The Impact of Vegetation Modelling Approaches on Soil-Plant-Atmosphere Interaction

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Abstract: Vegetation affects the soil's mechanical and hydraulic properties and its hydrological response to climate conditions. Vegetation can increase suction within the soil through transpiration. This increases the soil strength and Factor of Safety. It affects the infiltration rate and protects the soil against erosion. Nonetheless, serviceability problems may arise in densely vegetated slopes, primarily during dry periods, when water uptake via roots intensifies and the soil shrinks. This shrinkage is not fully recovered during wet periods, when the soil swells under the predominant effect of precipitation. Climate change is expected to exacerbate serviceability problems. For this purpose, a slope in Newbury, UK, has been chosen to analyse the effects of soil-plant-atmosphere interaction (SPAI). Currently, the slope is mostly covered with grass and shrubs, and its vegetation cover and soil properties are relatively uniform. In this paper, the hydraulic and mechanical properties of the Newbury slope were carefully selected and account for the SPAI in a fully coupled flow-deformation analysis. The effect of modelling vegetation dynamically or statically on the stability and serviceability of the slope was studied, providing valuable insights into the slope's behaviour under the applied climatic conditions.

Introduction

Cut slopes are important infrastructures as they support the engineering infrastructure (1,2). Slope stability and serviceability are affected by the interactions with the atmosphere and the vegetation cover, as these components change the distribution of pore water pressures (PWP) within the soil (3). If the suction within the soil reduces and the PWP increases, this will reduce the effective strength of the soil and its Factor of Safety (FoS) (4). Furthermore, the seasonal change in the water content within the soil will result in the shrinkage or swelling of the soil which will lead to serviceability issues (5).

One of the important components in modelling these geotechnical infrastructures is the boundary conditions and the modelling of the SPAI. An important parameter in modelling vegetation is the Leaf Area Index (LAI), which is the ratio of leaf to ground area, and which is affected by the climate and surrounding conditions. LAI evolves dynamically in time as a function of plant types (evergreen or deciduous) or as a response to environmental stress (e.g., leaf shedding due to drought). Ecosystem models can predict the dynamic evolution of LAI, which has been mostly neglected in engineering design. Consequently, LAI can affect the net inflow/outflow which is used as a boundary condition in the numerical analysis of cut slopes. Here, a closer look is taken at the difference when LAI is modelled dynamically, or when a constant average is applied. A cut slope located in Newbury, UK, was considered (6). The parameters needed to calculate the SPAI were obtained using an ecohydrological model (Tethys-Chloris)(7,8) and then implemented as an infiltration boundary condition in a geotechnical model (PLAXIS 2D) (9). This method was validated against existing data collected by (6).

Problem Definition

General

The cutting presented here is a cut slope located in Newbury, UK, with available field data from 2003 to 2008. An ecohydrological model (T&C) is used to capture water inflow/outflow and soil-plant-atmosphere interaction. This is coupled with a finite element geotechnical model (PLAXIS 2D) to conduct a numerical analysis. A stratigraphy of 3 m of Weathered London Clay (WLC), 46 m of Intact London Clay (ILC) and 23.65 m of Lambeth Group Clay (LGC) was adopted (10). Vegetation cover consists of 30% grass and 70% shrubs with a root depth of 150 mm and 800 mm, respectively. Hydraulic conductivities for WLC, ILC and LGC were 3.715E-3, 3.715E-4 and 3.715E-4 m/day, respectively. ILC and LGC were set to fully saturated and WLC was set to unsaturated following a Van-Genuchten curve which was interpreted by field data, with m = 1/3, n = 1.5 and α = 0.15 1/m. The residual and saturated degree of saturation were 0 and 1, respectively. The cut slope was excavated in 1997 (6) and was modeled for an initialization period from July 1997 to December 2008 and subsequently from 2021 to 2040.

