Rockfalls in the archaeological site of Delphi, Greece.

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ABSTRACT: In the present paper, the safety of the northern slope of the Delphi's archaeological site in Greece was investigated against rockfalls. The archaeological site is established over flysch and limestone rocks of the Parnassus – Ghiona zone. Three possible rockfall rebound tracks, passing through the ancient stadium, and the theatre, were studied for different rock dimensions and tracks resulting that the more dangerous and difficult in retention rockfall track is that which crosses the stadium. The use of barriers was investigated accepting, finally, that a 2.5m-high metallic barrier could be installed along the northern steep slope for the protection of the archaeological site.

KEY WORDS: ROCKFALLS, DELPHI, SLOPE STABILITY, RESTRAINING BARRIERS

1. INTRODUCTION

In the middle of September 2009, prolonged rainfall activated rockfalls from the upper sections of the archaeological site's northern slope and fall downslope, out of the enclosure wall of the Sanctuary of Apollo, north of the Portico of Attalus. Rockfalls also are being occurred in the stadium from 2003 onwards (Fig. 1). The slope, consisting of limestone, is steep and heavily broken due to a large normal fault namely herein Delphi fault. For the protection of the above slope and the archaeological site, the present scientific team visited the area, after the last rockfalls and expressed ideas on a protection scenario which must be proposed.

Rockfalls generally resulted during or after heavy rainfalls that dramatically change the geotechnical parameters of the rock e.g. pore pressure, friction angle etc. The retarding capacity of the surface material, in the event of a falling rock, is mathematically expressed by the coefficient of restitution, which depends on the hardness and surface weathering of a rock as well as ground vegetation.

2. REGIONAL SETTING

The archaeological site of Delphi is one of the most important sites of Ancient Greece and it is located on the steep northern slope of the Pleistos River valley in central Greece (Fig. 1B). The exposed rocks of the site belong to the Parnassus – Ghiona geotectonic zone (Jacobshagen 1986). This zone builds up the mountains of Parnassus, Ghiona, Elikonas and parts of Oiti. To the east, it is tectonically overlaid by the Beotian and Pelagonian zones, whereas to the west it tectonically overlies the Pindos zone. The Parnassus-Ghiona zone consists of a thick shallow-water carbonate sequence of Triassic-Early Tertiary age and flysch rocks that deposited in Early Paleogene. Within the carbonate sequence three distinct bauxitic horizons are recognised. The archaeological site of Delphi is established over the flysch rocks, while the northern slopes made up of sculptured limestone (Fig 2).

