FINITE ELEMENT MODELLING, EARTHQUAKE ANALYSIS, AND STRUCTURAL HEALTH MONITORING OF THE ORTAHISAR CASTLE

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ABSTRACT

FINITE ELEMENT MODELLING, EARTHQUAKE ANALYSIS AND STRUCTURAL HEALTH MONITORING OF ORTAHISAR CASTLE

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Ortahisar Castle is one of the valuable historic sites in Turkey at Cappadocia region. Besides being the largest fairy chimney, its irregular shape makes it difficult to carry out structural evaluation studies. This thesis targets a) to generate a detailed 3D Finite Element Model (FEM) of Ortahisar Castle for the purpose of structural evaluation under earthquake, wind, and temperature loads and b) evaluate collected data from 48 crack meters, one accelerometer, one temperature & humidity sensor, one anemometer, and one wind direction vane installed on the Castle. The FEM of the Castle is formed by using data obtained from 3D laser scanning of the Castle, which is then calibrated by checking against experimentally obtained natural vibration frequencies of the Castle. The stress results obtained from structural analyses are checked with Coulomb-Mohr Theory and Modified-Mohr Theory to see if the material capacity of the Castle is exceeded or not. Collected long term health monitoring data is post-processed into time-amplitude graphs and relevant conclusions are drawn. As a result 97.5% of all members have stresses smaller than 10% of their material capacity under earthquake loads.

Keywords: 3D Laser Scanning, 3D Finite Element Modelling, Structural Health Monitoring, Historical Structures, Coulomb-Mohr Theory, Modified-Mohr Theory

ÖZ

ORTAHİSAR KALESİ'NİN SONLU ELEMANLAR MODELLEMESİ, DEPREM ANALİZİ VE YAPISAL SAĞLIK İZLEMESİ

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Kapakdokya Bölgesinde bulunan Ortahisar Kalesi, Türkiye'nin en değerli tarihsel sahalarından biridir. En büyük peribacası olmasının yanı sıra, düzensiz bir şekle sahip olması; kalenin yapısal değerlendirme çalışmalarını zorlaştırmaktadır. Bu tezin amaçları a) detaylı bir 3 boyutlu (3D) sonlu elemanlar modelinin (FEM) oluşturulması b) kale üzerinde bulunan 48 çatlak ölçer, 1 ivmeölçer, 1 sıcaklık ve nemölçer, 1 rüzgâr hızı ölçer ve 1 rüzgâr yön ölçerin oluşturduğu sensör ağından gelen bilgilerin değerlendirmesidir. Kalenin deneyler sonucu elde edilen doğal salınım frekanslarıyla kalibre edilmiş sonlu elemanlar modeli, kalenin 3 boyutlu lazer taraması sonucu elde edilen bilgiler kullanılarak oluşturulmuştur. Yapılan yapısal analizlerin sonuçlarının değerlendirilmesi Coulomb-Mohr ve Modified-Mohr teorileri kullanılarak yapılmıştır ve kalenin malzeme kapasitesinin aşılıp aşılmadığı değerlendirilmiştir. Uzun dönemde toplanan yapısal sağlık izleme verileri derlenerek zaman-değişim grafikleri çizilmiş ve bu grafiklerden elde edilen sonuçlar değerlendirilmiştir. Deprem yükleri altında kaleyi oluşturan elemanların 97,5%'sinin stres değerleri malzeme kapasitelerinin 10%'nun altında kalmaktadır.

Anahtar Kelimeler: 3 Boyutlu Lazer Taraması, 3 Boyutlu Sonlu Elemanlar Modellemesi, Yapısal Sağlık İzlemesi, Tarihi Yapılar, Coulomb-Mohr Teorisi, Modified-Mohr Teorisi

To My Family

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CHAPTER 1

INTRODUCTION

1.1. General

Heritage does not only mean transfer of the cultural tangibles to the next generations but also sharing culture and history of the humankind is a way of legating. Protecting old structures, which have historical and cultural value for humankind, is one way for legating to next generations. These type of structures are also important for touristic activities. Ortahisar Castle is located in the Cappadocia Region, Turkey (Figure 1) and is the main subject of this thesis.

Figure 1 General View of Ortahisar Castle

The Cappadocia Region, consisting of Niğde, Nevşehir, and Kayseri, is one of the most charming touristic sites because of its magnificent and peerless landforms and historical heritage. The total area of Cappadocia Region is 5000 km^2 (Topal and Doyuran, 1995). The Cappadocia Region is one of the World Heritage List sites because of its significant historical, cultural and touristic features (Ulusay et al., 2006). Aydan and Ulusay (2003) mentioned that there are many underground cities and settlements which are more than 1500 years old in the Cappadocia Region. Topal and Doyuran (1995) illustrated that a number of stratovolcanoes, numerous calderas, and thousands of morphologically distinct earth pillars in other words fairy chimneys make the Cappadocia Region unique in the world. The fairy chimneys are the most important structures that is why more than 2 million tourists visit Cappadocia region in one year (Tunusluoğlu and Zorlu, 2008). Topal and Doyuran (1995) informed that as a result of differential erosion and weathering of ash flow tuffs deposited, the fairy chimneys came into existence.

Ortahisar Castle is located at the center of the Cappadocia Region at Ortahisar province of Nevşehir (Figure 2). The height of the Castle is 64 meters and is the highest fairy chimney in Turkey. According to Kamberoğlu (2012), Ortahisar Castle is an important structure in this region because of its location which makes the Castle visible from anywhere in the Ürgüp region (Figure 2). The castle had been used as sanctuary for local people during the Hittite Empire and caves in the the Castle were first carved by Hittites. After Hittite Empire period, the Castle had been continued to be used as a castle for other empires such as Byzantine, and Ottoman Empire. Topal and Doyuran (1995) mentioned that because of cave dwellings the fairy chimneys were excavated and the fairy chimneys were inhabited by Byzantines. Kamberoğlu (2012) illustrated that according to macro form of Ortahisar, the first zone of occupation started at the high elevation of the Castle and it went on into the surrounding skirts of the Castle. At the present day, the Castle is no more occupied by residents and solely used for touristic purposes. But not all parts of the Castle can be visited by tourists because of poor structural condition of the Castle. However, a restoration and strengthening

project was started in 2012. Within the scope of the project, damaged parts of the Castle posing source of danger are strengthened and a structural health monitoring system is installed on the Castle. Therefore, this thesis explored calibrated, three dimensional (3D) Finite Element Modelling (FEM) of the Castle, for the purpose of structural evaluation against earthquakes, wind, and temperature forces. Each one of the finite element members was individually checked if Columb-Mohr failure criteria was met to see if cracks will occur. Additional work was carried out for dynamic testing and calibration of the analytical model. Furthermore, a large sensor network collected data was evaluated for 48 crack meters, one accelerometer, one temperature & humidity sensor, one anemometer, and one wind direction vane.

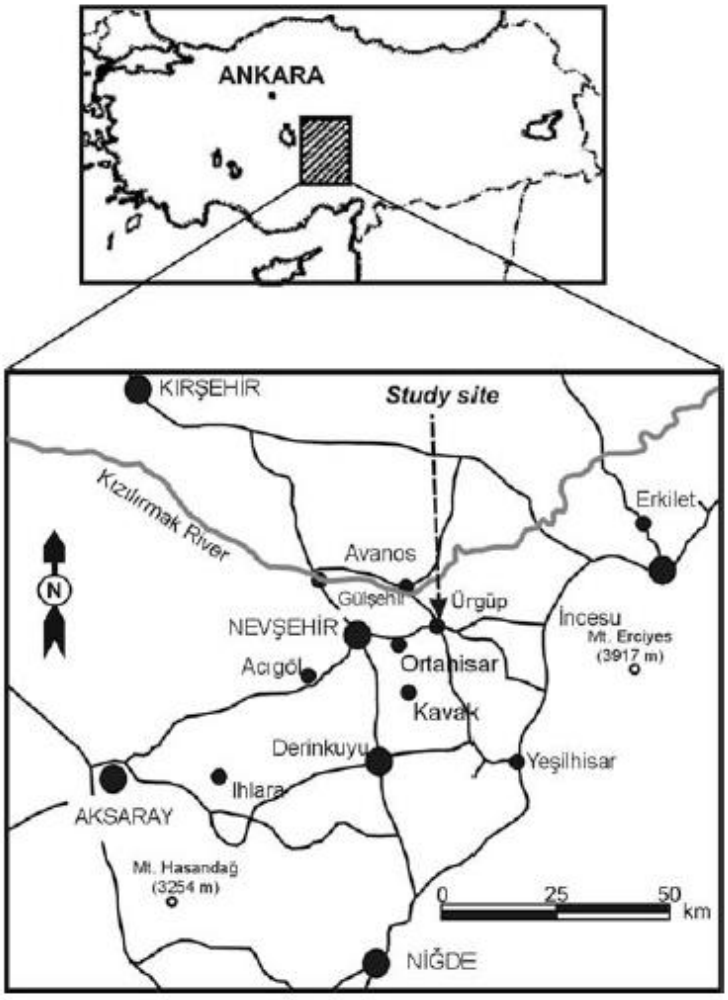

Figure 2 Location of Cappadocia Region and Study Area

1.2. Literature Review

Although Ortahisar Castle is the largest Fairy Chimneys in Nevşehir Region, there are limited number of academic studies on them. The existing ones are generally about the geological situation of the Castle most of the articles about Cappadocia Region are mainly dealing with geotechnical, geoenvironmental and geological problems of the region. There are limited resources about structural health monitoring and finite element modelling of the Castle to use at the thesis literature review part of the thesis. For this reason, the articles about SHM and FEM of historical structures are reviewed in general. The academic studies not only about the Castle and Ortahisar but also the Cappadocia Region, SHM, and FEM are used during the literature search of thesis. Herein after, brief summaries of these studies are explained.

Doyuran (1976) made a research about environmental and geologic problems of Ortahisar Castle. The aim of the research is considering rock fall from the Castle in a geologic approach, which threaten local people and tourists. Firstly, Doyuran (1976) explored the geology of Ortahisar region and cracks on the Castle. The reason of cracks on the Castle was founded as rain water leakage into rocks. When rain water leaks into the rocks, the water freezes because of winter conditions and volume of the frozen water increases, expanding the cracks. Doyuran (1976) reported that because of increment of cracks dimensions, rock fall can occur although there have not been any recent rock fall. A rock fall may cause loss of life. Therefore, reducing impact area of rock fall to a minimum instead of preventing the rock falls is advised. Doyuran (1976) mentioned that there are three ways to reduce the impact area of rock fall. The first one is vacating the residential houses in the region. Secondly, the region obtained from vacating should be covered with talus to prevent second jump of downthrown rock. Lastly, Doyuran (1976) suggested that retaining walls should be constructed around the impact region to block little particles to bounce from the fall, which might damage houses around the region.

Topal and Doyuran (1995) made research about the geological engineering characteristics of the tuffs of Kavak member discontinues on the development of the Fairy chimneys. Topal and Doyuran (1995) illustrated that the tuffs of the Kavak member of the Ürgüp formation is the main material of the Fairy chimneys in the Cappodocia Region. The formation of the fairy chimneys is controlled by the joints. Erosion along the joints affect the formation of the fairy chimneys (Topal and Doyuran, 1995). Topal and Doyuran (1995) mentioned that surface runoff water based erosion is more effective than wind actions at the formation of the fairy chimneys; lack of vegetation, steep topography and low permeability of the bed rock are also important parameters.

Aydan and Ulusay (2003) were dealing with the geotechnical and geoenvironmental characteristics of man-made underground structures in Cappadocia. They made several experiments like Schmidt hammer tests to determine the characteristic properties of Cappadocia tuff. The authors also tried to find a relationship between the environmental conditions such as temperature, humidity and behavior of the tuff. According to Aydan and Ulusay (2003), it is found that the Cappadocia tuffs are prone to temperature and humidity. Uniaxial compressive strength of Cappadocia tuffs can also be accepted as partially weak to very weak.

Ulusay et al. (2006) studied the environmental and engineering geological problems of deserted rock-hewn settlement in Ürgüp. Ulusay et al. (2006) investigated nearly 1200 rock-hewn underground openings and existing historical structures. Since the study region is in Cappadocia, they discovered that the rock material type is tuff and tuffites similar to Aydan and Ulusay's previous work (2003). In addition to Aydan and Ulusay's article in 2003; in their publication dated 2006, they also suggested corrective solutions for the structural problems. The study of Ulusay et al. (2006) included various problems such as block fall, rock fall, and erosion. To increase the stability of underground cave roofs, they advised to use timber beams as supporters, which is also a traditional method in Cappadocia. Strong prismatic tuff blocks can be constructed for weak entrances of openings. Individual blocks can be divided in to

smaller pieces and removed from the study area to ensure the necessary safety against rock fall.

Tunusluoğlu and Zorlu (2008) conducted rock fall hazard assessment in Ortahisar. They grouped problems of Ortahisar Castle in two groups which are natural effects and anthropogenic effects. Doyuran (1976) also grouped the problems of Ortahisar in the same way. The main purpose of Tunusluoğlu and Zorlu is investigating rock fall hazard of the Castle. Firstly, fieldwork research was done. This research consists of determination of location rocks, dimensions of blocks, an exhaustive discontinuity survey, description of topographic and morphologic characteristics, and location of fallen blocks. After that the cross-sections of the Castle were obtained and 2D rock fall analyses were made. Tunusluoğlu and Zorlu (2008) mentioned that the main reason for rock falls is changing in forces acting on a rock because of climatic and biological events; however, at Ortahisar Castle, reasons for a rock fall can be wind erosion, freeze thaw process and water influence. 2D rock fall analyses' results show that any falling block reaches high velocities at the bottom generating a very dangerous phenomenon. Tunusluoğlu and Zorlu (2008) also prepared a run out distance zone whose area is nearly 30,000m^2. They advised that the Castle and its surrounds should be closed for uncontrolled touristic activities considering the run out zone to reduce any loss of lives.

Kamberoğlu (2012) also evaluated the case of Ortahisar in her master thesis. The academic study mainly focuses social situation of Ortahisar, tourism facilities, city planning and economic facilities in Ortahisar. According to Kamberoğlu (2012), Ortahisar is settled around the Castle and all touristic activities in Ortahisar is occurred because of Ortahisar Castle that proves the importance of the Castle again. The records of Ministry of Tourism and Culture show that more than 600,000 tourists visited this region in 2009 annually which is a good income for local people of Ortahisar.

Guarnieri et al. (2013) illustrated that structural analysis of a historical structure is made to identify the probable state of danger and estimate the future behavior of the

structure. Finite Element Modelling (FEM) is used widely in structural analysis of historical structures. Guarnieri et al. (2013) mentioned that three-dimensional mesh generated from laser scanning data was used to obtain FEM model of the Olympic Theatre. Static and dynamic analyses were done with the FEM model according to Italian regulations.

Chellini et al. (2014) mentioned that because of great socioeconomic, historical, and intristic value of cultural heritage buildings, the interest in minimizing seismic hazard for these types of structures grew enduringly. Historical structures are mainly complex strucutres since they are built on the past design criteria, construction methods, and technical knowledge. Chellini et al. (2014) made a study about evaluation of seismic vulnerability of Santa Maria del Mar Church using terrestrial laser scanning three-dimensional survey and finite element analysis. Response spectrum analysis was used and two different collapse scenario were analyzed by changing inclinations of cracks. Chellini et al. (2014) concluded that design seismic action can overturn the facade upper part of the church.

Lima et al. (2008) illustrated that one of the most powerful way to manage infrastructures is structural health monitoring. Lima et al. (2008) made a scientific research about structural health monitoring of one historical building. The SHM system has 19 displacement sensors and 5 temperature sensors. The duration of data obtained from SHM system is 1 year. Lima et al. (2008) aimed to get information about the structure and find new techniques for restoration of the historical structure.

According to Marazzi et al. (2011), structural health monitoring (SHM) techniques to control and consideration of monumental structures was very important. A handled SHM studies is a way to increase information belongs to structural conditions of a monument and problems of the monument. Therefore, SHM can be used to select the most appropriate restoration response to satisfy required safety level. Marazzi et al. (2011) studied about experimental comparison between two techniques to measure the

crack widths whose origin is settlement. Marazzi et al. (2011) concluded that manual measurements and optical measurements have a very goof agreement between them.

1.3. Objectives and Scope

Historical structures are very important for cultural heritage. Ramoset al. (2010) mentioned that conservation of cultural and architectural heritage is a necessary concern in the cultural life of contemporary societies. Hossein and Tabrizi (2010) illustrated that imperfect knowledge about structural conditions of historical buildings is an important problem for many cities in the world. Since there are no structural drawings of historic structures, it is not possible to determine original material, dimensions, and behavior of these structures, which make structural health monitoring very important. In other words, structural health monitoring (SHM) is accepted as one of keys to ensure safety of historical structures (Damonte et al., 2007). Therefore, application of structural health monitoring on the Ortahisar Castle and monitoring the Castle's vital responses are one of the major objectives of this thesis. The monitoring work is carried out using a number of crack meters or LVDTs to measure possible changes in crack widths. Since the Castle has numerous cracks on its surface, the cracks should be monitored by using a large number of LVDTs. The LVDTs are connected to a data logger, which is used to communicate with the sensor, make measurement, convert to digital format, record the data, and transfer the data to a computer. The data consists of change of crack widths in time; therefore, obtaining data from the data logger is used for evaluating crack widths changes.

The second objective of the thesis is to make a comprehensive evaluation of the overall behavior of the Castle using detailed finite element modelling of Ortahisar Castle. The behavior of the Castle under an earthquake, wind or temperature load is a critical problem and needs to be considered. 3D finite element model of the Castle is generated using 3D laser scanning data by using solid members and afterwards

earthquake and wind loads are defined for structural analysis to obtain deflections and stresses. The expected response of the Castle against most important loads of nature are evaluated by FEM. The analytical model is also calibrated using dynamic measurements taken from the top level of the Castle.

Finally, the thesis is written to make relevant suggestions for future work.

The structural health monitoring system of Ortahisar Castle consists of LVDTs, accelerometers, data logger, battery, solar panel, and remote communication modem. The readily available monitoring system has been used in this thesis. The measurement data are sent to a computer with help of direct connection cable or remote communication by GSM modem, and post process works start at the computer. The change of crack widths are plotted using time versus crack width graphs. If the crack widths change dramatically, this change can be understood from the graphs and rock fall initiation can be sensed well ahead of time.

3D laser scanning is used to determine the dimensions of the Castle since there are not any architectural drawings. FEM is prepared by using the results of 3D laser scanning and SAP2000 analysis software. Earthquake loads, wind loads, and temperature loads are applied on the analytical model and the model is analyzed. Behavior of the Castle under earthquake load wind load, and temperature load is obtained, structural performance of the Castle is evaluated using the analysis results of the detailed 3D finite element model.

CHAPTER 2

FINITE ELEMENT MODELLING OF ORTAHISAR CASTLE

2.1. 3D Laser Scanning of Ortahisar Castle

The finite element modeling studies require geometric dimensions of the structure to be modelled. The Ortahisar Castle has no well-defined geometric shape and mostly has an amorphous shape. Fortunately, 3D laser scanning of the Castle was carried out in the past and FEM studies have taken advantage of that data. 3D laser scanning is a method which is used to obtain any geometric shape of physical objects by sending laser lights to the object. At the end of scanning, point clouds are collected, each point is described by using xyz coordinate system, and the shape of the object can be extracted from the point clouds. However, the point clouds in the format of xyz coordinate system of Ortahisar Castle could not be obtained; only slices of 3D points in 2D planes at AutoCAD (computer aided design programme) drawings of the Castle were found and used (Figure 3). In a previous unrelated study, the Castle's point cloud was used to generate 2D plots of 18 slices that are 10^{o} degree away from each other. Each one of the slices were separately stored in drawing files. If all 18 drawing files are combined together, an approximate 3D plot of the Castle can be obtained. These 2D plots were used to generate the 3D FEM of the Castle.

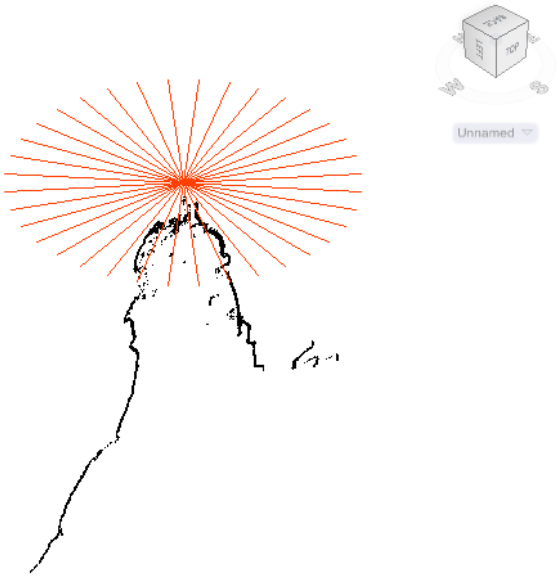

Figure 3 All 18 different slices shown together with one of the 2D plots

As it can be seen in Figure 3, red lines are the cutting axes. The name of first axis is east-west axis and the others are named as east-west 10^o, east-west 20^o etc. until the angle between axis reaches to 80^o. Afterwards, north-south axis starts and same denotation is used again. Figure 4 shows the Castle from east-west axis. The black dots in the Figure demonstrate surface of the Castle at the direction of the axis. Each one of the dots is obtained from 3D laser scanning. 3D location of each one of the dots are determined from their 2D coordinate and angle of the plane with respect to East or North. However, the coordinates of the dots could now be directly obtained from the AutoCAD file and reading each coordinate manually was taking too much time and effort. Instead, NetCAD (computer aided design programme), which is a GIS application that can read AutoCAD files, is used to get coordinates of each dot at each drawing file.

Firstly, the AutoCAD drawing file is imported to NetCAD. NetCAD loads information inside the drawing file. Secondly, all dots inside the drawing file are categorized by their coordinates inside NetCAD. Thirdly, the categorization by coordinate system is exported as an excel file. This procedure carried out using NETCAD was necessary to extract xyz coordinates of all dots that form the outer

surface of the Castle. The next step is importing these dots to SAP2000; however, before that the dots are arranged in such an order that the solid members can be easily generated. Since the available data of 2D planes slices the Castle like a cake into 18 planes, all these dots need to be reorganized and combined to generate the Castle as a whole in 3D.

Figure 4 View of the Castle From East-West Axis

2.2. Organization of Coordinates of the Castle

NetCAD just gives coordinates of dots but the order of the dots are mixed. In other words, which dot represents which part of the Castle is pretty much unknown when starting from a 2D data file. Therefore, dots need to be arranged in a 3D coordinate system. As it is mentioned above, drawing files are named in two main category which are east-west and north-south directions. East-west direction is accepted as x-direction, south-west direction is accepted as y-direction and height of the Castle is accepted as

z-direction. The drawing files, whose names begin with east-west, are used to get x-direction and z-direction of dots in the local coordinate system. The drawing files, whose names begin with north-south, are used to get y-direction and z-direction of dots in their own local coordinate system. Values of z-axis of dots are the same for both readings; however, values of x and y axes are different from each other which means correlation is needed between values of x and y axis of dots. Center point of the Castle is found and coordinate of the center point of the Castle is read with using NetCAD. X axis value of center point is subtracted from all x axis values of dots that were read from drawing files that had names beginning with east-west direction. The same procedure is repeated for y axis values of drawing files that have names begin with north-south direction. Result of correlation gives coordinates of dots in z-axis and new x' and y' axes. After that point, arranging dots with the new axis is carried out. The dots belong to the surface of the Castle at intervals of 10^o but there are not 36 drawings files; there are only 18 drawing files. Therefore, a vertical line from the center that divides the figure into two parts are used to generate 18 additional planes. The left part of East-West plots represents west part or left part of the North-South plot represents south part of the Castle. The difference between east and west or north and south is 180^o. For instance; a file, whose name is east-west 0^o, has surface dots of the Castle at 0^o and 180^o or north-south 50^o has surface dots of the Castle at 140^o from East and 320^o from East. This logic is used to prepare Table 1.

Values in white boxes at Table 1 shows values obtained from 3D laser scanning. As it can be seen from Table 1, all of the 2D slices do not start at the same elevation as well as they don't finish at the same elevation. There are two reasons for this misreading. The first one is that, the Castle consists of different elevations at the base and they do not match when the cutting plane is turned with different angles. The second reason is about the quality of 3D laser scanner which may skip some of the measurement points of the Castle. Therefore, mismatching of missing values in Table 1 are filled manually which are shown by colorful boxes. An example for calculation of purple boxes in Table 1 is given below. As an example, the radius of 60° and 80° are known at same elevation but 70° radius is missing. The valued is filled by taking

linear average of these two values. Similarly, the missing data may be regenerated using values of the neighboring elevations.

$$\text{Value 1 (in white boxes)} = 56{,}33542 \qquad \text{Value 2 (in white boxes)} = 52{,}66067$$

(Eqn. 1)

$$1st\ Unknown\ (in\ purple\ boxes) = \frac{(56{,}33542+52{,}66067)}{2} = 54{,}49805 \qquad \text{(Eqn. 2)}$$

