THE PROTECTION OF ARCHAEOLOGICAL MONUMENTS AGAINST MAN-MADE HAZARDOUS VIBRATIONS. PRESENTATION OF CASE STUDIES APPLIED ON ARCHAEOLOGICAL MONUMENTS IN GREECE AND ITALY.

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1. INTRODUCTION - GENERAL OVERVIEW

During the last decades people have become more and more interested in the protection and restoration of ancient monuments and structures appreciating the value of historic sites. The archaeological monuments are the most relevant links between present time and our course in history. Under a certain point of view they could be defined as “time-machines”. These excellent time-machines stand on for some thousands of years resisting to natural phenomena such as earthquakes, volcanic eruptions, floods and human activities such as war destruction and improper use.

During this last century, characterized as the industrial era because of the huge and rapid technological development of modern societies, the ancient monuments and structures have been found under severe conditions as regards air pollution, underground water quality and most of all the hazardous man-made vibrations. The accelerating deterioration of the archaeological monuments observed during the last years provoked an increasing administrative concern. Because of this justified concern a major attention has been imposed towards the activities which generate vibrations on earth’s surface and in the underground. Most of the worldwide standardizing organizations have compiled limitation standards. At the same time, many governmental bodies have introduced regulations aiming to protect the archaeological heritage. The international scientific community has produced a large amount of research work and practical studies for the conservation of ancient monuments. Modern technical disciplines such as computer sciences, electronics and signal analysis techniques provided the specialized engineers with the most efficient tools to monitor, study and keep under control the effects of the hazardous vibrations on the monument’s structure.

All the accumulated technical experience on this field should be disseminated for the worldwide monument’s protection and at the same time new thrust should be given to new technologies and updated research techniques.

Hereby a typical protection scheme against vibrations will be presented. Case studies of archaeological monuments protection in Greece and Italy will be discussed, as well.

2. DAMAGE CRITERIA, INTERNATIONAL STANDARDS AND REGULATIONS

Several man activities generate vibrations. Construction vibrations represent the largest and in many cases the most dangerous category of these activities. Rock blasting, soils dynamic compaction, pile driving, mines blasting, mechanical trenching, blast densification of sands, structures demolition with explosives are some of them. Other vibration sources are railway traffic, special machinery's functioning, heavy road traffic conditions, etc.

Whenever a vibrations source is found in the neighborhood of an archaeological monument, forces the structure of the monument to oscillate more or less by induction. Structural damage may occur the more or the less. At this point urges the need to employ damage criteria. The following considerations must be done before examining damage criteria options.

a. Seismic waves propagation in earth's interior is a complex and multi-parameter process. High anisotropy and inhomogeneity of the natural media in combination with the presence of joints, faults, discontinuities and pore's water render extremely difficult any attempt of theoretical approach of this issue.
b. The amount of transferred energy from earth to the monument through the shock waves depends of the coupling state between the monument's structure and the surrounding host material.
c. The monument structures are mostly characterized by an enormous complexity because of the many different constructional styles, the many different construction materials and the many different men-interventions on them during the lifetime of the monuments. Because of this complexity, it is very difficult (or quite impossible) for the specialists to produce any behavioral models based on SDF or MDF analysis techniques. Major concern for the structures integrity comes from the differential displacements (even between short sectors of the structure), which are the norm rather than the exception in the case of the archaeological monuments under shocks and impacts.
d. The nature of the shock is most important for the archaeological monuments. A single-cycle excitation has to be regulated by a damage criteria, which has to be different from the damage criteria that regulates a continuous or periodically repeated excitation. When multi-cycle excitation occurs, fatigue effects are quite unavoidable. In this case damage criteria must be flexible, adaptable and by time diminished, in any case.

The search for damage criteria began by empirical way and by the use of seismographs. The most popular empirical formula is the U.S.B.M 's one, which uses the particle velocity (P.P.V.) of the vibration as damage criterion in combination with the dominating value of vibrations frequency. Vibrations velocity has been adopted by many other standardizing organizations worldwide always in combination with frequency values, even though structural engineers prefer to use vibration's acceleration values as damage criterion.

The German standards DIN 4150 excel between them, because of their analytical approach and their precision on describing the measuring procedures. For the third category of structures (as they are referred in part 3 of DIN 4150) "Structures that because of their particular sensitivity to vibrations do not correspond to those listed in lines 1 and 2 and are of great intrinsic value (e.g. buildings that are under a preservation order)" the standards fix the limit value of vibrations velocity at 3 mm/s for frequencies below 10 Hz. For frequency range from 10 to 50 Hz the velocity limit value varies from 3 to 8 mm/s. The maximum allowable velocity value for this standard is 10 mm/s for frequency values up to 100 Hz.