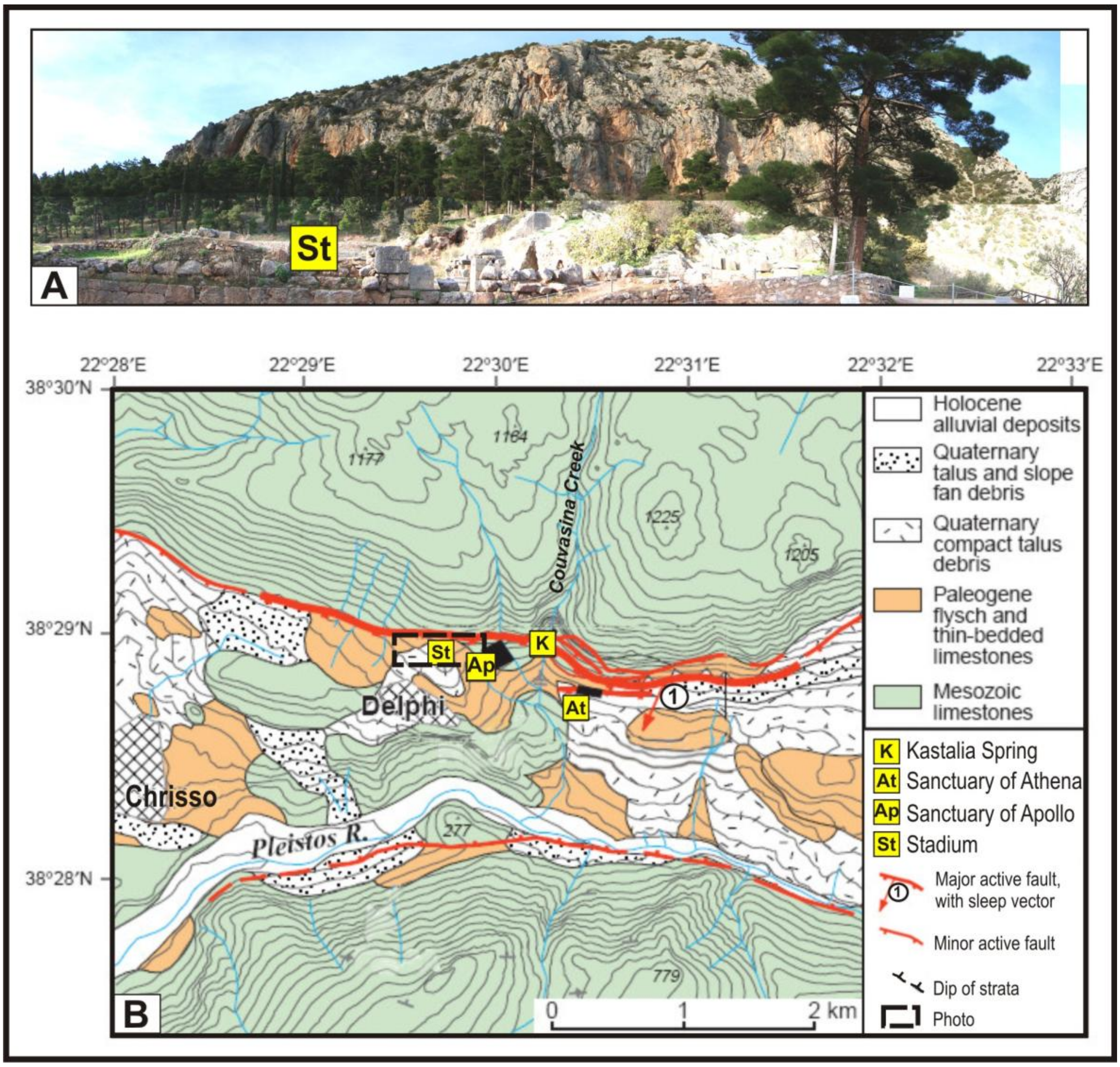

Fig. 1. A) General view of the slope, where the rockfalls occurred behind the stadium, in Delphi's archaeological site. It corresponds to the upper left side of Fig. 3.
B) Geological map of the archaeological site (modified from Piccardi, 2000), with location reference of the monuments.

The landscape is both controlled by tectonic activity and fluvial action (Valkaniotis 2009). The first is related to the E-W striking Delphi fault, whilst the second caused by the drainage of Pleistos River and its tributary Kouvassina Creek. The Delphi fault is an active normal fault that dips towards the South, subsiding the southern slopes of the Mount Parnassus for a total length of more than 25 km and terminates to the west at Mount Ghiona. The fault has been subdivided into three segments which from west to east are: (a) the WNW-ESE trending Agia Efthimia segment, (b) the E-W trending Delphi segment which cuts the archaeological site, and (c) the ENE-WSW trending Arachova segment.

In the archeological site, the Delphi fault is exposed with several sub-parallel fault surfaces that form step-like morphology. Moreover, the lowest fault surface bounds the site. On the other hand, the Holocene fluvial action causes intense down-cutting erosion that has as a result the formation of steep-sided valleys and gorges. The graded profile of these valleys defines a base level that lies lower than the archeological site's altitude. The most important affect of the fluvial action to the archaeological site is the Kouvasina Creek. It flows in an N-S direction at the eastern end of the site, carrying large counties of coarse bed-load with boulders and cobbles in the site.