Climate projections were considered under two vegetation covers: (A) dynamic grass and shrub cover, and (B) grass and shrub cover with constant LAI. The objective of modelling with constant LAI was to benchmark the effect of a dynamic vegetation and to show the effect of modelling LAI on both slope safety and serviceability, investigating whether calibrating vegetation parameters is necessary. The constant LAI was calculated as a monthly average of LAI from 1990 to 2008 and applied from 2021 to 2040.

Future climate projections were based on UK Climate Projections 2018 (UKCP18) (11), using the worst-case scenario, Representative Concentration Pathways 8.5 (RCP8.5), where no climate mitigation is used (12–14). Among all twelve UKCP18 scenarios, the wettest (W) and driest (D) extremes were selected, determined by calculating the net precipitation and evapotranspiration.

Ecohydrological Model (T&C)

The Tethys-Chloris ecohydrological model (T&C), is a mechanistic physics-based model that resolves the coupled water, energy, and carbon budgets on the land surface at an hourly time scale. Figs. 1 and 2 show the calculated parameters from T&C.

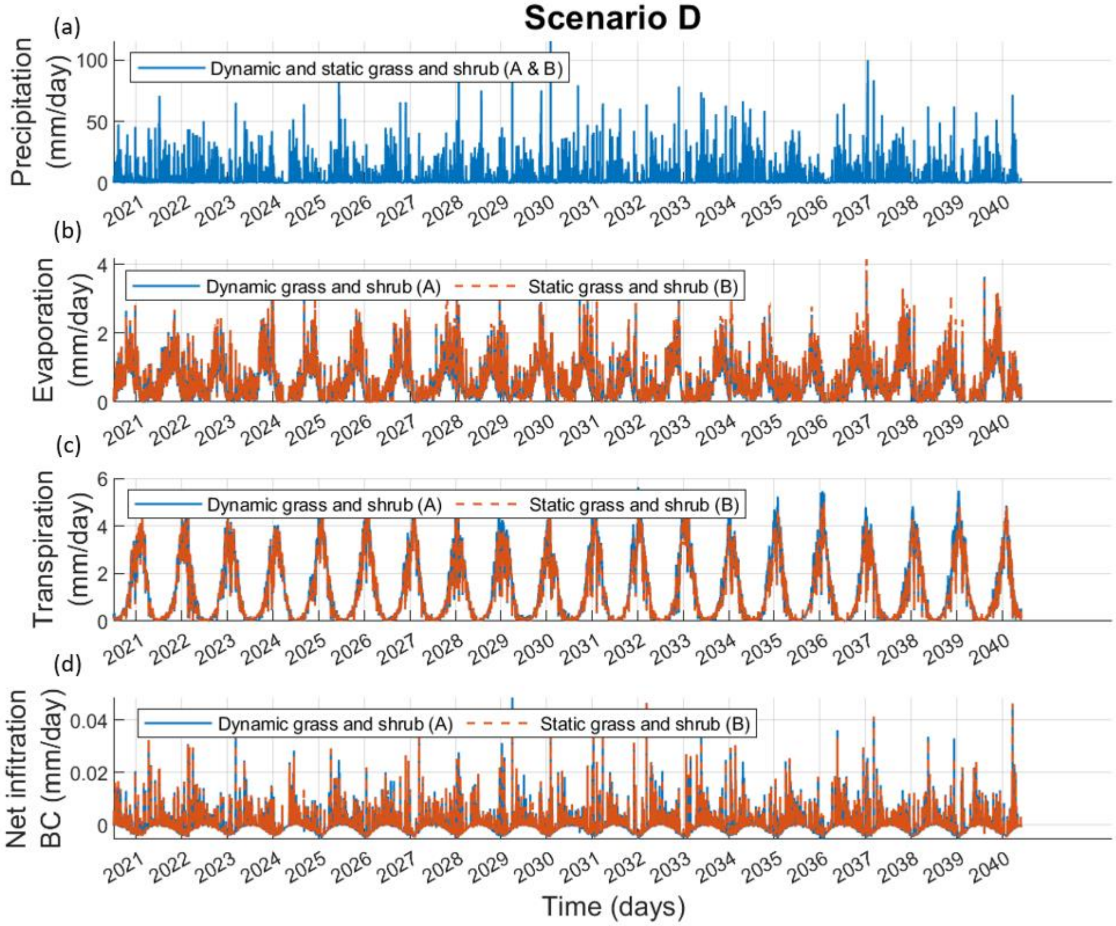

Figure 1: (a) precipitation, (b) evaporation, (c) transpiration and (d) net infiltration for both vegetation covers for scenario D.

Comparing both cases A and B, evaporation rates are nearly the same, with case B occasionally showing larger values. This is likely because case A, with dynamic vegetation, uses more water for plant growth, reducing water available for evaporation.

For case B, an average of LAI for the initialization period was calculated and repeated for the years 2021 to 2040. LAI is affected by climate, plant type, and weather. LAI can, in return, affect rainfall interception and evapotranspiration process (15,16) and radiation balances (reflection, absorbance, transmittance, and