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APPARATUS AND METHOD FOR PREVENTING SLOPE FAILURE

TECHNICAL FIELD

This invention relates generally to control of slope failure and relates more particularly, though not exclusively, to an apparatus and method for preventing slope failure such as slides and slumps.

BACKGROUND

Natural or engineered residual soil slopes often experience mass wasting as a result of slope failure due to water infiltration, especially in regions where tropical rainstorms occur. As water enters soil from above, it passes through pore spaces in the soil through a zone of aeration where the soil is unsaturated. As water infiltrates more pore spaces at increasing depths, a zone of saturation is reached in an underlying soil layer where all the pore spaces are filled with water. The water level in the zone of saturation is known as the water table. Other than rainfall, the water table can also be affected by water infiltration occurring due to melting of snow, floods, damage or overflow of a pipe or dam etc.

Shear strength of a soil layer is inversely proportional to its water content. Increased water content also lubricates soil grains, further reducing their cohesion, while increased pore pressure forces the grains apart. In times of heavy or extended rainfall, as the water table in an underlying soil layer rises, shear strength of the underlying soil layer can fall dramatically. When the shear strength in the zone of saturation drops to a level where it is no longer able to resist gravitational force acting on sloping soil above, catastrophic



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slope failure may consequently occur as a landslide or a slump wherein the underlying soil layer in the saturation zone gives way and soil above slides down-slope en masse, under the force of gravity.

Preventive measures against mass wasting due to water infiltration include slope reduction where possible, for example by cutting back or terracing the land; providing retention structures such as growing deep-rooted plants or installing retaining walls or rock bolts; and reducing water retention/infiltration by providing surface and subsurface drains or a soil cover to prevent water entry.

A commonly used soil cover is a low-permeability compacted clay cover that is abundantly available. However, after numerous wetting and drying cycles over some years of use, failure of the compacted clay arises due to desiccation-induced cracking, subsidence, root and animal intrusions, or shrink-swell or freeze-thaw effects. With failure, the compacted clay cover is no longer effective as a water barrier, allowing water to pass through the failed clay cover and infiltrate the slope to increase the risk of slope failure.

SUMMARY

In general terms, the invention proposes an apparatus and method for preventing slope failure due to water infiltration by preventing or reducing water infiltration into underlying soil in the slope.

The apparatus comprises a first layer having a first cell array for containing a first slope material in each cell of the first cell array. The first layer is placed on the slope to receive water input on the slope. The apparatus also comprises a second layer having a second cell array for containing a second slope material in each cell of the second cell array. The second layer is placed beneath the first layer on the slope.

An interface is formed between the first slope material on top and the second slope material below. Preferably, a capillary barrier is formed at the interface for preventing and/or limiting water movement from the first slope material into the second slope material, thereby preventing or reducing water retention or infiltration into the slope to prevent slope failure.

The apparatus is installed on the slope by laying the second or lower cell array on a slope, filling each cell of the lower cell array with the second or lower slope material, laying the first or upper cell array over the lower cell array on the slope, and filling each cell of the upper cell array with the first or upper slope material.

A first specific expression of the invention is an apparatus for preventing slope failure in a slope, the apparatus comprising: a first cell array for containing a first slope material in each cell of the first cell array, the first cell array being configured for placement on the slope to receive water input on the slope; and a second cell array for containing a second slope material in each cell of the second cell array, the second cell array being configured for placement beneath the first cell array on the slope.

A second specific expression of the invention is a method of preventing slope failure in a slope, the method comprising: laying a lower cell array on a slope; filling each cell of the lower cell array with a lower slope material; laying an upper cell array over the lower cell array on the slope; and filling each cell of the upper cell array with an upper slope material.

A third specific expression of the invention is a method of preventing slope failure in a slope, the method comprising: providing a first slope material contained in a first cell array on a slope; and providing a second slope material contained in a second cell array on the slope under the first slope material; and inhibiting water movement from the first slope material into the second slope material by a capillary barrier formed at an interface between the first slope material and the second slope material.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments, the description being with reference to the accompanying illustrative drawings.