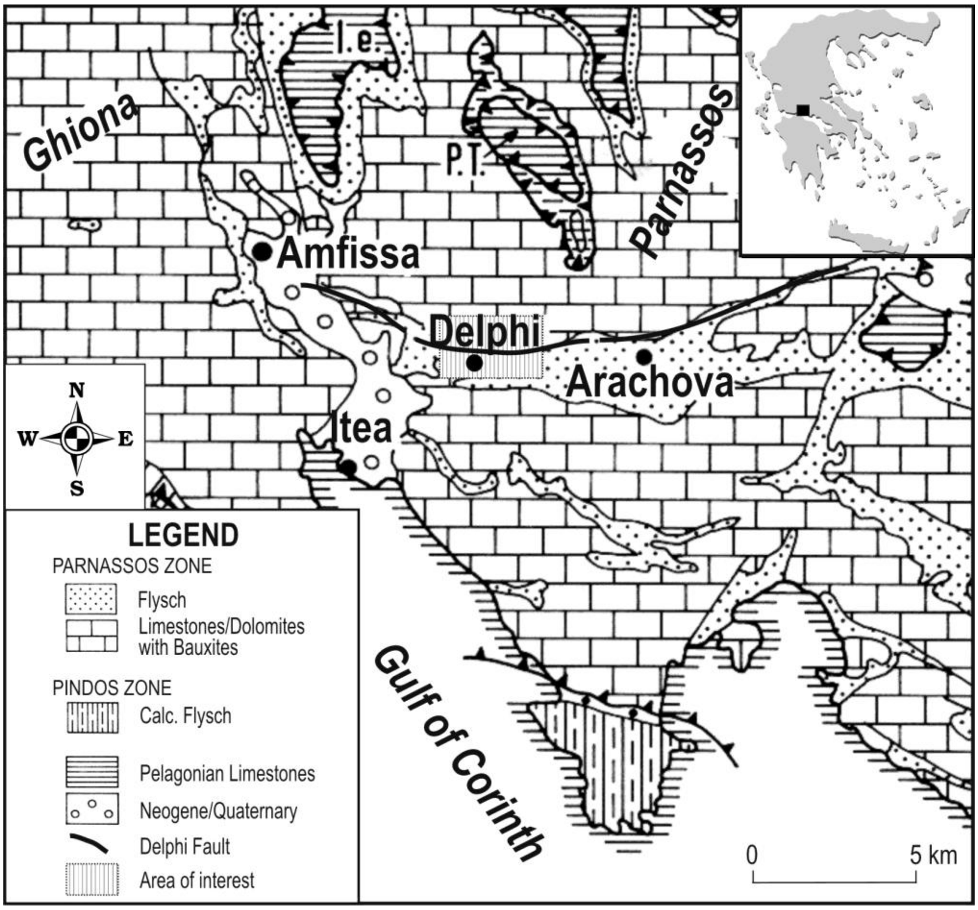

Fig. 2. Simplified geological and tectonic map of the Parnassus–Ghiona zone, Greece (modified after Dercourt et al. 1980).

3. ARCHAEOLOGICAL SETTING

In the Pleistos Valley(Fig. 1B), along the southwestern slopes of Mount Parnassus and within the angle formed by the imposing twin rocks of the Phaedriades (*shining ones*), lies the Pan-Hellenic sanctuary of Delphi, which had the most renowned and trustworthy oracle. As the oracle's reputation and influence grew, Delphi became the spiritual center and symbol of unity of the Hellenic world, a place visited by individuals in quest of advice and by delegations from Greek cities and every country of the known world.

The earliest finds in the area date to the Early Neolithic Period (Korykeion Andron, a cave on Parnassus, end of the 5th millennium B.C). However, permanent inhabitation is attested just in the Early Helladic Period (before 2000 B.C.) in the coastal settlements of Kirrha and Galaxidi. Due to a rise in population during the Middle Helladic Period (2000-1600 B.C.), new mainland sites were inhabited, Delphi possibly being one of them. The settlement of Delphi was established at the beginning and was inhabited throughout the Late Helladic (Mycenaean) Period (1600-1050 B.C.).

