IV The Consolidation and Stabilization of the Buddha niches and the cliff in Bamiyan (2003/04; 2006)

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Abstract

The historical site of Bamiyan is affected by geomorphological deformation processes which were worsened by the blowing-up of the Buddhas in March 2001, when the statues, dating back to the 6th century AD, were destroyed. Not only was invaluable cultural heritage irremediably lost, but also the consequences of the explosions as well as the collapse of the giant statues added greatly to the geological instability of the area. Traces of rocks recently slid and fallen are relevant proofs of the deterioration of its stability conditions and most parts appear prone to collapse in the near future.

Under the coordination of UNESCO, a global project to assess the feasibility conditions for the site's restoration was developed; field data were collected and a mechanism for the potential cliff and niches' evolution was provided. In the meantime some consolidation works were carried out in the most critical rock fall-prone areas to avoid any further collapse in the coming winter season, but also to enable archaeologists the safe cataloguing and recovering of the Buddha statues' remains, still lying on the floor of the niches. The emergency activities started in October 2003 and included: the installation of a monitoring system, the realization of temporary supports for the unstable blocks, the stabilization of the upper-eastern and upper-western part of the Eastern Buddha niche, the minimization of the environmental impact of the actions taken. Consolidation works were mainly implemented by professional climbers, directly operating on the cliff.

Fig. 1. The Giant Buddha statues of Bamiyan in a depiction by Burnes, 1834


Fig. 2a. The Eastern Giant Buddha before the destruction


Fig. 2b. The Eastern Giant Buddha after the destruction

Fig. 3a. The Western Giant Buddha before the destruction


Fig. 3b. The Western Giant Buddha after the destruction


1 Introduction

In the great valley of Bamiyan, 200 km NW of Kabul, central Afghanistan, two big standing Buddha statues appear to visitors (fig. 1), carved out of the sedimentary rock of the region, at 2500 meters of altitude. Following the tradition, this remarkable work was probably done around the 6th century AD by some descendants of Greek artists who had gone to Afghanistan with Alexander the Great.

The two statues were destroyed in March 2001 by the Taliban, using mortars, dynamite, anti-aircraft weapons and rockets (figs. 2 and 3). The Buddhists as well as the world community, UN and UNESCO failed to convince the Taliban to refrain from destroying this unique cultural heritage. Nevertheless, since 2002 UNESCO has been coordinating a large international effort for the protection of the World Heritage site of Bamiyan and the future development of the area.

2 General features of the area

Extensive investigations were conducted on the site, in spite of the limitation of field investigation due to landmines. In detail the following activities were performed in the period 2002 until now. Most of the collected information is reported in Margottini (2003/b), Margottini (2004/a), Margottini (2007) and Margottini et alii (2005), and developed according to the standards and procedure described in Hoek and Bray (1994), and Turner and Schuster (1996). The developed activities include:

1. the inventory of geological and geomorphological features and existing mass movements;
2. the identification of predisposing factors to slope instability (climatology, petrology, mineralogy, sedimentology, seismology, geophysical properties of rocks, mechanical behaviour of both rock masses [in situ and laboratory] and discontinuities, discontinuities distribution);
3. the investigation of potential triggering mechanisms of landslides;
4. the kinematic analysis to identify potential failure mechanisms for cliff and niches;
5. the numerical stability analysis of cliff and niches, to identify the relationship between shear strength along the potential failure surface and conditions required to trigger the collapse;
6. experiences in previous restoration/consolidation works;
7. a manual crack gauge monitoring system was also installed showing no movement in the period September 2003 – March 2007;
8. automatic crack gauge monitoring system operating at the time of stabilization works (November – December 2003 and April – May 2004)

The investigations performed in the Buddha niches and the surrounding cliff in the Bamiyan valley highlight the following main features (Margottini, 2004/a; Margottini, 2007; Margottini et alii, 2005):

1. The area is located in mountainous central Afghanistan in a dry part of the world that experiences extremes of

Fig. 4. Geological map of the Bamiyan region (Lang 1968, redrawn in Reineke 2006)

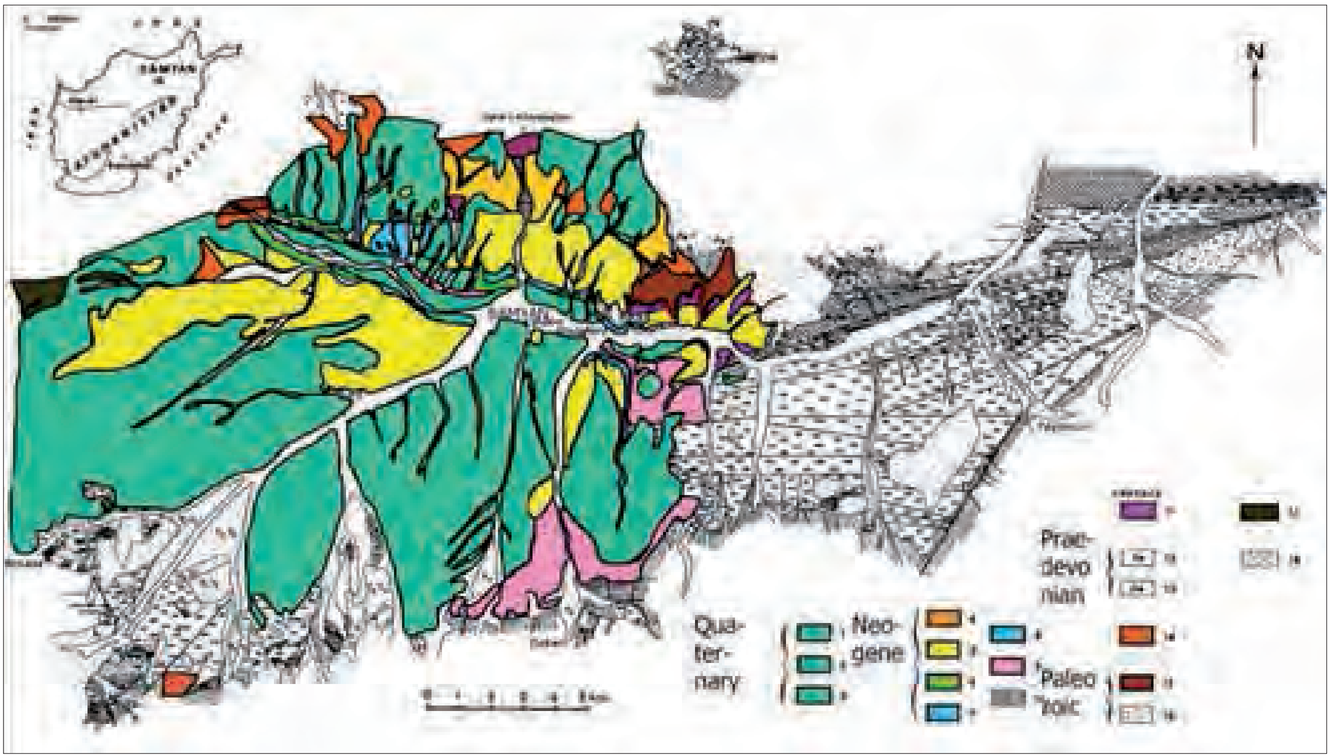
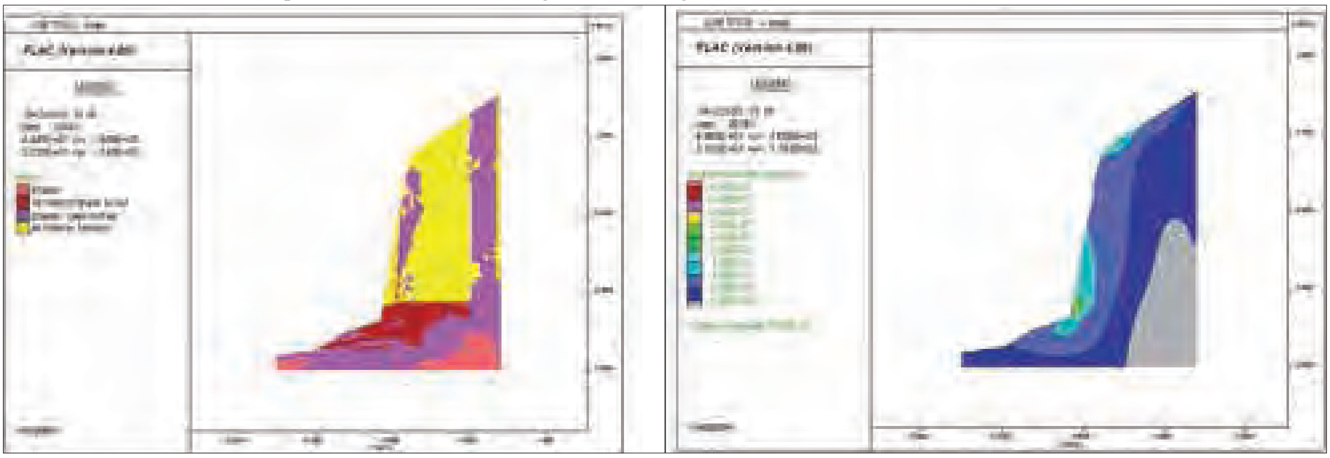


