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Use of reinforced concrete drilled shafts for supporting a building on landslide prone site - A case study

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ABSTRACT: The northern part of Pakistan is generally mountainous, having low hills in soft rocks to high rocky peaks of the Himalayas. Landsliding of mild as well as steep slopes is a common phenomenon in these formations. Recently, a building was designed on a potentially slide prone site in soft rock comprising predominantly Shale, in the hilly terrain of Murree, Pakistan. The site is characterized by sloping ground of variable strength, high rainfall, poor drainage, high seismicity and fragile geology, making it quasi-stable. Reinforced concrete drilled shafts were provided to (a) support the building and (b) prevent landsliding of the ground.The design of drilled shafts was based on boreholes, seismic refraction survey, characterization of complex geology, laboratory testing and slope stability analyses. The shafts were socketed deep into weak bedrock and designed to carry building surcharge and lateral thrust of sliding mass. The construction of the shafts was challenging due to weak sloping ground and difficult access. The behavior and stability of the site was continuously monitored using surface markers, inclinometers and hydraulic piezometers.The monitoring of ground behavior during construction of drilled shafts indicated stable slope conditions. The a nalysis of the designed foundation system under the expected landslide load, using limit equilibrium method, also showed a dequate factor of safety against sliding. It is therefore concluded that adequately designed reinforced concrete drilled shafts can be safely used to support structures even on landslide prone areas, at other sites too.

RÉSUMÉ: La partie nord du Pakistan est généralement montagneuse, avec des collines basses dans des rochers mous jusqu'aux hauts sommets rocheux de l'Himalaya. Le glissement de terrain au niveau des pentes douces et abruptes est un phénomène courant dans ces formations. Récemment, un bâtiment a été conçu sur un site potentiellement sujet à la glissade dans la roche molle comprenant principalement des schistes, dans le terrain vallonné de Murree, au Pakistan. Le site est caractérisé par un sol en pente de force variable, des précipitations élevées, un mauvais drainage, une forte séismicité et une géologie fragile, ce qui le rend quasi stable. Des puits forés en béton armé ont été fournis pour (a) soutenir le bâtiment et b) empêcher le glissement du sol.La conception des puits forés était basée sur des sondages, des relevés de réfraction sismique, la caractérisation de la géologie complexe, des essais en laboratoire et des analyses de stabilité des pentes. Les puits ont été sillonné profondément dans le substrat rocheux faible et conçus pour transporter le supplément de bâtiment et la poussée latérale de la masse coulissante. La construction des puits a été difficile en raison de la faiblesse du sol en pente et de l'accès difficile. Le comportement et la stabilité du site ont été surveillés en permanence à l'aide de marqueurs de surface, d'inclinomètres et de piézomètres hydrauliques.La surveillance du comportement du sol pendant la construction des puits forés a indiqué des conditions de pente stables. L'analyse du système de fondation conçu sous la charge de glissement de terrain attendue, en utilisant la méthode d'équilibre limite, a également montré un facteur de sécurité adéquat contre le glissement. Il est donc conclu que des puits forés en béton armé conçus de manière adéquate peuvent être utilisés en toute sécurité pour soutenir des structures même sur des zones sujettes aux glissements de terrain, sur d'autres sites également.

KEYWORDS: landslide, drilled shafts, instrumentation

1 INTRODUCTION

Murree hills, forming part of outer Himalayas, are located in the Galyat region of northern Punjab, Pakistan and constitute a high value tourist resort in the country. Landslides have always been a geohazard in the Murree hills owing to poor geology, high seismic environment and adverse weather conditions. These factors have made the experts alive to address the rampant issue of slope instability, in the design of various structures.

Recently, a seven storey building was designed at a sloping site located near General Bus Stand in Murree. The site slopes from an elevation of 6775 ft to 6690 ft over 280 ft horizontal distance in the northwest direction. Two drainage channels pass at the southern and northern edges of the site. The entire area is densely populated and appears to have been inhabited for many years. The area has a few signs of surficial creep though in general, the site is stable. Figure 1 shows plan view of the site and the neighboring areas.

This paper describes field and laboratory studies conducted for subsurface characterization, slope stability analyses performed for the estimation of lateral thrust of sliding mass, design and construction methodology adopted for drilled shafts as well as details of drainage works and slope monitoring system.