Table 1 Coordinates of Surface Dots

	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
1190							50,76367																													
1191							48,51415																													
1192							48,36702																													
1193																																				
1194						56,33542																														
1195						54,49805																														
1196						52,66067																														
1197						51,84173																														
1198	39,57697	41,89228	44,20759	46,52289	48,8382	51,15351																														34,94636
1199	39,48869	41,73292	43,97714	46,22137	48,4656	50,70982	50,64587	47,91232	42,44524	39,7117	39,16114	38,61058	38,06002	37,50947	36,95891	36,40835	35,8578	35,30724	34,75668	34,20612	33,65557	33,10501	32,55445	32,0039	31,45334	30,90278	30,35222	29,80167	29,25111	28,15	37,61063	42,08215	40,66577	39,24938	37,833	35,00023
1200	39,07018	41,07821	43,08624	45,09427	47,1023	49,11033	49,92602	47,39932	42,57124	40,2846	39,68038	39,16447	38,64856	38,13265	37,61674	37,10083	36,58492	36,06901	35,55311	35,0372	34,52129	34,00538	33,48947	32,97356	32,45765	31,94174	31,42583	30,90993	30,39402	29,4062	38,16605	40,28397	39,238	38,19203	37,14606	35,05411
1201	39,03267	40,96808	42,90348	44,83888	46,77429	44,48445	47,72056	46,88632	42,85473	40,8575	40,19962	39,71835	39,23709	38,75583	38,27457	37,79331	37,31205	36,83079	36,34953	35,86827	35,38701	34,90575	34,42449	33,94323	33,46197	32,9807	32,49944	32,01818	31,53692	30,66241	38,21973	39,30739	38,47829	37,64918	36,82008	35,16187
1202	38,92657	40,78198	42,63739	44,4928	46,34821	43,20817	41,11687	46,96492	42,94923	41,4304	40,71885	40,27224	39,82563	39,37902	38,9324	38,48579	38,03918	37,59257	37,14595	36,69934	36,25273	35,80612	35,3595	34,91289	34,46628	34,01967	33,57305	33,12644	32,67983	31,91861	37,84126	38,92076	42,21424	40,46462	36,96537	35,21575
1203	36,13311	35,88513	35,38917	35,14119	42,87884	42,04606	38,91965	45,52059	43,37397	42,0033	41,23809	40,82613	40,41416	40,0022	39,59024	39,17827	38,76631	38,35434	37,94238	37,53041	37,11845	36,70649	36,29452	35,88256	35,47059	35,05863	34,64666	34,2347	33,82273	33,17482	37,46279	38,70349	42,27683	40,46474	36,84055	35,02846
1204	34,48574	36,40344	35,36908	34,33472	37,74616	40,27559	36,98878	45,2822	44,32965	42,57621	41,75733	41,38002	41,0027	40,62538	40,24807	39,87075	39,49343	39,11612	38,7388	38,36149	37,98417	37,60685	37,22954	36,85222	36,47491	36,09759	35,72027	35,34296	34,96564	34,43102	36,70586	38,39028	42,23396	37,76607	36,51419	35,26231
1205	33,26833	35,10693	37,91495	33,52596	33,53053	37,47725	37,01619	44,4413	44,64821	43,72201	42,79581	42,48779	42,17977	41,87175	41,56373	41,25571	40,94769	40,63967	40,33165	40,02363	39,71561	39,40759	39,09957	38,79155	38,48353	38,17551	37,86749	37,55947	37,25145	36,94343	36,32739	36,78983	42,1544	37,75442	36,55845	35,36248
1206	32,17186	31,97077	35,86689	32,65299	33,19557	37,14934	36,78462	41,60005	44,40502	43,24344	42,08187	46,7179	50,80364	49,41304	46,63185	45,24125	44,68282	44,12439	43,56597	43,00754	42,44911	41,89068	41,33225	40,77383	40,2154	39,65697	39,09854	38,54011	37,98169	37,42326	36,3064	35,86793	42,21796	28,93203	38,49107	32,7488
1207	31,07384	30,74195	33,4168	32,15247	32,90925	36,21972	36,51883	40,81274	44,26128	42,66821	41,07515	41,78707	48,22985	47,45506	45,90547	45,13068	43,98025	42,82982	41,67938	40,52895	39,37852	38,22809	37,07766	35,92722	34,77679	33,62636	32,47593	31,32549	30,17506	29,02463	26,72377	34,29701	42,11261	30,99857	38,38451	32,91212
1208	29,43527	28,54771	29,51653	31,71759	31,88166	32,61339	35,16517	40,48224	40,81388	39,2524	34,41249	34,96996	42,23956	46,12868	42,55357	38,97846	38,55954	39,76991	39,36172	38,95353	38,54534	38,13714	37,72895	37,32076	36,91257	36,50438	36,09619	35,688	35,2798	34,87161	34,05523	33,48579	37,76617	29,98901	37,39622	30,85054
1209	29,43751	28,77727	29,79019	29,88053	29,60493	31,13092	34,99104	40,49283	39,12451	33,52487	29,00597	28,01396	36,45157	39,94064	37,76247	35,11926	38,50182	39,79139	39,54205	39,29272	39,04338	38,79404	38,54471	38,29537	38,04603	37,7967	37,54736	37,29802	37,04869	36,79935	36,30068	31,78405	30,03212	28,61825	35,99479	24,04703
1210	29,1896	30,0398	29,64629	29,18164	27,88247	31,32163	34,87496	39,84424	37,49475	31,3921	29,25404	28,7324	29,83552	32,57684	32,55524	32,37751	38,57564	40,05573	43,29329	44,91207	46,53085	48,14963	49,76841	48,27943	46,79045	45,30148	43,8125	42,32352	40,83454	37,85659	34,06829	31,90221	30,03795	28,85453	29,50614	26,55817
1211	28,67637	30,26408	29,41796	28,46473	28,57807	32,6875	34,95438	40,42935	32,85436	31,29296	29,05676	28,39323	28,35034	30,68198	29,20674	28,0827	37,58356	34,6329	36,6263	38,65797	40,41556	43,93075	45,68835	44,63736	43,58637	42,53538	41,48439	40,4334	39,38242	37,28044	34,2123	32,11592	30,17003	28,92515	24,73815	26,85633
1212	28,05613	29,47162	29,05659	28,08512	29,01134	32,30052	34,9229	36,48668	32,96175	30,97893	28,18208	28,2366	27,41261	28,13608	27,95776	27,77903	34,17832	33,95652	32,86349	38,58653	36,0751	38,42644	41,60829	41,00242	40,39656	39,79069	39,18483	38,57897	37,9731	36,76137	33,8995	32,05254	30,21533	28,48465	24,97634	26,6759
1213	27,4981	28,27178	28,49769	28,07236	29,34714	32,34643	34,6601	37,20207	32,76865	28,78833	26,17509	27,65119	26,59454	26,04376	25,99145	26,79756	33,99951	33,44803	31,8438	38,66627	32,51999	36,89041	39,15648	41,34754	38,10293	37,30272	36,78173	35,73974	35,21874	34,6339	33,20572	32,14721	30,24482	28,2656	25,44188	26,37541
1214	26,81849	27,2522	27,97219	27,87522	29,69667	31,96648	34,85102	37,97992	32,57191	28,65148	27,20865	27,47203	26,59806	25,4816	23,45327	26,39292	26,77867	33,37845	27,00063	33,59092	28,96488	40,15345	39,23958	30,80248	37,31519	37,53731	35,19582	35,19286	32,17275	32,26723	31,8667	31,59506	30,12023	28,17974	25,40108	25,85917
1215	25,84961	26,36946	27,22966	27,68028	29,8992	31,54673	33,81891	37,09363	30,79184	28,29326	26,94797	26,69242	26,36246	22,51989	21,19993	19,86294	24,3256	33,26079	26,50609	30,29919	25,56782	27,61906	29,90813	45,55922	31,33666	37,36108	34,94625	34,41133	30,53902	31,35891	30,43692	30,96829	29,6537	28,05981	25,58069	25,30863
1216	24,91958	25,46849	26,00607	27,44829	29,31411	31,03613	30,70374	29,60272	27,38812	26,55324	24,60666	24,56863	21,74389	15,47954	12,48351	16,0578	23,65181	33,55832	29,12554	30,62886	23,58157	24,09402	24,83055	26,84791	30,47905	36,55123	30,95589	32,21131	26,27792	28,46625	29,8034	29,88496	29,1734	27,46084	25,42624	24,50612
1217	23,83952	24,30215	24,67047	27,44108	29,28768	30,98684	29,85331	27,02901	25,42859	25,82176	20,82826	19,72479	13,75887	13,82931	13,40217	15,30381	24,61834	32,22093	27,61262	30,61059	19,1125	21,24453	20,92459	24,49994	26,09057	35,92633	29,64923	19,32616	16,91593	25,54231	26,1738	28,07953	27,45626	24,09307	23,60452	23,59435
1218	22,91298	23,36494	23,46223	27,28514	29,32232	30,55312	29,53444	26,41779	25,03311	24,97837	18,52247	15,91509	13,85566	13,99487	14,02969	15,77109	22,43619	20,57054	18,92108	16,3881	17,62281	19,06402	20,02972	22,01376	24,99532	29,5365	17,22233	16,70718	13,21858	18,30868	15,69948	15,45801	18,50736	19,09528	16,71379	18,48504
1219	21,07488	21,57966	22,63017	26,92997	29,63715	29,81765	28,2576	25,76789	25,00411	24,19783	17,91631	14,19125	12,48515	12,98826	13,75957	16,05836	20,97208	17,73869	17,46295	15,9748	17,60986	18,24373	19,79388	22,13109	22,4673	24,98807	21,09617	16,93929	14,52641	18,48959	15,74095	15,49615	16,6837	16,71452	14,22716	17,13603
1220	17,93274	18,96177	19,61962	25,52597	29,14695	28,84902	28,38756	25,80295	24,97426	25,46219	14,79406	11,14467	9,284711	11,33984	12,76659	16,27853	18,52881	17,68482	17,07449	16,04639	17,6793	17,12314	19,79517	23,71526	23,32286	23,83383	21,64537	16,40418	18,05986	18,23763	15,67185	15,72715	15,49484	13,65736	13,77445	17,0294
1221	15,70684	15,30302	18,13563	22,04135	28,22382	27,87468	28,05366	25,68558	24,72508	21,13249	12,99524	10,29598	9,916617	10,36419	11,77883	15,69261	18,49548	17,53875	17,00464	16,19448	17,75706	16,90656	19,2518	23,19585	25,17592	23,43465	21,04764	17,51162	16,71989	19,14323	15,97868	15,83621	15,28703	13,7902	14,17274	15,46509
1222	15,46042	12,76127	17,26417	23,02685	27,10008	26,62248	20,4389	24,68234	22,10195	16,68153	10,58181	9,258192	9,374807	10,03136	11,50152	12,84284	17,405	17,43744	16,8938	16,22362	17,63522	16,88089	17,97394	24,6235	25,36873	24,40647	21,90068	18,71834	14,68301	18,92761	15,56297	14,75723	14,98199	14,70067	14,72421	15,14569
1223	14,99294	12,92742	16,96582	23,80754	26,60161	26,32099	20,43064	18,63004	19,33138	12,9927	9,899113	8,070845	8,832998	9,88784	11,5058	12,55154	15,3455	16,1221	16,87741	16,10581	16,88316	16,43174	17,6887	23,32451	24,85346	24,38631	21,58585	18,51827	14,10671	16,2773	15,16119	14,60879	14,6982	14,33544	14,2916	14,68701
1224	14,49301	14,1691	17,33316	22,13513	26,06572	25,8668	26,38215	20,84239	15,80228	14,25976	9,571636	8,288534	8,697239	9,546469	11,97115	13,34786	12,13606	16,01217	16,41456	15,9388	16,5918	16,88915	16,93188	24,03519	24,11078	24,30578	21,17941	18,22023	14,96174	14,94679	14,88548	14,74019	14,23756	13,94337	13,85203	14,24267
1225	13,82443	14,46392	17,05557	21,09993	25,81137	25,23938	25,86601	17,50268	7,751946	7,271283	7,031426	7,624461	8,598016	9,80756	12,06039	13,09703	12,01622	14,48334	15,45987	15,35225	15,39563	16,22248	16,02804	23,87427	23,55663	24,09868	20,62591	17,86197	16,00641	14,60777	14,1704	14,72513	13,94522	13,53001	13,35745	13,7857
1226	13,16744	14,4485	16,62949	20,58829	25,66839	24,02882	20,9598	15,63246	8,028499	7,514689	7,283313	7,643155	8,697861	10,10973	12,76868	13,52418	11,87748	15,84669	15,49908	14,66752	15,3373	16,10403	15,11062	24,2537	23,0564	23,59362	20,1135	17,59472	15,60842	14,24862	14,4936	14,6798	13,57738	13,12828	12,92399	13,01144
1227	12,81198	14,02574	15,64966	21,42922	25,46563	24,15772	20,25863	17,7764	9,177827	7,636428	7,501087	8,286061	9,144937	10,71392	13,31345	13,13231	12,31887	16,24646	15,45641	13,82163	15,5594	15,23085	14,79652	24,58005	22,95956	23,32493	19,65112	17,12637	15,21204	14,01007	14,96104	14,81024	13,19898	12,7004	12,26923	12,0169
1228	12,11559	13,4289	14,83927	21,36493	25,36639	24,44298	23,49512	18,25493	9,154309	7,758689	7,847372	8,545517	9,757716	11,05765	13,31887	12,44289	12,78149	16,21268	14,73594	13,8964	14,86597	14,54131	14,54541	23,75785	22,65415	23,11549	19,21214	16,70786	14,93035	14,15026	14,99013	14,80337	12,81312	12,28905	11,91554	11,4679
1229	11,9	12,80644	14,49942	18,74817	25,25785	24,67528	22,9043	16,77109	8,968359	8,285906	8,304903	8,996594	10,3048	11,42967	13,38046	13,02622	13,2481	15,32131	14,01591	14,06521	14,30711	14,24566	14,38084	21,77697	21,81578	22,43741	18,80615	16,23925	14,7481	13,95913	15,15311	14,94437	12,73635	11,79871	11,60634	11,38087
1230	11,69322	12,50791	14,26086	17,93747	25,29135	24,64152	22,4019	15,36548	9,184058	8,422404	8,642294	9,362674	10,55757	11,95333	13,96191	13,27674	13,02324	13,77039	13,44246	14,20057	13,49496	13,25822	14,20003	20,47534	21,74864	21,08168	18,44889	15,42332	14,55039	13,87109	14,79712	14,95804	12,64141	11,69618	11,34959	11,24259
1231	11,38337	12,53217	14,13731	16,48448	23,789	24,35599	22,1864	15,19783	9,329284	8,541107	8,853957	9,641806	10,84151	12,76149	14,34764	12,73408	12,83166	13,13029	13,42866	13,88669	13,78895	12,80776	13,98406	20,39565	21,69057	20,59339	18,01561	15,0242	13,84511	13,79517	14,74842	14,76847	12,64051	11,3385	11,17552	11,10062
1232	11,18703	12,27051	13,90724	16,03505	21,78074	23,91855	20,83088	12,29906	9,109108	8,726808	9,1469	9,912404	11,15893	12,67638	14,21782	10,89638	13,17219	13,09492	12,99557	13,66147	13,77701	12,62771	14,49709	20,4113	21,64511	20,07178	17,57158	15,50597	13,30812	13,89128	14,95427	14,74913	12,87425	11,30841	10,96653	10,97956
1233	10,96919	11,71447	13,53673	15,59908	20,62836	22,41628	18,4355	13,10175	8,64502	8,97634	9,458531	10,22217	11,50571	13,22041	14,08039	13,75079	13,07724	12,86876	12,896	13,3138	13,65105	12,39407	14,70813	19,3185	21,07566	19,04337	16,80853	15,42169	13,42383	13,70193	14,91768	13,79688	12,68009	12,0685	10,79647	10,68633
1234	10,9269	11,47483	13,23254	15,19947	20,20283	20,74012	17,53933	13,17956	8,927308	9,18258	9,544808	10,44553	11,83026	13,4702	14,42593	13,88897	12,87644	12,72452	12,89613	13,06256	14,14123	12,18364	14,03293	18,14329	19,34223	18,86536	15,68288	14,97818	12,59734	13,31472	13,92342	13,23719	12,72839	12,48446	11,15676	10,52593
1235	10,83631	11,33944	13,26752	14,8656	19,8634	19,51159	17,32491	13,05576	9,695781	9,425799	9,815462	10,64512	11,94763	13,49266	14,48187	13,74648	12,59711	12,73164	12,65659	12,69523	13,60137	11,99	12,46253	15,27659	18,26396	18,49477	14,8149	12,62072	12,16876	13,35691	13,58769	14,62124	12,958	12,83969	11,64379	10,8
1236	11,07072	11,52381	13,31381	14,53378	19,29076	18,89417	17,69941	16,22392	10,34588	9,744714	10,11462	10,98083	12,11862	13,30352	14,44084	13,59085	12,69247	12,65653	12,37967	12,29605	11,66917	12,03849	8,929118	10,90505	14,12398	12,72946	9,846345	10,08668	11,75261	13,08358	13,3693	14,61721	13,21012	12,97455	12,35662	11,42423
1237	11,79856	12,4941	13,46918	14,55308	18,49596	18,77801	18,04254	16,51832	11,21038	10,41986	10,43423	11,31901	12,30887	13,48174	14,39758	13,40198	12,32069	12,45136	10,71398	9,703218	9,346971	7,159519	7,751315	7,729002	7,375691	6,964164	7,422832	8,538635	10,98972	11,8351	11,97033	13,43313	13,26665	12,84617	12,46819	11,82505
1238	12,3983	13,06818	13,70246	14,59318	17,86941	19,14716	18,05708	16,60124	12,85888	10,91123	10,73712	11,62288	12,54855	13,38304	14,20829	13,26815	12,26631	12,10903	9,57637	9,616754	9,39782	7,63456	6,817734	7,220736	6,99271	6,452672	7,081743	7,480959	7,92145	10,05062	11,37477	12,63556	13,11779	12,66616	12,44765	11,86299
1239	11,74172	13,09655	13,93516	15,08125	17,71038	19,45929	17,7889	16,54202	13,6534	11,28713	10,93045	11,72098	12,77224	13,24895	12,86289	13,07271	12,1957	10,16503	11,32615	11,14613	11,54676	8,092288	6,84311	7,167797	6,774514	6,344193	6,881117	7,606604	8,088517	9,878763	10,69439	12,96899	11,4542	12,17792	12,37747	12,12382
1240	11,76507	13,34163	14,14937	15,75705	18,27471	19,75371	18,01105	16,78966	14,58101	11,90328	11,22548	11,87747	12,78307	12,69957	12,49447	12,48702	11,71269	9,985004	11,00044	8,641756	10,97733	8,487465	6,18617	5,935943	6,589458	6,242218	7,206712	7,44591	8,079253	9,761965	9,956537	11,26723	11,52326	12,36244	12,23288	12,20006
1241	11,92835	14,11279	14,81094	16,44498	18,95046	20,1485	17,97308	17,21434	15,2936	12,9468	11,4258	12,28938	12,42044	11,64339	11,98217	11,95384	10,61606	10,72851	10,71601	8,956355	9,930038	8,990149	6,052128	5,674478	6,35643	6,386085	7,44181	7,557113	7,633054	8,142984	9,317001	10,57315	11,41431	12,08684	12,05401	12,15621
1242	12,11997	14,70115	15,60391	16,72494	19,13023	20,97231	18,52438	17,66764	15,14329	14,03023	12,43495	12,44984	12,41809	11,70032	11,71268	11,31275	10,00729	10,52967	9,557259	7,735599	10,29378	8,894241	7,115003	6,249792	5,975957	6,599785	7,834402	7,867833	8,099034	7,93776	8,58485	10,66651	10,52637	11,874	11,79033	12,08302
1243	12,51704	15,00169	16,16875	16,53243	19,28435	21,64683	19,14385	18,14806	14,90324	13,46938	12,97132	12,35265	12,42179	11,58654	10,91426	10,90788	9,874563	9,907686	9,622307	8,772774	10,31676	8,324677	6,849853	5,942233	6,12861	6,87936	8,254094	8,153639	8,226575	7,735642	8,022729	9,649154	10,41868	11,91237	11,53778	12,0401
1244	13,39647	14,69913	15,68017	16,70952	19,43105	22,09337	19,63088	18,52039	14,77121	12,80689	12,67476	12,23866	12,45338	11,48997	10,19014	11,0838	9,281828	10,05246	10,61998	10,63652	10,2122	7,873717	6,432265	5,722404	6,369395	7,208257	8,800511	8,151794	7,797432	7,74899	7,523392	9,07934	9,868537	11,91565	10,83911	11,70196
1245	13,09053	13,49538	15,18706	16,96032	19,38118	22,44441	20,00644	17,34015	14,48885	12,61517	12,29251	12,30832	12,26889	11,20082	9,924543	11,03138	11,14202	11,24808	10,56275	10,03015	9,423186	6,201926	5,763309	5,692426	6,40153	7,25616	9,018589	8,124209	7,377703	7,525522	7,085274	8,120303	7,685647	10,08014	10,40188	11,74743
1246	10,44446	13,02476	15,0033	16,99161	19,59628	22,4991	20,26478	16,46285	13,44476	12,49069	12,3456	11,94242	12,0211	10,78836	9,847423	10,93176	11,6996	11,61137	9,397153	9,103102	8,513784	6,49572	5,547256	5,583723	6,22191	7,103955	8,876416	7,617411	6,891125	6,621928	6,840839	7,909895	8,394353	10,98785	11,06516	11,3595
1247	10,56363	12,77526	14,82211	16,71093	19,26733	22,29511	20,56129	16,30287	13,21865	12,2535	11,98943	11,41929	11,55238	10,10751	9,817631	10,8609	11,4014	11,52515	9,370345	8,539109	7,357251	6,337593	5,155649	5,357868	6,165108	7,120823	8,519977	7,085433	6,291984	6,457428	7,182405	7,732561	8,09753	9,912637	9,887016	10,08383
1248	9,915703	11,04776	13,21534	14,56928	16,69405	20,36166	20,17343	16,19566	12,46818	12,0644	11,70118	10,6433	10,45018	9,740074	9,733428	11,1171	12,08016	11,51505	9,122213	7,69053	6,84828	6,026374	5,307253	5,231864	6,381441	7,340914	7,9123	6,531034	5,676607	6,539283	7,251795	7,793233	8,054015	7,656741	7,667405	11,05614
1249	9,312042	9,671747	13,02743	13,99183	16,63114	19,36355	15,01725	13,56283	8,559177	10,38233	10,8856	5,029093	9,202463	9,719144	9,747061	11,08627	11,95277	11,07923	8,725479	6,369488	6,326927	6,046886	4,84539	5,29833	6,553381	7,071934	7,432645	4,58382	5,456987	6,36262	7,062966	7,217034	7,542561	7,913931	9,966156	11,52191
1250	10,108	9,327565	15,22248	12,44041	16,4051	20,00422	15,32364	11,11149	8,642184	9,619291	9,365893	8,706446	10,41614	9,947544	9,465107	11,17243	11,67647	10,25937	8,288788	6,368771	6,524008	6,241139	5,410622	5,654066	6,234584	6,537193	6,811025	5,352988	5,169234	5,996315	6,390995	6,120272	6,615062	7,442097	11,41016	11,54625
1251	9,940286	9,895091	13,37756	10,88899	14,98054	19,49514	18,31312	13,16558	8,817443	9,574079	10,64132	9,802267	10,35641	10,24063	9,319115	11,10534	11,30248	9,490607	7,707791	6,793579	6,280675	6,029156	5,181506	5,442307	5,798772	5,602178	6,215913	5,873471	4,444574	4,470654	4,302148	3,738869	4,323968	5,867695	9,220985	9,72122
1252	4,379972	10,20055	10,23365	11,49855	14,14904	18,88743	17,18674	12,01	8,120837	9,072867	10,2417	9,706306	9,601646	10,10055	9,663984	10,97839	10,71015	8,747745	6,756377	5,867937	4,925293	4,794456	4,971886	4,983771	4,858713	5,523126	5,648976	4,576858	3,510841	3,481485	3,234297	2,960955	2,710382	2,708756	3,451143	6,756867
1253	11,01664	10,55111	10,75252	12,45754	12,30444	18,6176	16,02031	13,07286	8,11798	8,935149	9,545294	8,887135	9,042311	10,05388	8,641035	9,933908	9,835002	6,982571	5,058317	4,718087	4,592068	4,717613	4,989185	5,125441	4,809941	5,223543	5,308955	4,523021	3,414296	3,244162	3,182797	3,08413	3,300634	4,14696	6,209261	6,730477
1254	11,32715	11,08974	12,56564	12,59075	14,55481	18,15521	15,43601	12,42905	8,38	8,002	8,506781	8,191882	8,701787	9,927647	9,237962	8,042397	8,955483	6,727791	5,12438	4,767776	4,621407	4,658804	4,783953	5,057134	5,211071	5,333246	5,546193	4,402694	3,163016	2,948036	2,864271	3,009749	3,480674	4,556055	7,216966	10,33336
1255	10,23141	11,11077	12,49575	14,56573	15,61186	17,29644	14,36938	11,90543	7,542225	7,071751	7,553545	7,650848	8,31399	9,246106	8,13381	7,05549	5,401964	3,829509	3,820025	3,682726	3,966699	3,786049	4,055143	4,466385	5,080189	4,9516	4,856806	3,206262	2,58308	2,393208	2,330277	2,417681	2,627566	3,324034	5,664135	9,664923
1256	7,306947	3,902478	6,11428	13,59585	16,13331	17,30059	13,85112	11,25389	6,500001	6,377569	6,607204	6,96198	7,737263	8,12263	7,274385	5,891044	4,356937	3,808919	1,852607	2,48313	3,415138	3,316636	3,496331	3,850554	3,985571	3,786735	3,700651	2,200632	1,921999	1,756227	1,653743	1,648995	1,760427	1,913203	2,127857	8,013338
1257	8,173604	6,960148	8,235822	12,40106	15,85364	16,92127	13,07674	9,561148	5,14789	5,902596	6,100568	6,34297	6,901329	7,349791	6,38688	4,891215	2,883802	2,506429	0,336151	1,829804	2,353813	2,354886	2,533338	2,715122	3,211255	3,068549	3,820741	0,672539	0,37511	0,428388	0,559099	1,194999	0,636971	0,744802	2,432676	4,946959
1258	6,061847	4,94695	10,34019	12,32811	12,2204	15,13417	11,57151	7,996597	4,155676	5,835714	5,324245	5,662816	6,318921	6,807822	5,860034	3,612262	2,849852	2,108857	1,129714	1,876464	2,41438	2,507381	2,698293	2,865185	2,970546	2,926363	2,991875	0,833496	0,634517	0,784021	0,830816	1,235214	0,756597	0,748389	0,814731	2,846645
1259	5,655386	3,727217	9,027844	11,13979	8,58715	11,59668	7,352443	6,494499	3,678502	5,483317	5,362367	4,775809	5,911835	5,255071	4,598307	3,289329	3,246829	2,947045	1,839217	1,42051	1,748725	2,173358	2,38046	2,742641	2,658056	3,021485	2,692009	2,036653	1,572116	1,224431	1,254421	1,994301	0,717624	0,697117	0,71555	0,723105
1260	6,452635	4,450191	6,455245	9,091986	8,993309	6,201814	5,371615	2,772271	0,172926	1,109723	2,983315	3,920111	3,799689	3,558845	3,438423	2,949839	2,19321	2,144278	2,186952	2,622672	0,980868	1,909596	2,074577	2,058345	1,9438	2,086585	1,832136	1,062811	0,801936	0,797956	1,645927	3,492411	0,476753	0,467823	0,394039	0,475146
1261	2,712073	5,196958	4,099913	5,757666	5,111487	5,339322	4,010337	1,352365	0,02338	0,309503	0,881749	1,167871	0,982212	0,610894	0,425235	0,280835	0,200778	0,088332	0,208172	0,216584	0,157978	0,010107	0,022062	0,013328	0,014455	0,023804	0,995833	1,15252	0,86355	0,132089	1,250527	0,337827	0,235881	0,238529	0,072528	0,227187
1262	3,12205	5,890456	5,35797	4,825485	4,293	3,760514	3,228029	2,695543	1,630572	1,761428	2,02314	2,153996	2,017605	1,744825	1,608434	0,677951	0,560083	0,448509	0,336935	0,310863	0,27361	0,261676	0,238162	0,219099	2,455873	2,019065	0,159531	1,497302	1,704829	0,396795	1,98459	2,168281	1,698613	0,759277	0,289609	0,353645
1263	0,658676	0,78222	0,905765	1,029309	1,152853	1,276397	1,399941	1,523486	1,64703	1,68098	1,748881	1,782832	1,948375	2,279463	2,445006	2,038323	1,631639	1,224955	0,411588	0,411588	1,225009	1,63172	2,038431	2,445142	2,851853	2,122884	1,800004	1,477123	2,111227	2,12274	2,134252	2,640877	2,195019	1,749162	1,303304	0,411588
1264																																				

2.3. Importing Dots of the Castle to SAP2000

Finite element modelling of the Castle is prepared by using structural analysis program whose name is SAP2000. At SAP2000, a model can be generated in three different ways; these ways are 1) model by using lines for frames, shell members for areas, and 3) solid members for three dimensional volumes. Solid modelling is chosen for the FEM of the Castle since the structure is formed by solid tuff rock. Solid members consist of 8 nodes since they are 3D objects. At SAP2000, the nodes are described as joints with their values in x, y, z axis. As a first step, format using by SAP2000 to create solid models is learnt. The format is exported to Excel from SAP2000 since coordinates of surface dots of the Castle is saved as an Excel file. Eight joints with their coordinates need to be described to create solid member; however, as it can be seen from Table 1, the joints have only 2 coordinates which are in z-axis and x^{l} or y^{l}-axis. The lack of coordinate and the format that SAP2000 uses are main reasons to develop a code. The code is developed by Macro, which works under Excel. First aim or task of the code is obtaining coordinates of joints in x and y axis. Simple trigonometry is used for this process. The values in white and colorful boxes at Table 1 are multiplied with cosine and sine of angles on the first row of Table 1; hereby all coordinates of the joints are obtained in 3D Cartesian coordinates. Second task of the code is to sort the coordinates of dots that SAP2000 can generate solid model of the Castle. The sorting procedure starts from bottom of the Castle and starts from 0^{o} at each level. By the time degree reaches 350^{o} from 0^{o}, all solids at any level are created (Figure 5 and Figure 6) and solids at the level top of the previous one are started to create from 0^{o} to 350^{o} again. This procedure finishes when all of the solids are created.

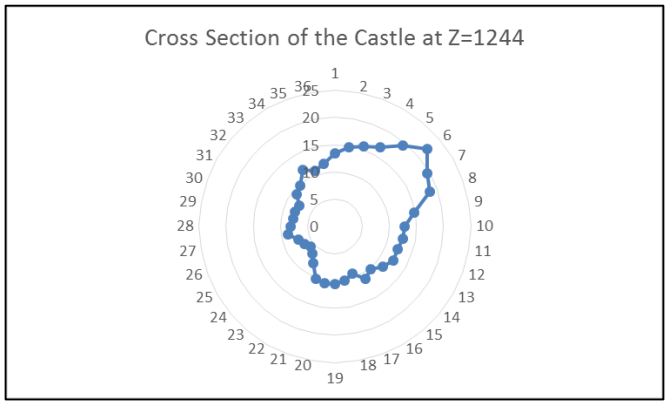

Figure 5 Cross Section of the Castle

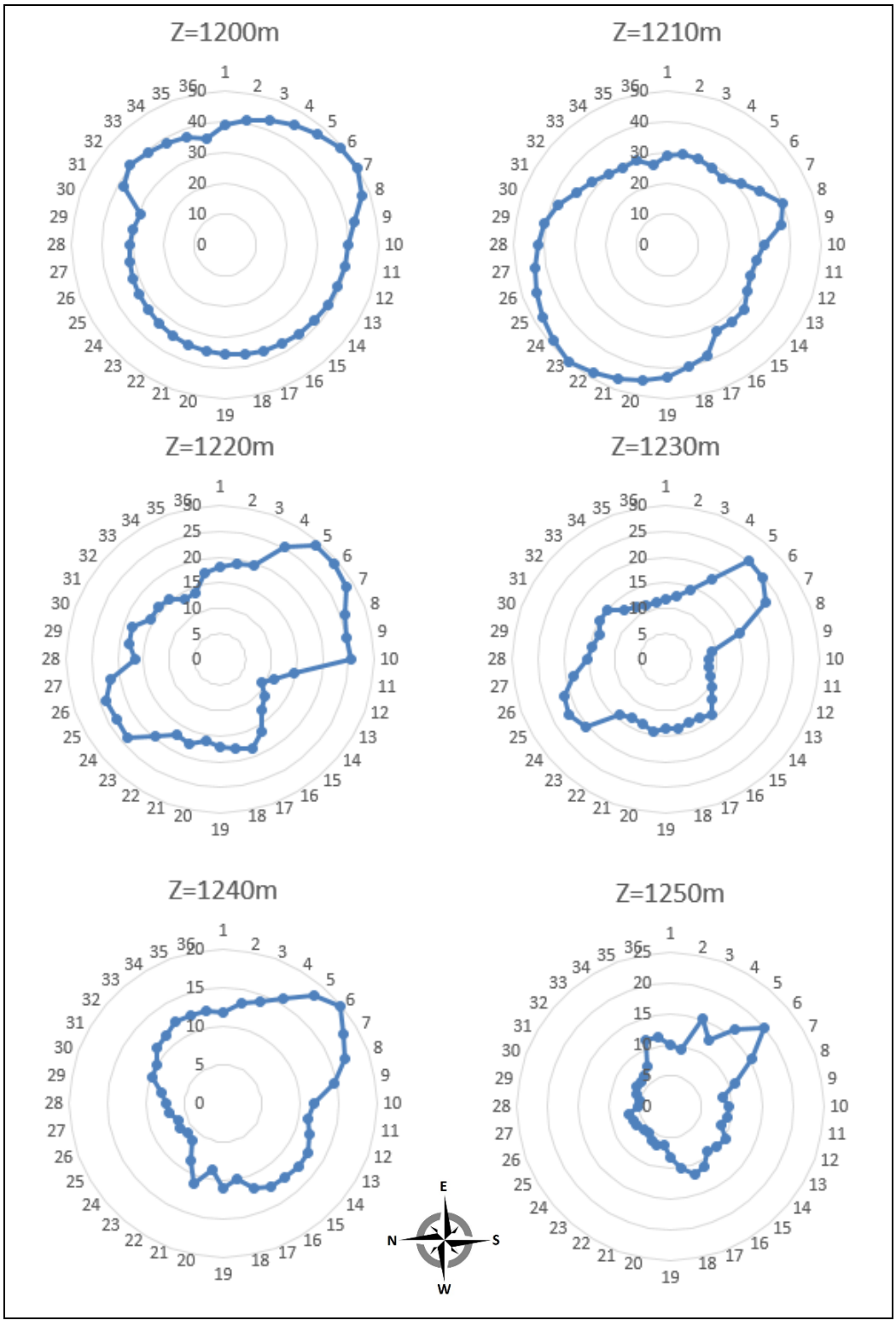

Figure 6 Cross Sections at Different Elevations

2.4. Drawing Finite Element Model of the Castle

The coordinates of dots are prepared according to SAP2000 solid joint order format before they are transferred to SAP2000. The transfer is made by copying the coordinates of dots from excel to SAP2000. FEM of the Castle is obtained only in general form as the transfer is completed. Definitions of materials, solids, load cases, and load combination are done as next steps. There are two important issues to mention at this step: The first important issue is definition of material properties. Although the Castle may have heterogeneous type material property distribution, the material properties are defined the same for all members assuming the correlation with dynamic measurements will be used for calibration and this will take care of changing material properties as a single smeared material property. The elastic modulus obtained from the material tests in the literature is 1.3 to 1.5 GPa. However, these values may be general and may refer to material that was exposed to weather conditions. The material of the Castle is original and kept inside the castle and analytical model calibration studies have shown that a 0.7 GPa for the modulus of elasticity gave better results. The reason to calibrate the modulus of elasticity is that the Castle has caves inside which cannot be modelled; moreover, the cracks at inside and outside of the Castle cannot be modelled. Since the cracks and the caves inside and surface of the Castle cannot be modelled, modulus of elasticity of Cappadocian tuff is reduced to 0.7 GPa. In addition to modulus of elasticity, additional parameters such as weight per unit volume and Poisson's ratio need to be defined in the SAP2000 analysis software. Weight per unit volume (17.37 kN/m^3), Poisson's ratio of tuff (0.27), and thermal expansion coefficient ($6.3x10^{-6}$ $l/^oC$) are entered according to material test reports made at field.

