Geotechnical Evaluation of Stability of Slopes - Mutrah and Mirani Forts, Muscat, Sultanate of Oman

Dr.Barin Chatterjee,
Er. Badri Narayan Basak and Er. Pradip Sengupta**

Abstract

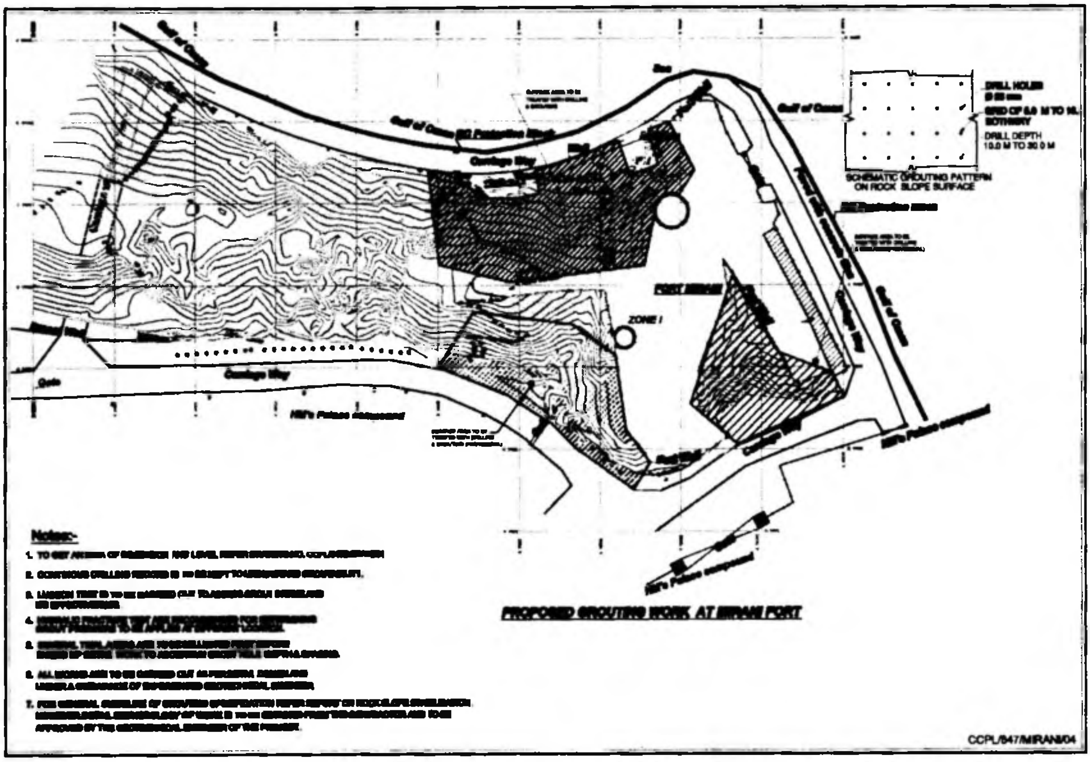
The paper covers a detailed geotechnical investigation for restoration works on the northern slope of the Mutrah fort and for the entire area around the Al Mirani fort, Muscat, Sultanate of Oman. The area around Mutrah fort is 1.2 hectare and around Mirani fort is 1.8 hectare. Mutrah Fort and Al Mirani Forts are located on rocky mountains, comprising volcanic rocks, and are situated on the southern shoreline of the east-west trending Gulf of Oman. These are very important defense cum archeological structures and have great historic as well as strategic significance. As per the information gathered, a significant restoration work had earlier been done In the case of Mutrah fort engineering structure from geological as well as geotechnical engineering perspective by M/s Atkins International. Zone-wise measures in the form of doweling, rock bolting, grouting, surface dressing and provision for structural support had been considered. Based on that, protection work for the Mutrah fort close to its base, has already been done by M/S Al Manar International LLC of Muscat, Sultanate of Oman. Objective of the present investigation at the instance of the Royal Estates of Oman was to review the surface condition of the slope by a detailed engineering geological mapping followed by determination of geotechnical properties of rock with a view to evaluate the rock strata for a realistic assessment of the probable hazards, likely to be encountered. This paper consists of detailed slope stability analysis and suggested remedial measures for the rock slopes at Muthra and Mirani Forts. The earlier recommendations in case of Mutrah fort have also been selectively incorporated. Further information is expected from the results of drilling and geotechnical Investigation being arranged by the client. Based on this additional information a detailed analysis will have to be carried out and proposal outlined here may have to be suitably adjusted and modified subsequently.

Introduction

The Mutrah and Al Mirani Forts are located on rocky mountains, along the southern shoreline of the east-west aligned Gulf of Oman, in the capital city of Muscat, Sultanate of Oman,. These are very important defense cum archeological structures and have great historic as well as strategic values.

Though these forts are founded on hard Basic and ultra basic rock stratum, with the passage of time, the weathering effect of the rock mass especially on the hill slopes has deteriorated the strength and caused disintegration in the form of development of cracks, fissures and cavities. The weathering effect is mainly caused by the saline windblast from the seacoast. In addition to this, the rainwater ingress through the joints has also resulted formation of cavities. Because of all these, the stability of the hill slope is endangered, and the foundation of the Fort structure Figure 1: Mirani fort layout has become vulnerable at places, leading to collapse of a tower in Mutrah fort. The present condition of the hill slope is as a whole critical at a number of places. Since stability of the slope is directly linked with the stability of the foundation of the fort walls near to the slope, The foundations at places are in danger.

Consultant Engineering Geologist ** Flat HIG-B-1/4, Calcutta Greens, 1050/2, Survey Park, Kolkata-700075, W.B, India, Phone +91-33-2416-2866 / (Cell) +91-9339287438;
(*E-mail: barin1940@yahoo.com; barin@vsnl.net*)
**Directors of Constell Consultant, KOLKATA



M/s Atkins International was earlier associated with the basic study in case of the Mutrah fort from geological as well as geotechnical engineering persp-ective. Topographical and Geol-ogical mapping of the hill slopes adjacent to the fort was done. Zone wise measures in the form of Rock bolting, Grouting, Surface dressing and provision for structural support were planned. Based on that, protection work for the fort wall has already been done by M/S Al Manar International LLC of Muscat.

All these basic information related to the construction work so far executed and planning for balance remedial measures to be done on the hill slope in Fort Mutrah and detailed study in Fort Al Mirani were the scope for the present work. Purpose of the study was to formulate and suggest remedial measures for stabilization of slope.

The engineering geological mapping / study in the inaccessible parts of the slope had to be done with the help of a Figure 2: Muthra fort layout cradle attached to a crane, having sufficient long arm to reach up to the top of the slope. A closer view of the specific reaches of the sub-vertical slope, recording attitudes of different sets of joints, faults and shear zones and their nature of weathering etc under the foundations of the forts was possible. In addition, the zigzag staircases through the slope on the NE corner and the SW corner of the Mutrah fort provided suitable access for measuring attitudes of the different planes of discontinuities with the help of Brunton compass. Though a geological map prepared by previous investigator was made available, the need of the site was to produce a most accurate geotechnical plan that provides spatial distribution of joints along with their specific orientation and various parametrs of joints like spacing, continuity, roughness, smoothness, filling and weathering behavior. The contours of the base map were prepared relative to an arbitrary datum plane, which enables any point on the face to be accurately located for plotting the observed geological data. This enabled correct determination of the volume of rock mass that requires stabilization and the planes of discontinuities to be anchored and treated.

