this study and the Baalbek columns were modeled using ADINA (Automatic Dynamic Incremental Nonlinear Analysis software).

Chapter Two

Computational Model

A numerical simulation of damage to massive stone columns was carried using the Automatic Dynamic Incremental Nonlinear Analysis (ADINA) software, which is based on the finite elements method and is able to model large displacements, nonlinear material behavior, and non-penetrating contact. This study compares the actual observed damage of the columns in Baalbek with the simulated one, thus enabling the estimation of the magnitudes of past earthquakes felt at the site of study. The analysis was done by utilizing two material models: linear-elastic material model and rock material model. The first allows the determination of the magnitude of the earthquake at which collapse or toppling of the column might occur. As for the second, it admits cracking and crushing in order to approximate the magnitude of the earthquake at which actual observed damage is similar to the simulated one.

2.1 Dimensions of the Model Column

Fig. 4 shows a photograph of the Baalbek colonnade in the Jupiter's temple. A typical column was used to derive all the physical dimensions of the model in ADINA. The model is composed of five blocks in contact with each other with the base of the first block resting on firm ground. The first four blocks, from bottom to top, have a radius of 1.1 m and a height of 1.0 m, 7.5 m, 5.5 m and 4.0 m respectively. As for the capital, it is an inverted frustum of a cone with the larger base of diameter 3.2 m, the smaller base of diameter 2.2 m and a height of 2.0 m (Fig. 5). The representation of the

column in ADINA was formed of 4 rectangles and one trapezoid. They were derived by projecting the actual column on a vertical 2-D plane.

2.2 Finite Element Meshes

The meshes used in the analysis are shown in Fig. 6. The mesh labeled 2D-mesh was used in the 2D analysis to determine the response due to all the earthquake records considered in this study. The “2D-mesh coarse” and “2D-mesh fine” were used only to investigate the sensitivity of the results to mesh element size. The mesh labeled 3D-mesh was used to compare the 2D results with the 3D results for one of the earthquakes. The 3D analysis was computationally intensive which prohibited using a finer mesh and limited the 3D analysis for all earthquakes.

Each stone block was meshed separately with no common nodes to allow for sliding and uplifting of the blocks. Non-penetrating contact was modeled by establishing contact surfaces around the perimeter of each block. Friction forces at the contact between stone edges was modeled by coulomb friction with a coefficient of friction = 0.5.

2.3 Material Models

Two different models were used for the analysis: the first model is the Linear Elastic material model and the second is the Rock material model. The linear elastic model was utilized to determine the factor of collapse since it is less computationally demanding than the other. Next, the rock material model made use of this factor to study the cracking pattern before the failure of the column.

2.3.1 Elastic Model

The linear elastic model was used as to model situations where the column collapses without appreciable damage. The input parameters are given in Table 1.

2.3.2 Rock Model

This model is more realistic since it admits crushing and cracking of the material. It can simulate chipping that occurs without collapse of the column. Although this model is named the “Concrete material model” in ADINA, the basic constitutive characteristics are such that the model can also be useful when representing rock material. The input parameters for the model are given in Table 2. Two sets of parameters were used to investigate the effect of the compressive strength on the cracking pattern.

2.4 Method of Analysis and Earthquake Loading

The sudden collapse of the column due to an earthquake requires a dynamic method for analysis. The explicit dynamic analysis was chosen after initial unsuccessful trials using the implicit dynamic analysis that encountered convergence problems. The explicit dynamic analysis is based on the central difference method and does not require iterations for converging to the solution. It is well suited to resolve sudden changes in geometry due to the contacting forces at the edges of the stone blocks.

Two types of loads were applied to the model. The first represents the self-weight and was applied using a ramp function to minimize vibrations due to sudden application of the weight. The second is the prescribed acceleration at the base according to the time history record of a real earthquake that occurred in the region (Jordan, Turkey and Iran). The records were downloaded from the PEER Ground Motion

Database for Shallow Crustal Earthquakes in Active Tectonic Regimes. PEER stands for the Pacific Earthquake Engineering Research Center maintained by the University of California, Berkeley.