Second important issue is boundary conditions of the Castle's model. Choosing the right type of support effects result of structural analysis considerably. The Castle is located on tuff foundation. Foundation on a fixed support is hypothetical; however, it may be better to assign spring coefficients for the tuff base instead of a fixed support. Therefore, two kind of models are prepared. First model has fixed end supports with all degrees of freedom are restrained and the second model has springs instead of fixed

supports. The reasons for preparing two models are to compare results of two models and to be on the safe side during analysis by taking the worst case scenario. Modulus of elasticity of the Castle's material is an unknown for both models and also spring constants are another unknown for model with springs. Modulus of elasticity is decided according to the model with fixed supports. The E value which gives similar result with natural frequencies is accepted as modulus of elasticity of the Castle material and it is used for both of models. The same E value gave even better match with the dynamic test results when springs were used. The determination of spring constant for second model is explained in Section 2.4. The material properties of tuff for the Castle are shown in Figure 7.

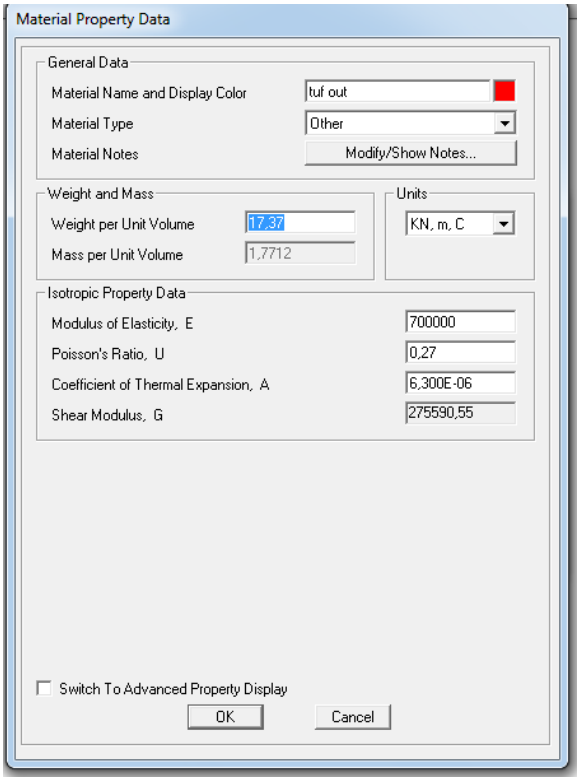

Figure 7 Material Properties of Tuff

Dimensions of solids are set automatically according to the results of developed macro program; however, the mesh is too coarse and it can be seen that solids need to be divided into smaller pieces to get more accurate solutions. Therefore, a solid is

divide into 4 pieces in the radial direction. The total number of solids forming the Castle is 105984 after further meshing. Fix supports and springs are used separately at the bottom joints of the Castle to satisfy the connection between the Castle and ground surface.

2.5. Determination of Modulus of Subgrade Reaction

Modulus of subgrade reaction (k_S) is the value which is used to define spring constant at support of the Castle. The Castle lays on tuff settlement; therefore, using only fixed supports is not a good estimation. Two different FEM of the Castle are prepared with fix supports and springs. A comparison is done using two models. Modulus of subgrade reaction is chosen as 12000 kN/m^3 according to soil property of combination of bed rock and tuff. The combination is classified as loose dense sand whose modulus of subgrade reaction is between 4800-16000 kN/m^3. After defining subgrade reaction, tributary area method is used to define spring coefficient in SAP2000 since the k_S cannot be described to all area of bottom of the Castle as same value. The spring values obtained from tributary area method are defined in SAP2000 (Figure 8).

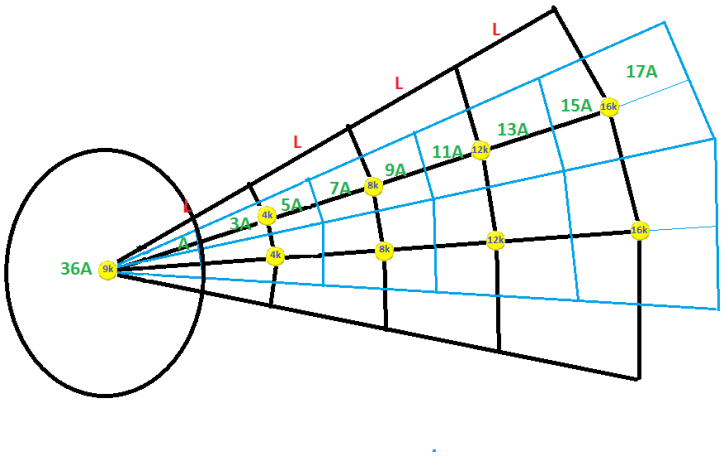

Figure 8 Spring Configuration of the Castle

2.6. Natural Frequencies of Ortahisar Castle

One of the main topics of the thesis is finite element modelling of the Castle and making earthquake and wind analysis with FEM. Therefore, generating a realistic FEM of the Castle is the key point for the accuracy of the analyses. Dimensions, material properties, and boundary conditions need to be modelled as correct as possible as to generate a realistic model of the Castle. The dimensions of the model is obtained after arranging data obtained from 3D laser scanning but defining material properties of the Castle is a problem for FEM; however, rooms and tunnels inside the castle could not be modelled. Modulus of elasticity in the literature is about 1.4 GPa; however, the region where the field tests are made is a small part of the Castle and modulus of elasticity of other parts of the Castle might show difference. For this reason, natural frequencies of the Castle is used to determine the material properties. In order to state that the model is reliable, similarities between natural frequencies of model and natural frequencies obtained from field tests are required to be consistent. Several models are prepared at SAP2000 with different modulus elasticity values. The model whose frequencies has best match with measured natural frequencies of the Castle is chosen as FEM of the Castle.

Natural frequencies of a structure can be obtained by help of accelerometers. Accelerometers record change in position of the structure and the record data is used to get the natural frequencies of the structure. Fast Fourier Transform (FFT) is one way to obtain natural frequencies and FFT is used at this analysis. FFT is an algorithm which is used to compute a sequence's discrete Fourier transform. A sensitive accelerometer was used to make 6 individual records of ambient dynamic response of the castle at the roof level (Figure 9). The first two readings could not give any meaningful results since they were taken to test the instruments and their durations were too short. Results of all records are analyzed with FFT using MATLAB commands and natural frequencies of the Castle are obtained. Arithmetic mean of similar peak frequencies are calculated, which is accepted as the test result and modal frequencies of SAP models with different modulus of elasticity are compared with the

test result. The best match is obtained with a model whose modulus elasticity is 0.7 GPa as it can be seen in Table 2.

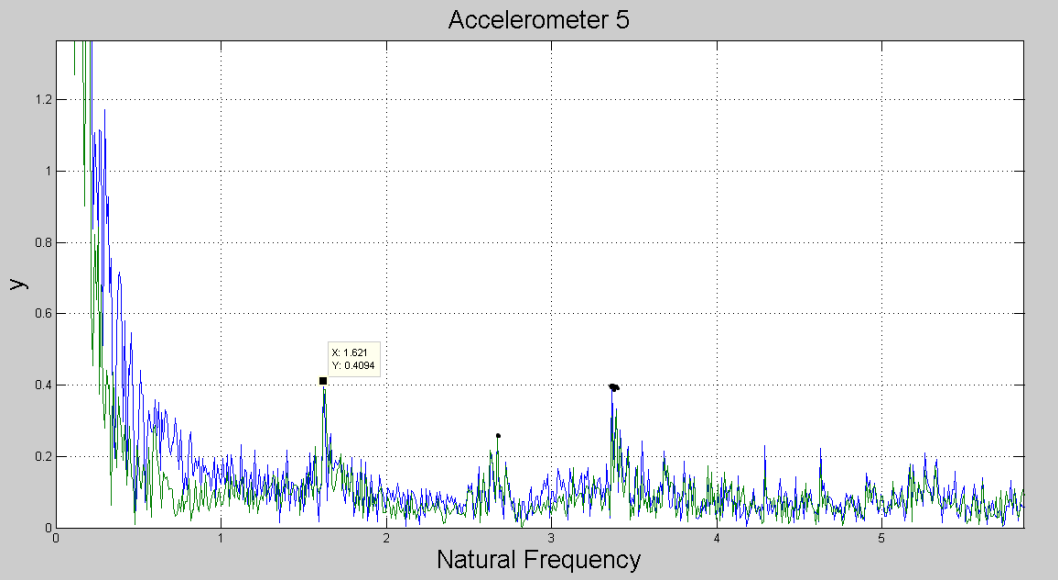

Figure 9 Result of Records from Accelerometer 5

Table 1 Natural Frequencies

	Natural Frequencies							
Modes	SAP	1st Record	2nd Record	3rd Record	4th Record	5th Record	6th Record	Test Resuts
1	1,64	0	0	1,633	1,64	1,621	1,633	1,63
2	2,25	0	0	2,122			2,183	2,15
3	3,36	0	0	2,656	2,66	2,671	2,655	2,66
4	4,77	0	0	3,385	3,51	3,364	3,36	3,40
5	4,84	0	0	5,096	5,1			5,10
6	5,01					5,26	5,258	5,26
7	6,73					6,67		6,67

2.7. Definition of Load Patterns and Load Cases in SAP2000

A structure can be effected by different types of loads such as: dead load, live load, wind load, temperature load, and earthquake load; however, in this thesis only

dead load, wind load, temperature load, and earthquake loads are considered for the FEM studies. There is limited touristic activity and surface that can be effected by live load is limited; therefore, live load is not considered during the analyses.

A load is firstly described as a load pattern to SAP2000 after it is described as a load case and the loads of the Castle are defined according to this procedure. SAP2000 can automatically calculate amount of dead load after defining material properties of solids. It is only needed to define dead load as a load pattern, indicate the gravity, and define relevant load case.

Wind load calculations are done according to TS498; however, wind load is described as a pressure and applied perpendicular to exterior surface of the Castle. SAP2000 automatically calculates wind load by multiplying wind load pressure and the surface area effected by the pressure. Since wind does not blow from one direction, wind loads are calculated at each 10^o intervals starting from 0^o to 350^o. For instance; W110, described as load pattern at SAP2000, means that wind blows to the Castle with angle of 110^o from East. Calculation of wind pressure, applied to the exterior surface of solids, is done using formulas mentioned at TS498. The wind load calculation is done using Excel for each direction of wind load. Firstly, exterior solids numbers are listed with their elevations from ground and coordinates of their joints in Excel. Normal vector of surface area is calculated from coordinates of joints to calculate the angle between the wind load and surface area. C_p, q are wind related parameters available in TS498. Wind pressure (w) acting perpendicular to the surface is calculated using Equation 3.

$$w = C_p * q \qquad \text{(Eqn. 3)}$$

Where:

w= wind pressure kN/m^2

q= wind pressure without absorption coefficient kN/m^2

C_p= absorption coefficient

Wind pressure coefficients (q) are taken from Table 3 which is also available in the TS648 code.

Table 2 Wind Velocity and Wind Pressure (TS 498)

Elevation from Ground (m)	Velocity of Wind – v (m/s)	q (kN/m^2)
0-8	28	0.5
9-20	36	0.8
21-100	42	1.1
>100	46	1.3

After using the formula and angles between the surface and wind directions, wind pressures are obtained for all exterior surface areas of the Castle, which means 3311 wind loads are calculated for each case. Since there are 36 wind load cases, 11196 loads must be entered to SAP2000. The simple way for this procedure is updating s2k file, text based input file name for SAP2000, for each case and importing s2k files to SAP2000 program. Therefore, 36 s2k files are created from the results of Excel and they are imported to SAP2000 one by one.

There are two different cases for temperature loading, which are temperature loads generated in winter and temperature load generated in summer. The common point of these two cases that the loads are applied to the Castle up to 10 cm inside from the surface. The temperature at the region in winter and in summer is chosen according to reports prepared by Turkish State Meteorological Service. Therefore; -20^oC is used for winter temperature load and 20^oC is used for summer temperature load. Additional 20^oC is also applied to the southern part of the Castle under summer temperature loading.

Earthquake load calculation is done using response spectrum method. Ortahisar is in the 3rd degree seismic zone which means that effective ground acceleration coefficient (A_o) is taken as 0.20. Spectrum characteristic periods are taken as 0.10 seconds for T_A and 0.30 seconds for T_B according to Z1 local site soil class since the

Castle is settled on tuff settlement. According to A_o, T_A, and T_B, response spectrum curve is drawn and imported to SAP2000 (Figure 9). Damping ratio is calculated ad 0.006 according to Half-power Bandwidth Method. The response spectrum curve is used to describe two main load case, U1 and U2 in SAP2000. U1 and U2 are the earthquake loads which effect the Castle in x-direction and y-directions. Their scale factor is 1.962 which is obtained by multiplication of gravitational acceleration and A_o. Earthquakes may affect the Castle in different directions. A similar procedure with wind load is applied for earthquake loads, too. New load cases are described at every 10^o angles from 0^o to 170^o. Differently from wind loads, earthquake loads are not described at SAP2000 since it is complex and makes SAP2000 give errors. A code is developed in MATLAB to capture results of SAP2000 for x and y direction earthquakes and MATLAB code for different earthquake directions acting on the Castle were calculated externally. Since the model is a linear one, combination of load cases in different directions gave correct results. To prove this idea, the results of earthquake coming with an angle of 110^o with x-direction are calculated in SAP2000 and MATLAB routine and gave the same results. The code creates combinations, explained below, with resulting stresses of each solids obtaining from U1, U2, and dead load and gives resulting stresses of solids according to the combinations. The resulting stresses of U1, U2, and dead load are obtained as a list after running SAP2000 input file. The list is imported to MATLAB.

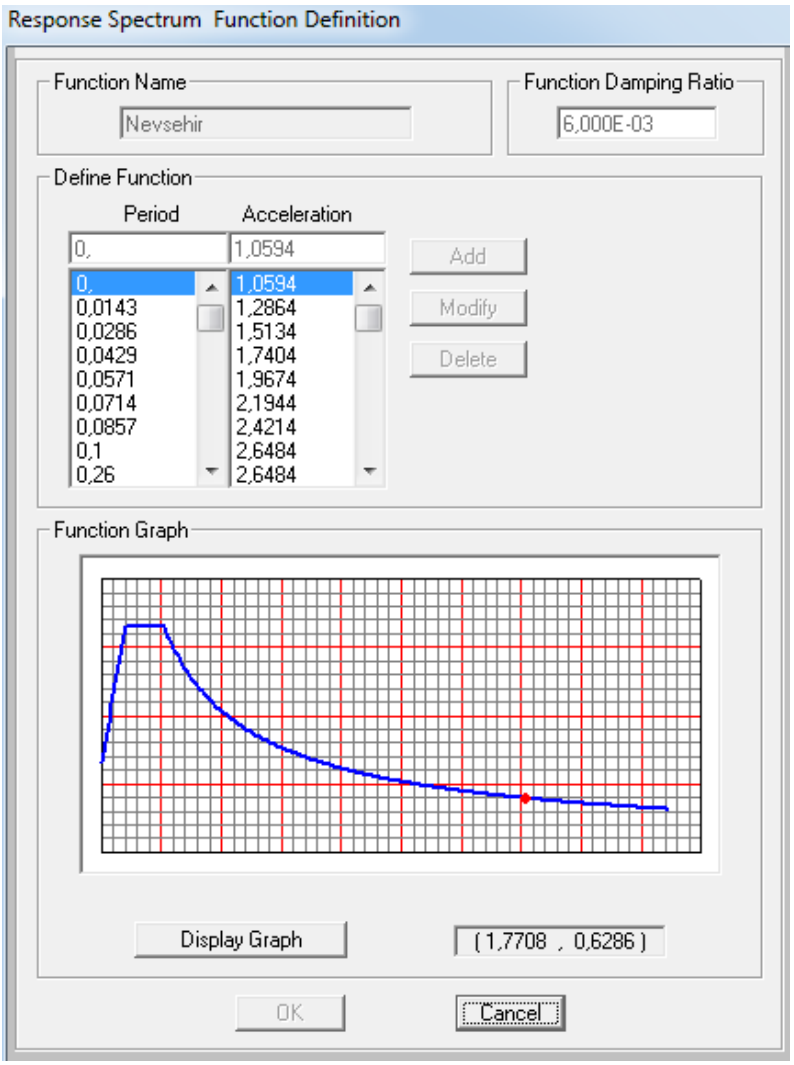

Figure 10 Response Spectrum of the Castle

2.8. Load Combinations

In this section, load combinations that are used for analysis of FEM of the Castle are listed. There are 39 combinations at SAP2000 which are wind load, dead load, and temperature laod combinations and 144 combinations at MATLAB which are earthquake load combinations. To sum up, 183 combinations are created for analysis of the Castle.

DL	DL+W350
TEMPwinter	TEMPsummer
DL+W0	DL+[U1Cos0+U2Sin0]+0.3[U1Cos(0+π/2)+U2Sin(0+π/2)]
DL+W10	DL+[U1Cos10+U2Sin10]+0.3[U1Cos(10+π/2)+U2Sin(10+π/2)]
DL+W20	DL+[U1Cos20+U2Sin20]+0.3[U1Cos(20+π/2)+U2Sin(20+π/2)]
DL+W30	DL+[U1Cos30+U2Sin30]+0.3[U1Cos(30+π/2)+U2Sin(30+π/2)]
DL+W40	DL+[U1Cos40+U2Sin40]+0.3[U1Cos(40+π/2)+U2Sin(40+π/2)]
DL+W50	DL+[U1Cos50+U2Sin50]+0.3[U1Cos(50+π/2)+U2Sin(50+π/2)]
DL+W60	DL+[U1Cos60+U2Sin60]+0.3[U1Cos(60+π/2)+U2Sin(60+π/2)]
DL+W70	DL+[U1Cos70+U2Sin70]+0.3[U1Cos(70+π/2)+U2Sin(70+π/2)]
DL+W80	DL+[U1Cos80+U2Sin80]+0.3[U1Cos(80+π/2)+U2Sin(80+π/2)]
DL+W90	DL+[U1Cos90+U2Sin90]+0.3[U1Cos(90+π/2)+U2Sin(90+π/2)]
DL+W100	DL+[U1Cos100+U2Sin100]+0.3[U1Cos(100+π/2)+U2Sin(100+π/2)]
DL+W110	DL+[U1Cos110+U2Sin110]+0.3[U1Cos(110+π/2)+U2Sin(110+π/2)]
DL+W120	DL+[U1Cos120+U2Sin120]+0.3[U1Cos(120+π/2)+U2Sin(120+π/2)]
DL+W130	DL+[U1Cos130+U2Sin130]+0.3[U1Cos(130+π/2)+U2Sin(130+π/2)]
DL+W140	DL+[U1Cos140+U2Sin140]+0.3[U1Cos(140+π/2)+U2Sin(140+π/2)]
DL+W150	DL+[U1Cos150+U2Sin150]+0.3[U1Cos(150+π/2)+U2Sin(150+π/2)]
DL+W160	DL+[U1Cos160+U2Sin160]+0.3[U1Cos(160+π/2)+U2Sin(160+π/2)]
DL+W170	DL+[U1Cos170+U2Sin170]+0.3[U1Cos(170+π/2)+U2Sin(170+π/2)]
DL+W180	DL+0.3[U1Cos0+U2Sin0]+[U1Cos(0+π/2)+U2Sin(0+π/2)]
DL+W190	DL+0.3[U1Cos10+U2Sin10]+[U1Cos(10+π/2)+U2Sin(10+π/2)]
DL+W200	DL+0.3[U1Cos20+U2Sin20]+[U1Cos(20+π/2)+U2Sin(20+π/2)]
DL+W210	DL+0.3[U1Cos30+U2Sin30]+[U1Cos(30+π/2)+U2Sin(30+π/2)]
DL+W220	DL+0.3[U1Cos40+U2Sin40]+[U1Cos(40+π/2)+U2Sin(40+π/2)]
DL+W230	DL+0.3[U1Cos50+U2Sin50]+[U1Cos(50+π/2)+U2Sin(50+π/2)]
DL+W240	DL+0.3[U1Cos60+U2Sin60]+[U1Cos(60+π/2)+U2Sin(60+π/2)]
DL+W250	DL+0.3[U1Cos70+U2Sin70]+[U1Cos(70+π/2)+U2Sin(70+π/2)]
DL+W260	DL+0.3[U1Cos80+U2Sin80]+[U1Cos(80+π/2)+U2Sin(80+π/2)]
DL+W270	DL+0.3[U1Cos90+U2Sin90]+[U1Cos(90+π/2)+U2Sin(90+π/2)]
DL+W280	DL+0.3[U1Cos100+U2Sin100]+[U1Cos(100+π/2)+U2Sin(100+π/2)]
DL+W290	DL+0.3[U1Cos110+U2Sin110]+[U1Cos(110+π/2)+U2Sin(110+π/2)]

DL+W300 DL+0.3[U1Cos120+U2Sin120]+[U1Cos(120+π/2)+U2Sin(120+π/2)]
DL+W310 DL+0.3[U1Cos130+U2Sin130]+[U1Cos(130+π/2)+U2Sin(130+π/2)]
DL+W320 DL+0.3[U1Cos140+U2Sin140]+[U1Cos(140+π/2)+U2Sin(140+π/2)]
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DL-0.3[U1Cos20+U2Sin20]-[U1Cos(20+π/2)+U2Sin(20+π/2)]
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DL-0.3[U1Cos40+U2Sin40]-[U1Cos(40+π/2)+U2Sin(40+π/2)]
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DL-0.3[U1Cos70+U2Sin70]-[U1Cos(70+π/2)+U2Sin(70+π/2)]
DL-0.3[U1Cos80+U2Sin80]-[U1Cos(80+π/2)+U2Sin(80+π/2)]
DL-0.3[U1Cos90+U2Sin90]-[U1Cos(90+π/2)+U2Sin(90+π/2)]
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DL-0.3[U1Cos110+U2Sin110]-[U1Cos(110+π/2)+U2Sin(110+π/2)]
DL-0.3[U1Cos120+U2Sin120]-[U1Cos(120+π/2)+U2Sin(120+π/2)]
DL-0.3[U1Cos130+U2Sin130]-[U1Cos(130+π/2)+U2Sin(130+π/2)]
DL-0.3[U1Cos140+U2Sin140]-[U1Cos(140+π/2)+U2Sin(140+π/2)]
DL-0.3[U1Cos150+U2Sin150]-[U1Cos(150+π/2)+U2Sin(150+π/2)]
DL-0.3[U1Cos160+U2Sin160]-[U1Cos(160+π/2)+U2Sin(160+π/2)]
DL-0.3[U1Cos170+U2Sin170]-[U1Cos(170+π/2)+U2Sin(170+π/2)]

The first two cases are belongs to temperature loading. The other 36 combinations are about wind load combinations, which are defined in accordance with TS498. Dead load and wind loads acting with angles of 0^o to 350^o from East in counter clock wise are sum up for each combinations and resultant loads are applied to the Castle. Other 144 combinations are obtained in accordance with National Earthquake Hazards Reduction Program (NEHRP) and Federal Emergency Management Agency (FEMA) and in essence can also be found in American Association of State Highway and Transportation (AASTHO) as well. In all EQ related load definitions coming with 10° intervals, 100% of main direction (U1) earthquake load and 30% of transverse direction (U2) earthquake load are defined and applied to the Castle at the same time.

Similarly, total of 8 combinations are created for EQ being multiplied with -1, indicating the negative effects (compression and tension) at the same time. The transverse 30% combination is also multiplied with -1 and combined with the main loading directions. The 30% transverse direction actually defined to count for different EQ application angles. In this study, this procedure is repeated for 10 degree increments generating new axes (x' and y') to stay on the safe side. Basic coordinate transformation is used to define x' and y' axes by multiplication of U1 and U2 with sinus and cosines belongs to angle of the new axis.

2.9. MATLAB Code

MATLAB is used to develop a code for creating combinations mentioned in Chapter 2 and analyzing results of the combinations. The code firstly reads data obtained from SAP2000 analyses results of dead load, U1, and U2. The data can be read from text file by MATLAB. Secondly, the code generates 144 combinations which are about different combination of earthquake loads. Then, results of 144 combinations are obtained as normal and shear stresses. The normal stresses are σ_x, σ_y, σ_z and the shear stresses are τ_{xy}, τ_{xz}, τ_{yz}. These stresses are used to obtain principal stresses of each solids of the Castle. At this point, the code uses the formulas shown in Equations 4 till 14 to get the principal stresses.

$$I_1 = \sigma_x + \sigma_y + \sigma_z \text{ (Eqn. 4)}$$

$$I_2 = \sigma_x\sigma_y + \sigma_x\sigma_z + \sigma_y\sigma_z - \tau_{xy}^2 - \tau_{xz}^2 - \tau_{yz}^2 \text{ (Eqn. 5)}$$

$$I_3 = \sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{xz}\tau_{yz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2 \text{ (Eqn. 6)}$$

$$R = \frac{1}{3}I_1^2 - I_2 \text{ (Eqn. 7)}$$

$$S = \left(\frac{1}{3}R\right)^{\frac{1}{2}} \text{ (Eqn. 8)}$$

$$Q = \frac{1}{3}I_1I_2 - I_3 - \frac{2}{27}I_1^3 \text{ (Eqn. 9)}$$

$$T = (\frac{1}{3}R^3)^{\frac{1}{2}} \text{ (Eqn. 10)}$$

$$\alpha = cos^{-1}(-\frac{Q}{2T}) \text{ (Eqn. 11)}$$

$$\sigma_a = 2S\left[\cos\left(\frac{\alpha}{3}\right)\right] + \frac{1}{3}I_1 \text{ (Eqn. 12)}$$

$$\sigma_b = 2S\{\cos\left[\left(\frac{\alpha}{3}\right) + 120^o\right]\} + \frac{1}{3}I_1 \text{ (Eqn. 13)}$$

$$\sigma_c = 2S\{\cos\left[\left(\frac{\alpha}{3}\right) + 240^o\right]\} + \frac{1}{3}I_1 \text{ (Eqn. 14)}$$

σ_a, σ_b, σ_c are the principles stresses of a solid of the Castle. The maximum one is σ_1, the minimum one is σ_3, and the middle one is σ_2. At the end of the code, (18×8×13248=) 1907712 principal stresses are found for each load combinations and this is the main reason for using MATLAB instead of SAP2000 during the earthquake analyses of the Castle. Definition of load cases in SAP2000 is more difficult, takes more time to run, and principal stresses cannot be obtained in SAP2000.

2.10. Coulomb-Mohr Theory and Modified-Mohr Theory

Cappadocian tuff is a brittle material which is suitable to be evaluated with using Coulomb-Mohr Theory. Another version of Coulomb-Mohr Theory is the Modified-Mohr Theory, which has slight difference in the shear region. Both of these theories are based on maximum normal-stress theory. The ultimate tensile strength, S_{ut}, is the limit of σ_1 for tensile strength on the other hand the ultimate compressive strength, S_{uc}, is the limit of σ_3 for compressive strength. The difference between Coulomb-Mohr Theory and Modified-Mohr Theory is the limit of case when σ_1 is in tension and σ_3 is in compression. The Coulomb-Mohr Theory is relatively more conservative compared to the Modified-Mohr Theory by decreasing the limits of ultimate strengths. These theories are used to evaluate the analysis results of the Castle. Each solids' principle stresses obtained from results of 183 combinations are analyzed according to

Coulomb-Mohr Theory and Modified-Mohr Theory and plotted on a 2D graph as shown in Figure 11.

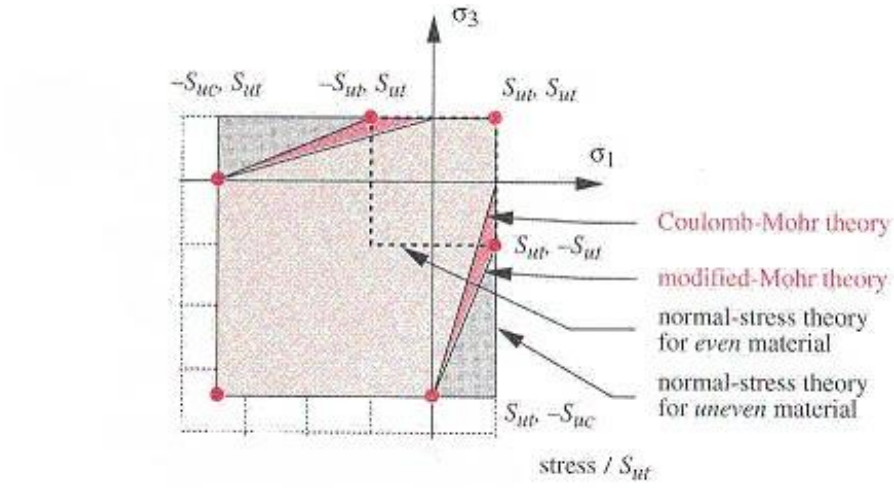

Figure 11 Coulomb-Mohr and Modified-Mohr Theories

2.11. Difficulties Encountered During the Analysis

Preparing FEM of the Castle has difficulties at stages of drawing, defining conditions, and analyzing. The Castle has an irregular shape, which is very difficult to define FEM. This problem leads to develop a code which reads coordinates of the Castle as single dots and transfers the dots to create solids for FEM of the Castle.