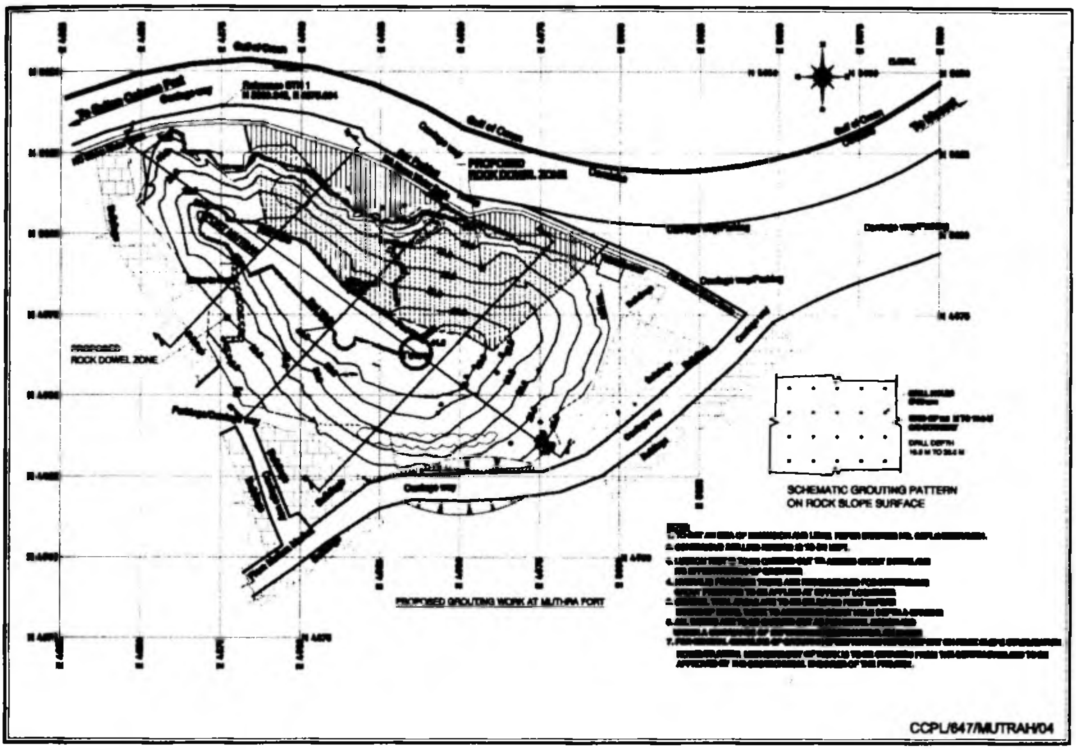


Fig. 2. Muthra fort layout

Geomorphology

The Sultanate of Oman occupies the southeast corner of the Arabian Peninsula. The coastline extends approximately 1700 km from the Strait of Homuz in the north, to the borders of the Republic of Yemen in the south overlooking the Arabian Gulf, the gulf of Oman and the Arabian Sea to the east. The kingdom of Saudi Arabia to the west and the United Arab Emirates to the northeast mark the land boundaries.

The Jurassic Sahtan Group exposed in northern Oman was deposited in shallow marine environments at the edge of the Arabian Platform facing the Neo-Tethys (Hamrat Duru Basin). The upper Sahtan Group is made up of a mixed siliciclastic–carbonate unit overlain by pure carbonate deposits, assigned to a Bathonian and Early Callovian age based on the life forms like brachiopods and foraminifers.

Geology and tectonics

The regional map has been consulted from the Field Guide to the Geology of Oman by Samir S Hanna published by the Historical Association of Oman in 1995. The oldest rocks in Oman outcrop most extensively in Dhofar, east of Marbat and on the Hallaniyat islands. They are crystalline basement rocks of the granite clan, gneisses and mica schists. Granodiorite also outcrops in a small area near Jabal Ja'alan at the southern edge of the Wahibah Sands. Late Proterozoic to Cambrian rocks outcrop in Al Huqf on the eastern side of the region of Al Wusta just south of the turning to Masirah Island, and on Saih Hatat south of Muscat. They have a largely terrigeneous and volcanic origin typical of continental shelf conditions with a transgression to a marine environment in later times.

The region of Al Jabal al Akhdar is an anticline plunging gently westwards. Its sedimentary and volcanic rocks formed an autochthonous platform over which contemporary and younger deep ocean sediments were thrust along with the overlying mantle ophiolites during the Cretaceous era. Paleozoic sediments of the Al Hajar super group form the northern flank of both the Al Jabal al Akhdar and the Seih Hatat anticlines. They dip steeply to the north.

Ophiolites of the Tethyan suture zone stretch through Iran, Turkey, Cyprus and southern Europe. The ophiolite of Oman is the largest and most studied in the world. Geologists disagree as to whether the Oman ophiolite was formed in a setting of mid-ocean ridge or in a supra-subduction zone. All workers however agree that it formed at an ocean spreading centre in the ancient Tethys Ocean. The contact is marked by a wide crush zone in which the ophiolite has been serpentinized. Fragments of ophiolite found on top of Al Jabal al Akhdar show that the mantle sequence once covered the sedimentary platform. Volcano-sedimentary rocks outcrop extensively in the centre of the Ghubrah Bowl on Al Jabal al Akhdar. Small pebbles of both igneous and sedimentary rocks are embedded in a tuffitic or sandstone matrix. Pillow lavas and greywackes succeed the volcanics. The sequence is thought to represent a series of submarine debris flows dating from the end of the Precambrian era.

The lithology of the ophiolite sequences in the Alps where it was first described by Maxwell (1973) as base comprising dunite, serpentinized peridotite and serpentine overlain by gabbro, diabase, pillow basalt, volcanic breccia, radiolarian cherts and calcareous oozes, ranging in thickness of 1 km ±. The oceanic crust (ophiolite) and flysch are squeezed and ultimately thrust over the lower thrust sheets. The low density of the continental rocks and consequent buoyancy prevented their subduction and as a result minimized the generation of magma and their thermal effects. The ophiolite and deep-ocean sediment cover is called allochthonous that is, moved from another place. The deep-ocean sediments are revealed in the Hawasinah nappe, while the ophiolites comprise the Samail nappe. The contact between the two nappes is marked by a thrust zone named the Samail thrust. Hence, this ophiolite sequence is an uplifted section through rocks, which form oceanic crust.

These rocks are very fine grained, locally containing vesicles possibly indicating different positions in the flows. Olivine is almost invariably the constituent mineral, highly stressed and weathered and serpentine veins are generally present along with secondary calcite/ magnesite veins. The olivine grains are penetrated by the serpentinite veins and altered to chlorite. The reaction process is in conjunction with the presence of high moisture and suitable temperature that exerts expansive force on the wall of the already cooled host rock resulting opening up of the joints through which the veins had entered originally. With passage of time, the veins disappear due to the weathering, which results a net work of interconnected open joints and cavities. The disposition of such structural discontinuities like faults, joints and shear zones in relation to the topographic slope, the interrelation of inclination and direction of both have great influence in causing cavities which ultimately leads to slope stability problem.

Site geology

The parent rock mass of the area is mainly Peridotite (hurzburgite) sequence in Mutrah fort area and Dunite in the Mirani fort area, with profuse quantity of olivine in a highly stressed condition, having been intruded by serpentine veins and dykes, which in turn maintain parallelism with the prevailing joints. The dykes vary in width from approximately 20 mm to 500mm. The basic bodies are also permeated by later injections of calcite/ magnesite, forming a network of veins in a columnar fashion with a basal joint. There are at least two period of dyke intrusion as evidenced by their crosscutting relation and faulting.

