III. STRUCTURAL STABILITY AND EARTHQUAKE VULNERABILITY

## ***<u>Location of Nemrut Dag with Emphasis on Seismic Issues</u>***

The artificial tumulus of Nemrud Dagi, a World Heritage Site, is located within boundaries of Adiyaman City at 47.73.47E and 420.39.24N UTS global coordinates (Figure 1). Turkey exists in the junction of many plates as shown in Figure 2. These plates form numerous active fault zones, which have the capability of generating intensive earthquakes. Nemrut dag is located very close to the East Anatolian Fault (Figure 3). The distance to the fault line can be approximately calculated using the Adiyaman and Kahta as reference points, then extrapolating the distances on the zoomed active fault maps as shown in Figure 4(c). As seen from the figures, the site is located very close, 5 to 10 km proximity, to the East Anatolian Fault, which is seismically active.


**Figure 1 Road Map of Adiyaman with Shown Distances**

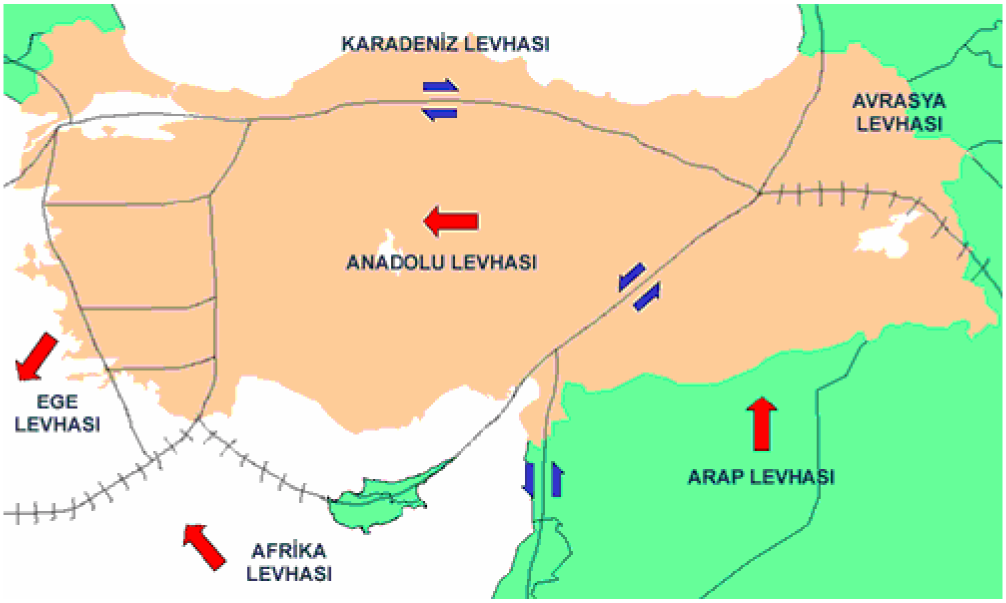



**Figure 2 Major Plates in Turkey**

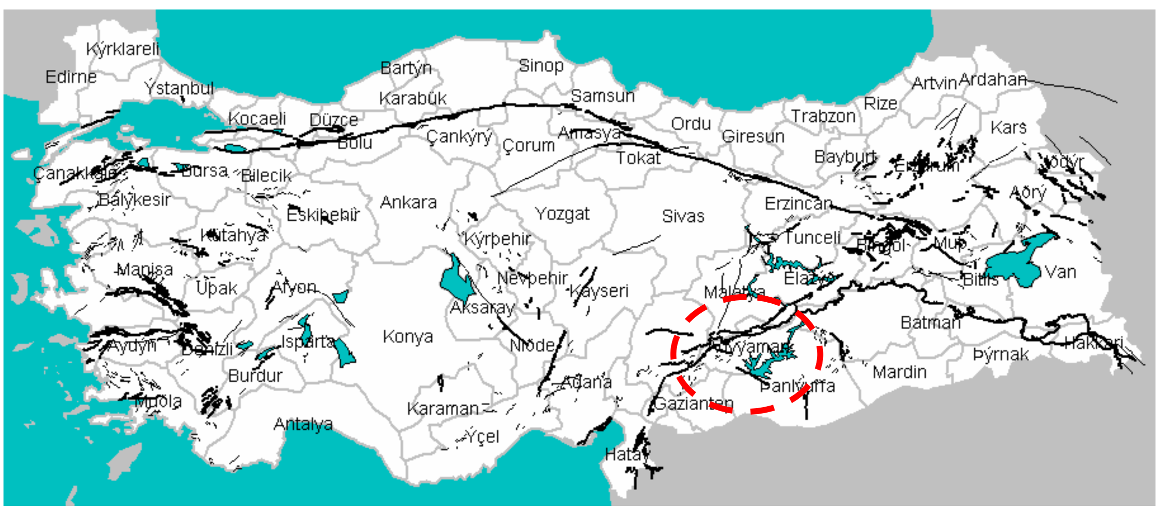
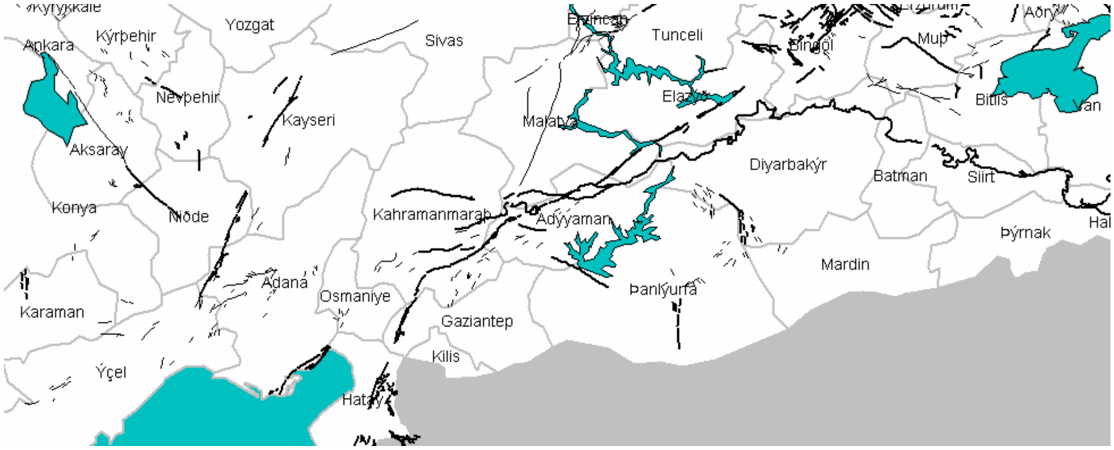
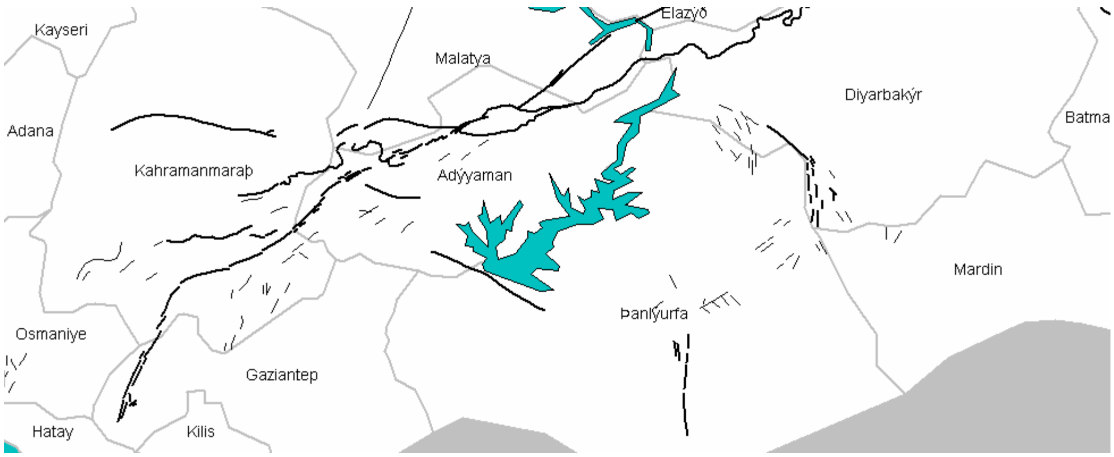