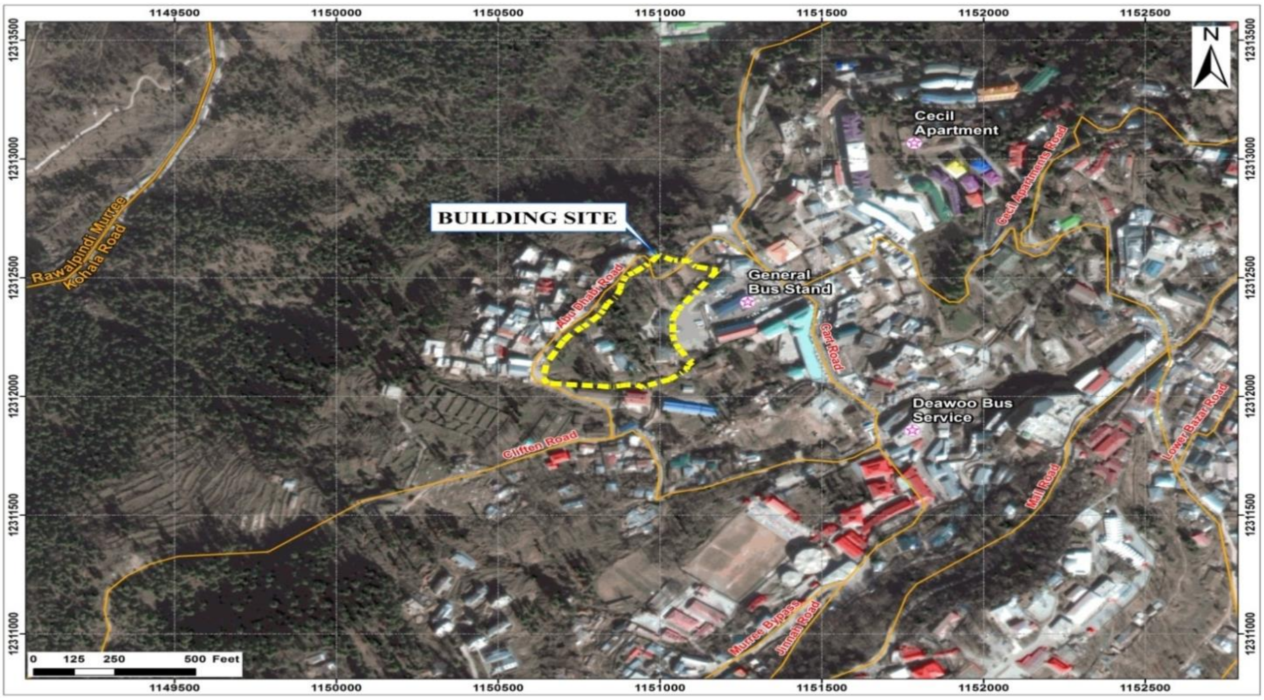


Figure 1. Plan view of the Site and the neighboring areas

2 REGIONAL AND SITE GEOLOGY

The project area lies in the Murree hills that are located on the western most, southern margin of Lesser Himalayas. Collision of Indian and Eurasian plates created the Himalayas, characterized by several lineaments. Murree hills comprise well-stratified alternations of Sandstone and Shale/Siltstone beds belonging to Murree formation of Miocene age. Main Boundary Thrust (MBT), a system of thrust faults and Jhelum fault are amongst the most significant tectonic features lying in the vicinity of the project site.

The site area comprises northwest directed gently sloping terraces. These terraces are densely populated and covered with civil structures. The area around the site is thickly vegetated with rock scarcely exposed, on the downslope of the settlements sited to the west of the site and in drainage channels in the vicinity of the site. Mostly the whole area is concealed with thick cover of colluvium, underlain by predominant Shale, and alternate beds of Sandstone and Siltstone of Murree formation. The beds dip at moderate angles in upslope direction and have strike N 28^o - 40^o E and dip 28^o - 35^o SE, which are favourable for stability of the slope at the site. Geological map of the site is shown in Figure 2. The presence of thick and continuous beds of strong Sandstone in the downslope area reduces the possibility of any major instability.

3 GEOTECHNICAL INVESTIGATIONS AND STRATIGRAPHY

Boreholes, testpits and seismic refraction survey were executed at the project site, in order to define characteristics of the subsurface materials. The subsurface profile consists of the following distinct lithological units:

- The soil cover/colluvium of about 15 to 40 ft thickness generally consists of medium plastic, overconsolidated Lean Clay present in very stiff to hard state. However, some cobbles and boulders also exist within Lean Clay.