In the analysis, the following earthquakes were used as loading at the base of the column:

1. The Aqaba, Jordan earthquake that occurred in 1995 with magnitude 7.1. The time history acceleration records (in units of g) of the East-West, North-South and Up-Down components are shown in Fig. 9 and are labeled Aqaba EW, Aqaba NS, and Aqaba UP respectively. The corresponding acceleration response spectrum is shown in Fig. 17.
2. The Caldiran, Turkey earthquake that occurred in 1976 with magnitude 7.2. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 10 and is labeled Caldiran. The corresponding acceleration response spectrum is shown in Fig. 18.
3. The Dinar, Turkey earthquake that occurred in 1995 with magnitude 6.4. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 11 and is labeled Dinar. The corresponding acceleration response spectrum is shown in Fig. 19.
4. The Duzce, Turkey earthquake that occurred in 1999 with magnitude 7.1. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 12 and is labeled Duzce. The corresponding acceleration response spectrum is shown in Fig. 20.

5. The Erzincan, Turkey earthquake that occurred in 1992 with magnitude 6.7. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 13 and is labeled Erzincan. The corresponding acceleration response spectrum is shown in Fig. 21.
6. The Kocaeli, Turkey earthquake that occurred in 1999 with magnitude 7.5. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 14 and is labeled Kocaeli. The corresponding acceleration response spectrum is shown in Fig. 22.
7. The Manjil, Iran earthquake that occurred in 1990 with magnitude 7.4). The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 15 and is labeled Manjil. The corresponding acceleration response spectrum is shown in Fig. 23.
8. The Tabas, Iran earthquake that occurred in 1978 with magnitude 7.4. The time history acceleration record (in units of g) of the horizontal component with the largest Peak Ground Acceleration is shown in Fig. 16 and is labeled Tabas. The corresponding acceleration response spectrum is shown in Fig. 24.

The acceleration response spectra listed above were obtained using software downloaded from the SeismoSoft website. This software was also used to determine a number of commonly computed ground motion parameters that are used to describe the damage potential of an earthquake. The ground motion parameters of the horizontal components of earthquake records listed above is given in Table 3.

Chapter Three

Results and Discussion

3.1 Overview

The purpose of the analysis was to determine the scale factor that multiplies the acceleration time history record and initiates collapse of the column. In cases where a scale factor of 1 does not cause collapse, the factor is increased and the analysis is repeated until collapse is achieved. In cases where a scale factor of 1 causes collapse, the factor is decreased and the analysis is repeated until no collapse occurs.

The results can be grouped into the following categories:

1. **Collapse Threshold:** Analysis results using the 2D-mesh with elastic material and one horizontal component applied at the base. The scale factor was computed for each of the earthquakes records considered in this study. Results are plotted on the collapse threshold chart that was determined using UDEC with harmonic ground motion applied at the base (Tabbara and Karam 2011).
2. **Sensitivity to mesh element size:** Analysis results using the 2D-mesh, “2D-mesh coarse” and “2D-mesh fine” with elastic material and one horizontal component applied at the base. The sensitivity of the scale factor to mesh element size was investigated for the Aqaba earthquake.
3. **Effect of vertical component:** Analysis results using the 2D-mesh with elastic material and one horizontal component and the vertical component applied at the

base. The effect of the vertical component on the scale factor was investigated for the Aqaba earthquake.

4. **Cracking and Damage:** Analysis results using the 2D-mesh with Rock Material 1 and Rock Material 2 and one horizontal component applied at the base. The evolution of the cracking pattern was investigated for the Aqaba and Dinar earthquakes. Dependence on the compressive strength was also noted.
5. **Three-dimensional Analysis:** Analysis results using the 3D-mesh with elastic material and (a) one horizontal component applied at the base, (b) one horizontal component and vertical component applied at the base, and (c) two horizontal components and vertical component applied at the base. The scale factor computed using 3D is compared with the corresponding 2D factor for the Aqaba earthquake. Additional 3D effects are noted.

