A REVIEW OF SLOPE STABILIZATION METHODS

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Abstract
Slope failure cause considerable damaging effect to engineering structures and hinder development, hence measure should be put in place to prevent such occurrence. Slope stabilization methods generally reduces driving forces and increases resisting forces or both. This paper provides a literature review on various methods of slope stabilization and its geotechnical engineering applications. it is intended to provide engineers with a background understanding of slope stabilization methods

Keywords: *Slope failures, Slope stabilization, Excavation, Soil reinforcement and Soil hardening*

Introduction

Slopes can be natural or man-made (e.g. excavations, embankments). Several natural and man-made factors contribute to slope instability (Shukla, 1997). Slope stability problems which activate or accelerate the movement of a soil mass are considered to be serious natural hazards. These hazards mainly caused by strength variations at the transition zones of soil layers (soft soil located on rock layer), heavy traffic loads, seasonal high-intensity precipitations, erosion at the toe of slopes, rapid snow melts and some other natural events (Pachauri and Pant 1992; Ercanoglu 2005). Slope failures in dams, levees and embankments possess major threat to both, lives and associated civil engineering structures. Cracks, slides and depressions are signs of embankment instability which are majorly caused due to both gradual and rapid changes in the environment. The repeated wetting-drying cycles causes loss of soil strength and also results in desiccation cracking of the surface. Repairs works are extremely expensive and the frequency and recurrence of failures increase the operation and maintenance costs. Slope stabilization methods generally reduces driving forces and increases resisting forces or both (Abramson et al. 2002). The actual or potential causes of slope instability must be determined before the best method can be selected. Failure to identify factors causing the instability in the slope could render the stabilization work ineffective and the slope instability recurrent. Various methods of slope stabilization have been identified (Abramson et al., (2002); Cornforth, (2005), however, Abramson et al. (2002) and Brencich (2010) indicate that not all stabilization methods are appropriate for every type of slope failure; the most expensive treatment may not always be the most effective, and vice versa. In the selection of the most effective and economical measure, other factors like safety, construction schedule, materials and equipment availability, environmental impact, site availability, political issues and labour matters must also be considered (Jefferis 2008; Keaton 2014; Kil et al. 2016; Abramson et al. 2002; Corkum and Martin 2004; Brencich 2010; Costa and Sagaseta 2010). To provide slope stabilization recommendations, there is need for a background understanding of slope stabilization methods. This work seeks to review various methods used for slope stabilization

Unloading

Unloading is a technique to reduce the driving forces within a slide mass to ensure stability of the soil mass (Abramson et al., 2002). This can be achieved by excavation or the use of lightweight fill materials. Excavation consist of the following measures like removal of a sufficient quantity of slope forming material at the head of the slide; removal of unstable materials; increasing the length of the failure surface within the weak stratum to create more sliding resistance; transforming the behaivour of one high slope into several ones (Gedney and Weber 1978; Saftner et al., 2017, Conduto et al., 2011). The required quantity of material to be removed must be carefully predicted by stability analyses using high quality laboratory and field data. In addition, economics and material usage may dictate whether unloading procedures are reasonable on any project. This approach is ineffective for infinite slopes or for flow types of earth movement. Cost linked to accessibility, implementing and maintaining safety measures for protection of workers and equipment, disposal of excavated materials are some of the challenges associated with this method. Also, the design of removal procedures must always consider the stability of the slope behind the area to be removed. Cornforth (2005) describes a case study of slopes surrounding the Pelton Dam in central Oregon. The slopes were repaired with a lower slope angle and significant decrease in slope failure was observed. Also, reduction of the weight of embankment construction using lightweight fill materials can be very effective in reducing the gravitational driving forces tending to cause instability. Lightweight fill materials impose lower loads on the underlying soft soils resulting in lower settlements and reducing the possibilities of shear failure (Kulathilaka and Muhunthan, 2004). Expanded shale, shredded tires, encapsulated sawdust, seashells, and polystyrene foam and pumice aggregates have been used as lightweight fill materials for embankment construction (Sree Rekha and Kumar, 2014; Soni and Sagane, 2014; Marradi et al., 2012; Abramson et al.,2002).

