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Prediction of creep behaviour of Geogrid reinforced fill structure using numerical analysis: A Finite Element Method

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ABSTRACT

Various types of geosynthetics are utilized in conjunction with concrete panels, gabions encased in steel wire mesh, or as a wrap-up solution to stabilize steep slopes. Geogrids have become a prevalent choice for stabilization and reinforcement in the environmental and civil sectors. However, due to their characteristics, they are susceptible to experiencing increased displacements in the long term as a result of creep deformations due to ageing under sustained loads. The degradation in the stiffness of reinforced fill structures is in fact primarily attributed to the impact of creep behaviour. Visco-elastic geogrid model and hardening soil model can be combined and applied in the prediction of time-dependent deformations of the geogrid-soil composite. In this study, extensive numerical analysis has been conducted to examine the deformation behaviour of geogrids over longer periods. With the information of technical details regarding geogrids from the manufacturer, we can have input parameters used by Plaxis2D, and then with the help of the Visco-elastic (time-dependent) model, we can predict the long-term behaviour of the geogrids. The Pull-out tests supported the interface values between the geogrid and the soil. The scope of this paper has been limited to showing preliminary results of a first stage of a Ph.D. study by predicting the creep strain of geogrid in long-term. The results of this study will aid in predicting the future creep behaviour of reinforced fill structures through the utilization of the Finite Element software, PLAXIS 2D.

Keywords: Geogrid, Reinforced Fill Structure, Creep, Finite element analysis, Visco-elastic

1 INTRODUCTION

In addition to being used as a reinforcement for walls and slopes, geosynthetics are also used to strengthen weak foundations and provide structural stability throughout their service life (Jiang et al., 2019). In most of the studies, geosynthetics were modelled as a linear elastic element, but in reality geosynthetics are not linear elastic but rate dependent materials (Bathurst & Naftchali, 2021). The long-term mechanical properties of geogrids like creep and stress relaxation can be established using the viscoelastic-plastic model that can replicate the attenuation creep (Du et al., 2022).

There are always some challenges involved in the design parameters of the geosynthetics reinforcement. For a specific project, different stakeholders have different goals to achieve. The manufacturer is interested in quality management and consistency of the product. The designer is interested in the strength and the parameters involved to satisfy ultimate and serviceability limit states. The contractor is concerned that he can identify the product delivered to his site and ensure that it meets the requirements of the contract. The project owner is interested in the structure's behaviour after construction, the aesthetics and durability. The long-term creep strength of geosynthetic reinforcement is normally determined starting from the short-term tensile strength, and then considering factors for the effects of creep, installation damage and durability (Liu, 2019). Selection of backfill is very much important in geosynthetic reinforced fill structure (Yoo n.d., 2004).

During the construction of an embankment, the deformation in the geogrids can be measured by the in-situ instrumentation using among other methods optical fibres. The optical fibres are therefore intended to be permanently integrated into the structure (Denies et al., 2017). These reinforcements are usually under tension during the design stage of structures (Costa et al., 2016). The presence of creep in the soil and reinforcements can affect the performance of geosynthetic structures. This is due to the materials' viscous properties. To gain a deeper understanding of the time-dependent geosynthetic behaviour, various studies were conducted on different types of geosynthetic materials (Liu, 2019; Jia et al., 2021; Stevens et al., 2021). For retaining walls, deformation behavior is usually minimal in the granular soils as compared to soft soils (Soe et al., 2016) . However, the reinforcement materials used in these walls can experience time-dependent creep. This can affect their overall performance. Reinforced fill structures are now commonly used as alternatives to more traditional retaining solutions (cast-in-place and precast concrete) (Rimoldi et al., 2015; Doulala-rigby, 2020).

This current study explains the methodology to predict not only short-term deformations but also long-term deformations of geogrids using Visco-elastic (time dependent) model for the geogrids and the hardening soil model for the soil. The numerical finite element method program, PLAXIS 2D, was used to perform the numerical simulations.