The dynamic analysis was performed on an Intel Xeon PC with CPU having a speed of 3.07 GHz, 4 cores with 2 threads each and a total of 6 GB of RAM. The run time for each 2D-Mesh with Elastic material was about 3 to 4 hours, for each 2D-Mesh with Rock material was about 5 to 7 hours, and for each 3D-Mesh with elastic material was about 36 to 40 hours. A total of 130 runs were performed in 2D and a total of 35 runs were performed in 3D.

3.2 Collapse Threshold

3.2.1 Aqaba EW

When one component (the largest) of Aqaba record was applied to the modeled column, no collapse occurred for all the factors below 8. For a factor of 7, the column

remains in its original state and position at $t = 60$ seconds. Nevertheless, large rotation was observed at $t = 22$ seconds which almost toppled it over. The first factor of collapse for Aqaba earthquake was found to be 8 and this can be seen in Fig. 28. It shows the mechanism of collapse where the top 4 blocks behaved as one as they disjoined from the first block. Large rotation occurred at $t = 50$ seconds which led to the collapse at $t = 51$ seconds.

3.2.2 Aqaba NS

When this component of Aqaba record was applied to the modeled column, the factor of collapse was also found to be 8 and this can be seen in Fig. 29 which also illustrates the behavior of the top 4 blocks as they disjoined from the first block. Large rotation occurred at $t = 25$ seconds which led to the collapse at $t = 26$ seconds.

3.2.3 Caldiran

Many runs were performed on the Caldiran record, varying from a multiplier of 1 to 28 which turned out to be the factor of collapse. Large rotation was observed at $t = 18$ seconds which led to the toppling of the first four blocks at $t = 23$ seconds (Fig. 30).

3.2.4 Dinar

Three runs were performed using Dinar record in order to note the collapse which took place at a factor of 3. As shown in Fig. 31, shifting of the blocks relatively to each other occurred at $t = 8$ seconds leading to complete loss of equilibrium at $t = 14$ seconds causing failure at $t = 15$ seconds.

3.2.5 Duzce

When the Duzce record was applied to the modeled column with a factor of 1, the column collapsed at $t = 24$ seconds (Fig. 32). Other factors were tested and the model showed failure before the factor of 1. Therefore, if such earthquake would occur, collapse will be inevitable.

3.2.6 Erzincan

Erzincan, the earthquake record tested from Turkey, showed a different behavior than the previous ones. The top three blocks collapsed first at $t = 7$ seconds (Fig. 33).

3.2.7 Kocaeli

As for Kocaeli, the last earthquake record tested from Turkey, it first collapsed at a factor of 7 at $t = 58$ seconds (Fig. 34). A large rotation occurred at $t = 50$ seconds even though it fell to the opposite direction with the top four blocks falling in unity.

3.2.8 Manjil

In addition to the records from Jordan and Turkey, an earthquake record from Iran (Manjil) was applied. At a factor of 1, the earthquake itself caused instability of the column (Fig. 35) leading to collapse at $t = 29$ seconds.

3.2.9 Tabas

This earthquake also took place in Iran and has the highest magnitude of all previous records. The column failed due to the application of that record itself as shown in Fig. 36 where the collapse took place at $t = 17$ secs.

3.3 Sensitivity to mesh element size

The above results were all obtained using the 2D-mesh shown in Fig. 6. To investigate the effect of element size on the results, two other meshes shown in Fig. 6 were used to determine the scale factor for the Aqaba EW component. For the case of the 2D-Mesh coarse, the scale factor was 3 and for the case of 2D-Mesh fine the scale factor was 5.