In the drawings:

FIG. 1 is a perspective view of an exemplary embodiment of the apparatus;

FIG. 2 is perspective view of exemplary embodiments of a part of the apparatus;

FIG. 3 is a schematic side view of the exemplary embodiment of FIG. 1;

FIG. 4 is a graph of volumetric water content against matric suction;

FIG. 5 is a graph of coefficient of permeability against matric suction;

FIG. 6 is a schematic flowchart of an exemplary embodiment of the method; and

FIG. 7 is a schematic flowchart of another exemplary embodiment of the method.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

As shown in FIG. 1, there is provided an apparatus 10 for use on a slope to prevent slope failure. The apparatus 10 comprises a first cell array 12a and a second cell array 12b. The first cell array 12a is for forming a first or upper layer 11a on the slope while the second cell array 12b is for forming a second or lower layer 11b on the slope under the first layer 11a. The first cell array 12a may be identical with or different from the second cell array 12b. Each cell array 12 comprises a plurality of adjoining open cells 14. Each open cell 14 is defined by an encircling cell wall 16 configured to contain a slope material within the cell 14. Exemplary embodiments of cell arrays 12-1 to 12-5 having open cells 14 of various shapes and sizes are shown in FIG. 2. The open cells 14 in a cell array 12 preferably are of one or more regular geometric shapes suitable for tessellation to form a repeating array 12 of adjoining cells 14. The cells 14 of the cell array 12 may be in a regular array, as shown, or may be in an irregular array. All cells 14 of the cell array 12 may be the same, as shown, or different sizes and/or shapes of cells 14 may be used.

For enhanced flexibility, the open cells 14 may comprise discrete individual cells 14 configured for connection with each other to form a cell array 12 having a customizable boundary shape. For protecting a slope area that is larger than the area covered by one cell array 12, each cell array 12 is preferably configured for connection with one or

more other cell arrays 12 so that each layer 11 on the slope comprises a plurality of cell arrays 12. Preferred configurations of cell arrays 12 allow sharing of common walls 16 between cells 14 from adjacent cell arrays 12 when multiple cell arrays 12 are interconnected, such as the embodiments 12-1 to 12-5 shown in FIG.2. This minimizes wall material required to form each layer 11 when multiple cell arrays 12 are needed to cover a large tract of sloping land, as well as facilitates in-plane drainage along each layer 11.

By providing a modular apparatus 10 with individual cells 14 that can be releasably interconnected and/or cell arrays 12 that can be releasably interconnected to enlarge each layer 11, the apparatus 10 may be readily transported when disassembled and on-site assembly on the slope may be easily adapted to the contour and size of the location.

When installing the apparatus 10 on a slope to achieve the configuration as shown in FIG. 3 and as illustrated by the method 100 in FIG. 6, the second or lower cell array 12b is first laid as a lower layer 11b on the slope 18, 102. The cells 14b of the lower layer 11b are then filled or compacted with the second or lower slope material 104. Next, the first or upper cell array 12a is laid over the second cell array 12b to form an upper layer 11a on the slope 18, 106. Finally, the cells 14a of the upper layer 11a are filled or compacted with the first or upper slope material 108.

Preferably, the first and second cell arrays 12a, 12b are configured to be anchored to the slope 18 to prevent them from sliding down the slope under the weight of the first slope material and the second slope material. Anchoring means include pins or dowel bars (not shown) inserted or driven into the slope 18 through an appropriate number of cells

14. The pins or dowel bars may be inserted after laying the lower or second layer 11b on the slope 18 before filling the cells 14b with the lower or second slope material compacted around the pins or dowel bars. The upper cell array 12a can then be fitted over the pins or dowel bars that should be long enough to extend upwardly beyond the lower layer 11b. Installation is completed by compacting the first or upper slope material into the upper cells 14a around the pins or dowel bars. Preferably, the walls 16 of the cells 14 in each array 12 are configured to have a deflection of 1/500 or less when each cell array 12 is completely filled with a slope material.