2 FINITE ELEMENT MODELLING

This research elaborates a case study of reinforced fill structure modelled in Plaxis-2D, that was constructed in Belgium. The wall height was 20 m as shown in figure 1. The facing of the wall was made of gabions encased in wire-mesh with geogrids having spacing of 1m as shown in figure 1. In this way geogrids behaves as primary reinforcement while wire mesh as secondary reinforcement (Lelli et al., 2015). The backfill soil used has an angle of internal friction 400 & cohesion as 20 kN/m^2, to represent a lime treated soil. The foundation and backfill are characterized using a Plaxis hardening soil model.

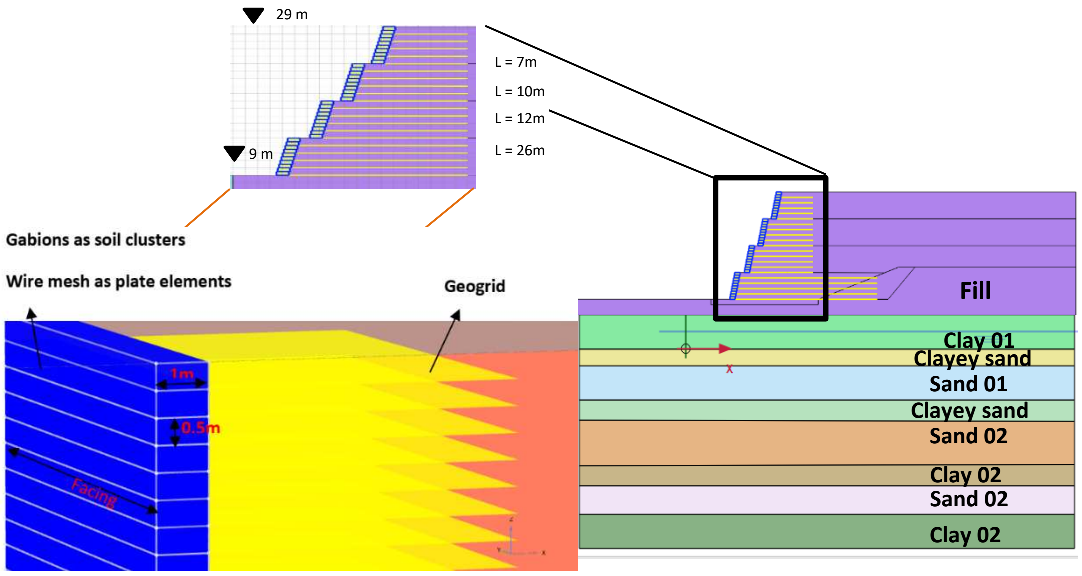

Figure 1. *Numerical model in PLAXIS*

The geogrids that were used as reinforcement have varied length as shown in figure 1. The creep effect of geogrid is simulated by the viscoelastic model (Du et al., 2022). Table1, below is showing the Input soil parameters for the Plaxis model of foundation soil and backfill soil while table 2, 3 & 4 are showing the Plaxis model input parameter of geogrid, gabion and wire mesh respectively.

Table 1. *Input soil parameters for the Plaxis model (HS = Hardening soil model)*

Soil type	Υ_{dry} **kN/m³**	Υ_{wet} **kN/m³**	**Plaxis soil model**	c'_{ref} **kN/m²**	**ϕ' [°]**
Fill	18	19	HS	20	40
Clay 01	16	19	HS	29	15
Clayey sand	18	19	HS	14.7	32
Sand 01	17	19	HS	02	30
Clayey sand	18	19	HS	12	30
Sand 02	19	20	HS	02	32
Clay 02	18	18	HS	08	20
Sand 02	19	20	HS	02	32
Clay 02	18	18	HS	08	20