3.4 Effect of vertical component

Aqaba

Two components (East-West and Up-Down) of Aqaba were applied to the 2D model. The scale factor was found to be 7 as compared to 8 for the case of East-West component alone. At $t = 37$ seconds the four upper blocks failed by disconnecting from the first one (Fig. 37).

3.5 Cracking and Damage

3.5.1 Aqaba

Damage due to cracking was analyzed using the rock material model. For some earthquake loadings the analysis encountered numerical convergence problems due mesh distortion caused by localized crushing of finite elements. Two different representative sets of material properties were used to study the cracking behavior. The input parameters are given in Table 2.

Results for Material 1

By applying a factor of 4, cracks started to show up at contact surface 1 and at the bottom of block 2. In addition, one crack appeared at contact surface 2 and another at contact surface 3 as shown in Fig. 38 left. Crack formation continued with time with a concentration at the bottom left of block two until the calculation stopped at $t = 24.9$ seconds (Fig. 38 center and right). Moving to 5 times the Aqaba record, the calculation ran all throughout the duration of the earthquake (60 seconds). Only one crack started to appear at contact surface 1 first (Fig. 39 left). The remaining cracks were later distributed between contact surface 3 and 4. A single crack was noticed in the middle of block 4 (Fig. 39 center and right). At a factor of 5.5, the calculation ran until the monumental column toppled over. The cracking pattern started at time $t = 20.7$ seconds with one crack at the bottom right of block 2. The crack concentration increased in that area and caused the column to collapse at $t = 37.7$ seconds (Fig. 40). Increasing the factor to 6, the crack concentration became evenly distributed at the four different contact surfaces. The top four blocks were shifted to the right (Fig. 41).

Results for Material 2

As shown in the graph in Fig. 8, material 2 is a stronger limestone material. Therefore, it is expected to show more tolerance to the earthquakes (less cracking). At a factor of 6 (Fig. 42), very few cracks showed up, one at the bottom right of the second block (contact surface 1), and one at the bottom right of the fifth block (contact surface 4). Increasing the factor to 7, led to a concentration of cracks in the upper right of block 1 and few cracks developed at contact surface 2 and 3 before the calculation stopped at

$t = 22.7$ seconds (Fig. 43). Even at a higher factor, 7, material 2 showed less cracks than material 1.

3.5.2 Dinar

Even though the collapse occurred at a multiplier of 3, only one crack showed for a factor of 1 (Fig. 44). At a factor of 2, the crack formation increased with a concentration at the right corner of the contact surfaces (Fig. 45).

3.6 Three-Dimensional Analysis

3.6.1 One Component of Aqaba

The modeled column collapsed at a factor of 7 in the 3-D depiction. Fig. 46 shows the process of deformation leading to failure at $t = 38$ seconds. It also shows how the column collapsed in the same manner as 2D.

3.6.2 One Horizontal and One Vertical Component of Aqaba

As opposed to the 2-dimensional analysis, the column collapsed at a factor of 3. Minor shifting between the blocks was noted at $t = 40$ seconds (Fig. 47 left). The collapse followed at $t = 51$ seconds with the same mechanism observed in 2D.

3.6.3 Two Horizontal and One Vertical Components of Aqaba

The components, East-West, North-South and Up-Down, were applied to the 3D model. Unpredictably conflicting all of the previous results, the failure of the monumental column started to appear at a much smaller factor of 4 (Fig. 48). However, the type of failure was similar to the previous dominant ones (the upper four blocks toppled over as one block).

3.7 Comparison with previous work

The scale factors obtained above (using the 2D-mesh with linear-elastic material) for all the horizontal components of the earthquakes were used to compute the peak ground acceleration that will initiate collapse. These values are represented by the star symbol in Fig. 49. The ground motion period was taken as the Mean period of the earthquake record as provided in Table 3. The solid line represents the collapse threshold as computed by UDEC for harmonic ground motion with 25 cycles.

