

Introduction

With the development of global economy, a large number of exposed soil and rock slopes have been produced in engineering construction. Traditional slope protection measures not only consume a large amount of cement, steel and other building materials, but also occupy the space of vegetation growth, reduce forest carbon sink and aggravate the greenhouse effect. It is not conducive to the restoration of natural environment and the long-term stability of slope.

1. research status

- The traditional slope protection method isolates the exchange of water and air between rock and slope. Not only can not ensure long-term stability, but also destroy the local ecological balance.
- The traditional ecological slope protection method is better than the traditional method. However, its growth is slow, the survival rate is low, the stability and the natural succession of indigenous vegetation are poor.
- In most studies on the mechanism of roots fixing slope, the root system is simplified into a simple anchor rod, which cannot truly reflect the soil fixing mechanism of root system.
- The effects of vegetation on slope reinforcement have not yet formed a complete stability calculation method, so designers can only use ecological protection as an auxiliary means or greening method.

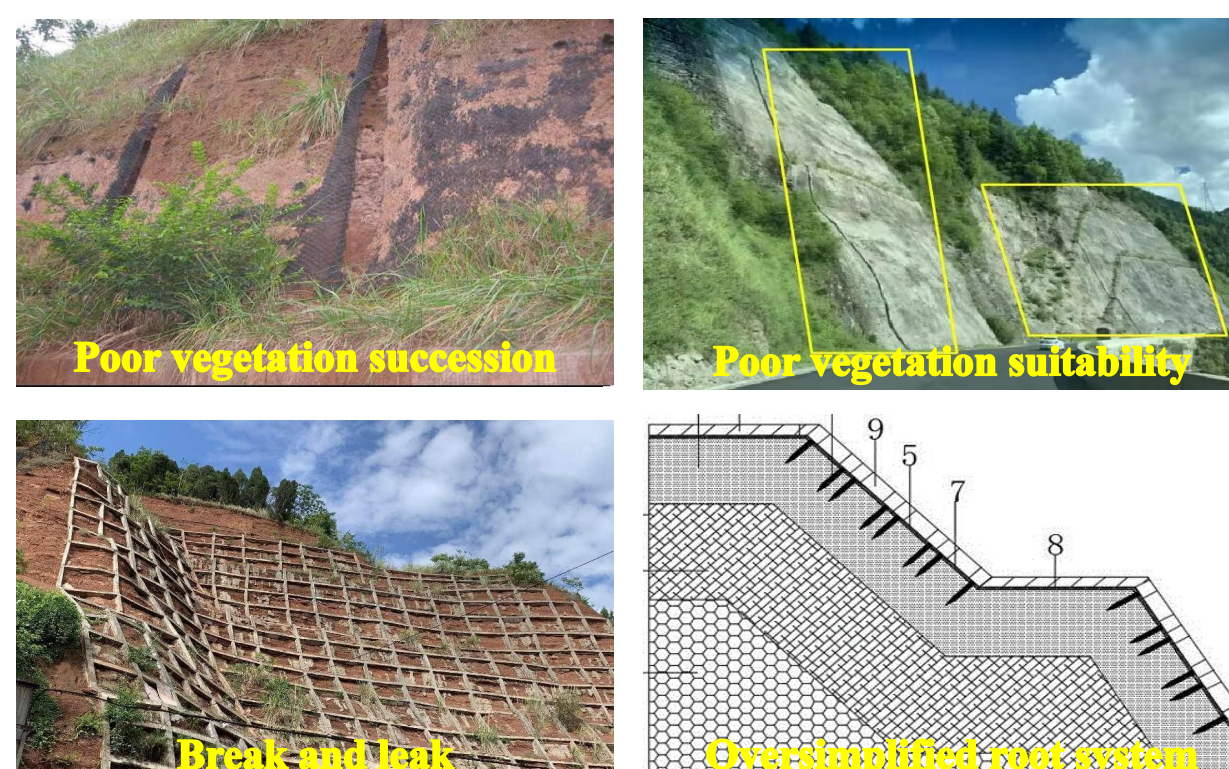
2. Problems of Existing

Insufficient resistance to erosion and drought of spray seeding substrate

The water and fertilizer retention and long-term effectiveness of the spray seeding substrate are poor

The ecological slope protection of steep rock slope lacks long-term effectiveness

The numerical simulation of root hierarchy is oversimplified



3. Objectives

- A green slope active mesh shotcrete vegetation protection technology is developed, which can solve the problems of slope protection and vegetation restoration.
- Develop a configuration program MechRoot that can well simulate three-dimensional root systems with different structures and levels, and a stability calculation method of ecological protection is proposed.