The area determined by 0 to 50 Hz as frequency range and by 0 to 8 mm/s as velocity range is the standard's area more involved in case of archaeological monuments protection against hazardous vibrations. This area could be better refined, if the worldwide specialists on monuments monitoring would submit their own observations based up to their experience to the German Institute for Standardization (DIN) in order to process and elaborate data from many archaeological monuments. In this way the first half of line 3 could result different from the actual, but surely closer to reality. By the occasion, this is a direct proposal towards the DIN's direction to invite the international scientific community to cooperate in this direction.

There are many other international standards, specialists can rely on. Some of them are the B.S.S. 117 (United Kingdom), the Explosive Code CA-23 (Australia), U.S.B.M.-RI8507 (USA), I.S.O. 4866 and the Schweizer Norm 640312a of V.S.S. (Vereinigung Schweizerisher Strassenfachleute) which is one of the very few standards that keeps in account not only the structures sensibility, but the excitations nature as well.

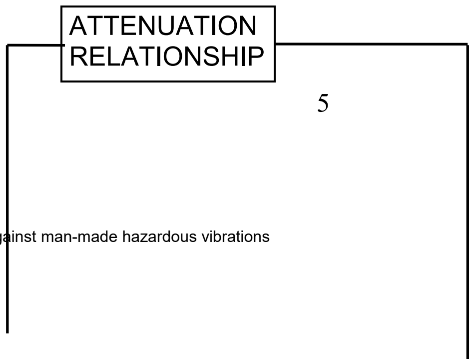
Despite all, when it comes to protect an archaeological monument against hazardous vibrations the international standards should be just a guideline and a reference during the pre-blast site survey and trial-blasts program. During the execution of the works the monument must be continuously (24 hours per day) monitored by a multi-parameters monitoring network, in order to provide the specialists with all the valuable information about his own behavior under dynamic load. In this way the same monument produces by itself his own vibrations standard and imposes his own damage criterion. No standard and regulation in this world can safeguard Parthenon in Athens-Greece or the pending Tower of Pisa-Italy as individual monuments. Only the information obtained by the direct monitoring of any single monument can impose safe damage criteria for them.