Table 2. *Plaxis model input parameter of geogrid*

Property	**Units**	**Geogrid**
Axial Stiffness (EA)	kN/m²	3000
Axial force (N_p)	kN/m²	300
Plaxis material type	---	Viscoelastic (time-dependent)

Table 3. *Plaxis model input parameter of gabions*

Property	**Units**	**Gabion**
Unit weight	kN/m³	18
Angle of internal friction	Degree	40
Cohesion	kN/m²	27
Poisson's ratio	-	0.3
Elastic modulus	Mpa	40
Plaxis soil model	-	Mohr-Coulomb

Table 4. *Plaxis model input parameter of wire-mesh*

Properties	**Symbol**	**Units**	**value**
Axial stiffness	EA	kN/m	62832
Flexural Rigidity	EI	kNm²/m	0.251
Weight	W	kN/m/m	0.023
Poisson's ratio	V	-	0.3
Maximum bending moment	M_p	kN/m/m	0.23
Maximum axial force	N_p	kN/m	135
Cohesion	C	kN/m²	27

2.1 Modelling of geogrids in Plaxis 2D

In Plaxis 2D, a geogrid element is a type of line structure that has no flexural stiffness. A geogrid element can only undergo tension, not compression. In the PLAXIS 2D version, the user can specify the normal elastic stiffness of a geogrid element (Edition, 2020). If the isotropic parameter is ticked, only one stiffness is needed. On the other hand, if the option is not selected, two values are entered for anisotropic geogrids, as:

- EA_1, EA_2: Normal elastic stiffness (in-plane) & (out-of-plane) respectively

Under elastoplastic option, the strength parameters would be:
- $N_{p,1}$, $N_{p,2}$: Maximum force (in-plane) & (out-of-plane) respectively

If the geogrid material is set to the elastoplastic ($N - \varepsilon$) option, a strain-dependent strength is specified through a table, as follows with:
- $N_1 - \varepsilon_1$, $N_2 - \varepsilon_2$: The strain-dependent strength diagram (in-plane) & (out-of-plane) respectively

Visco-elastic (time dependent) model should be chosen, if to consider the reduction of strength with time i.e. creep
- EA_1 short, EA_2 short: Normal elastic stiffness during an instantaneous (initial) strain increment (in-plane) & (out-of-plane) respectively
- EA_1 long, EA_2 long: Normal elastic stiffness during a long term (infinite) strain increment (in-plane) & (out-of-plane) respectively
- $N_{p,1}$, $N_{p,2}$: Maximum force in 1-direction (in-plane) & (out-of-plane) respectively

2.2 Retardation time

It is defined as, in a creep test the time required for a strain to reach its maximum value under constant stress provided the same strain rate as of its initial value. As per Plaxis2D manual, retardation time is the time required for a linear extrapolation of initial creep to reach the long-term creep level (Figure 2).

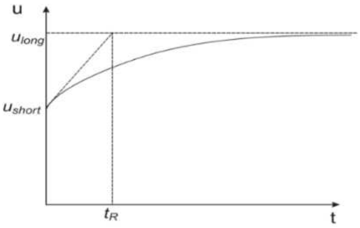

Figure 2. *Displacement versus time in a creep test (Plaxis2D, 2019a)*

To understand the whole phenomena of how viscoelastic model helps to predict the long-term creep strain of a geogrid, consider the Kelvin-Voigt element as shown in figure 3.

$$EA_0 = EA_{short} \tag{1}$$

$$\frac{1}{EA_0} + \frac{1}{EA_1} = \frac{1}{EA_{long}} \tag{2}$$

$$\eta = EA_1 \text{ x Retardation time} \tag{3}$$

Where η is viscous damping, EA_0 and EA_1 are internal stiffness used in the geogrid.

