Investigating and Mitigating Measures to Peat Fire, Sinkholes in Limestone Formation and Boulder Fall

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ABSTRACT

This paper discusses the contributing and triggering factor(s) of natural disasters possibly due to either natural processes or human activities. Three presented case studies illustrate the investigation and solutions to deter or mitigate the risks of these natural hazards. The first case study involves the peat fire hazards where excessive clearing of flood plain for planting economic crops. The hydrological and hydrogeological changes lower the groundwater table and increase the risk of underground peat fire due to provoked organic peat decomposition producing flammable methane gas. Unexpectedly, the subsequent channel construction for irrigation and transportation keep the groundwater table for increasing plantation yield. The second case study presents the sinkhole incident at limestone formation damaging the channeliased monsoon drain, where the groundwater drawdown by the quarry pit has provoked excessive loss of overburden materials with excessive drain water inflow into the solutioning channels flooding the pit until occurrence of sinkholes. Plugging the solution channel with active inflow of drain water was somewhat challenging, but a successful attempt finally. The third case study involves detached rolling diorite boulders from uphill slope destroying the buildings along their traversing path. It is interesting to observe the shrinkage and swelling characteristics of the weathered overburden materials around the detached round boulders by the repeated weather cycles.

1 INTRODUCTION

1.1 Natural Disasters

There are many types of natural disasters around the earth and these disasters might have their own uniqueness at different locality and timing. Every incident occurs with the support of all possible contributory factors as its sufficient conditions to incubate and requires only one or a few triggering factors in some incidents as its necessary condition to succeed. This paper will present three types of hazard, namely peat fires, boulder falls and sinkholes due to cavity collapse, which are related to geotechnical or geological processes with possibly indirect disturbance by either human activities or natural actions as triggering factors. Mitigation measures are also discussed to rectify the distresses and prevent recurrence where practically possible.

2 PEAT FIRE HAZARD

2.1 Background

This case study involves the environmental impacts in relation to the utilization of vast area of fertile coastal flood plain consisting of abundant peaty overburden soils. As many are aware that peats are remnants of carbon rich organic materials derived from the vegetation covers on the earth, which converts carbon dioxide in the atmosphere via photosynthesis process with sunlight. Once the living cycles of such organic plants are over, these light weight organic materials will fall on the floor and are very effectively transported to remote distance by flowing medium, likes storm flood, towards the coastal areas. The tomography and the shrub growth at the coastal flood plain is an ideal landform for depositing these light weight and floating substance in the basin before the mangrove swamp when the flood storm recesses from the low-lying poorly drained depressions at the flood plain. There are also peats in the inland area, which is commonly known as valley peats. The mechanically breaking down of the organic remnants during the flood transportation produces a widespread deposition of the young fibrous peats, in which the original structures of the plants substantially remain. Further chemically and biologically (microbial) decomposition of the cellulosic matter into smaller sizes, but more compact amorphous peats. Peatlands occupy about 3% of the land surface of the Earth with much well preserved in temperate climatic regions. Two-third of the tropical peatlands are located at Southeast Asia.

Peat fires characterize with low temperature, spreading slowly across vast areas and flameless like a smoldering coal, which is difficult to be put out when burning underground. This is quite similar to the fire at dump sites, which produce flammable methane from microbial decomposition of organic wastes as shown in Plate 1. Often the trash at certain illegal landfill was burnt by scavengers looking for valuable scrap metal.

Plate 1: Firefighters putting out blazes at an illegal waste dump in Klang (The Straits Times)

The major root causes of peat fires can be as follow:

- Droughts or changes of land drainage of peat marshes and arson for developing agricultural lands (contributory factors)
- Land clearing for development and logging (contributory factors)
- Lightning (triggering factor)
- Humans throwing out burning cigarettes and camping related activities (triggering factor)

The hazards associated with peat fires include the following:

- Emission of greenhouse gases (GHG), like carbon dioxide, methane, nitrous oxide (laughing gas) escalating the global warming effect, and some toxic gases, likes carbon monoxide, nitrogen dioxide and nitrogen monoxide. Plate 2 shows the generation of such GHG emission in action of peat fires with consequential bush fires during drought season.
- Atmospheric aerosol particles, also known as atmospheric particulate matter (PM), in which the PM2.5 (less than 2.5μm in aerodynamic diameter) can potentially cause health problems to respiratory and hearth illness and, also alter ambient microclimatic condition with haze as shown in Plate 3.
- Destroy or fragmentation of wildlife habitat.
- Underground burning destroys the root system of plants and falls the plants when adequately losing their ground support.
- Voids left in burnt ground after burning the organic matters into much reduced volume of ashes.
- Generation of high acidic discharge from decomposition of organic matters.
- Low visibility for air navigation, especially for landing.