Megascopically, the rock types may be described as greenish grey in color coarse-grained equigranular highly altered ultramafic, plutonic igneous rock, with occasionally met with (hypermelanocratic) black spots. The rock shows a few veins and stringers of serpentine.

Under the microscope, these rocks have been classified following their mineralogical composition, grade of alteration and strength, as follows:

The original fine porphyritic texture of the fundamental type of the ultra-basic submarine volcanics with Chromites gradually changes to a moderately coarse-grained intergranular one with granulated groundmass (matrix) due to autometamorphism caused by the extensive action of residual magmatic gases and fluids from the magmatic chamber. The fluid enters into the cooling joints as network of veins with a jacketed look, which subsequently alters when exposed to water action and exposure to the atmosphere. During the process of such alteration, the veins exert pressure on the vent wall, thus expanding the joint opening. The deposit of Chromites appears to be significant as there is interstitial distribution as well. As the veins weather out, the joints are left over as wide gaps that are inter-connected. The surface water enters through such gaps into the subsurface and come out on the slope surface where the intersecting joints emerge along their line of intersection exposed to the topographic slope.

Site Condition

The mutual intersection of the jointing systems, their spacing, continuity and surface characters produce different degrees of weakness on the rock mass. Based on the orientation of the joints with respect to the topographic slope, the stability of the zone has been identified. There are zones, which have already failed leaving behind the slip surfaces (slickensided surfaces) represented by the plane of sliding of rock mass. The process of sliding is a creep movement since the rock is solid, massive and crystalline and having heavy specific gravity. The direction of slip on the northern face of the slope of

Table 1: Microscopic study of rocks below Mutrah & Mirani forts.

Rock type	Principal minerals in order of abundance	Texture	Structure	Textural bonds
Peridotite (hurzburgite) Location: Mutrah fort	Olivine (55%) Orthopyroxene (40%) Chromites (5 %)	Interlocking texture with jacketed look due to alteration to serpentine	Massive More than 75 % of Olivine are altered to serpentine as well as iddingsite(brown)	Very strong, crystalline
Dunite Location: Mirani fort	Olivine (95%) Phlogopite (2 %) Chromites (2 %) Carbonates (1 %)	Interlocking text-ure with vigorous (>75%)alteration of olivine along fractures and serpentine produces a jacketed look	Massive with increased porosity, highly fractured (regular and irregular), with	Crystalline, weakened by fracturing and increased porosity
Dunite Location:: Mirani fort	Olivine (>90 %) Clinopyroxene(5%) Phlogopite (3 %) Chromites (2 %)	Interlocking text-ure with vigorous alteration of olivine produces a jacketed look	Massive with increased porosity,	Crystalline, weakened by recrystallization, increased content of secondary interval and porosity

the hill below the fort is inevitably towards north, i.e., facing the seaside. There are two conspicuous sub-vertical faults trending N-S close to the east of the western tower and the other to the immediate east of the eastern tower trending NNE-SSW with a very steep westerly dip. Other than the faults there is a very major shear zone striking NW-SE dipping at 60º to the NE, continuing from NW of the western tower along the base of foundation of the northern wall up to mid portion of it, near the collapsed tower in the front. From here, the shear zone takes a swerve below the foundation of the fort, crosses it and continues up to the backside SE corner. Here, the shear zone meets the eastern fault below a thick talus cover, where the line of intersection emerges towards the backside (SE) corner of the slope. At this location, slightly above the perhaps road level, and on a gully depression, a Photo 1: Loose material at the foot of slope dug well has been excavated which supplies water during or after the rains for some time. Along the shear zone, down the northern slope, rock slip surfaces are prominently visible on the sheared surface, due to continuous creep movement of the overlying rock mass. On such surfaces, the rocks are disintegrated into broken, small, more or less columnar fragments of the size of 10 mm. The exposed shear surface has a net work of white veins of calcite/magnesite. The veins are weathered and there are groove type of lineation resembling slicken sides. The shear zone is exposed on the front (NE) slope below the collapsed tower at about half portion of the base of the fort wall and about 10 m to the west of the railing of the northeastern staircase on the northern slope. This shear zone has caused an extensive rockslide due to creep movement along the sheared surface, accentuated by water action. Towards the eastern side of this shear zone, there is a more than 10 m block of a rocky ledge beyond the right arm of the rockslide, which rests precariously on the sliding surface. This has also been the victim of down slope creep movement along the said shear surface. There is another similar rock fall area towards western side of the bottom of the fort wall, which appears to have been resulted by a number of intersecting joints over the sheared surface, adversely oriented with respect to the topographic slope (photo 2). This needs thorough judgment whether to retain it by dowelling/ rock bolting/grouting or to unload it very safely without further disturbing the already disturbed slope.

The detailed structural analysis with the data on joint systems has been carried out by plotting the rose diagram, three dimensional represent-tation of the joint planes on Stereographic Net, plotting the δ-poles (projection of the normal to the joint planes) on equal area nets and then contouring these points by Gaussian method and by Schmidt's

method for evaluating the cluster of poles with a view to enumerating the direction of rock bolting/ doweling/rock anchoring in a multi-directional enviro-nment. From the rose diagram of the directions of joint dips, Photo 2: Muthra Fort- Rock mass condition it is evident that there are five predominant sets of joints.

(i) dipping northerly, (ii) dipping towards N30ºE, (iii) dipping toward S20ºE, (iv) dipping toward S30°W and (v) dipping towards Westerly. Out of these five sets, only three sets are vulnerable as these dip in the direction of slope. These are

i. Dipping Northerly,

ii. Dipping in N30ºE

iii. Dipping Westerly.

Accordingly, the direction of bolting / anchoring / grouting should be in the opposite direction (180º) to the mean direction of dip of the aforesaid three sets. The angle from horizontal should range between 60º to 70º towards S30ºW (210º), following the Contour Diagram of the ð- poles by Schmidt's method, in a grid pattern at spacing of 3 m both horizontally and vertically. The depth of penetration should definitely be staggered between 3-6 m in a haphazard way to avoid creation of another plane of rupture. The direction of anchoring may require to be changed at the time of execution depending on site condition.

Photo 3: Muthra Fort- Rock slope with joints

Although groundwater movements are considered restricted and insignificant factor, up in the hill slope, there are innumerable holes and cavities at levels up to more than 1000 m where at least temporary existence of subsurface water is beyond doubt. Here it is the question of exit point of rainwater that enters into the subsurface and then comes out along the line of intersection of the adverse joints to be exposed to the topographic slope. Repeated rains cause enhancement of holes