Chapter Four

Conclusions and Remarks

The effect of earthquakes on the collapse of one of the columns of the colonnade at Baalbek was investigated. A numerical simulation of damage to the massive stones of the column was performed using the finite element method. Historical earthquakes that occurred in the region were applied as loading at the base of the column. As a result of the analysis, the following conclusions and remarks can be made:

1. A total of eight historical earthquakes that occurred in the region (Jordan, Iran, and Turkey) were identified and processed for input into the ADINA software. The ground motion parameters were computed for the horizontal components of these earthquakes in order to identify the damage potential of each earthquake.
2. Earthquakes considered in the two-dimensional analysis were scaled to appropriate levels to initiate collapse of the column. The scaled peak ground accelerations were plotted on a chart versus the mean ground-motion periods. The results were in agreement with the collapse threshold computed using the distinct element method (UDEC software) for a harmonic ground motion.
3. Cracking and damage to the column subjected to earthquakes with no collapse is investigated. The analysis has shown that cracking is confined to the edges of the blocks and is induced by hammering of blocks against each other. No cracking is detected within the stone block itself. This is in agreement with the chipped parts that are visible in the colonnades of Baalbek.

4. Three-dimensional simulation has revealed good agreement with two-dimensional results when only one horizontal component is considered. However, marked differences exist when more than one component was used. This warrants further investigation.
5. Two-dimensional simulations have revealed that including the vertical component of the earthquake has little effect on initiating collapse.
6. Two-dimensional analysis has revealed mesh dependency. This may be attributed to resolving contact surfaces. This warrants further investigation.

Bibliography

ADINA, Automatic Dynamic Incremental Nonlinear Analysis (Version 8.8) [Computer software]. USA, MA, Watertown, 71 Elton Avenue: ADINA R & D, Inc.
<http://www.adina.com>

Ambraseys, N. N. (2004, June). The 12th century seismic paroxysm in the Middle East: A historical perspective. *Annals of Geophysics*, 47, 733-757.

Ambraseys, N. N. (2006). Earthquakes and archaeology. *Journal of Archaeological*, 33, 1008-1016.

Ambraseys, N. N., & Barazangi, M. (1989, April 10). The 1759 earthquake in the bekaa valley: Implications for earthquake hazard assessment in the Eastern Mediterranean Region. *Journal of Geophysical Research*, 94(B4), 4007-4013.

Ambraseys, N. N., & Melville, C. P. (1988). An analysis of the eastern Mediterranean earthquake of 20 May 1202. In W. Lee, H. Meyers, & K. Shimazaki (Eds.), *Historical seismograms and earthquakes of the world* (pp. 181-201). New York: Academic Press.

Daeron, M., Klinger, Y., Tapponnier, P., Elias, A., Jacques, E., & Sursock, A. (2007, June). 12,000-year-long record of 10 to 13 paleoearthquakes on the Yammounieh fault, Levant fault system, Lebanon. *Bulletin of the seismological society of America*, 97(3), 749-771.

Galadini, F., Hinzen, K.-G., & Stiros, S. (2006). Archaeoseismology: Methodological issues and procedure. *Journal of Seismology*, 10(4), 395-414.

- Galli, P., & Galadini, F. (2001). Surface faulting of archaeological relics. A review of case histories from the Dead Sea to the Alps. *Tectonophysics*, 335, 291-312.
- Komodromos, P., Papaloizou, L., & Polycarpou, P. (2008). Simulation of the response of ancient columns under harmonic and earthquake. *Engineering Structures*, 30(8), 2154-2164.
- Marco, S. (2008, February 7). Recognition of earthquake-related damage in archaeological sites: Examples from the Dead Sea fault zone. *Technophysics*, 453, 148-156.
- Papaloizou, L., & Komodromos, P. (2009). Planar investigation of the seismic response of ancient columns and colonnades with epistyles using a custom-made software. *Soil Dynamics and Earthquake Engineering*, 29, 1437-1454.
- Psycharis, N., Lemos, J. V., Papastamatiou, D. Y., Zambas, C., & Papantonopoulos, C. (2003). Numerical study of the seismic behaviour of a part of the Parthenon Pronaos. *Earthquake Engineering and Structural Dynamics*, 32, 2063-2084.
- Tabbara, M., & Karam, G. (2011). *Investigation of the dynamic response of large historical block masonry structures*. Byblos: LAU.
- SeismoSoft, Earthquake Engineering Software Solutions [Computer software]. Greece , 34100 Chalkida, 21 Perikleous Stavrou street. <http://www.seismosoft.com>
- UDEC, Universal Distinct Element Code (Version 4.0) [Computer software]. Minneapolis, USA: Itasca Consulting Group Inc. <http://www.itascacg.com>