Fig. 5. The cliff with the Buddha niches and the rupestrial settlement

Fig. 6. Rock slides affecting the caves inhabited since the 6th century AD

Fig. 7. State and displacement for the cliff of the Eastern Buddha with fracturing reaching the lower part of the cliff and the lower siltstone exhibit no cohesion as consequence of internal fracturing or weathering



climate and weather. Winters are cold and snowy, and summers hot and dry. Mean annual precipitation in Bamiyan is about 163 mm and mean annual temperature 7.4°C.

2. The area belongs geologically to an intramountainous basin, subsequently filled with debris originating from the surrounding mountain ranges (Lang, 1968 and 1971; Reineke, 2006). The neogenic, more or less horizontally bedded sediments can be distinguished into four strata, which are shown in figure 4. Starting with the Eocene Dokani-Formation (> 80 m sandy carbonates and anhydrite) and the Zohak-Formation (> 1000 m red conglomerates), the so called Buddha-Formation is deposited in the Oligocene and is built up by > 70 m yellow-brown pellites, sandstones, conglomerates and some volcanic material. At the top lie the miocenic Ghulghola Formation (> 200 m sandstone, clay and lacustrine carbonates) and the pliocenic Khwaja-Ghar Formation (approx. 200 m travertine, sandstone and conglomerate).
3. The rocks outcropping in the area are mainly conglomerates, with some strata of siltstone that largely slake when wet. The lower part of the cliff is predominantly siltstone, with two main sets of discontinuities spaced every 20–40 cm. The central part of the cliff is mainly conglomerate, well cemented and with a limited number of vertical discontinuities mainly paralleling the profile of the slope.

Figure 5 shows the general view of the site with the main morphological features and the rupestrial settlements. In such a light, the Bamiyan area is likely one of the most magnificent examples of cultural landscape worldwide. Major geomorphological processes include water infiltration, gully erosion, progressive opening of discontinuities in the outer parts of the cliff, weathering and slaking of siltstone levels, toppling of large external portions as well as isolated blocks along the cliff face, occurrence of mud flows probably when the siltstone is saturated, sliding of a large portion of the slope, accumulation of debris at the toe (Margottini, 2004/a).

Large rock slides were detected in the lower part of the cliff, now stabilized, covered by a large amount of debris; the occurrence of such a rock slide is kinematically conditioned by the presence of direct faults, not reaching the upper part of the cliff. With only two large rock slides it seems to affect the rupestrial caves and historical settlements.

3 Identification of the most unstable areas

The explosions of March 2001, apart from demolishing the statues, reduced the stability of the slope, mainly in the outer parts of the niches.

In the Eastern Giant Buddha niche, in addition to the collapse of the statue, there were three minor rock falls from the top of the niche. The blasting also degraded the upper eastern part of the niche where a stairway is located inside the cliff, and the wall between the stairs and the niche is quite thin (about 30–50 cm). This part was the most critically unstable site. The western side, as consequence of an existing buttress, suffered less damage. Nevertheless, a rock fall occurred and some instabilities are also evident in the eastern part.

Major effects in the Western Giant Buddha niche were the collapse of the statue and the consequent instability of the rear of the niche. Investigations of the possible long-term stability conditions of the cliff were computed using the explicit-difference-finite code, FLAC (Itasca Consulting Group, 2000). Considering the Hoek and Brown (1980) shear strength criteria for conglomerate and siltstone, and with a major discontinuity ranging from the middle of the cliff to the middle of the niche (only friction value for shear strength) the deformation of the cliff is relatively low and nowadays it seems to be in a stable condition. Since we consider the fracture in the conglomerate reaching the lower sandstone formation and decrease gradually the cohesion of siltstone due to fracturing/weathering, the cliff becomes unstable when the cohesion is near to nil. In such a situation maximum displacement and vector are at the base of the niche (fig. 7).

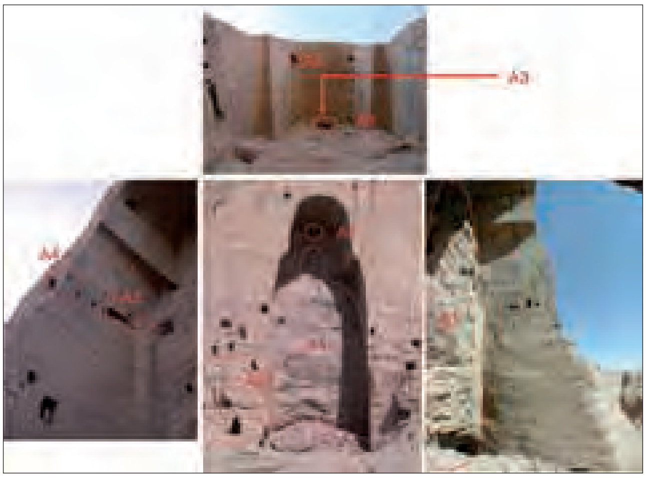
In general, the niche and the cliff need holistic stabilization work and not episodic and local intervention. Nevertheless, it must be recognized that one cannot propose a specific stabilization plan at the moment because any intervention has to be specified for the local conditions. At the present stage, it is convenient to set up a general master plan to be locally adapted according to further more specific investigations and data. The master plan includes mainly nails, anchors and grouting that will have a low environmental impact on the site.

Finally, the field data (Colombini & Margottini, 2003/a and 2003/b; Margottini, 2004/a), kinematic analysis, mathematical modeling, caves and crack distribution and detail inspection of the effect of the explosion allow the realization of figures 8 and 9 which show the most endangered sites for both niches. The explosions of March 2001, besides the demolition of the statues, reduced the stability of the shallower parts of the niches. In the Eastern Giant Buddha niche, in addition to the collapse of the statue, three minor rock falls occurred from the top of the niche. Blasting also degraded the strength of the rear of the highest right part of the niche, where a stairway is located inside the cliff and the wall between the stairs and the niche is quite thin (about 30–50 cm). This part presently has the most critical instability (A3 in fig. 8).