By providing the first slope material contained in the first cell array 12a on the slope 18, 202 and providing the second slope material contained in the second cell array 12b on the slope 18 under the first slope material 204 as shown in the method 200 of FIG. 7, an interface 20 is formed between the first slope material on top and the second slope material below. Preferably, a capillary barrier is formed at the interface 20 for inhibiting water movement from the first layer 11a into the second layer 11b, 206. The capillary barrier arises as a result of an appropriate selection of materials for the first slope material and the second slope material, and can be explained using material-water characteristic curves (MWCC) and permeability functions of the first slope material and the second slope material as shown in FIGS. 4 and 5 respectively. An MWCC is a relationship between water content and matric suction of a material, while a permeability function is a relationship between unsaturated coefficient of permeability and matric suction of the material. Matric suction is the difference between pore-air pressure and pore-water pressure in the material. A steeper MWCC and a lower air-entry value for material 1 layer is that the layer would be able to drain a larger amount

of water for a given range of matric suction change, rapidly increasing the storage capacity of the material 1 layer after rainfall or other water input on the slope.

The capillary barrier effect is caused by a contrast in the unsaturated coefficient of permeability between the first slope material and the second slope material. Beyond certain matric suction values, for example 10^0 as shown in FIG. 5, the coefficient of permeability of the second slope material is significantly lower than the coefficient of permeability of the first slope material. Rainwater falling on the apparatus 10 installed on the slope 18 will consequently be stored in or diverted laterally through the first slope material in the first layer 11a instead of flowing into the second layer 11b. In this way, excessive water infiltration into the slope can be prevented or reduced. This keeps the water table low enough so that shear strength of the underlying soil exceeds gravitational force on the soil above and slope failure is prevented.

The air-entry value of the material is the matric suction value that must be exceeded before air recedes into the pores of the material. Water-entry value, ψ_w , is the matric suction value at which water first moves into the smallest pores that form a continuous network through the initially dry second slope material. The water-entry value, ψ_w , is also called the breakthrough head since this value corresponds to the pore-water pressure head at which water first breaks through the interface 20 between the first slope material and the second slope material.

A steeper MWCC curve and a lower air-entry value for the first slope material means that the first layer 11a can drain a larger amount of water for a given range of change in

matric suction, rapidly increasing the storage capacity of the first slope material after rainfall or other water input on the slope.

Under heavy or extended rain, as water continues to infiltrate the slope 18, both the volumetric water content and the coefficient of permeability of the first slope material will increase. When the infiltrating water reaches the interface 20 between the first slope material and the second slope material, matric suction of the second slope material at the interface 20 will decrease. When the matric suction of the second slope material at the interface 20 reaches the water-entry value, ψ_w of the second slope material, the coefficient of permeability of the second slope material will increase to a level where water will begin to flow into the second slope material. As the matric suction of the second slope material further decreases due to water infiltration, the coefficient of permeability of the second slope material increases rapidly until it exceeds the coefficient of permeability of the first slope material. Under such conditions, there is no longer any capillary barrier effect and water will flow easily into the second slope material. Despite the loss of the capillary barrier effect, the apparatus 10 still serves to limit water infiltration into the slope 18 by acting as a surface drain that laterally diverts water in a parallel direction along the slope surface.

To facilitate lateral water diversion, drainage holes 17 may be provided in the walls 16 of each cell 14 in the cell arrays 12. The drainage holes 17 are to allow water to flow down-slope through adjoining cells 14a, 14b along each layer 11a, 11b respectively. The drainage holes 17 should be configured to allow water movement while preventing passage of the first slope material or the second slope material therethrough.

A drainage or separator sub-layer 19 may also be provided below one or both of each layer 11a, 11b to facilitate water flowing down-slope along the slope and enhance lateral drainage of infiltrating rainwater. For example, a geodrain of thickness ranging from 5mm to 50mm may be used as a drainage sub-layer 19. Where a sub-layer 19 is provided between the first layer 11a and the second layer 11b, the sub-layer 19 acts as a separator to minimise mixing of the first slope material with the second slope material. In a preferred embodiment, the separator sub-layer may be a geotextile or a geomembrane of thickness ranging from 2mm to 5mm.