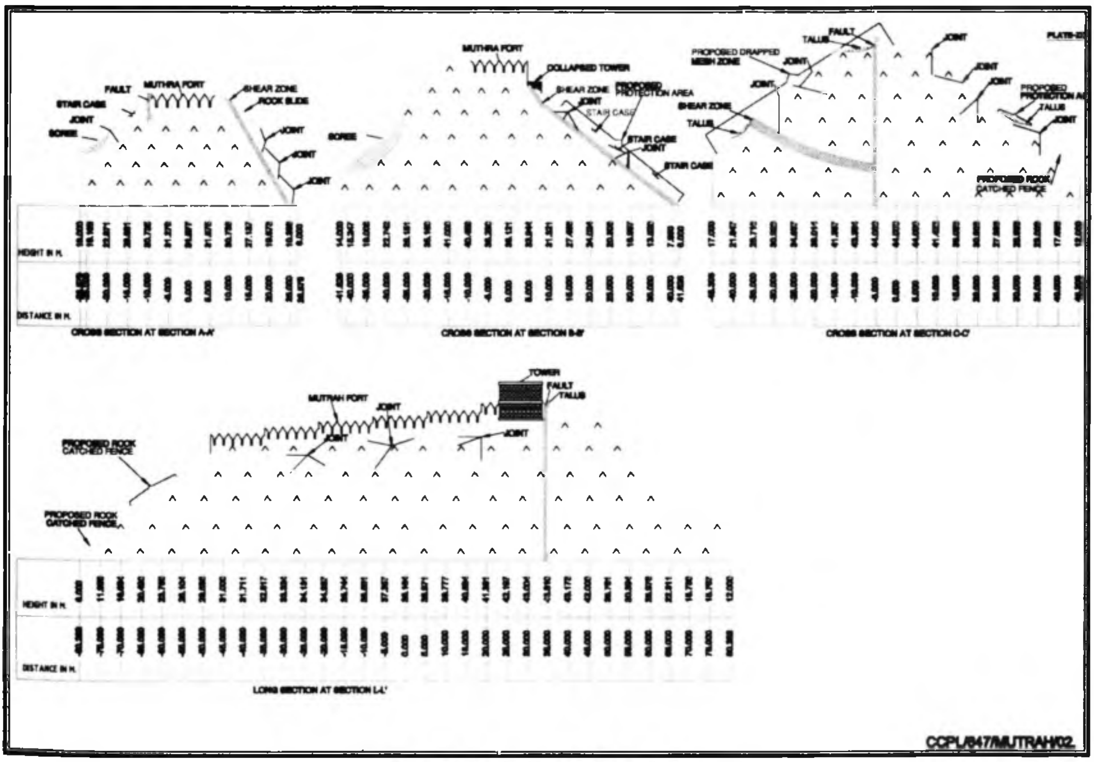


Fig. 3. Sections of Muthra fort

in the same location of the exit point. During dry season, the wind blast from the seaside carrying salty sand particles get stuck to these points of exit and as soon as the holes become dry, these sands mixed with salt act upon as abrading agencies due to whirling motion with the windblast. Thus, the whole hillock of a solid hard ultra-basic rock mass is punctured at innumerable places with well-extended lateral voids in different directions inside the hill. Such extensive voids lead to rock sprawls and collapses on the slope, giving rise to talus and bluff rock deposits.

Geotechnical aspect

The stability of the hill slope is critical, and the foundation of the Fort structure has become vulnerable at places, leading to collapse of a tower in Mutrah fort. The present condition of the hill slope is as a whole stable excepting a number of places, where the inherent weakness of rock mass has posed serious problems of slope failure / rock falls. Since stability of the slope is directly linked with the stability of the foundation of the fort walls near the slope, the foundations at places are in danger. Stability analysis has been done depending on the physical properties of the grabbed rock material and point load tests were done, since drilling work was yet to be done. Many attempts were made to classify the rock based on intact rock characteristics like uniaxial compressive strength, modulus of deformation and point load index. However, such simplified classification system is not very relevant to field engineers, but have served to understand the upper bound response of rocks. However, they form important constituents for arriving at rock mass classification. It is well recognized that the engineering behavior of rock mass is controlled by many factors; the influence of each of these factors vastly differ. A number of factors such as Joint Spacing, Joint Orientation, the nature of Joint Surface and nature of Joint Filling have been recognized to be influencing factors for rock mass behavior.

Slope stability analysis

As revealed from the slope stability analysis, the overall factor of safety of the rock mass against sliding is in many cases less than a desired value of 1.5. It is therefore been recommended that the entire zone needs to be treated to make the weak zone integrate with each other. This can be achieved by various methods but considering all aspects, following remedial methods have been recommended.

Rock properties like Shear strength parameters i.e. 'C' & 'ö' were assumed as follows with respect to their inherent weakness and weathering state.

i. For materials within shear zone a lower order value of the order of 25º to 30º degrees friction angle, with low order cohesion.

ii. That for intact rock below the defective zone friction angle of the order of 40º was assumed along with higher order cohesion value (200 KPa). These assumed values are to be further modified when actual laboratory test results along with drill records are made available.

Stability analysis has been carried out for the two sites/ fort areas, using state of the run software for slope stability analysis. Bishop and Peterson methods were followed, with typical circular and polygonal slip circles were considered for the analysis. Besides stability analysis was also done using Rock Slope Analysis software.

Muthra Fort

Slip circle analysis of the northern part of slope Cross section AA on northern side shows a lower factor of safety. Using Rock Slope software the out come of result is also same. Comparing two such analyses, with one having low shear zone extending to mid slope region and the other with low shear zone extending down to toe level of the slope, indicate the failure mode is expected to be

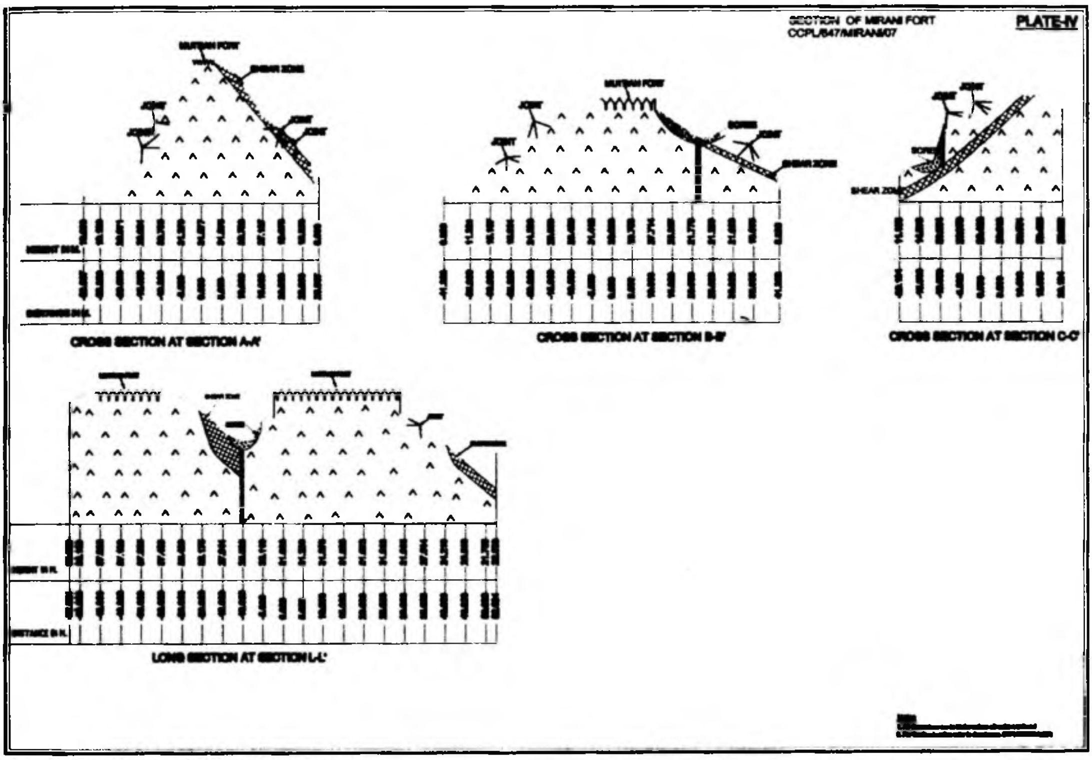


Fig. 4. Sections of Mirani Fort area

near the toe. Slip circle analysis of the southern slope of the same cross section shows the scree material to have very low factor of safety. Hence, some remedial measures were considered for this scree zone on the southern face of the Mutrah fort.