In the Western Giant Buddha niche, the major blast effects were the collapse of the statue and the consequent instability of the rear of the niche. A small rock fall occurred at the top of the niche (left side). Probably the greater thickness of the wall between the stairway going up into the cliff and the niche (about 1 m) inhibited the propagation of the blasting effects and resulted in less severe damage. A large crack, about 20-30 cm wide, is present in the corridor at the back of the head of the statue. Figure 9 shows the most critical areas found in the field inspection and/or identified by analyzing the different geological aspects investigated in this paper.

Fig. 8. Identification of the most critical instability areas in the Eastern Giant Buddha niche. The A3 block in the Eastern Giant Buddha niche exhibits the most acute instability

Fig. 9. Identification of the most critical instability areas in the Western Giant Buddha niche. The arrow points to a serious problem inside the niche. Other important areas to secure are A4 and the top of A6



4 Emergency measures taken from 2003–2006

4.1 Overall strategy in the Eastern Giant Buddha niche

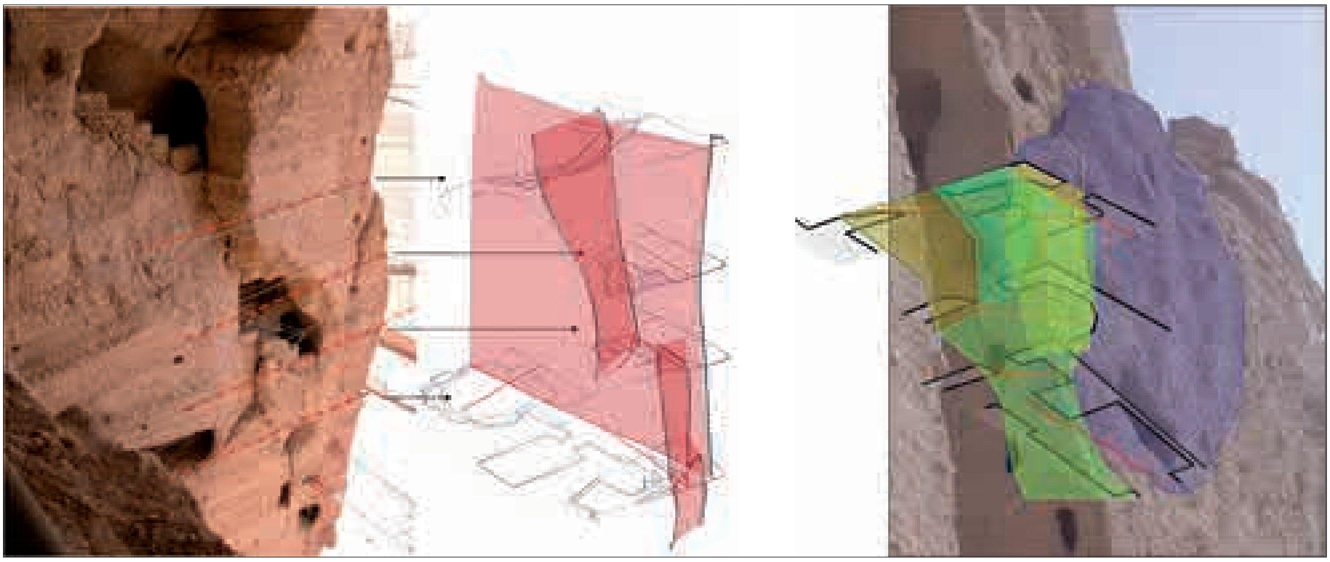
After the general strategy for stabilization, a follow up of activities was performed in September 2003, aimed to identify the potential negative evolution of the cliff and niches during winter 2003–2004. The result of a field mission suggested an immediate response to the upper east side of the Eastern Giant Buddha niche where the existing large fissures were widening and the risk of an immediate rock fall was estimated to be very high. This collapse could involve a large part of the upper eastern part of the cliff and then totally destroy the niche (fig. 10).

Emergency consolidation works were immediately planned and carried out in these most critical rock fall-prone areas to avoid any further collapse in the coming winter season, but also to enable conservationists to catalogue and recover the remains of the Buddha statues, still lying on the floor of the niches. The stabilization activities started in October 2003 and continued until the beginning of December 2003 (eastern side). A second operational phase was implemented in the period April – June 2004 (eastern side) and the final one in the period September – November 2006 (western side and top). Figure 11 shows all the study areas and the sites for intervention. Without considering the study phases, the practical activities included four different steps:

1. The installation of a monitoring system, to evaluate in real time any possible deformation of the cliff. Sensors were designed to monitor the entire working area, connected with an alarm system, to do work in safe conditions.
2. The realization of temporary protection includes steel ropes, and two iron beams suitable to avoid lateral deformation inside the niche from unstable cliff and blocks. Among the temporary work, a wire net was installed on the rear side of both niches to allow conservationists to work on the ground floor in safe conditions, just after the consolidation of the niche's wall.
3. The final stabilization of the east side of the niche, west upper side and top. In these areas anchors, nails and grouting were executed in order to reduce the risk of rock fall and collapse; particular care was addressed to the problem of grouting material due to the very high slaking capability of siltstone. The anchors placed in 2003 were pre-grouted to avoid any oxidation and then percolation inside the niche. As from 2004 it was decided to use only stainless steel materials, even if not pre-grouted.
4. Minimization of intervention (anchor/nail head finishing). Anchor and nail heads were designed to be placed slightly inside the rock and then covered by a mortar allowing a total camouflage of the work. A number of tests on the better mixture between cement, local clay/silt and water, to be used for covering the anchor/bolt heads, were also designed and developed in 2003, in cooperation with ICOMOS experts. The results highlight the better chromatic stability and robustness of the mixture.