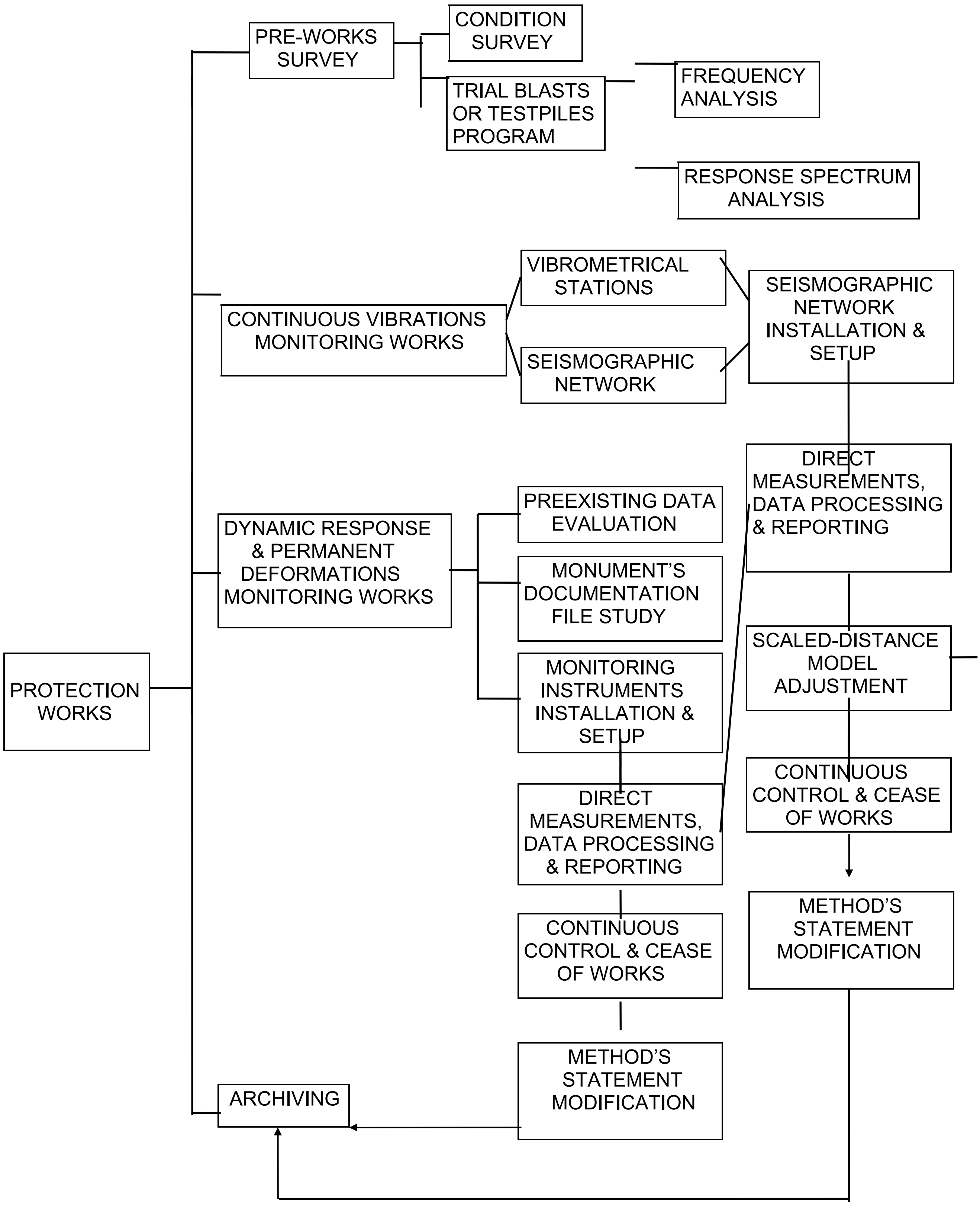
Closing this discussion about standards and regulations an UNESCO's (United Nations Educational, Scientific and Cultural Organization) recommendation must be mentioned. It is the "Recommendation Concerning the Preservation of Cultural Property Endangered by Public or Private Works" which was adopted by the General Conference of UNESCO during its fifteenth session held in Paris on November 1968. This recommendation, even if it was compiled thirty years ago, still remains actual. All the interventions aiming to the protection of the archaeological monuments against man-made hazardous vibrations should be in conformity with the spirit and the principles of this recommendation. Here are some citations. In article 7 it is reported "Measures for the preservation or salvage of cultural property should be preventive and corrective". In article 15b it is reported "The costs of preserving or salvaging cultural property endangered by public or private works including preliminary archaeological research should form part of the budget of construction cost". In article 22 it is reported "Thorough surveys should be carried out well in advance of any public or private works which might endanger cultural property to determine the measures to be taken to preserve important cultural property in situ".

3. A TYPICAL SCHEME OF PROTECTION WORKS

Hereby is described a typical scheme to employ as protection of the archaeological monuments against man-made hazardous vibrations. The spirit of this scheme is not confined to vibrations control only, but comprises the monitoring of the monuments structure behavior, as well. The scheme (figure 1) is deployed along three principal directions, which are:

Figure 1.





a. Pre-works survey.
b. Continuous vibrations monitoring works.

c. Dynamic response monitoring works and permanent deformations monitoring works.

3.a Pre-works survey

This survey has to be conducted before the start of any vibration producing activities near the monument and should provide detailed data on the state of monument's structure, complete with photographs and videotapes. Valuable data on this purpose could be provided by the local authority which is responsible for the monument's safeguarding. High susceptibility sectors of the monument should be particularly mentioned.

A program of trial blasts or a program of test piles has to be performed prior to the start of any blasting or pile driving activities in the monument's area, if such activities make part of the project. An analysis program should follow, in order to provide the statistical attenuation relationship, the frequency analysis and the response spectrum analysis.

3.b Continuous vibrations monitoring works

Here are described the continuous vibrations monitoring works in chronological sequence.

1. Location choice for the vibrometrical stations installation on the monument and sensors choice (accelerometer, velocitymeters or both).
2. Topological study of the seismographic network which permanently controls the vibrometrical stations. Telemetric capabilities and call-back options are preferred.
3. Installation and initial setup of the seismographic network.
4. Vibrations parameters in dual-mode measurements (single events and continuous), data post-processing and reports production including zero-point-crossing frequency analysis and 3-D representation of particles displacement.
5. Continuous adjustment of the scaled-distance model.

6. Continuous control of maximum vibrometrical parameters and cease of vibrations generating activities, if necessary, in case of maximum allowable limits override.