Similar analysis was done along cross section BB. Low order shear parameters were used for the fault zone material. Analysis shows though the slope is marginally stable but from the physical nature of the fault, it will be advisable to extend the remedial measure of section AA to this area as well. Slip circle analysis through the scree material of this zone indicates similar results as computed for section AA above. Section CC of the area contains shear zone & Fault along with some Talus. Such defects are difficult to analyze using simple tools like Slip Circle analysis as above. Engineering Judgment and instrumentation upto considerable depth will be a better option. Therefore, remedial measures like grouting is a preferred option than rock bolting or similar structural support.

Mirani Fort

At this rocky slope, most critical part is the northern face. (sectional views AA & BB). A shear zone with several joints and Scree deposit exist in the area. Slip circle analysis carried out based on assumed rock properties show that the Factor of safety against sliding force is inadequate and requires overall improvement of the rock mass characteristics.

Section AA indicates a shear zone on the northern face. Since quantitative analysis using slip circle was difficult, an assumed lower order shear strength parameters (C & ö) attributing to the shear zone material properties, were used in the analysis.

Analysis with the provision of rock anchors has shown considerable improvement of the rock mass characteristics. Practically rock anchors along with Injection grouting will strengthen the rock mass. Similar analysis was done along Section BB. With existence of Scree and Shear zone at the northern side of the area, the analysis result show the rock

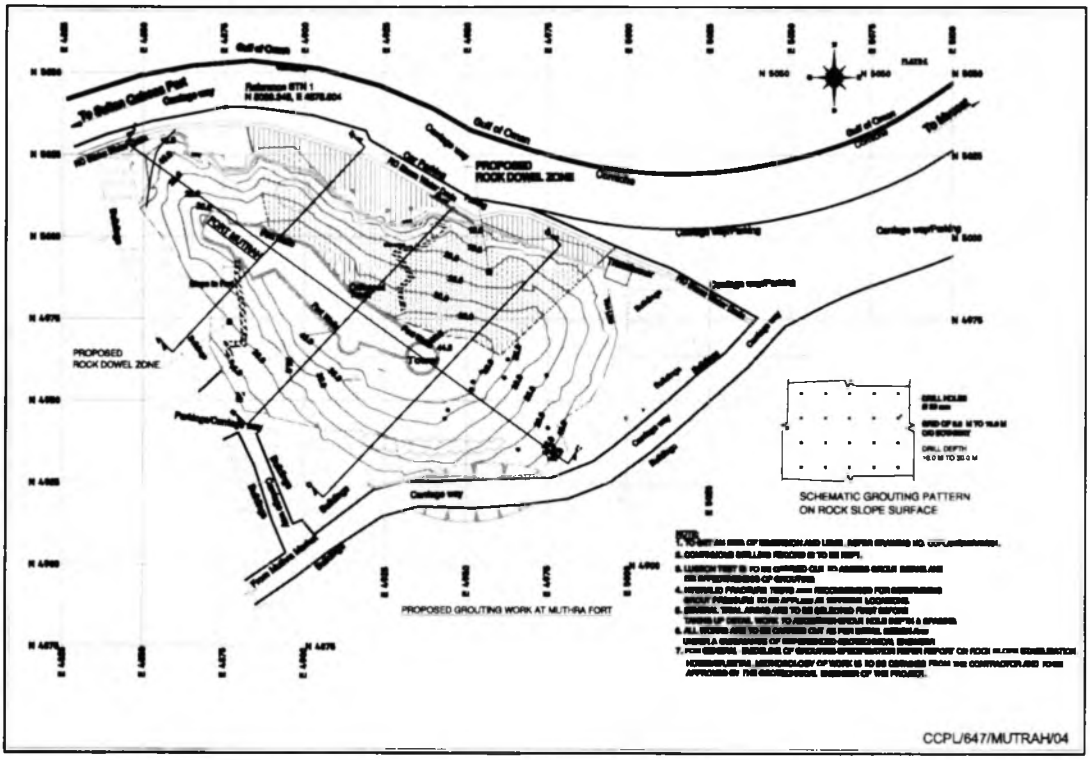


Fig. 5. Muthra Fort- Area requiring Grouting

mass to be stable with suitable protection measures.

Recommendations

Grouting

Cracks and fissures are to be filled in and this can be achieved by injecting grout. Cement grout is considered the preferred option. Surface openings are first to be filled to prevent the grout to remain inside the voids. This can be done by applying chemical paste. Alternatively, epoxy chemical grout / Polymer grout can be applied. Once the opening is closed, cement grout at a very low pressure or just by gravity pouring can be injected inside the cavities/ voids.

Pressure grouting by injecting a fluid grout in the rock very especially into the cracks, fissures and voids between the solid rock ingredients will be required. This grout will replace the air and water and allow the loose particles and thus will expel water through the mass and also provide added strength. High pressures are needed during the injections, not only to force the liquid grout into the fissures, but also to expel the water and loose particles already existing inside the fissures. Cement grout is the most common in use. Other forms of grout like various chemical grouts, Salt grout, clay grout etc are very much in use now a days.

The rock slope below the foundation of the two forts, the existing structure may get affected by uplift pressure of the grout, experienced supervision and engineering judgments are absolute necessities.

Fractures containing clay or other such fine material are difficult to be grouted. If the fractures are very tightly packed or filled with filler material, it will not be possible to grout except at the immediate surface of opening. Depending upon the condition, clearing of such fracture zones can be tried with compressed air and/or with high-pressure water jet. For deep cleaning a group of drill holes can be made in the cells for treatment. Water or air is applied alternately to the holes in rotation resulting in the gradual scooping out and removal of the clay filling which gets washed out through the other holes in the grid.

The type of grouting required in the project will be fundamentally consolidation grouting to achieve homogeneity in rock mass to avoid settlement and increase in the shear strength parameters and make the foundation monolithic.

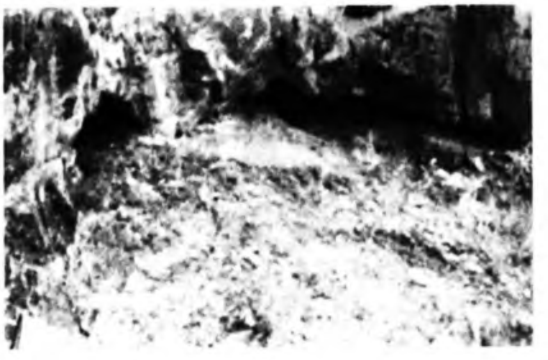
Consolidation grouting is normally carried out by treating a grid of holes at centers varying from 3m to 12m depending upon the nature of the rock. If grout intakes are large it is normal to adopt superimposed grid which will reduce the final spacing to 1.5m or even less. staggered pattern varying between 10 m and 30 m has been recommended.

It is often practiced to observe the improvement in the rock properties by assessing the modulus of elasticity. The dynamic modulus of elasticity can be measured by seismic sounding. Seismic refraction test is recommended for these two project locations which is to be carried out on the treatment surface/ zone before and after grouting.

Safe pressure is always a big question for such grouting work. The safe injection pressure which can be applied must depend on the state of stress in the rock mass at the time of the injection and, since this is not known in advance it should be judged from experience and through field tests. Hydraulic fracture tests are possible means to ascertain safe working pressures. In this test, water is pumped in for fixed period at successively higher pressures as long as the quantities of water being pumped in maintains laminar flow, i.e., the graph of water acceptance against pressure will be a straight line. Any sudden increase in the slope of the line, will indicate fracturing/ dilation of the joints.