4.1.1 Implementation on the eastern wall

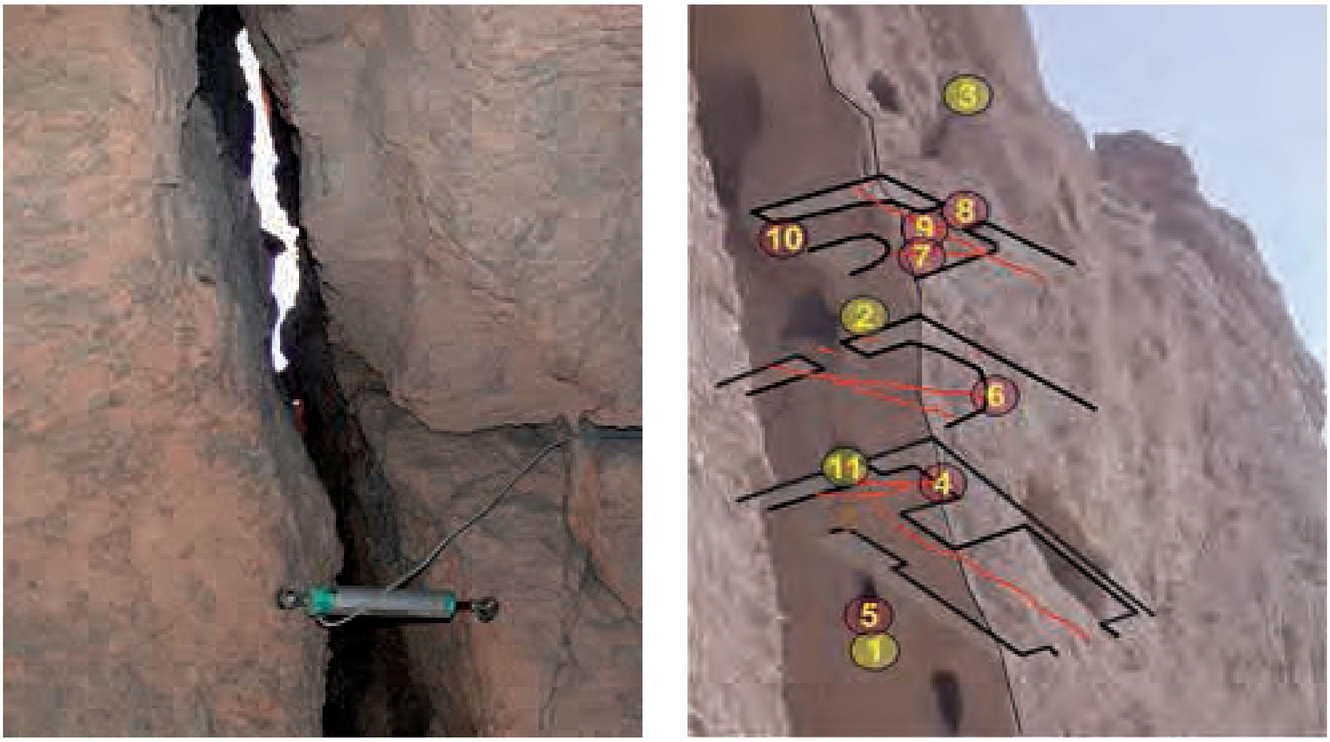
On the eastern side of the niche a large external block was prone to collapse (fig. 10), and many others in the inner part. A real time monitoring network was planned and realized to monitor the most remarkable cracks and discontinuities. 11 potentiometric crack gauges, 0–50 mm, 4–20 mA, fitted with couplings and connecting cable (total length 350 m) were supplied in the first phase in 2003, with acquisition system (data logger) and data management software. An alarm system to detect any deformation (movement) possibly induced by the works on the main cracks present in this part of the cliff was also installed. The accuracy of the gauges was requested in 0.01 mm, to allow an accurate measurement of even a small deformation. The position of sensors is reported in figure 12.
The temporary protection includes a network of 0.6"



△ Fig. 10. Pattern of existing discontinuities at four different stories (left) and reconstructed unstable blocks in the upper east side of the Eastern Giant Buddha niche (right)

Fig. 11. Localization of the three areas of intervention in the Eastern Giant Buddha niche ▷

▽ Fig. 12. Distribution of the 11 sensors monitoring the crack's underlining of the most unstable block. On the left a detail of such sensors



diameter steel ropes with a light pre-tensioning, to sustain the most unstable block from possible collapse; steel ropes were fixed to short nails, irregularly placed to avoid any stress concentration in a given line or area. Two temporary beams, located laterally, to support the cliff deformation were designed and executed. Each beam was calculated to offer a resistance of about 40 tons, similar to two designed long anchors. Figure 13 shows the steel ropes and the two iron beams. The temporary protection elements were removed in 2006.

The consolidation was designed by means of passive anchors and nails, correctly grouted. Long anchors have a spacing of about 4 m since they exhibit in this configuration a factor of safety equal to 2, without considering the contribution of nails. Nails will not follow a precise configuration since they have to be designed on site to strengthen the shallower part of the block. Even anchors may have some not-homogeneous distribution, function of internal cavities. Details of calculation are reported in the following figure 14. There we have:

1. the geometrical distribution of load and the assumption for calculation, based on mechanic of rigid mass, and the related moment;
2. the assumption for moment calculation of anchors and the related factor of safety;
3. a comparison test about the possibility to generate toppling according to the static loads and the uniaxial compressive strength of material.

A major concern, at the very beginning, was certainly the understanding of adherence between grouting material and siltstone, a very slaking material. For this reason the choice was addressed to low water release grouting. This can be achieved by mixing water and cement with superplasticizer, a chemical additive suitable to maintain the water inside the mortar. The adopted composition was: W/C = 1/2.0 + superplasticizer.

A comparison between the standard strength for anchors and the possible mobilized one was investigated. Since anchors are designed to provide 20 tons each, the borehole shows a diameter of 9 cm and the active length was limited to only 5 m, we have: 2 x 9 x 4.5 x 500 = 14131 cm^2.

Without direct tests, the adherence between the mortar and the rock is generally calculated between 6 - 8 kg/cm2; assuming 5 Kg/cm2 we have about 70 tons. Then, the assumed strength of anchor is 20 tons that divided by 70 gives a result of about 28% of normal standards; alternatively, the real obtained adherence is about 1.41 kg/cm2, that is much less than the design one of 5 kg/cm2. The resulting factor of safety is about 5, suggesting a reasonable security with the designed loads. Anyway, due to the missing of information on detail geomechanical distribution of discontinuities on the deep, these feasibility assumptions were considered in favor of security.

The correctness of the adopted solution and also of the bounding capacity of grouting mortar is given from the anchor suitability tests, performed in 2004 to understand the bounding capacity of anchors in both siltstone and conglomerate. The design strength of passive anchors was assumed to be 20 tons; for a bounded length, after the major

Fig. 13. The temporary beam (left) and steel rope (right) for the temporary support of the upper eastern part of the Eastern Buddha

