Building Infrastructure Resilient to Disasters

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ABSTRACT: This paper discusses impacts of disasters on infrastructure and counter measures that can be adopted in mitigating their impacts. Landslides, floods, tsunamis, and earthquakes are several major disasters that occur throughout the world, causing great destructions to infrastructure. Disaster mitigation, the first stage in disaster management, is the measures taken to minimize the impact of disasters. Slope stabilization, retaining walls for landslide mitigation; construction of floodways and flood prone buildings to control flooding; construction of seawalls to reduce the impact of tsunami run-up; and design and detailing of structures to be earthquake resistance are some methods that can be implemented in buildingdisaster resilient infrastructure systems.

1 INTRODUCTION

A disaster can be explained as a natural or manmade phenomenon causing large losses in social, economic, and environmental aspects of a community.Natural disasters such as earthquakes, landslides, windstorms, floods, and tsunamis pose a significant threat, particularly to infrastructure systems in developing countries, due to their vulnerability and inadequacy in disaster mitigation strategies. Structures cannot be made safe against all possible impacts of natural disasters. In some cases, it is simply not possible due to lack of technical means, while it would be much too expensive in other situations. For extreme natural hazards, structures are essentially not able to resist, while others can be dealt with by a correct design.

Enhancing the resilience of infrastructure systems to disasters refers not only to the technical advancements but also toreducing the damage to society from the failures that could occur and recovery process. At a time when Sri Lanka may be exposed to increased risks due to climate change, special consideration shall be given to measures that canminimize the damages to infrastructure such as buildings, transportation networks, bridgesand water supply systems in the country.

This paper discusses several disasters and their impact on infrastructure,while presenting several counter measures and case studies that can be adopted in the construction sector of Sri Lanka, in the efforts of creating a disaster free environment.

2 DISASTERS AND IMPACT ON INFRASTRUCTURE

2.1 Landslides

Landslides are significant ground movements on slopes such as rock, debris, and earth flows due to gravity. They could be the result of natural phenomenon such as intense rains, change in groundwater levels, water level changes in coastlines, and earthquakes as well as manmade causes such as grading, terrain, cutting and filling and other developments (Landslides 2010).Several factors for classification of landslides are; rate of movement (ranges from a slow gradual movement to a rapid movement), types of material (composed of bedrock, unconsolidated sediment and/or organic debris), and nature of movement (slide, slump, flow or fall) (Landslide Types 2010).Apart from the direct damage that can be caused to structures by debris or earth flow, landslides can also result in backwater flooding if water ways are blocked by the debris.

Rockfalls are a major component of landslide disasters, which consists of “free falling blocks of different sizes which are usually detached from a steep rock wall or a cliff" (Descoeudres et al.1999). The movement of the block may also be bouncing, rolling, and sliding as seen in Figure 1.

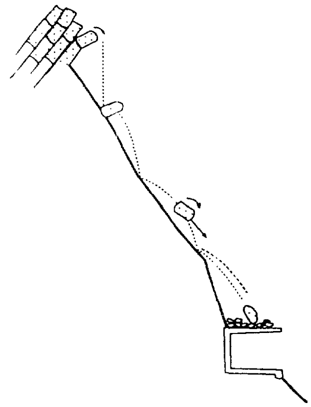

Fig 01Movement of free falling blocks (Descoeudreset al.1999)

2.2 Windstorms

A windstorm is classified as a severe weather condition with high winds. When designing for wind, it is important to conduct dynamic analysis in addition to static analysis, owing to the damage that may be caused by resonance.Typically, roofs are subject to significant wind forces because of the increasing height from ground, small weight, sharp corners without a proper bearing surface, and lack of proper anchoring to the superstructure. In intense wind conditions, structural walls may be damaged from vibrations.Bridges can also undergo extreme deformations leading to collapse under high winds. The vibrations and torsional effects on bridges may be significant depending on the type of bridge and other structural characteristics such as span length and construction material. Therefore, designing according to code provisions, conducting dynamic analysis, and wind tunnel testing when constructing infrastructure in mountains and exposed coastal regions, are vital factors to consider.

2.3 Flood

Floods are rising of large bodies of water, overflowing onto normally dry land. Either intense rains within short periods of time or continuousrainfalls over a long duration are the main causes of riverine flooding. Flooding has been the most destructive natural disaster in Sri Lanka, with a large financial spending on rehabilitation, relief, and reconstruction programs (Evans & Jinapala 2009).