Stracher, et al (2014) provide a very comprehensive review and case studies of coal and peat fires worldwide, which serve a good literature reference in understanding the nature and the smoldering behavior of these combustible matters underground and technology to identify their existence and its propagation from airborne and at ground as well. As this hazard is featured with rapid wide spreading, cross boundary without effective control at border unless it is timely mitigated at source, and has high immediate and long-term impacts to the environment and health, it therefore requires mitigation measures at policy level on land development, groundwater extraction and strict enforcement empowerment. If this hazard is left unattended, the release of GHG to the atmosphere and environmental pollution can be far more than that of the same directly by present human activities.

Plate 2: Emission of GHG and toxic gases under action of peat fires at peatland and the consequential bush fires at Sepang, Selangor

Plate 3: The Malaysian Prime Minister's office building is covered by haze in Putrajaya on April 22, 2016 (The Straits Times

2.2 Case Study

This case study presents the development of peatland for high value cash crops of oil palm plantation at eastern coastal flood plain in Riau Province of Sumatra, Indonesia. The extensive clearing of land (about 80,000 hectares) by removing the shrubs and forests for the planting blocks has significantly reduce the preservation of moisture in the peaty soils with direct evaporation of the bare land to the atmosphere despite slightly reduce the transpiration rate of moisture content by removing the original vegetation growth, hence inevitably lowering the ambient groundwater table. In view of the water consumption of the oil palm crops, whereby to yield 1kg palm oil requires 551 litres of water (Teh 2011), extensive irrigation channels at systematic configuration with weir control structure are constructed to maintain average water table not lower than 600mm below the planting level. Plate 4 shows the overflow weir structure for regulating the water table at the planting blocks, and also controlling the water depth for barge navigation as in Plate 5. These water channels are also used for transporting the harvested fresh fruit brunches to the processing mill. However, Ludwig, et al (2011) consider no sustainability issue for oil palm plantation in Southeast Asia countries in view of the general rainfed condition at the region.

The base camp of this project site is located at about 70km away from the eastern coastline, whereby the general surficial deposits are 1.5m to 3m thick clean amorphous peats overlying the soft compressible marine clay deposits as shown in Plate 6. The peats are deposited within the vast flood plain with previously thick shrubs of about 100km wide from the coastline. Generally, the peats are clean without course soil grains or fine soil. It is believed that the decomposed peats with high buoyancy were broken down by the transporting flood storm from its original location, spreading across the vast flood plain and finally deposited at the upmost layer with retention by thick vegetation growth. The high buoyancy of peats has therefore segregate the heavy soil particles from the light weight organic matters, thus leaving the very clean peaty matters deposited at the upmost layer. Some fertilizer producers extract these clean peats with post injection of nutrients, like nitrate, phosphate, etc to provide high value odourless fertilizing products for golf course. With further accelerated decomposition processes of the deposited peats above phreatic level, pore water with very low pH value of about 2.5 to 4 is leached out from the spongy peats resulting in dark brownish highly acidic water to the surface water body. When extensive land clearing was executed for the proposed planting blocks, groundwater table lowering during drought has resulted isolated spots of peat fires around the cleared sites, which were practically impossible to put out. The accelerated decay of the peats releases remarkable amount of methane, which can be ignited rather easily. However, due to common local practice of controlling water table with primary objective to maximise crop yield, the groundwater table was deliberately raised by regulating weirs at every zoning of planting blocks. With capillary fringe above the raised phreatic surface in the peaty soils, it keeps sufficient moisture within the peaty soil, which is equivalent to an artificial sub-terrain flooding, to extinguish the smoldering peat fires. The wetting of peat becomes very effective mitigative solution for peat fire and, also serves as a dual-purpose measure to maximise crop yield.