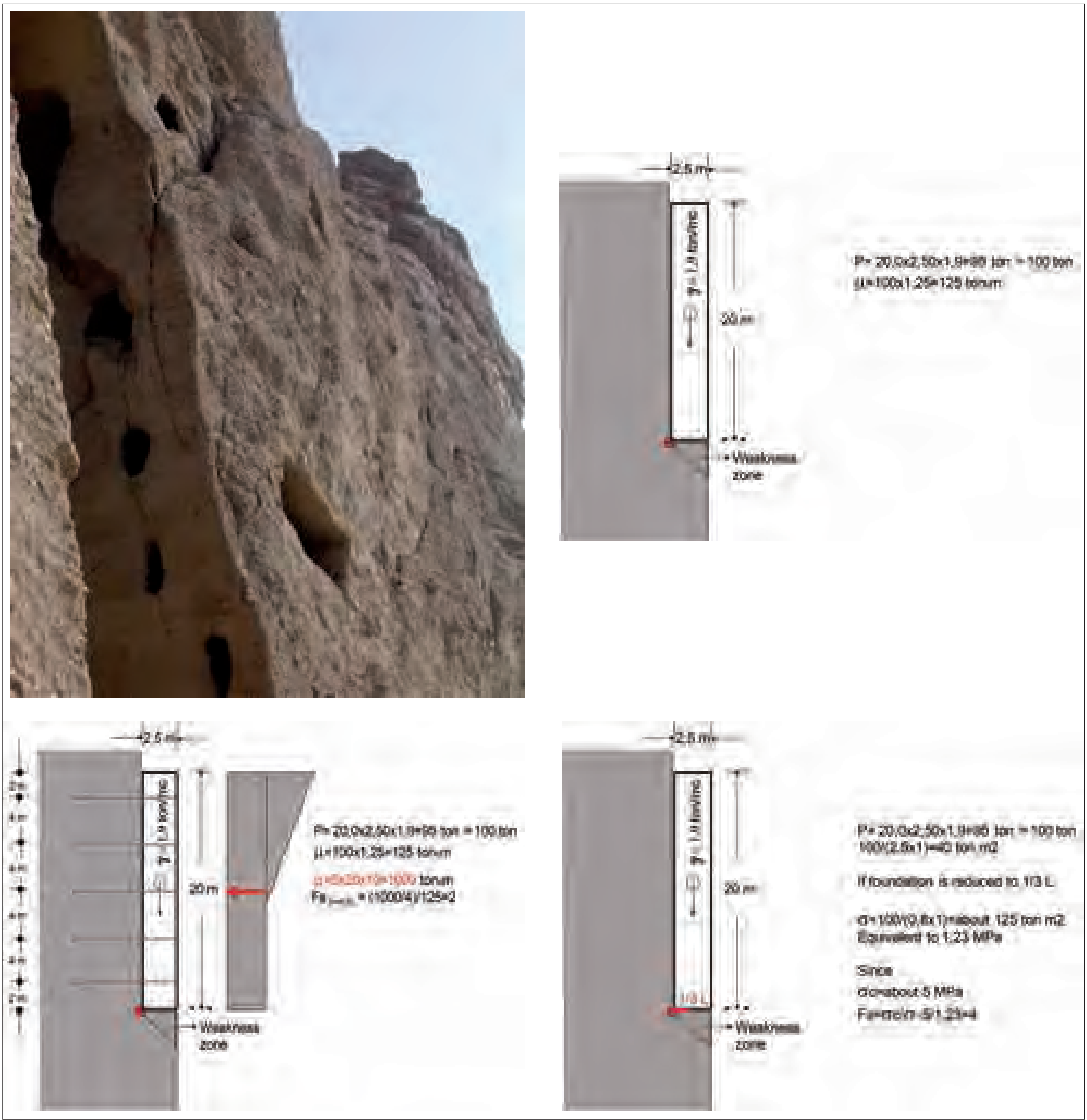


Fig. 14. The external block prone to collapse, the geometrical distribution of load and the assumption for calculation, moment calculation of anchors and the related factor of safety and an evaluation test about the possibility to generate toppling according to the static loads and the uniaxial compressive strength of material

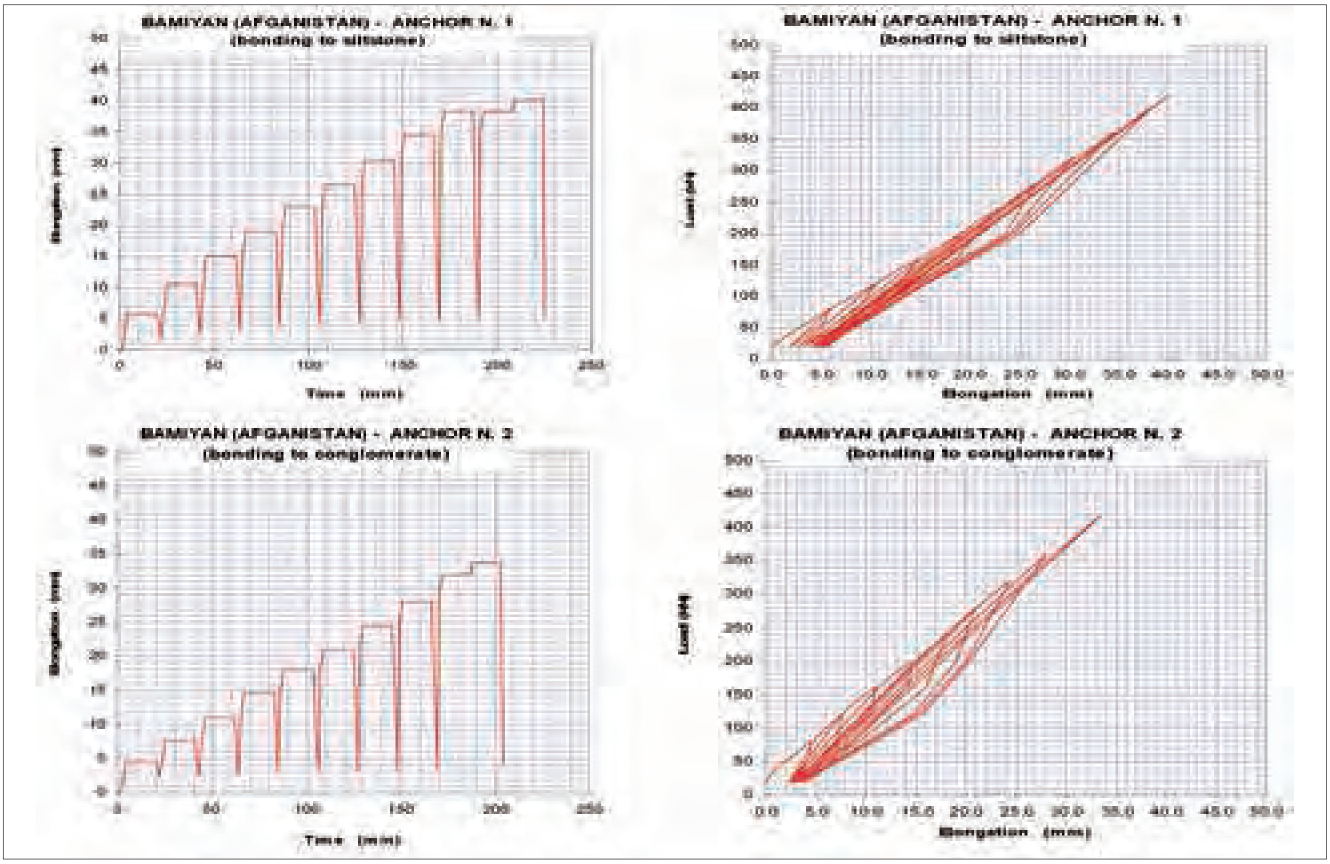


Fig. 15. Anchor suitability tests for siltstone and conglomerate, in 1 m length anchor. The load (kN) and respective time (min) and elongation (mm) are reported showing, up to 40 tons, the uphold of elastic domain and still the missing of any permanent deformation for the tested anchor

discontinuity, at least of 5 meters (about 4 tons per linear meter); the anchor suitability test was performed for 1 meter length, up to 40 tons, close to the yield capacity of steel. Up to this value no remarkable permanent elongation was detected, to demonstrate the correct bounding effect between siltstone and conglomerate and the anchors (fig. 15). These data confirm once more the appropriate choice of superplasticizer as an additive suitable to avoid any slaking phenomena in the siltstone.

In detail, in the eastern part of the niche have been placed:

1. 6 short passive anchors (steel nails, diameter 16 mm, FeB 44K, threaded, with couplers anchor plates and nut - single bar length L = 2.5 m) with diameter = 36 mm and length about 5 m, placed on the internal side of the niche (diamond head rotary machine);
2. 29 stainless steel passive anchors with diameter = 26 mm and a length of 5–10 m (in any case double of the last encountered fissure from the surface), 20 on the internal side and 9 on the external;
3. 17 passive anchors, pre-grouted to avoid oxidation, with diameter = 90 mm and length 15 m, for a total length of 200 m, placed on the external part of the cliff (Anchor bars VSL, diameter 26.5 mm, st 835/1030, pre-injected, with external corrugated sheathing, including plates and nuts).