In the 8th century B.C., the cult of Apollo was established at Delphi and the development of the sanctuary and the oracle began. From the 6th century B.C. onwards, the Amphictyonic League, a religious and political association of neighboring cites and tribes, undertook the administration of the sanctuary. Under its control the sanctuary was, until the 4th century B.C., at its peak. Every four years, the Pythian Games, the second most important games in Greece after the Olympics, were held in Delphi in honor of Apollo. The oracle was the core of the sanctuary. Its fame spread throughout the world and visitors thronged to read the prophetic utterances of the god which were delivered by the mouth of the priestess Pythia and interpreted by the priests.

The archaeological site includes two sanctuaries dedicated to Apollo and Athena (Fig. 1B). The sanctuary of Apollo lies in the westernmost point of the two Phaedriades known as *rose-red* (ancient Nauplia) and the one of Athena on the Marmaria terrace, below the wild easternmost rock crag *Phleboukos* (ancient Hyampeia) which soars 760 m into the blue sky. Beside the Castalian Spring, where the two Phaedriades have their roots, is the putative chasm of chasms whose two rock walls are separated by a sharp cleft, now known as "Bear Gorge", which extend far down into the plain of Pleistos.

Visitors coming from Athens first reached the sanctuary of Athena Pronaia, that is to say Athena who is before the main temple of Apollo. Within the sanctuary was the Tholos, a marble rotunda dating back to the beginning of the 4th century B.C., three temples dedicated to the goddess, constructed consecutively from the middle of the 7th century to the beginning of the 4th century B.C., altars, statues, treasuries and other buildings. To the northwest of the sanctuary of Athena lies the gymnasium and further up the slope the Castalian Spring, the sacred spring where Pythia bathed and the visitors purified themselves before reaching the oracle.

The sanctuary of Apollo is the central and most important section of the site. It was surrounded by an enclosure wall and spread over three artificial terraces supported by monumental retaining walls, boarded by porticoes. The main gate was at the southeast corner of the enclosure. From there the Sacred Way led to the temple of Apollo, where Pythia delivered her oracles. Along the Sacred Way and its cross streets were numerous votive monuments dedicated by Greek cities or wealthy individuals (tripods, statues and small buildings known as 'treasuries', where small votive offerings were stored) on the occasion of historical or social events or simply to express their gratitude to the god.

On the central terrace, surrounded by a polygonal wall, stood the imposing temple of Apollo and a monumental altar in front of it. The ruins that we see today, partially restored, correspond to the third Doric peristyle temple, erected at the same place after the destruction of the first archaic temple by fire in 548 B.C. and of the second in an earthquake in 373 B.C. The second and third temples were adorned by sculptures of famous artists.

To the northwest of the temple, on a higher level, lies the theatre, which was constructed in the 2nd century B.C. This is where the musical contests of the Pythian Games and other religious festivals took place. Outside the enclosure of Apollo's sanctuary in the upper part of the city, was the stadium which was used for athletic purposes. Around the sanctuaries of Apollo and Athena were the settlement of Delphi and the cemeteries.

The decline of the oracle began in the 3rd century B.C. but it was finally abolished in the 4th century A.D. The site was destroyed at the beginning of the 7th century A.D. by the Slavs and gradually the ruins were covered with earth. Some years later, a new village, Kastri, grew over the ruins. This village was removed by the end of the 19th century and the so called "Great Excavation" of the French School at Athens began, which brought to light the splendid monuments of the two sanctuaries.

The excavation, conservation and restoration works of the monuments are still in progress with the collaboration of the French School at Athens and the Greek Authorities (Jacquemin, A., 2000).

4. THE ROCKFALLS

The archaeological site is located at the southern base of a more or less steep slope, consisting of limestone lying over flysch, at a lower level than the Stadium. The rock mass is broken along the directions of the tectonic system of the area. The inclination of the slope is about 45-50^0 and a metallic barrier has already been installed by Greek authorities at the base of the slope. Rockfalls were activated due to prolonged rainfall.