scattering) (17). Fig. 3 shows the LAI for both vegetation covers for scenarios D and W. Fig. 1 and 2 (c) indicate higher transpiration rates in case A due to its larger LAI, as shrubs comprise 70% of the vegetation cover. But these differences are small and balance out in the outflow (net of evaporation and transpiration), as seen in Figs. 1 and 2 (d).

Two-Dimensional Geotechnical Model

The 8 m high and 28 m wide slope was modelled in plane-strain with PLAXIS 2D. A Mohr-Coulomb failure criterion with isotropic small strain stiffness was used for all soil layers (18–

20) and the mechanical properties for the User Defined Soil Model (UDSM) are presented in Table 1 (21,22). A non-linear anisotropic variation of permeability with mean effective stress was used for all soil layers (23).

$$k_v = k_{y,ref} e^{ap'} \tag{1}$$

where $k_{y,ref}$ is the reference permeability along the y direction, k_v is the current vertical permeability, p' is the mean effective stress and a is a fitting parameter that was taken as 0.007 (24). A ratio of 10 has been chosen between horizontal and vertical permeabilities (25).

The coefficient of earth pressure at rest (K_0) was 1.2, 1.5 and 1.0 for WLC, ILC and LGC, respectively. The excavation was done in three undrained phases. The net infiltration for each analysis was implemented as a surface boundary condition using the infiltration boundary condition, which is a dual boundary condition, capable of switching from prescribed pore water heads to an inflow/outflow infiltration rate. The maximum allowable head was set to -0.5 m and the minimum was set to -100 m (26). The right and left boundary conditions were set to impermeable. The bottom boundary condition that coincides with chalk was set to seepage. A parallel analysis calculated the Factor of Safety (FoS), using strength reduction methods (27,28).