Apart from the above-mentioned technical aspects, the main difficulty in this project was not only the typology of intervention and the used materials, but how to execute the work, also in a country like Afghanistan with low availability of equipment. Certainly, the first idea was the construction of a scaffolding but, due to the very high probability of rock fall and then the possibility of destroying it, with additional risk for the workers standing below hanging rocks, the economic cost of scaffolding itself, and the approaching winter season 2003–2004, the need to find an alternative solution came up. After a careful investigation and evaluation of possible alternatives for implementing the job, the choice fell on the use of professional climbers.

Climbers, also supported by ground staff, operated directly on the surface, abseiling from the top of the cliff, in a safe area, moving from top to bottom and then in safe condition with respect to any potential rock fall.

Another major difficulty was the calibration of drillings with respect to the existing cavities. In fact, a large number of caves (around 800) and tunnels are located in the cliff constituting a unique example of rupestrial settlement. The selection of drilling then required a detailed investigation of their orientation and inclination to avoid drilling and grouting in the archaeological caves.

As mentioned previously, great attention was paid to the methodology of consolidation. Short (16 mm) and medium (20 mm) length passive anchors (stainless steel) have been realized with a rotary drilling machine, with diamond head, to avoid any possible vibration. Cooling fluid faced the occurrence of slaking-prone siltstone in the presence of water: due to this the usage of water was limited when drilling the conglomerate and a mix of compressed air and water was adopted when discontinuities were detected and when a possible level of siltstone was encountered. Pre-grouted long passive anchors, used only in the first phase of 2003 (26 mm), were realized with a roto-percussion machine and the use of air as flushing medium. From a temporal point of view they were drilled only after the realization of shorter ones and from the further part of the unstable blocks, towards the most critical one. The purpose of small anchors is to sew all together the unstable masses and fix them to the nearby stable geological background. The long anchors have to homogenize this part to the most internal and stable geological material. Direction and inclination of anchors have been defined on site but, in any case, direction of deformation and perpendicularity to discontinuities have been taken into consideration. Temporal execution considered the principle to start from the most stable place to the most unstable. This is to start consolidation from the part where disturbance can better be sustained. In particular, with respect to the internal side of the niche, the lowermost unstable block was approached from the bottom of it to the top. In fact, at the top of the niche there is a hanging block that cannot be touched without having stabilized the lower part. Grouting was made with cement with added superplasticizer to avoid any water release capable of interfering with the slaking siltstone as well as to get the best possible adherence between bar and rock, namely composed as in table 1.

Table 1 Composition of grouting materials for both anchoring and crack filling

	Anchoring grout [kg/m³]	**Crack filling motar [kg/m³]**
Water	540	300
Cement	1360	610
Sand		1270
Additive Superplasticizer	7	7

In total, for grouting and filling in the eastern wall of the niche, approx. 17 m^3 were injected, with 19,000 kg cement divided into:

1. short anchors grouting as 1,200 kg;
2. anchors grouting as 8,200 kg;
3. crack filling (from top) as 9,600 kg;

A minimization of impact was implemented by covering all the anchor steel plates with mortar of suitable color. In such a way it is now very difficult to identify the place where anchors and nails were settled. The composition and color of the mortar was established with the support of technicians from the International Council on Monuments and Sites (ICOMOS). A final arrangement should be provided by a conservator. The following figure presents the results of the activity.

The solution and the techniques adopted as well as the four-step improvement of activities proved to be quite satisfactory, since the monitoring system did not record any remarkable deformation in the unstable blocks throughout the working period (fig. 23).

4.1.2 Implementation on the western wall

The western side of the niche also suffers from the effect of the explosion. The existing buttress was probably constructed to reduce the risk of collapse of this flank which was considered extremely unstable to justify a very massive intervention by a French archaeological expedition in the late 1950s and early 1960s, finally strengthened and mitigated in the impact by the Archaeological Survey of India in the 1970s. Since the buttress seems to be connected to the cliff with bolts, it is possible that the sunk of this structure may produce a horizontal stress towards the external, inducing additional instability as testified by the intervention of ASI (fig. 24, courtesy Prof. Maeda, Kyoto University). Nowadays, there is some evidence (e.g. widening of small cracks) from which it is possible to hypothesize that the buttress hangs from the cliff, rather than sustaining it. This situation might increase the existing damage.

The effects of the March 2001 explosion are mainly evident at the top of the niche, probably where there is a maximum concentration of stress in consequence of the morphology of the niche (arch and pillar, as described in Colombini & Margottini, 2003/a). In particular (Margottini, 2004/b and Margottini, 2006) there is a small pillar (fig. 25) that needs immediate emergency intervention before collapse, possibly inducing large deformation processes to the whole western part of the niche. This part was also completely restored by the Archaeological Survey of India in the late 1970s.

Apart from the planned minor emergency intervention, any large intervention in this area should include geotechnical investigation on the present buttress foundation and, later on, the complete stabilization of the niche. Likely, the manual monitoring system installed in 2003 does not exhibit presently any further deformation of most severe cracks. The present emergency intervention, planned in the upper part of niche, was designed in order not to fix any part of the buttress to the cliff, since its possible evolution has not been investigated.

Also in this situation the general strategy of an emergency intervention was developed in four steps:

1. A monitoring system on the most relevant discontinuities. No. 6 potentiometric crack gauges were newly installed and tested on the west wall of the niche of the Eastern Giant Buddha to monitor the cracks identified as being the most dangerous in the area of the drilling and grouting works. The scheme of installation is reported also in figure 26.
2. A temporary support (fig. 27), by means of:
   a. the two existing long iron beams moved in the upper part of the niche, to provide some lateral support to the niche;
   b. two iron/wood beams capable of supporting any lateral deformation of the small pillar; the construction details of the beam were finally adapted with the materials actually available in Afghanistan;
   c. steel ropes bounding completely the pillar and cliff; 13

△ Fig. 16
Installation of temporary struts. During the installation the strut is fixed at the top of the cliff, in the safe zone

Fig. 19 △
Execution of nails at the roof of the niche

◁ Fig. 17
Final consolidation with the use of professional climbers and large rotary machine

Fig. 20 ▷
Execution of nails with rotary machine and diamond head

▽ Fig. 18
Execution of nails for the stabilization of unstable blocks

Fig. 21 ▽
Detail of execution of nails from inside the caves by means of a small rotary machine and a diamond head

Fig. 22. Covering anchor heads with proper mortar (test site)

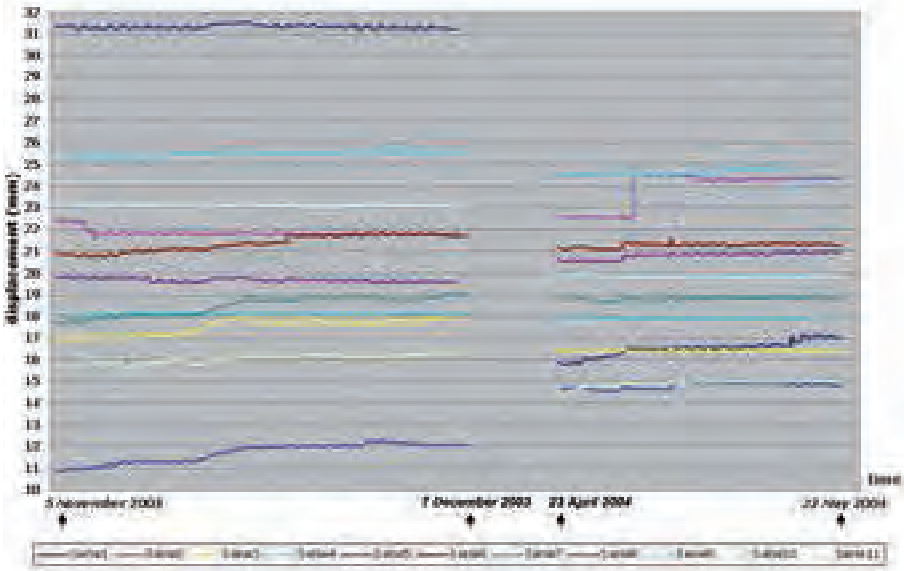


Fig. 23. Time evolution of the 11 extensometers operating in the period 5–7 December 2003 and 23 April – 23 May 2004 in the eastern wall of the niche, and showing no remarkable movements on the cliff. Some minor steps were caused by climbers, who hit the gauge placed on the cliff