Floods can critically interfere with the transportation network of a region where the roadways may be blocked or damaged. In addition, structural damage may occur in bridges, buildings, drainage systems, sewer lines, and water supply systems.Water contamination, soil erosion due to runoffs, and disturbances to ecosystems are some other effects of flooding.

2.4 Earthquakes

An earthquake, the sudden movement of plate tectonics of the earth to release energy accumulated over long period of time, is one of the most destructive forces of nature. Landslides and tsunamis can also be triggered by significant earthquakes. An earthquake can be quantified in terms of wave amplitude, energy release or intensity depending on the ground acceleration.

The severity of the impact of an earthquake can depend on several factors including the magnitude of the earthquake, geological conditions, focal depth, distance from the epicenter, and the design of buildings and infrastructure systems. In minimizing the severity, one controllable factor is the design of infrastructure to resist the impact of the earthquake.

Various structural systems such as buildings, bridges, and highways, subject to ground shaking, behave differently depending on the design specifications of the system. Hence, it is important to employ the correct procedure in designing structures that can respond to such seismic forces.

2.5 Tsunami

A tsunami, translated as the "harbor wave", can be generated by several natural occurrences such as volcano eruptions, earthquakes, and landslides causing rising sea levels due to the large displacements of the seafloor. Designing structures resilient to tsunamis still stands at an experimental stage due to the highly unpredictable nature of the effects of a tsunami.

The destruction to infrastructure from a tsunami can occur from the run-up, where a massive body of water reaches land releasing a large amount of energy. Not only the instant damage, but damage to water supply systems and sewage systems are major concerns, which can cause contamination of water and food sources, subsequently posing a significant impact on society.

3 DISASTER MITIGATION

Disaster mitigation is the first phase in disaster management and it is the measures taken in minimizing the impact of a disaster. Disaster mitigation methods can either be structural, where the infrastructure is designed such that the failure rate is minimized, or non-structural where educating the public and policy development is emphasized.

In order to develop mitigation strategies, the extent to which a country is vulnerable to hazards should be identified. Upon proper recognition of the types of hazards, it is possible to develop effective counter measures. It has been proven that investments in developing the infrastructure system of a country, immensely reduces the social and economic loss that a country has to suffer. This section will identify several counter measures that can be utilized in mitigating the previously discussed disasters.

3.1 Rockfall resilience

Rockfalls are common in mountainous areas, especially in areas where road construction has resulted in destabilizing the cut slope, as shown in Figure 2.

Fig 02 Rockfall onto a highway

For accurate counter measures to be put in place for protection against rockfalls, thorough stability analysis of cliffs posing danger is required. Some mitigation measures includemodification of slope geometry, barriers and wire net systems, rock sheds, and reinforced earth retaining structures (Descoeudres et al.1999).

A cut slope with unstable rock mass can be treated by modifying the slope geometry. In order to reduce the load and the shear force, unstable soil or rock mass can be removed from the head of an unstable slope as shown in Figure 3.

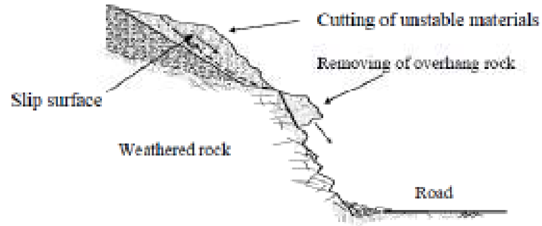

Fig 03Treatment for cut slope failure of rock mass

In highway construction, rock slopes are designed with a rock fall catchment area to prevent rock fall originating from the slope above the highway from reaching the highway lanes. Wider catchment in conjunction with appropriate geometry in general,equates to improved catchment reliability. According to the design standards, Ministry of Transport and highways, British Colombia, the recommended preliminary/conceptual catchment design to prevent rock fall onto the highway is shown in Figure 4.