R&D of new PCF ecological concrete

1. Introduction to key components of PCF ecological concrete (PFCEC)

- **PCF ecological concrete (Composition)**: It is composed of planting soil, sand aggregate, cement, polymer material regulator, PH regulator, FA fertilizer and plant fiber.
- **PAM (Agglomerate)**: It can adjust the soil aggregate structure, prevent the loss of soil, water and fertilizer.
- **CMC (Binder)**: It has good bonding properties and high bonding strength with thickening, water retention and other characteristics.
- **FA fertilizer (fertilizer)**: It can increase soil remanence, increase the content of trace elements in soil, and avoid soil acidification and compaction caused by long-term application of chemical fertilizer. shengzhangguancha



2. R&D of new PCF ecological concrete

Orthogonal test

- There are four factors in the base material composition: PAM, CMC, FA fertilizer component and water.
- The optimal ratio can be obtained by arranging orthogonal experiment according to L9 (3⁴).

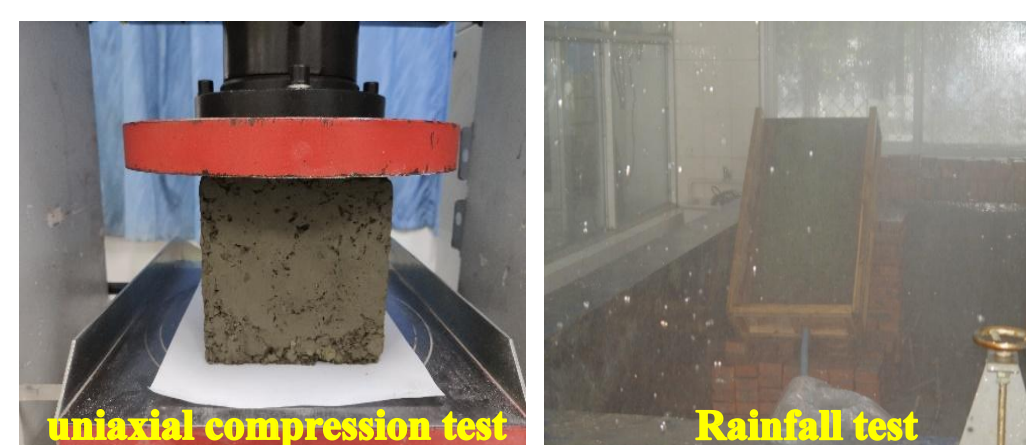


shear tests and Unconfined compressive strength

- The shear strength of PCF ecological concrete is up to 3-5MPa, which can provide a stable environment for the normal growth of plants on the rocky slope.