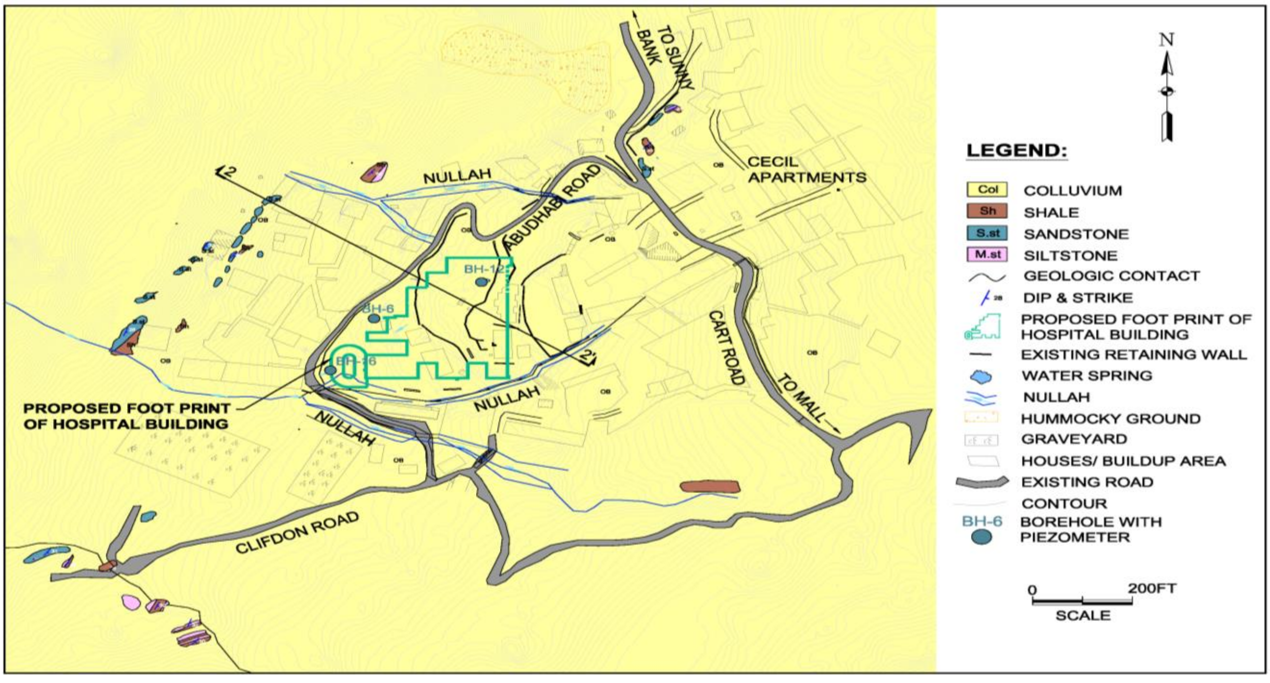


Figure 2. Geological Map of the Site

Measured compressional wave velocity of overburden soils in general ranges from 1300 - 3300 ft/sec.

- The colluvium is underlain by bedrock comprising predominant Shale with subordinate beds of Sandstone and Siltstone of Murree formation. Characterization of the rock mass was conducted using 1989 version of Bieniawski's Rock Mass Rating (RMR). The rock mass is on the boundary between 'Poor rock' and Fair rock' having RMR_{89} values in the range of 35 - 40. Measured compressional wave velocity of rock mass ranges from 4900 - 6900 ft/sec.

In order to monitor groundwater table fluctuations, standpipe piezometers were installed at the project site. In addition, ground movement was monitored through surface settlement markers and inclinometers along with extensometer magnets fixed at the site.

4 SHEAR STRENGTH PARAMETERS

One of the key aspects of slope stability analysis is the determination and selection of representative shear strength parameters. Long-term shear strength of overconsolidated clay that has not undergone previous sliding corresponds to the fully softened conditions (Skempton, 1977). Hence, drained fully softened shear strength of overburden soils/colluvium (Lean Clay) was determined by conducting direct shear tests under consolidated drained conditions, in the laboratory. Tests were performed at a controlled strain rate (0.005 mm/min) slow enough to ensure close to drained conditions. The results obtained were also compared with empirical correlations for secant fully softened friction angle suggested by Stark et al. 2005 and found in close agreement. In addition, value of effective cohesion (c′) for overburden soil was taken as zero, considering softening of cohesive overburden in long-term.

Rock mass parameters were determined using Generalized Hoek and Brown Failure criterion (Hoek et. al., 2002), which is widely used in slope stability problems where the failure plane passes through the rock mass instead of along a single discontinuity plane or joint set. RocLab - Rocscience software was used that implements the latest version (the 2002 edition) of the Generalized Hoek and Brown Failure criterion. The criterion requires two intact strength properties, σ_{ci} and m_i that were obtained from uniaxial compressive strength testing and published literature, respectively. Adopted overburden and rock mass parameters are presented in Table 1.

Table 1. Shear strength parameters

Material	c′ (psf)	ϕ′ (deg.)
Overburden Soil	0	23
Predominant Shale with subordinate beds of Sandstone and Siltstone	1700	33
Sandstone	6300	57

5 EVALUATION OF LANDSLIDING POTENTIAL

In order to carry out slope stability analyses, soil and rock information obtained from subsurface exploration, laboratory testing and geological mapping was combined with topographical cross-sections to develop subsurface geological profiles.

Numerous techniques of slope stability analysis are available, for instance, Limit Equilibrium Method (LEM), Limit Analysis Method, Finite Element and Finite Difference Methods, etc. However, Limit Equilibrium Method is still the most widely used method for evaluating slope stability because of its simplicity and reliability. Slope stability analyses for the site were carried out by Morgenstern & Price Method; a rigorous limit equilibrium technique that satisfies both force and moment equilibrium, and includes all interslice forces, using SLOPE/W module of GeoStudio software.