7. Modification of the works method statement (if necessary) in order to fit again into the maximum allowable limits. There are many suitable techniques to mitigate vibrations hazard on monuments. In case of blasting works some of these techniques are the sequential blasting technique, the various controlled blasting techniques (presplitting in particular), the favorable blast's direction, the immediate muck removal and the proper use of dumping materials.

3.c Dynamic response and permanent deformations monitoring works

Dynamic response and permanent deformations monitoring works aim to study the behavior of monument's structure under dynamic load conditions and record any permanent deformation of it, because of the project's progress. Here is the sequence of these works.

1. Evaluation of preexisting data, especially as regards vibrations acceleration records.
2. Study of the monuments documentation file as regards the present condition and high susceptibility sectors.
3. Specifications study, installation of monitoring instruments (3-D crackmeters, dynamic jointmeters, deflectometers etc.) and initial setup.
4. Direct measurements, data processing and reporting in correlation with vibrometrical monitoring data.
5. Continuous control of peak values and cease of vibrations generating works, if necessary.
6. Modification of the works method statement.

3.d Archiving

A vibrations archive must be created and kept in parallel by the works owner, the supervisor engineer, the contractor and by the local authority which is responsible for the monuments safeguarding, as well. This archive is necessary in case of litigation, because then the archive's data will be called into evidence and as evidence they have to be absolutely incontestable.

The vibrations archive must contain at least the following data:

1. The pre-works survey complete documentation i.e. the monuments condition report, the trial blasts or the test piles program's report.

2. The original and the modified method statements of the vibrations-generating works.
3. All the monitoring instruments records in hard and soft copies.
4. A complete list of monitoring instruments.
5. Technical data regarding the source of hazardous vibrations (types and quantities of explosive materials, pile drivers, etc.)

4. **CASE STUDIES**

Some case studies are discussed here regarding experiences on archaeological monuments in Greece and Italy.

Greece is well known worldwide because of the ancient Greek Civilization that left to us many excellent monuments. A lot has been written about the Greek monuments of the Classic Era, such as Parthenon on Acropolis, Apollo's Temple in Delphi and the famous Olympia in Peloponnese. There is another period in Greek history, the Byzantine Empire's period, that was characterized by the deep spirituality and mysticism of early Christianity. The second important city of Byzantine Empire after Constantinopolis was Thessaloniki. This is the main reason why actually in Thessaloniki many important Byzantine and post-Byzantine monuments are found. These monuments are declared as international cultural heritage and lay under the protection of UNESCO. The monuments are well conserved and restored in their majority and are founded in a red clays formation that overlays the metamorphic bedrock.

The principal threat comes from the hazardous vibrations as bad effect of intensive urbanization. Most common vibration sources are heavy traffic conditions, construction vibrations, industrial machines functioning and in some cases the improper use of the monuments. All these sources create a constantly fluctuating "noisy" background of vibrational pollution, that sometimes reaches the level of 0,9 mm/s as particle velocity on monuments structure. The frequency spectrum is well assorted, but generally the structure's natural frequency

prevails. Thessaloniki's geographic area is extremely earth-quake prone. Despite this the Byzantine and post-Byzantine monuments seem to resist well to the telluric motions. The major threat for the monuments during an earthquake is represented by the induced motion of the surrounding modern buildings, because of the extremely close vicinity of their foundations, which will act as multiple secondary vibrating sources.

Some of Thessaloniki's monitored monuments are the Byzantine churches of Rotonda, Acheiropoietos, Aghia Sofia, the fortification of White Tower and the Pazar Hamam public baths complex.

An interesting case study regards the excavation by blasting of a railway tunnel under the mediaeval castle of Platamon at the southeast foot of Mt. Olympus. The tunnel project is actually under execution and since now the pre-works survey (with a trial blasts program) is completed and occasional vibrations monitoring is applied. As came out from the attenuation relationship, the frequency analysis and the response spectrum analysis, special attention must be paid on this project. That is why a complete proposal (fully conform with the typical scheme of protection works just described) has been submit to project's owner. In the mean time a scientific team formed by owner's consultants and engineers from the Greek Culture Ministry is supervising the contractor.

Another case study comes from Trieste-Italy where the Servola's Cathedral church was seriously endangered during the excavation by blasting of a double tunnel. This church was constructed in 1300 b.C. and stands on the top of a mediaeval urban aggregate, actually protected by the Soprintendenza alle Belle Arti (Superintendence for the Fine Arts). The geological formation of the area is the Flysch of Trieste, a stratified torbidity flow formation of the middle Eocene. The lithology of this formation is an alternation of sandstone and thinner layers of marl.