In the present work, we investigated some possible future rockfall tracks, along three representative cross-sections, located between the stadium and the theatre of the archaeological site, in order to estimate possible bounce tracks and calculate the related kinetic energy of the falling rocks. Furthermore, we estimated the locations and general characteristics, such as the type, height and resistance of restraining barriers which could protect the archaeological site from future unexpected rockfalls (Fig. 3).

The falling blocks vary in size and weight, and for this reason, the simulation tests were performed for indicative blocks of weight of 20tn.

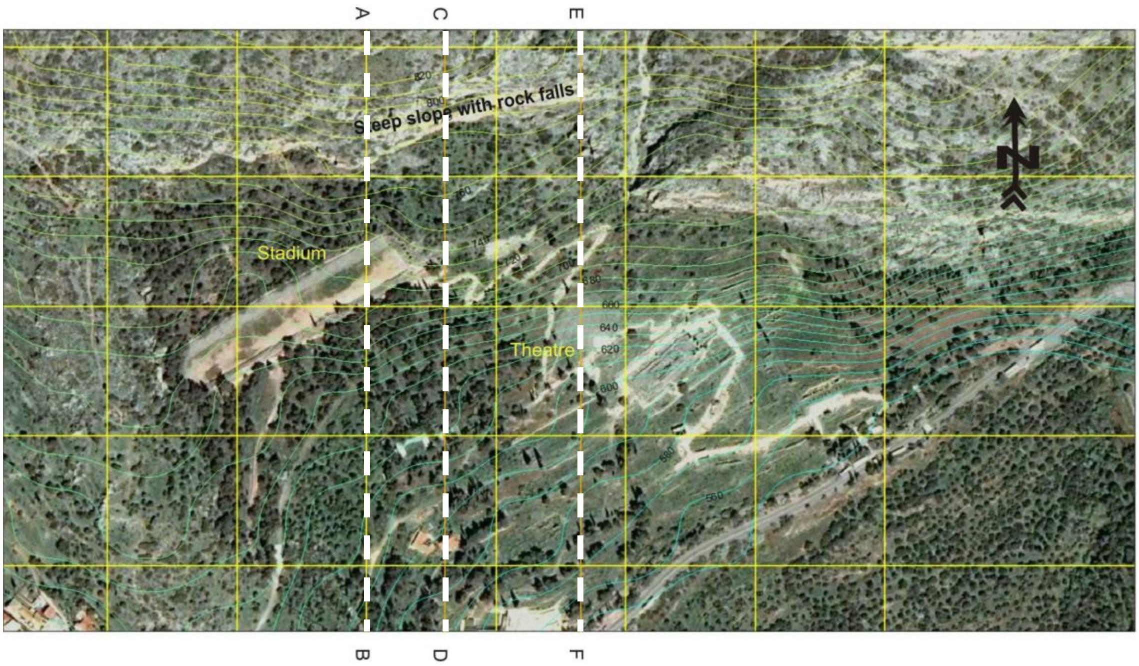

Fig. 3. Cross-sections of rockfall simulation

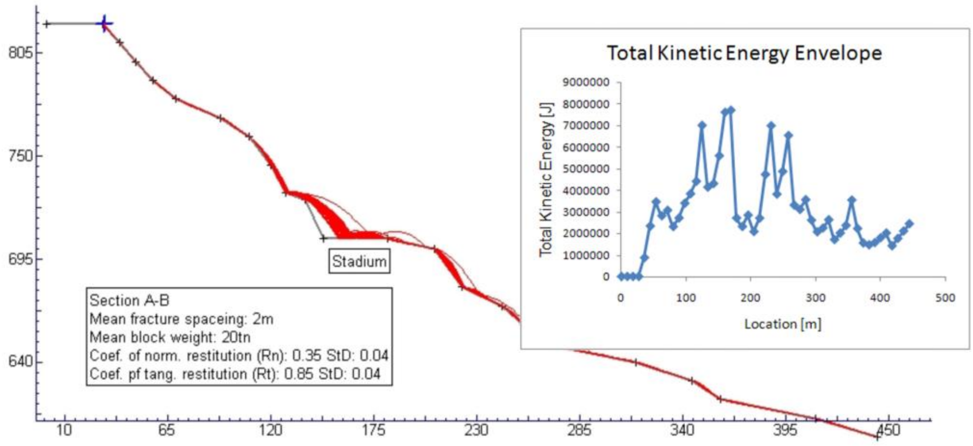

Fig. 4. Simulation of rockfalls along the cross-section A-B which crosses the stadium. The change of the related total kinetic energy along the falling track is also presented.

4.1 *Cross section A-B, passing through the stadium*

At the western part of the slope, important rockfalls repeatedly occurred, obliging the authorities to close the entrance to the stadium. Furthermore, recent rockfalls just out of the easternmost part of the Sanctuary of Apollo imposed the temporary closing of the temple's entrance as well.