Reliable estimation of pore water pressure within a slope is very important owing to its significant effect on shear strength of materials and slope stability. To monitor groundwater table fluctuations, three standpipe piezometers (BH-6, BH-12 & BH-16) were installed at site with their response zones located in bedrock at elevations 6640, 6685 and 6605 ft, respectively. Their locations have been indicated on Figure 2. The monitoring record indicated that piezometric surface was located between 20 and 50 ft depth below existing ground level. In addition, as the project site is located in an area that experiences periods of intense precipitation especially during the monsoon season (July - August) with mean monthly precipitation up to 300 mm; therefore, it was expected that overburden layer may get almost saturated for some time.

This irregular and complex pore water pressure condition within the slope was defined using two piezometric lines in Slope/W software. Piezometric line-1 was defined at the existing ground level to represent fully saturated condition in

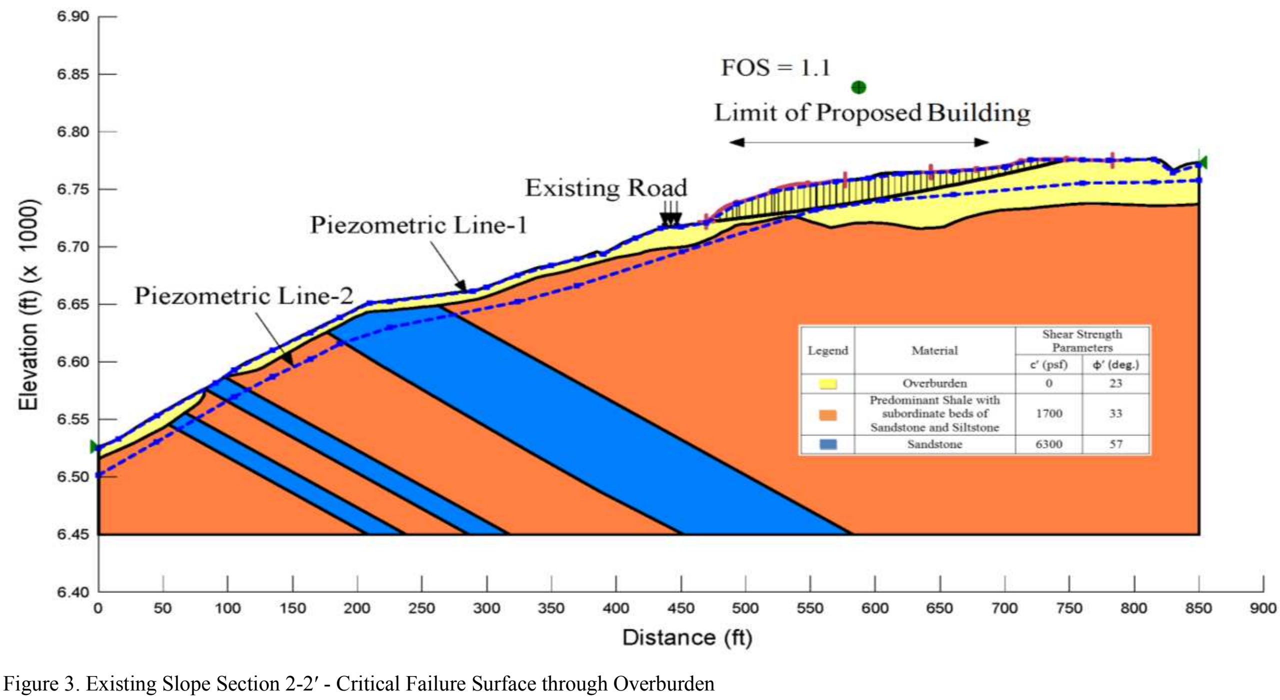


Figure 3. Existing Slope Section 2-2′ - Critical Failure Surface through Overburden

the overburden. Piezometric line-2 was defined at 20 ft depth below existing ground level based on the piezometers' record to represent pore water pressure in bedrock.

Seismic stability of the site was evaluated using pseudo-static method in which the seismic forces are defined by the product of seismic coefficient and the weight of the slice ($F_h = k_hW$ & $F_v = k_vW$). As per Building Code of Pakistan - Revised Seismic Provisions (2007), project site falls in Zone-3 with peak horizontal ground acceleration (PGA) of 0.24 to 0.32g with an average value of 0.28g (ground motion having 10% probability of exceedance in 50 years, i.e. 475 years return period). It was considered that the actual ground motion would be made up of both horizontal and vertical components of the seismic force that could be in phases. As per standard practice for stability analysis, horizontal seismic coefficient, k_h was considered as 2/3 of average PGA, i.e. $k_h = 0.20$ and vertical seismic coefficient, k_v was taken as 1/4 of k_h, i.e. $k_v = 0.05$

Appropriate factor of safety is required to ensure satisfactory performance of slopes throughout their design life. Minimum required factors of safety (FOS) for the site were adopted as 1.5 under static condition and 1.0 under pseudo-static condition, on the basis of various considerations including uncertainties in the design parameters and the consequences of failure.