A total quantity of 125 Kg of gelatin was exploded at each blast, fired electrically and distributed in 12 intervals of 500 ms each. The length of the tunnel is 250 meters and the altitude difference between the Cathedral's foundation and the tunnel's roof is 35 meters.

A previously performed survey had imposed the value of 8 mm/s as safe damage criterion for the archaeological monument. Because of the particular geotectonic character of the Flysch formation this safe velocity value was over passed quite immediately after the start of the tunnel's excavation with blasting techniques. The explosive quantity per delay interval was an untouchable parameter because of other restrains in blast design. After the vibrations records were analyzed, it came out that the blast's core charges raised up immediately the particles velocity level and kept it protracted for several consequent delay intervals. It was observed that the contractor detonated contemporarily all the blast core's charges by zero-delay electric caps. That was the main cause of the particles velocities immediate raise up. By eliminating at all the zero-delay caps, the velocities level was significantly lowered. This is owed to the fact that between many electric caps of the same delay number, there are slight time differences, because of manufacturing defects of the chemical retardant. This is a good example of taking advantage of a defect and turn the situation in safety's favor. This solution kept the particle velocities maximum peaks below the safe limit value for the whole duration of the tunnels excavation.

The last case study to present here comes from Parma-Italy and regards to the vibrometrical survey on the bell-tower of the San Sepolcro's church. This church was built during the Italian Renaissance period and recently was heavily exposed to high vibration levels because of improper use of the monuments area. The major threat comes from the traffic of big buses for the public transportation. Continuous vibrations monitoring was applied in several points of the monument in combination with different controlled traffic situations. These traffic situations were obtained by different setups of buses passages traveling with different velocities, loaded by different numbers of passengers, passing by different distances from the monument and behaving in different ways (accelerating or braking). All these situations were monitored by the Autovelox speed monitoring devices of the Italian Traffic Police.

After the data were analyzed several interesting conclusions came out. The dominant frequency range was between 10 and 20 Hz. Under normal traffic situation the mean particle velocity value during daytime was 0,95 mm/s and 0,45 mm/s during nighttime. The peak particle velocity value during daytime was 1,96 mm/s and 1,40 mm/s during nighttime. The peak vector sum was 2,25 mm/s. All these values are rather high and of great concern for the monuments safeguarding. The controlled traffic situations showed that the buses velocity is

the most influencing factor on particles velocity increase. The major increase is observed after the value of 30 Km/h on buses cruising velocity. The other factors (i.e. passengers load, distance and vehicles behavior) are less influencing on the monuments dynamic response. Major irregularities on road mantle surface are responsible for minor peaks on particle velocities recordings.

After these conclusions, repairs on road mantle have been made and a maximum speed limit of 20 Km/h was imposed on the cruising velocity of public transportation buses and other heavy vehicles. The consequent fall of the particle velocities values was of 60%, recording 0,78 mm/s as daytime peak values and this is well acceptable.

5. CONCLUSIONS

Archaeological monuments are part of the cultural heritage of mankind and must be preserved and protected against natural catastrophic phenomena, industrial development and urbanization collateral effects. Hazardous vibrations are part of these collateral effects. Modern science and technology provide the specialists with all necessary tools to protect the archaeological monuments, when they are endangered by public or private works. The typical scheme of protection works, here proposed, is a global solution to the monuments safeguarding problem. If correctly employed, such schemes can guarantee the monuments safety and permit the execution of big common-utility works, either.

In conclusion, the need for dissemination of these edge-technologies should be emphasized. New methods should be divulged using all those information capabilities this end-millennium offers. At the same time young engineers and scientists should get educated and trained on purpose.

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INTERNET RESOURCES

SEISMOTER - GEOPHYSICS & BLASTING: www.freeyellow.com/members/seismoter

CONSTRUCTION VIBRATIONS COMMUNITY: www.civil.nwu.edu/people/dowding/chdpage.html

SOCIETY OF EXPLORATION GEOPHYSICS: www.seg.org/

INTERNATIONAL SOCIETY OF ROCK MECHANICS: leo.lnec.pt/~isrm/

D.I.N. (DEUTSCHES INSTITUT FUR NORMUNG): www.din.de

EL.O.T (Hellenic Standardizing Organization): www.elot.gr/

U.S.B.M. (United States Bureau of Mines): www.usbm.gov/

O.S.M.RE (OFFICE OF SURFACE MINING & RECLAMATION): www.osmre.gov/osm.htm

EUROPEAN UNION/GENERAL DIRECTION 22: europa.eu.int/en/comm/dg22/dg22.html

GREEK CULTURE MINISTRY: www.culture.gr/