In Fig. 4, a possible rockfall track is simulated along the cross-section A-B (see Fig. 2), which passes through the stadium. The mean spacing of the fractures is about 2m, creating the impression that a possible block weight of 20tn would be realistic in our rockfall calculations. According to the data in Fig. 4, falling blocks reach the stadium, having significant kinetic energy and continue downslope.

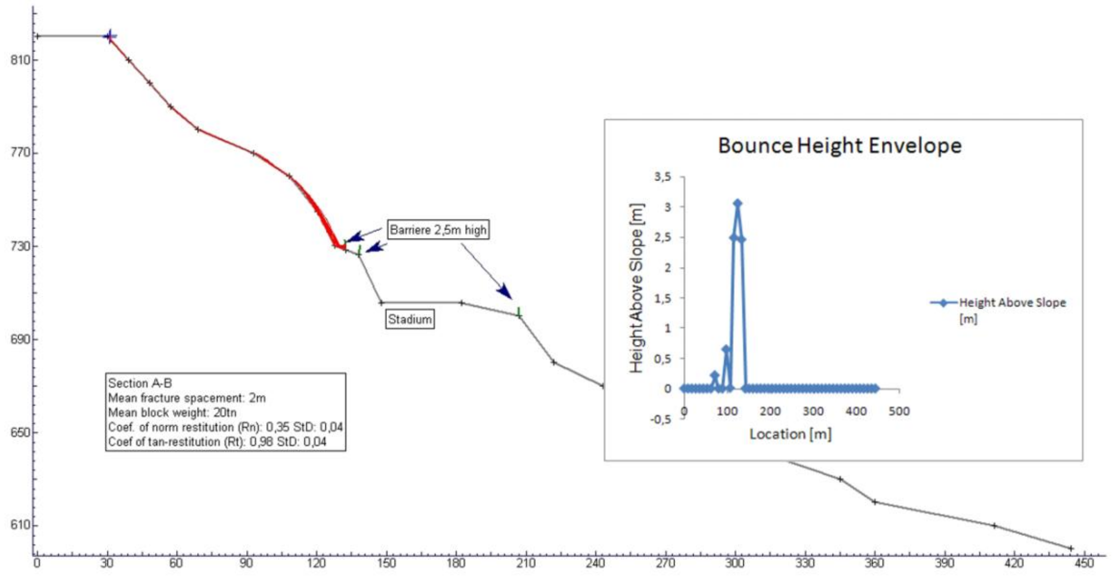

Fig. 5. Cross-section A-B. A barrier, 2-2.5m high, with capacity of 3000kj, installed (at two possible points) in the upslope vicinity of the stadium, can protect the stadium from rockfall. An additional barrier, could also be installed in the downslope area of the stadium

According to the diagrams of Fig. 5, a barrier with a height of 2.0-2.5m and capacity of 3000kj could restrain the falling 20tn rocks. These barriers could be elastic, such as metallic barriers which could be easily adapted to the environment and be removed without creating permanent damage to the monument's environment. These barriers could be installed, at an altitude of about 725m, in the upslope vicinity of the stadium, where the relief is relatively smoother, the bounce height is lower than 2.5m and the total kinetic energy is manageable.