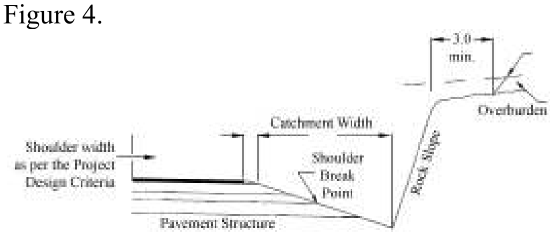

Fig 04Typical cross section for safe rock slope

Table 1 Recommended catchment width and depth for different rock slope heights

Rock cut height (m)	Catchment width (m)	Catchment depth (m)
up to 8 m	3 m	0.75 m
8 m to 16 m	4 m	1.00 m
over 16 m	5 m	1.25 m

However, for high rock cuts, catchment width that would successfully retain all rockfall from reaching highway lanes is considered excessively expensive. In such a situation, other mitigation methods such as benches or ditches in slopes can be used to stop the falling blocks together with appropriate catchment width. Along with the ditches, barriers and flexible wire net systems may be placed. Furthermore, rock sheds and reinforced retaining structures can absorb the energy of the falling rocks which helps reduce the impact of the rocks. Rock sheds are concrete structures covered in an absorbing material as seen in the following Figure5.

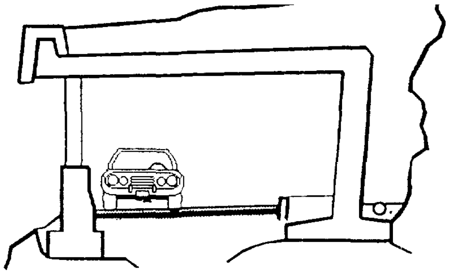

Fig 05 Schematic of rock shed (Descoeudres et al. 1999)

3.2 Landslide mitigation

Civil and Geotechnical Engineers of Sri Lanka are facing the most challenging task of mitigation and prevention of landslides. Catastrophic effects are avoided or minimized commonly by adopting appropriate landslide control techniques before the slope reaches the condition of incipient failure. There are many methods available for the control of landslides.

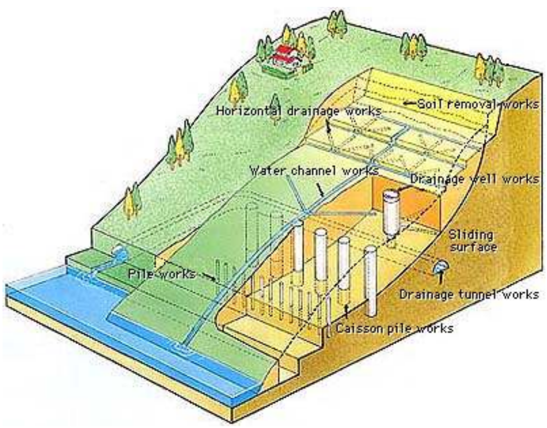

Fig 06 Landslide mitigation methods

These control methods include prevention and determent work.The purpose of prevention work is to stop or prevent landslide movement by changing natural conditions, such as topography, geology, and groundwater condition. On the other hand, the purpose of determent workis to deter part or all of landslide movement with structures. The application of the above methods for landslide mitigation is schematically shown in Figure 6.

3.2.1 Modification of slope geometry

It has been noted that the modification of slope geometry and drainage are the most commonly used and economical measures in minimizing the impact of landslides (Popescu and Sasahara2010). In order to improve the geometry of a slope, the stability of the slope should be determined through the material the slope is made of, slope gradient, and the geological structure of the slope(Skinner & Hancock2010). Placing an appropriate cut or fill in the correct location of the slope will increase the slope stability. Geological and hydro geological conditions and soil parameters should be analyzed prior to cutting of the slope.

The recommended standard maximum slope gradient for cut slope with different ground conditions is shown in Figure 7. However, the gradient indicated in Figure 7 is only indicative and detailed assessment and design of cut slopes should be carried out by considering the actual site condition.

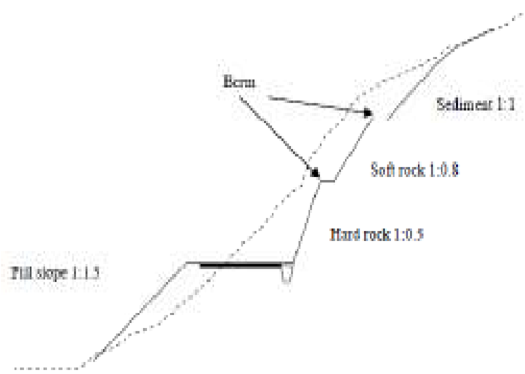

Fig 07Ground conditions and shape of cut slope

Filling can be carried out at the toe of the slope to balance the driving force of loading from top, with proper gradation, compaction, and gradient. When selecting fill material, it is important to pay attention to their strength and deformation characteristics.