Plate 4: General view of irrigation drainage and transportation network with overflow weir structure at canal system regulating water level at the oil palm plantation estate

Plate 5: Water transportation channel for fresh brunch fruits (FFB) to processing mill

Plate 6: 1.5 to 3m thick clean amorphous peats overlying soft compressible marine clay deposits

3 LIMESTONE SINKHOLE HAZARD

3.1 Background

The limestone formation contains many hydrogeological connections with many inherent solution channels developed along joint sets formed within the rockmass under all both geological stresses and hydrogeological events historically. As limestone is an important resource for construction materials as aggregates and also as raw material for cement production, good quality limestone formation has been explored for quarry development in Malaysia. However, being a resource with soluble compounds, problems with existence of all typical karstic features are inevitably experienced in the quarry development. The past ice age with fixing most of the fresh water at the poles results in drastic drop of sea level and therefore provokes active and deep infiltration of surface runoff into the overburden soils and, also the underlying rockmass formation. This infiltration processes generate sizeable solutioning channels within the jointed limestone rockmass. In many cases, the fine migration from the overburden flowing along with the infiltration seepage also carries infilling materials to gradually plug the channels when the flows slow down allowing sedimentation. The cease of the last ice age era also results in rise of sea level, thus the sedimentation level also rises synchronically with the rise of sea level, which controls the discharging level of groundwater from higher ground. The end products of the formation of tectonically induced joint sets in the limestone rockmass, solution channel and the infillings provide the condition of sinkhole hazards at present time.

3.2 Case Study

This case study presents an open pit limestone quarry operation with river immediately next to the mining lease boundary, where the karst features in the upper weathered limestone formation has given rise of hazards of hydrological hazards related to the breaching of infilled solution channels under the high piezometric head of groundwater. The river within the quarry site was diverted and channelised running outside along the mining lease boundary due to the expansion of the quarry site adjoining to the residential development to maximise the reserve extraction. Plate 7 shows the interfacing condition between the housing development and the quarry site. As a result, drastic profile is generated between the residential development over the flat alluvial deposits and the steep quarry benches towards the quarry site as depicted in Plate 8. However, the hydrogeological conditions between the two adjoining lands has developed into a rapid drawdown phreatic profile from the ambient groundwater table at the alluvial deposits with constant replenishment of river water into the ground, whereas the water pumping within the quarry pit keeping the excavation pit dry for working has continuously lowered with the pit level. As the gradually developed critical hydraulic gradient in the groundwater regime provokes internal erosion of the previously infilled solutioning channels until breaching to flow passage. Progressive cavity collapses appear on the ground surface where river water was directly discharged into the quarry pit through the eroded channels within the limestone rockmass. The undermining of supporting foundation soils beneath the reinforced concrete lining of the diverted river was also structurally damaged the river section badly. Plates 9, 10 and 11 show the progressive propagation of the isolated overburden collapses along the solution channels with active erosion of high inflow of groundwater and finally the river water.

Plate 7: Interface of diverted river between the residential housing development and the quarry site