4.2 *Cross-section E-F, passing through the theatre*

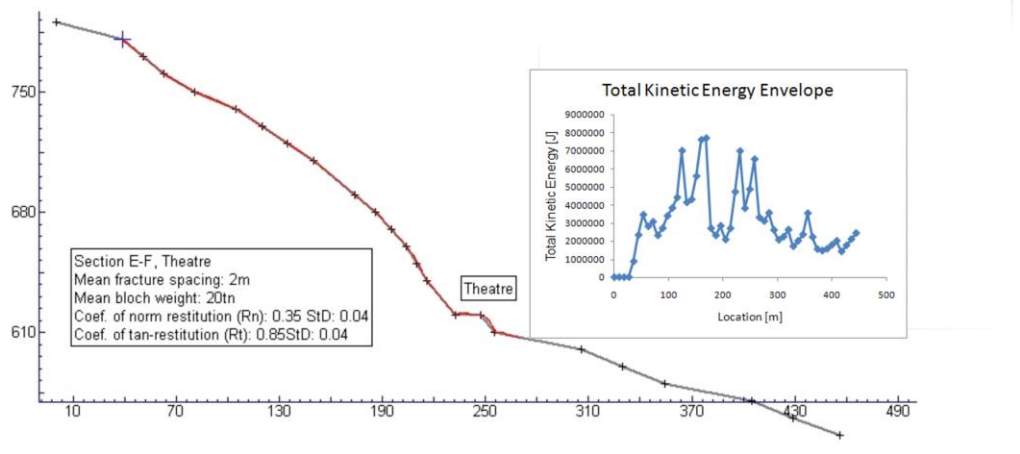

Fig. 6. Simulation of rockfall along the cross-section E-F, which crosses the theatre. The change of the related total kinetic energy along the falling track is also presented.

In Fig. 6, a possible rockfall track is simulated along the cross-section E-F, which crosses the same slope and rock material, passing from the theatre (see Fig. 3). In the rock fall simulation along this section, the mean spacing of the fractures also remained at 2m and the block weight 20tn. According to the data in Fig. 6, the maximum total kinetic energy of the falling blocks is expressed at higher altitudes than the theatre, where these blocks arrive by rolling down on the ground, having relatively low kinetic energy.

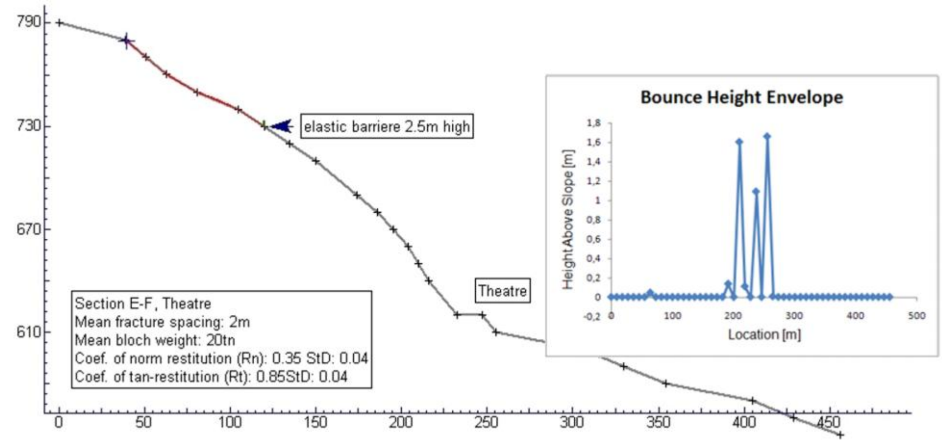

Fig. 7. Cross section E-F. A barrier, 2-2.5m high with a capacity of 3000kj, installed at an altitude of 730m.