3.2.2 Improvement of drainage

Majority of landslides mostly occur along with rainfall and consequently water is the main cause of landslides. The presence of water in a potential or existing sliding area can adversely affect the stability of the slope due to the increase in the water content of the soil resulting in a decrease in the shearing resistance of the soil, an increase in pore water pressures and seepage forces and the possible surface erosion.Thus,the control of surface and subsurface water by appropriate drainage techniques is of prime importance in controlling landslides as it results in improving the stability of the slope.

In general, proper drainage in slopes consist of surface and subsurface drainage systems that are capable of taking away the water to the natural drainage system safely and as quick as possible. Proper drainage technique to be adopted could be determined only with the knowledge on cause and mechanism of slope failure.Studies regarding the rainfall, topography, catchment area, ground surface condition, soil parameters, ground water conditions and existing natural and artificial drainage systems should be carried out and assessed to determine the required drainage discharge. Combination of both the surface and subsurface drains could be effectively used to manage the surface and groundwater conditions.

A properly designed surface drainage network has to be constructed in order to prevent surface runoff water from springs and rainfall infiltrating the slopes and/or landslide area to avoid increase in pore water pressure. The surface water can be removed from the unstable slope by using a surface drainage system which comprises of cut off drain, berm drain, toe drain, drainage channels, and cascades (Figure 8).

Fig 08 Surface drainage ditches (Popescu&Sasahara 2010)

When lowering of ground water level is required in order to stabilize the slope, subsurface drains are constructed. In such cases, the ground water table is lowered by installation of horizontal drain, vertical drains, trench drains, drainage wells (Figure 9), drainage tunnels, inclined drains by directional drilling etc.

Fig 09 Wells for ground water drainage(Popescu&Sasahara 2010)

3.2.3 Retaining wall construction

Stability of the slope can be improved by increasing the resisting forces by the construction of an appropriate type of retaining structure. Commonly used retaining structure types are masonry, reinforced concrete, Gabion wall and sheet pile walls. Crib walls are a more flexible type of retaining wall system. The retaining wall should be properly designed to resist the soil pressure. Other retaining structures include contiguous bored piles, steel sheet piles, reinforced soil walls, buttressed counterforts to increase shear resistance and geogrid walls (Sin & Meng 2005). All of these structural measures are to increase the resisting forces along the slip plane.

Soil nailing and anchoring have been widely used in the stabilization of cut slopes, especially in the construction of highways and roads, where limited building space isavailable. Also these methods create the minimum disturbance to the natural slope andcan be used as internal soil reinforcement measures in reducing the susceptibility of certain land areas to landslides. Soil nailing is a stabilization method of reinforcing existing soil by installing threaded steel bars into the slope or cut as construction proceeds from the top down. Grouted bars are installed to create a stable mass of soil and build a solid wall as shown in Figures10 and 11.

Fig 10Soil nailing

Fig 11Soil anchoring for slope stabilization

Despite of the development of new stabilisation techniques, the long term reliability of disaster resilient infrastructure tends to decrease with time, due to maintenance problems, whereas the safety requirement and induced risks increase, following the construction of more and more buildings and lifelines in exposed zones. Therefore any type of slope stability improvement works has to be completed by a comprehensive monitoring system allowing for early detection of a critical behaviour, based on adequate warning signals. (Bonnard and Vulliet 1999)

3.3 Flood mitigation

Counter measures that can be employed to minimize the effects of flooding can depend on the existing conditions of particular regions susceptible to flooding. Construction of floodways, levees, dikes or dams reduces the risk of extensive damage by flooding.

Floodways are channels constructed to carry the flood water on flood plains near overflowing rivers or streams, to be discharged. It is basically an area adjacent to a river free of obstruction, which can allow the excess water to divert (Floodway 2010).An area reserved for a floodway shall not comprise of any developments.

Levees (Figure12), dikes or dams are possible measures to contain the overflow of a watercourse, which can be constructed along the water way. A levee can also be seen as a type of embankment and is constructed by piling concrete along the river banks, consisting of a slope angled to the river and a flat top. In order to determine the best suited flood control technique, proper analysis must be conducted to predict the rainfall and possible stream flows.