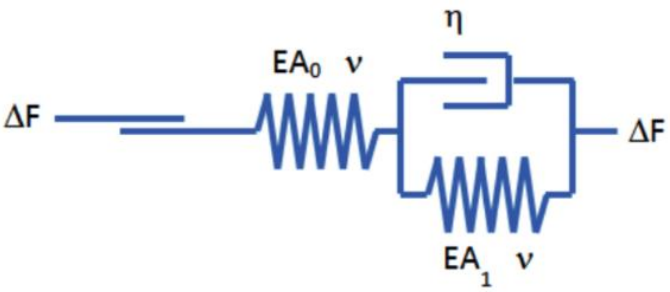

Figure 3. *Kelvin-Voigt single element*

$$t_{retardation} = \frac{\eta_1}{E_1} \tag{4}$$

$$E_{short} = \frac{1}{EA_0} \tag{5}$$

$$E_{long} = \frac{F}{U_{long}} \tag{6}$$

$$U_{short} = \frac{F}{EA_{short}} \tag{7}$$

$$U_{long} = \frac{F}{EA_{long}} \tag{8}$$

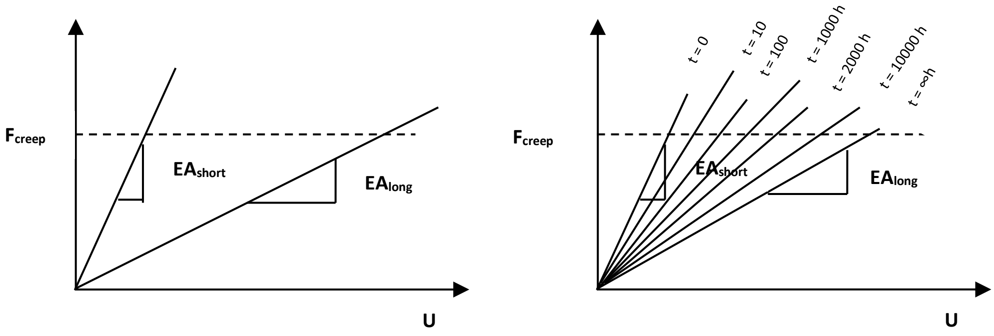

Figure 4. *Force versus displacement showing EA_{short} & EA_{long}*

As shown in figure 4, by measuring the corresponding displacement at any time, we can find the short term as well as long term stiffnesses.

2.3 Determination of Parameters

The design strength of the geogrids T_{all} can be obtained by the following equation (Koernel, 2005):

$$EA = \frac{T_{ult}}{S} \tag{9}$$

$$T_{all} = \frac{T_{ult}}{RF_{CR} \times RF_{ID} \times RF_{CBD}} \tag{10}$$

where: T_{ult} = short term ultimate tensile strength, RF_{CR} = reduction factor due to creep, RF_{ID} = reduction factor for installation damage, $RF_{CBD} = RF_{CD} \times RF_{BD}$, RF_{CD} = reduction factor for chemical damage,

RF_{BD} = reduction factor for biological damage.
For long term strength, the reduction factors can be obtained as per BS 8006 Part-1 (British Satndard, 2016), and BBA (British Board of Agreement) certification of the manufacturer.