Influence of components on strength of substrate

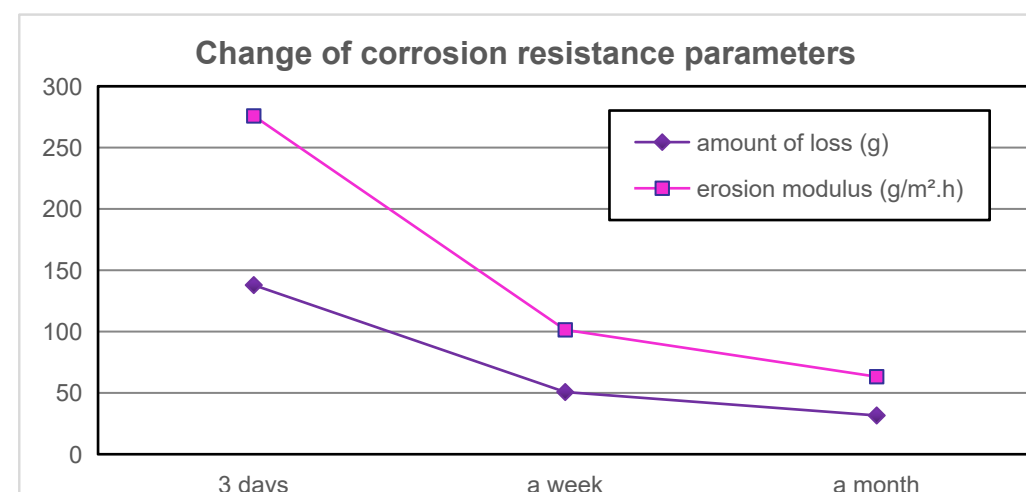
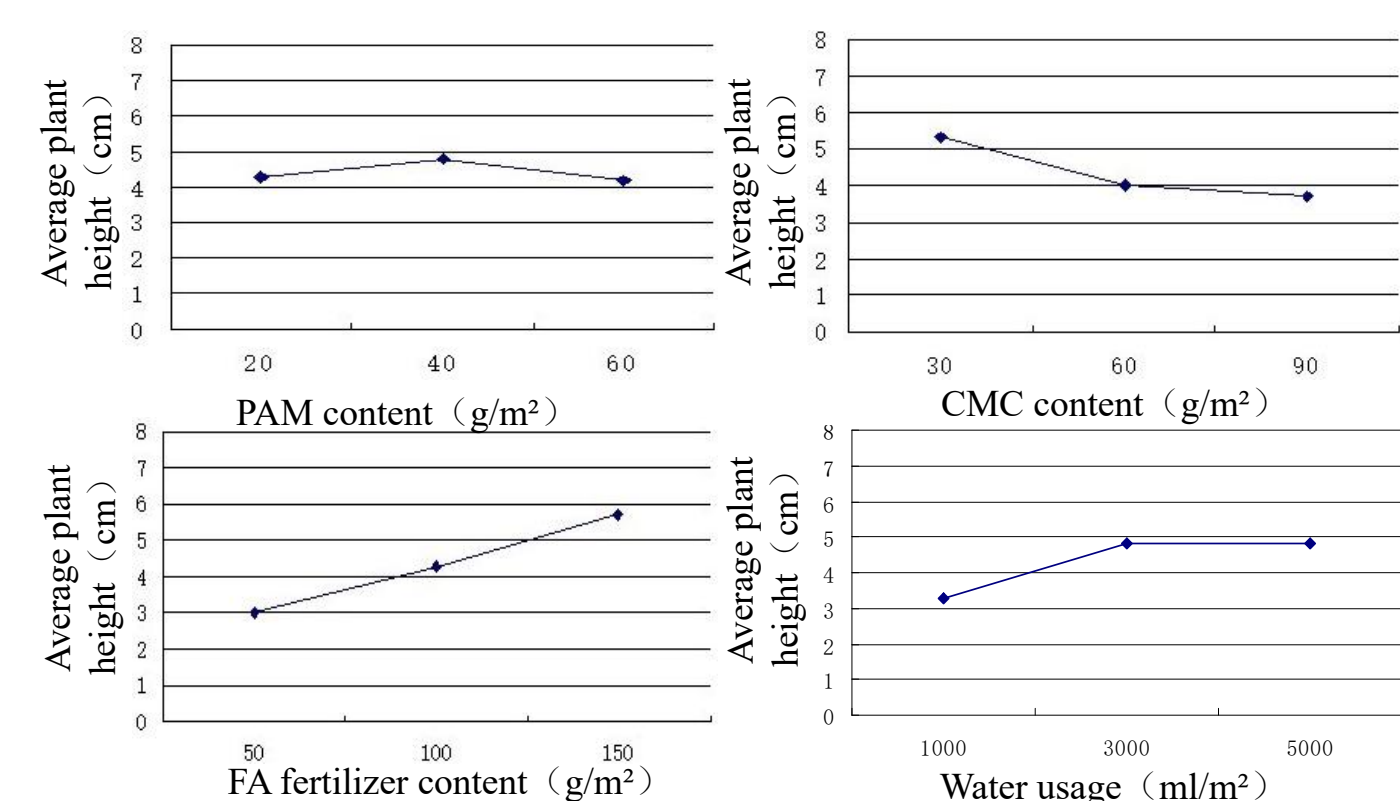
- Soil strength increases with the increase of PAM content, and when PAM content exceeds a certain value, the viscosity of the binder increases, not easy to disperse in the soil, but reduce the strength of the substrate.