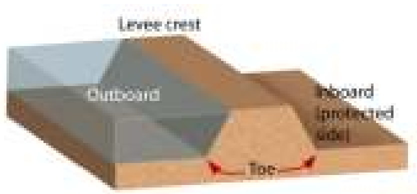

Fig 12 Typical levee construction for flood control (National Science Foundation 2010)

Several other guidelines that are suggested by the United Nations report on flood protection concerning buildings are as follows and can be illustrated in Figure13 (Vischer 1999);

- Hood-proof design of buildings typically on small earth pourings, on piers or behind local embankments.
- Omission of basements or addition of seals for entrances, light and airsupplies.
- Structural means against erosion and water pressure, including buoyancy.
- Improvement of flood resistance of water and power supply to the buildings.

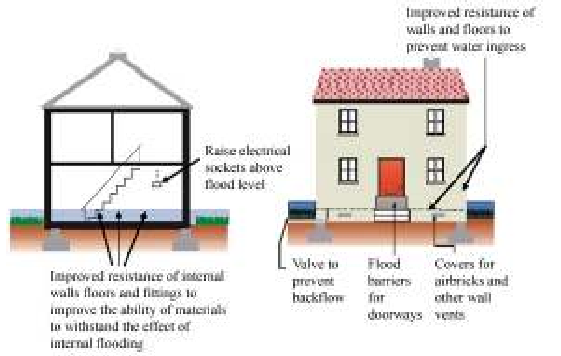

Fig 13 Construction techniques for flood resistant buildings (Planning and Building Standards Advice on Flooding 2006)

For the protection of transportation systems, construction of embankments and increased bridge heights may be possible solutions.

3.4 Tsunami mitigation

Avoiding construction near coastal areas and providing early warning systems are two major counter measures in reducing the risk of tsunamis. However, it has been a difficult task to establish a proper scientific methodology in analyzing structures affected by tsunami forces, considering the highly unpredictable nature and existing unknown parameters of tsunamis.

In terms of structural mitigation measures, construction of protection barriers such as seawalls, tsunami breakwaters, increasing embankment heights, designing according to codes and planning for maximum security, and retrofitting of existing non-engineered structures should be employed. Buildings constructed on elevated lands near coastal areas and planning the building with higher floors such that there is maximum protection from tsunami run-up are means of reducing the risk.

The construction of offshore or onshore barriers may help reduce inundation, water levels, wave energy that can be released on land, and wave speed, which are factors determining the degree of the impact of a tsunami (Tsunami Risk Mitigation Strategy for Thailand 2006).

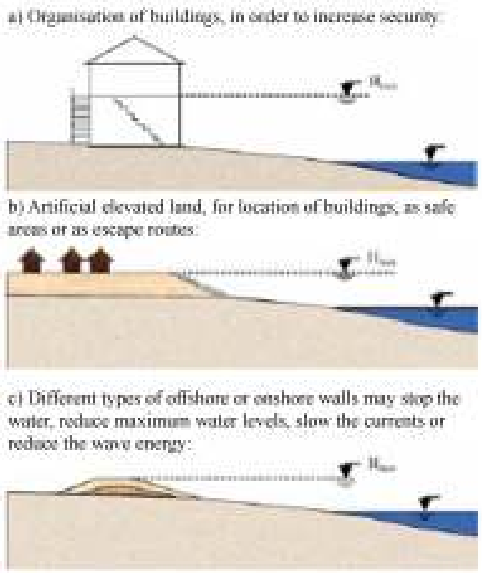

Fig 14 Possible tsunami mitigation strategies (Tsunami Risk Mitigation Strategy for Thailand 2006)

3.5 Earthquake resistance

In constructing infrastructure resilient to earthquake damage, it is most important to develop building codes, which regulate design and construction standards. This can help prevent unexpected failures of structures.

Well detailed structures are the solution to resisting earthquake loads. Detailing all structures to perform in a ductile manner, which is the ability of a structure to “sustain its load and dissipate energy for several load cycles after initial yield” (Szakats 2006), prevents abrupt failures of structures, which are most destructive. Lateral loads can effectively be resisted utilizing shear walls, moment resisting frames, or braced frames (Figures 15, 16, and 17).

Additionally, maintaining the symmetry of a structure by distributing the seismic force resisting component evenly in all directionsis crucial in reducing the earthquake impact.