According to the diagrams in Fig. 7, a barrier 2-2.5m high could be installed at an altitude of about 730m, similar to that of section A-B, before the bounce height of the falling blocks increases to a maximum value of 1.6m.

4.3 *Section C-D*

This section lies between the sections passing through the stadium and the theatre. It does not pass through any monument and for this reason the slope does not show artificial changes which could cause unexpected bounces with high kinetic energy. According to Fig. 8, the falling blocks roll down only for a short distance, to an altitude of about of 750m. As a few blocks could roll downslope, a barrier similar to those used in the other sections, could be installed at an altitude of about 730m, higher than the area where the falling rocks obtain their maximum kinetic energy.

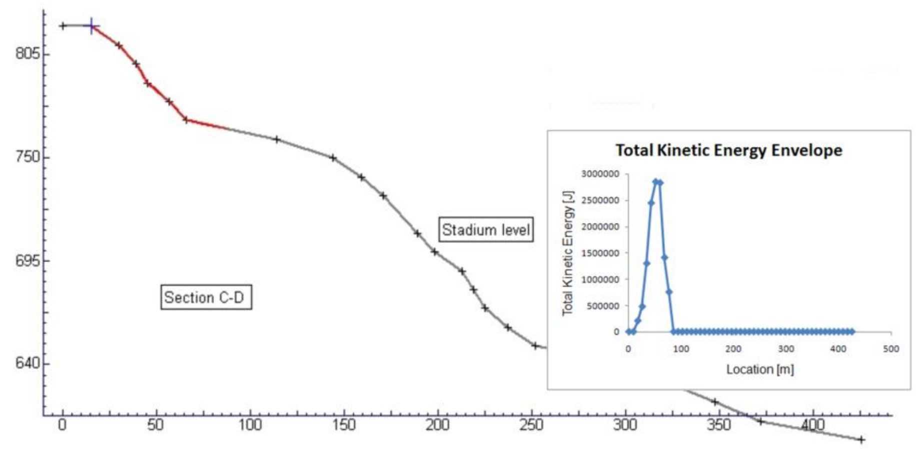

Fig. 8. Cross section C-D, located to the East of section A-B

5. CONCLUSIONS

The area consists of limestone cut into blocks of various dimensions, as a result of the active tectonics of the area.

The rockfalls are generated on the steep slope located on the northern side of the archaeological site, and have already caused damage to the stadium. The theatre is located at a short distance to the southeast of the stadium.

The falling blocks vary in size and weight and for this reason, the simulation tests were performed for indicative blocks of weight of 20tn.

According to our investigation, we conclude that:

1) <u>In section A-B which crosses the stadium (Fig. 3)</u>
    a) The simulation of the falling track confirmed the damage caused to the stadium.
    b) The falling blocks could continue actively till the southern part of the archaeological site (Fig. 4).
    c) The maximum kinetic energy of 20tn falling blocks is about 8MJ in the stadium area (Fig. 4),
    d) A barrier, 2.5m high, installed in the upslope area of the stadium (at an altitude of about 730-740m) at a location just after the rebound of the block, where the kinetic energy is low, could retain the falling blocks. For higher (additional) safety an additional barrier could also be installed in the downslope area of the stadium, for protecting the rest of the archaeological site (Fig, 5).
2) <u>In section E-F which crosses the theatre (Fig. 3)</u>
    a) The falling blocks roll on the ground in the upslope area of the theatre (Fig. 6).
    b) The kinetic energy is relatively low in the upslope area of the theatre (Fig. 6)
    c) According to the above results, a barrier, 2.5m high, could be installed at an altitude of about 730m in order to protect the theatre.
3) <u>In section C-D which passes between the stadium and the theatre (Fig. 3)</u>
    a) The major part of the falling blocks stops at the plateau at an altitude of 730-750m but a barrier, similar to those in the other sites, could be installed at an altitude of 730m.
4) The more dangerous and difficult in retention rockfall track is that which crosses the stadium.
5) We could finally accept that a 2.5m-high metallic barrier could be installed along the northern steep slope for the protection of the archaeological site.

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