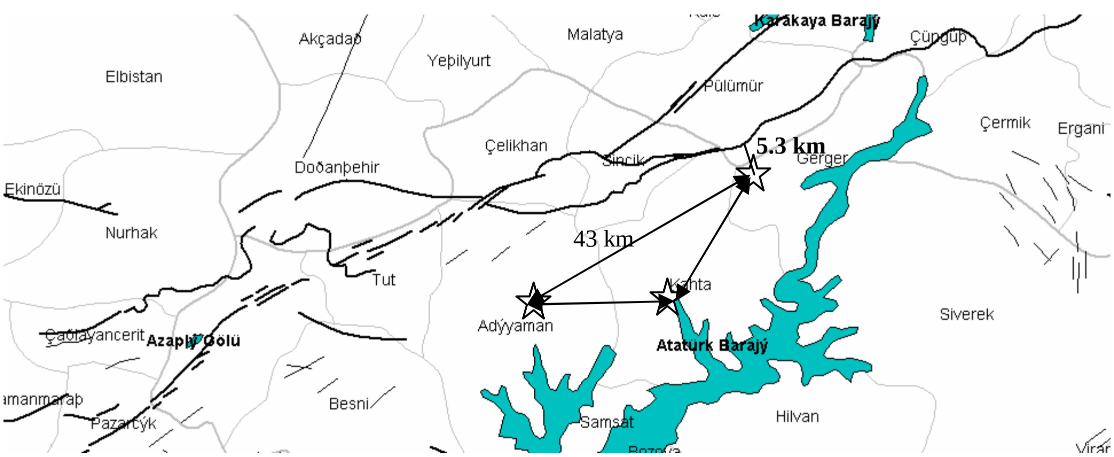

**Figure 3 Major Active Faults in Turkey**




**(a)**




**(b)**




**(c)**

**Figure 4 Location of Nemrut on Major Active Faults Map of Turkey (zoomed)**

The activities recorded on the East Anatolian Fault can be seen using the *earthquake location and magnitudes* map from USGS database for 3.0 to 9.9 and 4.0 to 6.9 ranges in Figure 5 and

Figure 6, respectively. The Nemrut Site is marked with a ‘star’ in both figures. As clearly seen from these figures, the faults are seismically active and capable of generating large earthquakes.