The second problem is defining material properties and load combinations of FEM of the Castle. Since the cracks and the caves cannot modelled, calibration was done to get more realistic model. The calibration is done only for modulus of elasticity to count for existing cracks. The third problem is about temperature loading at Sap2000. The results of temperature loads at SAP2000 has a relationship with how fine or coarsely the solid members are meshed in SAP2000. If coarse meshing for solids is used, the calculated temperature load at SAP2000 is higher than hand calculated realistic values. Since the FEM used at this thesis is coarse because of computer limitations, the temperature loads calculated at SAP2000 is higher than the values calculated by hand. Smaller models with fine meshing showed close agreement with the theoretical hand

calculation. However, this difference can be accepted since the stress values are higher than values calculated by hand therefore, the results are on the safe side. Another problem is number of loading combinations: MATLAB code is develop to solve the extensive number of load combinations problem for SAP2000.

The last problem is faced at analyzing step: SAP2000 runs each analysis in an hour or more and sometimes gives error during the analysis which causes loss of time

2.12. Analysis Results

The analysis results are studied to see if the castle is safe against EQ, wind, and temperature loads. A criteria is needed to consider the analysis results: The Coulomb-Mohr Theory and Modified-Mohr Theory are chosen for evaluating the results. EQ results obtained from SAP2000 and post processed in MATLAB to obtain principal stresses are plotted on Coulomb-Mohr Theory and Modified-Mohr Theory graphs (Figure 12 and Figure 13). The plotted data are principal stresses of each one of the solids which are separately plotted for all 183 load combinations as explained in Section 2.6. The wind load combination results are also post processed and plotted in Figure 14 while the temperature load results are plotted in Figure 15. If the plotted data remains inside the boundaries defined by both theories, then those solid members can be accepted safe against 183 load combinations including EQ, wind, and temperature loading. Only a few members have stresses exceeding the tensile capacity of the material (Figure 12) for the fixed case modeling condition. When the base rock stiffness is defined using springs or when the wind load is acting on the Castle, the stressed do not exceed the capacity of the material and remain within the boundaries (Figures 13 and 14). Temperature loading results show that a solid member located at the top of the Castle with high aspect ratio has stresses exceeding the tensile capacity of the material (Figure 15). This may be due to modeling properties and even if one member exceeds the limits, the overall castle remains intact.

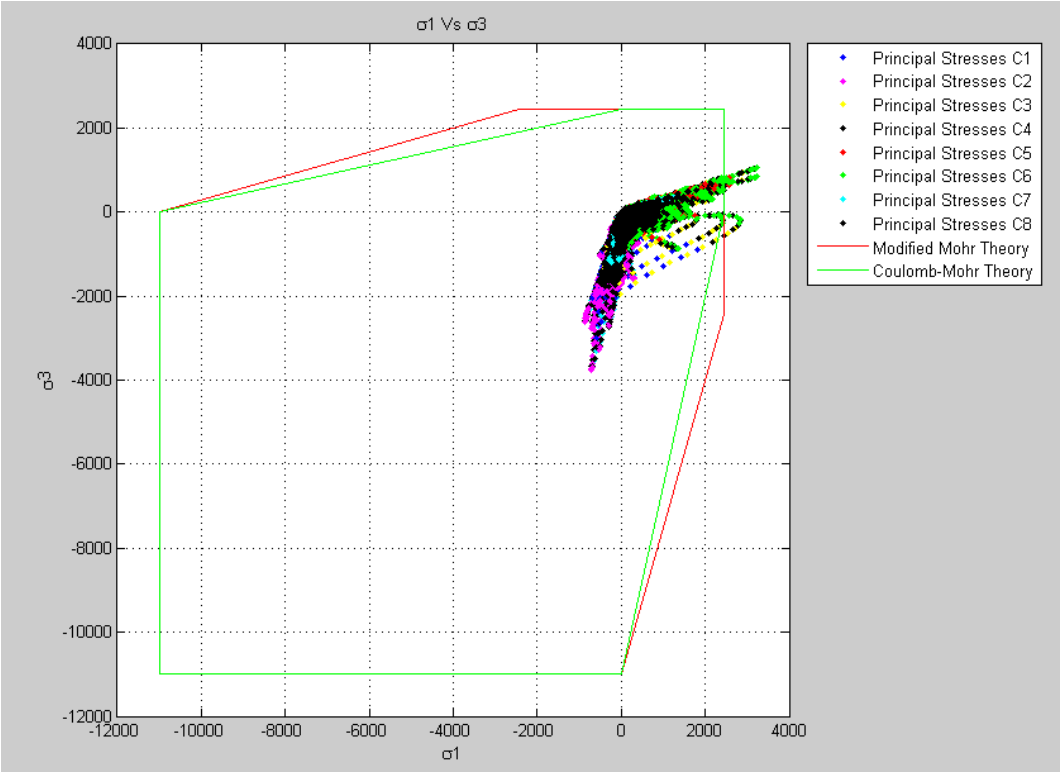

Figure 12 Analysis Results of Earthquake Loads with Fixed Supports (144 cases)

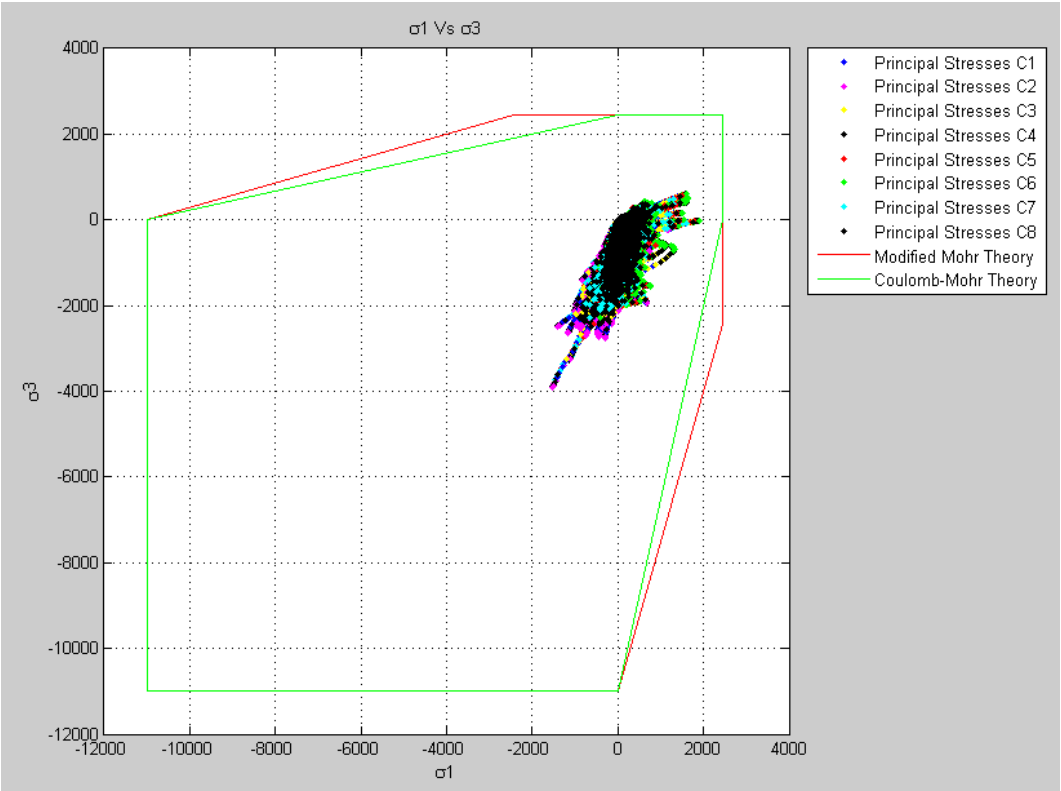

Figure 13 Analysis Results of Earthquake Loads with Springs at the base (144 cases).

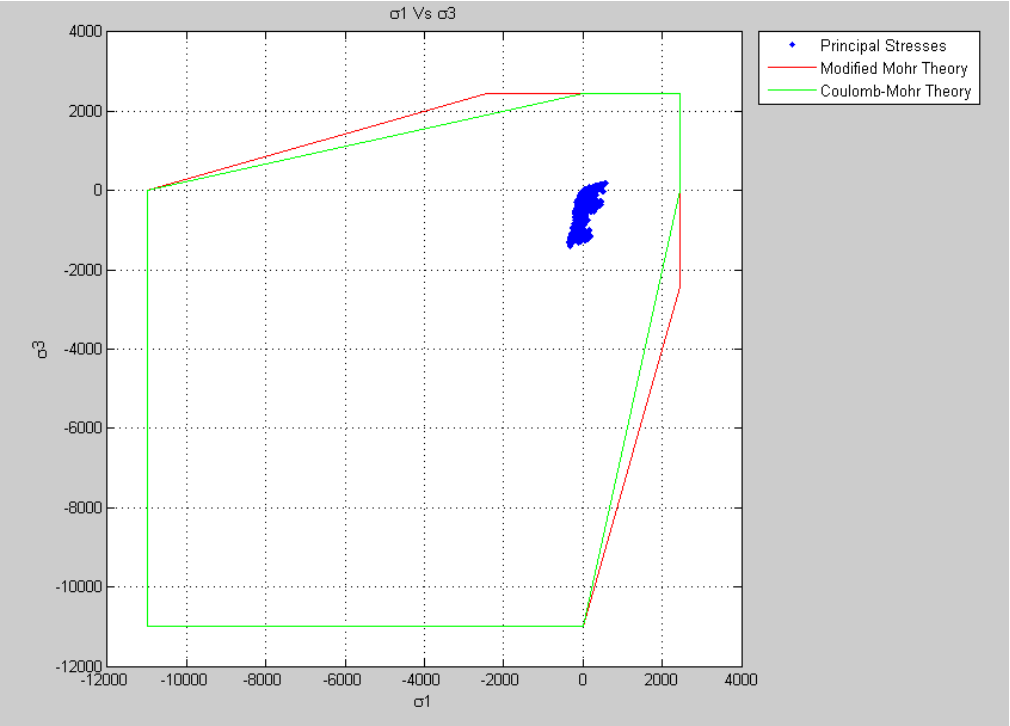

Figure 14 Analysis Results of Wind Loads (36 cases)

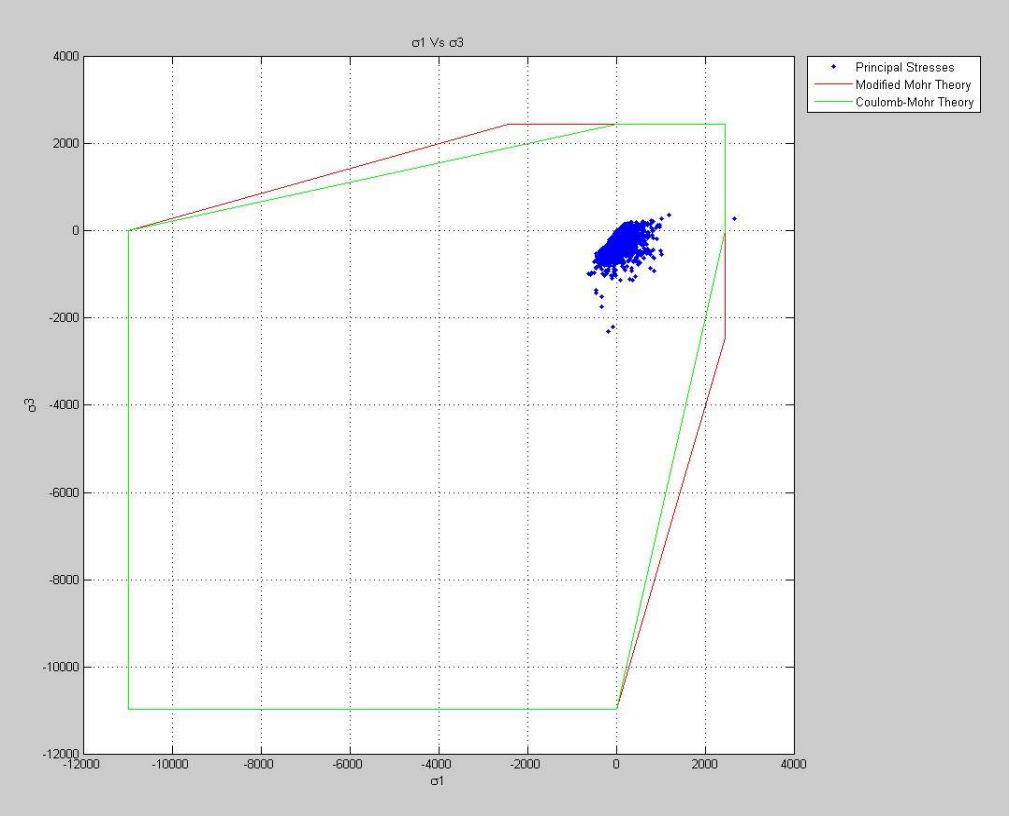

Figure 15 Analysis Results of Temperature Loads (2 cases)

In addition to the Coulomb Mohr Theory related comprehensive analyses, the stress levels for a limited number of load cases are directly obtained from SAP2000 and plotted on the castle FEM to see the distribution of stress. It should be noted that the load case results shown here are only a subset of all the combinations processed by the MATLAB code. The stress contour plots here are also used as a second check to ensure MATLAB results are reliable. As it can be seen from Figures 20 to 32, the normal stress levels (S11, S22, S33 etc) are well below the material capacity indicating that no significant damage is expected on the structure during a design earthquake or wind loading defined by the Turkish code (Figures 20-32). Figures 33 and 34 also show the Von Mises Stress results for temperature loading of ±20 C° and +40 C° partial temperature loading.

As a summary, although the maximum EQ stress obtained for S22 is 2.45 MPa overall stress levels are generally smaller than the tensile and compressive load capacity of the material (Figure 24). The stress directions and amplitudes are prepared in a table format and listed in Table 4. S11 stress direction is horizontal in global degrees of freedom, which is aligned with the x-axis. S33 stress direction is a vertical component in global degrees of freedom, which is aligned with the z-axis. S22 stress direction is a horizontal stress in global degrees of freedom, which is aligned with the y-axis. The maximum S22 stress of a member exceeds the tensile capacity of the material by about 10%. This member has member id # 19606 and is located towards the top of the castle with irregular shape. General stress definition of SAP2000 is shown in Figure 17 and the stress directions are shown in Figure 16.

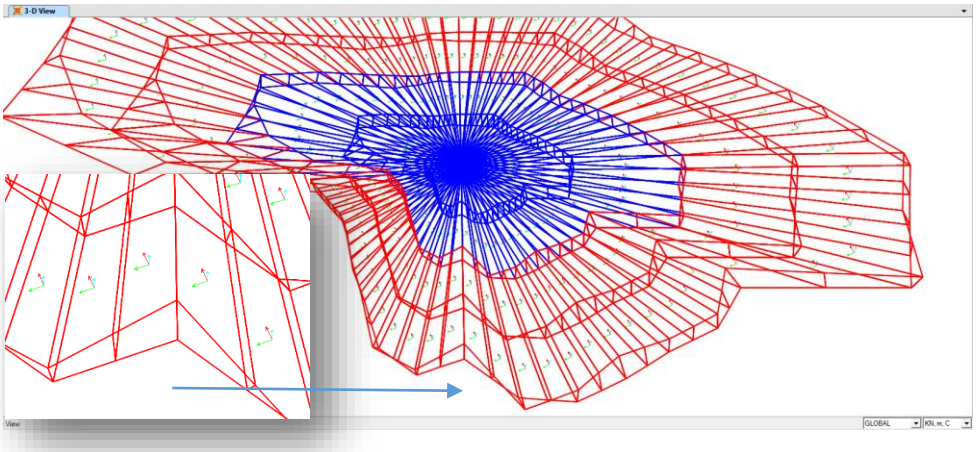

Figure 16 Global Coordinates of FEM

Table 3 Stress Results Under DL, U1, and U2

Stress direction	Min and Max stresses	Capacity check
S33	-1.81 MPa; 0.94 MPa (Figure 21-22)	>-12 MPa; <2.2 MPa
S22	-2.18 MPa**; 2.45 MPa (Figure 23-24)**	>-12 MPa; <2.2 MPa
S11	-2.55 MPa; 1.85 MPa (Figure 25-26)	>-12 MPa; <2.2 MPa
S12	-1.16 MPa; 1.04 MPa (Figure 27-28)	>-2 MPa; <2 MPa
S13	-0.66 MPa; 0.83 MPa (Figure 29-30)	>-2 MPa; <2 MPa
S23	-0.43 MPa; 0.43 MPa (Figure 31-32)	>-2 MPa; <2 MPa
DL	-1.29 MPa (Figure 20)	>-12 MPa; <2.2 MPa

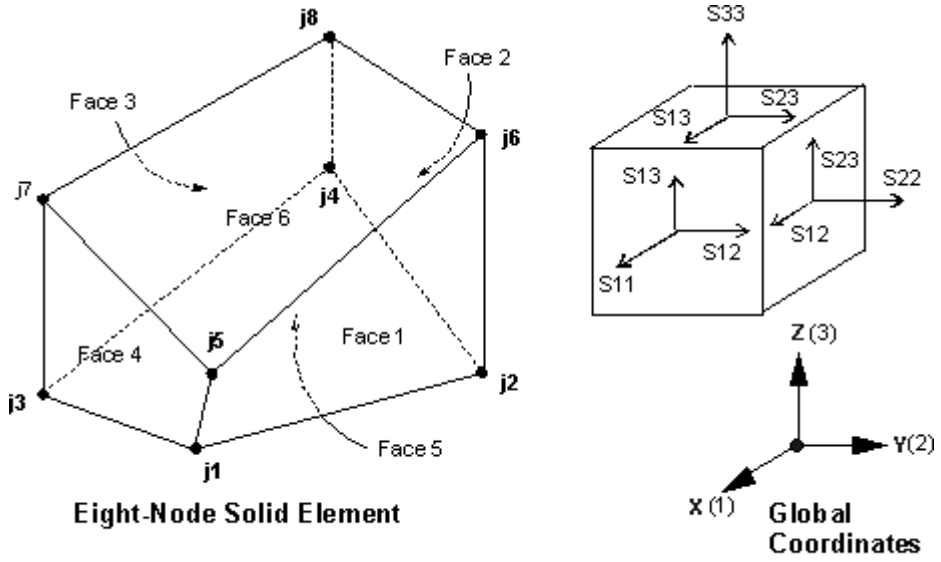

Figure 17 Global Coordinates of a Solid

The calculated overall stress levels for the indicated loading directions (S11, S22, etc) are much smaller and the stress capacities as it was expected, since the castle has survived many EQs, wind, and temperature loads in its past and SAP2000 stress contours are a subset of MATLAB code checks. According to Figure 35; the percentage of damaged solid members of the Castle is 0.0047%. On the other hand; the percentage of the solids, which are in the zone whose limit is reduced by 90%, is

97.5%. This means that the Castle shows very strong behavior against earthquake loads like wind loads.

According to wind load analysis results, it is seen that the principal stresses generated by wind load has small effect compared to EQ where the maximum stress levels do not exceed more than 10% of the material capacity under wind loading. However; analysis results belong to temperature loading at SAP2000 show differences with the results calculated by hand. The values that SAP2000 found is higher at the outer solid members of the Castle. This phenomenon was investigated using higher mesh density and smaller analytical models. Although the SAP2000 course mesh analysis results are on the safe side, the reason for this needs to be explored: Stress distribution between the outer solid members and inner solid members is sharp. While outer solid members, whose thicknesses are 10 cm according to FEM prepared at SAP2000, have high stresses; inner solid members next to outer ones have low stress.

There are two important points to get more realistic results under temperature loading. The first one is that stress distribution between the solid members should be smooth. The second one is that minimizing the mesh size, increasing the number of members, and having proper aspect ratio for the solid members in SAP2000 is important. The second point can be achieved by obtaining optimal mesh ratio; however, obtaining optimal mesh ratio is not easy at this study because of computer's capacity used during the analyses. Figure 18 shows that the model (Figure 18a & c) with high mesh ratio gives better results than model with low mesh ratio (Figure 18b & d).

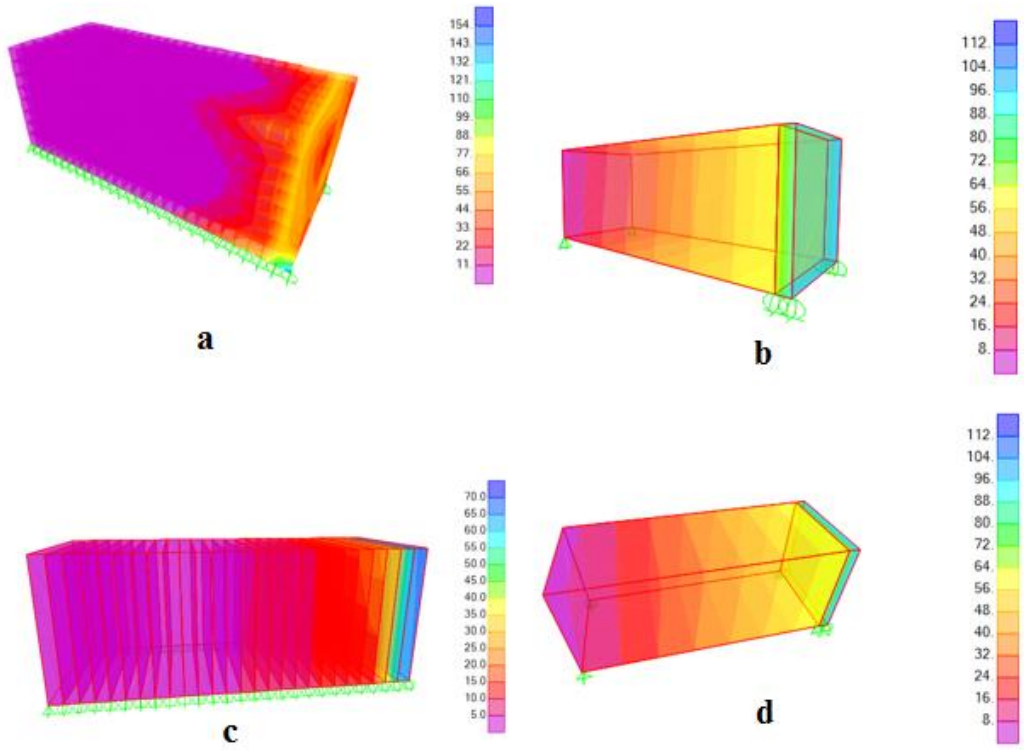

Figure 18 Temperature Load Analysis of a Rectangular Pris

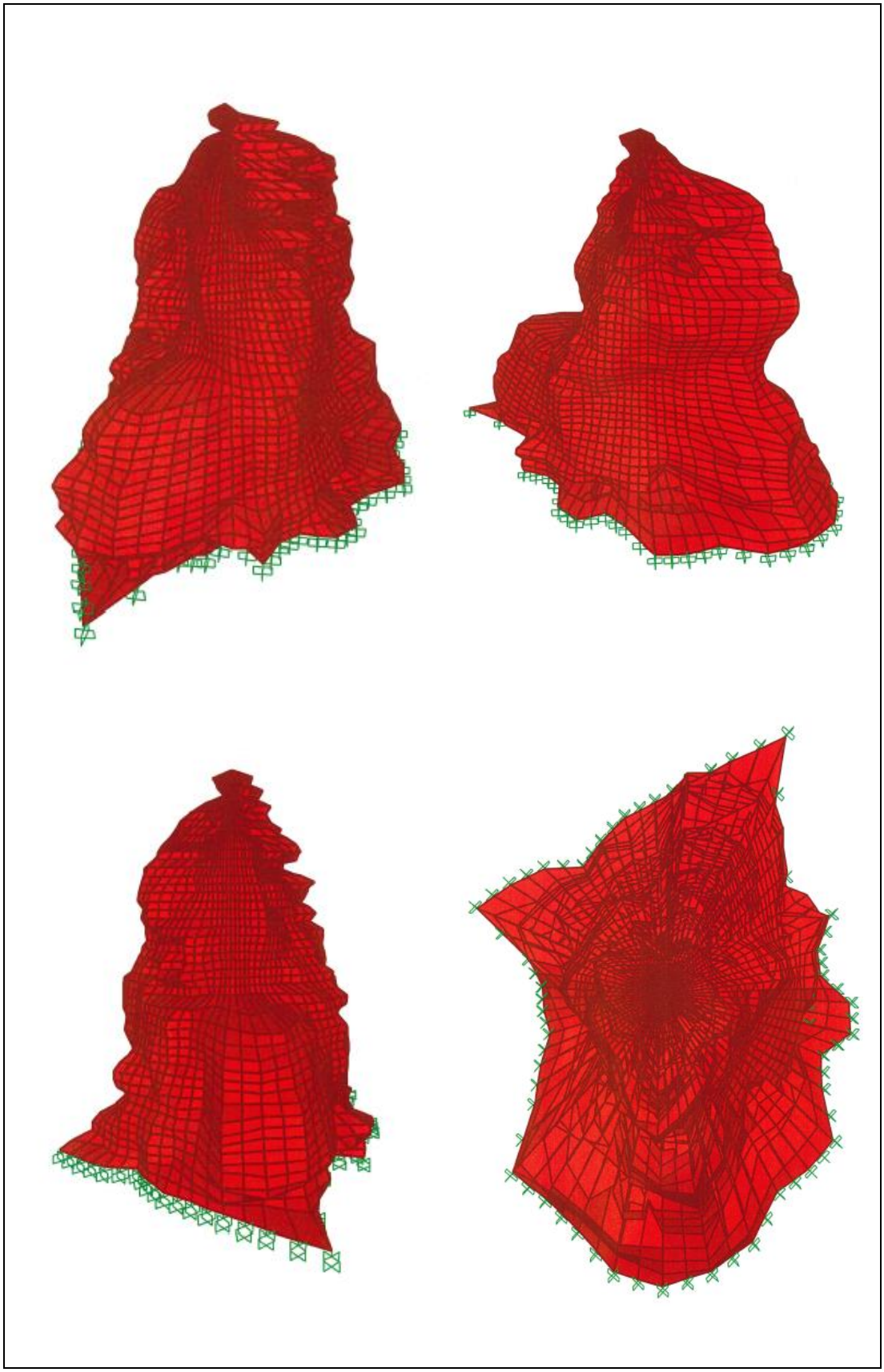

Figure 19 FEM of the Castle

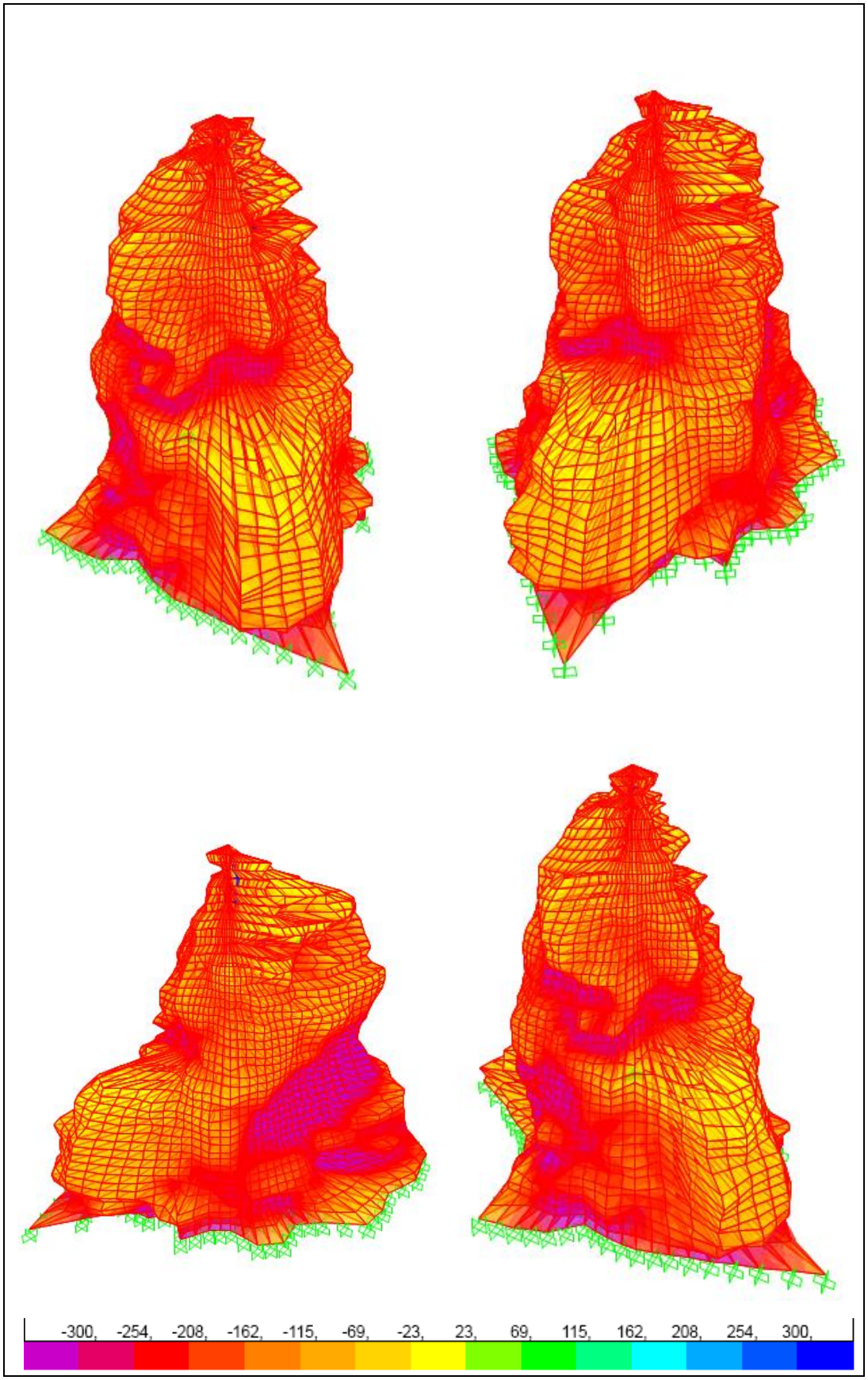

Figure 20 S33 Dead Load Stresses (kPa)