$$EA_{long} = T_{ult}/4\% \tag{11}$$

$$N_p = T_{all} \tag{12}$$

$$EA_{short} = N_p/4\% \tag{13}$$

3 PULLOUT TEST FOR GEOGRID-SOIL INTERFACE

The pull-out test is used to determine the interaction between the soil and the reinforcement in the anchorage zone of a reinforced fill structure. It can be done by measuring the pull-out force and the displacement of the reinforcement. Studies have shown that the size, shape, and thickness of the reinforcement, as well as the test box's mesh size, can influence the characteristics of a reinforced soil interface (Teixeira et al., 2007; Esfandiari & Selamat 2012). The orientation of the geogrid has also has also an impact on the design of reinforced structures (Gupta et al., 2014).
The purpose of the tests is to pull elements built into a test box. As shown in figure 6, the upper load imposed by pressure pads is exerted on these elements. The elements are pulled by means of hydraulic jack. When the elements are pulled out, the force is registered by a force sensor. The distance over which elements are extended is measured by LVDT. The test box consists of steel plates which are welded together to form a box with a height of 61cm, a width of 77cm and a length of 115.5cm. The internal dimensions of the box are 1m long, 0.60 wide and 0.605m high. This structure provides the possibility and space to install both the LVDT's and the force sensor and serves as a reaction frame for the hydraulic jack. The text box is filled with sand and the geogrids that are pulled. The required air pressure for the pressure pads is provided by a compressor. A coupling is provided between the force sensor and the built-in elements which makes it possible to pull the elements properly. Figure 5, below, is showing the interface between soil and reinforcing elements. Table 5 is showing the values of friction coefficient for wire mesh & geogrid respectively (Khan & Di Emidio, 2023).

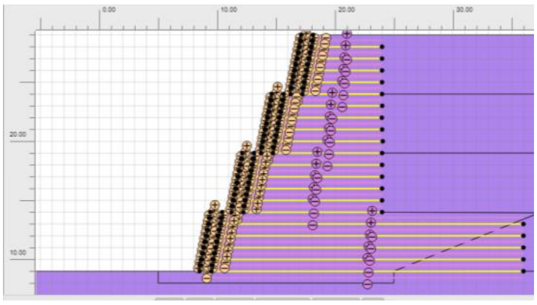

Figure 5. *Interaction between soil & reinforcing elements*

Table 5. *tan δ / tan φ friction coefficients for wire mesh products & geogrids*

Soil	tan δ / tan φ (wire mesh)	tan δ / tan φ (Geogrid)
Clay	0.3	0.4
Silt	0.5	0.7
Sand	0.65	0.9
Gravel	0.9	0.9