Buttressing

This technique is used to offset or counter the driving forces of a slope by an externally applied force system that increases the resisting force (Abramson et al., 2002). Buttressing is placing a soil or rock mass against a slope face to add stabilizing force and decrease the overall slope height (Nelson et al.,2017). The principle behind buttress design for slope stability involves to provide sufficient dead weight or artificially reinforced restraint near the toe of the unstable mass to prevent movement. Stability analyses based on the unretained slope geometry and available soil shear strengths predict the forces tending to cause movement and those that exist within the soil mass to resist the movement. A buttress design provides an additional resistance component near the toe of the slope to ensure an adequate safety factor against failure. Buttressing may consist of soil and rock fill; counterberms; shear keys (Sills and Fleming, 1992); mechanically stabilized embankments (Elias and Swanson, 1983); Pneusoil (Forsythand Egan, 1976). Gedney and Weber (1978) described the reconstruction of a slide in a shale embankment in Indiana by the use of a large earth-and-rock counterweight buttress. Millet et al. (1992), described an interesting use of a large buttress (nearly 500 000 m3) constructed of granular materials to stabilize a large, potentially unstable landslide threatening Tablachaca Dam, a major hydroelectric power dam in Peru.

Drainage

Drainage reduces the seepage and hydrostatic forces on a slope as well as the risk of erosion and piping (Abramson et al., 2002). An increase in pore pressure leads to a decrease in effective stress and subsequently decrease in soil's shear strength (Saftner et al., 2017). Drainage of surface water and groundwater is the most widely used and generally the most successful slope stabilization method (Committee on Ground Failure Hazards 1985). Controlling groundwater in the slope area is a fundamental way to increase the resistance to shear failure. Drainage is a basic way to minimize the amount of water present in the slope. Drains provide a path for water to flow away from the potential slide area and increase shear strength. Surface drains, trenches, horizontal drains, and drainage wells are some methods to control water in the slope area (Cornforth, 2005). Surface drains limit the amount of infiltration into slope material. Trenches and drains are used to divert water after infiltration; their construction varies greatly by project type. Subsurface drainage can be used to lower the groundwater table within an unstable slope. Rahardjo et al. (2003) describes several drainage features designed to increase slope stability. Local conditions often govern material selection. A general suggestion is to place drains close to the failure zone, and near the steepest angle exhibited by the slope (Stanic, 1984). Drains placed near the toe generally remove the most water.