* Envelope = Max (DL;EQx;EQy;DL+1.0EQx+0.3EQy; DL+0.3EQx+1.0EQy)

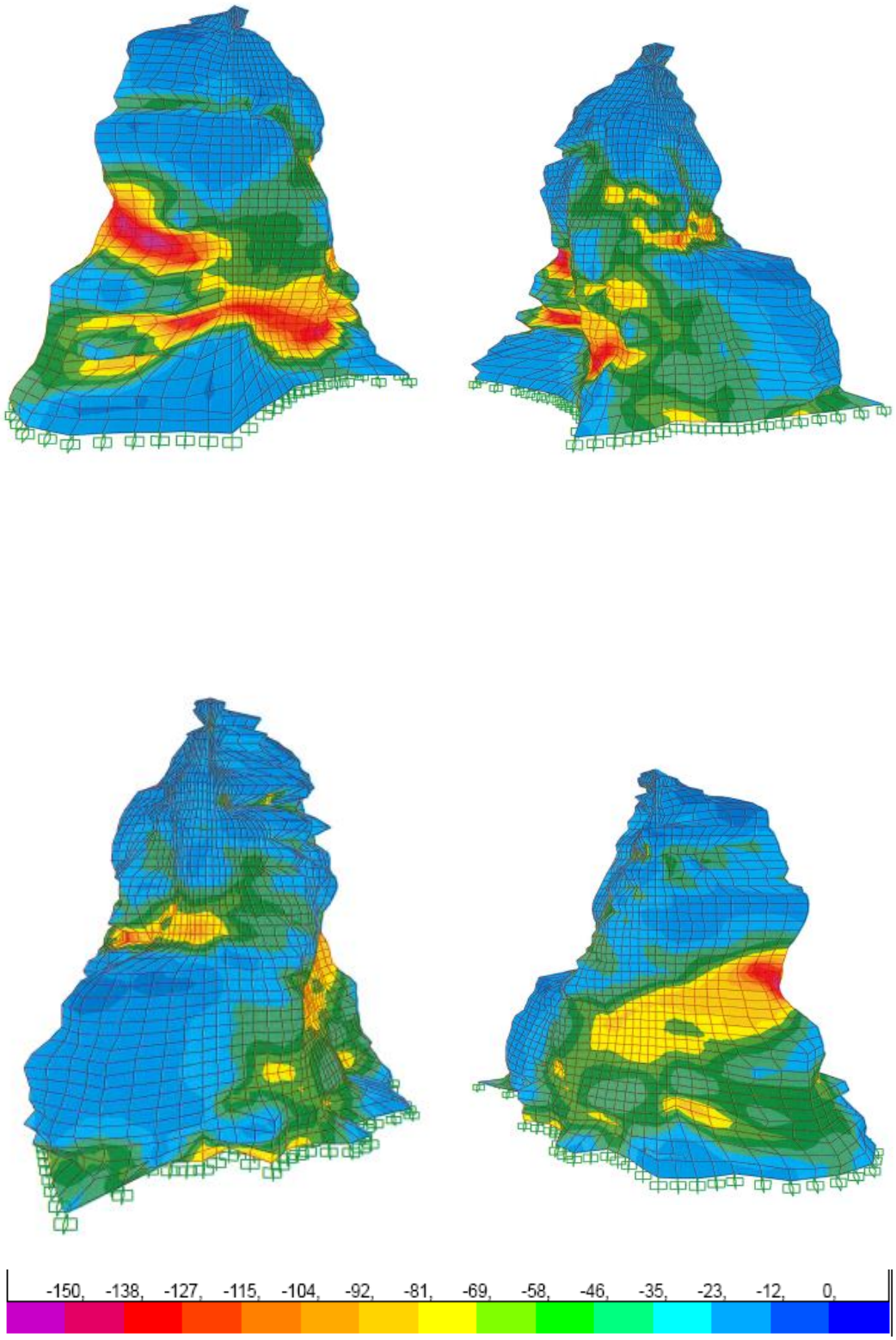

Figure 21 S33 *Envelope Min Stresses (kPa)

* Envelope = Max (DL;EQx;EQy;DL+1.0EQx+0.3EQy; DL+0.3EQx+1.0EQy)

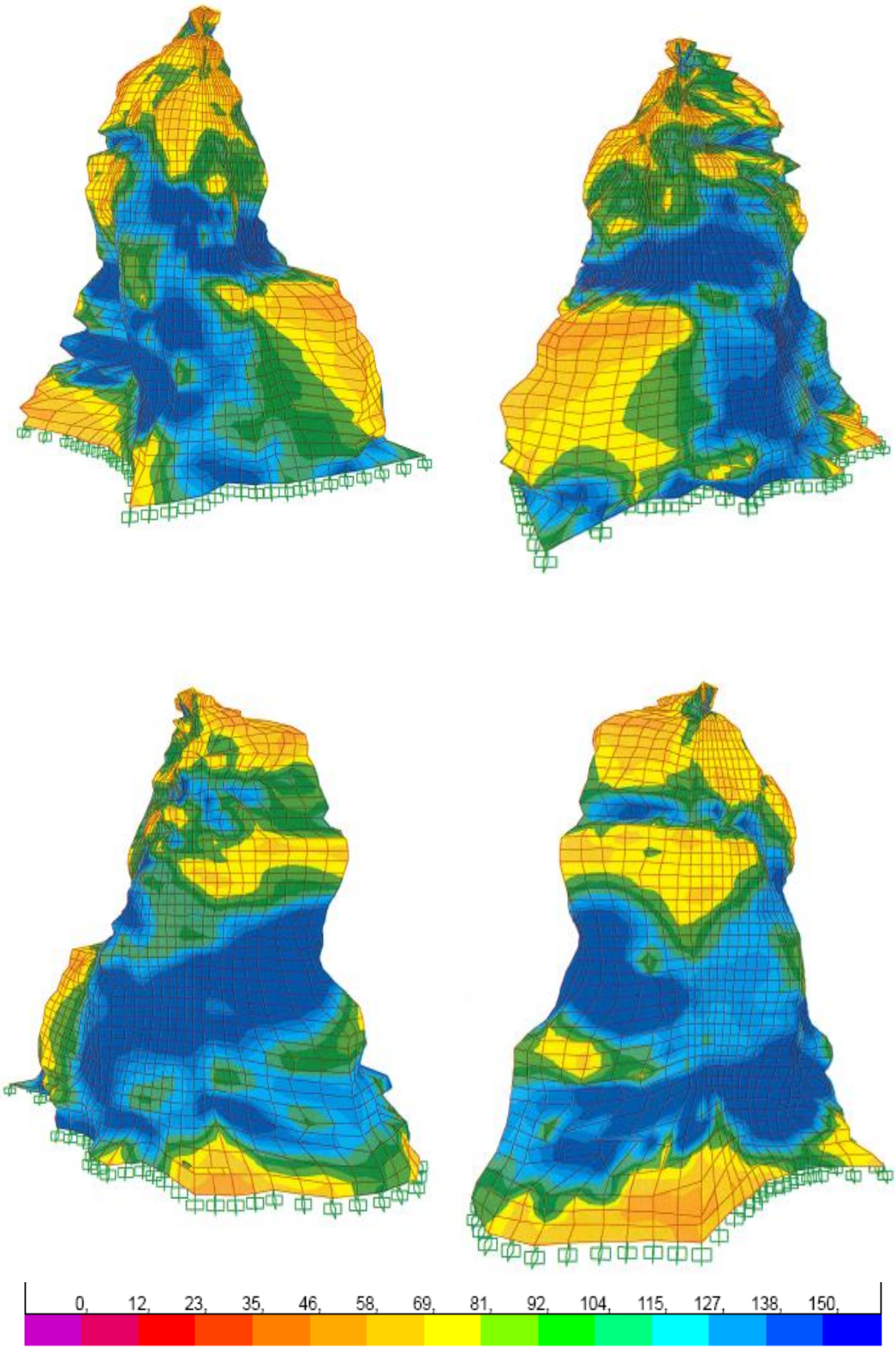

Figure 22 S33 *Envelope Max Stresses (kPa)

* Envelope = Max (DL;EQx;EQy;DL+1.0EQx+0.3EQy; DL+0.3EQx+1.0EQy)

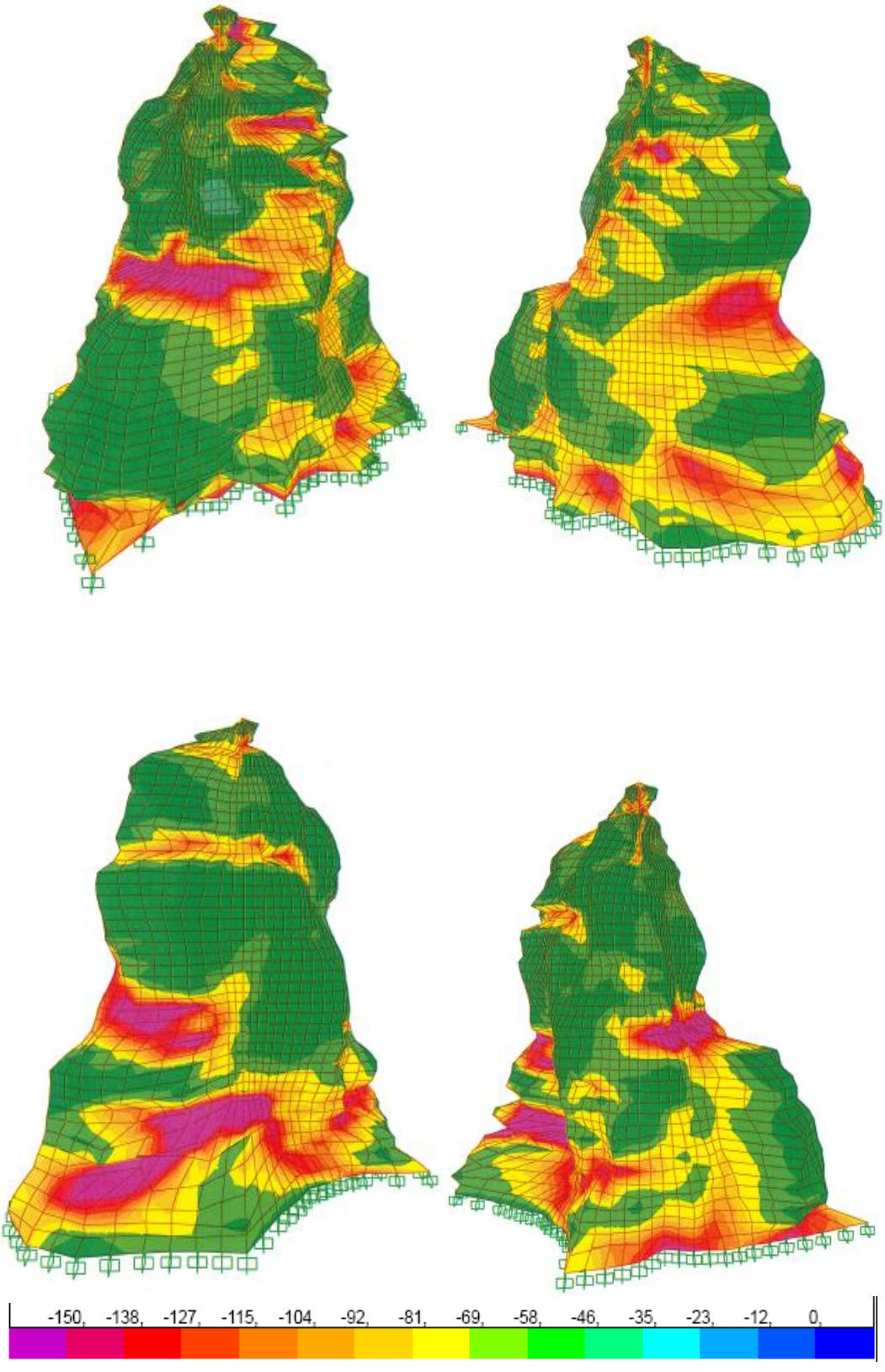

Figure 23 S22 *Envelope Min Stresses (kPa)

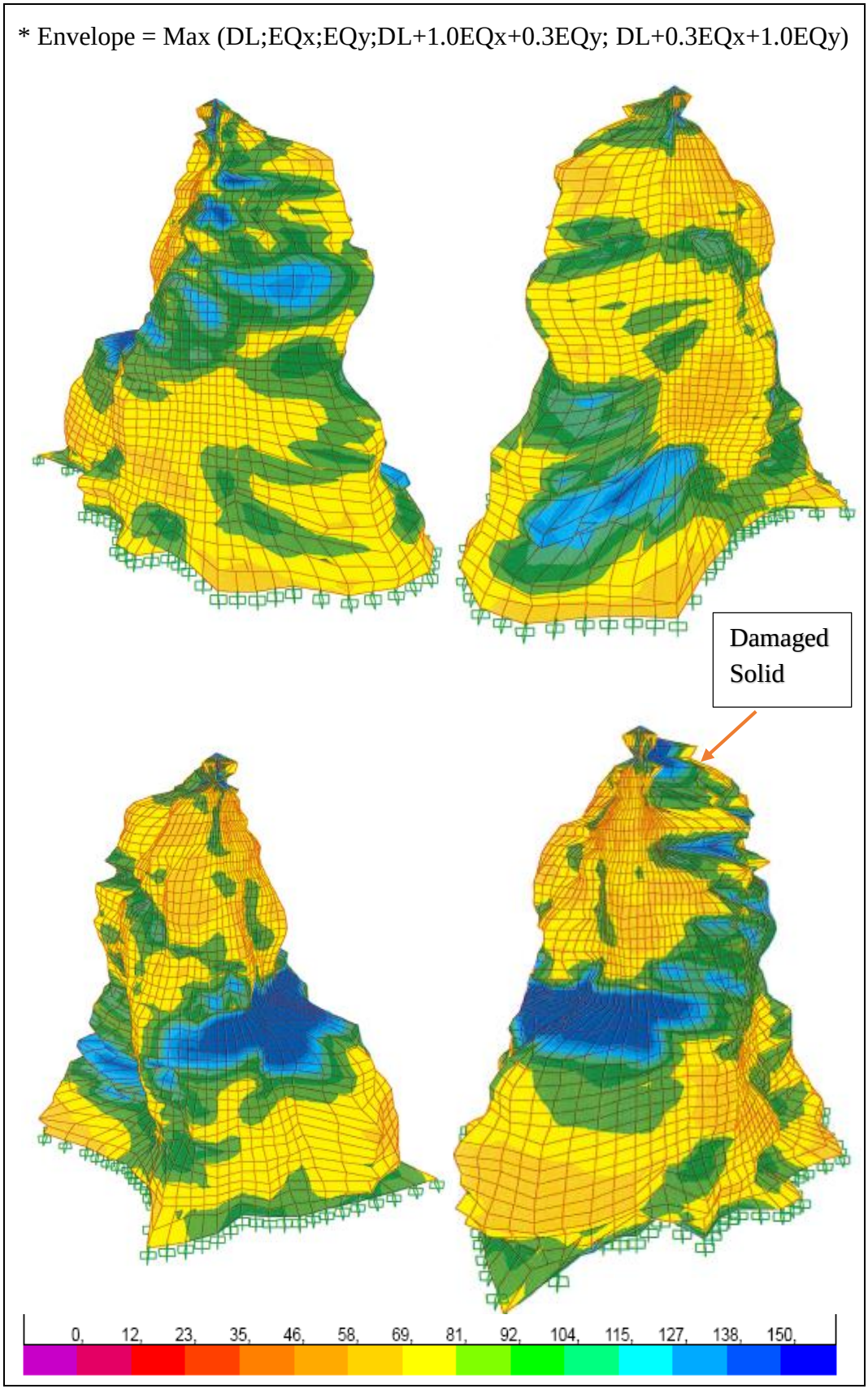

Figure 24 S22 *Envelope Max Stresses (kPa)

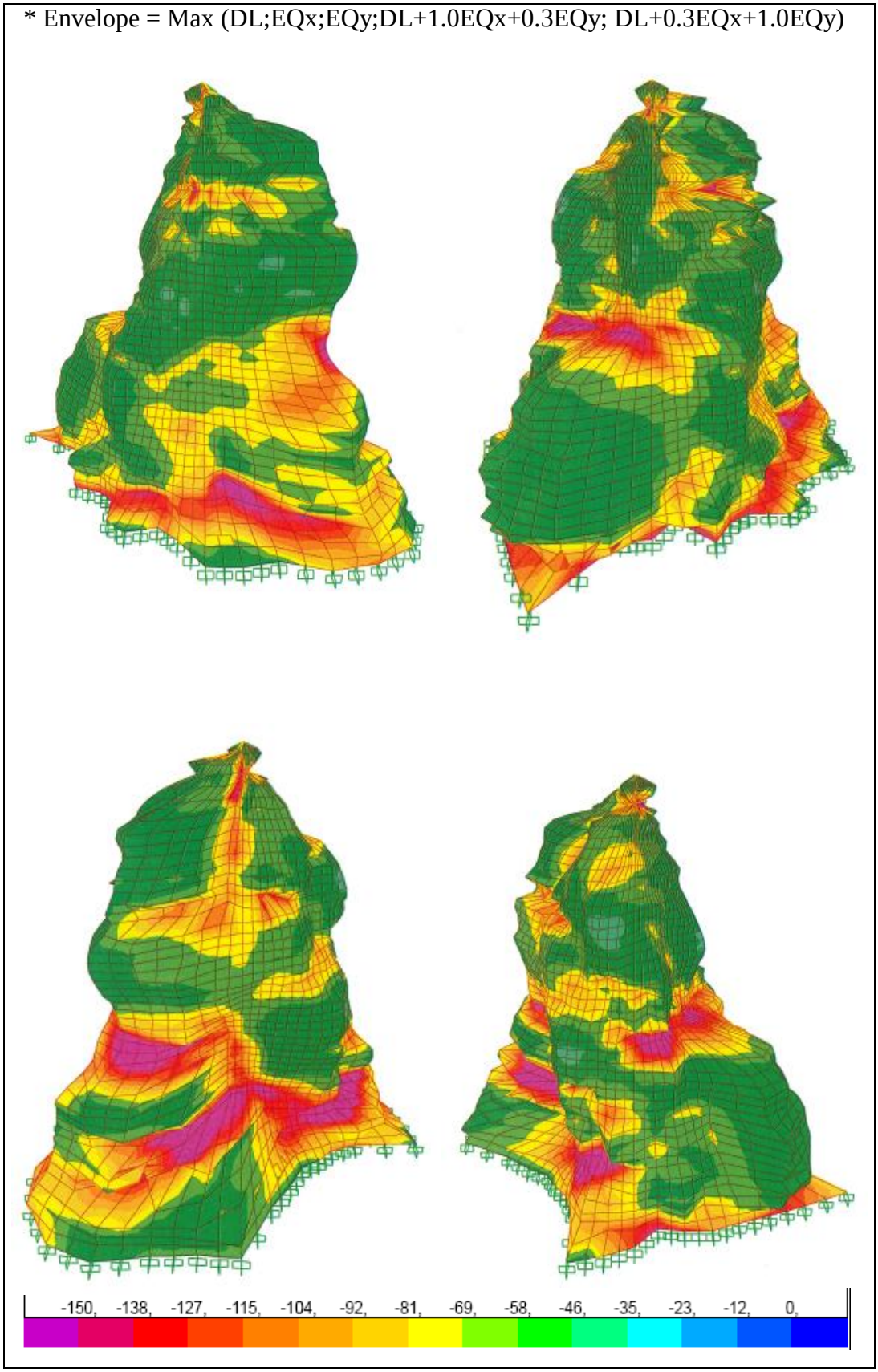

Figure 25 S11 *Envelope Min Stresses (kPa)

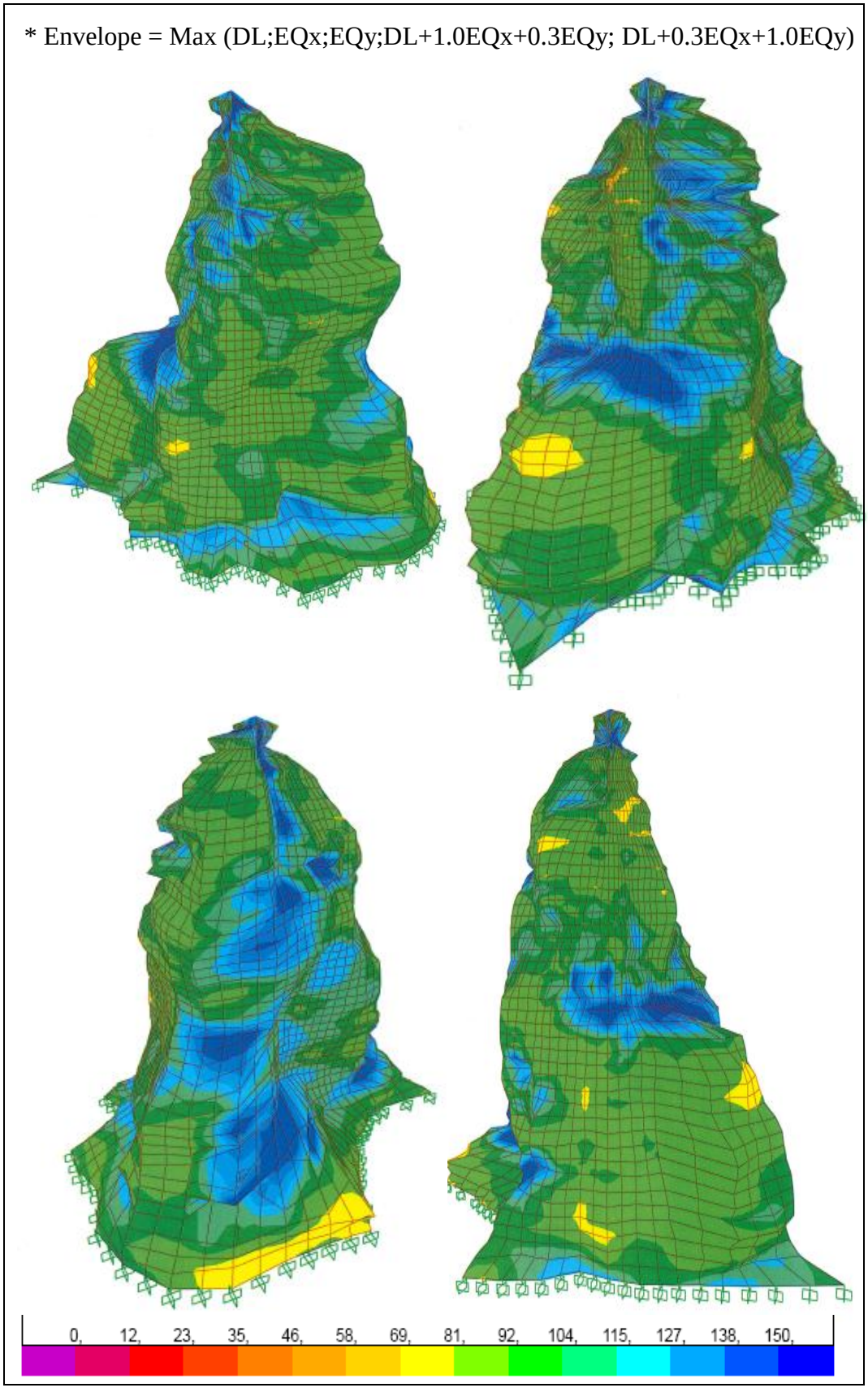

Figure 26 S11 *Envelope Max Stresses (kPa)

* Envelope = Max (DL;EQx;EQy;DL+1.0EQx+0.3EQy; DL+0.3EQx+1.0EQy)

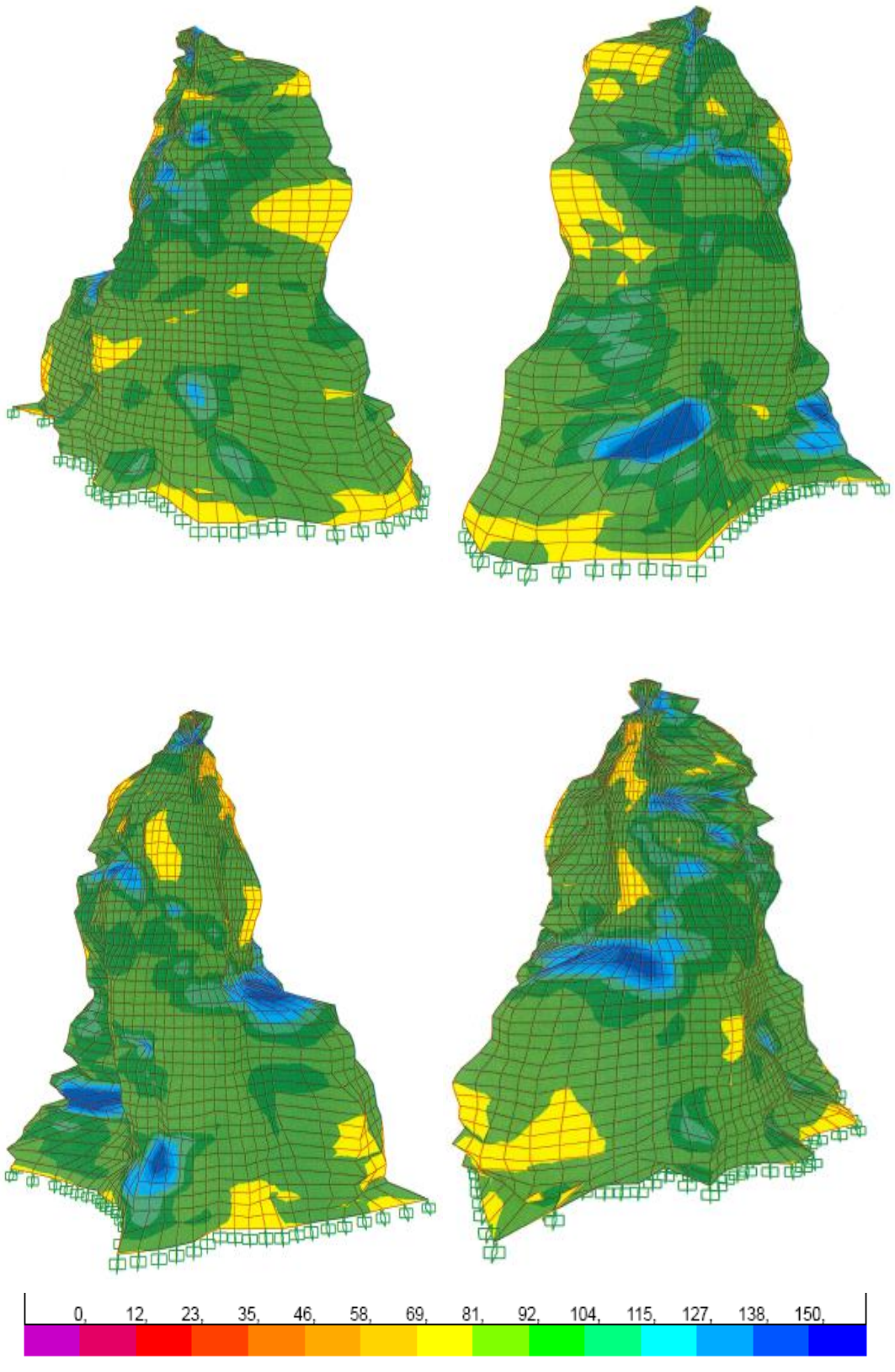

Figure 27 S12 *Envelope Max Stresses (kPa)

* Envelope = Max (DL;EQx;EQy;DL+1.0EQx+0.3EQy; DL+0.3EQx+1.0EQy)

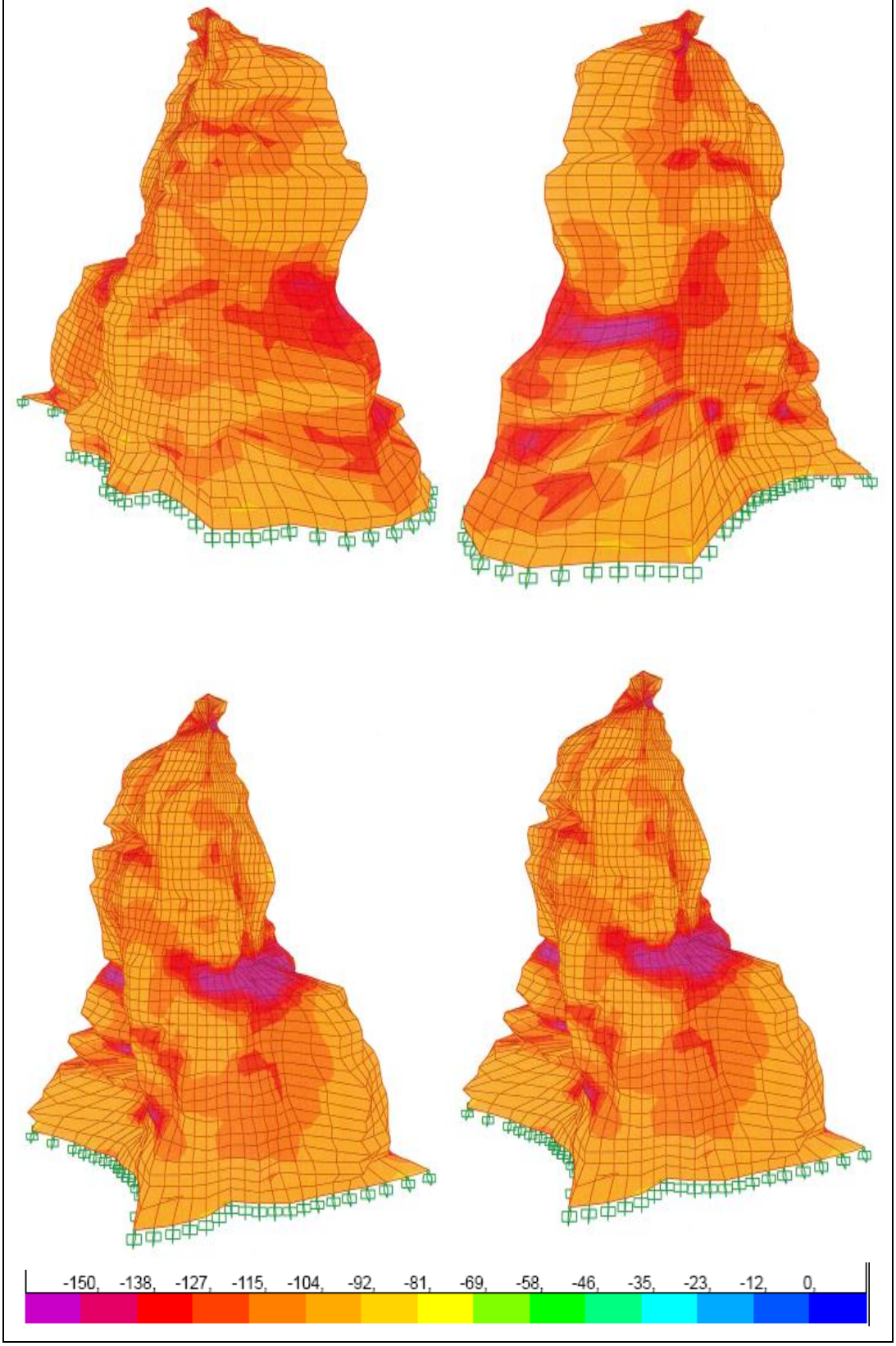

Figure 28 S12 *Envelope Min Stresses (kPa)