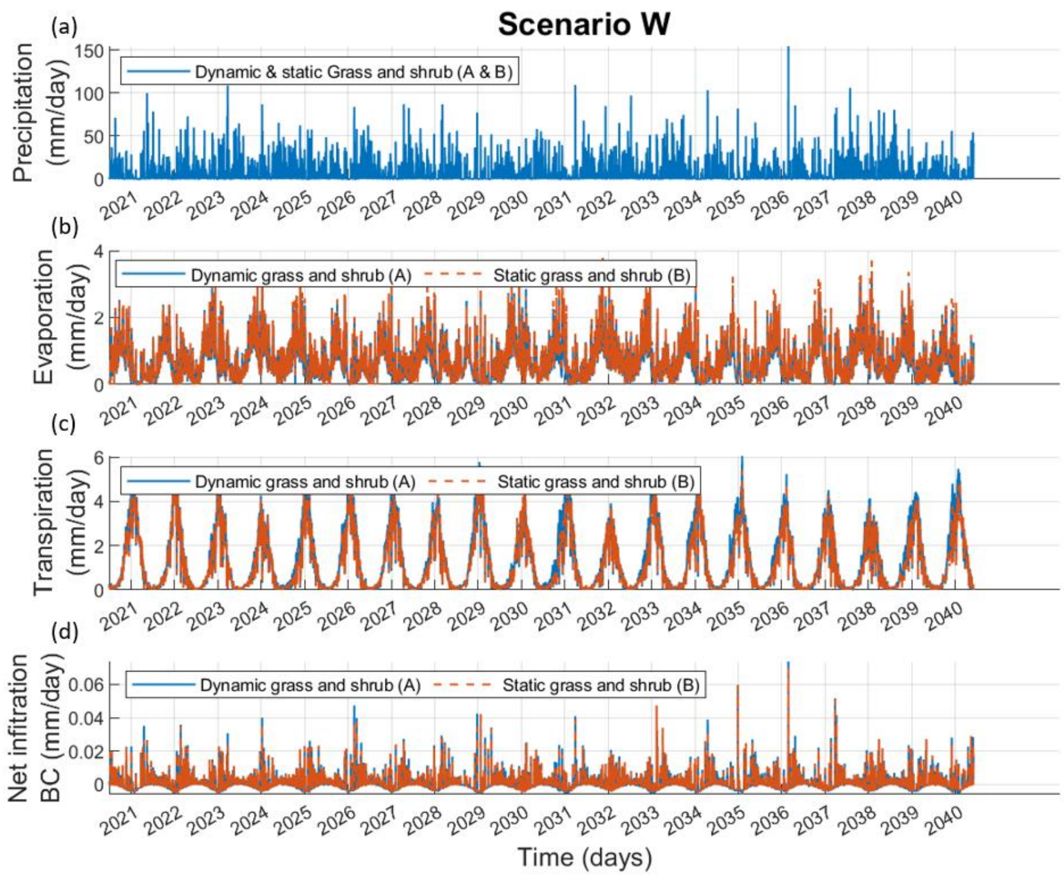

Figure 2: (a) precipitation, (b) evaporation, (c) transpiration and (d) net infiltration for both vegetation covers for scenario W.

Table 1: Mechanical parameters for all three soil layers.

UDSM Parameters		Values	UDSM Parameters		Values
$G_{ref}\ [kN/m^2]$	Reference shear modulus	955	$K_{ref}\ [kN/m^2]$	Reference bulk modulus	1665
$m_G\ [-]$	Nonlinearity of stress dependency of shear modulus	0.7	$m_K\ [-]$	Nonlinearity of stress dependency of bulk modulus	0.7
$a_0\ [-]$	Basic degradation parameter for G_{tan}	0.181E-3	$r_0\ [-]$	Basic degradation parameter for K_{tan}	0.3E-3
$b\ [-]$	Nonlinearity of degradation of G_{tan}	1.3	$s\ [-]$	Nonlinearity of degradation of K_{tan}	1.1
$RG_{min}\ [-]$	Normalized degradation limit for G_{tan}	0.05	$RK_{min}\ [-]$	Normalized degradation limit for K_{tan}	0.079
$G_{min}[kN/m^2]$	Minimum shear stiffness	2000	$K_{min}\ [kN/m^2]$	Minimum bulk stiffness	3000
$p_{ref}\ [kN/m^2]$	Reference pressure	1	$c\ [kN/m^2]$	cohesion	7
$\varphi\ [°]$	Angle of shearing resistance	23	$\psi\ [°]$	Dilatancy angle	0

Analysis Results

Safety and Factor of Safety

The safety analysis results for the four analyses, the two vegetation cover cases under the two climate projection scenarios, are shown in Figures 5 and 6. In scenario D, FoS for both cases are similar. In scenario W, FoS for more instances in case A, have either improved or is very close. However, in general the maximum difference for both cases is around 0.1. Simulating dynamic vegetation shows slight differences with a marginal change in FoS, but these are negligible. Overall, similar results can be reached with the constant LAI. This indicates that uncertainties in vegetation parameters affecting LAI can be disregarded and using a constant average LAI provides results comparable to a dynamic LAI. This removes one extra degree of uncertainty, simplifying the model, as T&C calculates all parameters in an hourly timescale, without compromising accuracy.