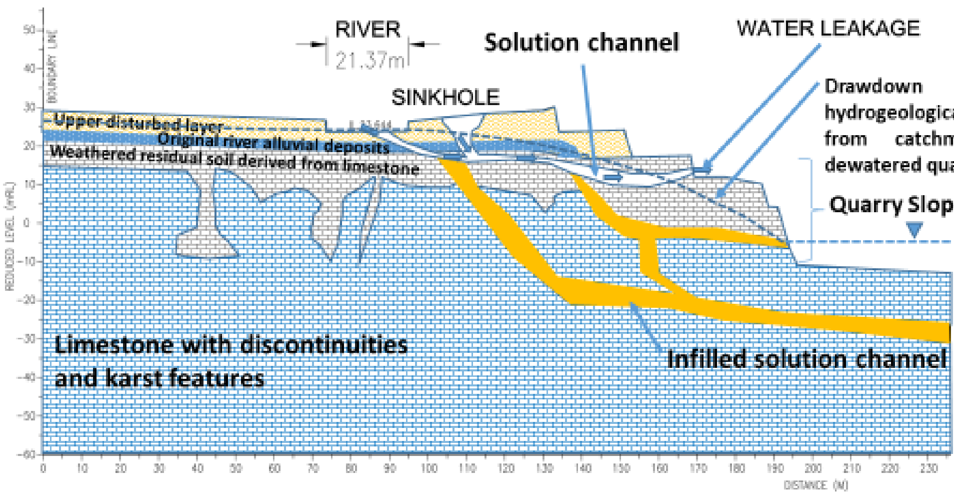

Plate 8: Drastic phreatic drop of groundwater between the residential housing development and the quarry site

Plate 9: Sinkhole developed behind channelised river section with solution channel connection to quarry benches

Plate 10: Sinkhole developed in overburden behind the quarry benches

Plate 11: Discharge of solution channel at quarry bench surface and plastic debris from river water

The inflow of water into the quarry pit interrupts the quarry operation and, also intercepts river flow downstream. There was an imperative need to plug the channel passage to cease the inflow and convey the upstream river flow to downstream. The quarry team had attempted to dump quarry wastes into the sinkholes appear on ground, but without noticeable success. The conditions were only under controlled after the authors were appointed to carry out the emergency rectification. The recommended action was to dump materials in sequential batches with three different particle gradings of sufficient volume into the sinkholes. The concept is to have the larger blocks of rock fragments to stuck at the narrow channels forming the primary blockage. From the earlier mentioned process on the formation of solution channel, most channels are developed along the joint sets, which are planar by nature. The differential solutioning process and, also the abrasive erosion of solid particles in the seepage flow tends to enlarge the flow passage on the planar joint surface. Water flow will also find the most efficient path under the gravity pull to develop the channel. Nevertheless, the formed channels will always be irregular, whereby constricted passage shall exist along the entire channel. As such, so long as there are some larger rock fragments can follow the inflowing water to reach a constricted section and retain there as a primary blockage. The subsequent dumping of medium and smaller size rock fragments will then form the secondary and tertiary blockages to the voids of blocked rock fragments. Generally, the larger rock fragment is half of the sinkhole diameter at the lower portion. The medium and smaller rock fragments are half of the preceding diameter of rock fragment as shown in Plate 12. It is also envisaged that the sequentially dumped rock fragments to travel further reaching the gentler invert profile for deposition and subsequent transported dumps can therefore form a stronger plug upstream until the appeared sinkhole on the ground surface. This is similar to the retention concept in the filter design by using the voids formed in coarser grain matrix structure to retain the smaller grains in the flowing medium. At last, cohesive earth was placed over a filter geotextile over the dumped rock to seal the vertical funnel shaft of the sinkhole. In the actual remedy, water was pumped in the sinkholes to destroy premature arching of the dumped rock fragments at the vertical sinkhole during the dumping. Until the flow discharge ceased at the quarry bench surface, the reinstatement works of the river section and the ground leveling were commenced.

Plate 12: Sequential dumping rock fragments of varying sizes to infill the solution channel for plugging

In the next stage of investigation work to detect the connectivity of the solution channels between the river and the quarry benches, exploratory boreholes and geophysical resistivity survey were proposed and executed. The principles of resistivity survey to detect solution channels are based on the ground resistivity to differentiate the following interpreted feature as per Table 1. The findings were calibrated with the borehole information. Plates 13 and 14 depict the interpreted features from the ground resistivity tomography next to the river and quarry benches respectively for comparison. Higher groundwater table is at the river side whereby the solution channels are more prone to lower resistivity with higher water content. As the water table becomes lower towards the quarry benches, the solution channel has more air voids resulting higher resistivity. When more survey spreads are performed, it is not difficult to establish the underground connectivity of solution channels between the sinkholes near the river side and the observed solution channels on the quarry benches. There is limitation of the resistivity survey spread length to energise sufficient current down to greater depth to produce the resistivity tomography for interpretation.