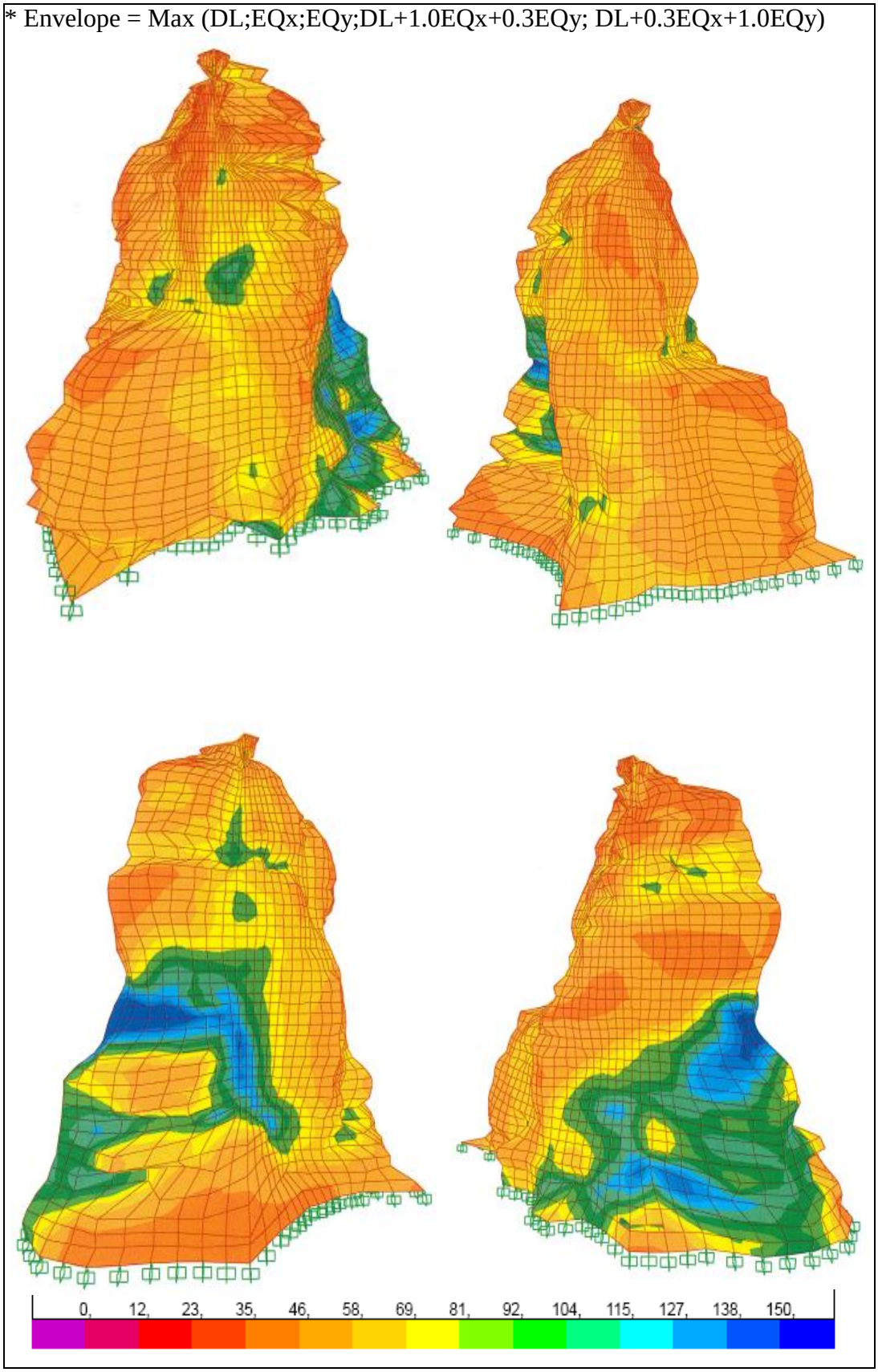

Figure 29 S13 *Envelope Max Stresses (kPa)

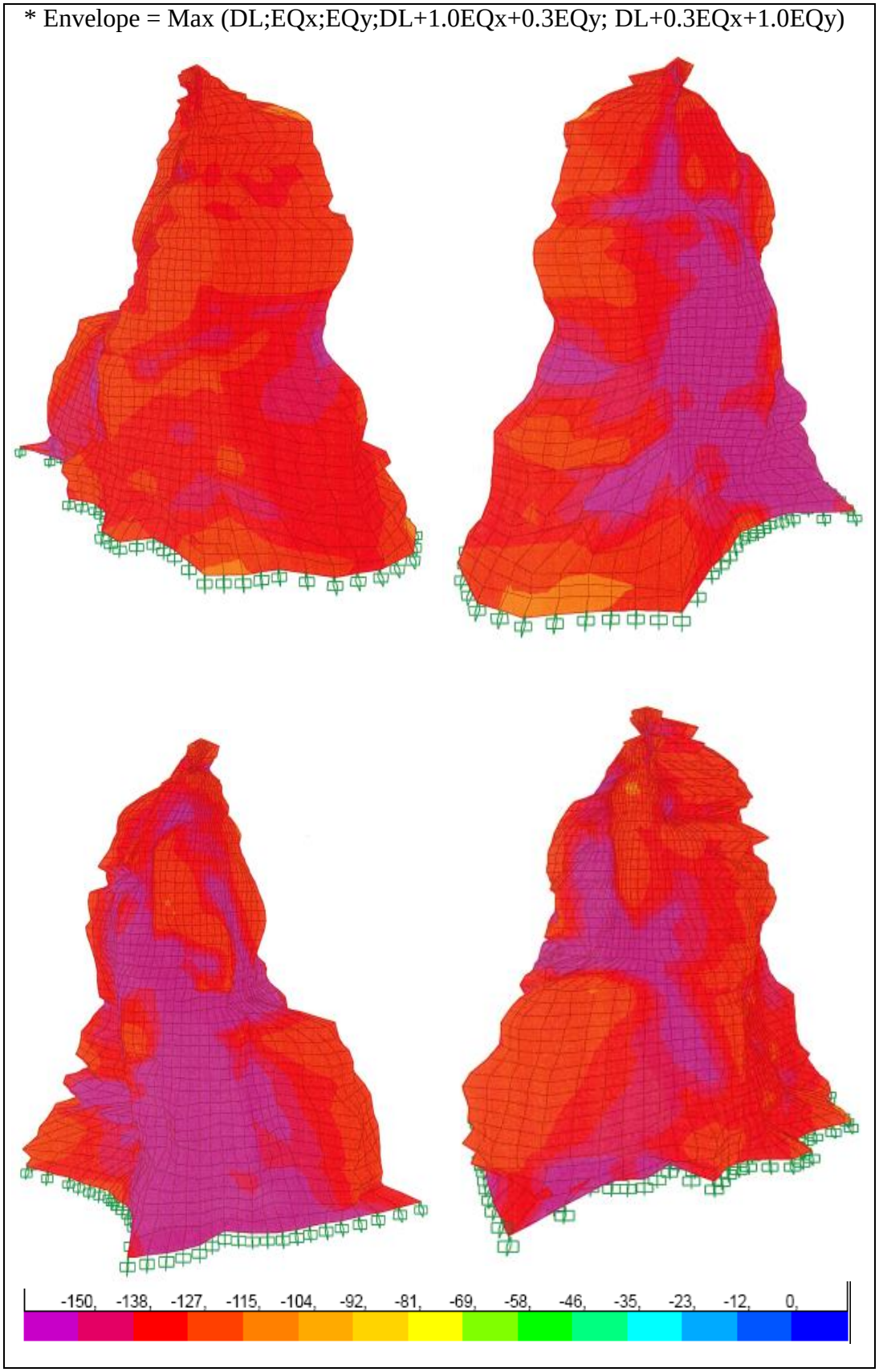

Figure 30 S13 *Envelope Min Stresses (kPa)

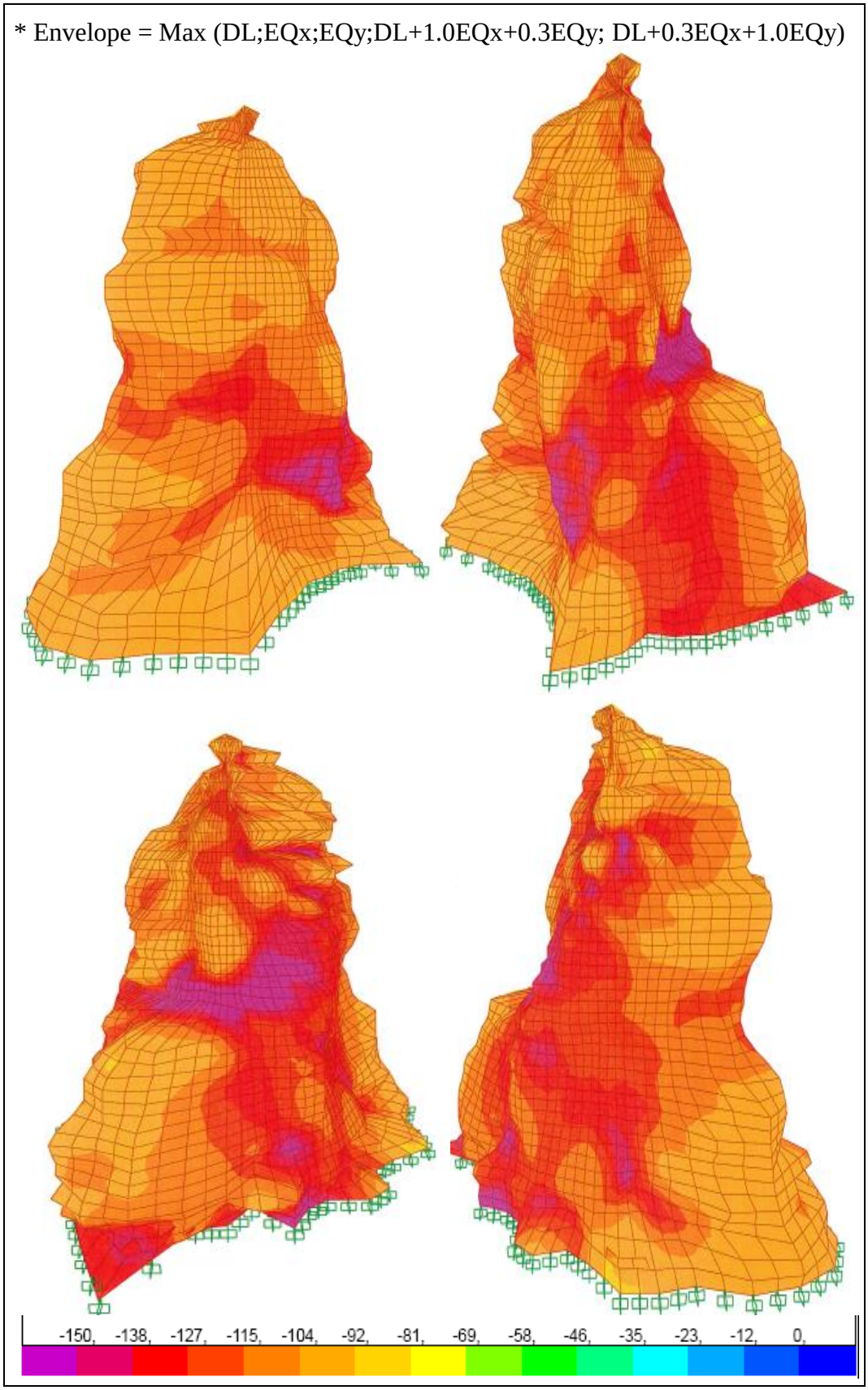

Figure 31 S23 *Envelope Min Stresses (kPa)

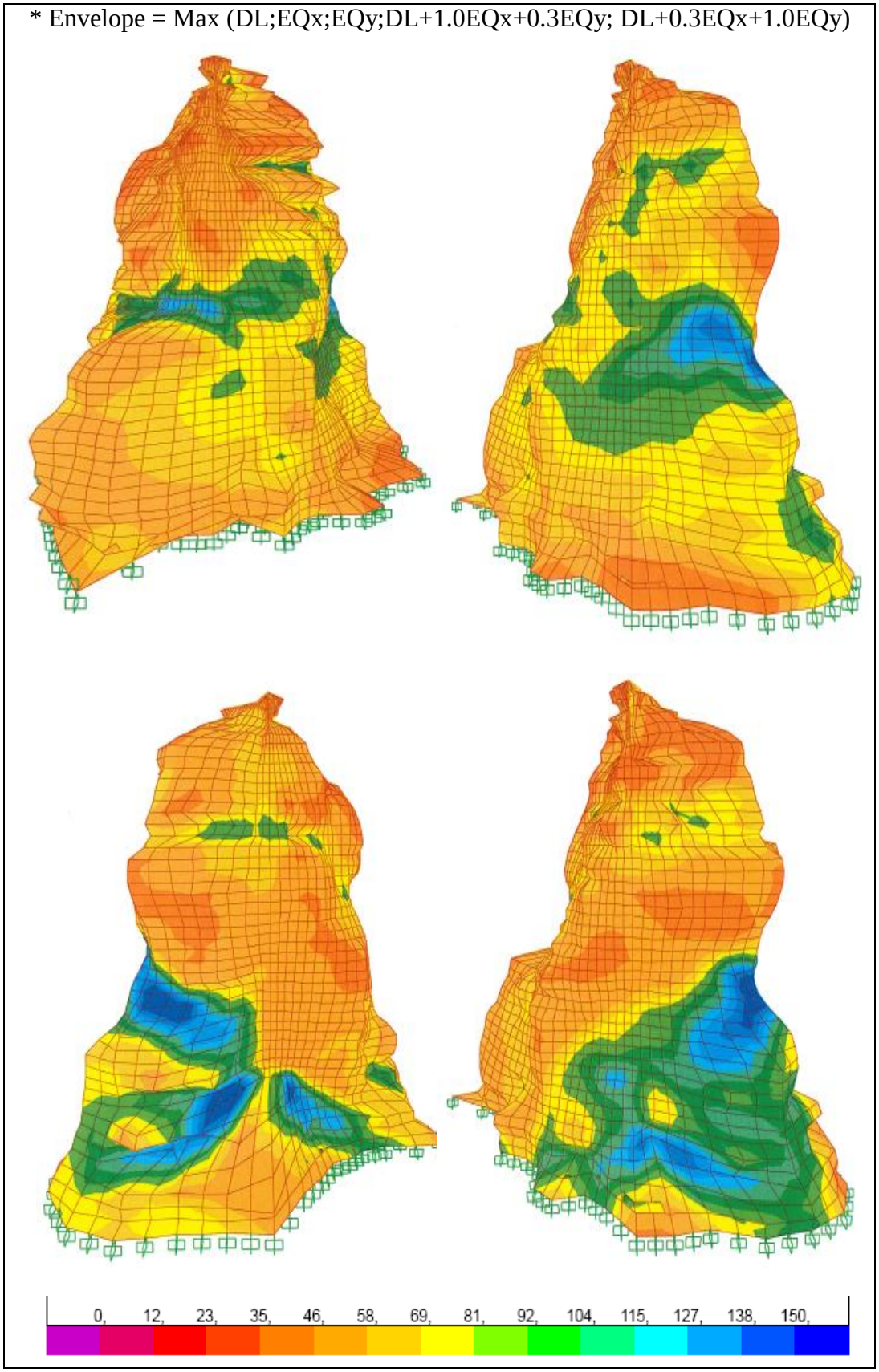

Figure 32 S23 *Envelope Max Stresses (kPa)

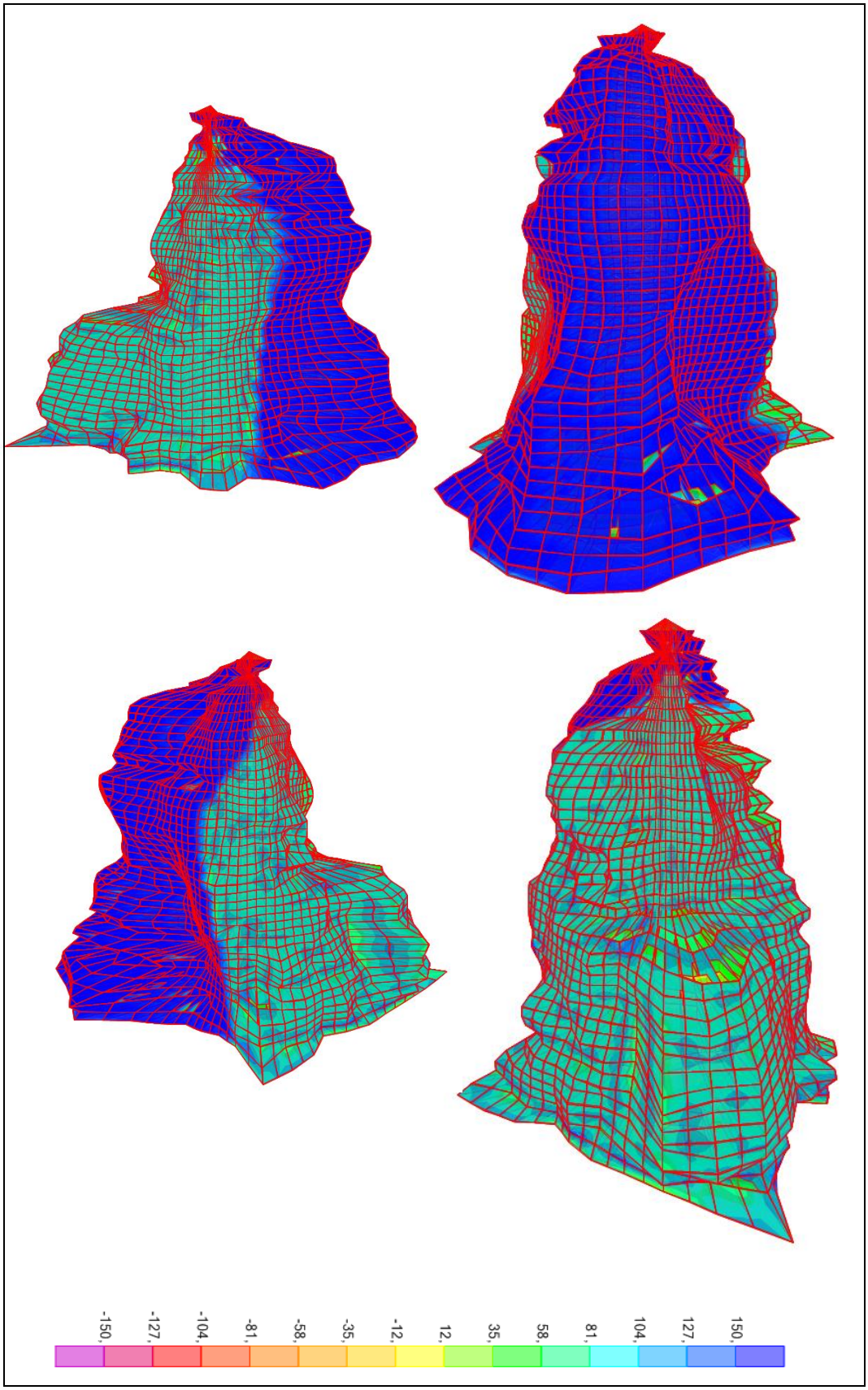

Figure 33 Von-Mises Stress Under Temperature Summer Loads

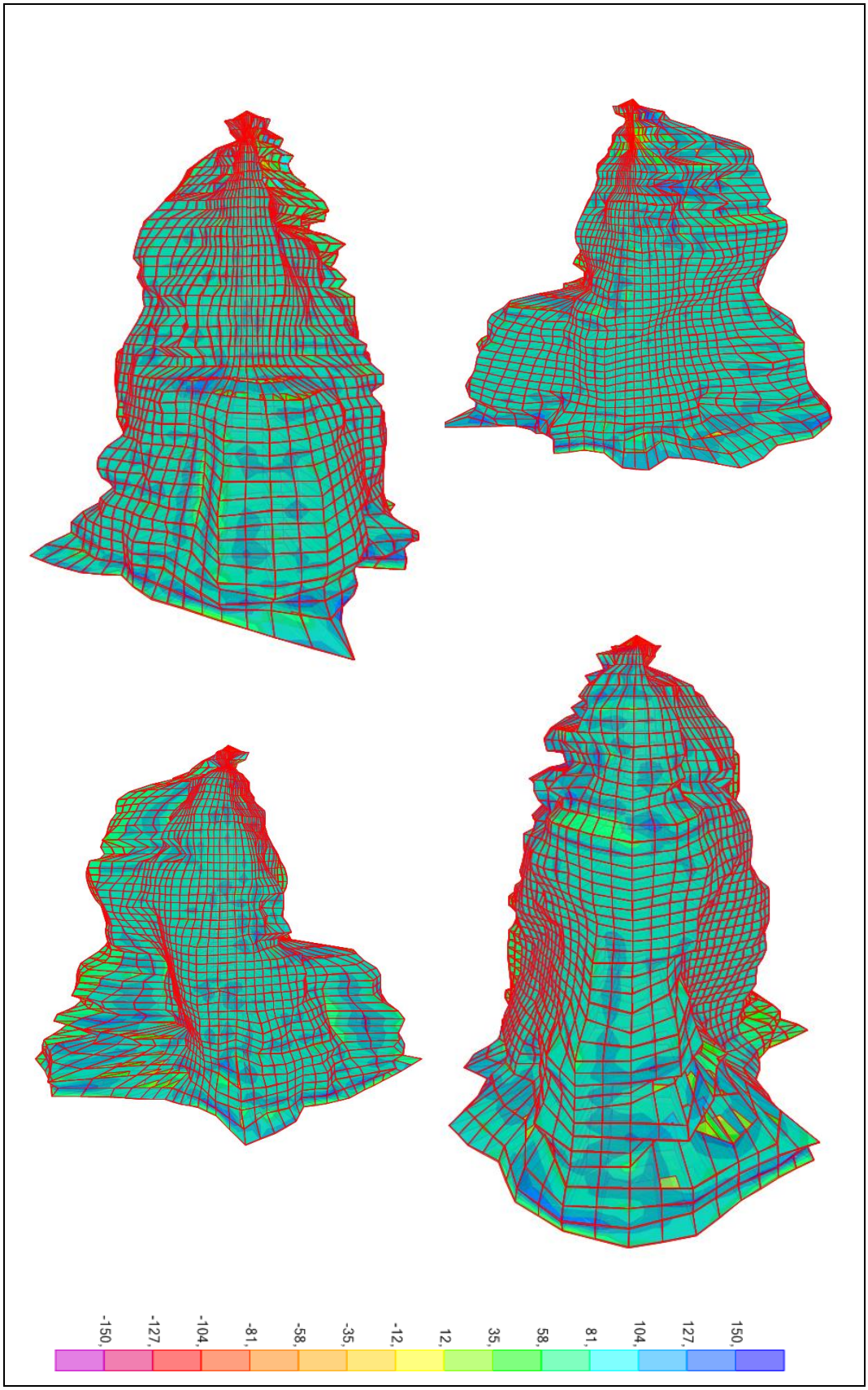

Figure 34 Von-Mises Stress Under Temperature Winter Loads

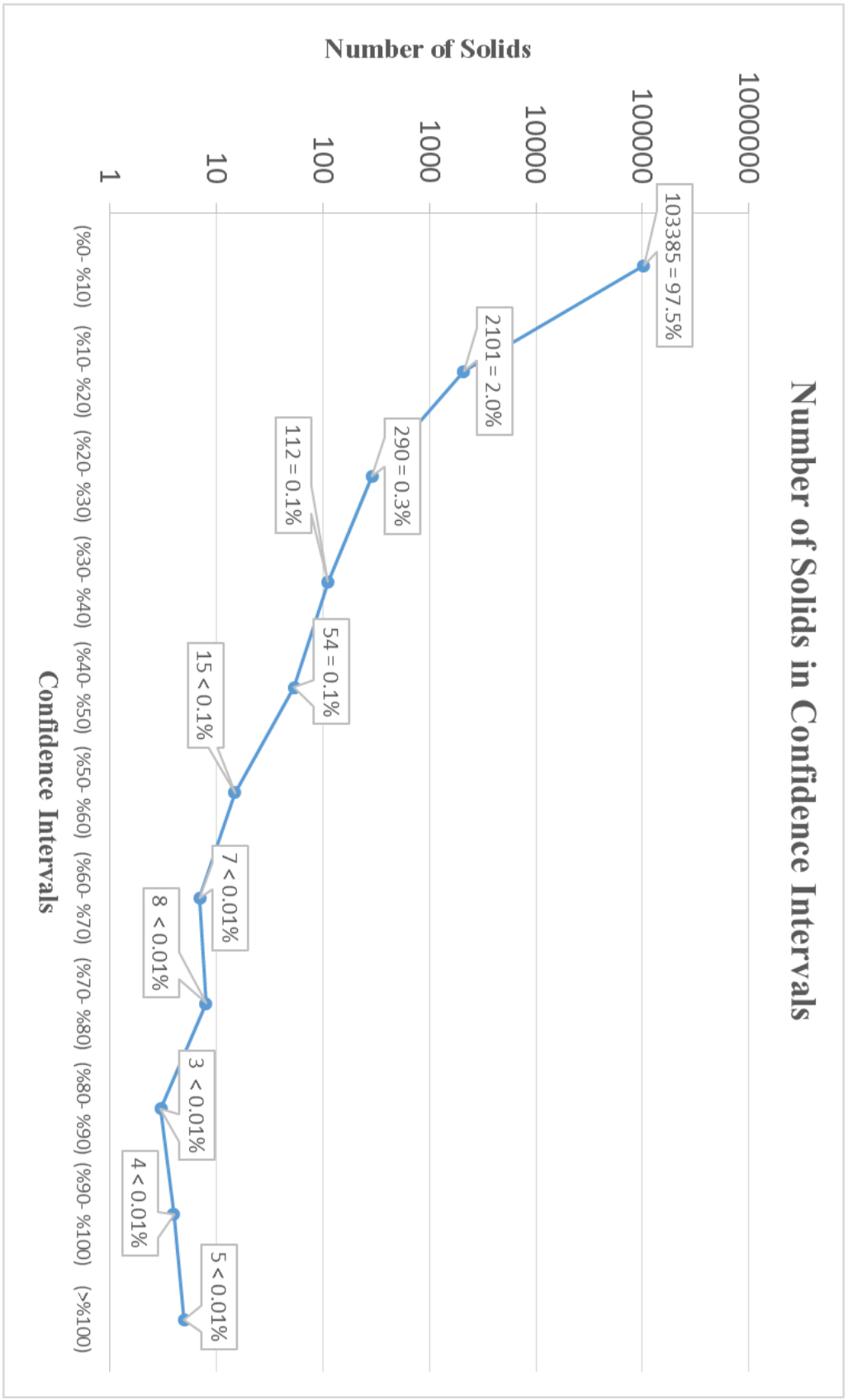

Figure 35 Number of Solids in Confidence Intervals According to Earthquake Analysis

CHAPTER 3

STRUCTURAL HEALTH MONITORING STUDIES ON THE CASTLE

3.1. Importance of Structural Health Monitoring for Historical Structures

The main reason for choosing Ortahisar Castle as a topic of study is protecting a historical structure and historical heritage. Protection of a historical structure does not only mean making analysis under several loads and determining behavior of the structure. Protection is also done by monitoring the structure and controlling structural condition of the structure for long term. Structural Health Monitoring (SHM) is subsidiary branch of structural engineering. SHM is a process of damage detection for long, short time period and, it is monitoring behavior of structures. If any damage indication was detected by SHM system, immediate measures can be taken to prevent progress of the damage to a point where the historic structure might get damaged beyond repair. The monitoring studies might also reduce the risk to public residing around or visiting the site.

There are five main reasons to monitor structures: The first reason is understanding the structures' behavior under different loads. Monitoring the current status of structural health is the second reason. The third reason is preventing any collapse by monitoring of degradations. Fourthly, learning existing structural parameters is a reason to monitor structures. Last reason is that structures with high level of importance and having important structural problems are monitored for safety. As it is mentioned at Section 1.3, there are not any structural design drawings, explained material type, and structural properties belongs to historical structures.

These types of uncertainness's increase the value of SHM for historical structures. Lima et al. (2008) mentioned that the importance of SHM is doubled up when consideration the conservation and behavior of historical heritage. Determination of damage localization for monumental historical structures can be very difficult because of extreme complexity and hyper static behavior of these structures (Damonte et al., 2007). Therefore, SHM system is installed to the Castle to monitor behavior of the Castle.

3.2. Sensor Types Used at Ortahisar Castle

Structural health monitoring system of the Castle consist of forty eight crack meters (LVDT), one accelerometer, one temperature & humidity sensor, one anemometer, one wind direction vane, one multiplexer, and one data logger.