The results of slope stability analyses indicated that the potential critical failure surfaces (within overburden) had factor of safety (FOS) of about 1.0 in static case. Thus the existing site slope had inadequate factor of safety and strengthening measures were required. However, deep-seated failure surfaces cutting through the rock mass had FOS greater than 2.0 in static case. This showed that deep-seated failures were not likely at the site. Figure 3 and Figure 4 show computed FOS along existing slope section 2-2′, as shown in Figure 2.

practical to construct and stable, requires thorough evaluation of the ground conditions/characteristics, assessment of the prevailing causes responsible for the instability and project requirements.

The proposed structural system for the seven storey building was conceived as R.C. moment resisting frame with shear walls, i.e. a dual system with 20 ft span in both directions. At the project site, overburden of around 15 to 40 ft thickness is present over the stable bedrock, having a tendency to slide, thereby rendering the placement of any type of shallow foundation within the overburden out of the question. In addition, owing to the considerable thickness of overburden, any attempt of placing spread foundation into the stable bedrock would involve substantial excavation works that could trigger landslide. Therefore, provision of some suitable deep foundation system was inevitable to safely transfer building loads to the underlying stable bedrock.

Instead of providing a separate slope stabilization system, like multiple drilled shaft walls or ground anchors, a more feasible and economical solution was to design deep foundations necessary to carry building loads, against lateral force of sliding overburden as well. On the basis of construction considerations, local experience and cost, R.C. drilled shafts were considered as the best option. The shafts would transmit driving force of the sliding overburden that would act on the shaft segment above the sliding surface to the underlying bedrock. Therefore, RC drilled shafts were provided under each column of the building along with surface and subsurface drainage works.

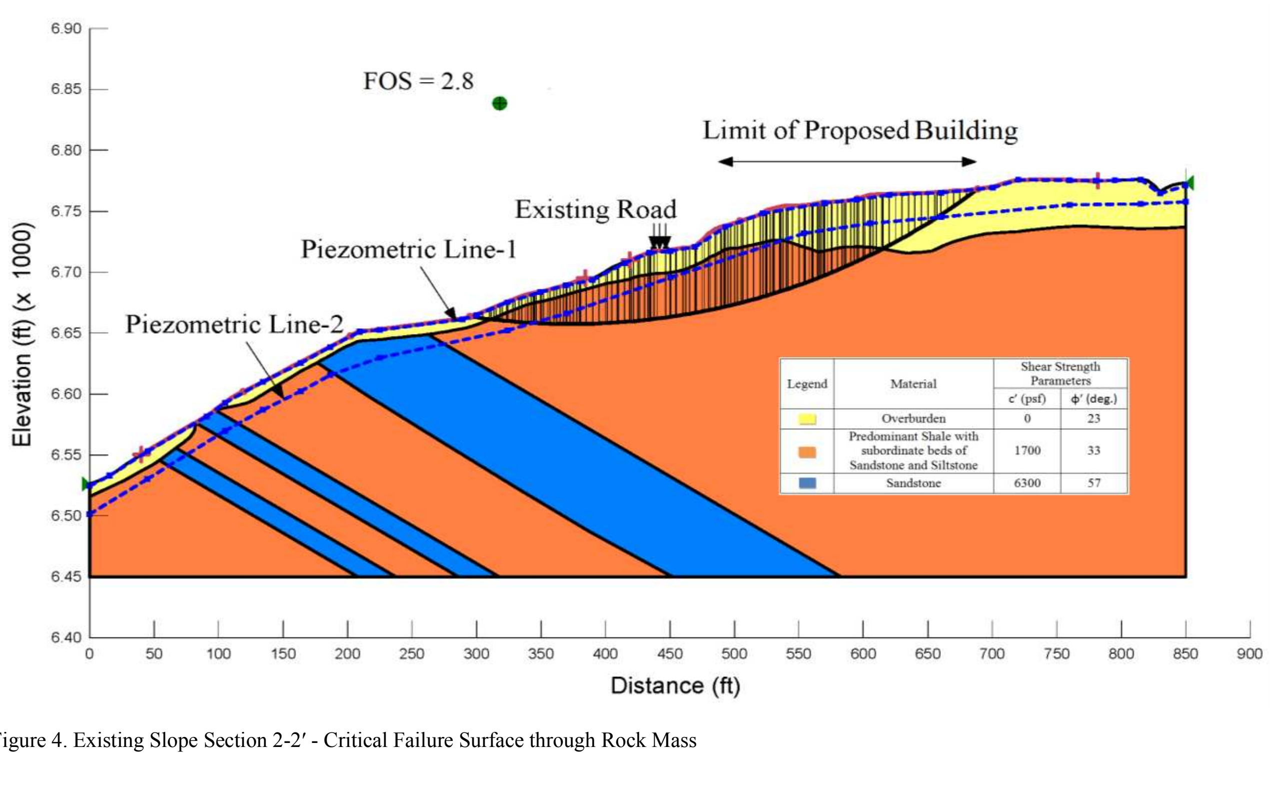


Figure 4. Existing Slope Section 2-2′ - Critical Failure Surface through Rock Mass