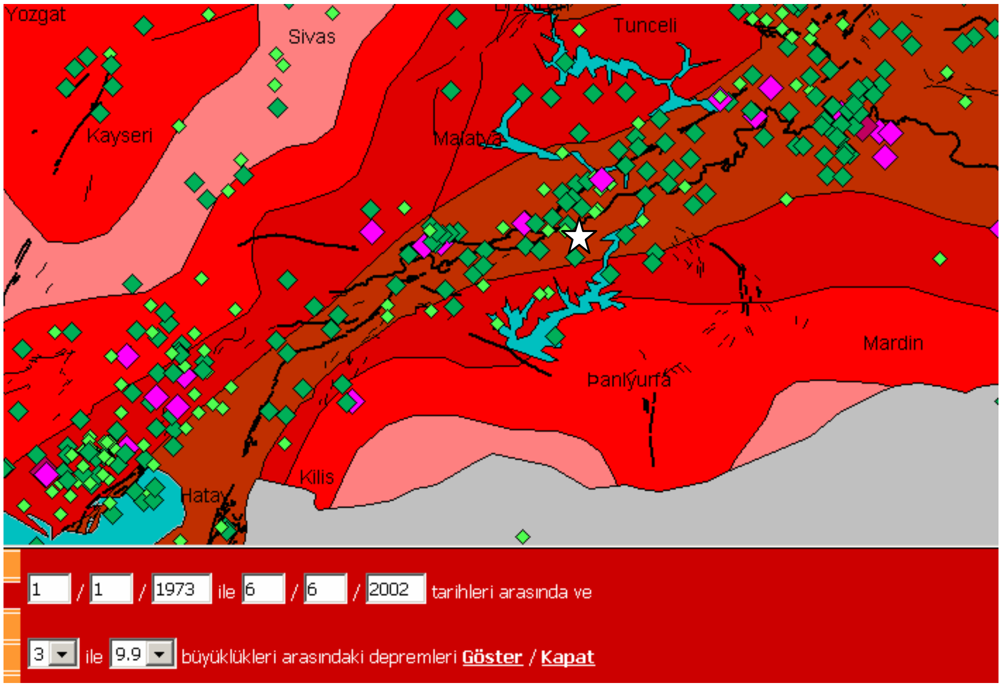



**Figure 5 Earthquakes in the Region Since 1973 for Magnitudes Between 3.0 and 9.9**

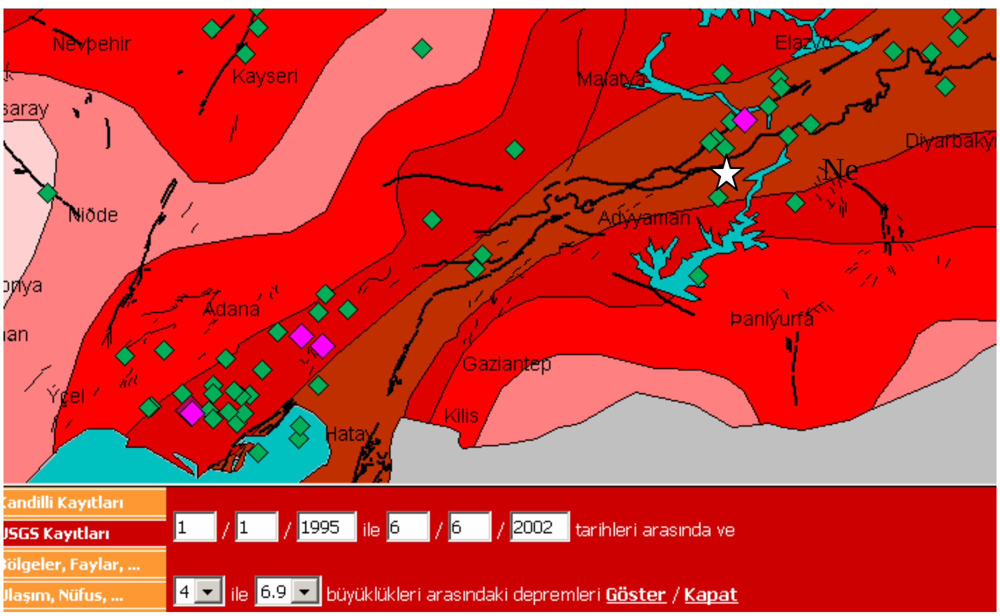



**Figure 6 Earthquakes in the Region Since 1973 for Magnitudes Between 4.0 and 6.9**

Both of the maps shown in the above figures overlapped with the *Earthquake Zoning Map of Turkey*. It is clearly seen that the Nemrut site is located within 1$^{st}$ degree earthquake zone. The earthquake zone map of Adiyaman (Figure 7) is also provided below for further examination.