Several other counter measures to effectively design earthquake resilient buildings are to avoid soft storeys, asymmetrical floor plans, which can induce torsion, poor connection between members, changes in stiffness of load bearing members, and use of brittle materials in construction.

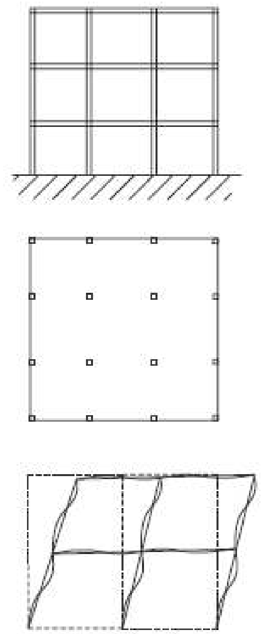

Fig 15 Elevation, plan and deformed shape of moment resisting frame (Szakats 2006)

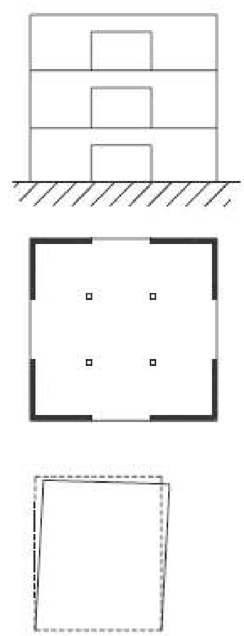

Fig 16 Elevation, plan and deformed shape of shear wall system (Szakats 2006)

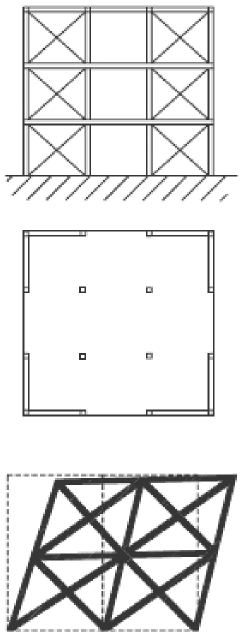

Fig 17 Elevation, plan, and deformed shape of cross braced frame (Szakats 2006)

Apart from the structural measures, educating the public, developing seismic zone maps, and land use planning are strategies to be investigated for seismic hazard reduction.

4 CASE STUDY

4.1 Stabilization of Watawala landslide

Watawalalandslide occurred in June 1992 damaging nearly 100 m length of the Colombo-Badulla railway track between Galboda and Watawala.

Fig18Damage to the railway track

The landslide was found to cover an area of approximately 22,920 m^2 and about 322,700 m^3 slide volume. A typical longitudinal section of the landslide is shown in Figure19.

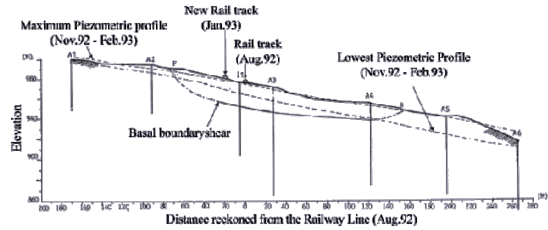

Fig 19 Longitudinal section of Watawala landslide (Rajaratnam & Bandari 1994)

Rajaratnam and Bandari (1994) reported the followinginformation based on their studies on Watawala landslide.

- The Watawala landslide formed as well developed boundary shears involving nearly 25m depth of colluvium at the deepest point. The entire slide mass was found to lie within the colluvium, overlying highly weathered rock.

- The earth slide is estimated to have undergone tens of meters of movement. Theslicken sided slip surface carry legible signatures of the sliding mass. The residual shear strength parameters operate on them.

- The peak shear strength of the colluvium is found to fall within a very wide band, between 27^0 to 45^0. The scatter is because of the highly heterogeneous nature of the colluvium and inappropriateness of small sample size tested in the laboratory. The value of the shear strength mobilized on the inclined slip surface within the colluvium was fixed as 32^0. The residual shear strength parameters on the slickensided slip surface determined by field shear box tests were c'=0, $\varphi'_r = 16^0$

- The Piezometer variations used in the stability analyses of the earth slide were as monitored through piezometric observations. The piezometric pressures in the head region of the earth slide were found to be artesian. Considerable drop in the pore pressure levels was observed during the dry i.e. rain free period.