Colgrout

Where the openings are of large sizes, gravel / cobble may be packed from the surface, leaving perforated pipes kept inside prior to placing the gravel / cobbles. After packing, the openings grouting can be resorted through these perforated pipes. A number of pipes may have to be inserted depending upon the volume of grout to be injected. Open cavities can also be filled in by this process.



Such aforesaid cavities (photo-4), especially on the rock slopes below the base of the Mirani fort were studied in detail by taking very close photographs along with plotting in front elevation drawing on the northern and the southern faces in order to understand the nature and origin of such harmful features and suggest suitable measures for controlling their enhancement. It required complete detailing in case of the Mirani fort hill on either flank to Photo 4 : Mirani Fort- Cavities under the slope understand the nature and origin of such harmful features and suggest suitable measures to arresting their increase. Though in general the cavities appear to be aligned along the direction of intersecting predominant joints, there is exception on the eastern face in particular and to a major extent on the southern face as well, where human activities play the most dominating role

Rock Reinforcement

Rock support is the application of passive resistance to the discontinuities to accept loads imposed by rock, to arrest failures and instability. Rock reinforcement is a method of adding strength to such destabilising rock mass against failures. The most usual forms of reinforcement are rock bolts and stressed cable. These are used to stitch the rock in such a way that resistance to shear along plane of weakness is improved and some tensile strength is given to the rock mass. Steel rods, known as dowels are often grouted into rock to act as reinforcement; these are not stressed when positioned.

i. Rock Bolts

This is a reinforcing element, normally made of solid or tube formed steel installed, as un-tensioned or tensioned, in the rock mass. Different types of rock bolts are now used worldwide. In general following group of bolts are considered.

Mechanically Anchored Rock Bolts

The expansion shell anchored rock bolt, of standard or bail type, is the most common form of mechanicaly anchored rock bolts. The expansion shell anchor operates in the same norm whether it is of standard or bail types. A wedge attached to the bolt shank is pulled into a conical expansion shell as the bolt is rotated. This forces the shell to expand against and into the wall of the borehole. The two mechanisms by which the shell is anchored against the borehole wall are friction and interlock. The interlock is the most significant in order to provide optimum support action for the rock bolt. Expansion shell anchor has the advantage of low cost. The bolt gives immediate support after installation. In hard rock, high bolt load can be achieved. The bolts are mostly used in moderately hard to hard rock. This can only be used for temporary reinforcement unless corrosion protected with post grouting.

Grouted Rock Bolts

Grouted rock bolts have been commonly used worldwide for the past forty years both in mining and civil engineering applications. The

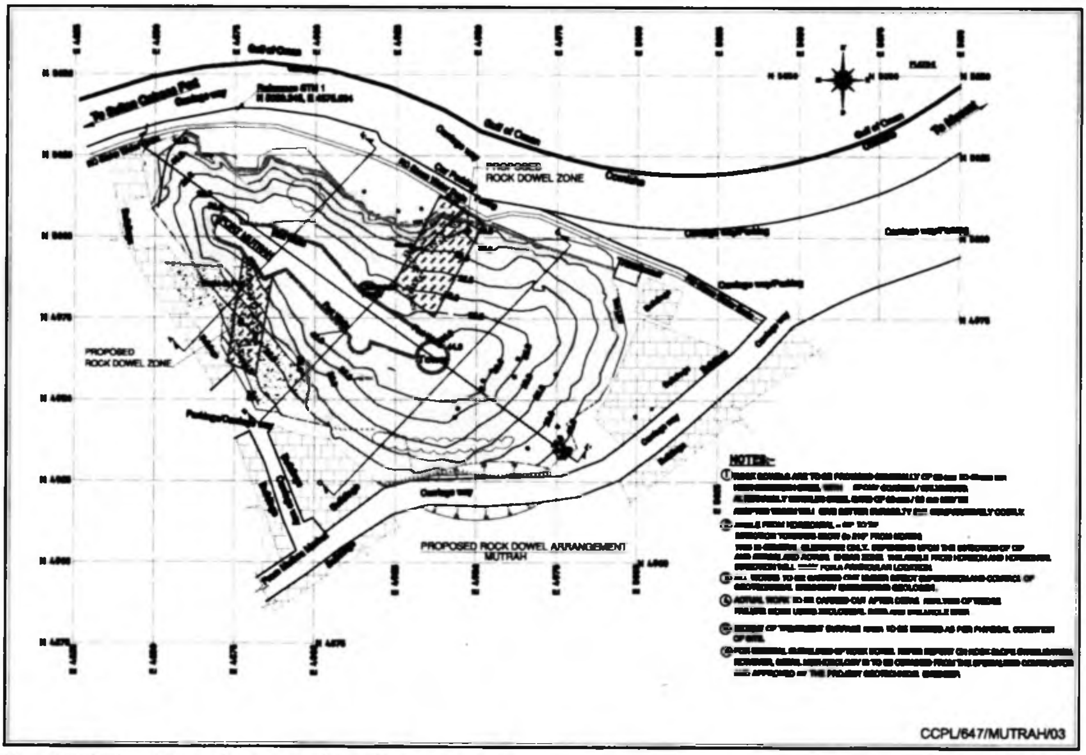
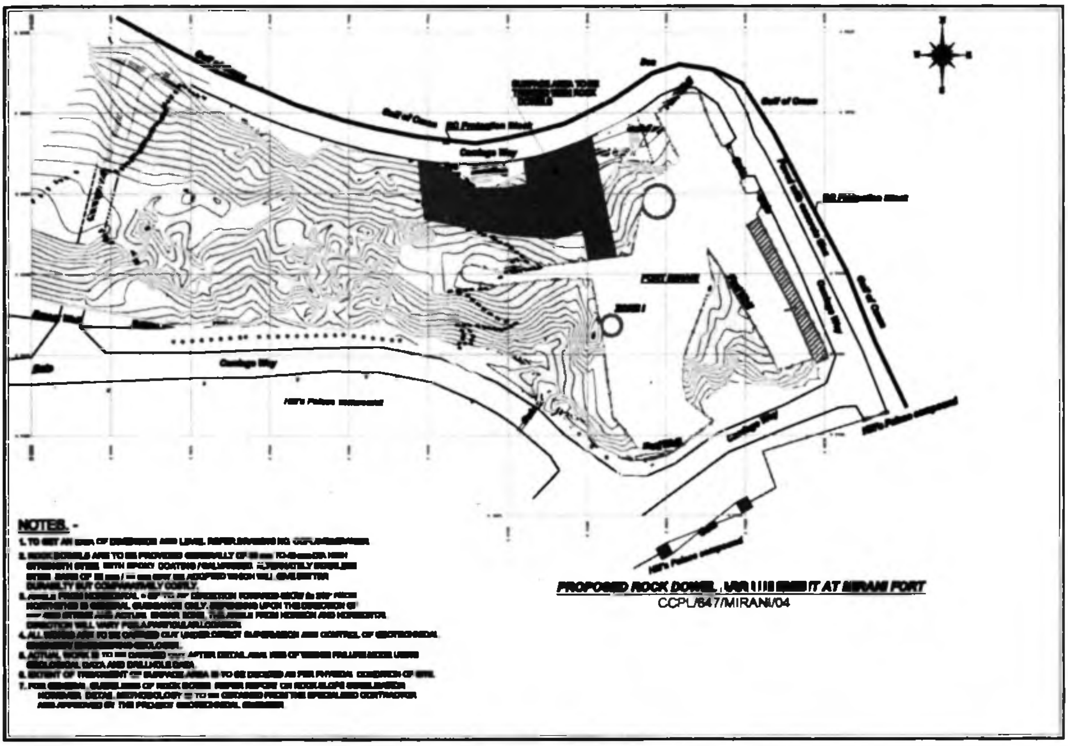


Fig. 6. Muthra Fort- Area requiring Rock dowels



most commonly used grouted rock bolts is the fully grouted rebar or threaded bar made of steel. Cement or resin is used as grouting agent. The rebar or the threaded bar used with resin grout creates a system for tensioned rock bolts. More common, however is the rebar or the threaded bar used as un-tensioned bolts, i.e., dowels, with cement or resin as grouting agent. Cement or Resin grouted Rock bolt – Rebar has the advantage of durable reinforcement system if properly installed. The system provides high load bearing capacity in hard rock conditions. In case of resin bonded one, the setting time is very fast. Resins have a limited self-life.