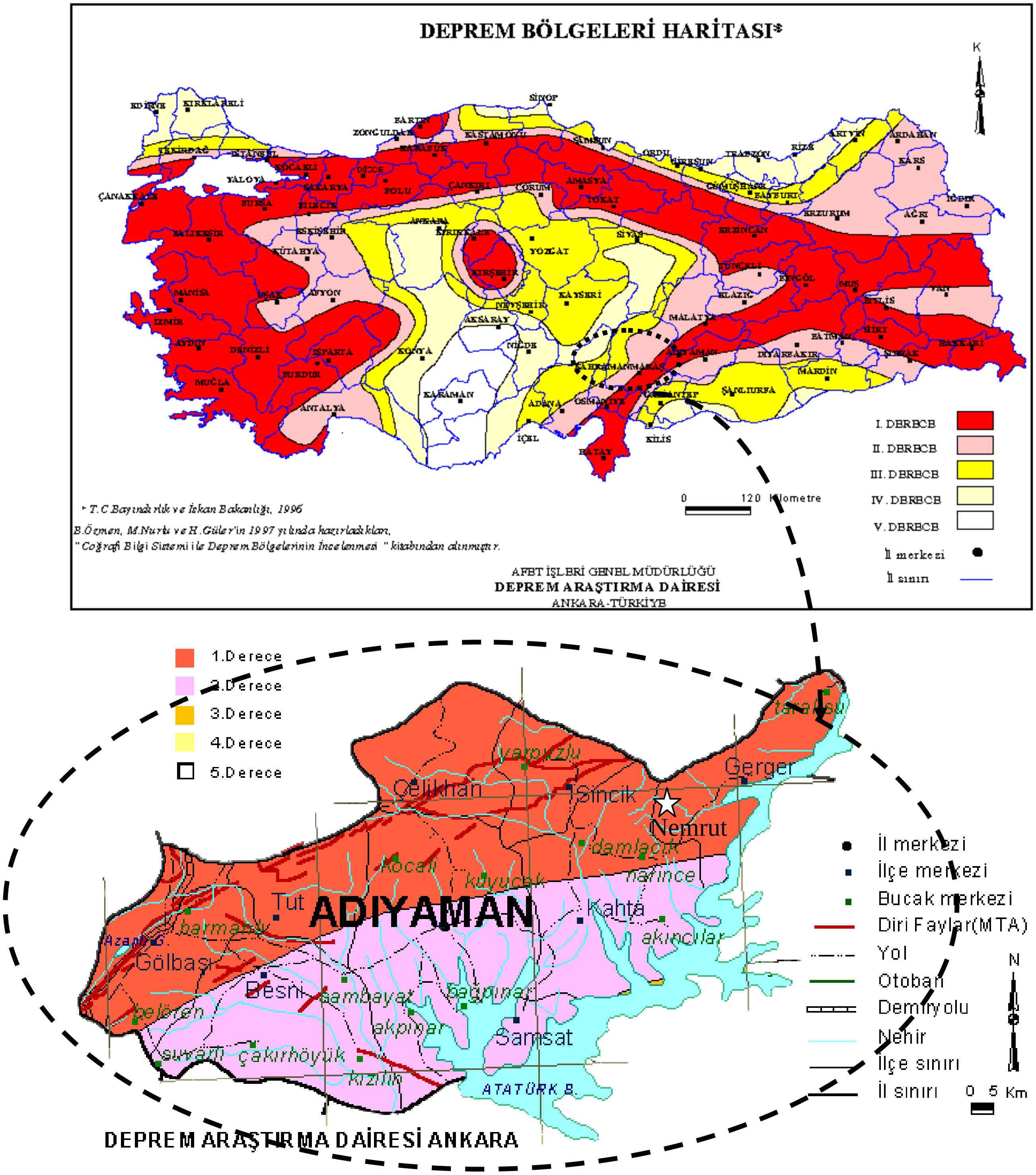



**Figure 7 Adiyaman Earthquake Zone Map**

The *Earthquake Zoning Map of Turkey* is prepared by the Ministry of Public Works and Settlement considering the latest knowledge and approved by the Government of Turkey and published in 1996. The earthquake zones are determined by using the acceleration contour maps (which were calculated using probabilistic methods). It assumes that a normal construction, which has 50 years of economical life, may not be exposed larger than these expected maximum acceleration values with %90 probability. This is equivalent to an earthquake with return period of 475-500 years. For the important constructions or buildings that have longer economical life, maximum acceleration values should be calculated.