Appendices

Appendix I: Tables

Table 1: Input parameter for the Linear-Elastic material model

Material Property	Material 1
Poisson's ratio	0.25
Material density (kg/m ³)	2720
Modulus of Elasticity (GPa)	100

Table 2: Input parameter for the rock material model

Material Property	Material 1	Material 2
Poisson's ratio	0.2	0.2
Material density (kg/m ³)	2720	2720
Tangent modulus at zero strain (GPa)	30	40
Uniaxial cut-off tensile stress (MPa)	10	15
Post cracking tensile stress (MPa)	10	15
Uniaxial maximum compressive stress (MPa)	-70	-105
Uniaxial compressive strain at sigma C	-0.004	-0.005
Uniaxial ultimate compressive stress (MPa)	-50	-75
Uniaxial ultimate compressive strain	-0.006	-0.009

Table 3: Ground Motion Parameters for the horizontal earthquake records used in the analysis

Accelerogram	Aqaba EW	Aqaba NS	Caldiran	Dinar	Duzce	Erzincan	Kocaeli	Manjil	Tabas
Max Acceleration (g)	0.0967	0.0863	0.0975	0.3516	0.5353	0.5153	0.0532	0.2087	0.8518
Max Velocity (cm/sec)	13.96	10.57	6.786	40.16	83.51	83.96	8.999	55.21	121.22
Max Displacement (cm)	4.5602	4.3830	1.1785	9.4155	51.5885	27.6708	8.2291	27.2513	95.0671
Vmax/Amax (sec)	0.1472	0.1248	0.0710	0.1165	0.1590	0.1661	0.1724	0.2696	0.1451
Acceleration RMS (g)	0.0156	0.0142	0.0144	0.0673	0.0857	0.0678	0.0044	0.0641	0.1509
Velocity RMS (cm/sec)	2.2502	2.1984	0.9420	11.6573	22.9095	17.6838	1.2966	20.8196	32.2128
Displacement RMS (cm)	1.4794	1.2919	0.3015	3.6412	16.9431	7.3988	1.4779	11.5978	27.1299
Arias Intensity (cm/sec)	0.2256	0.1864	0.0906	1.9530	2.9284	1.5090	0.0389	1.8664	11.5311
Characteristic Intensity	0.0151	0.0131	0.0092	0.0924	0.1276	0.0815	0.0033	0.0881	0.3360
Specific Energy Density (cm2/sec)	303.82	290.00	25.184	3802.3	13588	6665.5	218.56	12787	34098
Cum. Abs. Velocity (cm/sec)	531.9	489.7	275.3	1251	1355	771.0	291.0	1451	3056
Acc Spectrum Intensity (g*sec)	0.1011	0.0968	0.0890	0.3350	0.4014	0.3160	0.0373	0.2535	0.9297
Vel Spectrum Intensity (cm)	51.47	43.71	19.18	213.1	255.8	297.0	18.08	108.9	303.8
Housner Intensity (cm)	47.78	41.36	15.71	205.3	260.9	319.9	17.15	116.9	294.1
Sustained Max.Acceleration (g)	0.083 4	0.0767	0.0683	0.2567	0.3503	0.2418	0.0298	0.1886	0.6275
Sustained Max.Velocity (cm/sec)	7.300	8.736	3.424	29.12	54.18	51.11	6.584	44.64	103.0
Effective Design Acceleration (g)	0.0952	0.0849	0.0860	0.3438	0.5176	0.5158	0.0488	0.2157	0.8389
A95 parameter (g)	0.0950	0.0848	0.0958	0.3472	0.5313	0.5140	0.0520	0.2029	0.8280
Predominant Period (sec)	0.4400	0.1800	0.2800	0.3000	0.2200	0.3000	0.220	0.3000	0.2000
Mean Period (sec)	0.524	0.555	0.296	0.862	0.827	1.326	0.513	1.417	0.472
Significant Duration (sec)	21.1650	23.0350	18.2300	15.5700	10.7800	7.4650	38.0300	21.1100	16.1200