Reinforcement

Soil reinforcement is the inclusion of tensile resistant elements in a soil mass to improve its overall shearing resistance. Slope reinforcement can be an effective slope remediation technique compared to conventional practices for relatively shallow (<5m) slope failure conditions. In situ reinforcement methods for stabilizing cut slopes and embankments have included soil nailing, micropile, stone columns, Geosynthetic (Abramson et al., 2002; Thompson et al., 2005). Soil nailing, as one of the slope stabilization techniques, has been widely used in upgrading cut slopes (Zhou et al., 2009; Liu, et al., 2014), and is particularly useful for strengthening the existing slopes (Garg et al., 2014), because of their low construction cost, simple installation procedure, and the ease and speed of construction (Cheuk et al., 2005; Kim et al., 2013). The fundamental concept of soil nailing is to reinforce the soil with closely spaced passive inclusions to create a coherent gravity structure, and consequently increase the overall shear strength of the soil in situ, restraining its displacements (Wei and Cheng 2010). A micropile is a small diameter drilled and grouted pile that is typically reinforced. The diameter is usually less than 300mm and this type of pile would be considered a non-displacement pile. Micropiles can be installed at any angle, where access is restrictive, and in virtually all soil types and ground conditions. Micropiles are used for slope stabilization to provide the necessary restraining forces to structurally support the slope. Battered, and possibly vertical, micropiles are installed through the unstable slope to a designed depth below the failure surface. In doing this, the micropiles provide axial, shear, and bending resistance. Most importantly, they help resist the shear forces that develop along the failure surface (William and Howe, 2010). Stone column can be used to stabilize or prevent slope instability (Abobhiy et al., 1997; Gouhnnour et al., 1990). This technique increases the average shear resistance of the soil along a potential slip surface by replacing or displacing the insitu soil with a series of closely spaced, large-diameter columns of compacted stone. The advent of geosynthetic-reinforcement materials has brought a new dimension of efficiency to the design and construction of reinforced slopes due to their corrosion resistance and long-term stability. Geosynthetics offer a welcome additional technology for low-cost slope stabilisation (Hausmann, 1990; Shukla et al.,2011). They may be used to protect slope surfaces against erosion Reinforced slopes are basically compacted fill embankments that incorporate geosynthetic tensile reinforcement arranged in horizontal planes. The tensile reinforcement holds the soil mass together across any critical failure surface, to ensure stability of the slope. Geosynthetic reinforcement is another stabilization option. Geomembranes are another type of geosynthetic that can keep fines from pumping to the surface. The advantages of using these materials are cost efficiency, convenience for transport and installation, lower repair and maintenance costs, predictability of the design, quick installation, applicability to a wide range of soils, space savings, improved performance and extended life, good-quality control due to homogeneity in nature, less environmentally sensitive, increased safety factor, and compatibility with field conditions. However, the geosynthetic materials need to meet certain requirements and to be checked and tested before using them in the field. Westfall (2014) describes how geogrids were used in combination with other methods to stabilize slopes along U.S. 50 in Nevada, near Lake Tahoe. Most reinforcing structures require specialized experience and are likely more suitable solutions for large projects. There are standardized design approaches for many stabilizing structures. Although reinforcing structures are an expensive option, they are sometimes necessary to stabilize slopes.

Surface Slope Protection

Another method of stabilizing slopes is surface cover. Appropriate soil cover can prevent drainage related instability by diverting water, limit the effects of erosion, and provide stabilizing forces for the upper layer of a slope (Nelson, et al., 2017). Vegetative cover, rip-rap and suitable fill are common approaches to slope stabilization by ground cover (Saftner et al., 2017). Vegetation can enhance the shear strength of the soil thus increase the stability of a slope by root reinforcement (Wu et al 1979). Operstein et al. (2000) present the effect of plant roots on soil shear strength with research involving lab testing of roots and analysis of mechanical properties. Case studies have shown that slope failures can be attributed to the loss of reinforcement provided by tree roots (Wu et al. 1979; Riestenberg and Sovonick-Dunford 1983; Riestenberg 1987). Numerous researchers have quantified how root reinforcement influences the shear strength of soil (Shewbridge and Sitar 1989; Sidle 1992; Schmidt et al. 2001). Tree and grass roots have the ability to resist tension, thereby increase the shear strength of shallow soils through mechanical reinforcement (O'Loughlin 1974; Shewbridge and Sitar 1989; Skaugset 1997). Vegetation stabilizes the soil surface by intertwining of its root, minimizes seepage of runoff into the soil by intercepting rainfall and retards runoff velocity. In addition, vegetation may have an indirect influence on deep-seated stability by depleting soil moisture, attenuating depth of frost penetration, and providing a favourable habitat for the establishment of deeper-rooted vegetation (shrubs and trees). Vegetation is multifunctional, relatively inexpensive, self-repairing, visually attractive, and does not require heavy or elaborate equipment for its installation. To be successful, the vegetation must be compatible with soil and site conditions including soil type, water availability, nutrient status, soil pH, and climate (Bergado, 2004; Robles- Austriaco, 2007). However, there are certain limitations, Vegetation is susceptible to blight and drought. It is difficult to get established on steep slopes. It is unable to resist severe scour or wave action, and it is slow to established. Stabilization of slopes by the combined use of vegetation and manufactured structural elements working together in an integrated manner is known as biotechnical slope stabilization. This relatively new concept is generally cost-effective as compared with the use of structures alone; it has increased the environmental compatibility of such treatments and allows the use of indigenous natural materials. Soil-bioengineering has been used mostly for erosion control but has been shown to be successful in the stabilization of shallow slope failures. Live poles (Barker 1997; Wu, 2008).