6 SELECTION OF SLOPE STABILIZATION SYSTEM

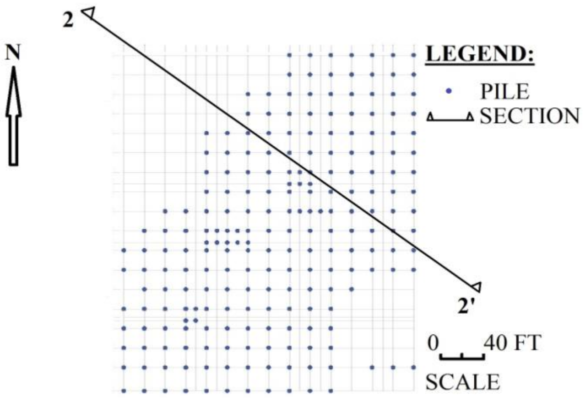
There are various slope stabilization techniques such as: provision of surface and subsurface drainage system, flattening of slopes, installation of retaining structures like drilled shaft walls or ground anchors, etc. However, selection of an appropriate slope stabilization system which is cost-effective,

7 ESTIMATION OF LATERAL FORCE ACTING ON STABILIZING DRILLED SHAFTS

The proposed building was conceived as a frame structure with columns spaced at 20 ft in both directions. Drilled shafts of 4 ft diameter were proposed under each column as shown in Figure 5. The drilled shafts were connected with beams to behave as a synergistic pile group. The drilled shafts would act like shear dowels installed in staggered configuration across the sliding plane and serve to increase the resisting force in the sliding overburden, with a resulting improvement in the factor of safety.

Drilled shafts were modeled in Slope/W software by using ‘pile reinforcement’ option that allows the user to specify any desired value of shear resistance per foot length of slope. Building surcharge was incorporated into the model by utilizing ‘point load’ option. Point loads were assigned along the shaft socket length to simulate load transfer mechanism through skin friction.

The analyses were carried out along various sections with the inclusion of drilled shafts at their specific locations. A trial and error procedure was used to get the shear resistance value (lb/ft) corresponding to a stipulated factor of safety (1.5 under static condition and 1.0 under pseudo-static condition) against the most critical failure surface (critical failure surfaces’ zone was found alongside overburden-bedrock interface). This shear resistance value was then multiplied with the c/c spacing between the shafts to get the lateral force needed to be resisted by each shaft. The lateral force per shaft was determined as 55 - 155 kips under static condition and 325 - 415 kips under pseudo-static condition. Figure 6 and Figure 7 show computed FOS along design section 2-2′, as shown in Figure 2.



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8 DESIGN OF STABILIZING DRILLED SHAFTS AGAINST LATERAL FORCE

Drilled shafts were designed to safely carry the lateral force of the sliding overburden mass and super-structure loading. To determine soil/rock strength and stiffness characteristics, eleven instrumented test shafts of 4 ft diameter were tested under both compressive and lateral loading as per design requirements. Shafts to be tested under compressive loading were instrumented internally with vibrating wire strain gauges and telltale rods while inclinometer casings and vibrating wire strain gauges were installed within shafts that were to be tested under lateral loading. Test shafts were constructed with rock sockets ranging from 23 to 35 ft, in order to assess the effect of embedment depth on the shaft resistance and behavior.

Test results were analyzed to determine load-deformation characteristics. LPILE software was used to develop p - y curves of soil and rock. Similarly, t - z curves for side resistance and q - w curves for end bearing were generated based on pile load test results.

Subsequently, a three-dimensional finite element model (FEM) of the building (super structure + drilled shafts) was prepared in ETABS software that could take into account soil-structure interaction between the foundation and the surrounding strata through non-linear p - y, t - z and q - w curves. In addition to the super-structure loading, lateral force of the sliding overburden mass was applied to the model. Model was analyzed to calculate forces transmitted to the shafts. Figure 8 shows a 3-D view of the model.

9 CONSTRUCTION OF REINFORCED CONCRETE DRILLED SHAFTS

The construction of 4 ft diameter and about 50 to 70 ft long reinforced concrete drilled shafts at a steeply sloping and weak ground in heavy rainfall environment was a highly challenging task. The construction activities involved the earthworks necessary to construct an access road and working platforms for piling rigs, cranes, concrete mixer trucks, etc. Stable working platforms were obtained by cutting temporary benches into the slope.