Fig. 25. The most unstable element (pillar) on the western side of Eastern Giant Buddha niche ▷

▽ Fig. 24. Consolidation works done by the Archaeological Survey of India in 1969 (Courtesy of Prof. Maeda)

no. temporary steel cables have also been installed on the western side of the niche. Four of them were fixed through steel bolts on the inner/outer wall of the niche, whereas nine cables were circular cables embracing horizontally (6 no.), or vertically (3 no.), the rock pillar and the septum at elev. 2570.

3. Emergency intervention includes nails and grouting as follows:

a. Prior to starting the drilling works the large cracks in the area of the pillar at the left wall of the Eastern Giant Buddha were thoroughly filled in and grouted with cement. After the preliminary caulking, the main fissures were filled in using 0.96 m^3 of low water-release cement grout, with some 1,200 kg of cement. Grout composition utilized was, as usual, C:W= 0.5 with superplasticizer.

b. For the drilling operations, a diamond rotary system, 50 mm diameter, has been adopted with the aim of limiting interferences as far as possible, produced by vibratory effects, to the limited stability of the structure in this area. A total of no. 12 stainless steel passive anchors, diameter 20.0 mm, have been installed, with a total drilled length of 52.4 m for these 12 anchors. In detail, nine of these nails connect the pillar internally, in both directions parallel to the face and perpendicular to it to create a robust net; two short passive nails located below and above the critical pillar, with depth less than the rear side plane, where a large crack was detected after the removal of fragments in the lower caves behind the feet of the statue. One passive anchor parallel to the surface aimed at stabilizing the upper gallery where a large fissure is present.

c. Low water release grouting in the boreholes, maintaining the composition of water and cement successfully adopted on the eastern side, which includes: W/C = 1/2.0 + superplasticizer. Approx. 2.0 m^3 were grouted for the nail installation with 2,400 kg of cement.

4. A minimization of impact follows the same criteria established for the eastern side.

In the western wall of the niche, the total grout for grouting and filling was estimated at approx. 3 m^3, with 3,600 kg cement (cracks and anchors). As mentioned before, the correctness of grouting was demonstrated by the suitability test for the anchors, that do not differentiate the anchor bounded to the conglomerate from the one bounded to siltstone, in which slaking is highly possible.

Figure 28 shows the distribution of the anchors as well as the chronological sequence of them. The latter is quite important to avoid disturbance to the most critical part of the cliff without having stabilized the boundary conditions. In addition, it provides further protection against water infiltration potentially slaking the siltstone as well as generating additional pore pressure.

4.1.3 Implementation on the upper part

In the upper part of the niche it was decided to install three permanent stainless steel passive anchors, 12 m long, sub-horizontal, with the following purposes:

1. to monitor the tensional state of the rock masses by means of 10 strain gauges placed in two of the anchors;

Fig. 26. The location or potentiometric crack gauges for discontinuity monitoring and alarm; in green are external sensors and red are internal to the cave

Fig. 27. The temporary support necessary for a secure execution of the work in the western wall: two long iron beams replaced in the upper part of the niche, the short iron resp. wood struts for local support and the steel ropes

Fig. 28. Distribution of the anchors and their chronological sequence ▷

Table 2 Characteristics of the installed strain gauges

Transducer Type	Vibrating wire
Standard range	3.000 microstrain
Sensitivy	1.0 microstrain
Accuracy	0.1 % FS
Non linearity	Less than 0.5 % FS
Temperature range	-30°C
Gauge length	

Fig. 29. Drilling for the setting of nails ▷

◁ Fig. 30. Position of anchors on top of the niche. The yellow ones are monitored with 10 strain gauges

2. to grout the medium part of the cliff to avoid water infiltration within the niche during snowmelt or prolonged rainfall.

The position of these long anchors is shown in the following figure 30.
540 l of cement mix were utilized for the grouting of the anchors (600 kg of cement). Open vertical fissures, reaching downwards in the niche, were intercepted in the three boreholes at depths of up to 8 m (anchor no 39) and 9 m (anchor 41).

Anchors no. 39 and 41 were instrumented with the installation of a series of five spot weldable strain gauges (fig.31) in each anchor. The characteristics of these instruments are described below. The cables connecting the sensors were conveyed into small grooves to suitable steel boxes located in the niche, where readings can be taken utilizing the portable datalogger with LCD display.

3.1.4 Location and types of anchors and nails on the Eastern Giant Buddha Niche
In conclusion, in the Eastern Giant Buddha niche 64 passive anchors and nails were installed, for a total length of 443.5 m. The total amount of grouting was established in 19.7 m^3 of cement grout with 24,000 kg of cement.

The following figure 32 summarizes all the long passive anchors and nails and the related location.

The following table 3 reports type and length of each anchor and nail previously described.

Fig. 31. Detail of a strain gauge

4.2 First interventions in the Western Giant Buddha niche

Despite the destruction of the statue, the Western Giant Buddha niche did not suffer extensively as a consequence of the explosion (Margottini, 2006). Emergency intervention includes (fig. 33):

a. grouting of the large fissure placed in the corridor, rear side of the niche,
b. other minor sites to consolidate.

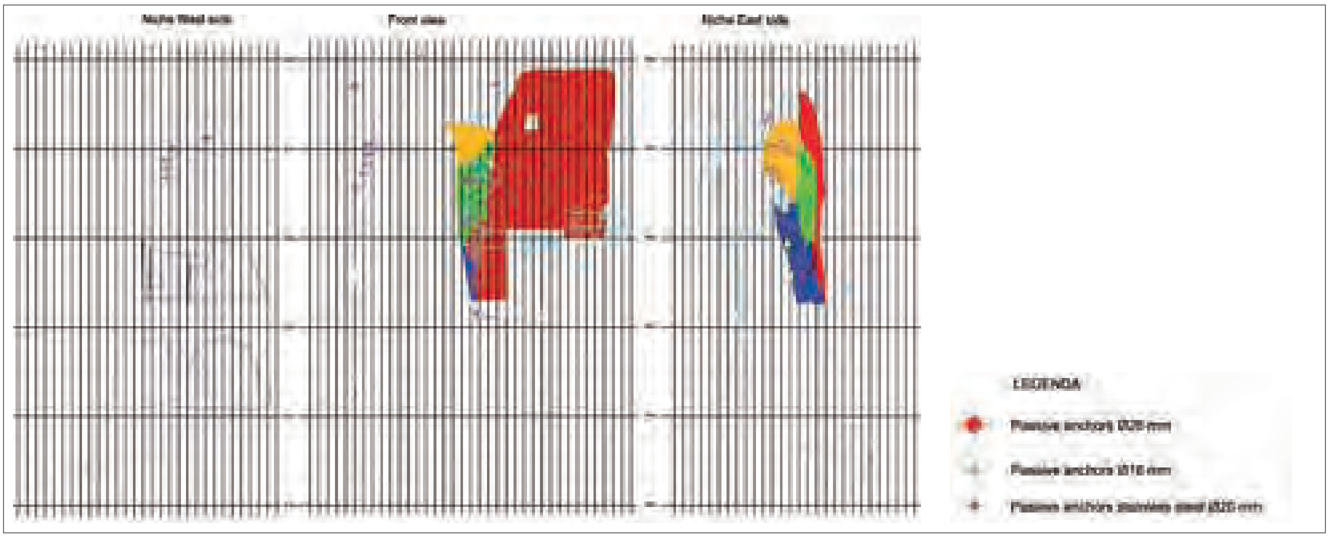
The grouting of the large crack at the rear of the niche was carried out from the inside as well as from the outside (top of the cliff). Initially, the fissure was grouted and closed in the internal part of the niche, in order to protect the niche from cement infiltration and leaching from the top. Small pipes were required inside the cement to avoid internal overpressure. From the top of the cliff, inclined drills were performed and, when the fissure was encountered in the perforation, it was grouted with the same mixture of cement and superplasticizer described in Margottini (2003/a). Major attention was required for the execution of drillings on top of the cliff, due to the possible existence of land mines, even after a complete de-mining of the site as a result of rainfall run off.