Friction Anchor Rock bolts

Friction anchored rock bolts represent the most recent development in rock reinforcement techniques. Two friction anchored rock bolts types are available, the split set out the swellex. For both types of rock bolt system, the resistance to sliding (for the swellex combined with inter locking) is generated by a radial force against the borehole wall over the whole length of the bolt. Friction anchored rock bolts are the only type of bolts where the load of the rock is transferred to the reinforcing element directly without auxiliaries like mechanical locking devices or grouting agents. The anchoring mechanism of the split set will prevent the bolt from sliding up a load of about half the ultimate tensile strength of the steel tube, when the bolt will start to slide. The bolt can thus accommodate large displacements.

Swellex- Swellex is a simple friction rock bolt. It is a deflated tube like a snake balloon; instead of case of balloon), it is a deflatable steel tube. The anchor mechanism of the swellex is friction and mechanical interlock. When the EXL Swellex is subjected to a load that approaches the ultimate tensile strength of the bolt, the bolt starts to slide. The EXL Swellex can thus accommodate large rock displacements. In deflated (crimped) condition , the diameter is smaller than that of hole drilled in rock. Then the tube is inserted and inflated by hydraulic pump with a pressure of about 200 bar. As it inflates in hole, the entire surface of tube exerts high pressure on rock surface and creates a passive resistance force on it. This prevents unrestricted rock deformations. Another unique advantage is that, the bolt never fails. If the deformation stress is more than friction resistance then the bolt allows just marginal deformations to take place and it still imposes same frictional resistance after such marginal deformations. The life is not more than grouted rock bolt as the grouting around it is not feasible. However, with special non-corrosive steel the life can be enhanced.

Rock Dowels

To integrate the fractured rock mass Rock dowels are considered at the site extensively. These rods should be of high strength deformed bar similar to the reinforced concrete structural works. High yield strength (460 N/mm$^{2)}$ bars of 36 mm to 40 mm dia may be suitable. To give the dowel rod durability. Epoxy treatment is recommended. Drill holes of approximately double the Figure 7: Mirani Fort- Area requiring Rock dowels bar diameter i.e., say 75 to 100 mm (or ever 125 mm) is to be drilled using low vibration drilling machine. The pattern and layout of the drill holes have been adequately demonstrated. After drilling of hole it is to be cleaned properly using compressed air or clear potable water. The rod treated with epoxy-based coat will be lowered into the hole. The annular space between the bar and the hole will be cement grouted. Number of dowels is to be staggered as of various lengths being positioned at various angles.

Wire Mesh/Face Netting

Wire mesh (often known as "face netting") may be fixed to the rock face to prevent rock from a free fall or hung loosely over the slope. It is useful in guiding the falling rock blocks to a rock trap/ ditch at the toe of the slope. When there is no rock trap/ ditch at the slope toe, the lower end of the mesh should be kept no more than about 0.6 m above the toe to prevent rocks from falling and bouncing onto the road or facility at the slope toe. These methods are generally effective for retaining rock fragments of dimensions up to about 0.6 – 1m. Two critical factors govern the choice of mesh:

a. The likely volume/extent of material to be retained.

b. The minimum typical block size of the rock face.

In general, the material to be retained will comprise a blocky, moderately to highly fractured rock mass. More particularly, weathered materials are not well suited to this approach. Twisted wire PVC covered netting or 200 mm opening cable nets are suitable on steep faces for controlling rock falls with dimensions less than about 0.6 m, and woven wire rope may be suitable for rock blocks with dimensions up to about 1 m. For larger blocks, ring nets (200 mm opening gauge and smaller gauge twisted wire PVC covered netting) can be utilized. In all cases, the upper edge of the mesh should be placed close to the potential source of the rock fall so that the blocks will have little momentum when they strike the mesh. The mesh should be anchored at intermediate points by U-hooks at a spacing of about 3 m. This spacing permits rocks to work their way down to the toe rather than accumulating behind the mesh. For the same reason of avoiding accumulation of debris, the mesh is not usually used on slopes flatter than ¾ :1 (37º from horizontal). At the bottom of the slope, U-hooks with an extension connector are recommended at the lowest row so that they can be loosened and removed from the anchored end and the mesh can be lifted for removal of fallen loose rock blocks. The use of netting systems requires the use of specialized retainer units commonly termed cable anchors. These comprise a looped cable

grouted into a borehole that provides an eye at the rock surface. The eye is used to secure main hawsers (horizontal, vertical or diagonal) to which the cable netting and twisted wire netting systems are securely attached.

Local stripping and removal

Local areas may be stripped in order to avoid localized instability. In particular, failure of a portion of rock slope may form an overhang on the face, which may be a hazard if it is allowed to fail. Loose rock can also be removed by hand-held scaling bars. However, removal should only be used where it is certain that the new face will be stable and there is no risk of undermining in the upper part of the rock slope. The designer should re-examine and re-assess the stability of the rock face following local trimming and scaling of specified loose rock. Removal of loose rock on the face of a slope is not effective when the rock is highly fragmented. Other measures such as wire mesh may be considered in such case.

Surface Drainage

U-shaped Catch-water drains can be provided to drain out any water coming out of the weep holes/ drainage pipes in the up-hill side rock slope surface. Dwarf walls can be provided to crest channels, and minimize possible spillage of surface water onto the slope. Special attention should be given to the layout and detailing of the surface drainage system to ensure adequate flow capacity and containment of flow within the channels and adequate discharge capacity at the downstream side. Catch pits should be provided at the junctions of channels. Excavation in rock for the construction of drainage channels may be difficult. Half-round channels may be used on berms to minimize excavation in rock. If the amount of surface runoff on the rock slope face is not large, berm channel, which requires excavation in rock may be omitted. However, the berm should still be paved by concrete to avoid