Earthquake zones of Turkey classified as fallow due to expected acceleration values

1st degree earthquake zone: more than 0.4g

2nd degree earthquake zone: between 0.3g - 0.4g

3rd degree earthquake zone: between 0.2g - 0.3g

4th degree earthquake zone: between 0.2g - 0.1g

5th degree earthquake zone: less than 0.1g

g: gravity(981 cm/s*s)

It is evident from this data that an earthquake of 500 year return period with maximum peak acceleration **larger** than 0.4g might be expected in this region in the next 50 years. The 90% of survival probability is assumed for civil engineering structures and does not comply with the monuments located at the Nemrut site:

The monuments of Nemrut are built using blocks of stones that are piled on top of each other. There are no connection between the stones and any shear keys. As the ground starts to move with accelerations larger than 0.4g, large inertial forces will be generated due to the mass of each stone. The force on each stone is going to be a linear function of mass and acceleration (F=m*a). The stone pieces are going to be pushed horizontally trying to slide or overturn them in pieces or as a whole.

In addition to the horizontal forces generated during a possible earthquake, there will be “near field effects” associated with the closeness of the Nemrut site to the active fault. Nemrut is located 5 to 12 kilometers away from the fault line (see Figure 4). When a site is located too close to a fault line, the permanent displacement and vertical accelerations combined with the horizontal accelerations generate even a worse condition on existing structures. The pieces of stone blocks piled on top of each other (without shear keys) are extremely vulnerable to earthquakes. Re-erection of monuments should definitely be prohibited without making any detailed analysis and tests on scaled lab models.

Only the heads of the large monuments (human figures) have shear keys (at the head level only). The lion and the eagle do not have a similar shear key. The heads will definitely fall off in the first earthquake causing further damage at the surface level, even possibly damaging the integrity of individual stones (probably splitting them into pieces). From a structural and seismic point of view, <u>re-erection of the extant sculptural fragments (anastylosis) should be strictly prevented and prohibited</u> until all the necessary calculations, analysis, modeling, simulation activities are conducted, stability concerns are addressed, and possible strengthening or other alternative approaches are fully discussed. Re-erection of the monuments is an open invitation to damaging a historical heritage in the first earthquake.

The stone blocks of the west side are all dislocated and resemble rubble (Figure 8). The east side monuments suffer serious dislocation although the larger monuments still stand up excluding the heads. The eagle and lion statues are down at both sides of the mountain. The standing portions on the east side have serious structural conditions that must be addressed as an emergency:

**<u>East Side:</u>**

- Base stone of Herakies, the one next to the eagle, has a base stone with a critical cavity underneath (Figure 9). The base stone is carrying a large load in flexure, simply supported at both ends and might possibly let the whole massive weight go soon with the initiation of the first crack. Although the void underneath the stone is in the range of about 10cm, a failure in the base stone tension zone would lead to instability of the remaining stones.
- Herakies again has a seriously fractured stone block, as shown in Figure 10, which may lead to structural failure. The stabilization of the fractured blocks should be addressed immediately.
- Monument of Apollo, the first standing one from the left, has a series of dislocated stone blocks (in the second and third layers) which may lead to failure if they move outwards a little bit more. They should be carefully pulled back to original locations.
- The shoulder of Antiochos is instable over the slope, and may come down breaking and smashing against the heads at the ground level.