Rainfall test and corrosion resistance test

- Under extreme rainstorm conditions, the loss amount is only 0.1%, Long-term rainstorm erosion will not destabilize itself, nor affect the germination of grass seeds and the growth of vegetation.

Analysis of influence of vegetation growth



3. summary

- Through more than 100 groups of proportioning test, the composition and ratio of ecological slope protection concrete are determined.
- The nutrient content of ecological concrete with the optimal ratio is much higher than that of fertile farmland soil.
- It has good shear strength, which is helpful to maintain the long-term stability of slope and create a long-term soil environment for plants.

Field slope ecological protection test

1. PCF ecological concrete components

- The thickness of PCF Eco-concrete is 10cm;
- Planting loam + humus: 150kg/m² (planting loam 80%, humus 20%, planting loam requires a certain viscosity);
- Sand and stone aggregate: 20kg/m²;
- Fiber: straw, edible fungus residue, crushed to 10 ~ 15mm long: 1.5kg/m²;
- Polymer material regulator: PAM40g/m²+CMC60g/m²;
- FA fertilizer: 150g/m²;
- Grass seed selection: ryegrass, bluegrass, tall fescue, alfalfa, white clover seed combination;
- Concrete: 11kg/m²;
- PH controlling agent: 2kg/m².

2. Field test construction steps

- Construction process: Surface clearing→Hanging net→Spraying eco-concrete→Post curing.
- The root system, eco-concrete and rock soil mass have formed a whole. The fibrous root system plays a stabilizing and reinforcing role in connecting rock mass, while the main root system forms the plant anchor rod and plays an anchoring role.



3. Observation and analysis of field test results



4. Tracking and Testing Results of slope ecological protection test

- Three years later, the natural succession of exotic slope vegetation and native species is realized, with a large number of shrubs growing on the slope, reaching a height of 2.0-3.0m.
- PCF eco-concrete has super water holding capacity, and the extreme drought resistance days can reach 60 days.
- The nutrient content is far greater than that of fertile farmland soil, which can provide sustainable plant growth for more than 15 years.
- FA fertilizer makes the nitrogen, potassium and other nutrients in the slope easier to be absorbed by vegetation after magnetization.

New PCF ecological concrete slope protection technology

1. Concept and scope of application

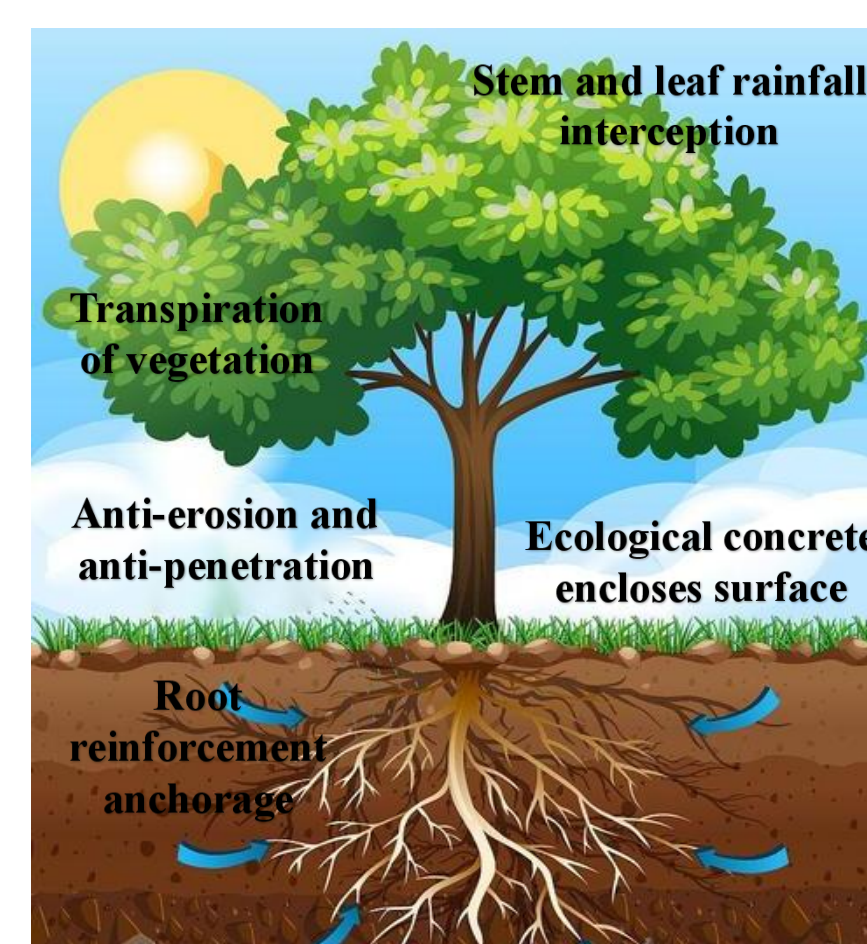
Slope drilling installation mat pier anchor, hanging protective net, spraying vegetation concrete, using cushion pier anchor deep anchor rock and soil, the protective net is close the slope to prevent rolling rock and collapse disasters, vegetation concrete quickly close the slope to reduce rain erosion and vegetation root anchorage and stem and leaf rainfall interception function, jointly form an active slope protection system.