Table 1: Differentiation of Ground Resistivity for Solution Channel Detection

Interpreted Features	High water content		← Contrast in Resistivity →		Low water content	
	Low	Low Medium	Medium	Medium High	High	Very High
Unsaturated Soils				✓		
Saturated Soils		✓				
Voids with Air						✓
Voids with Water	✓					
Jointed Rockmass			✓			
Intact Rockmass					✓	

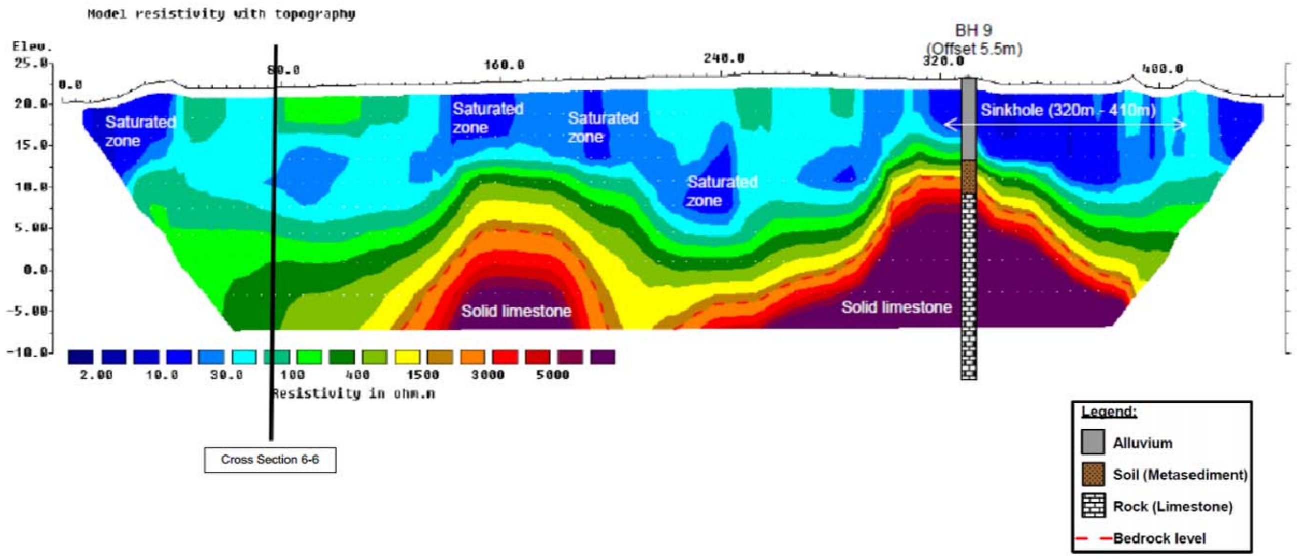

Plate 13: Interpreted features from ground resistivity tomography (River side)