Soil Hardening

The use of chemicals to treat unstable soil slopes is an attractive possibility. Most of the soils naturally do not have the required engineering properties to serve as a good foundation material. Under these conditions additives or admixtures are used to improve the engineering properties of less desirable soils (ARBA, 1976). The treatment of soils is achieved using methods such as compacted soil-cement fill, lime column, electro-osmosis, thermal treatment and grouting. Compacted soil-cement fill is a highly compacted mixture of soil, cement, and water that has been used for decades to meet engineering purposes for a variety of infrastructures to improve unsuitable subgrade or to modify soft soil properties (Bergado et al. 1996; PCA 2016). By compacting a mixture of cement and soil to a designated density, both shear strength and durability of the material increase substantially. Cement stabilization improves soil structure by increasing intercluster cementation bonding and reducing the pore space (Horpibulsuka et al. 2010). Therefore, it can be used to construct embankments or rebuild failed slopes (Gill and Bushell 1992; Abramson et al. 2002). In comparison with other remedial solutions, compacted soil-cement fill presents many advantages. It can use on-site materials and therefore reduces the need for debris disposal. It does not need a retaining wall and thus provides more space and a more attractive appearance. It eliminates excess moisture problems and promotes easier workability for silty soils. Its cost and construction time are also competitive compared to other solutions. Also, slope can be stabilized by injection of lime columns to increase the shear strength of clayey and silty soils but not for sandy soils. Lime piles have been used as a method of slope stabilization (Handy and Williams, 1967; Brandl, 1973; Ruenkrairergsa and Pimsarn, 1982; Lutenegger and Dickson, 1984). The mechanism behind the method as explained by Rogers et al., (2010) is that of first, the idea of pile expansion and clay dehydration. As the quicklime pile reacts with the water in the surrounding clay, further water is drawn into the pile from the clay to be consumed by the reaction, thus causing progressive clay dehydration. The piles thereby expand and subsequent lateral consolidation of the surrounding soil. The second reaction mechanism discussed concerns the migration of calcium and hydroxyl ions into the surrounding soil where subsequent modification and stabilization of the soil occurs which leads increase the strength of the soil mass. Electro-osmosis technology has been used since 1930s for removing water from clay and silt soils (Bruell et al., 1992). Since then, several successful applications have been reported by researchers such as Casagrande, 1952, Bjerrum et al., 1967, Chappell and Burton, 1975, Jones et al., 2011). Direct current (DC) electric fields have been used in electro-osmotic dewatering and consolidation for many decades (Casagrande, 1952; Esrig, 1968, Morris et al., 1985; Yoshida et al., 2013; Iwata et al., 2013). In response to the application of a DC potential, pore water tends to migrate from the anode to the cathode in most soil types (Casagrande, 1952; Esrig, 1968; Vijh, 1999; Taoet al., 2016) The common materials used for electrodes are metals such as iron, aluminum, and copper (Xue et al.,2015) The EO method has a peculiar advantage: It is unaffected by soil particle size; thus, it is often used in low-permeability soil with a long consolidation period (Gary and Mitchell. 1967; Mitchell. 1997; Citeau, 2016). At present, some limited theoretical studies and engineering practices confirm that EO can effectively accelerate the drainage rate and strengthen the soft soil (Bjerrum, et al., 1967; Burnotte, 2004; Jami and Iwata, 2008; Olivier, et al., 2014; Sun et al., 2015). However, the complicated EO mechanism and its relatively high cost have prevented it from becoming the routine method for foundation treatment (Ziwang et al., 2017). Grouting has also been used in the stabilization of slopes. It helps to seal the pores in the ground, in order to increase bearing capacity and decrease settlement (Akbulut and Saglamer, 2003). Successful grouting depends on the filling of voids in the soil sufficiently and the presence of the connections between the soil particles and grout material. The effect of grouting is to displace water from the fissure or pores in the ground as they are filled with cement mortar. The mortar hardens and create a stable skeleton around the solid soil. The grouting pressure is usually greater that that produced by the weight of the overburden to allow effective grout penetration into the fissures or voids and along active slip surface. Portland cement is used as a grout to fill the voids of the soil media and improve the strength and elastic properties of soil (Karol, 2003; Sinroja et al., 2006). In order to decrease the cost of grouting some industrial by-products such as silica fume(SF) and fly ash (FA) are also used as admixture (Pierre et al., 1984; Sandra and Jejjrey, 1992) Grout mixture vary widely depending on site conditions, desired results, available materials and economics (Borden and Groome, 1984).