2. Slope condition

- Type: Most kinds of soil and rock slopes.
- Slope rate: Not steeper than 1: 0.3, especially suitable (POE 1: 0.3 ~ 1: 0.75).
- High slope: Not more than 20m, can be multistage slope.
- Slope stability: The slope is stable overall.

3. Ecological protection mechanism



4. Technical effects

- The coverage rate reaches more than 90% in one month;
- Vegetation completely covers the masonry structure within 3 months;
- The integration succession with local vegetation is realized in 1-2 years.

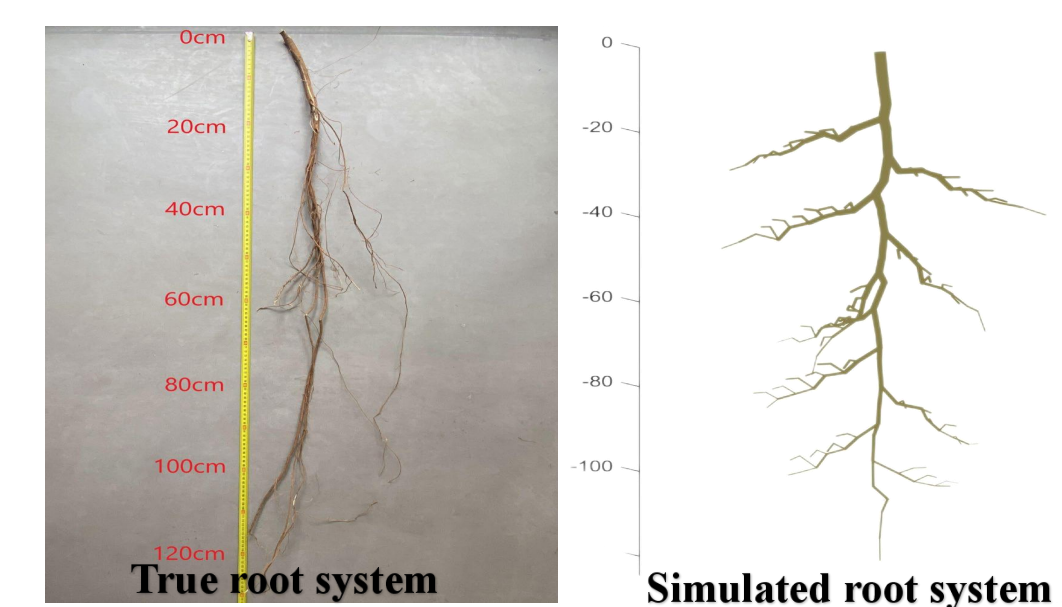


Root architecture and slope stability calculation method

1. Root configuration program: MechRoot

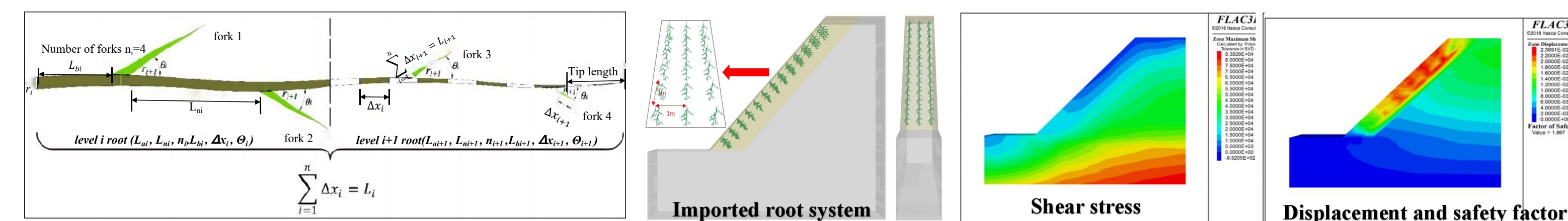
Based on fractal geometry and L system theory, a modeling program MechRoot is developed to realize gravity direction growth, random free bending, automatic bifurcation, dynamic growth changes of root length and diameter, and mechanical parameters change with root diameter in three-dimensional space.

- The simulated root was easy to distinguish the primary and secondary, and the diameter and length of root system were well restored.
- It has a high degree of imitation, and can better simulate the morphological and mechanical characteristics of root system in natural state.



2. Calculation effect

- The root model was generated by MechRoot and imported into FLAC3D to build the analysis model of the influence of shallow slope stability.
- The reinforcement effect of vegetation roots on slope was considered under 12 calculation conditions including different growth cycle, seed density and growth direction.



3. Calculation formula of ecological slope stability

- The fitting function relationship between safety factor and distribution density was obtained: $y = -0.0014x^2 + 0.0327x + 1.6827$.
- Therefore, $\tau_R = N(\tau_x + \tau_r)$, where N -- root distribution density coefficient.