3.2.1. Crack Meter (LVDT)

Linear Variable Differential Transformer (LVDT) is a sensor that measures change in linear motion of an object. LVDT converts mechanical motion to electrical signals to determine the linear motion. It consist of primary, secondary windings, and a core. The windings cover the core; however, there is not any connection between the windings and the core (Figure 36). When the primary winding is supplied with constant current, a magnetic region is created and position of the core is determined by created induced voltage at the secondary windings. The difference between induced voltages at the secondary windings is used to determine the change in linear motion. LPC150 is name of the model of LVDT used at the Castle. LPC150 can measure change in linear motion up to 150mm. Its linearity is ±%0.05 and its resolution is infinite. Its working temperature is between -20^{o}C and 80^{o}C. Displacement speed of LPC150 is 5 m/s. It can be supplied by 28 V DC Max.

Figure 36 Inside and Outside View of LVDT

3.2.2. Accelerometer

SHM system of the Castle has one accelerometer. The accelerometer is used to find natural frequencies of the Castle. Six field tests are done to determine the natural frequencies of the Castle by using the accelerometer. Therefore, an accelerometer is used for this purpose at SHM systems. The model of the accelerometer used at the Castle is AS-5GB by Kyowa. It is a biaxial acceleration transducer. Its rated capacity is ± 49.03 m/s^2. Nonlinearity of the accelerometer is ±1% RO. Rated output is 0.5 mV/V. The frequency response range of AS-5GB accelerometer is DC to 100 Hz at 23^{o}C. Sensitive accelerometers are used to measure ambient vibration for short term on-site tests, which can pick up vibrations at micro g level.

3.2.3. Anemometer

Anemometer is a structural health monitoring sensor which determines velocity of wind (Figure 37). The location of the anemometer is an important issue to get clear data about velocity of wind. At Ortahisar Castle, the anemometer is located at the top of the Castle. C3 Anemometer by Second Wind is chosen for the SHM system at the Castle. Its rated bearing pressure-velocity factor is 20. Rotor assembly moment of inertia of the anemometer is 92.2 x 10-6 kg-m^2. Transfer Function (m/s) is (Hz x 0.766)+0.324 and its accuracy is 0.1 m/s for the range 5m/s to 25m/s. The anemometer at the Castle is out of order.

Figure 37 C3 Anemometer

3.2.4. Wind Direction Vane

Wind direction vane is a sensor which is only used to determine the direction of wind. A voltmeter is located in main body of the vane. The vane generates an analog voltage output whose direction is rational to the wind direction when a stable DC excitation voltage is applied to the voltmeter. Model of the wind direction vane is NRG200P (Figure 38). NRG200P can be used for wind resource assessments, meteorological studies and, environmental monitoring. Its operating temperature range is between -55ºC and 60ºC. Its operating humidity range starts from 0 to 100% RH and lifespan of NRG200P is 50 million revolutions.

Figure 38 NRG200P Vane

3.2.5. Temperature and Humidity Sensor

Temperature and humidity are important factors that are effecting structural conditions. Temperature and humidity sensor is used to measure temperature and humidity. The structural health monitoring system of the Castle has one temperature and humidity sensor which is located at the top of the Castle with anemometer and wind direction vane. Temperature and humidity sensor measures temperature and humidity once in an hour. The measured data is transferred to data loggers for saving. APC temperature and humidity sensor is the brand of the sensor used. Its operating temperature is between -15^{o}C and 65^{o}C and, its operating humidity is between 0% and 95%. These limits are suitable for the Cappadocia Region whose environmental conditions are in these limits.

3.2.6. Data logger

A data logger is a device that record the data at structural health monitoring systems. Sensors at SHM system control the condition, create the data, and send it to data loggers. Data logger can be programmable which makes data in a shape. Ortahisar Castle has two data loggers and the data loggers have been already programmed. For instance, data obtained from LVDTs shows dimensions of crack clearly.

3.3. Location of LVDTs on the Castle

LVDTs are placed on the cracks which can have a determined role to change structural condition of the Castle. The cracks are not always at easy locations to place a LVDT (Figure 39 till 41). A special team, consists of mountaineers, is used during the installation of LVDTs.

3.4. Graphical Data Obtaining From LVDTs

LVDTs measure situation of a crack at that moment which cannot be used to understand behavior of the crack without any processing. Therefore, the measurement values are processed. The first measurement value is accepted as origin and it is subtracted from other values measured after the beginning. The result gives the condition of crack from the beginning. For instance; when the first measurement data, which is measured on 25th of April 2013 at 12:30 am, is subtracted from the data measured on 14th of February 2014, the result shows the change of crack width in that time period. After the subtracted is done, the result is used to draw a graph. X-axis of the graph shows time by half-hour intervals and Y-axis shows the result of subtraction. The figures 42 to 50 show the graphs of change of crack widths.

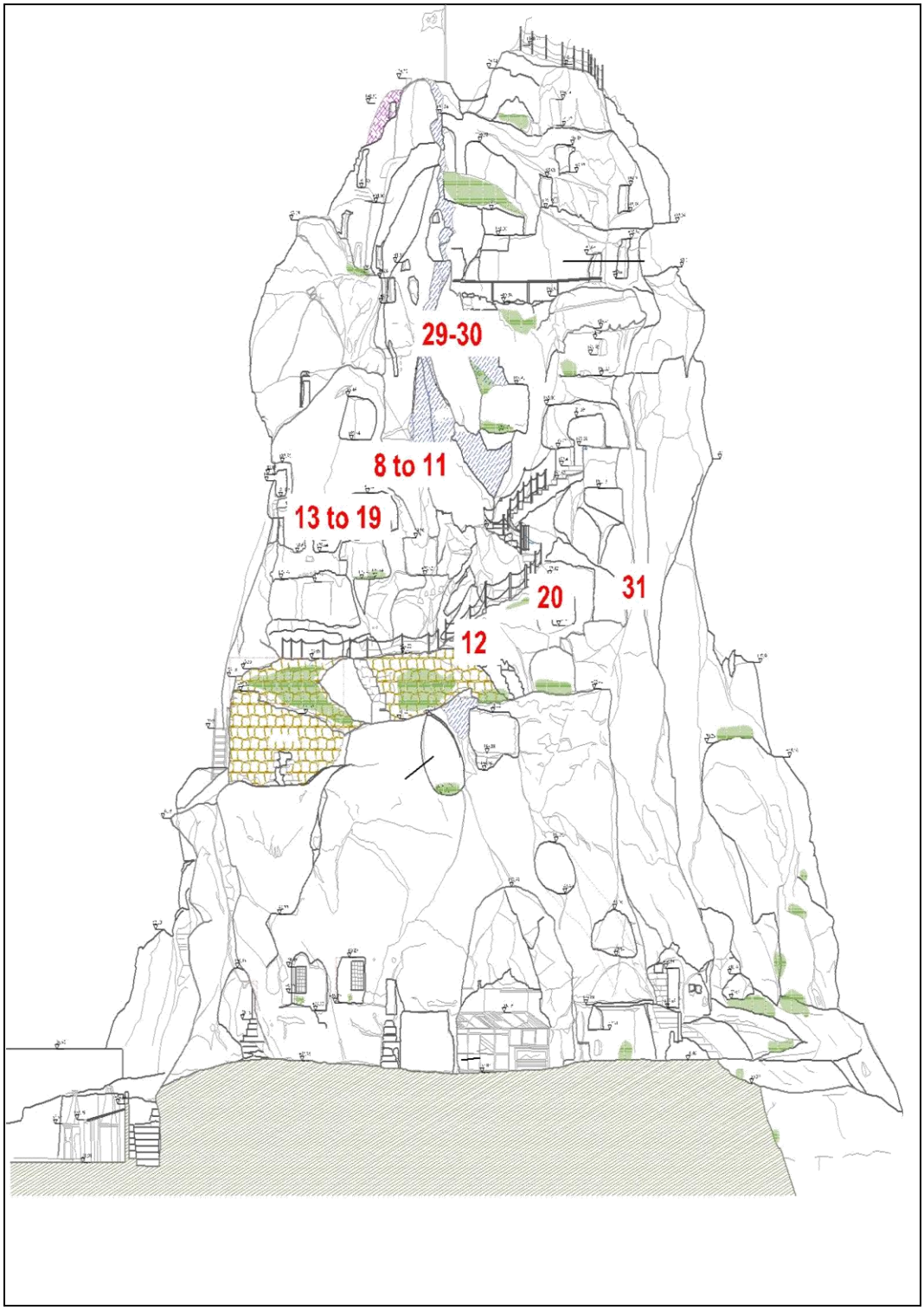

Figure 39 LVDTs Location from North of the Castle

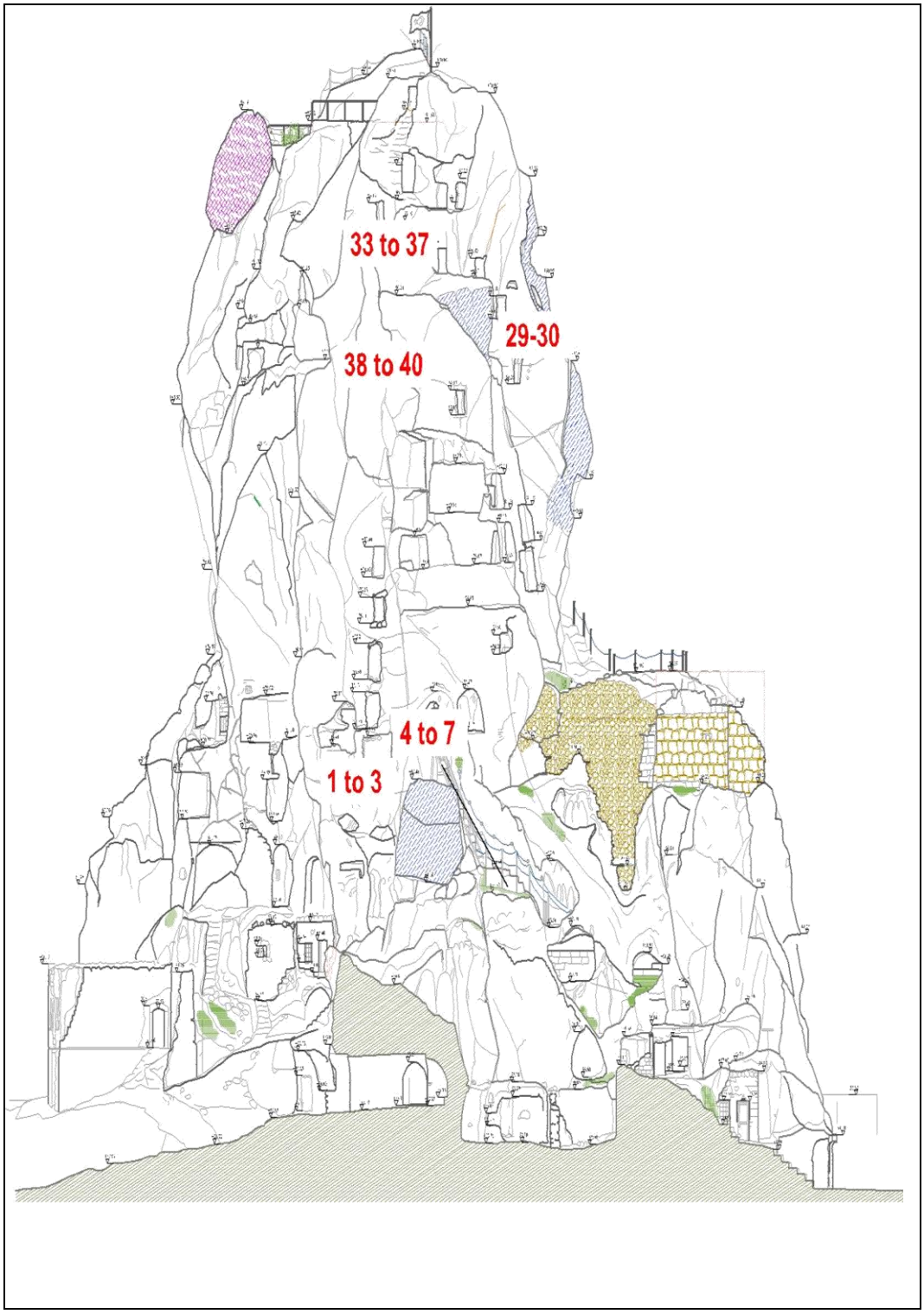

Figure 40 LVDTs Location from East of the Castle

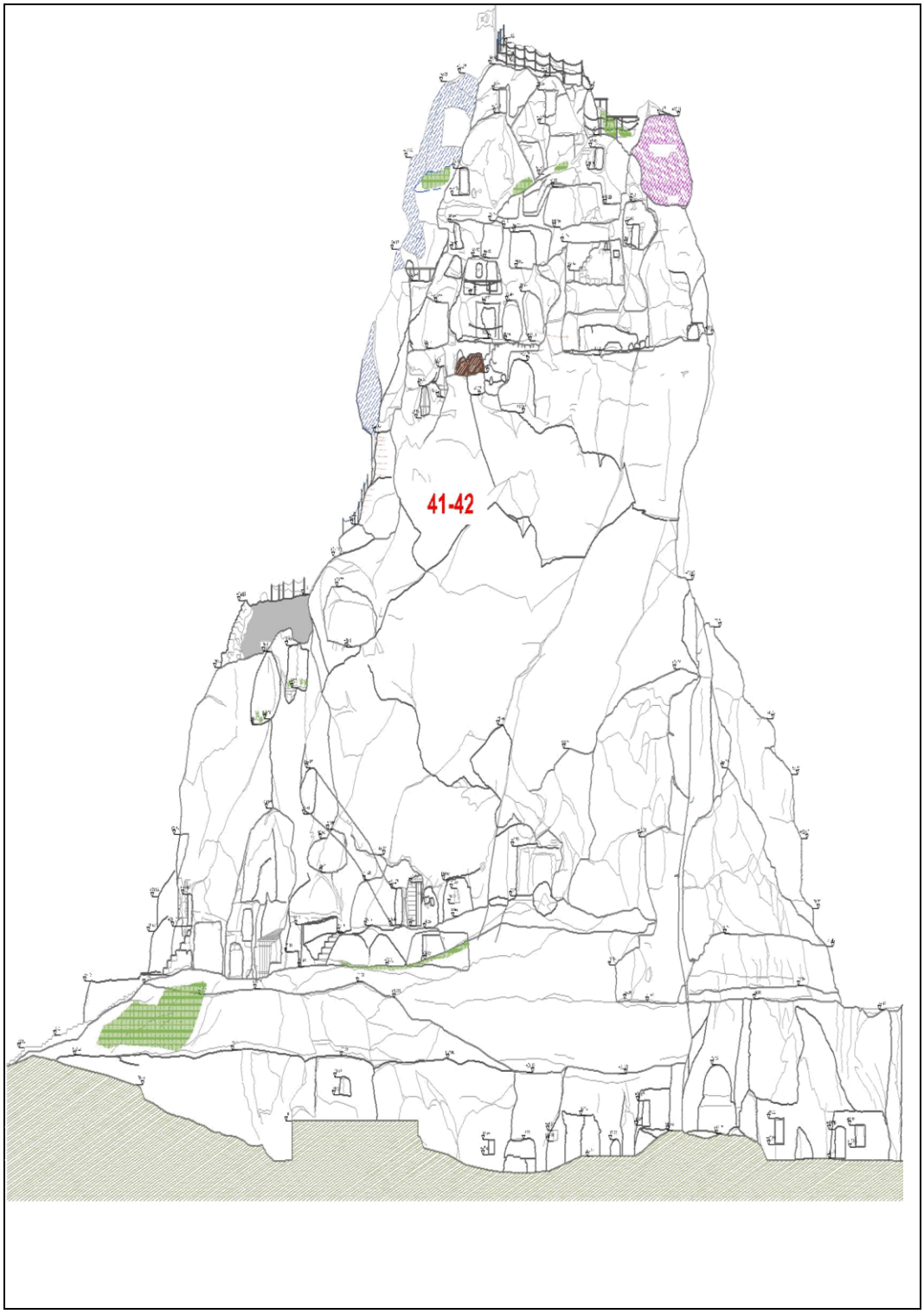

Figure 41 LVDTs Location from West of the Castle

3.5. Evaluation of Data Obtaining From LVDTs

Data obtained from LVDTs starts by 25th of April 2013 and finishes on 16th of January 2015. The LVDTs measure the crack dimensions every 30 minutes and send the measured data to the data loggers. First measurement is accepted as a starting point (origin point) and the first measured data is subtracted from other measurements, results give changes of crack widths at the provided time interval, graphs based on these change of crack widths are prepared, and evaluations are done according to the graphs.

No.1 Sensor (Figure 42) shows that the change of crack width is maximum 0.3 mm during the summer, spring, and autumn months of 2013 however on 28th of November 2013, the crack starts to enlarge 0.2 mm until 15th of December 2013 within 20 days. Since the crack width opening does not return back to its original value, it is considered to be a plastic deformation of the crack. The reason for large enlargement might be climatic change. Leaking water into the cracks would freeze in cold winter days because of low temperature and increment volume of frozen water might enlarge the crack width. After 15th of December 2013, there is not any large enlargement seen until 16th of January 2015.

The data obtained from No.2 Sensor, No.3 Sensor, No.5 Sensor, and No.31 Sensor is loud and questionable. No.10 Sensor, No.17 Sensor, and No.45 Sensor record data inaccurately. Therefore no evaluation was done for these sensors.

No.4 Sensor (Figure 42) shows that change of crack width is maximum 0.1 mm in summer, autumn, and spring. Similar to No.1 Sensor, 0.05 millimeter increment is shown in winter of 2013; however, this increment does not make plastic deformation. After winter of 2013, the crack dimensions return to normal but this return has two 0.05 millimeter increment in March of 2013 and one 0.05 millimeter increment in October of 2014. These increments thought not to cause plastic deformation. Another

0.1 mm increment is seen on 06th of January 2015, which apparently have not returned back to origin. More records for years is necessary to tell if deformations are plastic or not.

No.6 Sensor, No.8 Sensor, No.12 Sensor, and No.14 Sensor (Figures 43-44-45) show same behavior. The change of crack width is 0.1 mm again in summer, spring, and autumn. In winter of 2013 and 2014, 0.1 millimeter increment is recorded. There is one difference between two sensors which a 0.15 millimeter decreasing is shown on 10th of August 2013 at No.6 Sensor.

Recorded data by No.7 Sensor (Figure 50) is slightly noisy compared to the other sensors, which means the sensor is effected by environment while it is recording. It may be possible that the sensor is exposed to direct sunlight or cable noise problem might exist. No.7 Sensor can be accepted as a malfunctioning sensor.

The dimensions of crack, whose sensor no is 11 (Figure 44), do not show any change larger than 0.05 mm in spring, summer, and autumn months. However, 1.5 millimeter increment is detected in December of 2013. 1.5 millimeter increment ends up 1 millimeter plastic deformation which can damage the Castle in future. Moreover, 1 millimeter increment is recorded in January of 2015 again. Therefore, this crack is important and should be carefully monitored.

The obtained data from No.13 Sensor and No.18 Sensor (Figures 45 and 47) do not show any increment up to 0.10 millimeter. The change of crack width is in between -0.05 mm and 0.05 mm except from summer 2014. In summer 2014, 0.10 millimeter decreasing is recorded however this change does not result with plastic deformation which makes the change stable.

No.15 Sensor and No.16 Sensor (Figure 46) behave the same in summer, autumn, and spring months. The change of crack width belongs to that months is in between -0.1 mm and 0.1 mm. The difference between two sensors are occurred in winter months. The changes of crack width reading from No.15 Sensor is maximum 0.3 mm in winters and they are elastic deformation. However, the changes of crack width belongs to No.16 Sensor reach to 0.4 mm in winters and a permanent plastic deformation of about 0.1mm is observed between summers of 2013 and 2014.

No.19 Sensor (Figure 47) shows that the change of crack width is in between 0 mm and 0.15 mm. In winter of 2013, the change of crack width reaches the maximum value which is 0.2 mm; however, it comes back to its original values, similar to the case in in January 2015. There are no plastic deformations that can be detected.

The shapes of graphs obtaining from No.20 Sensor and No.30 Sensor (Figures 48 and 49) are similar to a sinus function. The crack widths belonging to that sensors increase in winter months and the crack width at No.20 Sensor reaches up to 0.35 mm. Similarly, the crack width at No.30 sensor reaches up to 0.50 mm in winter of 2013. On the other hand, the crack widths are decreasing in summer months up to -0.10 mm at No.30 Sensor and -0.20 mm at No.20 Sensor but these changes do not create any plastic deformations.

No.29 Sensor (Figure 48) shows that the crack width increases in winter months and decreasing in summer months. However, in summer of 2014, the crack width decreases until -0.30 mm. 0.30 mm decreasing is the highest value that all sensors record and this decreasing generates -0.1 mm plastic deformation comparing summers of 2013 and 2014.

The data obtaining from No.32 Sensor (Figure 49) is different from other sensors. The change of crack width is constant between 0.00 mm and 0.06 mm from

April, 2013 to November, 2014 and looks very noisy. On 16th of November 2014, the crack width suddenly decreases 0.10 mm. The reason for this decreases is not known but this type of changes can cause permanent damage. When cracks change very abruptly and stay in this way may also be indication of birds or other animals touching the sensors. The change of channel 32 follows the same pattern it had before the abrupt jump in November 2014.

According to readings belong to No.44 Sensor (Figure 50), the crack width changes between 0.15 mm and -0.25 mm. The crack width increases in winter months and decreases in summer months. Plastic deformation is not seen at this crack.

Sensors with numbers 9, 21, 22, 23, 24, 25, 26, 27, 28, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 46, 47, and 48 have problems. The connection between these sensors and data logger is probably missing or damaged; therefore, the data obtaining from these sensors is empty.