Retaining Wall

Retaining wall is predominantly use for slope stabilization of cut or full without sufficient space or right-of-way available for just the slope itself (Abramson et al., 2002) Retaining walls are usually built to take over the function (static effect) of a ground body removed from a natural slope. These vertical, or slightly inclined walls are constructed for the purpose of preparing a horizontal surface for roads, water course, or foundations for cranes, industrial buildings, warehouses, quays, and harbours. The purpose of the retaining wall does not usually have any bearing on its design. The structure of the wall must be capable of transferring the lateral pressure of soils or rocks, together with the weight of the wall and any load placed above it, safely into the load-bearing foundation ground. Comforth, (2005) classified retaining walls into four categories namely; gravity walls, cantilever walls, tied-back walls and reinforced soil walls. Gravity walls in which the foundation of the wall provides the resistance to sliding and overturning. Cantilever walls in which the support is provided from a vertical or inclined cantilever usually of relatively modest height. Tied-back walls in which the vertical or inclined wall face is restrained by ground anchors to limit outward deflection. While reinforced soil walls in which soil is reinforced by metal strips, plastic strips, grids, soil nails or fabric reinforcement to allow the outer face to stand at relatively steep slope and provide internal stability.

Conclusion

Stabilization of a man-made or natural slopes critical as there is every possibility that the structures might collapse if the slopes are found to be unstable. The potential causes for instability of slopes are ranging from deep-seated failure to surface erosion by wind or water. Methods available for stabilization of slopes such as mechanical, earthwork, and bioengineering. The mechanical technique utilizes nonliving components such as rock, concrete, steel pins, gabion baskets, geosynthetics to reinforce slopes. The earthwork technique does reshaping of surface slopes by several methods such as creating terraces or benches, flattening oversteppened slopes, soil roughening, and land forming. Surface protection methods are used on small scale to provide protective covering over materials that are prone to erosion and scouring. The bioengineering technique includes installation of a geotextile followed by seeding and plantation of saplings. This facilitates the vegetation to grow, as a result, after some days the roots of the vegetation take care of the soil that ultimately protects the slope from erosion. This technique has been found very effective for stabilization of different kinds of slopes. The main advantages of the reinforced earth are economical and great deformability which enables it to adapt without risk to important motions. The use of chemicals to treat unstable soil slopes is an attractive possibility. It is used to improve the engineering properties of less desirable soils. Retaining wall is predominantly use for slope stabilization of cut or full without sufficient space or right-of-way available for just the slope itself. The selection of slope stabilization method to use in a project depends on various factors and also it is evident that not all techniques are appropriate for every type of slope failure. Most times, the final choice between several methods may not entirely belong to the engineer. In conjunction with selecting the most effective and economic stabilization measure, other factors must also be considered, including safety, construction scheduling, availability of materials, site accessibility, equipment availability, aesthetics, environmental impact of the end project, political issues and labour considerations.

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