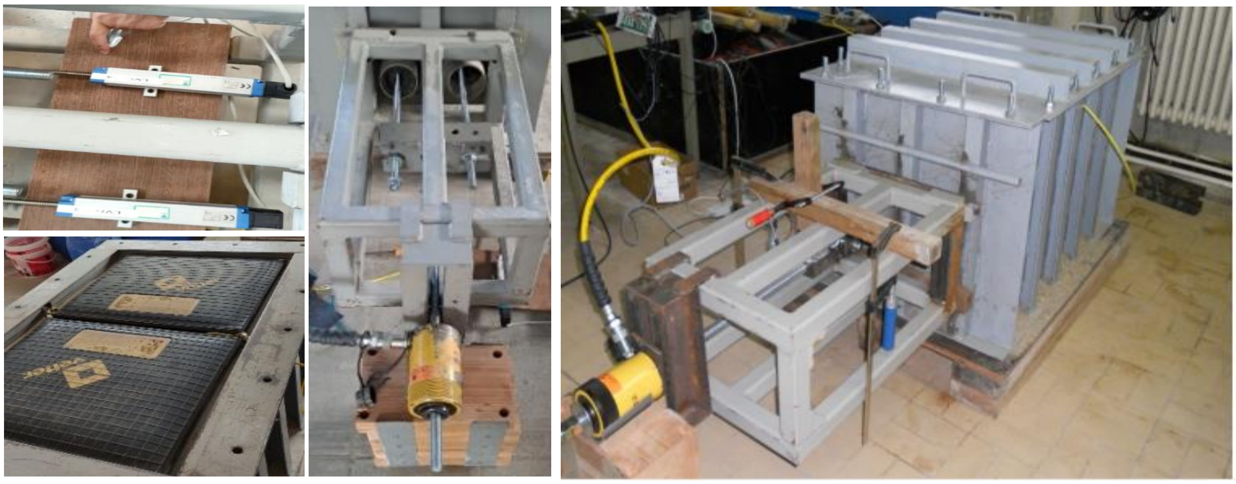

Figure 6. *Pull out test setup*

4 RESULTS & DISCUSSION

The present study investigates the stability of a reinforced fill structure and the prediction of creep behavior of geogrids. Figure 7 shows the factor of safety, which indicates the stability of this reinforced fill structure. Figure 8 comprises six graphs, that plot time on the x-axis and horizontal deformation on the y-axis, with retardation time serving as the third variable. Retardation time is the time required for the strain, under constant stress, to reach its maximum value while maintaining a constant rate of strain. In this study we assume 50, 100 & 200 as retardation time. The analysis was observed over a time span of one year and three years. The graphs are showing a clear trend of increasing deformation with time. However, an inverse relationship between retardation time and deformation is observed. These findings provide insights into predicting the creep effect of geogrids and have practical implications for their use in various applications. Further research may explore the underlying mechanisms behind the observed phenomena to optimize the use of geogrids.