Besides lateral water diversion, water storage capacity of the apparatus 10 is also important under high precipitation rates, especially in areas where intense rainfall occurs in short periods at a time. This is because lateral water diversion cannot immediately occur when the apparatus 10 has been subjected to a short period of intense rain as the infiltrating water needs time to flow to the lateral drainage outlets such as the drainage holes and the drainage sub-layers. It is therefore preferable to use materials with a relatively high coefficient of permeability for the first slope material in order to have a high water storage capacity, so as to produce a high lateral water diversion in a relatively short time and minimize water infiltration into the second layer 11b.

When selecting the first slope material and second slope material that are to be used together in a particular application of the apparatus 10, parameters or material characteristics that need to be considered are: ratio of the water-entry value of the first slope material to the second slope material (ψ_w -ratio), the saturated coefficient of

permeability (k_s) of the first slope material, the water-entry value (ψ_w) of the second slope material, and the shrinkage properties of both the slope materials.

Water-entry ratio

When the water-entry ratio (ψ_w -ratio) of the slope materials contained in the apparatus 10 is high, a significant capillary barrier effect is produced and breakthrough or percolation of water from the first layer 11a into the second layer 11b can be minimized. A high contrast of the hydraulic properties between the first slope material and the second slope material is therefore desirable.

The water-entry value ψ_w of a material is often related to the particle size distribution of the material. A coarse material (i.e. a material with large particle diameters, e.g. D_{30} and D_{60}) normally has a small water-entry value ψ_w . Thus, the capillary barrier effect produced in the apparatus 10 may also be related to the particle size of the materials selected. A second slope material that is 2.5 times coarser than the first slope material (e.g. D_{50}) will result in 80% of the maximum lateral diversion occurring in the first slope material when the apparatus 10 is applied to a slope. A second slope material that is at least 5 times coarser than the first slope material will result in 90% of the maximum lateral diversion occurring in the first slope material. D_n is the maximum particle size for the passed (finer) particles for the n^{th} sieve. The first slope material should therefore normally be of a finer grain than the second slope material. For example, the first slope material may have a particle size of less than 5mm while the second slope material has a particle size ranging from 0.075mm to 75mm.

Preferably, the water-entry ratio (ψ_w -ratio) of the slope materials should be at least 10. For example, fine sand may be used as the first slope material and gravelly sand used as the second slope material to provide a ψ_w -ratio of 11.5. In an alternative embodiment, fine sand and pea gravel may be used as the first slope material and second slope material respectively to give a ψ_w -ratio of 44.3.

Saturated coefficient of permeability of the first slope material

Besides selecting slope materials that have a high ψ_w -ratio, it is also important that the first slope material that has a high matric suction compared to the second slope material in order to minimize water from passing from the first layer 11a into the second layer 11b. If the saturated coefficient of permeability of the first slope material is low, infiltrating water will remain trapped in the first slope material due to difficulty in lateral drainage of the water along the first layer 11a. With continued infiltration, the matric suction of the first slope material will reach zero when the pores in the first slope material are filled with water. When the matric suction along the interface 20 between the first layer 11a and the second layer 11b is lower than the water-entry value of the second slope material, a significant amount of infiltrating water will eventually penetrate into the coarse-grained second slope material in the second layer 11b.

There should therefore be a lower bound of the saturated coefficient of permeability of the first slope material used in the apparatus 10. A threshold value of 10^{-5} m/s may be used as a guideline since a material with coefficient of permeability lower than 10^{-6} m/s is generally considered a poor drainage material. For example, clean sand and clean

gravel having a coefficient of permeability of 10^{-5} m/s and 10^{-2} m/s respectively may be suitable for use as the first slope material.