Other minor interventions were required in two small sites, as reported in the design of figure 36. The possible risk of collapse, even for small pieces of rock, was completely avoided.

5 Conclusion

The present paper describes all the emergency interventions performed in Bamiyan for the consolidation of the niches and unstable blocks resulting from the explosions in March 2001, which were aimed at destroying the 6th-century giant Buddha statues.

The effect of the explosions was quite dramatic: the two statues totally collapsed and also some small parts of the niches fell down and mainly a large part of the Eastern



△ Fig. 32. Typology, position and length of executed anchors and nails (red is for passive anchors, pre-grouted, with diameter = 26 mm and length 15 m.; violet is for stainless steel passive anchors with diameter = 26 mm and a length 5–10 m.; green is for short passive anchors with diameter = 16 mm and length about 5 m, placed on the internal side of the niche (topographic data from Pasco, 2003)

Table 3 ▷

Type and length of each installed anchor and nail (for numbers refer to fig. 32)

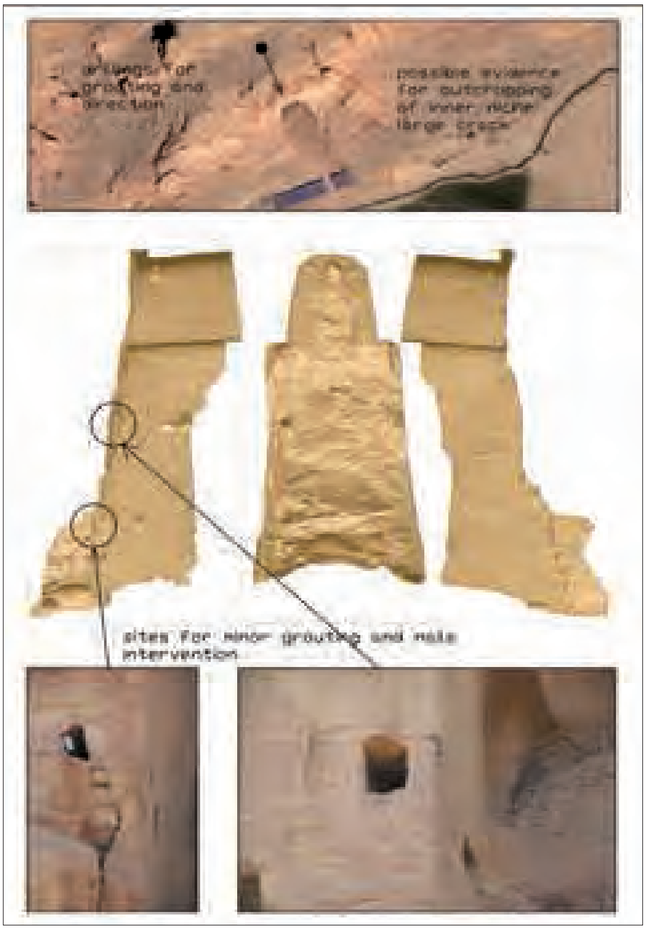
anchor	[illegible]
n°	m
A	7.50
B	7.50
C	7.50
D	15.00
E	15.00
F	15.00
G	15.00
H	7.50
I	7.50
L	7.50
M	7.50
N	15.00
O	15.00
P	15.00
Q	7.50
R	7.50
S	7.50

anchor	[illegible]
n°	m
1	4.20
2	5.10
3	5.20
4	5.20
5	4.80
6	4.50

anchor	[illegible]
n°	m
7	6.50
8	4.00
9	4.50
10	4.80
11	5.00
12	1.30 [illegible]
12 bis	5.00
13	5.00
14	7.00
15	7.50
16	7.50
17	7.50
18	7.50
19	7.50
20	7.50
21	3.50
21 bis	2.50
22	5.50
23	6.50
24	5.70
24 bis	5.00
25	4.00
26	2.50
26 bis	7.00

anchor	[illegible]
n°	m
27	1.50
28	1.50
29	2.50
30	4.30
31	4.30
32	4.80
33	5.00
34	8.00
35	6.00
36	3.00
37	2.50
38	5.00
39	12.00
40	15.00
41	12.00

Fig. 34a



△ Fig. 33. Emergency intervention in the West Giant Buddha niche (topographic data from PASCO, 2003)

△ Fig. 34b ▽ Fig. 34c

◁ Fig. 34a
Large crack in the corridor at the rear of the niche before the grouting

◁ Fig. 34b
Large crack in the corridor at the rear of the niche during the grouting

◁ Fig. 34c
Large crack in the corridor at the rear of the niche after the grouting

Fig. 35. Detail of the grouting from the top of the cliff

Fig. 36. Drilling the lower part of the niche

Giant Buddha Niche was close to collapsing. UNESCO was prompt to undertake an emergency intervention to secure the remains of such an outstanding cultural heritage and, thanks to the generous financial support from the Government of Japan, work started in November 2003.
The activities were developed according to the following general scheme:

1. engineering geological study of the site, including laboratory testing and field work (the first were conducted in Europe in few samples and the latter conditioned in their execution by the presence of land mines);
2. installation of a high precision monitoring system;
3. realization of a temporary support infrastructure, to keep the blocks stable at limit equilibrium, also during the execution of works;
4. execution of the consolidation work, with professional climbers to avoid any activities below the hanging and unstable blocks, with a system of small and long passive anchors and grouting;
5. minimization of impact of anchor heads, with a mixture of special mortar, investigated in detail with the support of ICOMOS experts.

The result was quite satisfactory for an area that is slowly coming out from decades of war, and in which it was necessary to adopt the maximum of professional judgment in identifying weak points and limits in knowledge and, in the meantime, to adopt technologies capable of solving the problems in a very short time and in safe conditions.
After the investigations started in September 2002 and the practical intervention of October – December 2003, March 2004 and October – December 2006, the cliff and niche of the Eastern Giant Buddha (the most critical part) are now more stable and the risk of collapse has almost been prevented. The niche of the Western Giant Buddha has also been protected from water infiltration. Further work will be needed in the future, especially at the rear of both niches, but at least the major risk of collapse, including also the few remains not destroyed by the Taliban, has now been averted.

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