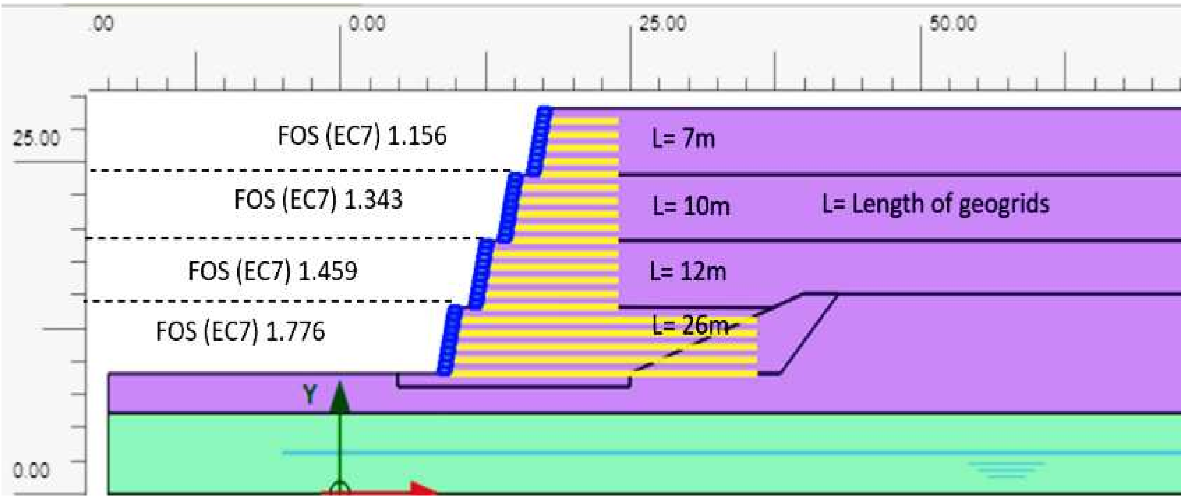

Figure 7. *Factor of Safety*

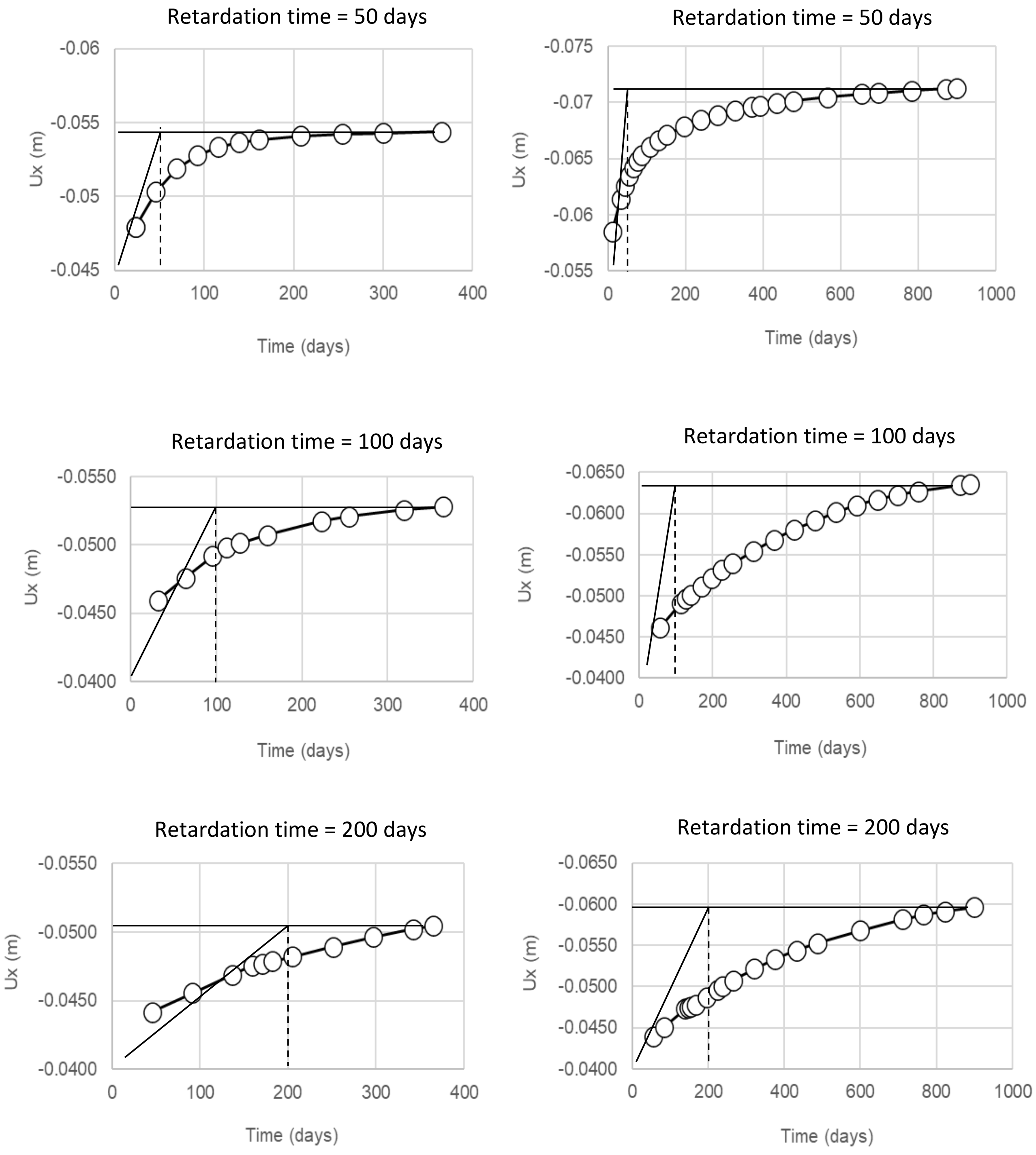

Figure 8. *Deformation Vs Time*

5 CONCLUSIONS & RECOMMEDATIONS

An encouraging usage of geogrids is highlighted in recent years as an alternative to the conventional retaining solutions. In this paper, the authors illustrate the method of predicting the long-term creep strain data using Plaxis2D. With the information of technical details regarding geogrids from the manufacturer we can have input parameters used by Plaxis2D and then with the help of Visco-elastic (time-dependent) model, we can predict the long-term behavior of the geogrids. The interface values between the geogrid and the soil were supported by the Pullout tests.

To conclude, it is ascertained that in the future, additional work is ongoing to assess the validity of these values. The scope of this paper has been limited to show preliminary results of a first stage of a PhD study, by predicting the creep strain of geogrid in long-term, however a study with the combination of more reinforcement configurations, backfills and structural geometries has been addressed for future publications. Also, these deformation values should be compared with the in-situ measurements of the deformations of the geogrids at site, which will help us to validate this study and adapt this practice for further work. Also, use of others software like Abacus is foreseen to implement the long-term interaction between geogrids and soils.

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