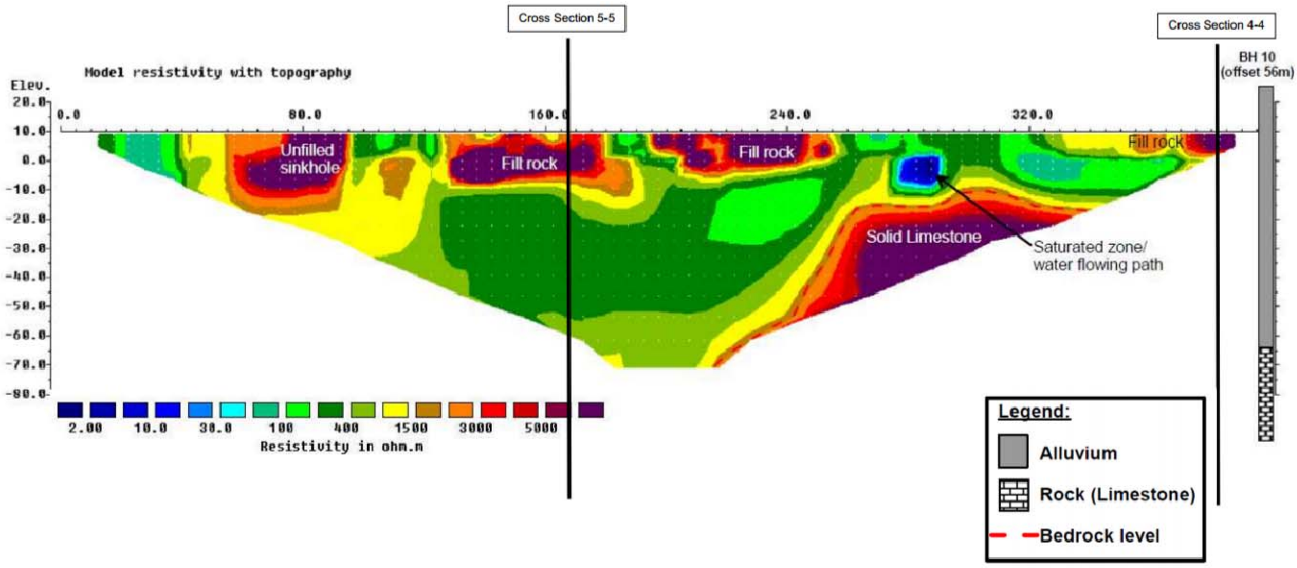

Plate 14: Interpreted features from ground resistivity tomography (Quarry bench side)

4 BOULDER FALL HAZARD

4.1 Background

This case study involves the natural weathering process of a diorite rock mass near to a quarry site, whereby the erosion of surface runoff along the gap formation developed from the shrinkage of embedding overburden soils around the diorite boulders causing detachment and rolling downhill under gravitational action damaging a few illegal squatters.

Hutchinson (2005) gave a very brief, but insightful general geology of the project site. The project site consists of hypersthene diorite forming a line of hills near Tawau area in Sabah, namely Mouth Gemok, Middle Hill and Kukusan Hill. The diorite rocks are grey, medium-grained and only slightly porphyritic, in which the phenocrysts are andesite, hypersthene and clinopyroxene. Hornblende has been pseudomorphed. However, Kukusan Hill pluto is not homogeneous, and contains andesite tuff breccia. Composed of andesite and diorite clasts, euhedral feldspar, altered hornblende and pyroxene in a glass matrix devitrified to a mixture of smectite and zeolites. Plate 15 shows the texture on a fractured surface of diorite within the project site.

Plate 15: Texture of diorite boulder with inclusions during cooling stage

The deep seated spheroidal weathering processes along the joint discontinuities within the diorite rockmass under the tropical climatic condition have resulted in onion-skin weathering, which is a process of the layers of the rock being peeled off and, also known as exfoliation, thermal expansion and insolation weathering. The outcome of the spheroidal weathering forms many round core boulders as illustrated in Plate 16. Once the core boulders are partially exposed, the embedding weathered saprolite surrounding the core boulder might have relatively higher shrink-swell potential when subject to changes of moisture content due to drying and wetting cycles of climatic condition. The differential movements interacted between the volumetric changes of saprolite and the rigid core boulders can end up with gaps as shown in Plate 17, which might provoke erosion of the embedding saprolite beneath the boulder leaving the upper boulder sitting atop the lower boulder clusters with only few point contacts and largely unsupported at the underside as shown in Plate 18. Such concentrated support condition is highly unstable when the upper boulder starts to move and gain momentum from its potential energy after brittle contact crushing due to overstressing at the point contacts as shown in Plate 19. Despite the average uniaxial compressive strength (UCS) of 244.9MPa was reported by Raj (2004), the stress concentration at the nearly point contact of boulders after erosion of the embedding saprolite may still exceed the intact strength leading to brittle crushing. Once the overall release rate of potential energy from the imposing boulder exceeds the straining energy absorption rate at the contact support system, the progressive brittle crushing at the supporting contact starts with domino effect to allow the boulder gaining momentum to translate and rolling. The boulder movement will only cease when the energy stored for the work done can be fully dissipated by the resistance.