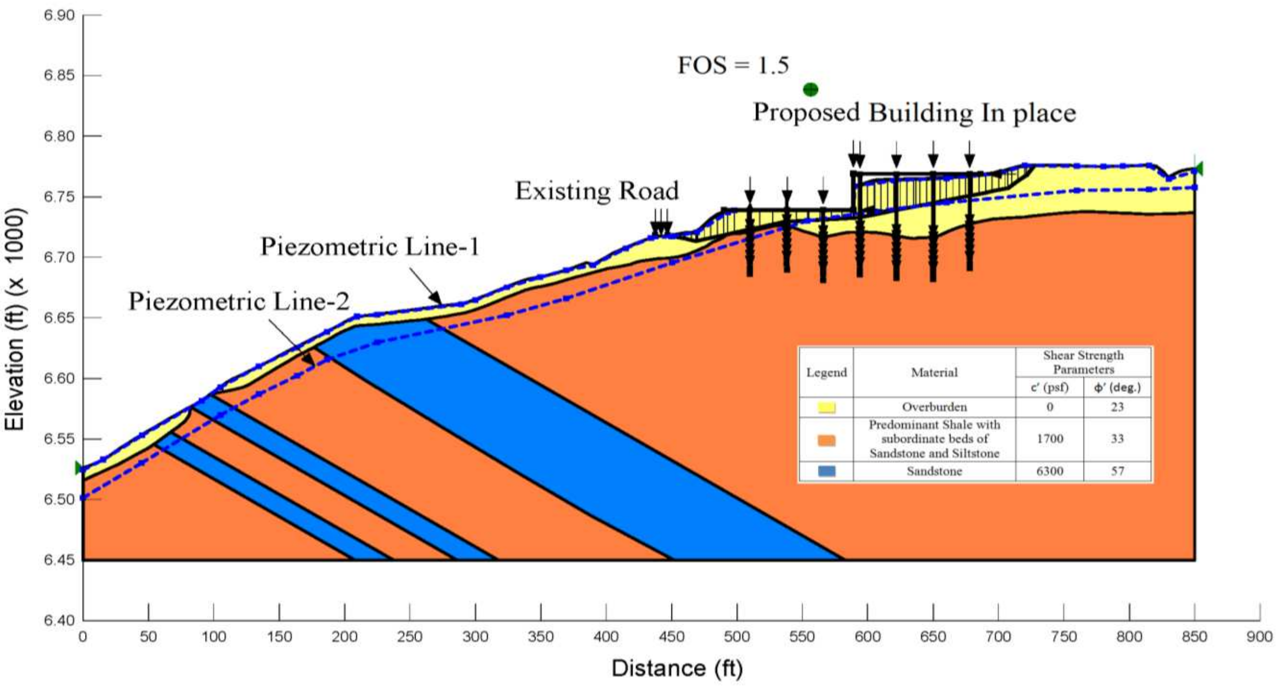

Figure 6. Design Section 2-2′ - Static Condition

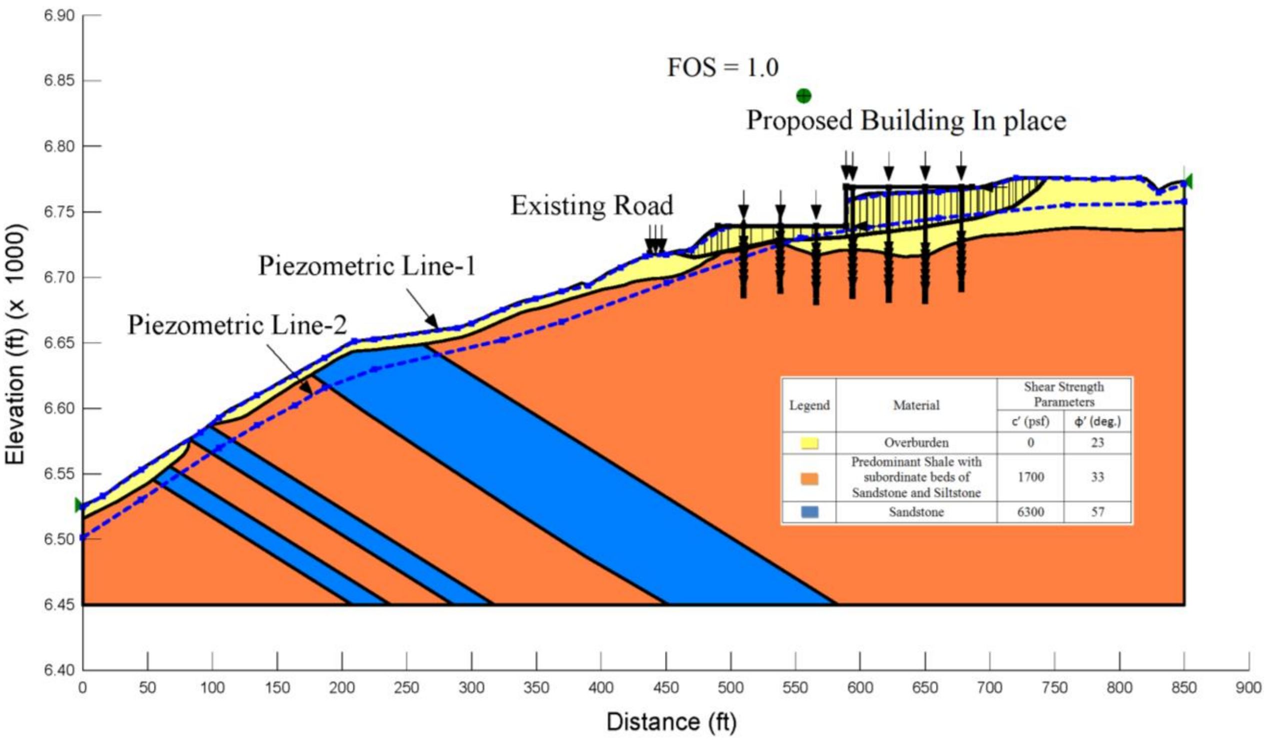

Figure 7. Design Section 2-2′ - Pseudo-Static Condition

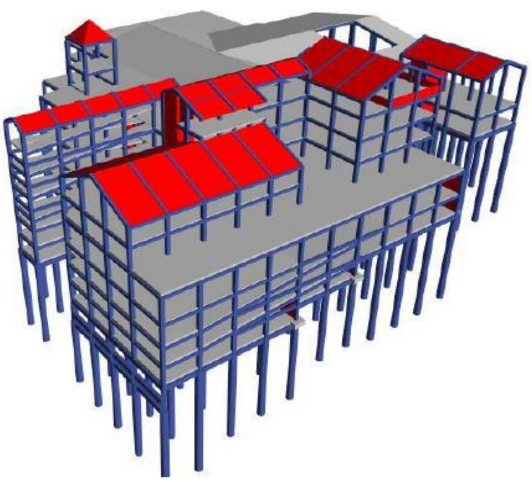

Figure 8. 3-D view of FEM of the Building

Dry rotary bucket-auger method was used to drill holes in colluvium and bedrock. To prevent cave-ins of the soil, 15 to 40 ft long temporary casing was used within the colluvium. A steel reinforcement cage was placed in the hole and then concrete was poured using a tremie pipe. The construction of building is currently in progress at the project site and installation of drilled shafts has been completed.

10 SURFACE AND SUBSURFACE DRAINAGE WORKS

Ground water in slopes is often a primary cause of instability, and a reduction in water pressure markedly improves stability. Therefore, adequate drainage of water is one of the most important factors for a slope stabilization scheme. The proposed drainage network included series of surface and subsurface drains along with horizontal drainage holes.

Lined surface drains were proposed to intercept surface water/run-off and prevent its ponding and infiltration. Similarly, gravel-filled subsurface drains (French Drains) of around 10 ft depth were recommended at various locations of the slope, including upper and lower perimeter of the site. Layout plan of the proposed drainage network is shown in Figure-9. Surface and subsurface drains will discharge collected water to the lateral drainage channels that exist at the southern and northern edge of the site. In addition, horizontal drainage holes will be drilled from inside of subsurface drains, inclined 5 degrees upward into the potential sliding body, to drain potential sliding zone or overburden-bedrock interface.

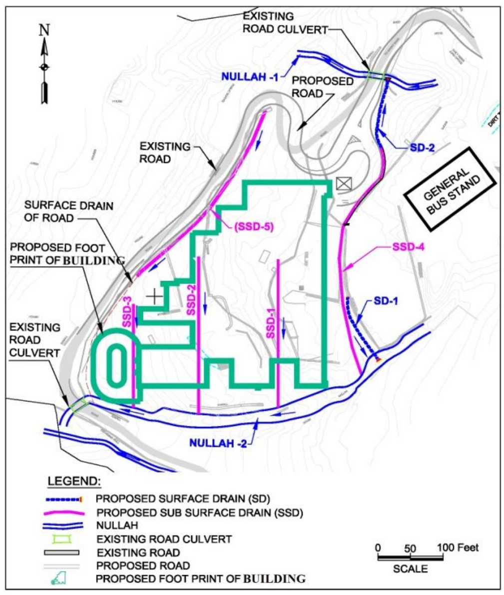

Figure 9. Layout Plan of the proposed Drainage Network

11 SLOPE MOVEMENT MONITORING