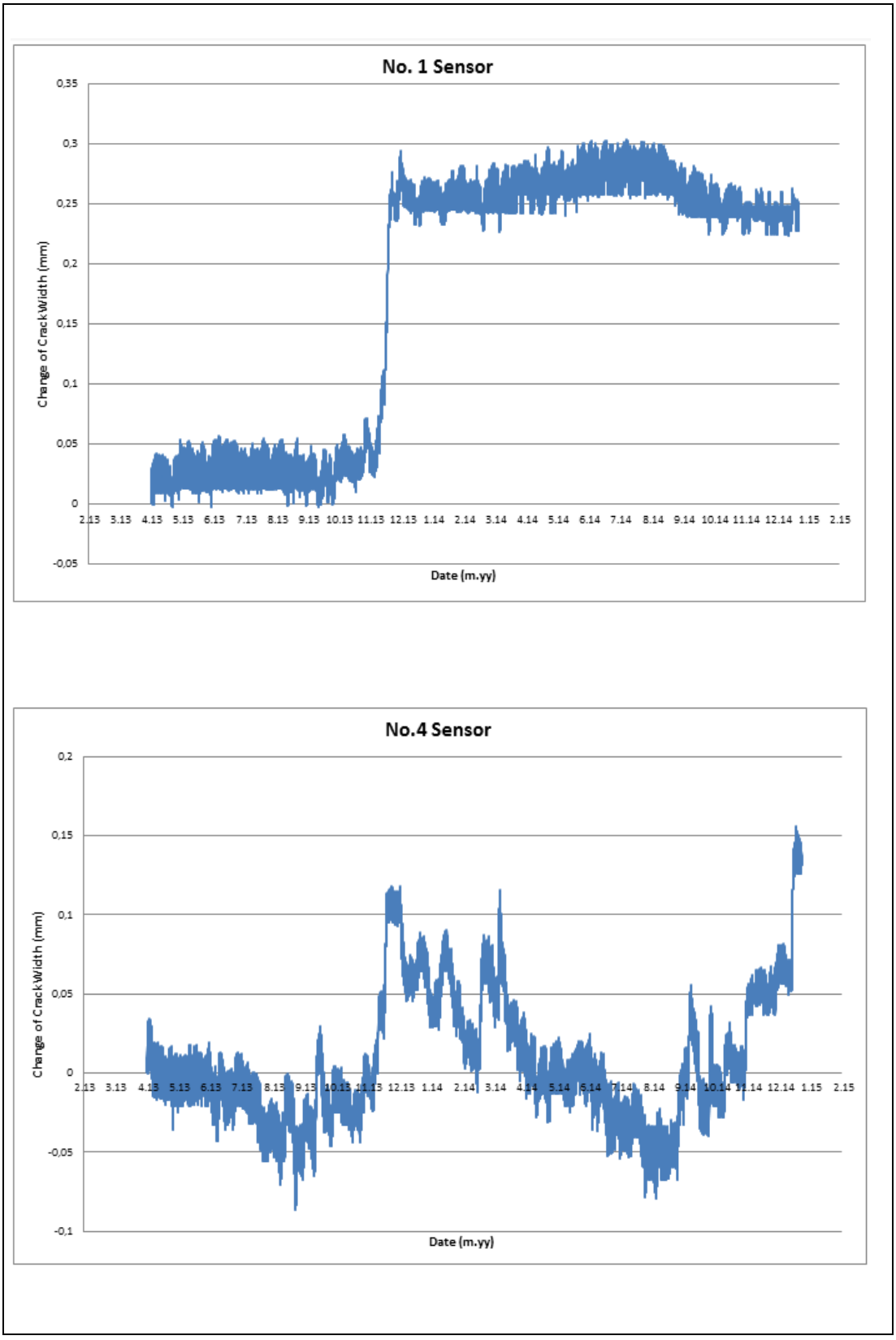

Figure 42 Sensors No.1 No.4 Change of Crack Width

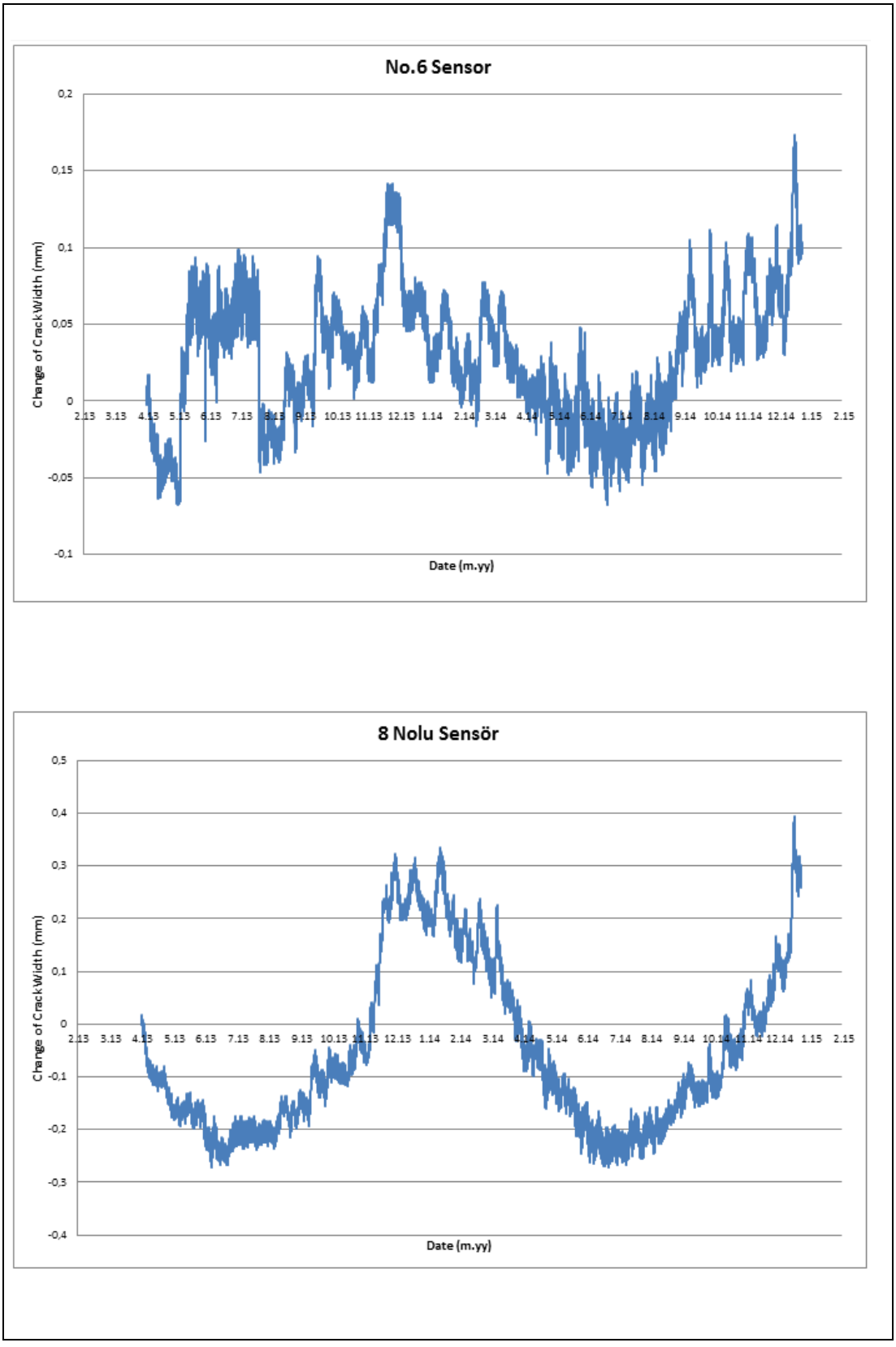

Figure 43 Sensors No.6 No.8 Change of Crack Width

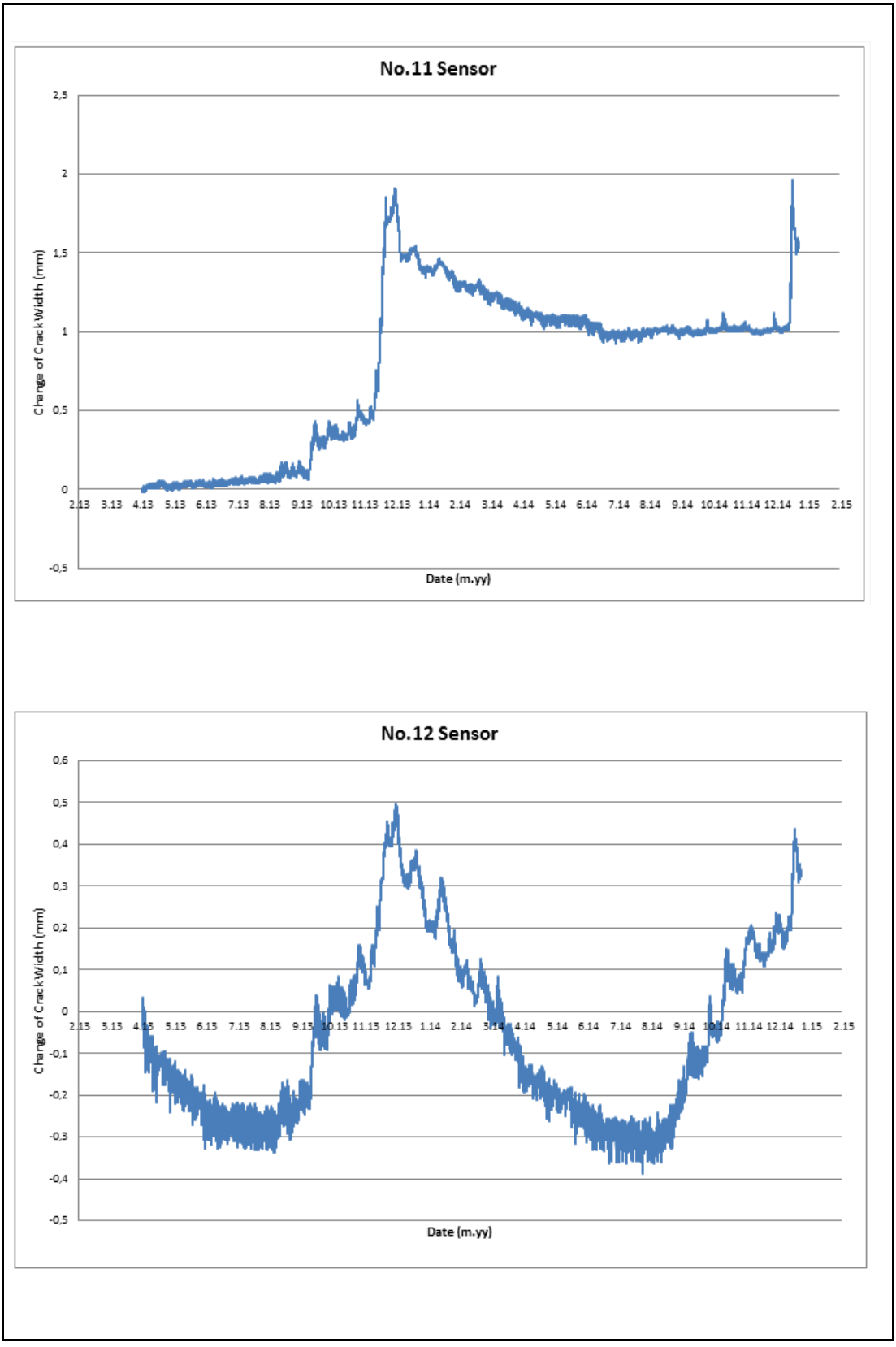

Figure 44 Sensors No.11 No.12 Change of Crack Width

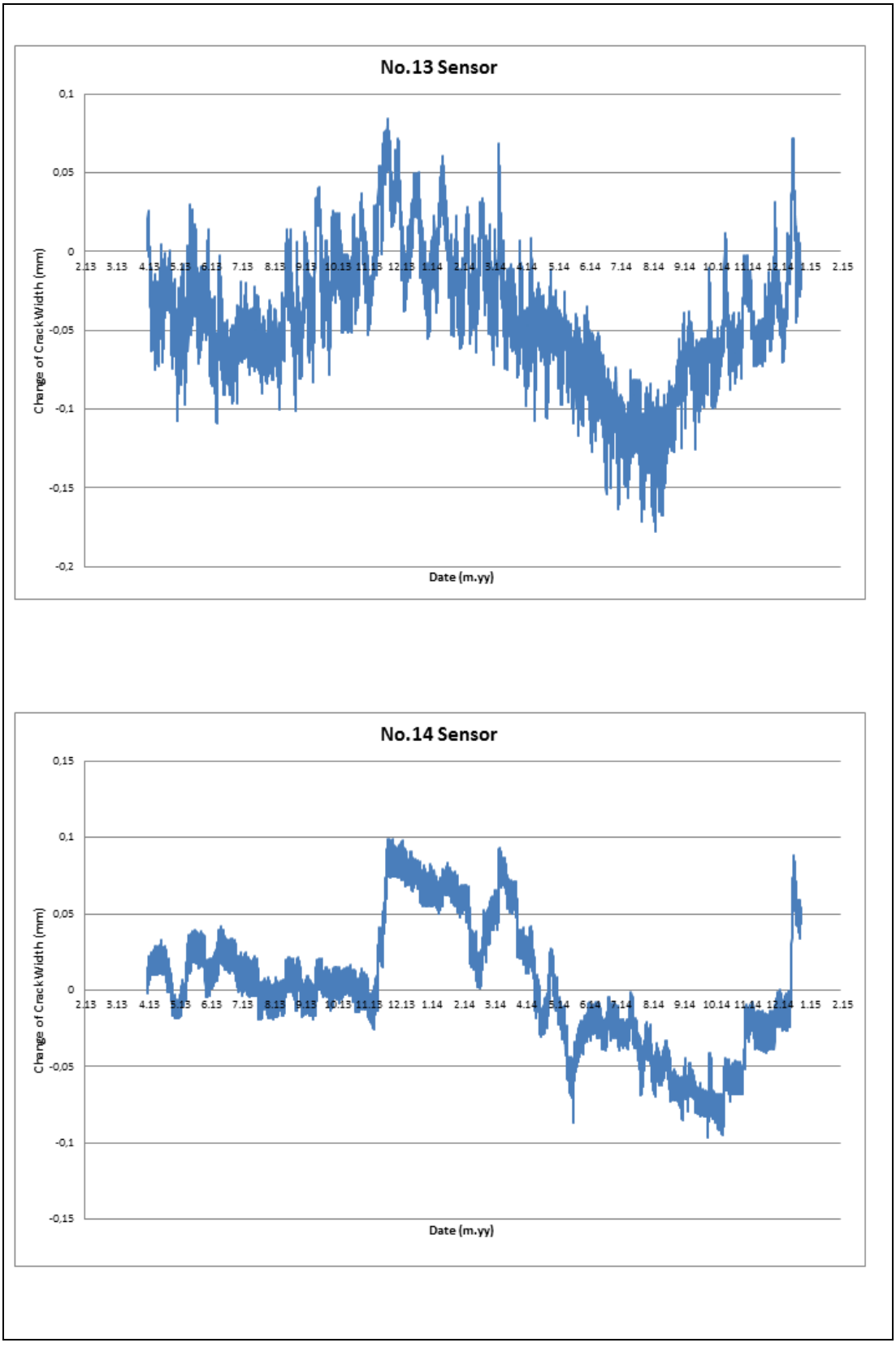

Figure 45 Sensors No.13 No.14 Change of Crack Width

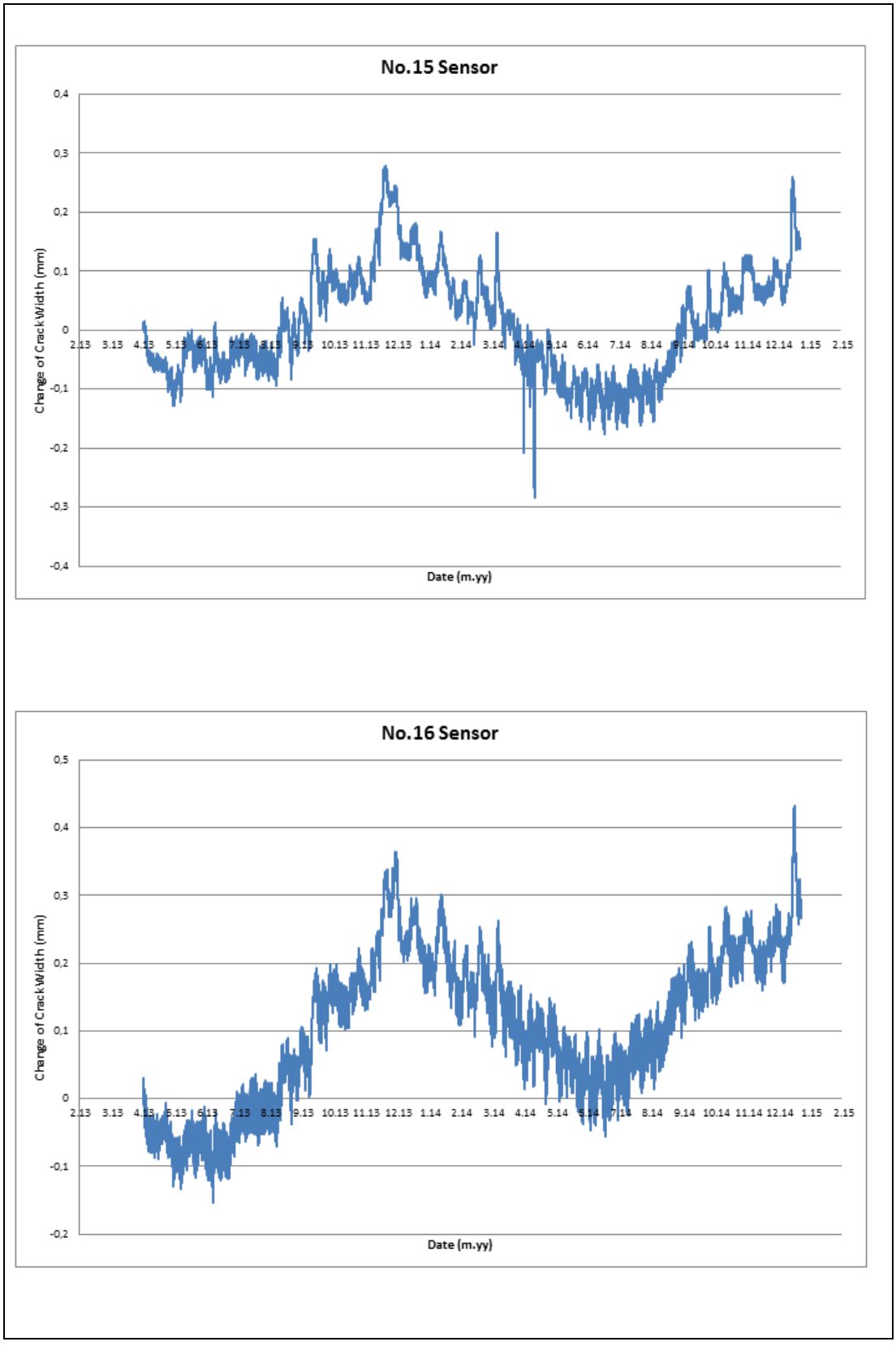

Figure 46 Sensors No.15 No.16 Change of Crack Width

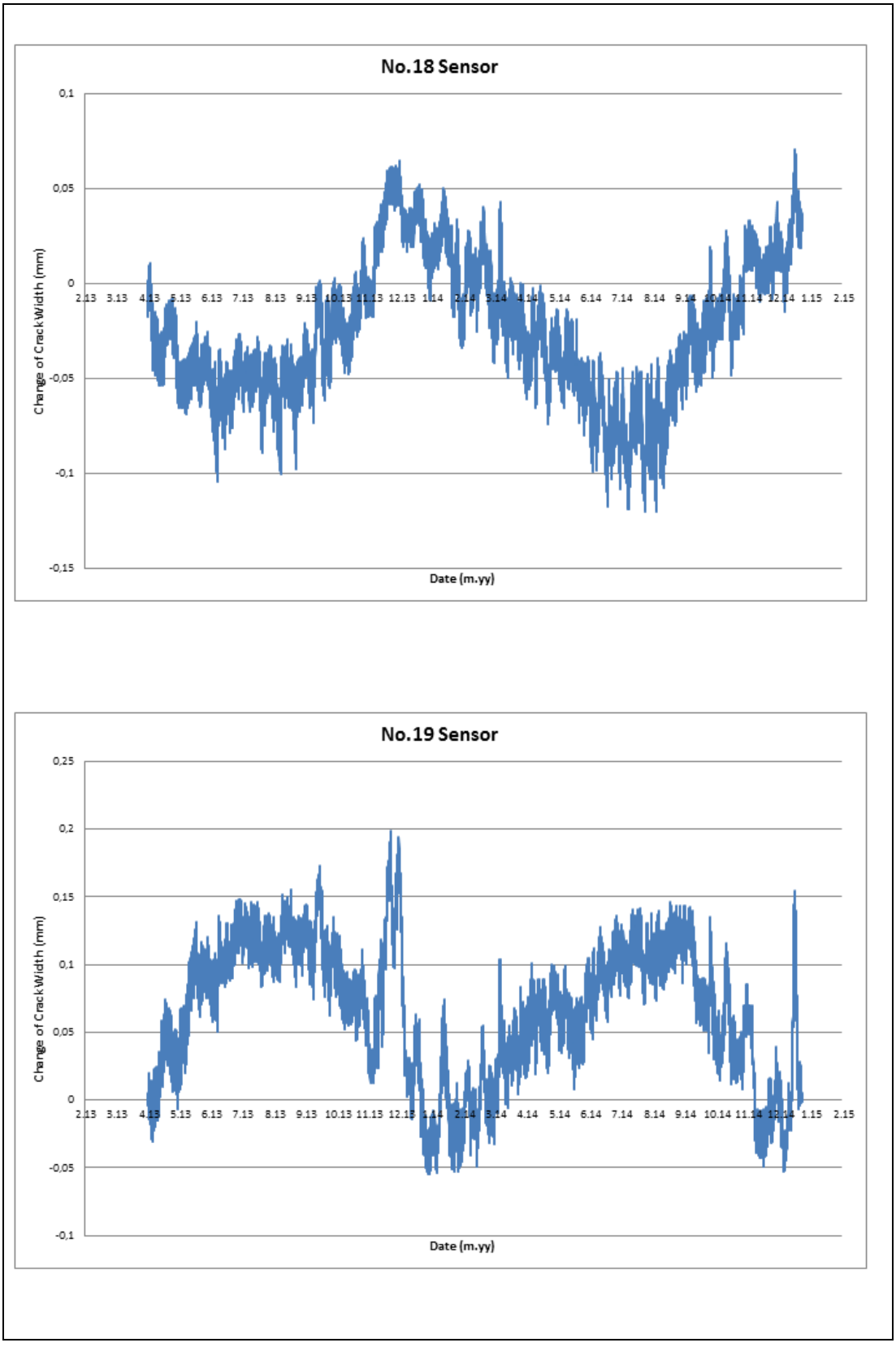

Figure 47 Sensors No.18 No.19 Change of Crack Width

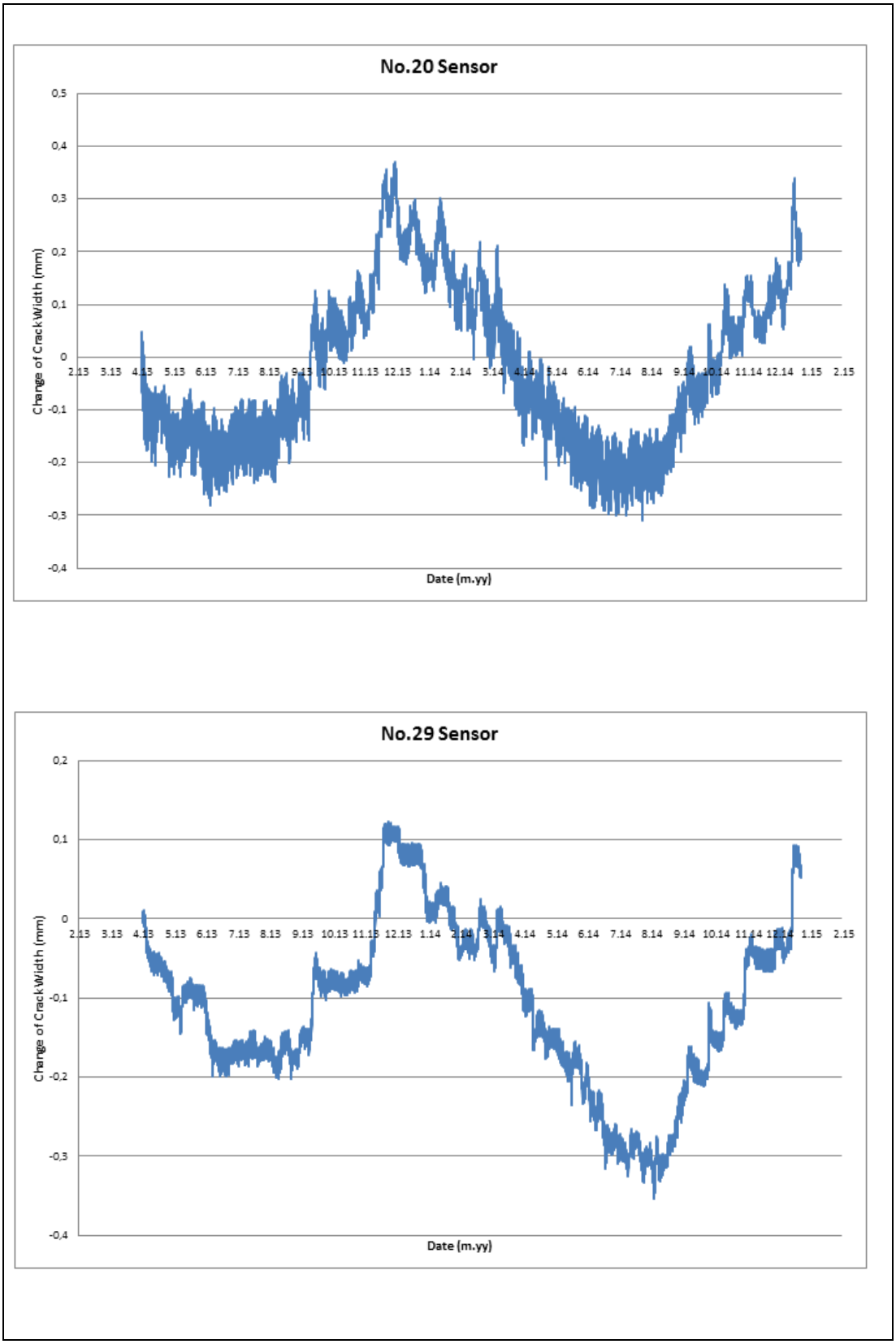

Figure 48 Sensors No.20 No.29 Change of Crack Width

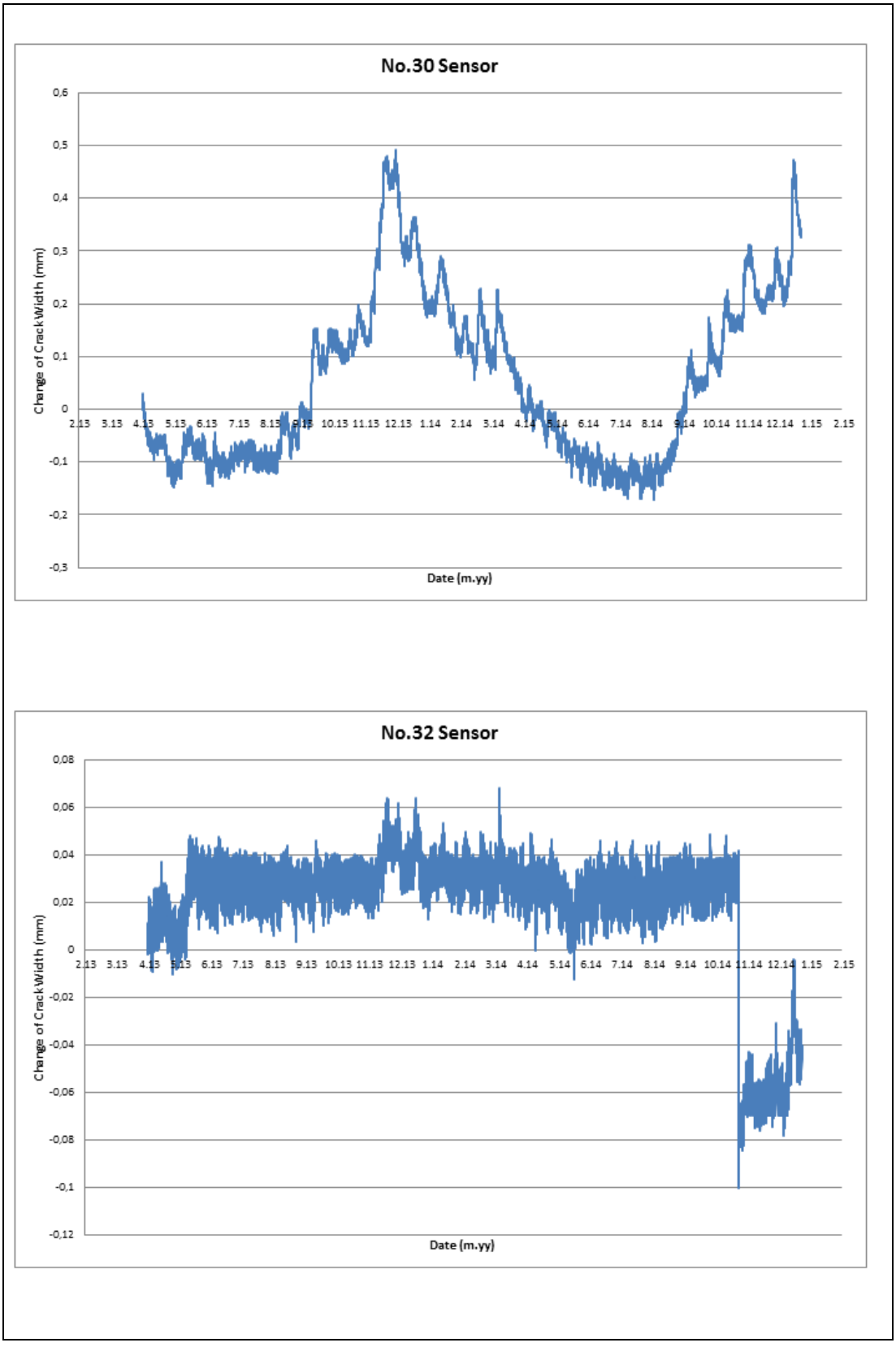

Figure 49 Sensors No.30 No.32 Change of Crack Width

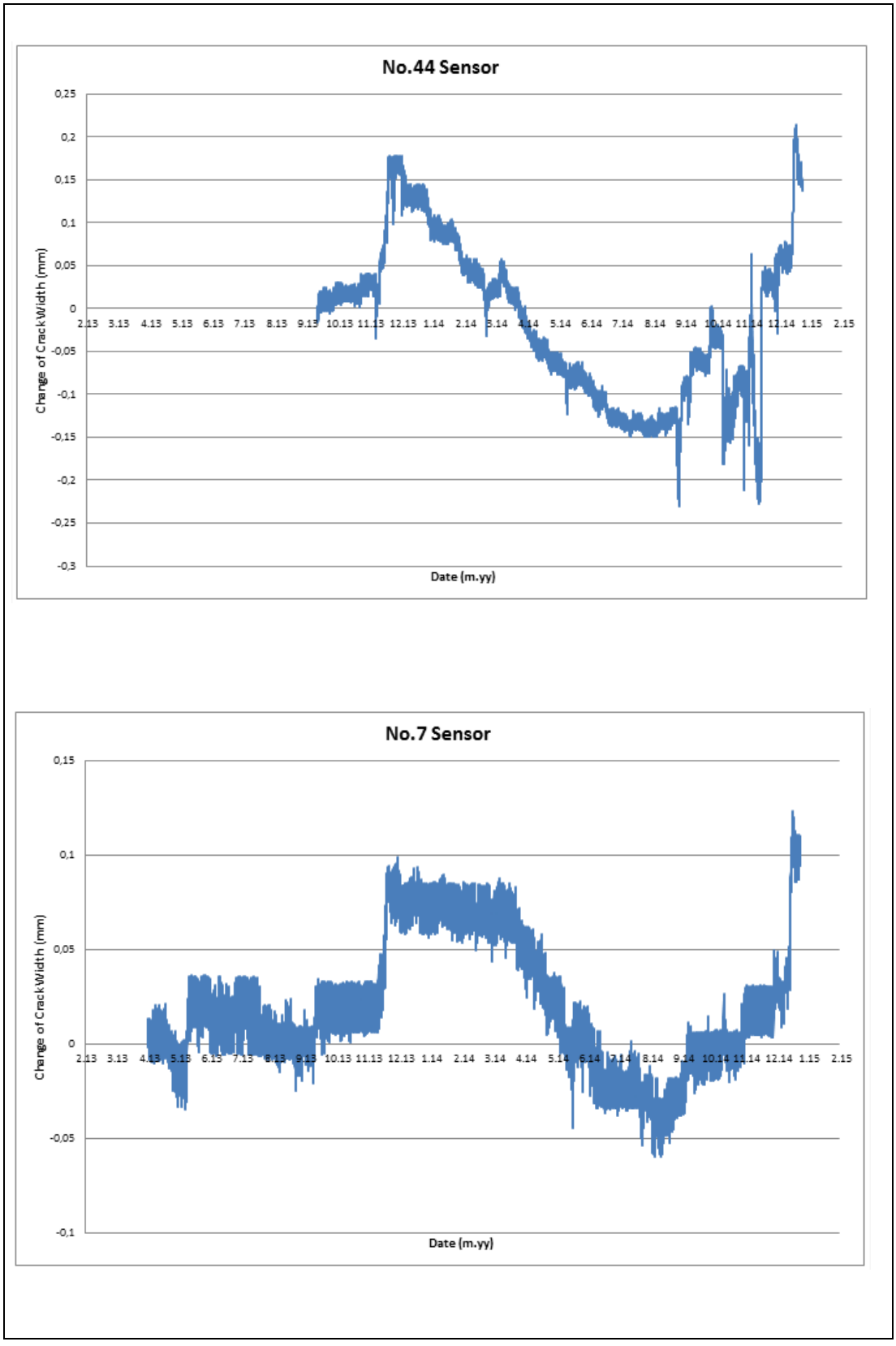

Figure 50 Sensors No.7 No.44 Change of Crack Width

CHAPTER 4

CONCLUSION

This thesis mainly consists of two main topics: The first topic is three dimensional (3D) Finite Element Modelling (FEM) of the Castle, for the purpose of structural evaluation against earthquakes, wind, and temperature forces. The second topic is the evaluation of a large sensor structural health monitoring network collected data for 48 crack meters, one accelerometer, one temperature & humidity sensor, one anemometer and one wind direction vane. For the first part of the thesis, 3D FEM of the Castle was generated by using 3D laser scanning data for dimensions of the Castle, field test results for material properties of the Castle were used, and dynamic test results to utilized to calibrate the FEM. Earthquake loads and wind loads were applied to the Castle with 183 different load combinations, which differ from each other by the applied force direction angle to the Castle. This was achieved by applying earthquake and wind loads to the Castle at every 10^{o} angle increments. The result of the analyses were post-processed to find principal axes stresses and checked according to the Coulomb-Mohr and Modified-Mohr Theories. For the second part of the thesis, the data obtained from the sensors on the Castle were evaluated. The evaluation was mainly plotting data on time vs amplitude graphs for 48 LVDTs, which have measured the crack widths on the Castle at critical locations.

The results of the first part shows that the FEM with fixed supports have only 5 solid members out of 105984 members have slightly exceeded the principal tension capacity of the material. These members that fail at the most critical earthquake loading direction combination are located at the very top of the Castle and may cause

some stones to fall down but would not create a substantial damage to the overall integrity of the Castle since 5 out of 105984 corresponds to only 0.005% of the Castle. This is a very small percentage and the Castle can be accepted castle against earthquake. Majority of the members forming the Castle have relatively low stresses developing on them during worst possible loading scenario; 97.5% of all members have stresses smaller than 10% of their material capacity (Figure 35). Furthermore, the FE model with vertical springs at the base to model flexibility of the underlying ground has yielded no members exceeding their material capacity. Therefore, the members of the FEM forming the Castle has stresses smaller than the considered material ultimate capacity. A factor of safety (FS) evaluation is difficult to make although 97.5% of all members have less than 10% of their strength limit. Most of the members that have higher stress concentrations are located at the top of the Castle, which is in part due to the irregular shape of the members with high aspect ratios. The analytical model was also used to analyze stresses under wind loading since the height of the Castle is about 60 meters which might generate large wind loads. However, wind loading generates even smaller stresses for wind load when compared with earthquake load acting on the Castle. The results of stresses generated by temperature change during summer and winter are also considered in this study. Most of the members had stresses within limits for temperature loading made by hand calculation, small FEM, and large Castle model. Only one solid member which is located at the top of the Castle and has irregular shape has passed material tensile capacity. FEM with high mesh density has better results compared with the hand calculation but not possible to model in the Castle scale due to computer limitations. The cracks forming at the outer surface of the castle could not be linked to EQ or temperature related loads; the wind load is also irrelevant. Therefore, the crack formation can be linked to weathering effects of wetting and drying cycles, freeze and thaw cycles, and preexisting cracks in tuff material during its geological formation phase. Monitoring of crack widths over long periods would reveal more information about how they progress and what are the parameters that effect their width growth.

As it was mentioned at Chapter 1, the outer surface of the Castle has cracks, which were being monitored by use of limited number of LVDTs. LVDTs measure

the crack width changes with high precision (0.01mm) at every 30 minutes. The thesis evaluated the collected data measured between 23rd of April 2013 and 16th of January 2015, which is about 1 year and 9 months. The evaluation showed that most of the LVDTs have malfunctioned (17 working out of 48); however, the working LVDTs showed important results. The crack width changes should be monitored for the remaining life of the Castle since seasonal environmental effect play an important role on the crack width and safety of the visitors may be improved by monitoring and alarm systems. If cracks are monitored over shorter periods (such as months), seasonal changes may be misinterpreted as structural changes.

The cracks open and close on seasonal and daily cycles because of temperature changes. The cracks may also be filled by dust and small sand particles making it difficult to close and generates additional stresses. This may be another mechanism for the crack widths to increase over time. The meteorological changes also have other effects on crack width changes such as freezing and thawing, which might permanently change the crack width. The deformations that return to their original values are considered as "elastic deformation" while permanent deformations that does not return to their original values are considered as "plastic deformations". For example, cracks of LVDT-01 (Figure 42a) and LVDT-11 (Figure 44a) show permanent plastic deformations. The malfunctioning LVDTs should be repaired or replaced, the monitoring system should be maintained and monitored continuously to detect growing cracks in time and to take timely precautions to protect the Ortahisar Castle as a valuable cultural heritage structure as well as ensure safety of visitors and local people around the castle from rock falls and similar disasters.

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