Serviceability

Fig. 7 shows the vertical displacement, for some time instances, for both vegetation covers against the distance from the excavation centerline to the toe of the slope (as highlighted in Fig. 4). Results show minimal differences in vertical displacement and maximum differential displacement for the two vegetation covers in both scenario D and W. It is commonly expected that vegetation and its extraction of water have a negative effect on serviceability. It is shown here that modelling vegetation with dynamic or static LAI has negligible effects on serviceability. For example, in August 2021, a slight difference in the vertical displacement, as can be seen in Fig. 7 (a), where the dynamic vegetation cover has a larger vertical displacement, but the maximum differential displacement remains nearly unchanged.

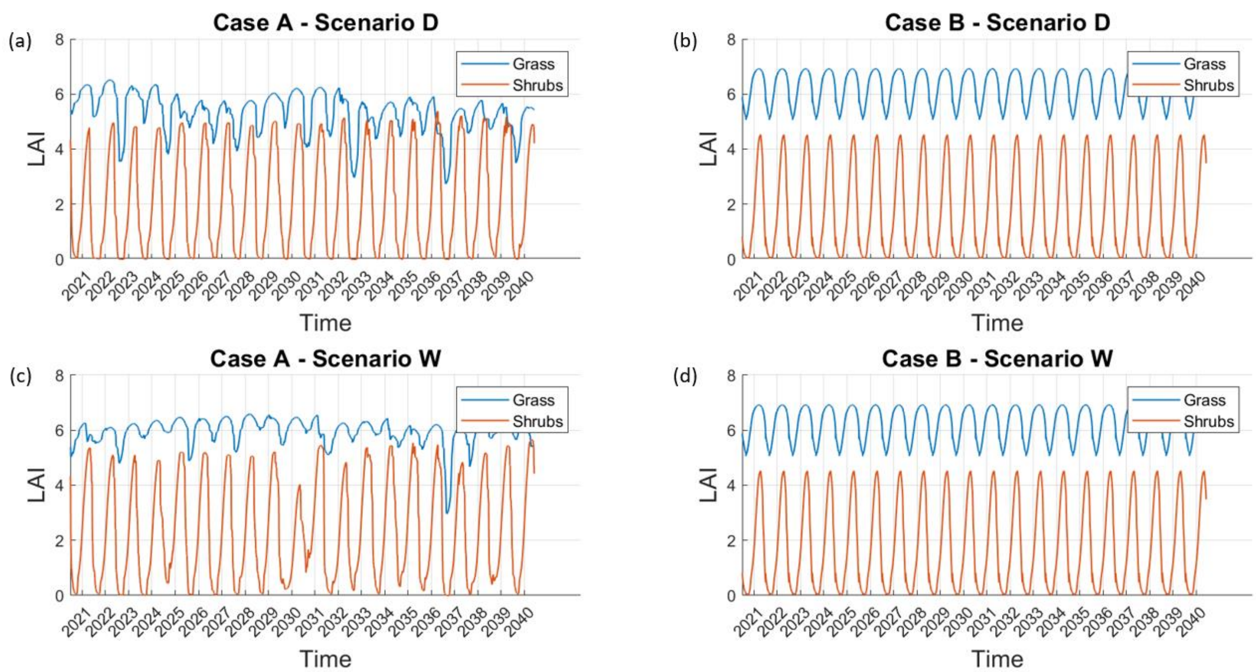

Figure 3: LAI for (a) dynamic and (b) static vegetation covers for scenario D and LAI for (c) dynamic and (d) static vegetation covers for scenario W.