Table 4: Scale factor that multiplies the earthquake loading that initiates collapse of the column

Column Model	Earthquake Loading	Scale Factor
2D-Mesh, Elastic Material	Aqaba EW	8
2D-Mesh, Elastic Material	Aqaba NS	8
2D-Mesh, Elastic Material	Caldiran	28
2D-Mesh, Elastic Material	Dinar	3
2D-Mesh, Elastic Material	Duzce	0.5
2D-Mesh, Elastic Material	Erzincan	2
2D-Mesh, Elastic Material	Kocaeli	7
2D-Mesh, Elastic Material	Manjil	1
2D-Mesh, Elastic Material	Tabas	0.5
2D-Mesh coarse, Elastic Material	Aqaba EW	3
2D-Mesh fine, Elastic Material	Aqaba EW	5
2D-Mesh, Elastic Material	Aqaba EW and Aqaba UP	7
3D-Mesh, Elastic Material	Aqaba EW	7
3D-Mesh, Elastic Material	Aqaba EW and Aqaba UP	3
3D-Mesh, Elastic Material	Aqaba EW, Aqaba NS, and Aqaba UP	4

Appendix II: Figures

Fig. 1: The dominant tectonic feature of the Levant (Ambraseys, 2004)

Fig. 2: Faults in Lebanon (Daeron, Klinger, Tapponnier, Elias, Jacques, & Sursock, 2007)

Fig. 3: Chronological applications of different sciences (Galadini, Hinzen, & Stiros, 2006)

Fig. 4: Actual Baalbek Colonnade

Fig. 5: Dimensions in meters of the Baalbek column used in the analysis

2D-Mesh coarse
 $h = 0.5 \text{ m}$
 292 elements

2D-Mesh
 $h = 0.25 \text{ m}$
 1356 elements

2D-Mesh fine
 $h = 0.125 \text{ m}$
 5127 elements

3D-Mesh
 $h = 0.5 \text{ m}$
 5067 elements

Fig. 6: 2D and 3D meshes used in the analysis, h represents the typical element size.

Fig. 7: Uniaxial Stress-strain relation used for the rock model material 1 (compressive strength = 70 MPa)

Fig. 8: Uniaxial Stress-strain relation used for rock model material 2 (compressive strength = 105 MPa)

Fig. 9: Acceleration time history records for the Aqaba earthquake (two horizontal components and one vertical component)

Fig. 10: Acceleration time history record for the Caldiran earthquake (horizontal component)

Fig. 11: Acceleration time history record for the Dinar earthquake (horizontal component)

Fig. 12: Acceleration time history record for the Duzce earthquake (horizontal component)

Fig. 13: Acceleration time history record for the Erzincan earthquake (horizontal component)

Fig. 14: Acceleration time history record for the Kocaeli earthquake (horizontal component)

Fig. 15: Acceleration time history record for the Manjil earthquake (horizontal component)

Fig. 16: Acceleration time history record for the Tabas earthquake (horizontal component)

Fig. 17: Acceleration Response Spectra for the Aqaba earthquake

Fig. 18: Acceleration Response Spectrum for the Caldiran earthquake

Fig. 19: Acceleration Response Spectrum for the Dinar earthquake

Fig. 20: Acceleration Response Spectrum for the Duzce earthquake

Fig. 21: Acceleration Response Spectrum for the Erzincan earthquake

Fig. 22: Acceleration Response Spectrum for the Kocaeli earthquake

Fig. 23: Acceleration Response Spectrum for the Manjil earthquake

Fig. 24: Acceleration Response Spectrum for the Tabas earthquake

Fig. 25: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 3 using a mesh of element size 0.5m. The images are shown at increasing response time.