- Combined with Bishop's method and WMM model, the calculation formula of the safety factor of the shallow stability of slope under the action of root reinforcement was deduced:

Value table of root distribution density coefficient

Distribution density plants/m ²	0	1	2	3	4	5-7	8-10	11-13	14-15	15-17	18
Distribution density coefficient N	0	0.45	0.76	0.9	1.0	0.9	0.71	0.63	0.55	0.45	0.36

$$F_s = \frac{4N \left(\frac{ar^b}{a_s} + \frac{4ar^b \mu m_x g}{\pi W^2 csc \theta} \right) [\sin(\psi - 45) \tan \phi + \cos(\psi - 45)]}{(M + m_a + \frac{1}{2} \gamma L \cos \psi) \sin \theta}$$

Conclusion

- The reinforcement of root system enhances the stability of slope, and the cost is saved by 10-20% and the construction period is shortened by more than half;
- The green active protective system of anchor shotcrete ecological concrete for slopes solves the problem of shallow slope sliding and rockfall protection, and carries out demonstration project construction to verify its long-term stability;
- Based on the "root-net-rock" slope reinforcement mechanism, a calculation method for the stability of ecological protection slope is proposed according to the influence factors such as slope height, slope ratio, vegetation root form and length;
- The main raw materials of this technology can be obtained locally. After the growth of slope protection vegetation, carbon sequestration and oxygen release will enhance the carbon sink capacity of the slope ecosystem, which is of great significance to promote the strategic demand of "carbon peak and carbon neutralization" in China.

References:

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- [2] Hua Xu, Xin-Yu Wang, et al. 2021. A 3D root system morphological and mechanical model based on L-Systems and its application to estimate the shear strength of root-soil composites. Soil & Tillage Research. 212, 105074.
- [3] Hua Xu, Hai-Li Yuan, et al. 2022. Influences of morphology and hierarchy of roots on mechanical characteristics of root-soil composites. Chinese Journal of Geotechnical Engineering. 44(5), 926-935.