Plate 16: Spheroidal weathering forming core boulders


Plate 17: Gap formation at the interface of saprolite and core boulder after drying and wetting cycles


Plate 18: Core boulders supported on few point contacts from lower boulder cluster


Plate 19: Brittle crushing at concentrated contact of underlying core boulders beneath the gigantic boulder

4.2 Case Study

A gigantic sub-rounded diorite boulder weighing about 2,400 tonnes detached from the uphill location rolling downhill descended about 146m in elevation and travelled about 250m horizontally. Along the travelling path, few illegal squatter houses were damaged as shown in Plate 19. From the energy view point, the potential energy used to drive this gigantic boulder is about 3,504 megajoules (973kWh), which is equivalent to about four months electricity consumption of an average household in Malaysia (Nakagami, 2008). The travelling distance of boulders can vary quite substantially depending on the shape of the boulder, hardness and, also the condition of the ground where the boulder traverses through. Some diorite boulders, which is believed from the same diorite hill, are located about 500m away from the centre of the hill top. Hence, the rheology of the ground support to the rolling boulder, shape of the rolling boulder and the hardness of the boulder contacts will play significant role in the travelling distance. It is reasonably postulated that higher rolling or/and translational speed is expected to be higher when the boulder rolls over the smaller underlying boulders cluster deposited within the valley. Higher hardness at the contacts represents lower losses in the impact energy transfer, thus preserves the kinematic energy for continuous movement to a more longer travelling distance. The resistance to decelerate the boulder will be from the rheology of the contact medium along the travelling path, which dissipate the boulder energy by permanently deforming the contact soils and, also damaging the objects blocking the boulder along its movement path.

Plate 19: 2,400 tonnes sub-rounded diorite boulder rolling downhill

In view of the hazard and threat to the downhill squatter housing, it will be risky trying to breakdown the gigantic boulders at the mid hill along the valley as any action of splitting the marginally stable boulder can result in triggering the movement of the boulders. Hence the mitigative measure is to resort with stabilizing the hazardous boulders in-situ. The approach taken is to solidify the under lying boulder clusters in the valley and integrated with gigantic overlying boulder. The solidification of the smaller round boulders is by injection with highly flowable cement grout slurry first, then cement mortal with chippings bottom up from the valley floor using flexible grout pipe through the voids in between the boulders. Once the grout mortar is up to the boulder cluster top level, then pump mixed concrete will be used to infill the cavity space beneath the gigantic boulder with side forms to contain the concrete. To better integrate the gigantic boulder with the grouted underlying boulder clusters, reinforcement meshes and anchorage dowels into the gigantic boulder are included in the concrete for ductility. Plate 20 shows the schematic diagram of the stabilization measure. As such, the integrated boulder mass will form an overall shape that is not prone to rolling movement. In one case, as the infilling will take time to complete and, also there were signs of brittle crushing at the contacts. It was decided to construct a reinforced concrete buttress to support the marginally stable huge boulder as shown in Plate 21 and then followed by the recommended infilling methods.