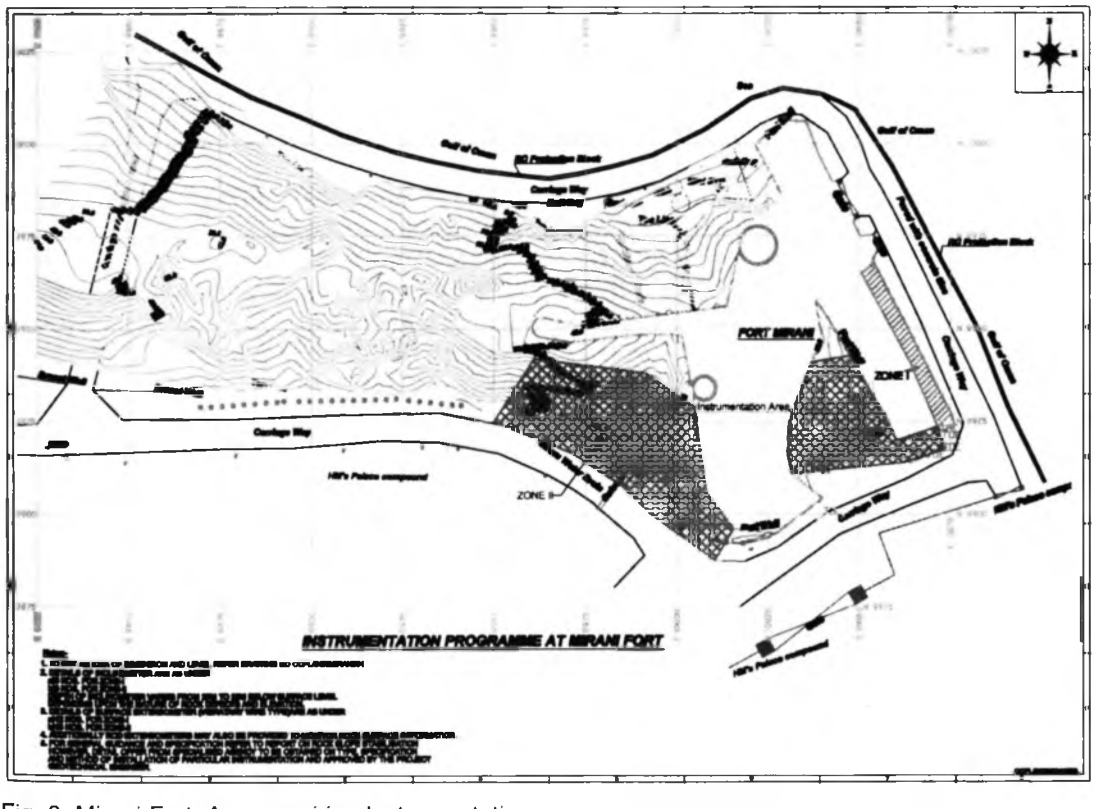


Fig. 8. Mirani Fort- Area requiring Instrumentation

infiltration of water into rock joints from the berm. Site-specific designed down pipes are alternatives to stepped channels for transferring water down to the slope toe.

Instrumentation

Measurement of rock slope for its long-term behavior is considered essential and at the same time ensures proper additional remedial measure to stabilize the rock slope. This can be best achieved by adopting proper instrumentation at the proposed site for regular monitoring of the ground. This will not cost much but a regular collection of data and periodic analysis will give very precise method of future corrective action if required. Considering the importance of the structure, monitoring the rock slope through instrumentation is considered a rational approach. It will be advisable to install some geotechnical instrumentation for precisely monitoring the behavior of the rock mass of the susceptible zones, before finalizing the detailed remedial measures. This instru mentation needs measurement of:

a. Horizontal movement at depth (by Inclinometer)

b. Surface movement (by Magnetic Settlement Gauge etc.)

Records of the instruments are to be kept properly with regular intervals for a considerable period. Study of this record will be a better guide for actual long-term measures.

The data obtained from rock slope monitoring may be used in the slope design process. Based on survey data and geological/ geotechnical information volume of rock mass and water forces may be quantified for a more realistic analysis. However, some data provided by an instrumentation program may be difficult to be used directly. For example, the rate of displacement and their changes with time. are difficult parameters to be incorporated in a design, which is based on limit equilibrium methods of analysis.

Site-wise recommendation

The site wise recommendations are as follows:

Northern slope of the Muthra Fort

i. Rock dowels have been recommended. The angle from horizontal should range between 60º to 70º towards S30ºW (i.e. 210° from North), in a grid pattern at a spacing of 3 m both horizontally and vertically. The depth of penetration will be staggered between 3 to 6 m. Location, direction and exact pattern of anchors may have to be changed at the time of execution, depending on the site condition.

ii. Wire mesh should be fixed to the rock face to prevent bluff rocks from free fall, or hung loosely over a slope. This is in fact to guide rocks to a rock trap ditch at the toe of the slope. When there is a problem of space for providing rock trap ditch at the toe of slope. The lower end of the mesh should not be more than about 0.6 m above the toe, to prevent rocks from falling and bouncing onto the road.

iii. Loose bluff rocks should be removed by hand-held scaling bars. This has to be confirmed by proper specialist's judgement of an Engineering Geologist.

Eastern face of the Mirani fort

i. Rock slope the bolting/ dowels may be finalized after obtaining the instrumentation data shown in enclosed drawing. When adopted, the bolting / anchoring / grouting should be in the direction towards NW in a grid pattern of 3 m both horizontally and vertically. The depth of penetration should definitely be staggered between 3-6 m to avoid creation of another plane of rupture. The direction of anchoring may require to be changed at the time of execution depending on site condition.

ii. Surface drains: This slope has to be provided with adequate de-watering arrangement in the form of trench drains with provision of Geo-web cells. This is honeycomb like cellular structure, made of High Density Polyethylene and there are specialist suppliers in the field of geotechnical engineering who may be consulted for further details. There are perforations in the cell walls and this is available in various cell depths and sizes so that the entire seepage of the sewerage water from inside the fort is safely drawn into it. The subsurface water pressure requires to be very urgently released by providing trenches with gradient leading to the side vertical chute drains along existing depressions. The trench is to be made 2-3 m on surface and 4-6 m in depth, lined with geotextile on the hillside and geomembrane on the valley side as well as the invert of the trench. "Presto buckets" made of geopolymer to be filled by assorted spherical cobbles and pebbles and lowered into the trench in rows and columns. The purpose of the geotextile will be to allow subsurface water to enter into the trench while retaining the soil material behind. The purpose of the geomembrane will be to retain the accumulated subsurface water within the interstices of the hand-packed cobbles and pebbles and leading it to the side chute drains on either side. The trench should be covered at top 0.5 m by soil and subjected to vegetation turfing. In between the rows of trenches, properly designed cement lined storm water contour / garland drains have also to be provided leading to the side chute drains, for taking care of the storm rainwater.

Southern face of Mirani Fort

The bolting/ anchoring/ grouting should be in the direction towards NNW in a grid pattern of 3 m both horizontally and vertically. The depth of penetration be staggered between 3 and 6 m, so as to avoid creation of a plane of rupture. The direction of anchoring should require proper guidance from a specialist.

Acknowledgements

The authors express their heartfelt gratitude to H.E Mohsin Bin Mohd Al Sheikh, Head of Royal Estate Affairs Diwan of H.M. for protocol, Sultanate of Oman for the award of the job to M/S Constell Consultant Pvt.Ltd of Kolkata under the leadership of the senior author. They also express their humble gratitude to Engr. Khalid Al Khadoori, Director, CERE Royal Estates, Shadhan A. Al Khalili Head of Structural Engineers / Dy. Director of Design, Md.Al Shoeli, Senior Architect Central Design Office, Royal court affairs and Engr. Walid Youssef Agha, Managing Partner of Al Manar International LLC for extending facilities like provision of Cradle with Crane and his field staff for assisting the survey work. The topographical and geotechnical mapping work was started from July, 26, 2007 and continued till August, 08, 2007 in the company of surveyors Mr. Sukamal Majumdar and Dipak Kumar Mitra. Er. Partha Sengupta helped in carrying out the slope stability analysis.