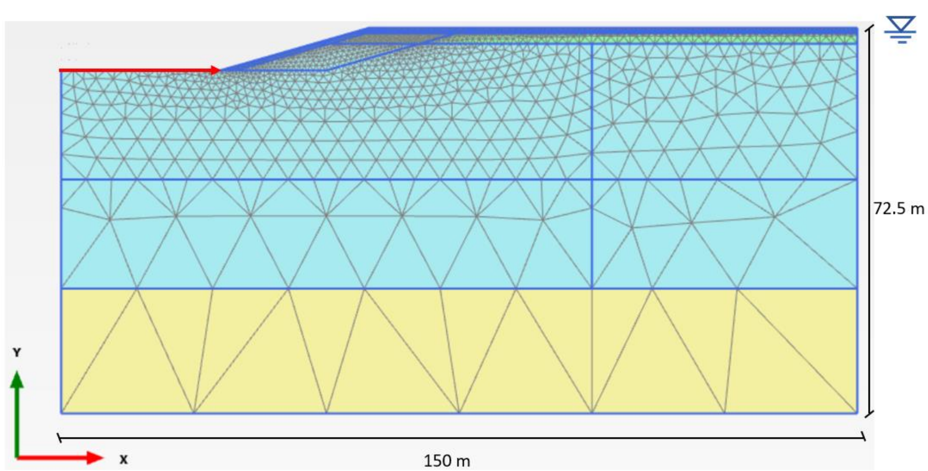

Figure 4: 2D model of the cut slope after excavation and its meshing.

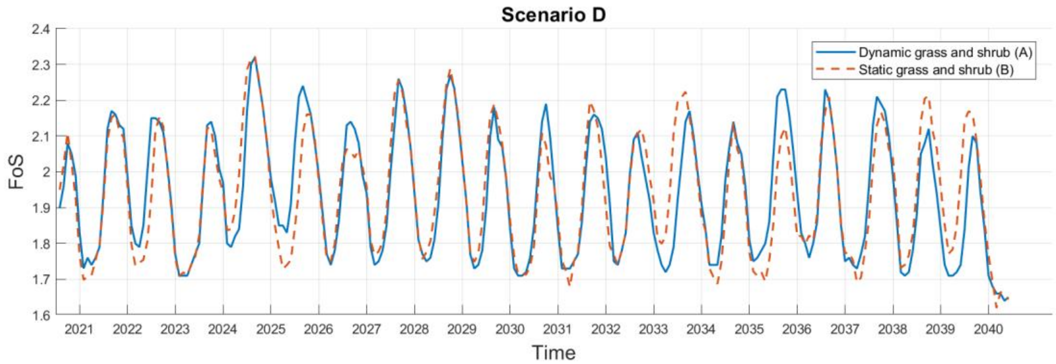

Figure 5: FoS for both dynamic and static grass and shrubs vegetation cover for scenario D.

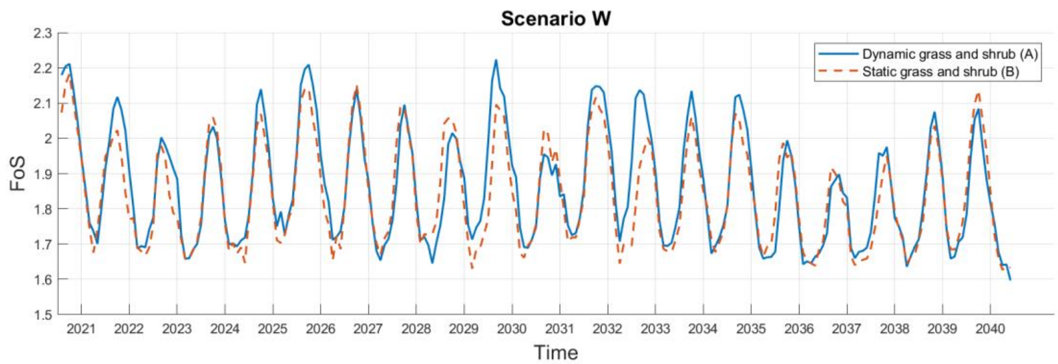

Figure 6: FoS for both dynamic and static grass and shrubs vegetation cover for scenario W.