Fig. 26: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 8 using a mesh of element size 0.25m. The images are shown at increasing response time.

Fig. 27: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5 using a mesh of element size 0.125m. The images are shown at increasing response time.

Fig. 28: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 8. The images are shown at increasing response time.

Fig. 29: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Aqaba earthquake (NS component) scaled by a factor of 8. The images are shown at increasing response time.

Fig. 30: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Caldiran earthquake scaled by a factor of 28. The images are shown at increasing response time.

Fig. 31: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 3. The images are shown at increasing response time.

Fig. 32: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Duzce earthquake scaled by a factor of 1. The images are shown at increasing response time.

Fig. 33: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Erzincan earthquake scaled by a factor of 2. The images are shown at increasing response time.

Fig. 34: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Kocaeli earthquake scaled by a factor of 7. The images are shown at increasing response time.

Fig. 35: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Manjil earthquake scaled by a factor of 1. The images are shown at increasing response time.

Fig. 36: Dynamic response of column using the 2D-Elastic model loaded horizontally at the base by the Tabas earthquake scaled by a factor of 1. The images are shown at increasing response time.

Fig. 37: Dynamic response of column using the 2D-Elastic model loaded at the base by two components of the Aqaba earthquake (horizontally by the EW component and vertically by the UP component) scaled by a factor of 7. The images are shown at increasing response time.

Fig. 38: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 4. The images feature the evolution of cracking at increasing response time.

20.7 sec

22.7 sec

60 sec

Fig. 39: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5. The images feature the evolution of cracking at increasing response time.

20.7 sec

24.7 sec

37.7 sec

Fig. 40: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 5.5. The images feature the evolution of cracking at increasing response time.

21.5 sec

23.7 sec

44.4 sec

Fig. 41: Dynamic response of column using the 2D-Rock model (Material 1) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 6. The images feature the evolution of cracking at increasing response time.

21 sec

29 sec

60 sec

Fig. 42: Dynamic response of column using the 2D-Rock model (Material 2) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 6. The images feature the evolution of cracking at increasing response time.

Fig. 43: Dynamic response of column using the 2D-Rock model (Material 2) loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 7. The images feature the evolution of cracking at increasing response time.

Fig. 44: Dynamic response of column using the 2D-Rock model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 1. The images feature the evolution of cracking at increasing response time.

Fig. 45: Dynamic response of column using the 2D-Rock model loaded horizontally at the base by the Dinar earthquake scaled by a factor of 2. The images are shown at increasing response time.

Fig. 46: Dynamic response of column using the 3D-Elastic model loaded horizontally at the base by the Aqaba earthquake (EW component) scaled by a factor of 7. The images are shown at increasing response time.

Fig. 47: Dynamic response of column using the 3D-Elastic model loaded at the base by two components of the Aqaba earthquake (horizontally by the EW component and vertically by the UP component) scaled by a factor of 3. The images are shown at increasing response time

Fig. 48: Dynamic response of column using the 3D-Elastic model loaded at the base by three components of the Aqaba earthquake (horizontally by the EW and NS components and vertically by the UP component) scaled by a factor of 4. The images are shown at increasing response time.

Fig. 49: Collapse threshold chart for the column as computed using UDEC for a harmonic ground motion with 25 cycles. The ADINA results of the current study using real earthquakes are represented by the * symbol (Tabbara & Karam, 2011).