Water-entry value ψ_w of the second slope material

In addition to the ψ_w -ratio and the saturated coefficient of permeability of the first slope material, the water-entry value ψ_w of the second slope material also plays an important role in ensuring the effectiveness of the apparatus 10 to limit downward movement of water into the underlying soil. A significant amount of water will only flow into the second layer 11b when the matric suction at the interface 20 between the first layer 11a and the second layer 11b decreases to a value close to the water-entry value ψ_w of the second slope material. Thus, the smaller the water-entry value ψ_w of the second slope material, the lower the likelihood of water breaking through the first layer 11a into the second layer 11b. Preferably, the second slope material should have a water entry value ψ_w of less than 1kPa. It is observed that the coarser and the more uniform a material is, the lower the water-entry value ψ_w is. For example, gravelly sand having a water entry value ψ_w of 0.4kPa may be used as the second slope material contained in the second layer 11b.

Material shrinkage

During dry periods, the first and second slope materials used in the apparatus 10 should not exhibit shrinkage cracks as these will affect the hydraulic properties of the materials. Generally, materials with shrinkage potential of less than 4% will be suitable.

Layer thickness

Thickness of the first and second layers 11a, 11b on the slope 18 also affects the effectiveness of the apparatus 10 in preventing or reducing water infiltration into underlying soil layer of the slope 18. A breakthrough can be minimized or even avoided by increasing the thickness of the first layer 11a.

The thickness of the first layer 11a has a direct relationship with the maximum water storage capacity of the apparatus 10, as shown in the following equation:

$$S_{\max} = \theta_s * t_f * A$$

where

$S_{\max}$ is the maximum water storage capacity of the apparatus 10,

θ_s is the volumetric water content of the first layer 11a at saturation,

t_f is the thickness of the first layer 11a, and

A is surface area of the slope covered by the apparatus 10.

From this equation, it can be seen that the maximum water storage capacity of the apparatus 10 will increase if the thickness of the first layer 11a increases. An apparatus 10 having a thick first layer 11a layer can store more water than before breakthrough occurs.

The volumetric water content of the apparatus 10 at breakthrough varies with depth or height of the first layer 11a. The water storage capacity of the apparatus 10 can thus be

calculated by integrating the material water content (i.e., volumetric water content profile) over the height of the first layer 11a as shown in the following equation:

$$S = A \int_0^{t_f} \theta(h).dh$$

where

S is the water storage capacity of the apparatus 10,

$\theta(h)$ is the volumetric water profile of the first layer 11a,

dh is the height of the first slope material in the first layer 11a,

t_f is the thickness of the first layer 11a, and

A is surface area of the slope covered by the apparatus 10.

Once the first and second slope materials to be used with the apparatus 10 on a slope at a particular location have been selected, the required thickness of the first layer 11a to store a particular amount of infiltrating water can be estimated using the above formulae. This estimation may be performed after determining the maximum total rainfall for the particular location where the apparatus 10 is to be used. The maximum total rainfall serves as an estimation of the desired storage capacity of the apparatus 10. In this way, the required minimum thickness of the first layer 11a to be applied on the slope may be determined.

The primary function of the second slope material is to provide a capillary barrier break. Since downward water movement from the first layer 11a into the second layer 11b is controlled by the water-entry value of the second slope material, thickness of the second layer 11b only has small impact on the performance of the apparatus 10 as a whole to

impede water movement into the slope. This is because the second slope material 2 layer serves to provide the hydraulic impedance at the interface 20 between the two layers 11a and 11b. If the hydraulic properties of the second slope material in the second layer 11b are not suitable to form the hydraulic impedance at the interface 20, increasing the thickness of the second layer 11b will not help to prevent rainwater infiltration. Conversely, if the hydraulic properties of the second slope material can provide a sufficient hydraulic impedance at the interface 20, the required thickness of the second layer 11b may simply be as low as the water-entry head of the second slope material in the second layer 11b. Once the thickness of the second layer 11b is greater than the water-entry head of the second slope material, a continuous water phase in the second slope material in the second layer 11b can be avoided. Therefore, the minimum effective thickness of the second layer 11b can be approximated from the water-entry value of the second slope material.