- The earth slide was, for most part of the year, found to display "knife edge" stability. The factor of safety corresponding to the residual shear strength condition assumed on the entire slip surface was found to range between 0.57 and 0.79, corresponding to the highest piezometric profile. Very large movement and movement rates were observed corresponding to this situation.

- With the drop in the piezometric pressure during the rain free period, the factor of safety was found to improve. The value of factor of safety of the earth slide ranged between 1.07 and 1.77, depending on the location of the slip surface (assumed to be at residual state of strength). These improved values of factor of safety were found to be ephemeral.

- Assuming that the inclined slip surfaces falling within the colluvium has a higher angle of shearing resistance of about 32^0 (between the peak and the residual) and recognizing the highest observed piezometric profile, the earth slide was found to be "unstable" to "just safe".

The results clearly show that remedy lies in very effectively draining the slope so as to lower the piezometric profile. Unless that is done, the earth slide movements would continue to repeat year after year and if new thrusts develop in the head region of the earth slide and if instability of slide toe grows, it may expand in dimension both laterally as well as depth wise. Protection of toe of the earth slide was therefore absolutely essential, if the slide was to be contained. The mitigation of Watawla-landslide was associated with subsurface and surface drainage system. A typical surface and subsurface drainage system is given in Figures 20 and 21.

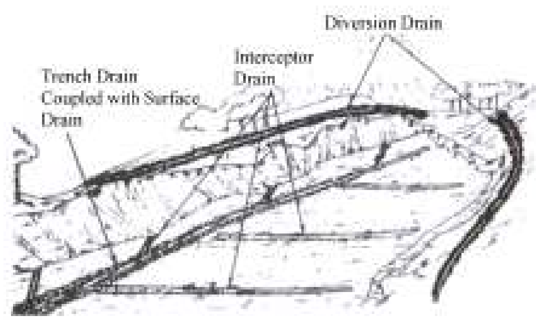

Fig 20 Typical Surface drainage system

Fig 21Sub surface drainage system

With the installation of a proper surface and subsurface drainage system it was possible to stabilize the Watawalalandslide and for the last 18years, theColombo-Badullatrain haspassed through this area without any disruptions (Figure 22).

Figure 22Present situation at Watawala after mitigation

4.2 Yuzurihara landslide prevention – Japan

In Yuzurihara region, landslide activities have occurred prior to 1940s and have been reactivated since 1991 due to heavy rainfall.

The size of the slide is noted as 600m in length; 1700 m in width; and 40 – 50m depth. The reactivation of the slide had caused damage to the residential structures and the roadways. Hence, counter measures to prevent landslides have been introduced in the area.

Eleven units of drainage borings works, 20 water catchment wells, and two drainage tunnels of length 683m and 541m, have currently been implemented in the prevention area of Yuzurihara (Popescu& Sasahara 2010). The effectiveness of these counter measures have also been monitored by conducting stability analyses, ground movement measurements, and ground water level measurements, each year. The stability analyses have confirmed that the slides have become inactive after the implementation of the mitigation procedures. A schematic of the implemented measures is shown in Figure 23.

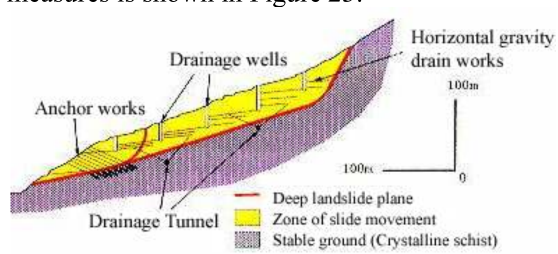

Figure 23 Cross section of Yuzurihara landslide with typical drainage (The Japan Landslide Society)

5 CONCLUSION

With the increased risk of natural disasters and their consequences, the consideration given to building disaster resilient communities have amplified. One aspect of building such communities is to build a disaster resilient infrastructure system. Currently, there are many counter measures that can be adopted in mitigating disasters in a community.

Several disasters and mitigation measures that can be adopted are discussed in this paper, which have been experimented and implemented in different parts of the world. Improvement of structures in terms of their designs and construction, ground improvement techniques, and conducting valuable research to perform analysis to develop mitigation strategies pertaining to specific regionsare the factors to be aware of when dealing with disaster prone areas.

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