Conclusions

This paper utilised an ecohydrological model, T&C, to calculate the inflow/outflow rates, which were applied to a geotechnical model of a cut slope in Newbury, UK, in PLAXIS 2D. The analysis compared two scenarios: (A) dynamic vegetation cover and (B) static vegetation cover under two extreme UKCP18 scenarios, to evaluate the impact of different vegetation modelling approaches. The results show minor differences in inflow/outflow parameters between the two cases, with the dynamic vegetation's LAI responding more realistically to climate conditions and its changes. However, this requires more data and time to calibrate the model to get the exact parameters. Therefore, the differences in safety and serviceability also remain small for the two cases. Since the differences in FoS and vertical displacement are small and can be neglected, the model can be simplified using the constant LAI. This requires less data and calibration. It is important to note that the constant LAI was averaged based on the dynamic LAI calculated by an initialization model that had run for 18 years; so, although the LAI did not change specifically to each year, it still captured seasonal and annual changes from 2021 to 2040, but they were not significant enough to show major differences in inflow / outflow and subsequently, safety and serviceability. It should also be emphasised that this depends on the vegetation cover and that the findings of this research cover only a small sample of vegetation and geometries. Therefore, the conclusions may not be directly applicable to other cases and further research is required to generalise the findings.

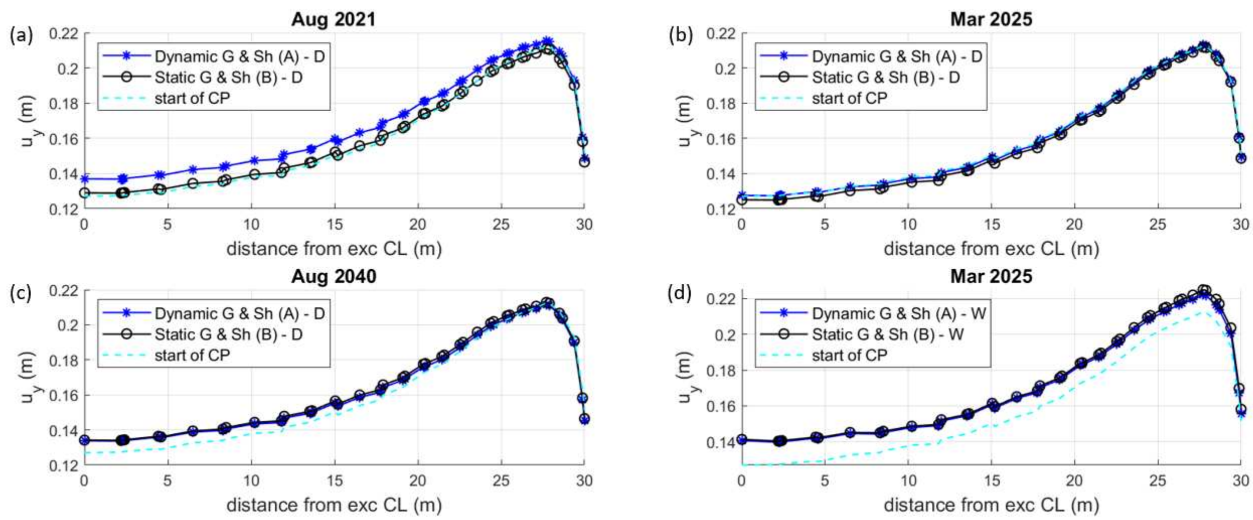

Figure 7: Vertical displacement against distant from excavation centerline until the slope's toe for months (a) August 2021, (b) March 2025 and (c) August 2040 for scenario D and (d) March 2025 for scenario W.

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