Whilst there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the present invention.

CLAIMS

1. Apparatus for preventing slope failure in a slope, the apparatus comprising:
 - a first cell array for containing a first slope material in each cell of the first cell array, the first cell array being configured for placement on the slope to receive water input on the slope; and
 - a second cell array for containing a second slope material in each cell of the second cell array, the second cell array being configured for placement beneath the first cell array on the slope.
2. The apparatus of claim 1, wherein the second cell array containing the second slope material is placed beneath the first cell array containing the first slope material and a capillary barrier is formed at an interface between the first slope material and the second slope material for inhibiting water movement from the first slope material into the second slope material.
3. The apparatus of claim 2, wherein matric suction at the interface between the first slope material and the second slope material is greater than the water-entry value of the second slope material.
4. The apparatus of any one of the preceding claims, wherein the water-entry value of the second slope material is less than 1kPa.

5. The apparatus of any one of the preceding claims, wherein ratio of the water-entry value of the first slope material to the water-entry value of the second slope material is at least 10.
6. The apparatus of any one of the preceding claims, wherein the saturated coefficient of permeability of the first slope material is at least 10^{-5} m/s.
7. The apparatus of any one of the preceding claims, wherein the shrinkage potential of the first slope material and the second slope material is less than 4%.
8. The apparatus of any one of the preceding claims, wherein the first slope material is of a finer grain than the second slope material.
9. The apparatus of claim 8, wherein the first slope material has a particle size of less than 5mm and the second slope material has a particle size ranging from 0.075mm to 75mm.
10. The apparatus of any one of the preceding claims, wherein a minimum effective thickness of the first slope material when laid on the slope is determined from a desired water storage capacity of the apparatus.
11. The apparatus of any one of the preceding claims, wherein a minimum effective thickness of the second slope material when laid on the slope is approximated from the water-entry value of the second slope material.

12. The apparatus of any one of the preceding claims, wherein the first cell array and the second cell array each comprise a plurality of adjoining open cells.
13. The apparatus of any one of the preceding claims, wherein drainage holes are provided in the first cell array for lateral water diversion, the drainage holes being configured to prevent passage therethrough of the first slope material.
14. The apparatus of any one of the preceding claims, wherein drainage holes are provided in the second cell array for lateral water diversion, the drainage holes being configured to prevent passage therethrough of the second slope material.
15. The apparatus of any one of the preceding claims, wherein at least one of the first cell array and the second cell array comprise discrete cells configured for connection with each other to form an array of adjoining cells.
16. The apparatus of any one of the preceding claims, wherein the first cell array and the second cell array comprise a plurality of adjoining first cell arrays and a plurality of adjoining second cell arrays respectively.
17. The apparatus of any one of the preceding claims, wherein the first and second cell arrays are anchored into the slope to prevent down-slope movement of the first and second cell arrays when filled with the first and second slope materials respectively.

18. The apparatus of any one of the preceding claims, further comprising a sub-layer for placement below at least one of the first cell array and the second cell array, the sub-layer being configured to facilitate lateral water diversion.
19. The apparatus of claim 18, wherein the sub-layer is further configured to minimize mixing of the first slope material with the second slope material when placed between the first cell array and the second cell array.
20. A method of preventing slope failure in a slope, the method comprising:
 - laying a lower cell array on a slope;
 - filling each cell of the lower cell array with a lower slope material;
 - laying an upper cell array over the lower cell array on the slope; and
 - filling each cell of the upper cell array with an upper slope material.
21. The method of claim 20, further comprising inserting at least one anchoring pin through at least one cell of the lower cell array into the slope after laying the lower cell array on the slope and before filling each cell of the lower cell array with the lower slope material.
22. A method of preventing slope failure in a slope, the method comprising:
 - providing a first slope material contained in a first cell array on a slope; and
 - providing a second slope material contained in a second cell array on the slope under the first slope material; and

inhibiting water movement from the first slope material into the second slope material by a capillary barrier formed at an interface between the first slope material and the second slope material.