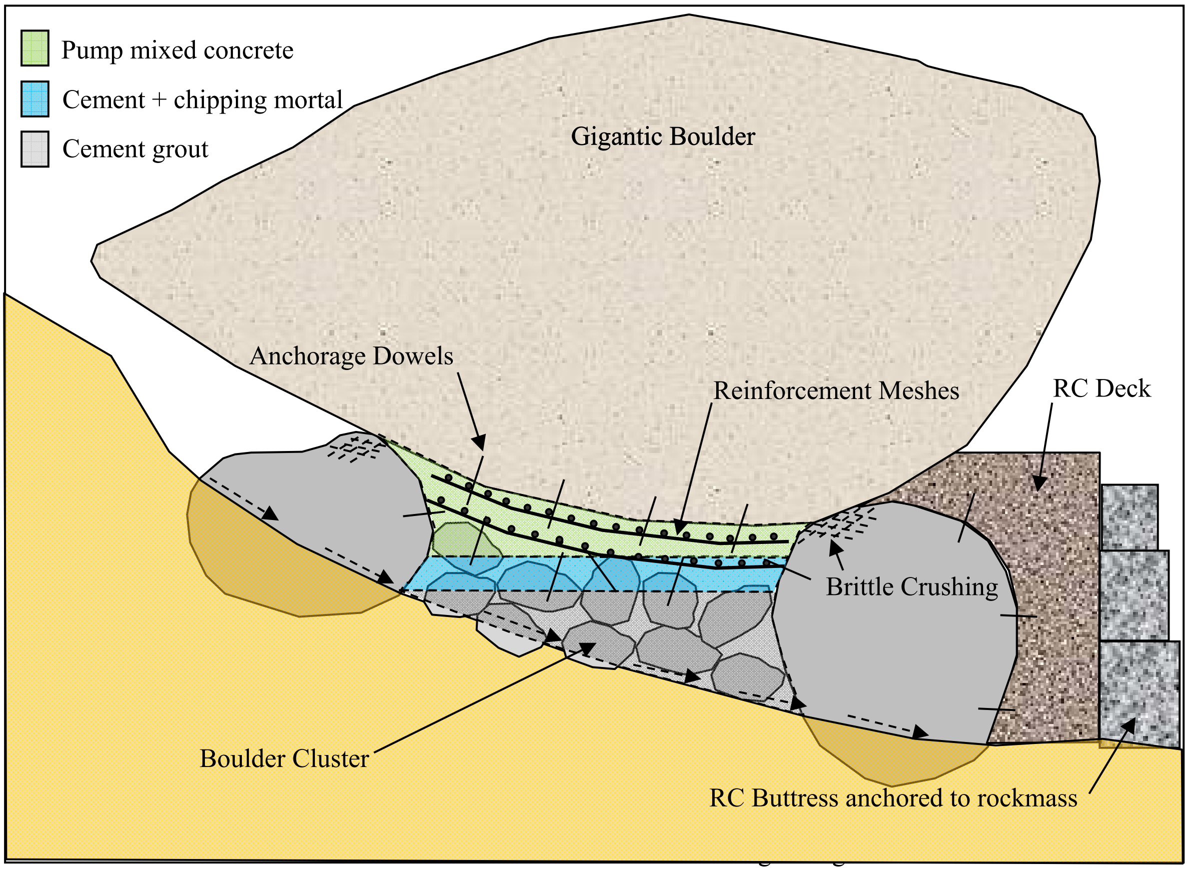

Plate 21: Reinforced concrete buttress abutting to huge diorite boulder

5 CONCLUSIONS

This paper discusses three case studies with potential hazards of non-conventional geotechnical problems. Descriptions of contributory factors and the triggering factor(s) in each type of hazard are given to understand the mechanism. The summary of the learnt lessons and remedial solutions are concluded as following:

a. Lowering of groundwater in peats will accelerate the decomposition of the organic peaty matters generating GHG with high combustible methane, which induces uncontrollable smoldering of peats underground unless with real effort with extensive treatment over vast area. Putting out the spotted peat fires that observed on surface will not be effective at all.
b. Raising of groundwater table within the peats is an effective measure to put out the peat fire. This can be achieved by bunding up the open drainage system by weir. This is how peats are preserved in the water-logged depressions.
c. When critical hydraulic gradient is formed within the limestone formation by locally lowering of water table, internal piping erosion of the infills within the existed solution channels can migrate materials and induce collapse of sinkholes when the vertical overburden materials lose the supports by erosion undermining.
d. Retention concept by sequential dumping rock fragments of varying sizes can form effective plugging within the solution channels to reduce water inflow, thus allowing grouting or other infilling methods in the channels without being washing away by active flow.
e. Resistivity survey with appropriately interpreted tomography with features corresponding to the resistivity response proves effective identification of the solution channels within the limestone rockmass.
f. Most natural soils will subject to shrink-swell behavior with change in moisture content in the soils and the atmosphere. The volumetric changes in soils that embed rigid boulder will form gaps at the interface of weathered soil and the parent core rock boulders, which can erode the supporting soils to the boulders. With extensive erosion, the boulders will lose the ground supports and become boulders with high mobility resulting in boulder fall hazard to the downhill occupants and properties.
g. Effective approach to solidify loose boulder clusters at the hill site by grouting, mortal infill and concrete bedding has been proven capable of stabilizing gigantic boulders without inducing the boulder fall.

The abovementioned three case studies do not require sophisticated engineering analysis, but rather to utilize logical thinking and knowledge of the subject matters in understanding the mechanism and formulating the effective solutions to mitigate the risks.

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