Fourty (40) surface settlement markers were installed for making surface measurements of slope movement. Total station was used for monitoring of the settlement markers.

In order to get a complete picture of the slope movement behavior, four (4) borehole inclinometers along with magnetic probe extensometers with spider magnets at different depths were also installed. The boreholes were extended deep into the bedrock so that readings were referenced to a stable base. Readings were taken by lowering the probe into the boreholes.

The surface and subsurface movement monitoring record that spanned over a period of almost two years have so far not depicted any cognizable movement, indicating stability of the site slope.

12 CONCLUSIONS

- The natural slopes in Murree formation in northern Pakistan are in general quasi-stable and therefore a change in the geo-environmental conditions may cause instability. Hence, they need to be strengthened at the sites of important projects.
- Limit Equilibrium Method (LEM) can be used to evaluate landsliding potential and calculate lateral force of the sliding mass acting on the stabilizing drilled shafts against a desired factor of safety.
- Reinforced concrete drilled shafts can carry considerable lateral loads because of their high shear and flexural strength. Therefore, in addition to supporting multistorey building surcharge, drilled shafts can be effectively used to stabilize slopes by embedding them into a stable stratum below the sliding surface, and utilizing the mechanism of arching between them to increase the resistance against sliding to the point of stability.
- To adequately estimate the response of drilled shafts against the applied loading, full-scale load tests should be carried out on instrumented test shafts to develop site-specific strength/stiffness characteristics of the strata, including non-linear p-y, t-z and q-w curves. This will lead to more realistic design of shafts.

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