**Figure 8 Totally Collapsed Statues at the West Side**

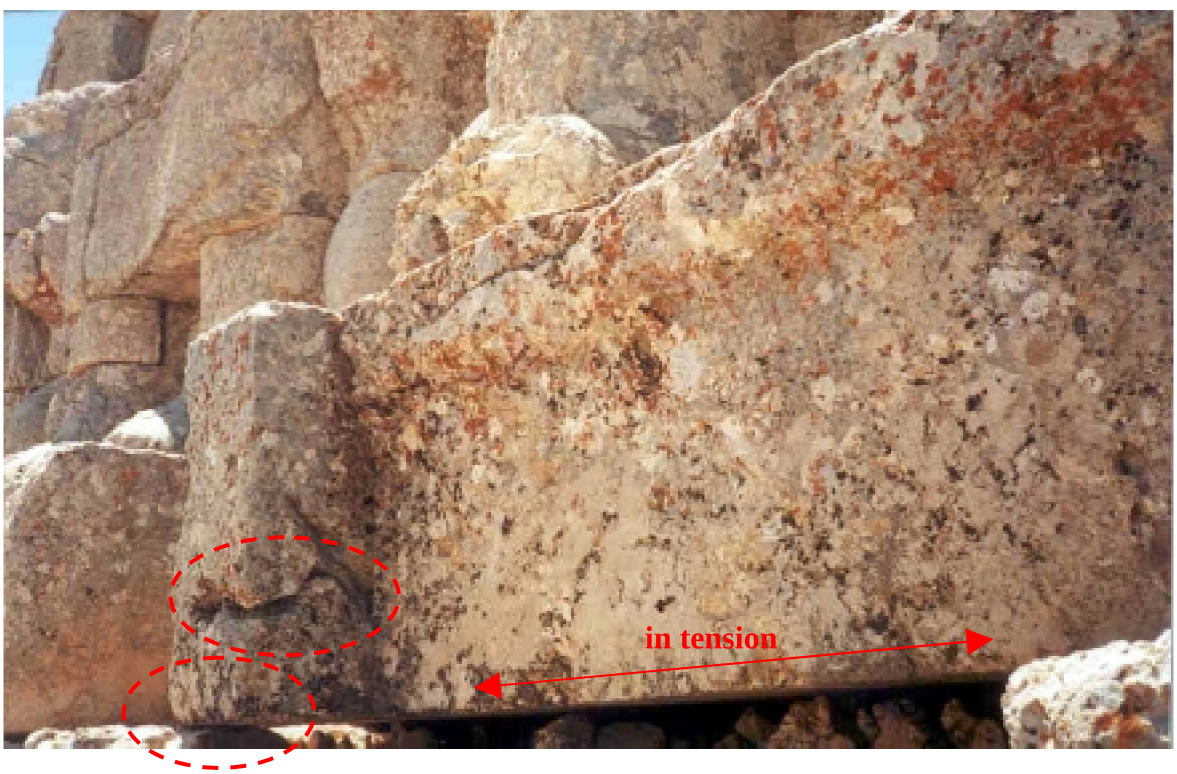



**Figure 9 Base Stone of Herakies, Simply Supported and Fracture Critical (East)**

**Figure 10 Fractured Upper Block of Herakies, May Lead to Sudden Failure**

**West Side:**

- The second Stelae from the left was tipped and fell face wards during snowy season (Figure 11). (Before damage condition can be seen from the local postcards Figure 12). The current condition of the stone is very unstable and in a dangerous condition for itself and for the visitors. The Stelae must be urgently stabilized.
- Other (still standing) Stelaes are poorly designed for lateral forces. The contact areas at the base are very small. Concrete mortar was used in a previous attempt to fix the base of the Lion Stelae (see Figure 13). Only about ¼ of the base is keeping the Stelae up and all Stelaes are very vulnerable to earthquake forces. Even the snow pressure from behind (the mountain side) is enough to tip the Stelae (Figure 11). Combined with degrading and deteriorating stone structure of Stelaes (due to freezing and thawing) it may be recommended to place them on the ground with full base contact to prevent any bending moment formation. They may be preserved in plastic airtight wraps during off-season and from precipitation.
- Base stone of Stelaes' are in bad condition and should be strengthened.
- Stability of the stone pieces over the tumulus must be addressed.

- Snow pressure on Stelaes must be addressed.

Stabilization studies conducted in 1980's on the Lion Stelae at west side were very badly designed and actually ended up damaging the Stelae even more. The steel rods placed inside the two facing stone pieces were very short compared to 'development length' to fully make use of the steel rods (Figure 14). Therefore, the rods slipped out of the drill holes without resisting overturning. The epoxy used had no use holding the pieces together. The two rods placed at the cross section were of different diameters and different material properties (rusting and stainless steel) as it can be seen in Figure 15. The rods were located close to the center of the stone cross section where the neutral axis is expected to exist. Over a cracked section, the rods would have better be placed close to the edges of the section for improved overturning resistance. <u>Careful planning and investigation should be conducted at the Nemrut Site to prevent further similar mistakes and losses.</u>

**Figure 11 Tipped Stelae on West Side**

**Figure 12  Stelae on West Side before Damage**

**Figure 13  Poor Base Design of Stelaes (West Side)**

**Figure 14  Very Short Rod Length Incapable of Generating Axial Force**

**Figure 15  Different Diameter and Materials (Stainless-Rusting) Used for Re-bars**

There are additional issues that must be addressed at Nemrut Site other than the emergency issues:

- International Nemrut Foundation (INF) should share the documents that they have gathered so far including the detailed drawings of the stones, studies-analyses conducted so far, and the remaining work they have done with the Turkish team.
- INF proposed re-erection of the eagle and lion statues. Most of the stone blocks remained in the field exposed to various aging processes following the dislocation from their original locations. There are concerns about the integrity and strength of each block prior to any re-erection process.
    - The strength and integrity of stone blocks should be addressed, and necessary conservation and strengthening studies must be conducted on the stones.
    - Due to erosion, the stone blocks may not be leveled.
    - If any earthquake (EQ) analysis carried out for the monuments, they should be shared by the Turkish team.
    - The 90 ton crane should not be placed inside the garden. The dislocation of any stone block should be carefully planned and minimized to prevent any possible damage.
    - The road constructed in June 2002 makes the site susceptible to stealing pieces from the site. Existence and possible usages of the road should be re-evaluated.
- The material properties of the stone blocks must be determined. The material properties should include (but not limited to) Modulus of Elasticity (E), Stress-Strain behavior, Ultimate Compressive Strength, Ultimate Shear Capacity, Friction Coefficient, Unit Weight, etc.
- Simple overturning and sliding analysis must be conducted followed by more complex nonlinear Finite Element Modeling (FEM). The computer model should be excited using measured earthquake accelerations, as well as response spectrums given by the code. (i) Overturning the heads and/or the monument as a whole or (ii) sliding off the cliff or between the blocks are two possible collapse scenarios. As a third option, the failure might be a combination of these two.
- The monuments might be strengthened against EQ using base isolators and (plastic) shear keys between blocks.
- Each activity conducted on site must be recorded using video camera(s).

***Proposed Work Plan for Nemrut Monuments from a Structural Point of View:***

Nemrut monuments are located in the 1st degree earthquake (EQ) zone, and carry overburden of poor initial design. Stelaes, tumulus, and statues are all vulnerable against earthquake and in part against snow loading. Stelaes might be secured by lowering flat on the ground against EQ and snow loading. Instability of the stone rubble over tumulus during an EQ may not be an issue since it has been fairly stable over the 2000+ years, and there seems to be trenches underneath the stone rubble for added stability. However, statues are formed of massive stone blocks that are not interconnected and probably exhibit to be the most critical structure on site.

The structural studies can be grouped under the following headings:

1- Material tests (3 months – about 765 USD)
    - Obtaining stress-strain relationship for axial and shear forces of stones: tensile strength, modulus of elasticity, ultimate strength, shear modulus, Poisson's ratio, etc.
2- Analytical studies and tests (18 months – 38000 USD)
    - Simplistic dynamic analysis of monuments,
    - More complex FE analysis of monuments,
    - Lab tests and simulations on scaled-down replicas of the monuments using shaking table,
    - Investigation of structural strengthening options, testing each alternative, and repeating tests to improve behavior under EQ loading.
3- Field studies (2 years to 4 years – the cost is expected to be about 50000 USD, however there are many uncertainties)
    - Application of the best option, found in the lab tests and analyses, on one of the actual monuments.
    - Repeated field tests on dynamic behavior of the strengthened monument for pre- and post-strengthening conditions.
    - If selected strengthening method proves to be as successful as it was in the lab, sturdy, and durable in the long run, the strengthening method would be repeated for the rest of the monuments to improve their behavior against earthquakes.

Detailed listing of Part 2 expenditure (as planned):

| | months | | |
|---|---|---|---|
| $300 | 18 | $5,400 | A. Turer |
| $250 | 18 | $4,500 | PhD Student |
| | | $5,000 | Travel expenses |
| | | $9,950 | Material, testing utilities, setup, shaking table rent, etc. |

| | |
|---|---|
| $24,850 | Total |
| $4,473 | VAT 18% |
| $8,698 | University overhead 35% |

| | |
|---|---|
| **$38,021** | **TOTAL** |

List of Figures: